GEOLOGY OF MILLARD COUNTY, UTAH

by

Lehi F. Hintze and Fitzhugh D. Davis

BULLETIN 133
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
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Cover photo: East face of the Canyon Mountains north of Scipio. Photo by Ken Hamblin.

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UTAH GEOLOGICAL SURVEY

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Frontispiece. *Northern House Range as viewed looking north from Tatow Knob. Fish Springs Range on central skyline. Small darker hill at left middle is Swasey Mountain (not Swasey Peak) which marks the northernmost hills of the House Range beyond which Sand Pass lies between the two ranges. Fish Springs Flat is the white desert on the right beyond the upper ledges of the House Range. Tule Valley is located to the left of Swasey Mountain. Picture was taken in 1901 by W.D. Johnson, topographer for geologist G.K. Gilbert. Photo from U.S. Geological Survey Field Records Library, Denver, Colorado.*

FORWARD

by
Lehi F. Hintze

This bulletin serves not only to introduce the non-geologist to the rich geology of Millard County, but also to provide professional geologists with technical information on the stratigraphy, paleontology, and structural geology of the county.

Millard County is unique among Utah's counties in that it contains an exceptionally complete billion-year geologic record. This happened because until about 200 million years ago the area of present-day Millard County lay near sea level and was awash in shallow marine waters on a continental shelf upon which a stack of fossil-bearing strata more than 6 miles (10 km) thick slowly accumulated. This bulletin summarizes what is known about these strata, as well as younger rocks and surficial deposits in the county, and provides references to scientific papers that describe them in greater detail.

Because Millard County contains superb, world-renowned fossil assemblages of Middle and Late Cambrian, Early Ordovician, and Mississippian geologic ages, many fossils are illustrated in this bulletin. The House Range, in particular, is world-famous among paleontologists for its wonderful sequence of Middle and Late Cambrian trilobite faunas; and the Wheeler Shale at Antelope Spring near Swasey Peak has yielded more whole trilobite specimens than any other locality in the world. Early Ordovician fossil-bearing strata near Ibex in western Millard County serve as the North American standard reference section for trilobite, conodont, and other fossils of this age.

Structural geologic events dominated the record in Millard County after about 200 million years ago, which caused the geologic record since that time to be incomplete and spotty. Beginning in Jurassic time, Millard County was uplifted from the sea and then compressed into a north-south-trending mountain chain called the Sevier orogenic belt. Erosion of this belt removed most of the upper Paleozoic rocks from the area of the present-day Sevier Desert, and eastward-flowing streams deposited the eroded material as mostly Cretaceous sandstone and shale to the east in Utah. Although the Sevier mountains no longer exist, many Sevier-age folds and faults are preserved in Millard County.

After the Sevier mountain building, between about 40 and 20 million years ago, Millard County was partially covered by ash and lava from volcanoes in the Drum Mountains in Juab and Millard Counties, in the Wah Wah and San Francisco Mountains mostly in Beaver County, in the Marysvale volcanic field in Beaver, Piute, and Sevier Counties, and from calderas on the Utah-Nevada border north of Caliente, Nevada. Basin and Range extension began about 17 million years ago, with block faulting creating the familiar, present-day, alternating, north-south-trending mountain ranges and valley basins between central Utah and the Sierra Nevada. Fault scarps in surficial deposits in the valleys indicate that block faulting is ongoing, and earthquakes like those that produced these fault scarps could shake Millard County.

Because more than two-thirds of Millard County is covered by surficial deposits in valley basins, the subsurface geology, particularly under the wide basin of the Sevier Desert, has been the subject of considerable investigation and interpretive effort. Subsurface data incorporated into this bulletin include: seismic reflection profiles (used to look for oil and gas); gravity profiles and a new gravity contour map; and borehole data from oil and gas, mineral, geothermal, and water exploration wells.

This bulletin is the product of over a half century of personal geologic studies in Millard County and contributions from numerous other researchers. Geologic maps covering Millard County have been published separately by the Utah Geological Survey as the Delta, Richfield, Tule Valley, and Wah Wah Mountains North 30′ x 60′ (1:100,000-scale) quadrangles. These companion maps and this bulletin portray the geology of Millard County more completely and accurately than any previously published work.

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Note on usage of geographic names for geologic features

Decisions made by the U.S. Board on Geographic Names in recent years have changed the spelling or the description of the following features in Millard County:

Older map usage	New Official usage
Canyon Range	Canyon Mountains
Pavant Range	Pahvant Range
Hell'n Maria Canyon	Hell N' Moriah Canyon
Needle Range	Mountain Home and Indian Peak Ranges

The older geographic names have been applied to geologic features that have become widely used in published geologic reports.

Example

Canyon Range thrust
Pavant thrust
Hellnmaria Member of the Notch Peak Formation
Needles [sic] Range Group

The geologic application of these names will be used in this report retaining the original designations. The recent official geographic name changes will be used in this report for the geographic features. This results in dual name usage such as:

Example

The Canyon Range thrust is in the Canyon Mountains.
The Pavant thrust is in the Pahvant Range.

GEOLOGY OF MILLARD COUNTY, UTAH

by

Lehi F. Hintze and Fitzhugh D. Davis

INTRODUCTION

by Lehi F. Hintze

Millard County is unique among Utah's counties in containing an exceptionally complete billion-year record of how it came to look as it does today, as interpreted from the bedrock exposed in its mountain ranges and the soils of its desert basins.

Until about 200 million years ago the area of present-day Millard County was part of a continental shelf upon which a stack of fossil-bearing, shallow marine sediments more than 6 miles (10 km) thick had slowly accumulated. Then, in Jurassic time, tectonic forces in western Nevada, along the juncture of the North American continental plate and plates of the Pacific Ocean basin, initiated a series of geologic events that have produced Millard County's present landscape. Since this time, the area was successively: covered by Jurassic sand dunes; locally intruded by Jurassic granite; folded and faulted into a now-vanished Cretaceous mountain belt; covered by lava and ash from Eocene and Oligocene eruptive centers in eastern Nevada and western Utah; cut by faults beginning 17 million years ago that created present valleys and mountains; and, finally, 20,000 to 12,500 years ago, largely covered by fresh-water Lake Bonneville, which left its legacy of shorelines and its remnant, Sevier Lake. The level of Lake Bonneville fell below the threshold of the "Old River Bed" (located in Juab County between the Keg and Simpson Mountains) about 12,500 years ago. After that the lake waters in Millard County receded to within the Sevier Desert basin, which only intermittently supported a body of water in Sevier Lake, because of decreased rainfall and warmer climatic conditions at the end of the Ice Age.

Purpose and Scope of This Bulletin

This bulletin is a comprehensive summary of the geology of Millard County. It serves not only to introduce the non-geologist to the rich geology of this area, but also to provide professional geologists with a complete published reference database for this information.

This text is supplemented by an updated display of the county's geology shown on four 1:100,000-scale geologic maps (Hintze and Davis, 2002a-c; Hintze and others, 2003) (figure 1). Non-geologists will need to become familiar with the system of geologic map symbols that show the age of a map unit first (for example, capital "T" means Tertiary) and secondly, the lower case letters that identify a particular package of rocks (for example, lower case "f" for the Flagstaff Limestone). Thus, the geologic map symbol Tf stands for Tertiary Flagstaff Limestone. The more than 200 map units on the four geologic maps represent a refinement of more than 300 units used by various authors of the 151 source maps used in these compilations. The base maps for many of the geologic source maps are the 7$^{1}/_{2}$-minute (1:24,000-scale) topographic maps shown on figure 2.

Much new geologic field mapping was done in the preparation of this bulletin. Fitzhugh Davis and C.G. "Jack" Oviatt mapped the Quaternary deposits covering the basin floors and comprising more than two-thirds of the county's area. Several bedrock areas were newly mapped and all previous maps of bedrock areas were field-checked by L.F. Hintze. The companion maps to the bulletin show the geology of Millard County more accurately than any maps previously available.

We hope that the information available in this report will enable wise use of Millard County's natural resources, evaluation of its lands for various purposes, and abatement of geologic hazards to which certain areas may be naturally prone. Rockhounds and fossil collectors, too, may become better able to understand the significance of Millard County's outstanding geologic heritage.

Geography and Physiographic Divisions

Most of Millard County is within the Great Basin subdivision of the Basin and Range physiographic province of the western United States (Fenneman, 1946). Fenneman included the Pahvant Range and Valley Mountains on the eastern edge of the county within his High Plateaus of Utah subdivision of the Colorado Plateaus physiographic province. Interstate 15 on figure 3 is slightly west of Fenneman's (1946) boundary between the provinces.

Fenneman's boundary between the Basin and Range Province and the Colorado Plateaus Province is strictly based on geomorphology, which, in turn, is largely controlled by geologic structure. In general, structures within the Great Basin are much more complexly cut by faults than those within the Colorado Plateaus. But the change in structural style from basin to plateau is not the knife-edge line that Fenneman's physiographic boundary might suggest. Rather, the north-south normal faults of late Cenozoic age which are typical of the Great Basin are also present in the Wasatch Plateau east of Salina, 50 miles (80 km) east of the provin-

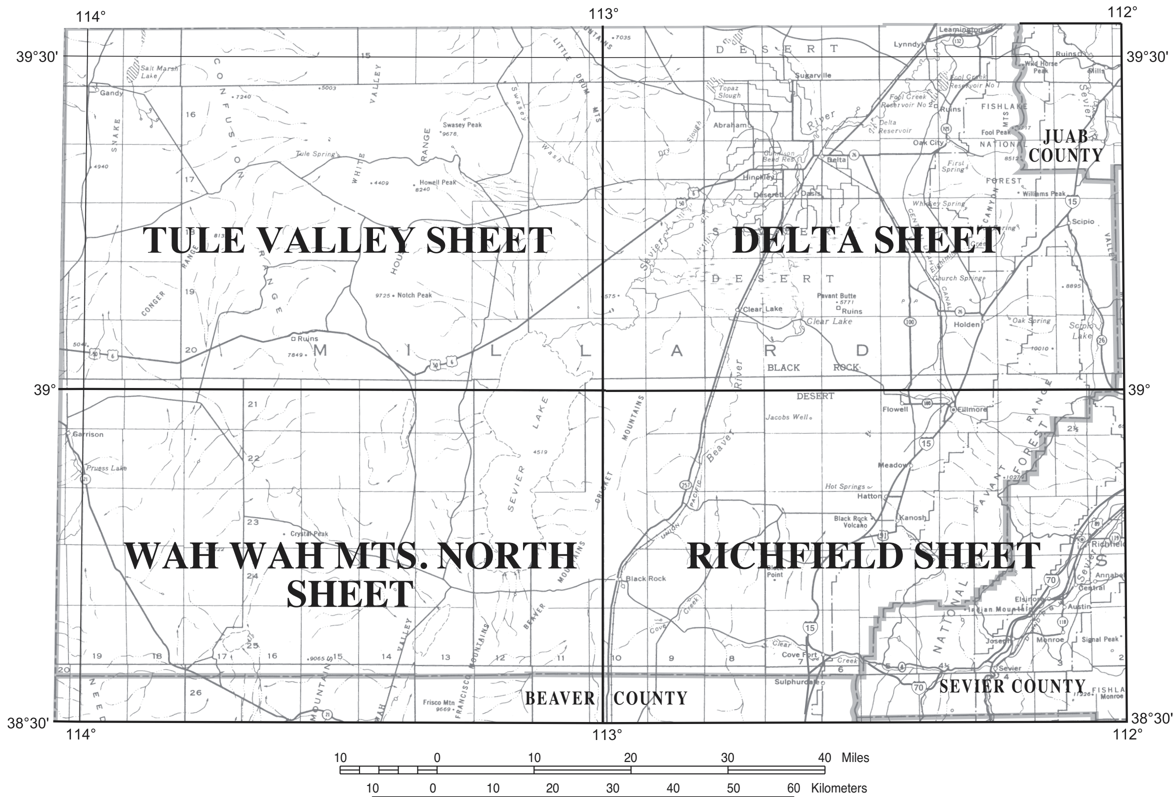


Figure 1. *Index map showing areas covered by 1:100,000-scale geologic maps that cover Millard County. Name of each sheet is taken from the principal U.S. Geological Survey 30 x 60-minute topographic quadrangle covering the area, although strips of the following quadrangles were also used to cover the western and northern edges of the county: Garrison, Ely, Kern Mountains, Fish Springs, and Lynndyl.*

Figure 2. *Index map showing names of the 146 U.S. Geological Survey 7½-minute topographic quadrangles that cover Millard County as well as names of nearby quadrangles. Each quadrangle covers an area of about 58 square miles (150 km²).*

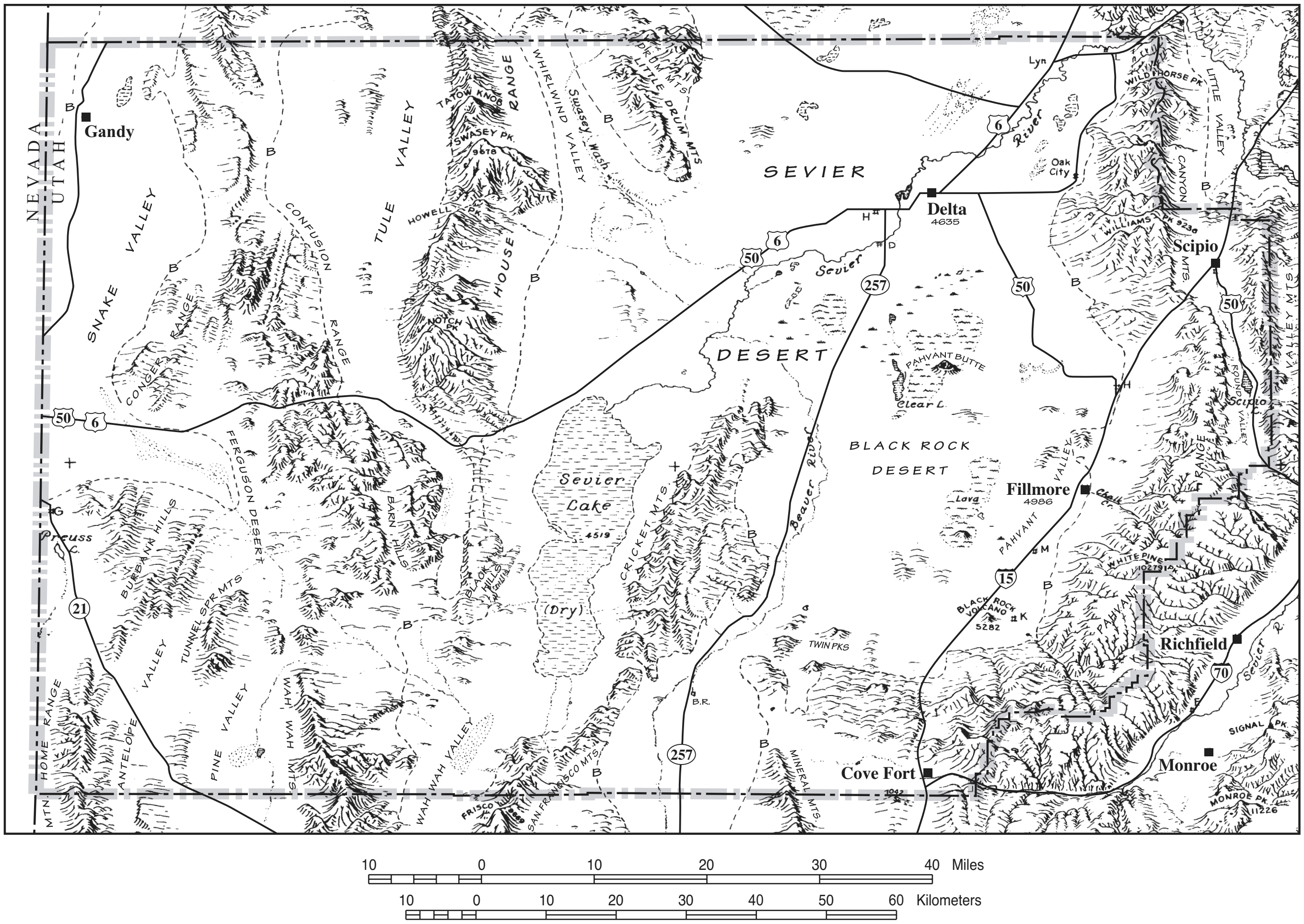


Figure 3. *Principal geographic features of Millard County. Fillmore and Delta are the largest towns; Fillmore is the county seat. Millard County covers 4,346,310 acres or 6,791 square miles (17,589 km^2). Agriculture is the county's chief industry, with production concentrated on alluvial slopes at the west base of the Pahvant Range between Kanosh (K) and Holden (H), and on the Lake Bonneville bottom flats west of Delta. The western two-thirds of the county is virtually unpopulated because of limited water resources. The U.S. Bureau of Land Management (BLM) administers 69 percent of the land within Millard County; U.S. Forest Service oversees 7 percent; State of Utah (School and Institutional Trust Lands Administration) owns 9 percent of the land as school sections scattered across the county; 15 percent is privately owned, primarily in the agricultural eastern part of the county. The dashed line marked -B- on the map shows the highest shoreline that Lake Bonneville attained between 16,000 and 14,500 years ago. Several peaks in the Pahvant Range are more than 10,000 feet (3,048 m) above sea level and supported small glaciers during the Ice Age. The highest peak in Millard County is Mine Camp Peak east of Meadow (M); its elevation is 10,222 feet (3,116 m). Landform map is modified from Ridd (1963).*

cial boundary. In addition, the complex fold and thrust structures of Mesozoic age that are typical of the Great Basin also extend eastward in the subsurface beneath the Wasatch Plateau. Most geologists now speak of the basin-plateau boundary as a "zone of transition." In 1976, a number of geologists of the Rocky Mountain Association of Geologists published several papers related to this transitional zone (Hill, 1976) noting the many changes in the structures and thicknesses of sedimentary rock units that occur across this physiographic boundary, which delineates a long-lasting zone of differential structural behavior to which the term "hingeline" has been applied. Hingeline indicates not only the fact that layered Paleozoic and late Precambrian strata are 10 times thicker west of the hingeline than beneath the plateaus to the east, but also that strata in the plateaus are relatively flat-lying as compared to more complex structures found in the Great Basin. Major Mesozoic thrust faults, with tens of miles of horizontal eastward displacement, are located mostly west of the hingeline.

Valleys, Deserts, and Mountain Ranges

As mentioned above, most of Millard County is in the "Basin and Range Province," a brief descriptive title for the alternating valleys and north-trending mountain ranges that typify the topography between central Utah and the Sierra Nevada. Geologists use the term "basin" here to describe a subsiding area in the Earth's crust in which sediments have accumulated, brought into the basin by streams draining adjacent highlands. Basins are of interest, not only because their relatively flat, soil-covered surfaces may be farmable, but also because ground water may be present in porous and permeable parts of their basin-filling deposits. Oil or other economic resources might also lie concealed in basins.

Because the block-faulting that created the Basin and Range topography did not begin until about 17 million years ago, the basins are filled with sedimentary and volcanic deposits that are all geologically quite young, compared to the older rocks upon which they lie. Prior to block-faulting the older bedrock had been folded and thrust-faulted, creating an uneven topography that is now concealed at the bottom of the basins. Some basins subsided more than others and accumulated thicker deposits. From looking at just the surface of a basin (in Millard County both the western "deserts" and "valleys" listed below are basins) one cannot tell what lies beneath; geophysical (seismic, gravity, and magnetic) work, or drilling is needed to decipher the subsurface geology.

Thirty valleys, deserts, and mountain ranges in Millard County are shown on figure 3 and described briefly below. A general description of the stratigraphy and structure of each mountain range is also given; cross sections through most of the ranges are displayed on the four companion 1:100,000-scale maps (Hintze and Davis, 2002a-c; Hintze and others, 2003). More detailed information on small structures within ranges is given in the structure section of this bulletin. Each valley or desert basin is briefly described, including what is presently known about its depth and configuration. The figure in appendix A show locations of deep wells referred to below, and appendix A contains geologic data for these wells.

The following list of these geographic features begins with the westernmost and ends with the easternmost.

Snake Valley

This broad valley extends north-south from Juab County to Beaver County along the Utah-Nevada line. It conceals the structural juncture between the complexly deformed Precambrian and lower Paleozoic strata of the Snake Range in Nevada, and the middle and upper Paleozoic strata of the Mountain Home Range-Burbank Hills-Conger Range-Confusion Range synclinorium. Well 56-1 penetrated 4,180 feet (1,274 m) of valley fill; well 79-1 penetrated 5,608 feet (1,709 m); and well 95-1 penetrated 1,080 feet (329 m) (figure 4) (appendix A). Well 79-1 was drilled just west of the center of the gravity low in northern Snake Valley, the largest gravity anomaly in Snake Valley. Elsewhere in Snake Valley, Paleozoic bedrock is exposed at the surface, as at well 82-2, and also 3 miles (4.8 km) northwest of Eskdale, which is just north of U.S. Highway 6-50 at the western toe of the Conger Range.

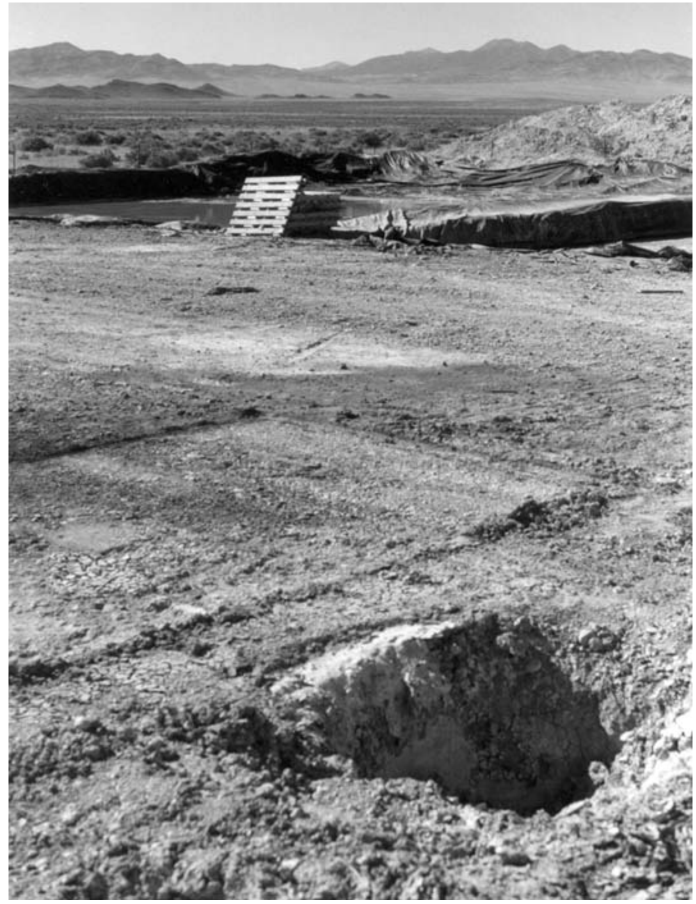


__Figure 4.__ Well 95-1, Balcron's 12-36 Cobra State (appendix A) drilled 2 miles (3 km) east of Gandy in Snake Valley. View northwestward from abandoned well site (pit in foreground) to nearest hills which are 3 miles (4.8 km) north of Gandy. Hills on skyline are Tin Springs Mountain and Kern Mountains just west of the Utah-Nevada line.

Confusion Range

The names Snake Valley and Confusion Range first appeared on the Wheeler Survey topographic maps of 1872 and 1873. Confusion is an apt name for the sprawling gray ridges of folded middle and upper Paleozoic strata that erosion has shaped into many look-alike vistas readily confused with one another. The general structure is synclinorial with the oldest rocks exposed on the east and west flanks; the highest part of the Confusion Range is around King Top (8,350 feet [2,545 m]) where resistant Upper Ordovician, Silurian, and Devonian strata form high cliff lines (figure 5). The axis of the synclinorium contains rocks as young as early Triassic. Overturned folds and thrust faults abound in the thick Permian stratigraphic section, and the Mississippian Chainman Shale is commonly structurally attenuated (Hose, 1977). Many local folds and faults are named and briefly described in the structure section of this bulletin. Many normal faults of small displacement and indeterminate age offset folded structures locally. However, the Confusion Range shows no major normal faults of typically large Basin and Range-type displacement except in its southeastern sector between Kings Canyon and Crystal Peak.

Exploration well 52-2 at the north end of the Confusion Range drilled a normal Paleozoic sequence, but well 52-3 encountered thrust faults that caused repetition of part of the otherwise normal section (appendix A). Mineral analyses in Bureau of Land Management (BLM) Wilderness Study Areas in the Confusion Range were given by Zimbelman and others (1990).

Conger Range

Structurally, this is the southwest arm of the Confusion Range synclinorium. Its slightly different appearance from the main range to the north is largely the result of exposures of resistant Silurian and Devonian dolomites in the westernmost part of the range near Eskdale. Hose (1977) included the Conger Range in his discussion of the Confusion Range synclinorium.

Barn Hills

Structurally, the Barn Hills are the southeasternmost part of the Confusion Range synclinorium. They are set apart from the rest of the Confusions by an architecture of cliffs of

Figure 5. *U.S. Highway 6-50 winds westward up through Kings Canyon in the southern part of the Confusion Range. Dark rocks at base of hill in foreground are Silurian Laketown Dolomite, which are overlain by light-gray Sevy Dolomite of Devonian age. The dark Laketown Dolomite is seen again, out of its normal stratigraphic sequence, resting on top of the light-gray Sevy. The upper stack of Silurian rocks was emplaced by thrust faulting in late Cretaceous time, about 100 million years ago, during the Sevier orogeny. The King Top high country is at the left edge of the photo.*

Ordovician, Silurian, and Devonian dolomites that are horizontally banded and light- to dark-gray. The banded strata are repeated in each of several late Cenozoic, Basin and Range fault blocks, which step down to the Tule Valley Hardpan (figure 6). Local patches of Oligocene volcanic rocks, that rest unconformably upon the tilted Paleozoic strata, are also offset by the late Cenozoic normal faults.

Burbank Hills

Structurally, the Burbank Hills are part of the large Confusion Range-Burbank Hills-Mountain Home Range synclinorium. Exposures of Permian strata extend across Highway 21 at Mormon Gap, confirming the geologic continuity of Burbank Hills with the Mountain Home Range. North of the Burbanks, surficial deposits in the Ferguson Desert and Snake Valley (figure 7) mask the connection with the Confusion Range, but similarity of structural style and stratigraphy strongly suggests subsurface continuity. In addition, the Bouguer gravity map (figure 8) confirms this continuity. Internally, the Burbank Hills are broken by thrust faults, tear faults, and asymmetric folds of Mesozoic age, and are intruded by a tiny dioritic plug of Jurassic age. The southeast border of the Burbank Hills is riddled with north-trending, down-to-the-east normal faults, probably Cenozoic in age. Cowboy Pass, between the Burbanks and Tunnel Spring Mountain, is a graben filled with chaotic blocks of Devonian strata and Oligocene volcanic rocks.

Petroleum exploration wells 52-1 and 68-1 penetrated a normal sequence of Paleozoic strata to their total depths of about 7,000 feet (2,100 m) (appendix A).

Mountain Home Range

The east side of the Mountain Home Range displays a structurally uncomplicated west-dipping section of Devonian through Permian strata that comprise the east limb of the large Mountain Home Pass syncline (figures 9 and 10). The west limb of the syncline is truncated by an overthrust complex made up of the same stratal sequence exposed in overturned folds and attenuated thrust slices. Oligocene volcanic rocks lie with angular unconformity on folded Paleozoics on the flanks of the range where they are cut by late Cenozoic normal faults of small displacement.

Petroleum exploration well 80-4 at the north end of the range penetrated 12,238 feet (3,730 m) of Paleozoic strata in an apparently normal sequence, although the well records are incomplete (appendix A). Other shallower wells drilled earlier nearby bottomed in rootless Mississippian strata above the Mountain Home thrust.

Antelope Valley

The Bouguer gravity map (figure 8) shows no large negative anomaly in the area of this small valley, so its valley-fill deposits likely are not very thick (figure 11). Well 81-6 penetrated only 230 feet (70 m) of surficial alluvium and 900 feet (274 m) of Tertiary slide blocks and volcanic tuff before encountering Paleozoic bedrock in a normal sequence cut by a minor thrust fault (appendix A). Extensive brecciation of Silurian and Devonian bedrock exposed along the east side of the valley in the Tunnel Spring Mountains and Halfway Hills suggests that a major, probably Tertiary, normal fault

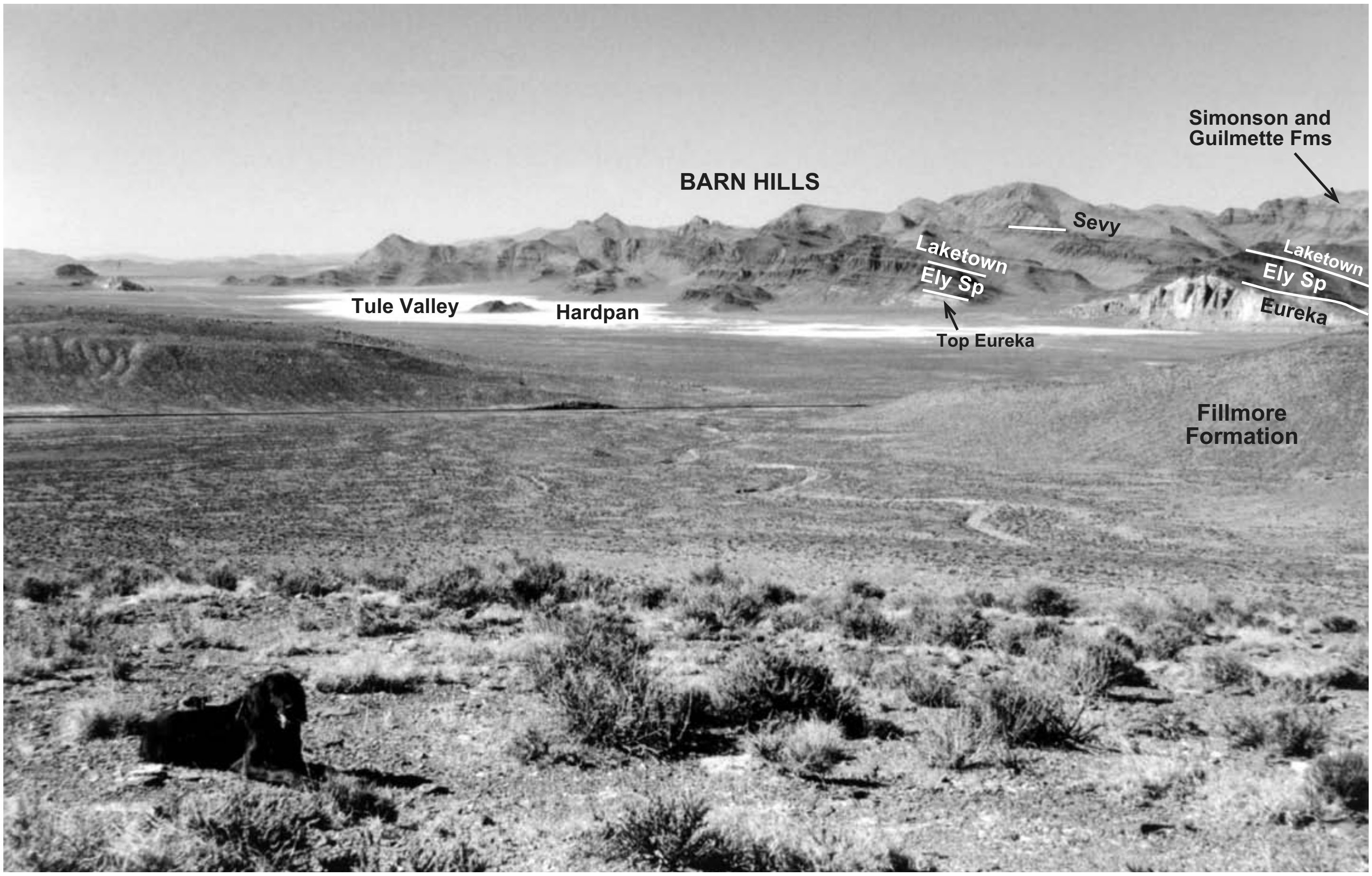


Figure 6. *View southwestward of the Barn Hills as seen from near the Ibex Well turnoff on U.S. Highway 6-50. The Barn Hills consist of several down-to-the-east fault blocks which repeat Ordovician, Silurian, and Devonian strata west of the Tule Valley Hardpan (white on photo). The Hardpan is about 5 miles (8 km) long. U.S. Highway 6-50 from Delta enters left middle edge of photo and is hidden behind low hill of Lower Ordovician Fillmore Formation in right third of photo. Nonresistant strata on both sides of highway and in the foreground are also Fillmore Formation. Light cliffs in right side of photo are Middle Ordovician Eureka Quartzite; black ledges above Eureka are Upper Ordovician Ely Springs Dolomite. Banded ledges above the Ely Springs are Silurian Laketown Dolomite, with lighter-colored ledges of Lower Devonian Sevy Dolomite above the Laketown, and Middle and Upper Devonian Simonson and Guilmette Formations on the right horizon of the photo.*

Figure 7. *View south across the Ferguson Desert towards the northwest end of the Burbank Hills from a point about 8 miles (13 km) east of the Nevada border. Geology is enhanced by March snow. Stair-step ledges on hills left of road are Pennsylvanian Ely Limestone, here tilted eastward. Ledges on the hills on the right half of the picture are Mississippian Joana Limestone, here folded into a small, broad anticline (North Burbank dome). Saddle between the hills is on the erosionally weak Mississippian Chainman Formation.*

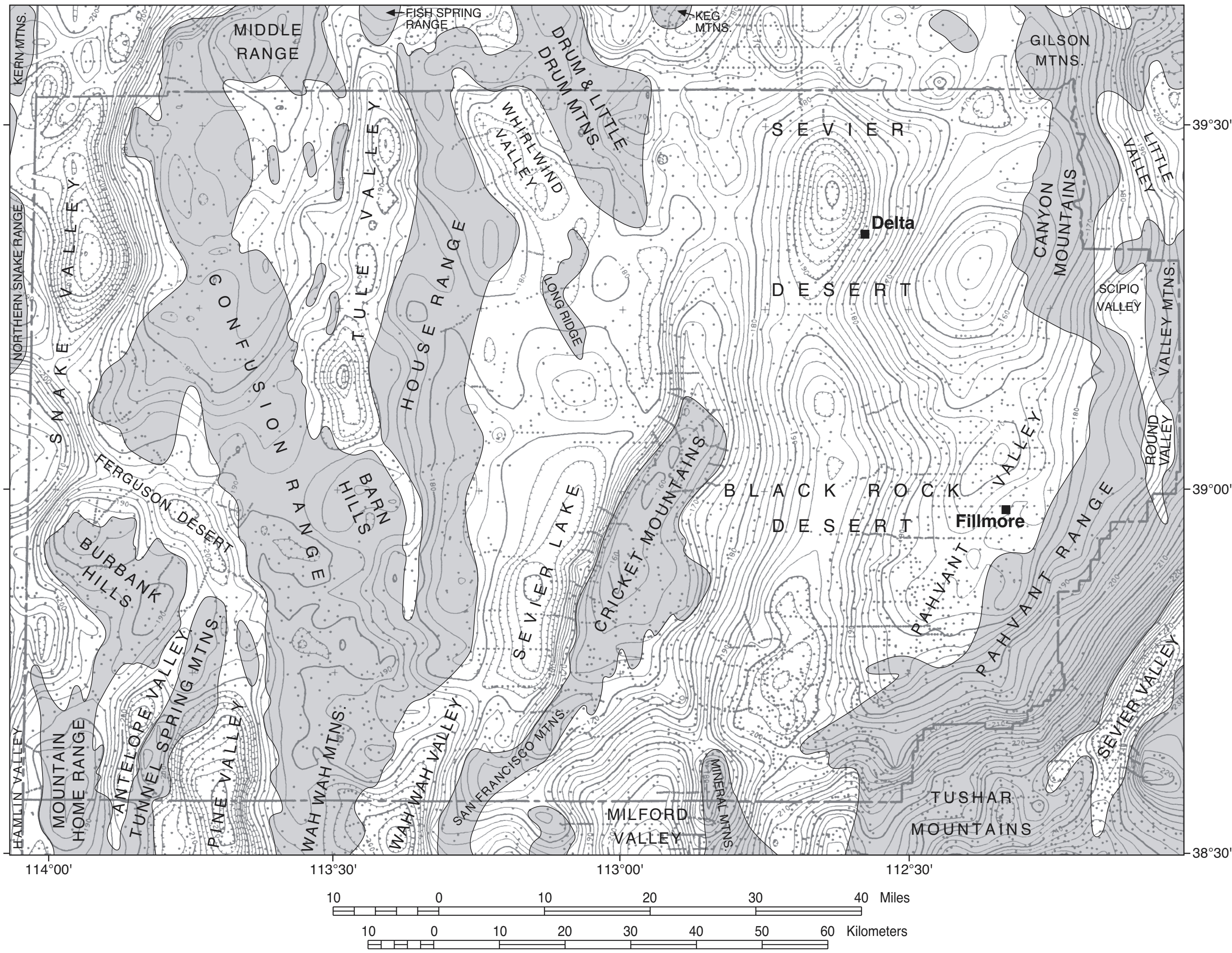


Figure 8. *Outline of bedrock exposures in mountain ranges superimposed on the Bouguer gravity map of Millard County (modified from Bankey, 1991). Contour interval is 2 milligals.*

Figure 9. *View northwestward from crest of the Mountain Home Range a few miles south of the Millard-Beaver County line. Snow-capped mountains on horizon are, from left to right, the southern Snake Range, the northern Snake Range, and the Deep Creek Mountains along the Nevada-Utah border. Dark hill between the snow-capped mountains on the right is composed of Mississippian and Pennsylvanian strata on the east limb of the Mountain Home Pass syncline.*

Figure 10. View looking south at folded Devonian strata within the axis of a small syncline west of the Mountain Home Range syncline.

Figure 11. View northeast toward Tunnel Spring Mountains across east side of Antelope Valley at Desert Experimental Range boundary.

extends from the east side of Cowboy Pass to the southern end of Antelope Valley in Beaver County. Well 81-6 is located very close to Devonian bedrock in the Burbank Hills. The concealed normal fault that is located between the well and the bedrock likely extends some distance to the southwest, down the center of the valley.

Tunnel Spring Mountains

Tunnel Spring Mountains and its southern extension, the Halfway Hills, contain Ordovician, Silurian, and Devonian strata in a much-faulted block that is structurally incongruent with the Burbank Hills-Mountain Home Range block. A major breccia zone locally separates the two blocks. Internally, the Tunnel Spring Mountains block locally includes a tight synclinal fold with attenuated axial strata. Numerous small down-to-the-west normal faults repeat the section on the east flank of the mountain. At the south end of Tunnel Spring Mountains, Oligocene intrusive and extrusive rocks are also cut by normal faults. Faulting is so pervasive within the Tunnel Spring Mountains-Halfway Hills block that great care must be exercised to find suitable places to measure portions of the stratigraphic section so that they can be combined to reconstruct the thickness of the whole (figure 12).

Ferguson Desert

No deep exploration wells have been drilled in this desert, which is located between the southern Confusion Range and the Tunnel Spring Mountains-Burbank Hills area. Subsurface relationships are inferred from the Bouguer gravity map (figure 8) and extension of features exposed in the mountains. The gravity map shows a moderate low in the center of the desert near Probst Pond, suggesting that valley-fill deposits are thickest there, perhaps 1,000 feet (300 m) or more. A concealed down-to-the-west normal fault probably bounds the desert along its east side. The Cowboy Pass graben probably extends north from the Burbank Hills beneath the desert, as does the Jensen Wash trough of Tertiary volcanic and sedimentary rocks. Isolated outcrops of Ely Limestone, about a mile east of Deadman Point, are not readily explainable without additional subsurface information.

Pine Valley

This large valley (figure 13) west of the Wah Wah Mountains harbors a large elliptical negative anomaly on the Bouguer gravity map (figure 8). Well 75-1 passed through 2,810 feet (856 m) of Oligocene tuffs, slide blocks, and rhy-

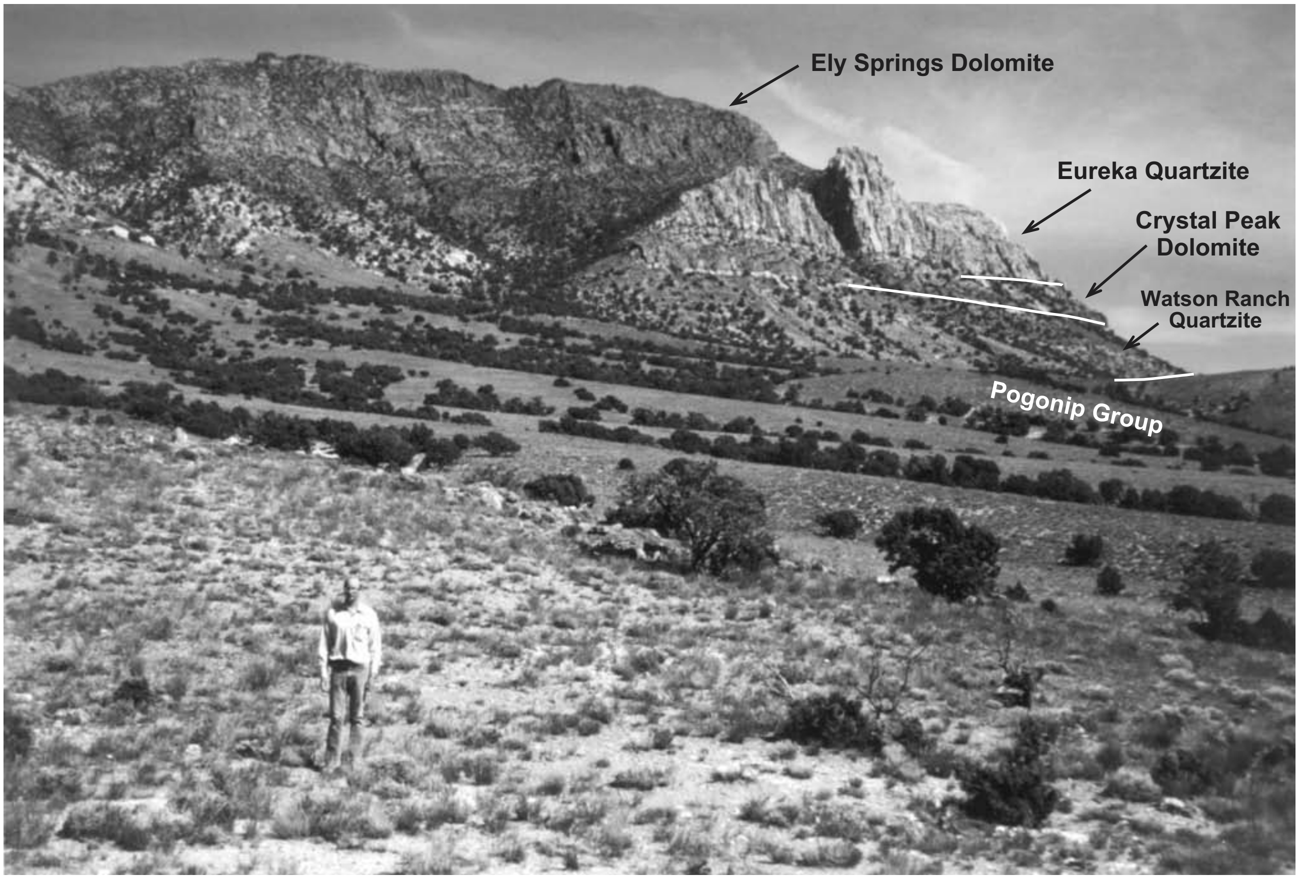


Figure 12. *West side of Tunnel Spring Mountains. Brigham Young University geology student mapper, Bruce Fife, is standing on brecciated dolomite that marks a major fault zone along the west side of the mountain. Dark rocks on skyline are Upper Ordovician Ely Springs Dolomite. Prominent light cliff is Middle Ordovician Eureka Quartzite, beneath which ledges of Crystal Peak Dolomite and Watson Ranch Quartzite form the steep slope. Rounded hills below contain a locally attenuated section of Lower Ordovician Pogonip Group limestones and shales.*

Figure 13. *Headquarters buildings for the U.S. Forest Service Desert Experimental Range station located in the northeast part of Pine Valley. Faulted Silurian and Devonian strata are exposed in the Halfway Hills behind the station, which was built in the 1930s to assess the optimum sheep and cattle grazing load in the western Utah desert.*

olitic flows before encountering Cambrian bedrock like that exposed in the Wah Wah Mountains (appendix A). The well is located about 4 miles (6.4 km) west of the lowest of the gravity contours. A major down-to-the-west normal fault is concealed along the west side of the Wah Wah Mountains. Normal faults of smaller displacement are probably beneath the west side of Pine Valley. Pine Valley Hardpan is the remnant of Pleistocene Pine Valley Lake, a small contemporary of Lake Bonneville.

Wah Wah Mountains

Only the northern third of this prominent range is in Millard County, where it is composed of Middle and Upper Cambrian strata that dip gently northward (figure 14) and become overlain by Ordovician strata north of Lawson Cove. Crystal Peak, a white volcanic hill at the south end of the Confusion Range, forms a landmark along the county road. South of the peak, the low hills are the northern end of the

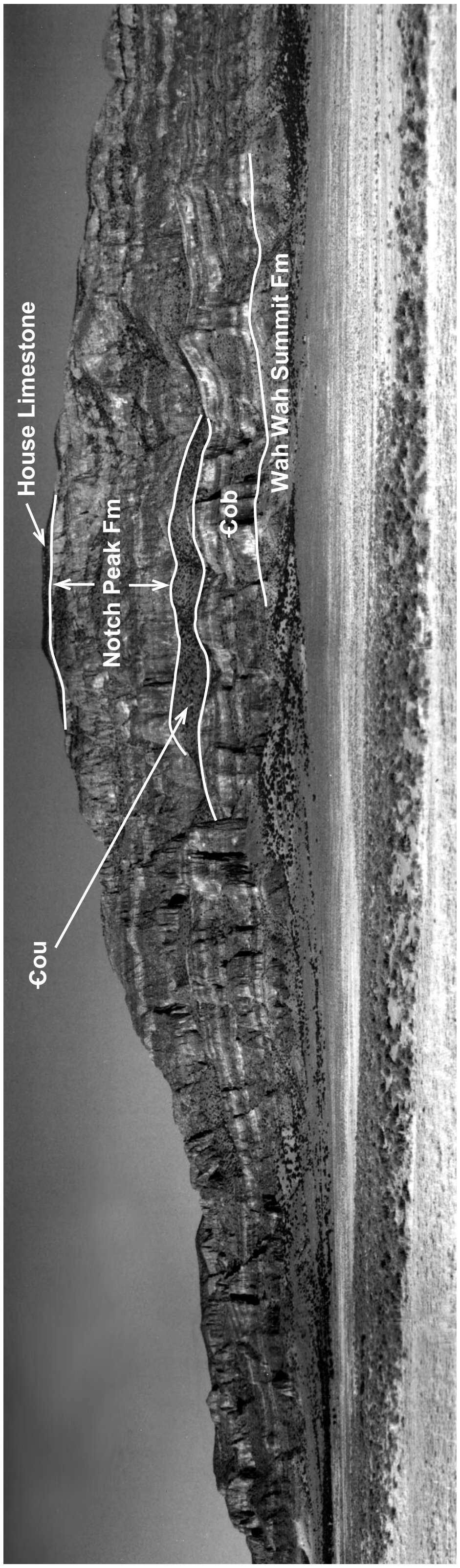


Figure 14. *West face of the northern end of the Wah Wah Mountains as viewed east of Pine Valley Hardpan. High point, elevation 8,441 feet (2,573 m), has thin capping of Lower Ordovician House Limestone. Massive cliffs that make up the upper two-thirds of hill 8441 are Upper Cambrian Notch Peak Formation; tree-covered bench is upper shaly part of the Orr Formation (Ꞓou); lowest cliff is the Big Horse Limestone Member of the Orr Formation (Ꞓob). Base of mountain is upper part of the Wah Wah Summit Formation.*

Wah Wah Mountains. Separation of the Wah Wah Mountains from the Confusion and House Ranges along the Crystal Peak-Black Rock road is mostly a convenience of placing a boundary (and road) along low topography, because the continuity of the bedrock geology does not change between the Wah Wahs and the ranges to the north. The northern Wah Wahs are on the south limb of a broad shallow syncline whose east-west axis trends through the Tule Valley Hardpan and Needle Point on Sevier (dry) Lake.

Mineral resources in the BLM Wilderness Study Area in the Wah Wah Mountains have been assessed by Cox and others (1989).

Wah Wah Valley

Although there is a negative anomaly in the Bouguer gravity map (figure 8) that coincides with the Wah Wah Valley Hardpan, it is not as great as the low in Pine Valley, suggesting that the valley fill in Wah Wah Valley is not as thick as that in Pine Valley. Gravity contours in Wah Wah Valley extend northeastward under Sevier Lake at about the same values and indicate continuity of depth to bedrock. The principal Basin and Range fault in Wah Wah Valley is on the east side, but is concealed along the foot of the San Francisco Mountains. No deep exploration well has yet been drilled in the Millard County portion of Wah Wah Valley.

San Francisco Mountains

The Frisco thrust, best exposed a few miles south of the Millard-Beaver County line, places upper Proterozoic quartzite over lower Paleozoic strata. Rocks of the upper thrust plate can be traced to the north end of the San Francisco Mountains where they conformably underlie the Cambrian Prospect Mountain Quartzite, the basal unit of the Cambrian sequence to the north in the Cricket Mountains. The east side of the San Francisco Mountains is covered by Tertiary sedimentary and volcanic rocks that rest in angular unconformity on the older rocks.

Tule Valley

Called White Valley on older maps, this large closed basin has been occasionally occupied by lakes. The varied deposits in the valley were mapped by Sack (1990) who recognized 18 types of Quaternary sediments. Under present climatic conditions streams reach the desert floor only after exceptional rain storms. However, in occasional wet periods during the Ice Ages, Tule Valley supported a lake. The most recent episode occurred when Lake Bonneville, fed by large streams in northern Utah, began to rise about 25,000 years ago. About 19,500 years ago, when it reached an elevation of 4,675 feet (1,425 m), it spilled over the threshold at Sand Pass and occupied Tule Valley (Sack, 1990). About 14,000 years ago, again because of long-term climatic change, Lake Bonneville dropped below the Sand Pass threshold. Cut off from its chief water supply, the Bonneville arm in Tule Valley dried up.

Upper Cenozoic valley-fill deposits are not very thick in most of Tule Valley, as suggested by the low ridges of the Coyote Knolls, Chalk Knolls, and Coyote Hills (figures 15 and 16). These are bedrock outliers of Confusion Range affinity. The Bouguer gravity map (figure 8) shows a moderate gravity low between the easternmost Coyote Knoll and the House Range. A line of small lows extends between this low and the deepest gravity low, which is at the south end of the valley in the area between U.S. Highway 6-50 and the southernmost Chalk Knoll. This line of gravity lows parallels the concealed down-to-the-west, Basin and Range, normal fault along the west side of the House Range.

Figure 15. Tule Valley as viewed westward from East Coyote Knoll, with exposures of Cambrian dolomite in foreground. West Coyote Knoll in middle distance across the valley.

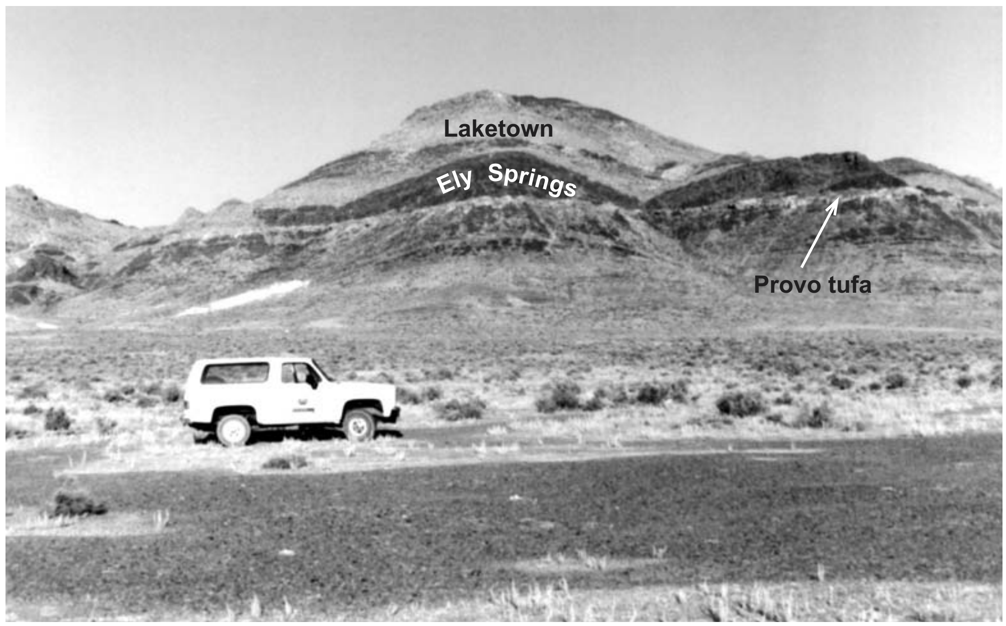


Figure 16. West Coyote Knoll's northern high point made up of banded light- and dark-gray rocks of the Silurian Laketown Dolomite. Lowest dark cliffs are Upper Ordovician Ely Springs Dolomite. Desert pebble pavement in foreground. Light band halfway up the hill is tufa-rich deposits along the Provo shoreline level of Lake Bonneville.

No deep exploratory well has yet been drilled in Tule Valley.

House Range

This is the most imposing range in western Millard County. Its highest point, Swasey Peak, at 9,669 feet (2,947 m), is only 15 feet (4.5 m) higher than its more precipitous neighbor, Notch Peak (figure 17), 17 miles (27 km) to the south. The northwest face of Notch Peak forms one of the tallest sheer cliffs in the west (Kelsey, 1997).

The House Range is world-famous among paleontologists for its wonderful sequence of Middle and Late Cambrian trilobite faunas. The Wheeler Shale at Antelope Spring near Swasey Peak has yielded more whole trilobite specimens than any other locality in the world (Hintze and Robison, 1987).

At first glance, the House Range appears to be a simple east-tilted, late Cenozoic extensional fault block with Cambrian strata boldly exposed on its west face, and the same strata forming dip slopes on its east side. On closer inspection, the range reveals several features formed during Mesozoic mountain-building tectonism. Oldest of these is the Notch Peak intrusion of Jurassic age. In late Cretaceous time this intrusion and the Cambrian strata it had intruded were moved southeastward tens of miles as part of a large thrust plate. This plate was broken internally by tear faults that are oriented parallel to the direction of movement of the plate and that allowed small blocks of the plate to slide by each other. Tear faults separate coherent blocks of Cambrian strata from adjacent blocks made up of brecciated and brittly attenuated strata. This Cretaceous brecciation made the affected blocks less resistant to erosion. This can be easily observed by looking at the west face of the House Range from Tule Valley. Unbrecciated blocks form bold unbroken cliff lines (figure 18); brecciated and attenuated blocks form lower topography and more rounded and irregular cliff lines (Hintze, 1978). Oligocene volcanic and sedimentary rocks in the House Range were generally deposited in those portions of the range where the Cambrian strata had been previously attenuated.

Mineral resources in BLM Wilderness Study Areas in the House Range have been assessed by Lindsay and others (1989), and Stoeser and others (1990).

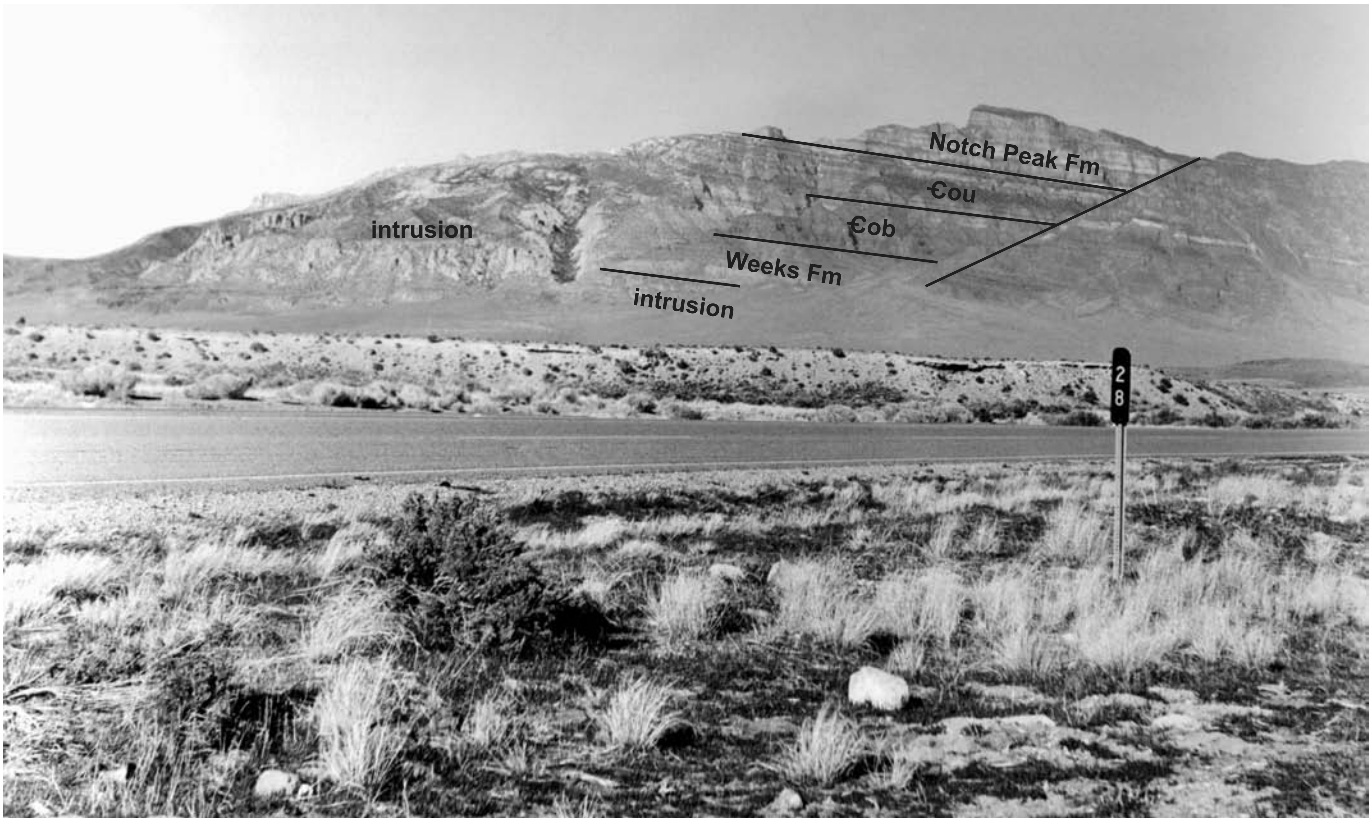


Figure 17. West side of the House Range as seen from milepost 28 on U.S. Highway 6-50. Upper third of Notch Peak (also called Sawtooth) is the type section for the cliff-forming Upper Cambrian Notch Peak Formation. The tree-covered slopes at the base of these cliffs expose fossiliferous shales of the upper Orr Formation (Ꞓou). The Big Horse Limestone Member of the Orr (Ꞓob) and Weeks Limestone are also shown. White layers are limestone beds that were recrystallized and bleached (marblized) by heat and fluids from the Jurassic granitic intrusion exposed in the knobby slopes left of the straight canyon. This metamorphism took place at a depth of several thousand feet. Unlabeled exposures on the right side of the photograph have been offset by faulting. Present exposure of the limestone beds is a result of uplift and erosion during the Cretaceous Sevier orogeny and later block faulting during late Cenozoic time.

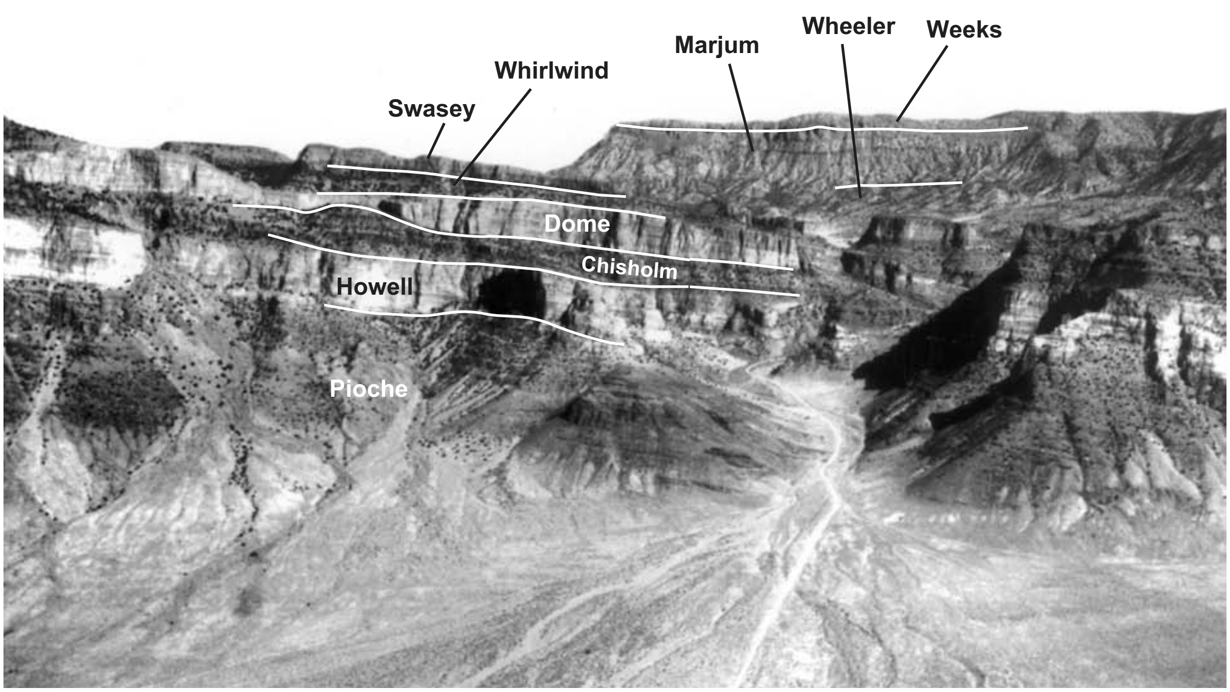


Figure 18. Aerial view of Marjum Canyon looking east at Cambrian strata in the central House Range. Gravel road was U.S. Highway 6 until it was relocated 15 miles (24 km) to the south over Skull Rock Pass about 1950. Dark rocks at the mouth of the canyon are the Lower Cambrian Pioche Formation, which contains the oldest trilobite fossils in Utah. Cliff-forming limestones above the Pioche are, successively, the Howell, Dome, and Swasey left of the road; shaly slopes between the limestones are the Chisholm and Whirlwind. The ridge on the right skyline exposes the Marjum Formation (lower) and Weeks Limestone (upper), with the Wheeler Shale forming the slope below the cliffs.

Black Hills

The Black Hills comprise the southernmost end of the House Range. Compared with the main part of the range north of Skull Rock Pass, they are only small hills, but they are part of the structural block bounded by the House Range fault on its west side. The name of these hills is descriptive of the very dark-gray Cambrian carbonate strata they contain (figure 19). The Black Hills form the south flank of a broad syncline whose east-west axis crosses the southern House Range about halfway between the Black Hills and Skull Rock Pass. Ordovician strata are exposed in the trough of this syncline.

Whirlwind Valley

The Bouguer gravity map (figure 8) shows only a moderate low under this valley, suggesting that depth to the Cambrian bedrock, exposed in the adjacent House Range and Drum Mountains, is not great. Upper Eocene-Oligocene volcanic deposits probably extend beneath the valley from exposures in the Little Drum Mountains, Red Knolls, and on Long Ridge.

Drum Mountains

Cambrian strata form the northwest-trending backbone of the Drum Mountains (figure 20), which are bisected by the Juab-Millard county line. Cambrian strata are truncated in southern Juab County by the arcuate Joy fault, which there forms the south rim of a caldera in a late Eocene eruptive center. In Millard County the Cambrian strata are disrupted by late Cretaceous east-trending tear faults and are locally attenuated along minor thrust faults, which served to localize gold mineralization in the Drum open-pit mine. Cambrian strata along the Millard-Juab county border are intruded by small porphyry bodies and pebble dikes of earliest Oligocene age (Nutt and Thorman, 1992; Nutt and others, 1996).

Cambrian formations in the Drum Mountains are the same as those in the House Range. However, the Wheeler Shale is notably thicker in the Drum Mountains (figure 21), and the entire sequence is not as fossiliferous.

Little Drum Mountains

A thick succession of west-dipping Late Eocene volcanic conglomerates and ash-flow tuffs is exposed in this small range. Hintze and Oviatt (1993) mapped the east side of the Little Drums where the oldest part of the Eocene succession is exposed (figure 22). The main part of the range was mapped by Leedom (1974) and Pierce (1974). The Delta and Tule Valley geologic maps (Hintze and Davis, 2002b-c) present a revised version of their work. No significant prospects or mineralized areas have been noted in these volcanic rocks.

Sevier Desert

About half the size of the Great Salt Lake Desert, the combined Sevier-Black Rock Desert nonetheless occupies more than one-third of Millard County. There is no obvious line of demarcation between the northern "Sevier" part and the southern "Black Rock" part; hence the use of Sevier basin in this bulletin. In the following discussion we follow Oviatt (1991a) in using the 39th Parallel as the south boundary of the Sevier Desert. The Black Rock Desert has no barrier on its southwestern side; it merges imperceptibly with the Escalante Desert to the south. The western part of the Sevier Desert extends south of the 39th Parallel between the Cricket Mountains and the House Range where it is the basin of Sevier Lake.

All of the conspicuous landmarks rising above the floor of the Sevier Desert in Millard County are of late Cenozoic volcanic origin (figure 3). From north to south they are: (1) the south edge of the Fumarole Butte basalt shield, which is northwest of the Intermountain Power Plant; (2) the Smelter Knolls bimodal rhyolite-basalt complex; (3) the Deseret basalt flow (it is labeled "Black Rock" on the topographic base map, but other places near Kanosh and on the railroad line west of Kanosh also are called Black Rock, so we here follow Oviatt (1989) in designating this flow for its nearest town); (4) Pot Mountain, a volcanic vent; (5) Sunstone Knoll, a volcanic vent; and (6) Pahvant Butte, the largest volcano in the Sevier Desert and the source of successive basaltic ashes and flows that extend some distance away from the base of its cone.

Figure 3 shows the highest shoreline of late Pleistocene (Ice Age) Lake Bonneville encircling the Sevier Desert; thus, one might expect to find substantial Bonneville lake deposits covering the desert floor. Surprisingly, the only major lake deposits of Bonneville age are the deltaic sediments that stretch out from the mouth of Leamington Canyon where the Sevier River dropped its load upon entering the standing waters of the lake (figure 23). The town of Delta and the Intermountain Power Plant both lie at the toe of this large delta. The west side of the Sevier Desert (figure 24) is mostly lacking in significant Lake Bonneville sediments, except for local gravel bars that mark stillstands of lake levels. Pink lake deposits exposed along U.S. Highway 6-50 north of Sevier Lake are about 2 million years old, much older than the time (20,000 years ago) when Lake Bonneville began its rise in Millard County. Even the floor of Sevier Lake has almost no record left from Lake Bonneville.

Subsurface geologic relationships under the Sevier Desert have been the subject of considerable investigation and interpretive effort (see structure section in this bulletin). The Bouguer gravity map (figure 8) shows a broad high covering the northeast corner of Millard County. Well 81-1 encountered only 150 feet (46 m) of valley fill before penetrating bedrock, in which it stayed to a depth of 13,106 feet (3,995 m) (appendix A), confirming thin valley fill under this part of the Sevier Desert, as indicated by the gravity high. The low near Delta shows where the greatest thickness of valley-filling Tertiary deposits are located just west of the broad high, as confirmed by wells 57-1 and 78-1 (appendix A) as well as by seismic lines. The section on subsurface geophysical information in this bulletin gives a more complete discussion of this topic. None of the wells drilled to date encountered oil or gas. In the arm of the Sevier Desert south of the 39th Parallel, the valley of Sevier Lake is centered over the gravity low associated with Sevier Lake, which is probably caused by a moderate thickness of upper Tertiary sedimentary and volcanic valley-filling deposits.

Numerous normal faults of small displacement offset Quaternary surficial deposits in the Sevier Desert; they con-

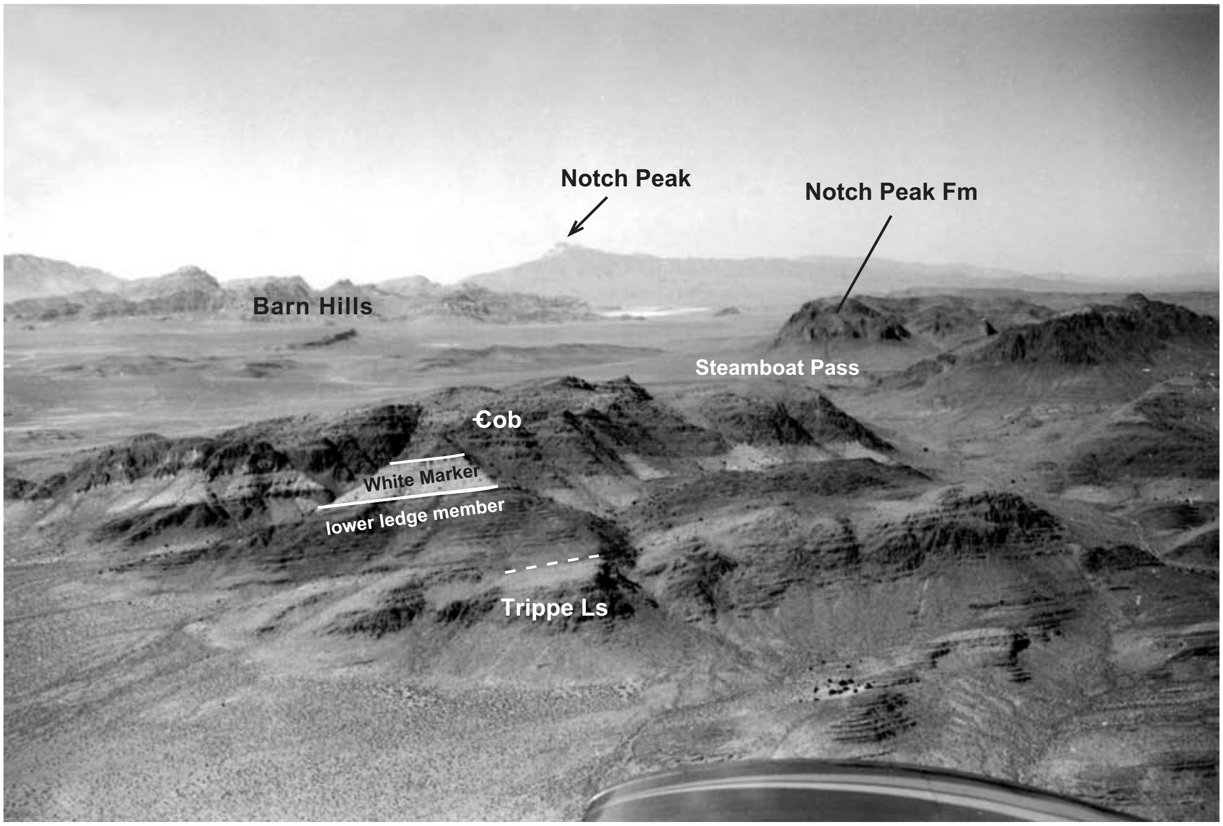


Figure 19. Black Hills at the southern end of the House Range, view to north-northwest, comprised of mostly Cambrian strata. White marker bed is the upper member of the Wah Wah Summit Formation, a laminated dolomitic boundstone about 170 feet (52 m) thick. It is overlain by the dark, cliff-forming Big Horse Limestone Member of the Orr Formation (Єob), the swale-forming Steamboat Pass Shale Member of the Orr, and the cliff-forming Notch Peak Formation. Underlying the white marker, in the foreground, are the lower ledge member of the Wah Wah Summit Formation and the Trippe Limestone. The Barn Hills are in the left middle distance.

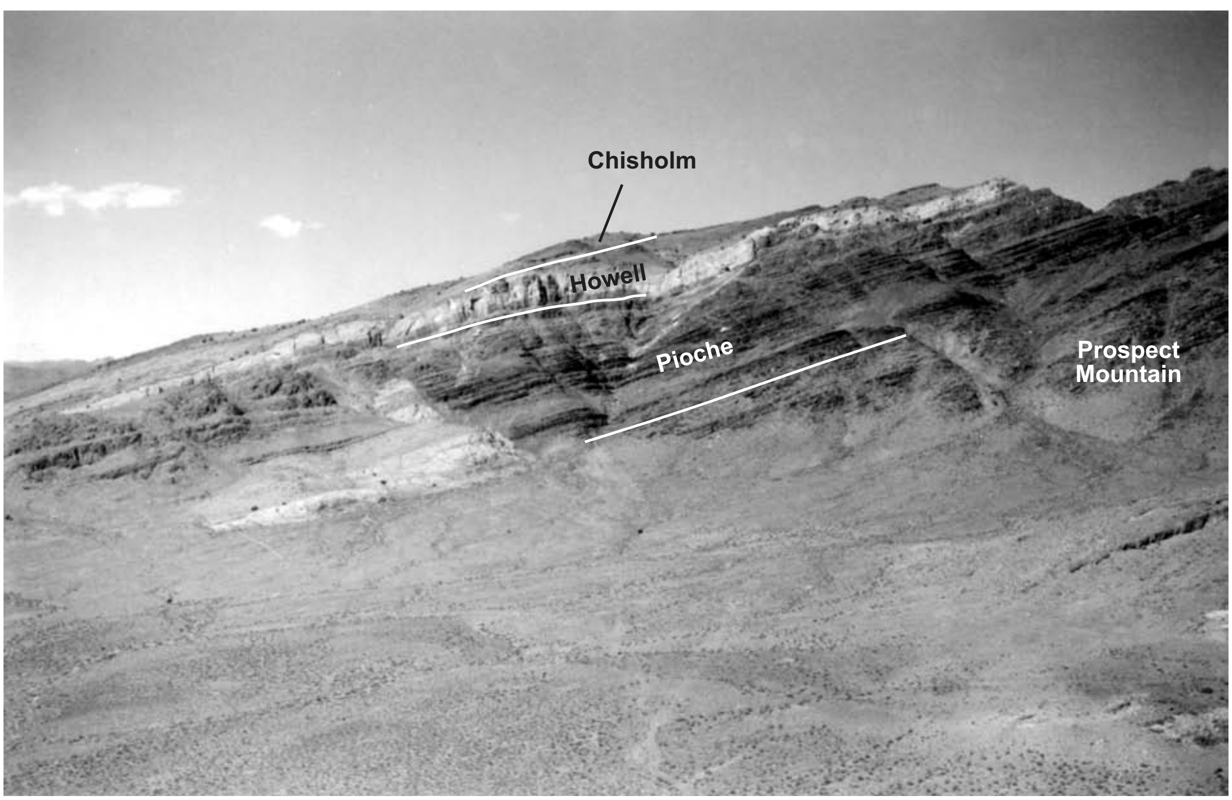


Figure 20. View westward of Cambrian strata at southeast end of the Drum Mountains. Lower Cambrian Prospect Mountain Quartzite forms ragged ledges in right-central part of photo. Darker ledges above are quartzite and orange dolomite beds of the Pioche Formation. Light-gray cliff is the Howell Limestone, repeated by faulting in left center of photo. Hilltop and backslope are Chisholm Formation and lower Dome Limestone.

Figure 21. *Middle Cambrian strata at the south edge of the Drum Mountains, view to northwest. Dark ledges on left skyline are dolomitic limestones in the Pierson Cove Formation. Light slope beneath ledges is the upper member of the Wheeler Shale, 125 feet (58 m) thick. Dark ledgy slopes from middle to right foreground are the middle and lower members of the Wheeler Shale totaling 785 feet (239 m) thick (Hintze and Oviatt, 1993). This is the thickest section of Wheeler Shale known.*

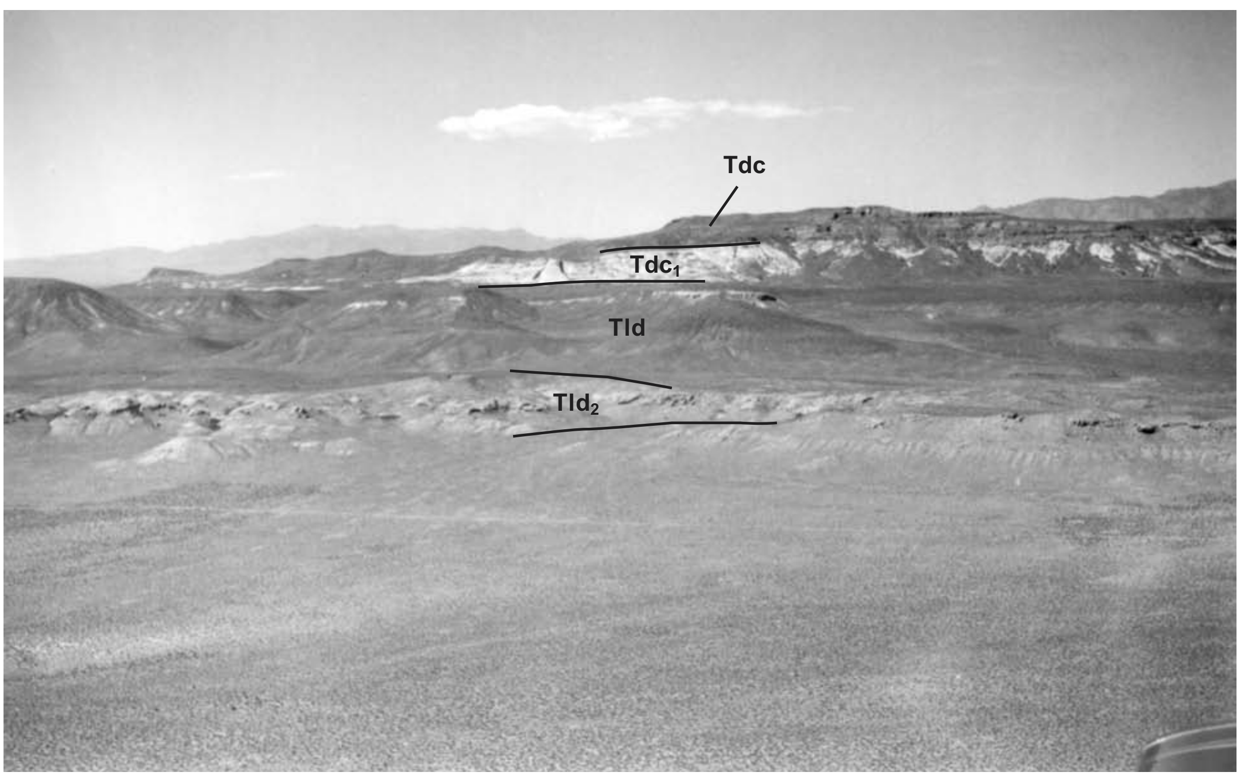


Figure 22. *Aerial view of east side of the Little Drum Mountains. The light-colored low ridge that extends across the middle of the photo is made up of the oldest (38.6 Ma) tuff member (Tld_2) of the Little Drum Formation. It is overlain by volcanic conglomerates and tuffs of the Little Drum Formation (Tld) (Hintze and Oviatt, 1993). The prominent light outcrops below the skyline are the basal ash-flow tuff (Tdc_1) of the volcanic sequence of Dennison Canyon, about 37 million years old, and about 500 feet (150 m) thick; it is overlain by volcanic debris flows of the volcanic sequence of Dennison Canyon (Tdc).*

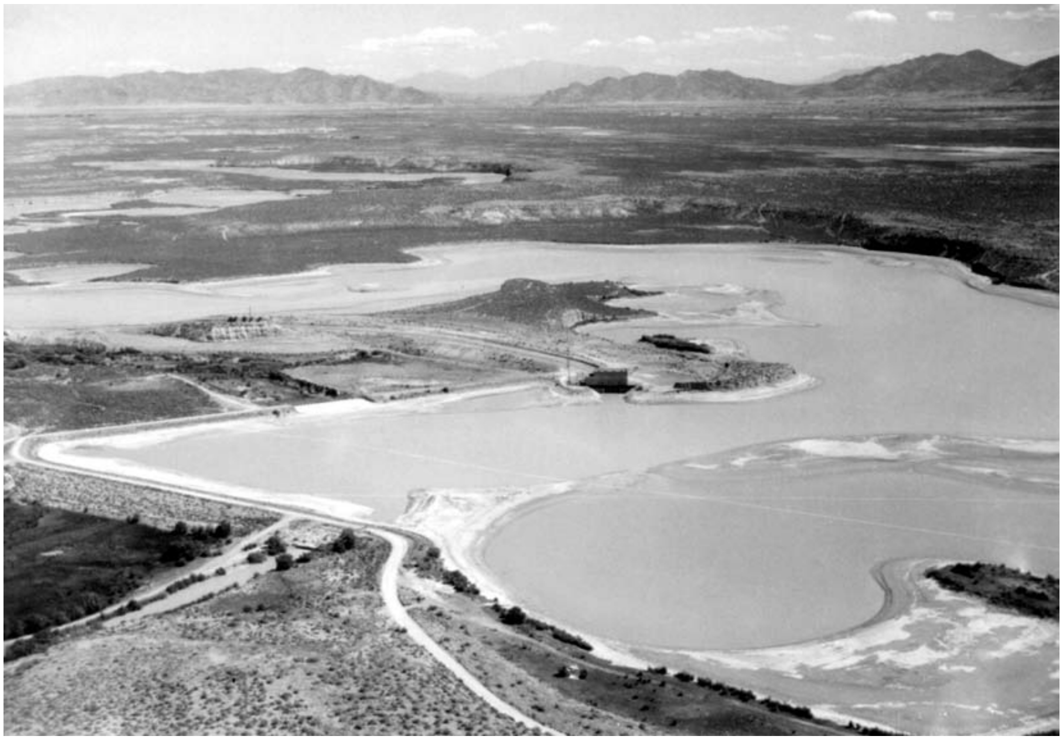


Figure 23. Aerial view northeastward from DMAD Reservoir near Delta toward Mt. Nebo at center distant skyline. Canyon Mountains are on right skyline; Gilson Mountains are on left skyline. Sevier River enters Millard County through Leamington Canyon between these mountain ranges. The flat bench area between Delta and Leamington is made of silt, sand, and pea gravel deposited as a delta in Lake Bonneville by the Sevier River beginning about 20,000 years ago. When the climate changed and the level of the lake dropped, the Sevier River cut a broad meandering channel through its own deltaic deposits. The DMAD Reservoir impounds water in the oxbows of the Sevier River flood plain for use in irrigation on land south and west of Delta. In June 1983, after record-breaking runoff filled the Sevier River to overflowing, the DMAD dam broke, causing extensive flood damage downstream on the outskirts of Delta and in the town of Deseret (Palmer, 1992).

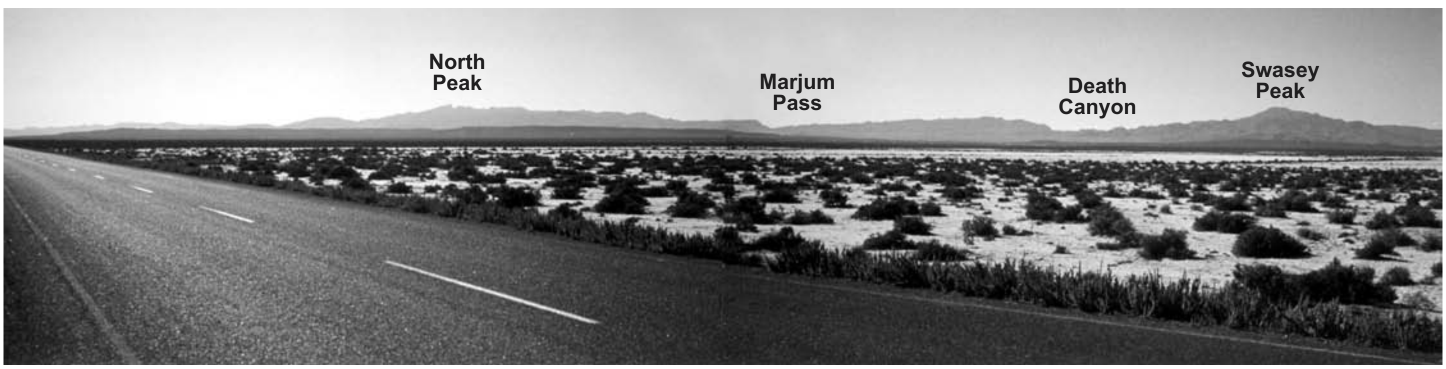


Figure 24. View westward from milepost 70 on U.S. Highway 6-50 looking across the Sevier Desert floor. Nearest dark low ridge on left half of photo is Long Ridge, a low fault block that exposes Oligocene conglomerate and ash-flow tuff. Prominent topographic features from left to right are: Notch Peak (Sawtooth) in the House Range; Marjum Pass; Death Canyon; and Swasey Peak. The desert floor has a thin veneer of fine-grained Lake Bonneville deposits in which small, white fresh-water snail and clam shells are common.

firm that large earthquakes, accompanying Basin and Range extension, have occurred in Millard County in geologically recent time, although not within historical time since pioneer settlement.

Cricket Mountains

Paleozoic strata in these mountains were folded into a broad syncline from which all strata above the Cambrian were removed during late Mesozoic erosion. Lower Cenozoic lacustrine beds of the Flagstaff Formation unconformably overlie tilted Cambrian strata, and both Flagstaff and Cambrian beds were offset by late Cenozoic, Basin and Range, block faulting. The Cricket Mountains form a strong high anomaly on the Bouguer gravity map (figure 8).

Cambrian strata in the Cricket Mountains are underlain by thick, upper Proterozoic, mostly quartzite strata which lie at the base of the Frisco-Canyon Range thrust plate, a late Mesozoic feature that can be traced under much of Millard County. Despite having been transported tens of miles southeastward on this thrust plate, Cambrian strata in the Crickets are generally coherent and form bold cliffs (figure 25) similar to Cambrian strata in the House Range and Drum Mountains, and in marked contrast to Cambrian strata in the Pahvant Range where cliffs are subdued because the strata have been pervasively fractured and jostled.

Black Rock Desert

Because a large part of the desert south of Pahvant Butte is covered with dark lava flows, it is called the Black Rock Desert. Hoover (1974) described seven lava fields, here listed from north to south: (1) basalt of Pahvant Butte, 128,000 years old; (2) basalt of Ice Spring, about 700 years old (figure 26); (3) basalt of Tabernacle Hill, 14,400 years old (figure 27); (4) basalt of Beaver Ridge, 900,000 years old; (5) andesite of Beaver Ridge, 1,500,000 years old; (6) rhyolite Dome of White Mountain, 400,000 years old; and (7) basalt of Kanosh (Black Rock Volcano), 600,000 years old.

Eruptive centers in the Black Rock Desert were likely

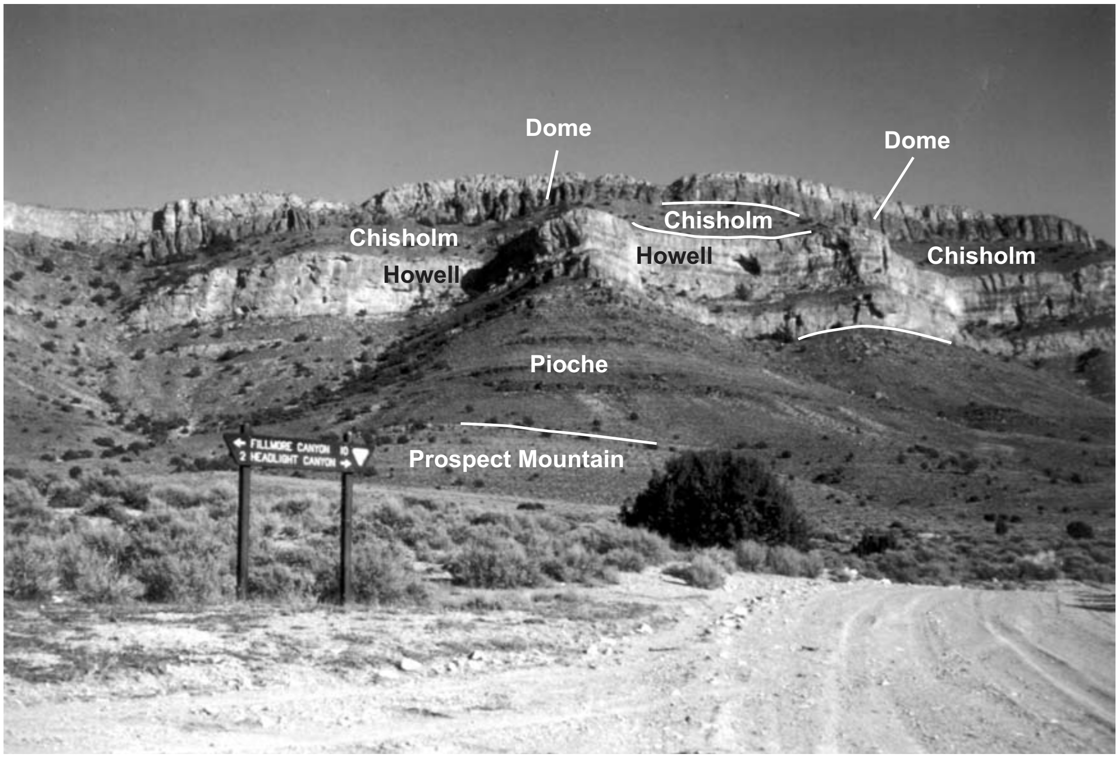


Figure 25. *West side of the Cricket Mountains near Petes Knoll. Prospect Mountain Quartzite is exposed at base of hill. Pioche Formation makes up dark, ledgy slope to base of light cliff, which is Howell Limestone. Slope above Howell is Chisholm Formation. Cliff on ridge on skyline is Dome Limestone. This sequence is exposed repeatedly in fault blocks in the Cricket Mountains.*

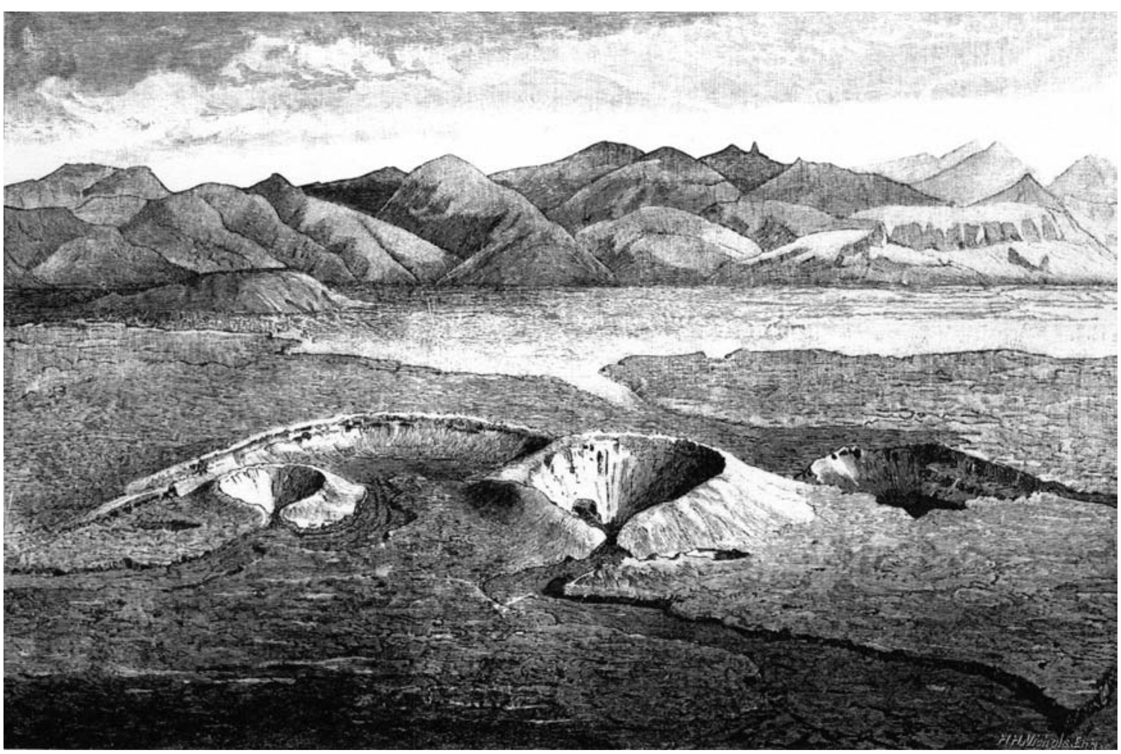


Figure 26. *G.K. Gilbert, in his monograph on Lake Bonneville (1890), made the first geologic map showing the basalt fields west of Fillmore and noted the ages of the basalts relative to Lake Bonneville's history. This lithograph shows the youngest eruptions in the Black Rock Desert. Gilbert captioned it: "Ice Spring Crater; bird's-eye view from the west."*

Figure 27. Aerial view of the Tabernacle Hill eruptive center about 14 miles (22 km) southwest of Fillmore. Oviatt (1991a) dated the eruptions at about 14,400 years old. The ragged dark area surrounding Tabernacle Hill is made of basalt flows that were erupted into Lake Bonneville. The smooth hills are volcanic ash from the eruptive center, which is the dark rocky area within the cone. Pahvant Butte (also called Sugarloaf) is the volcano on the distant skyline.

localized on north-trending extensional faults. Lavas in several of the fields are offset by post-eruption faulting. No close correlation is seen between the location of surface lavas and the subsurface gravity low (figure 8).

Mineral Mountains

Most of this range is located in Beaver County where it contains Utah's largest granitic intrusion. The northern tip of the Mineral Mountains in Millard County is a complex of thrust-faulted and metamorphosed Cambrian strata overlain by a few small patches of much younger conglomerate and basalt (Coleman and others, 1997).

Twin Peaks

The Twin Peaks stand just within the northern boundary of a large eruptive field composed mostly of rhyolitic domes and flows about 2.5 million years old. Some basalt flows and fresh-water limestone beds are interlayered with the rhyolites. These Pliocene rocks have been locally domed in the Cove Creek area (Oviatt, 1991a) about 8 miles (13 km) south of the Twin Peaks.

The rhyolite at Cudahy Mine, 6 miles (10 km) west-southwest of Twin Peaks, is famous as the source of snowflake obsidian, a black rock speckled with light-gray blotches. Indian arrowheads made from this rock are found in widely scattered places in the Great Basin, attesting to its popularity. Rhyolitic pumice rock, associated with the obsidian, has been mined for building aggregate.

Pahvant Valley

This name is applied to the agricultural area that is between the Pahvant Range and the various non-farmable basalt flows of the Black Rock Desert. The Bouguer gravity map (figure 8) shows nothing to suggest that any thick Tertiary valley fill underlies this area. Rather, it is thinly covered with upper Cenozoic alluvium, deposited by streams, both intermittent and perennial, that issue from the Pahvant Range. Ground water that flows within the alluvium from the range towards low points in the Black Rock and Sevier Deserts comes up as springs in such places as Clear Lake. It is intercepted by wells for agricultural and other uses higher on the alluvial slopes before it reaches the less desirable lowlands in the Sevier and Black Rock Deserts (figure 28).

Pahvant Range

This range is composed of four suites of rocks: (1) Upper Paleozoic, Triassic, and Jurassic strata which, although they are now folded, have not been moved much from their original site of deposition; (2) Lower Paleozoic strata above the Pavant thrust fault (figure 29), on which they were moved tens of miles southeastward during late Cretaceous time and emplaced above the in-place rocks of the first suite; (3) post-thrusting strata that consist of the Canyon Range Conglomerate, and the North Horn and Flagstaff Formations, which rest unconformably across suites one and two; and (4) middle Cenozoic volcanic rocks, which overlap all older rocks in the southeast corner of the county.

The Pavant thrust is an uncomplicated structure exposed along the range front between Fillmore and Kanosh. In that same sector, subsidiary thrusts are partially exposed in the low hills at the base of the range. The subsidiary thrusts are better exposed in the low part of the Pahvant Range between Kanosh and Cove Fort where the Paleozoic strata are overturned, and lie nearly flat locally, but are upside-down.

Subsurface relationships in the Pahvant Range are documented in four wells (appendix A). Well 60-1, east of Meadow, passed through a tilted but not overturned Triassic and

Figure 28. *A small "blowout" playa in the northwest part of Pahvant Valley. This type of playa is commonly fringed on the northeast side by sand or silt dunes, seen here on the far side of the playa. The Canyon Mountains are in the background. View is north-northeastward.*

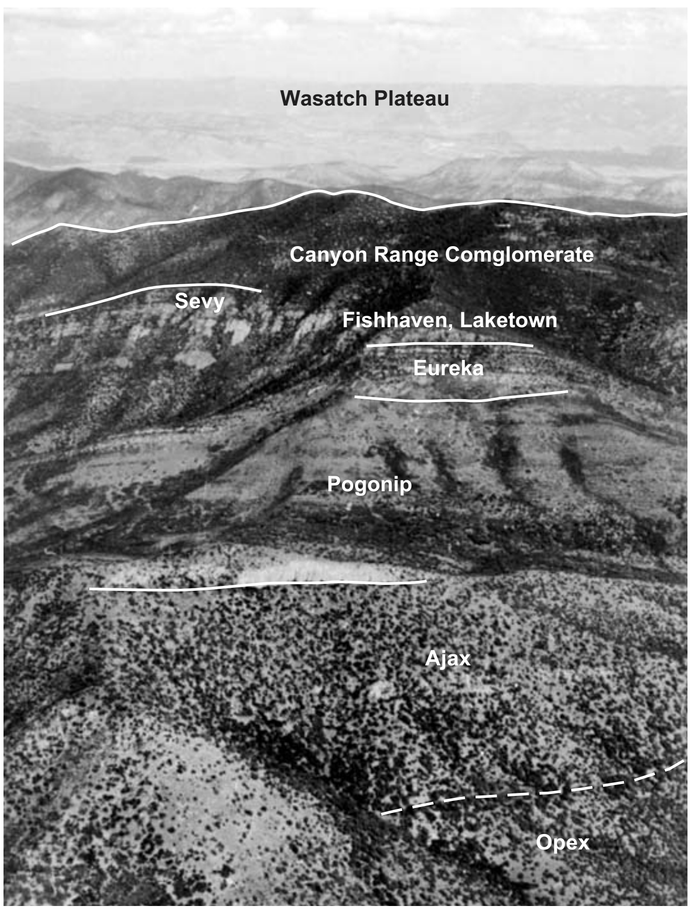


Figure 29. *Aerial view of west face of Pahvant Range between Ebbs Canyon and Wild Goose Canyon in the Scipio Pass quadrangle (Michaels and Hintze, 1994); this is one of the least deformed lower Paleozoic sections in the Pahvant Range. Prominent light cliff just below middle of photo is the basal Pogonip Group (Ordovician); it is underlain by the Cambrian Ajax Dolomite and Opex Formation. Ledges just above middle of photo are, from bottom to top, Eureka Quartzite, Fish Haven and Laketown Dolomites, Sevy Dolomite, and Canyon Range Conglomerate. Wasatch Plateau east of the Pahvant Range is on skyline of photo.*

Paleozoic section; well 78-2, north of Dog Valley, encountered structural complications in Paleozoic strata; well 78-3, 2 miles (3 km) east of Cove Fort, penetrated a representative portion of each of the four suites of rocks listed above, and ended in Triassic strata of the first suite; and well 82-3, in Sevier County 3 miles (5 km) east of Joseph Peak, encountered thrust faults at depths greater than 2 miles (3 km), indicating that thrust faulting extended farther east than shown at the surface. Interpretive cross sections are given later in this bulletin under the structure heading.

The Pahvant Range contains the highest peaks in Millard County; some are above 10,000 feet (3,050 m) and supported glaciers during the Pleistocene Ice Ages. There is little doubt that the range is a large normal fault block, raised to its present prominence within the last 17 million years. Fault scarps of late Quaternary age can be traced along the eastern base of the Canyon Mountains, through a southeasterly diagonal offset by Scipio, and then along the eastern base of the Pahvant Range (figure 30) southwards along Round Valley. Offset along the fault in Round Valley is not great, being about what the present topography shows, 4,000 feet (1,220 m). The puzzle comes when we try to locate a large normal fault on the west side of the range. No late Quaternary fault scarps cut the alluvium along the base of the range in Pahvant Valley. The Bouguer gravity map (figure 8) shows no gravity low against the Pahvant Range to indicate any great thickness of valley-filling deposits. Instead, the west sides of both the Pahvant Range and the Canyon Mountains are flanked by deposits of the upper Cenozoic Oak City Formation, an exhumed valley-filling deposit that appears to rest near Fillmore on a 10 million-year-old deposit of white volcanic ash. Geologic mapping shows that numerous fault scarps cut alluvium and basalt from Tabernacle Crater to Cove Fort; but these are some distance away from the base of the Pahvant Range. The area covered by the Oak City Formation is probably mostly a complex of brecciated and attenuated Paleozoic strata such as are exposed in the low knobs at the base of the range and in the small exposures near Holden and in the Church Mountains.

Figure 30. View to southwest from Scipio toward the east face of the Pahvant Range. Triangular faceted spurs between the rills and canyons are typical indicators of a fault scarp.

Canyon Mountains

Lower Paleozoic strata at the north end of the Pahvant Range continue across Scipio Pass to the south end of the Canyon Mountains, and join the two ranges into a continuous structural block, bounded on the east side by a down-to-the-east normal fault that is marked by scarps cutting surficial alluvium in Scipio Valley and Round Valley. These Lower Paleozoic rocks (figure 31) were overridden by Precambrian and Cambrian strata of the Canyon Range thrust plate (figure 32). At the time of Canyon Range thrusting, the Precambrian strata lay flat on the thrust surface. Both the thrust surface and its overlying rocks were folded, during Pavant and later thrusting, into the large asymmetric syncline whose axis follows the crest of the Canyon Range (figure 33).

On the crest and east side of the Canyon Mountains, coarse synorogenic conglomerates and sandstones of Cretaceous age overlap folded strata of the thrust plate (figure 32). These conglomerates have locally been tilted and overridden by minor late thrust movements.

On the west side and at the south end of the Canyon Mountains, the upper Cenozoic Oak City Formation unconformably overlies all older rocks. Near Oak City this formation includes large slide masses of recemented quartzite and limestone breccia.

Little Valley

The Low Hills (figure 34) composed of the North Horn and Flagstaff Formations extend westward from the Valley Mountains and partially separate Scipio Valley from Little Valley, which is located north of the Millard County line in Juab County. Quaternary and Pliocene alluvial and lacustrine deposits mostly conceal the Cretaceous and Paleocene strata that are exposed on the flanks, and locally in the middle of the valley. The Sevier River forms meanders through Little Valley in its lowest portion, which is called Mills Valley. West of there, the river's downcutting is inhibited by the very resistant Paleozoic and Precambrian bedrock that the river encounters as it enters Leamington Canyon just downstream.

Scipio Valley

The Bouguer gravity map (figure 8) shows only a moderate eastward-lowering gradient off the high to the west, suggesting that the surficial fault scarps in Scipio Valley do not reflect major offset on the normal fault along the west side of the valley. Scipio Valley (figure 34) is unique in not being drained by surface streams. Ground water apparently migrates through both the Scipio Valley alluvial fans and the bedrock of the Low Hills into Little Valley to the north, probably utilizing a system of northeast-trending fractures that show locally on the valley floor as elongate sinkholes. The town of Scipio is in a graben in the middle of the valley.

Round Valley

Gravity data points (figure 8) are so sparse in Round Valley as to be of little value in defining thickness of valley fill there. Bedrock crops out at several places in the valley suggesting that valley fill is thin.

Valley Mountains

The Millard County portion of this range (figure 35) is made up of only three sedimentary formations. They are, in ascending order, the North Horn, Flagstaff, and Green River Formations of latest Cretaceous and early Tertiary age. These strata are offset along normal faults that generally downdrop stratal blocks towards Round and Scipio Valleys. At the north end of the Valley Mountains, in the hills south of Sevier Bridge Reservoir, the normal faults trend northeastward and form small horsts and grabens.

Wilderness Study Areas in Millard County

In 1964 the U.S. Congress directed that federal lands be identified and set apart as "Wilderness Areas." The U.S. Forest Service (USFS), the National Park Service (NPS), and the Bureau of Land Management (BLM) are the principal federal agencies to which this directive applies in Utah. Accordingly, they have inventoried the lands for which they are

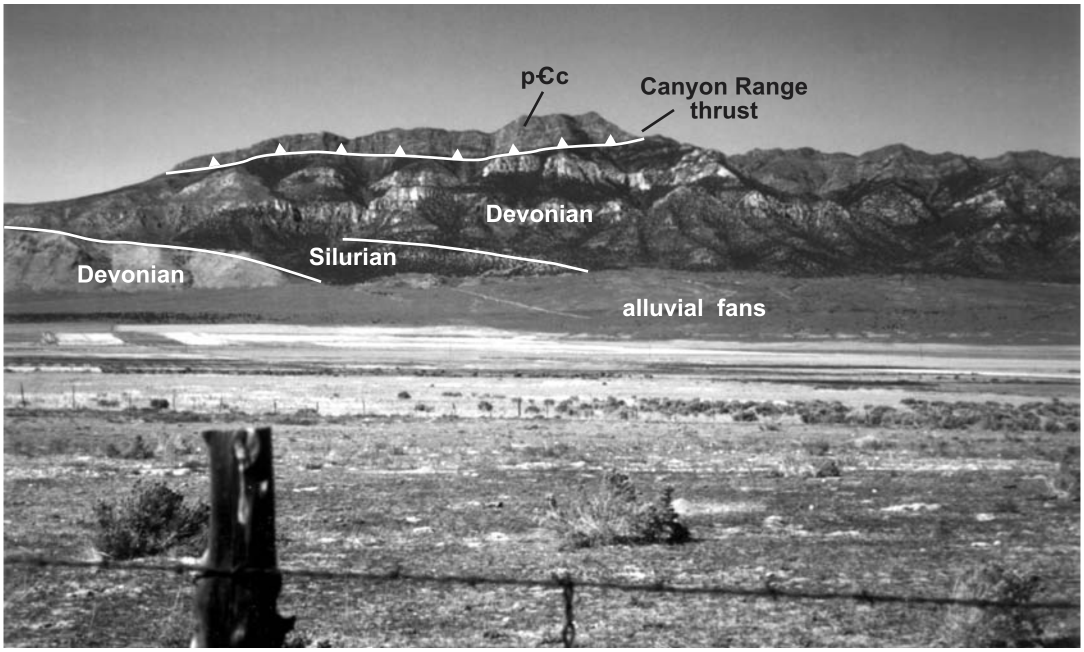


Figure 31. *East face of the Canyon Mountains north of Scipio. Dark rocks on skyline are Precambrian Caddy Canyon Quartzite (p-Ꞓc) of the Canyon Range thrust plate that rest on Devonian dolomite, which forms the light-gray cliffs. Strata at the base of the mountain are Silurian Laketown Dolomite.*

Figure 32. *Aerial view from Leamington eastward up the valley of the Sevier River of nearly vertical strata of the Canyon Range thrust plate exposed at the north end of the Canyon Mountains in Leamington Canyon, Juab County. Oldest rocks shown are the dark maroon quartzites of the Precambrian Mutual Formation (p-Ꞓm). Successively younger Cambrian strata are the Prospect Mountain Quartzite (Ꞓpm), Pioche Formation (Ꞓp), Dome-Chisholm-Howell Formations (Ꞓdh), and Wheeler-Swasey-Whirlwind Formations (Ꞓww). These are overlain unconformably by the Canyon Range Conglomerate (Kc). Light-colored beds in the valley of the Sevier River are deltaic deposits of Lake Bonneville (Qd).*

***Figure 33**. View northward of the south end of the Canyon Mountains from Interstate Highway I-15 south of Holden; Pahvant Valley in the foreground, Church Hills are the low dark hills beyond the town of Holden. Skyline ridges give an end-on view of the Canyon Range syncline, an asymmetric fold with an eastern limb that dips westward about 40°, and a western limb that dips eastward between 60° and 80°. Strata in the axis of the syncline are mostly quartzites of Precambrian and Lower Cambrian age that are part of the Canyon Range thrust plate.*

***Figure 34**. View northward from Scipio Pass into Scipio Valley. Canyon Mountains on left. Town of Scipio just off right side of photo. Aptly named Low Hills are low hills on right side of photo below the crossed wires.*

***Figure 35**. View eastward across Scipio Valley toward Valley Mountains. Rocks exposed on west face of these mountains are mostly yellow sandstones of the North Horn Formation.*

responsible and recommended certain areas as "Wilderness Study Areas" and other areas as "Wilderness or Primitive Areas." The latter designation restricts the use of those lands to specific purposes. Most of the lands in Utah that now have attained formal "Wilderness or Primitive Area" status are in NPS and USFS areas.

Millard County includes six areas, shown on figure 36, that were designated in 1986 as "Wilderness Study Areas" by the BLM. It is up to the U.S. Congress to decide whether "Wilderness Study Areas" become "Wilderness or Primitive Areas" or whether they are removed from further consideration for that restrictive designation. However, until a deci-

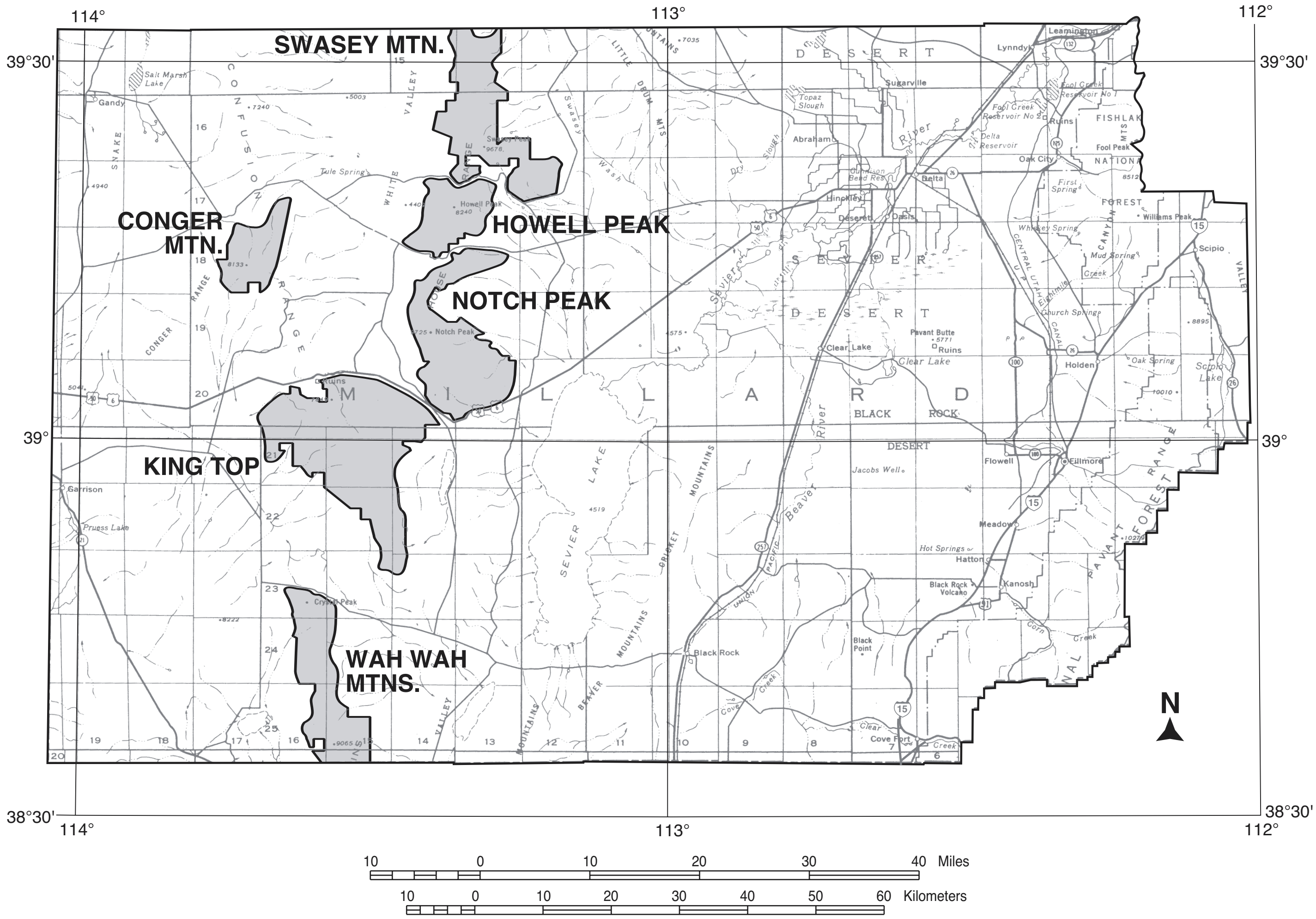


Figure 36. Wilderness Study Areas in Millard County, as designated by the Bureau of Land Management in 1986.

sion is made by Congress, these lands are managed as "Wilderness or Primitive Areas" and are subject to the same use restrictions as "Wilderness or Primitive Areas." Persons interested in the classification of these lands should contact the BLM field office in Fillmore.

Mineral resource assessments published for Wilderness Study Areas in Millard County include: Swasey Mountain and Howell Peak (Tuftin, 1987; Lindsey and others, 1989); Wah Wah Mountains (Brown, 1987; Cox and others, 1989); and Notch Peak (Lundby, 1987; Stoeser and others, 1990). Similar assessment studies have not been published for the Conger Mountain and King Top areas because the BLM initially recommended that they be dropped from wilderness designation. But in its latest wilderness inventory (U.S. Department of Interior, Bureau of Land Management, 1999) they were included. However, Congress has not yet acted to designate any of these areas as Wilderness.

History of Geologic Investigation

Simpson and Engelmann in 1859

The earliest reported scientific geological observation made in Millard County was the discovery of what has become the world's best-known trilobite, *Elrathia kingii* (Meek). The discovery was made by a young geologist, Henry Engelmann, on July 27, 1859, at Antelope Spring in the House Range (Engelmann, 1876). The trilobite he collected was given a preliminary description and name by the paleontologist F.B. Meek (1870) in a paper entitled "Descriptions of fossils collected by the U.S. Geological Survey under charge of Clarence King, esq." Although he listed the collecting locality correctly, Meek mistakenly attributed the collection of the trilobite to the wrong field party and named it after Clarence King whose 40th Parallel Survey's field work never reached as far south as the House Range. The trilobite species *Elrathia kingii* would better have been named after Engelmann or Simpson.

J.H. Simpson, in explorations for the U.S. Army Corps of Engineers, named many mountain ranges, valleys, and springs along his exploratory routes between Camp Floyd (now Fairfield), where Johnston's Army was camped south of Salt Lake City, and Carson Valley, now in Nevada, but then in Utah Territory. Most of his names have been replaced by later names. For example, he called the spring where Engelmann picked up the trilobite specimen "Chapin's Spring." The same spring is shown as Antelope Spring on the Wheeler survey sheet number 50 published in 1873 and that is the name we use today. But Simpson named the House Range for "the resemblance of portions of its outline to minarets, houses, and other structures," and that name has been retained.

Wheeler's Geographical Survey Between 1869 and 1873

Although several crude sketch maps showing travel routes and approximate or supposed positions of lakes, rivers, and mountains in western North America had been published in the 1800s after the Dominguez-Escalante expedition of 1776 (Willis, 1996), the first accurate topographic maps of the Millard County area are those made by the Wheeler Survey (Wheeler, 1875-1889). First Lieutenant George M. Wheeler was assigned by the U.S. Army Corps of Engineers the ambitious project of making a topographic and geologic survey of all U.S. territories west of the 100th Meridian (central Nebraska). Wheeler completed only part of this vast project. Those Wheeler Survey maps that include parts of Utah are shown on figure 37.

The Wheeler Survey topographic maps are valuable historically for they show the names of towns in Millard County just 25 years after the Mormon settlers entered Utah. These include Deseret City, Oak Creek (now Oak City), Scipio, Holden, Fillmore, Meadow Creek (Meadow), Corn Creek (Kanosh), Lower Settlement (now Hatton), Black Rock, and Cove Creek (now Cove Fort). The maps show wagon roads between settlements, as well as some trails through the west desert. The Deseret Telegraph Line between Salt Lake City and southern Utah mines and settlements is also shown.

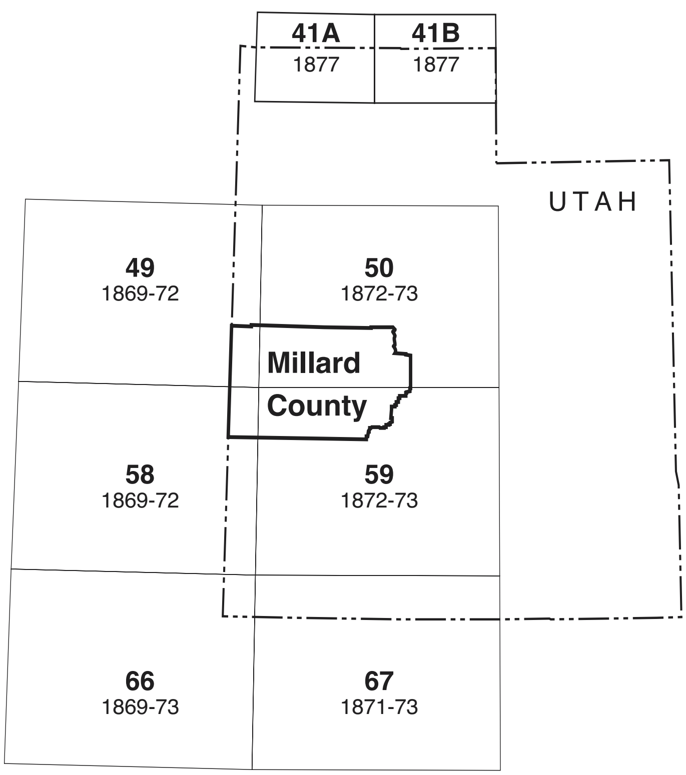


Figure 37. *Map showing the sheet numbers of the topographic maps of the U.S. Geographical Surveys west of the 100th Meridian (Wheeler, 1875-1889) that cover parts of Utah. Scale of the larger maps is 1:506,880 (1 inch = 8 miles), and the dates of field work for each map are shown in small numbers. Scale of maps 41 A and B is 1:253,440 (1 inch = 4 miles).*

Wheeler's survey party included several civilian geologists, biologists, and other scientists, but Wheeler's focus was on mapping water, terrain, and travel routes and he allowed no extra time for scientific studies beyond reconnaissance surveys. Nevertheless, the colored geologic maps of the Wheeler Survey Atlas show the geology of some areas not covered by other concurrent surveys. Wheeler Map sheet 50 (see figure 37 for location), for example, shows 10 geologic map units: Quaternary, Tertiary, Cretaceous, Jurassic, Triassic, Carboniferous, Silurian, Archaean [sic], Trachyte and Rhyolite, and Basalt. Considering the ground they covered and the time allowed to do it, the Wheeler Survey geologists provided a sound basis for further work. Bartlett (1962) summarized the accomplishments of the great U.S. exploratory surveys of the American West, including the particular contribution made by the Wheeler Survey.

Grove Karl Gilbert in Millard County Between 1871 and 1901

G.K. Gilbert (born 1843, died 1918) was one of three young geologists assigned to the Wheeler Survey. He had graduated from Rochester College in New York and spent two years as a volunteer with the Ohio Geological Survey before he joined the Wheeler Survey. A keen observer and consistent note-taker, he wrote a summary account of the geology mapped by the Wheeler Survey in 1871 and 1872 (Gilbert, 1875). Page 27 of his report gives the first published geologic cross section of the House Range (figure 38). Page 59 shows a cross section of the Pahvant Range near Fillmore. Page 137 has a cross section through Pahvant Butte showing the inclination of its volcanic ash layers. Pages 138 and 139 give sketches of the Ice Spring cluster of volcanic craters (figure 26). Page 167 shows a measured section of Cambrian strata at Antelope Spring in the House Range and lists the following fossils from the Cambrian shale there:

Asaphiscus wheeleri (trilobite)
Conocoryphe kingii (trilobite)
Agnostus (trilobite)
Discina (brachiopod)

Gilbert's reconnaissance introduction to the bare-rock geology of the American West during the three years he was with the Wheeler Survey impelled him to return again and again to Utah where he formulated a number of new concepts in the developing science of geology. He advanced physiographic concepts related to stream erosion, retreat of escarpments, and peneplanation; he studied volcanic processes in many places and wrote a landmark report describing laccoliths in the Henry Mountains (Gilbert, 1880).

In his most famous work, the monograph on Lake Bonneville (Gilbert, 1890), Gilbert developed concepts on shore processes and beach erosion (figure 39). He personally traced the shoreline of this Pleistocene lake throughout its extent from the Utah-Idaho border to its southernmost shore south of Milford (Gilbert, 1890, plate 3) criss-crossing Millard County along many routes (figure 40). He was also a

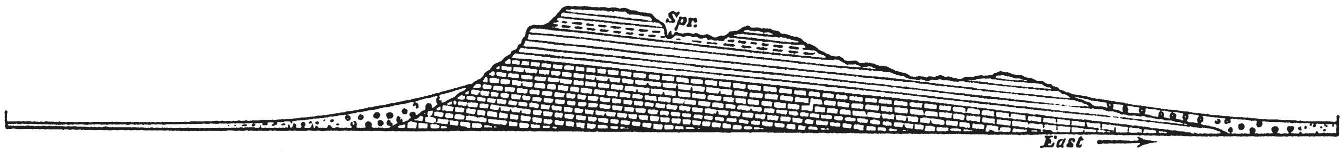


Figure 38. West-east cross section through the House Range at Dome (Death) Canyon by Gilbert (1875). "Spr." shows Antelope Spring located on the shale beds (dashed lines) later called the Wheeler Shale.

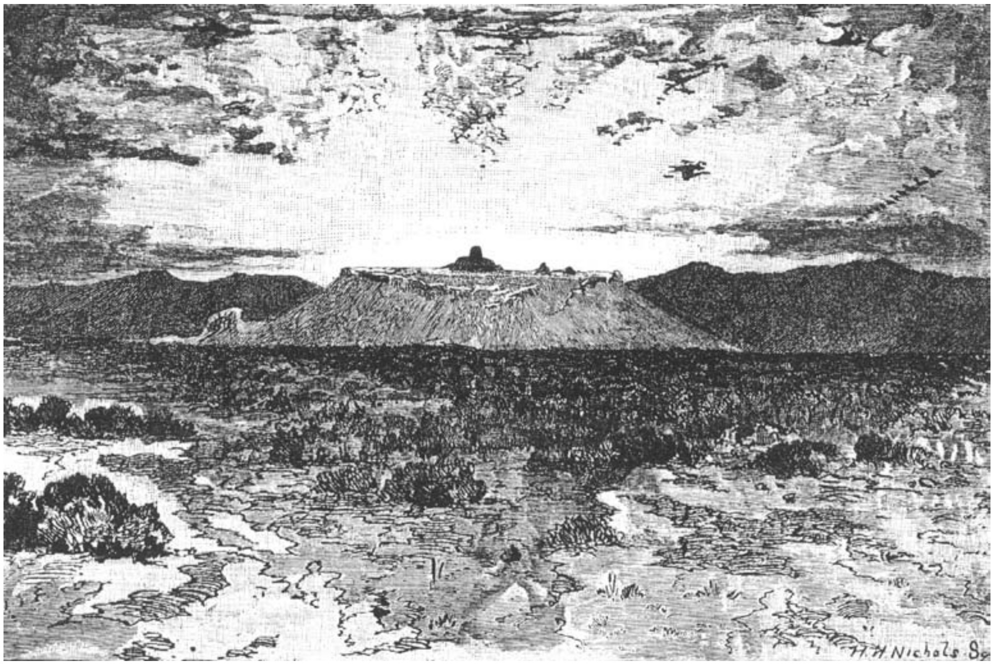


Figure 39. Dunderburg Butte, now called Pot Mountain, is located on the floor of the Sevier Desert 2 miles (3 km) west of Clear Lake station on the railroad south of Delta. This drawing by H.H. Nichols is from Gilbert (1890) who noted that the top of this small volcano was truncated by wave action at the Provo level of Lake Bonneville, leaving only resistant basaltic dikes projecting above the wave-worn surface.

Figure 40. Grove Karl Gilbert; field geologist, 1894, left; portrait, right (both from Davis, 1926).

pioneer in the recognition of the potential earthquake significance of fault scarps that cut recent alluvial and lacustrine deposits. Because he recognized such scarps at the base of the Wasatch Range near Big Cottonwood and Little Cottonwood Canyons, he warned the public of the earthquake danger that the dormant Wasatch fault posed to Salt Lake City (Lund, 1988).

Gilbert became intrigued with the origin of the basins and ranges in western Utah and Nevada at a time when there was no consensus among geologists that block-faulting was the mechanism. He had recognized the recent fault scarps that cut alluvium on the east side of the Fish Springs Range, and had reasoned that the bold west face of the House Range must have been caused by normal faulting. He returned to Millard County in 1901 and made field observations that confirmed his belief that the House Range had, indeed, been uplifted along a concealed major normal fault along its west side. He was, however, puzzled by the relationship between this main north-south normal fault and the southeasterly trending faults that cut through the House Range. Gilbert's field sketch (figure 41) shows several of these transverse faults as viewed from Tule Valley toward the west face of the House Range. Gilbert speculated in his unpublished field notes that these transverse faults might be older than the main range-front fault, an observation later verified by Hintze (1978). Unfortunately, because of other assignments by the U.S. Geological Survey, and also because some of his 1901 field notes on the House Range were lost, Gilbert never published the study of block-faulting in the Great Basin that he started in 1901. A comprehensive history of the outstanding geologic career of G.K. Gilbert (figure 40) was compiled by his friend, himself a noted physiographer, William Morris Davis (1926). He has also been the subject of an outstanding biography by Pyne (1980).

Charles Doolittle Walcott in Millard County in 1903 and 1905

C.D. Walcott (born 1850, died 1927) is preeminently the father of Cambrian paleontology and stratigraphy in North America (figure 42). Born and raised near Utica, New York, he started a systematic collection of bird eggs and minerals at an early age, and by age seventeen had already planned to study the oldest fossiliferous rocks in North America. These had been designated as the Cambrian by Adam Sedgwick in Wales in 1835. He pursued his collection and identification of fossils, with the help of adult collectors, with such proficiency that in 1876 he was appointed paleontological assistant to James Hall, the famous State Geologist of New York. In 1879 he joined the new U.S. Geological Survey, and became Director of the Survey in 1894. He resigned the directorship in 1907 to become Secretary of the Smithsonian Institution, an office he retained until his death in 1927. Walcott was one of the few leaders in the field of science who had no collegiate or formal scientific education, but he was an incredibly effective administrator who was also able to write useful paleontological papers at the same time. Walcott's summary at the end of his diary for 1920 tells much:

> "I am now Secretary of Smithsonian Institution, President National Academy of Sciences, Vice Chairman National Research Council, Chairman Executive Committee Carnegie Institute of Washington, Chairman National Advisory Committee for Aeronautics....Too much but it is difficult to get out when once thoroughly immersed in the work of any organization."

Walcott's first bulletin for the U.S. Geological Survey (Walcott, 1884) summarized what was then known about Cambrian fossils in North America. His second paper (Walcott, 1886) presented, among other things, descriptions and drawings of the same fossils (figure 43), with some names emended, that Gilbert (1875) had listed from Antelope Springs, as well as two species (starred below) not listed previously:

Asaphiscus wheeleri Meek
Ptychoparia kingii Meek
**Ptychoparia housensis* n. sp. (one specimen only)
Agnostus interstrictus White
**Olenoides nevadensis* Meek
Acrothele subsida White (brachiopod)

The modern names for these fossils can be found in Robison (1964a).

Walcott, himself, did not see the Cambrian strata in the House Range until 1903. He had been director of the U.S. Geological Survey for nine years by that time and, as a respite from his administrative responsibilities in Washington that year, he came West for two months in the field. His first chore was to check on the progress of a Reclamation Service field project in Wyoming and Idaho. He then spent time with a Geological Survey field party in the Park City mining district. Finally taking his own long-awaited fieldwork-type vacation, he made a reconnaissance survey of the stratigraphy and fossil-collecting possibilities in the Cambrian strata of the House Range, and a four-day trip to check out collecting possibilities in the Snake Range near Osceola, Nevada. His "vacation" is summarized below from his notes (Yochelson, 1998a-b).

On August 27, 1903, Walcott and his field assistant, Fred B. Weeks, left Salt Lake City at 7:30 a.m. in a buckboard, followed by a wagon driven by its teamster, Dan Orr, and containing camp supplies and the camp cook, Arthur Brown. The first day they drove around the north end of the Oquirrh

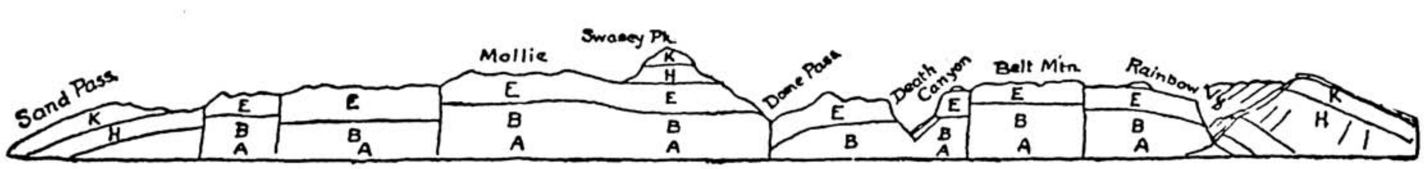


Figure 41. Gilbert's north-south field sketch of the west front of the House Range between Sand Pass and Marjum (Rainbow) Canyon. The sketch is from Gilbert's unpublished notebook of 1901 and was reproduced by Davis (1926).

Figure 42. *Charles Doolittle Walcott (from Taft, 1928).*

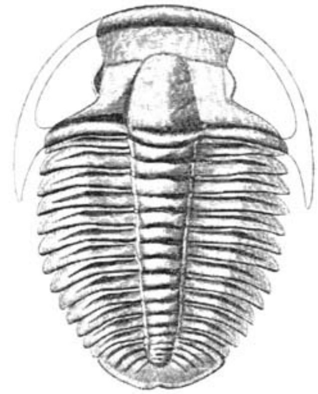


Figure 43. Elrathia kingii *(Meek). Walcott's (1886) sketch of the type specimen collected by Engelmann and described by Meek (1870).*

range (now Mountains), and camped 5 miles (9 km) north of Tooele beside a flowing well. The next three days they passed Stockton, crossed the Stansbury Range (now Mountains) at Lookout Pass, followed the Pony Express route past Simpson's Spring, and then turned south through the Old River Bed and passed through Joy in the Drum Mountains. On August 31st, they drove across Whirlwind Valley and put up camp at Antelope Spring in the House Range after a long, hot day.

The first nine days in September were spent in serious fossil collecting in the vicinity of Antelope Spring but included a day of measuring and describing the stratigraphic section there (figure 44), and a Sunday day of rest in camp writing letters. On September 10th, Walcott's party moved down Dome (now Death) Canyon to the west side of the House Range and traveled northward toward Sand Pass. The photograph shown in figure 45 was probably taken during this day, which Walcott's note described as "A long, tedious day owing to extreme heat and heavy roads in White (Tule) Valley. Dry camp." On September 12th, Walcott's party moved southward to the wagon road west from Dome (Death) Canyon, thence across the Confusion Range to a dry camp just west of Cowboy Pass, making 32 miles (51 km) in a long, hard day. September 13-18 were spent making a reconnaissance inspection of Cambrian strata near Osceola, Nevada, then returning to the House Range, where they camped in the lower end of Marjum Canyon. September 19th and 20th were spent collecting in the vicinity of Marjum Pass, and on the 21st, the Walcott party headed east, collecting some Cambrian fossils on a ridge 4 miles (6 km) south of Antelope Spring, then camping in the desert about 15 miles (24 km) west of Deseret, Utah. On September 22nd, they drove to Oasis on the San Pedro-Los Angeles & Salt Lake railroad line, where Walcott and Weeks boarded the train (Delta, Utah did not exist in 1903), and the wagon and buckboard went north with Dan Orr and Arthur Brown.

Figure 44. *Walcott's unpublished 1901 panoramic photograph of the upper part of the Wheeler Shale (foreground) and the Marjum Formation on the east side of the Wheeler Amphitheater near Antelope Spring. Many of the fossils from the House Range described by Walcott came from the area shown in this picture. Photo from U.S. Geological Survey Field Records Library, Denver, Colorado.*

***Figure 45**. Charles D. Walcott's unpublished photograph of his paleontological exploration party in Tule (White) Valley on September 11, 1903, view to east. High point on right side is Tatow Knob capped by the Swasey Limestone. Light cliff just below top is the Dome Limestone, which can be traced nearly continuously to the left skyline of this view. The thicker light cliff is the Howell Limestone. The dark slope below, and of about the same thickness as the Howell cliff, is formed on the Pioche Formation. Prospect Mountain Quartzite is exposed above the alluvial fans along the base of range. Photo from U.S. Geological Survey Field Records Library, Denver, Colorado.*

In 1905, Walcott returned for his second (and last) field trip to the House Range. From his 1903 reconnaissances he had identified where the best measurable sections of Cambrian strata in western Utah are located, and in September 1905, he came specifically to measure those sections and collect fossils from them. Leaving Salt Lake City on September 1st, his 1905 field personnel were the same as in 1903, but with the addition of a second geological assistant, Lancaster D. Burling. The party arrived at Antelope Spring on September 5th. They spent 11 of the next 13 days measuring and describing stratigraphic sections, making fossil collections as they measured. Two days were Sunday rest days. Walcott boarded the train at Oasis on September 14, 1905, never to return to the House Range.

Walcott became the Secretary of the Smithsonian Institution in 1907, and thereafter that organization published his writings on Cambrian strata and fossils in Utah. Despite his heavy administrative responsibilities, he continued to publish descriptions of Cambrian fossils throughout his lifetime, one paper being published posthumously. His descriptions of fossils from the House Range are scattered through a number of his papers, chiefly because each of his papers was devoted to a particular kind of organism such as trilobites, brachiopods, sponges, echinoderms, or algae, regardless of where he had collected those fossils. Those papers that contain House Range information are listed under his name in the references section of this bulletin.

Readers who wish to know more about the amazing geologist-administrator, Charles D. Walcott, are referred to Taft (1928) and Yochelson (1967, 1998a-b).

O.E. Meinzer and Ground Water in 1911

In 1908, Caleb Tanner, State Engineer of Utah, entered into a cooperative agreement with the U.S. Geological Survey to make a survey of water resources in Millard County, with a view to obtaining information that might lead to a greater utilization of ground-water supplies. O.E. Meinzer, a pioneering expert in the geology of ground water, was appointed to make the study. Meinzer's (1911) report described the water potential of all of Millard County's major valleys: Round Valley, Pahvant Valley, Sevier Desert, Wah

Wah Valley, Sevier Lake Bottoms, White (Tule) Valley, and Snake Valley. Use of Sevier River water for irrigation in the Delta area was just beginning; because it was not a ground-water project, it was not described. Meinzer's report had its greatest effect on development of ground water in Pahvant Valley. Not until 1944 was Meinzer's work superceded, as discussed below. Water resources in Millard County are still under continued monitoring and study by the U.S. Geological Survey under cooperative arrangements with the Utah Department of Natural Resources.

B.S. Butler and Ore Deposits of Utah in 1920

The only mention of any ore deposit in Millard County in Butler and others' (1920) comprehensive survey of ore deposits in Utah is that made by Loughlin (1920). He described the general geology of the Canyon Range and the local occurrence of ore deposits in the Leamington district from which a small amount of lead-silver ore was shipped to Salt Lake smelters between 1903 and 1906. Butler and others (1920) compiled the first geologic map of the state of Utah (scale 1:768,0000). It gave a generalized identification of the ages of rocks in all of the ranges in Millard County. Its greatest error was in identifying most of the strata in the Canyon Range as Carboniferous on the basis of Loughlin's (1920) appraisal. Loughlin had collected Mississippian fossils from the Gilson Mountains northeast of Leamington and had extrapolated that age southward into the Canyon Range, not realizing that he had crossed a major fault in Leamington Canyon. Christiansen's (1952) mapping corrected the error.

Geologic Information Drought in Millard County, 1921-1942

Nothing was published on the geology of Millard County in the 22 years following Butler and others' (1920) report, except a few papers on paleontology. In an effort to stir up some interest in Millard County, Frank Beckwith, editor of the weekly newspaper in Delta, invited several paleontologists to visit the Cambrian trilobite beds at Antelope Spring (figures 46 and 47) and the Ordovician beds at Fossil Mountain near Ibex (Beckwith, 1931, 1947; Kelsey, 1997). Also, Ulrich and Cooper (1938) described Ordovician brachiopods sent to them by Beckwith. Deiss (1938) included the Cambrian section in the House Range in his review of Cambrian strata in the Cordillera. Salmon (1942) described an Ordovician brachiopod she found on a fossiliferous limestone slab from Millard County in the Grabau collections at Columbia University. Resser (1942) described the remaining tag ends of Walcott's 1905 collection from the House Range.

Geologic Interest in Millard County Picks Up, 1943-1959

Dennis and others (1946), Livingston and Maxey (1944), Nelson and Thomas (1953), and Woolley (1947), U.S. Geological Survey geologists who had been working to improve agricultural productivity in Millard County during World War II, published papers on water resources. Woolley (1946) examined floods in Utah. Maxey (1945) published the first new geologic maps made in the county in 25 years. Additional Millard County areas were geologically mapped by Christiansen (1952), Crosby (1959), Gehman (1958), Lautenschlager (1952), Liese (1957), Tucker (1954), and Varnes and Van Horn (1951). The Intermountain Association of Petroleum Geologists (1951) published a guidebook to the geology of the Canyon, House, and Confusion ranges, with 13 papers by several authors and a geologic map of west-cen-

Figure 46. *Frank Beckwith, Sr. (with canteen) and Charles E. Resser, paleontologist from the Smithsonian Institution, at Antelope Spring in July 1930 (photo courtesy of Jane Beckwith).*

Figure 47. *Professor F.F. Hintze and his University of Utah paleontology class on a fossil-collecting trip at Antelope Spring in May 1931.*

tral Utah at a scale of 1:192,000, the best map available for the area at that time.

Papers on stratigraphy and paleontology were published by Bacon (1948), Bright (1959), Clark (1957), Cooper (1956), Flower and Gordon (1959), Hintze (1948, 1949, 1951, 1952, 1953, 1954a-b, 1958a-b, 1959), Hintze and Jaanusson (1956), Hose and Repenning (1959), Newell (1948), Ogden (1951), Osmond (1954), Palmer (1954), Rush (1951, 1956), Waite (1956), Webb (1956, 1958), and Wheeler (1948). Hansen and Scoville (1955) gave formation tops for oil exploratory wells in Utah, including those in Millard County. Harris (1959) introduced the term and concept for the Sevier arch. Johnson and Cook (1957) presented a gravity map of part of Millard County. Nackowski and Levy (1959) reviewed mineral resources in the area, and Crawford and Buranek (1942a-b, 1944, 1945a-b) wrote about specific deposits. The U.S. Department of Agriculture, Soil Conservation Service, issued the *Soil Survey of East Millard Area, Utah* in 1959 (Wilson and others, 1958). A summary of numbers of publications from 1950 to 2001 is shown on figure 48.

Geologic Interest in Millard County Peaks and Declines, 1960-2001

In the remaining decades of the twentieth century, geologic interest in Millard County greatly expanded, as shown by the number of publications on figure 48 and listed in appendix B. The number of publications in the 1980s was about four times the number in the 1950s. Most of this interest was likely associated with increased federally funded geologic research in the 1960s and increased domestic energy exploration in the 1970s and 1980s. Geologic publications on Millard County peaked in the 1980s and, if the limited number of publications from this new century is any indication (appendix B), the decline of the 1990s is continuing. This decline may reflect the overall decline of federal funding for geologic studies and the decline of energy and mineral exploration in the United States.

Project Background

The foundation for this study was laid in the summer of 1947 when my father, Ferdinand F. Hintze, Jr., introduced me to the joys of fossil collecting in the Ordovician strata near Ibex, an abandoned ranch in the Barn Hills, east of the southern Confusion Range. Dad had just retired from teaching geology at the University of Utah and he was trying to help me lay the groundwork for a graduate thesis at Columbia University in New York City. We spent a day at Ibex (figure 49) measuring Ordovician strata and collecting trilobites and brachiopods from our measured section. Going home, as we traveled through the magnificent sequence of Cambrian limestones and shales in Marjum Canyon, Dad casually remarked that someday I might map the geology of the House Range, a notion that, at the time, I regarded as highly unlikely, if not ridiculous.

The next year at Columbia, I completed a master's degree, making preliminary identifications of the fossils we had collected at Ibex. During the summers of 1948 and 1949, I measured fossiliferous sequences of Ordovician strata in western Utah and eastern Nevada and began writing descriptions of them for my doctoral dissertation. In the fall of 1949 I began teaching geology at Oregon State University and finished my dissertation, which was published by the Utah Geological and Mineralogical Survey (Hintze, 1951, 1952). Arthur Crawford, director of the survey, asked me then if I would write a bulletin on the geology of Millard County and gave me copies of the new 1:250,000-scale Army Map Service topographic maps on which to compile the geology. Neither of us realized, at that time, what a large undertaking that would be, nor how long it would take.

Leaving Oregon in 1955, because my wife developed asthma in the lush Willamette Valley, I came to Brigham Young University (BYU) to teach. As the newest member in the Geology Department, I was immediately assigned to be in charge of the geology summer field course. I decided to take the 1956 field camp to the only place in Utah where I was acquainted with the dirt roads and the geologic formations, namely Ibex.

There being no potable water at Ibex, we set up a dry camp. I assigned each of the 22 geology students about 10 square miles (26 km^2) to map on aerial photographs, and each produced a map and report on his area from which we compiled the first of many geologic quadrangle maps to be generated in this fashion. Between 1956 and 1979, nearly 400 BYU geology students mapped small parts of Millard County as their senior field course requirement for graduation. We initially released these maps on open-file (Hintze

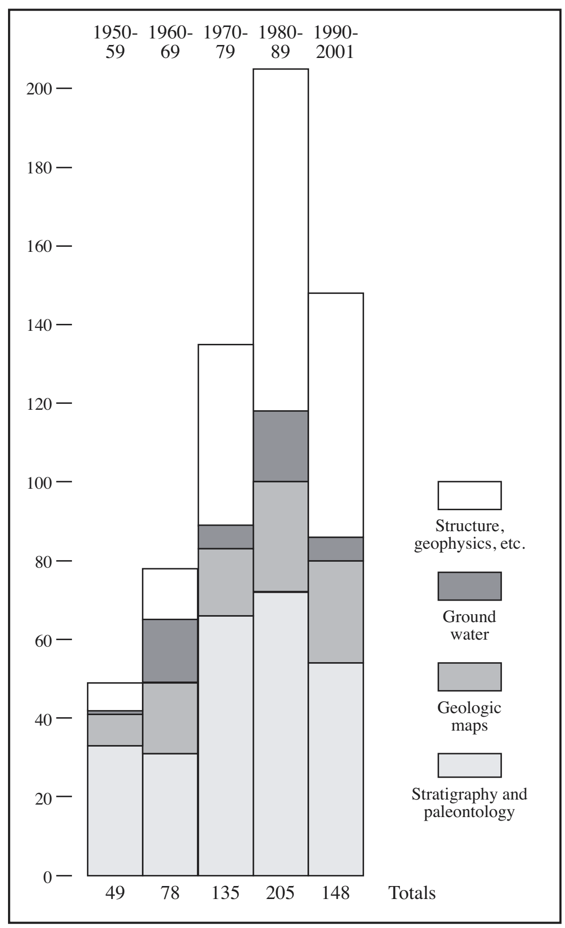


Figure 48. *Graph showing number of publications on geology of Millard County by decade since 1950. Stratigraphic studies and geologic maps have provided a firm foundation upon which structural, geophysical, and other studies have been built.*

***Figure 49**. Ferdinand F. Hintze, Jr., in September 1947, on a hill about 1 mile (1.6 km) west of Warm Point, looking northeast across the valley toward Ibex, located in a cove at the left side of the light-colored outcrops of Eureka Quartzite.*

1958a-b, 1959, 1960a) and later they were published by the state and federal geological surveys. During the 1970s, Myron Best shared with me the responsibility for the summer field course. He trained the students in the mapping of igneous rocks and I supervised mapping in Paleozoic strata. We were co-authors of some quadrangles (Best and Hintze, 1980a; Hintze and Best, 1987), but Best went on to lead students in extensive mapping of the large volcanic terrane that straddles the Utah-Nevada border south of Millard County. His summaries (shown under his name in the reference list) have revolutionized our understanding of Oligocene-Miocene events in this region. He has graciously verified the identity of most of the igneous rocks discussed in this bulletin and shown on the geologic maps of the county (Hintze and Davis, 2002a-c; Hintze and others, 2003).

The U.S. Army Map Service had produced 1:250,000-scale topographic maps from high-altitude photographs during World War II and these maps were converted to a civilian edition by the U.S. Geological Survey in 1955, just as I returned to Utah. Using these accurate new topographic maps as a base, I compiled the first new geologic map of western Utah (Hintze 1960b, 1961) done since Butler and others (1920). Armand J. Eardley, a geologist who was a dean at the University of Utah, persuaded the Utah State Land Board that it would be to their benefit to have an up-to-date geologic map of Utah because state lands in western Utah that had been taken over for military purposes during the war were not going to be returned to the state. However, the State Land Board could select federal lands of equivalent area anywhere in the state. A geologic map would help experts to decide which federal lands would be most beneficial to select. Accordingly, the State Land Board funded the production of the new 1:250,000-scale Geologic Map of Utah (Stokes, 1962; Hintze, 1963b) published by the Utah Geological and Mineral Survey.

In 1972, Max D. Crittenden, a U.S. Geological Survey branch chief who had mapped much of the Wasatch Range, entered into a cooperative agreement with the Utah Geological and Mineral Survey for the federal survey to match funds with the state survey for the publication of the geologic maps being generated by the BYU geology field course program. The 1:48,000-scale version of 20 larger scale geologic quadrangle maps in Millard County (Hintze 1974a-e) were the first products published by the U.S. Geological Survey under this arrangement. Subsequently, 26 more 1:24,000-scale geologic quadrangle maps in Millard County were published under these auspices. In addition, geologic maps of 11 quadrangles in the Canyon Mountains, Pahvant Range, and Black Rock Desert were mapped as master's theses by BYU graduate students. The BYU mapping was focused on bedrock areas rather than valley areas covered by surficial deposits. As such, the BYU geologic mapping of 57 1:24,000-scale quadrangles covered 75 percent of the bedrock area exposed in Millard County.

Given the above, it is perhaps not surprising that, upon my retirement from teaching at BYU in 1986, I was hired by Genevieve Atwood, then director of the Utah Geological Survey, to work half-time on producing the present geologic maps and report. Initially I worked under the supervision of Hellmut Doelling, chief of the mapping section. When he retired from administrative duties, his place was taken by Grant Willis. Until 1995, the emphasis was on field mapping of bedrock and, with the help of Fitz Davis of the Utah Geological Survey, mapping of surficial deposits. In 1996, our emphasis shifted to writing this report and publication of the geologic maps listed above.

Acknowledgments

In addition to administrative support and encouragement from Genevieve Atwood, Lee Allison, Rick Allis (Utah Geological Survey directors), Hellmut Doelling and Grant Willis, other Utah Geological Survey (UGS) personnel have reviewed sections of this bulletin related to their areas of expertise. Mike Hylland and Kimm Harty of the UGS reviewed the entire bulletin and companion geologic maps, greatly improving their quality.

Many other geologists have contributed to the betterment of this bulletin by critiquing early manuscript drafts within their specialties, and/or by furnishing preprints of their own reports concerning geology in Millard County. These include: Rick Allmendinger, Ernie Anderson, Myron Best, Frank Brown, Eric Christiansen, Jim Coogan, Peter DeCelles, Dick Hose, Bart Kowallis, Tim Lawton, Britt Leatham, Bill Lund, Don Mabey, Allen McGrew, Elizabeth

Miller, Jim Miller, Gautam Mitra, Bill Nash, Connie Nutt, Jack Oviatt, Pete Palmer, Barney Poole, Keith Rigby, Richard Robison, David Rohr, Charles Ross, Reuben Ross, Pete Rowley, Frank Royse, Charlie Sandberg, Bob Smith, Doug Sprinkel, Tom Steven, Walt Sweet, John Welsh, Grant Willis, and Ellis Yochelson.

Brigham Young University continued to contribute its long-term support of the Millard County project through the Department of Geology under Chairs Wade Miller and Bart Kowallis by providing me with office facilities and secretarial services while I worked for the state survey. Stacy Kennerley, Katie Greener, and Mindy Johnston were particularly helpful. Doug Reid, District Ranger in Fillmore, kindly let me use U.S. Forest Service color aerial photos of the Canyon and Pahvant Ranges to facilitate my revision of geologic maps of these ranges. His office manager, Takako Scottorn, graciously checked photos in and out. Rex Rowley, head of the Bureau of Land Management office in Fillmore, supported field reviews of our work in Millard County. Lynn Fergus, BLM geologist, gave information on Wilderness Study Areas. My co-author, Fitz Davis, supported the completion of the Millard County bulletin by working at home, without pay, to help with editorial work.

Special thanks go to Jon King of the Utah Geological Survey who painstakingly proofread the geologic maps, cross sections and text of this publication, facilitating its progress through the review process in many ways. Jim Stringfellow and his publications production team are thanked for ensuring the high quality of the printing of the text and maps.

GEOLOGIC HISTORY OF MILLARD COUNTY

by Lehi F. Hintze

Millard County's soil and rock layers contain the records of its geologic history. For most of its sojourn as a part of western North America, Millard County lay near sea level and was awash in shallow marine waters on a continental shelf; later it was covered with Jurassic sand dunes of Saharan magnitude; still later, Tertiary volcanic ash blanketed the county and Quaternary lava flows spewed from local volcanoes. Finally, within the past 20,000 years, Lake Bonneville, a large Ice Age freshwater lake, covered half the county as well as much of the rest of western Utah; it was more than 650 feet (199 m) deep over the present site of Sevier Lake's dry bed, and, had you been here then, you could have sailed a boat from Lynndyl to Black Rock and points south.

An overview of the main aspects of the geologic history of Millard County is presented briefly on figure 50, and summarized more fully on the following pages. Descriptions of the many consolidated bedrock and unconsolidated surficial units that are exposed in the county are given later in this bulletin, accompanied by references to scientific papers that describe them in greater detail. Stratigraphic columns (columns 1-11, appendix C) list the names applied to rock units in the 11 areas of the county shown on figure 51. On these columns, rock thicknesses and lithologies are shown schematically and ages are listed along with key fossils and other data. Other diagrams, termed correlation charts (charts 1-8, appendix C), show comparative ages of rock units. Geologic time is stacked vertically on a correlation chart, and rock nomenclature from several areas is shown side-by-side; rock units of the same age are shown at the same horizontal level on the correlation chart. Rock units whose deposition occurred over a brief time interval are shown in narrow time boxes on this kind of chart. Units whose deposition occurred over longer time intervals are shown in taller time boxes. Vertical height on a correlation chart represents passage of time and does not portray the depositional thickness of a rock unit, which is shown on the stratigraphic columns. Rock units vary greatly in thickness, age, and areal extent; some are thick, some are thin, some are extensive, and some are local. Both stratigraphic columns and correlation charts are needed to show the ranges of age and thickness of rock units. These columns and charts are a geologic shorthand that supplements geologic maps and cross sections in order to condense geologic field relationships into managable size for display in this bulletin.

In the following summary, events in Millard County's geologic history, as documented in this bulletin, have been divided into eleven intervals. The youngest interval covers the history of Sevier Lake and its predecessors, Lake Gunnison and Lake Bonneville (figure 52). In this summary, yr B.P. means radiocarbon years before the present (actually before 1950 A.D), and Ma means millions of years ago.

Event Interval XI 20,000 yr B.P.- present Time

Sevier Lake and its predecessors Lake Gunnison and Lake Bonneville rose and fell during this interval. Gilbert (1890), Currey and others (1983a), Oviatt (1988, 1989, 1991a, 1992, 1994), and Oviatt and others (1994a-b) provide details on Lakes Gunnison and Bonneville. Also during this interval, earthquakes produced fault scarps along the base of the Pahvant, Canyon, Cricket, Drum, and House mountain ranges, in many places in Sevier and Black Rock Deserts, and locally in Snake Valley near Garrison.

2000-1880

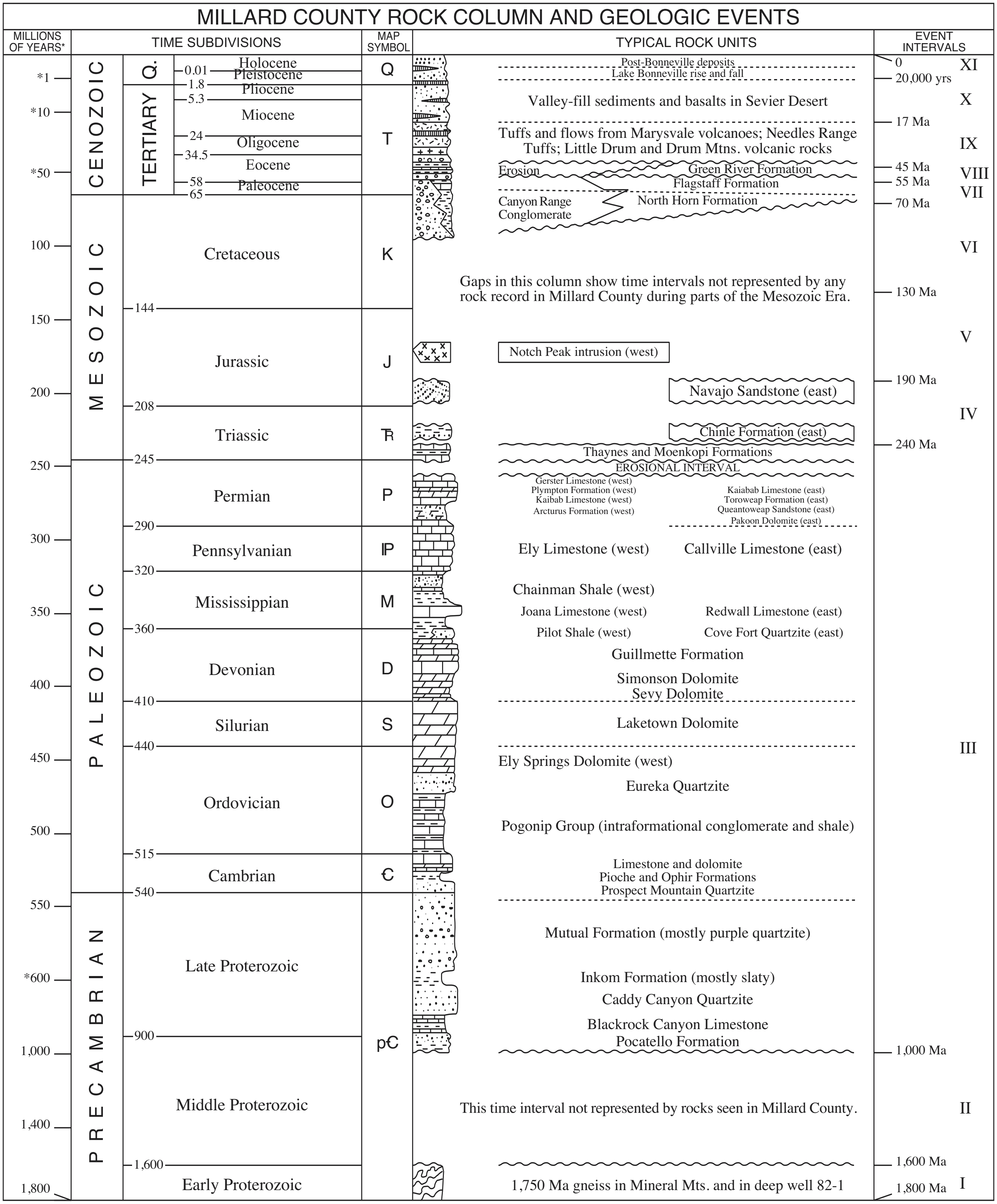
Sevier Lake dried up periodically, typically seasonally, during this interval. From 1985 through 2000 the lake bed was dry all year. During the wet years of 1983 through 1985, the lake didn’t dry up seasonally and rose to 4,523 feet (1,378.9 m); its maximum depth was 7 feet (2.1 m). From 1880 through 1982, Sevier Lake dried up each year after seasonal snowmelt runoff. The lowest lake floor elevation is 4,516 feet (1,376.5 m).

1880-10,000 yr B.P.

Sevier Lake fluctuated between dried up and a 4,534 foot (1,382.3 m) lake level. The maximum depth of Sevier Lake was 18 feet (5.8 m). The basalt flows of Ice Springs, west of Fillmore, were erupted some time between 4,000 and 660 yr B.P. At the start of this interval Lake Gunnison receded to the historical Sevier Lake playa.

10,000-12,500 yr B.P.

Freshwater Lake Gunnison overflowed into the Great Salt Lake Desert via the Old River Bed between the Keg and



*Change in scale of age intervals at 1, 10, 50, and 600 million years

Figure 50. *Millard County rock column and geologic event intervals used in the text.*

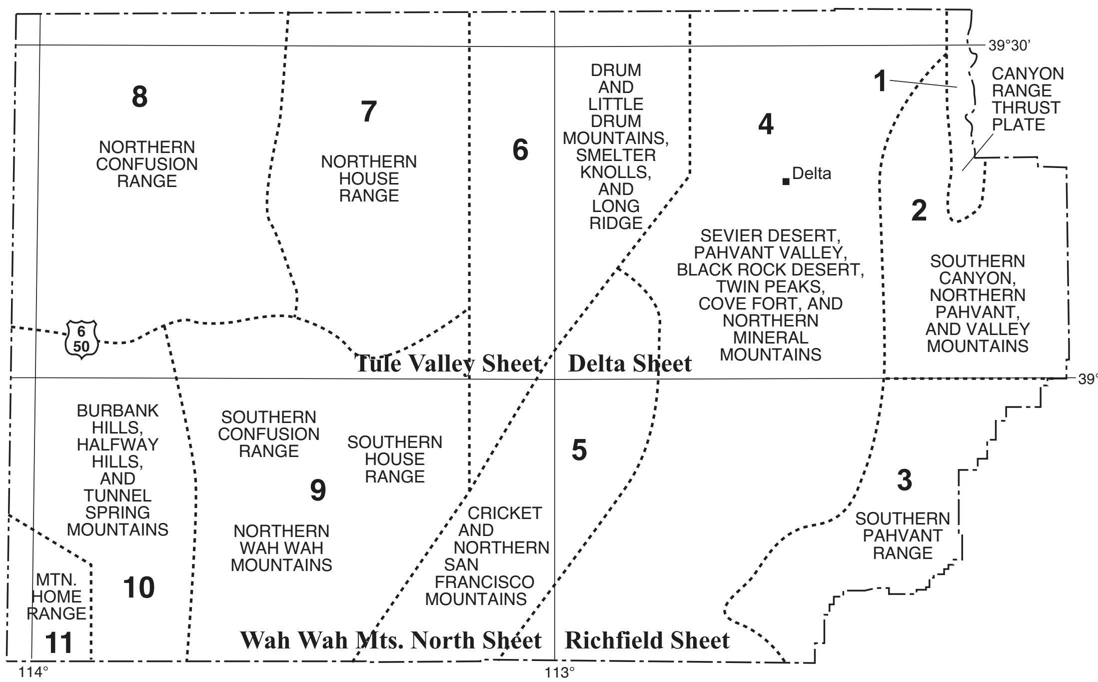


Figure 51. Location map for stratigraphic columns.

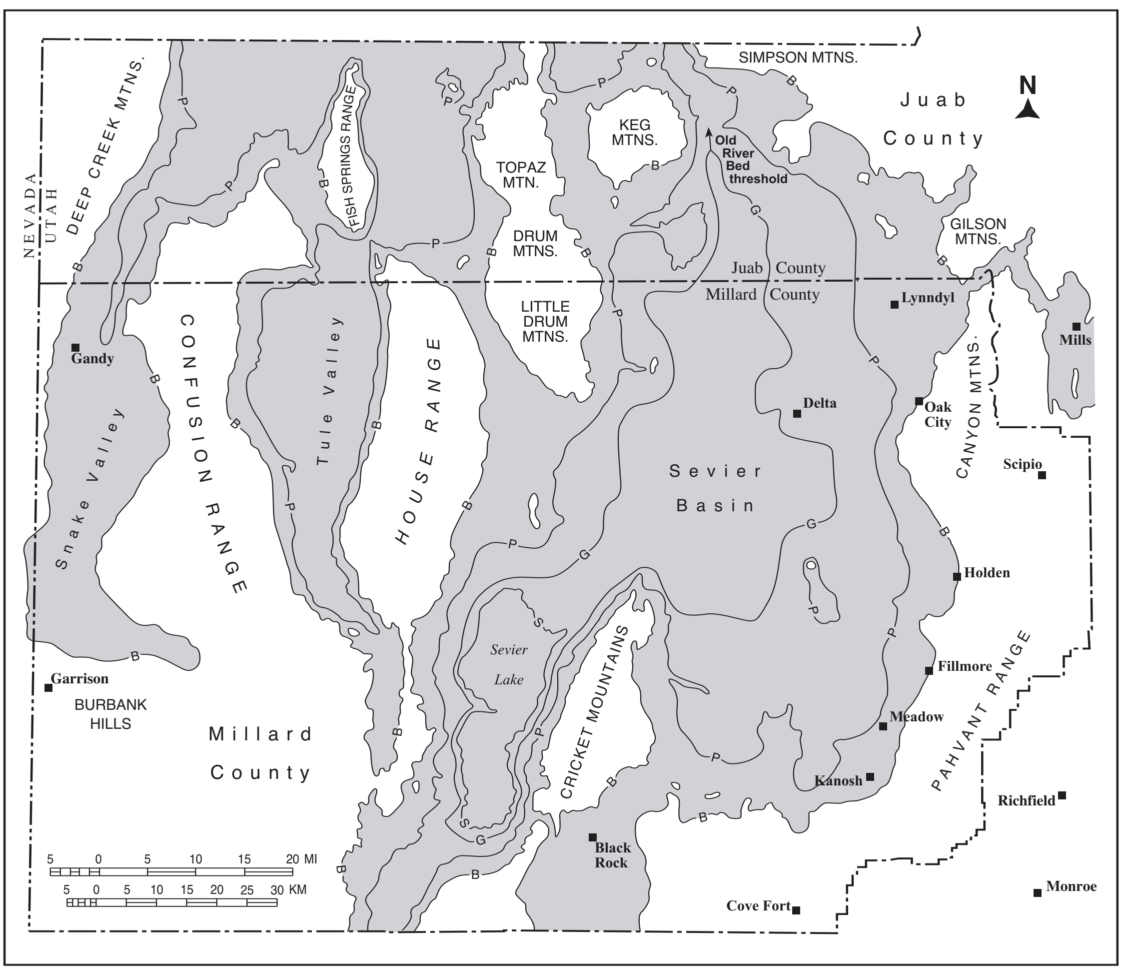


Figure 52. Shorelines of Sevier Lake and its late Quaternary predecessors, Lake Gunnison and Lake Bonneville in Millard and Juab Counties: S=Sevier Lake shoreline, G=Lake Gunnison shoreline, P=Provo shoreline of Lake Bonneville, B=Bonneville shoreline of Lake Bonneville; after Currey and others (1983a) and Oviatt (1988).

Simpson Mountains. The maximum depth of Lake Gunnison was 44 feet (13.5 m). It covered the present location of U.S. Highway 6-50 for about 25 miles (40 km), from 2 miles (3 km) west of Delta, Utah westward to Long Ridge.

12,500-14,000 yr B.P.

During this interval Lake Bonneville regressed from the Provo level (4,790 feet [1,460 m]). About 12,500 yr B.P., Lake Bonneville dropped below the Old River Bed threshold (4,560 feet [1,390 m]) and the lake became divided. A southern lake formed, Lake Gunnison, with a level 230 feet (70 m) below the Provo level.

14,500 yr B.P.

The Bonneville flood occurred when rapid erosion breached the outlet of Lake Bonneville north of Preston, Idaho. The lake drained into the Snake River and the flood caused the lake to drop about 350 feet (107 m) from its highest level to the Provo level. Jarrett and Malde (1987) estimated that the Bonneville flood was the second-largest prehistoric flood in the world, exceeded only by one of the floods from glacial Lake Missoula that scoured eastern Washington. Basalt was erupted from Tabernacle Hill about 14,400 yr B.P., likely soon after the Bonneville flood.

14,500-20,000 yr B.P.

Lake Bonneville inundated the Sevier and Black Rock Desert basin about 20,000 years ago and rose slowly to its maximum level of 5,170 feet (1,576 m) in Millard County. At its maximum, the lake was about 654 feet (199 m) deep over what is now the Sevier Lake playa. The highest shoreline of Lake Bonneville (Bonneville level) shows conspicuously along the bases of most mountain ranges in Millard County and numerous lower shorelines are visible. The shorelines are typically marked by wave-cut benches, and well-rounded sand and gravel in beaches and bars. The best developed lower shoreline is the Provo level. The Provo, Bonneville, and other levels are shown on the geological maps of the county (Hintze and Davis, 2002a-c; Hintze and others, 2003). Glaciers feeding the lake persisted in the Pahvant Range above 10,000 feet (3,050 m) until about 15,000 yr B.P. and basaltic ash was erupted from Pahvant Butte (Sugarloaf) about 15,000 yr B.P.

Event Interval X 20,000 yr B.P.-17 Ma

During this 17 million-year interval, mountains formed in Millard County, along with the entire Great Basin. Topographic relief increased from about 1,000 feet (300 m) to present-day elevations, which range from 4,516 feet (1,376.5 m) at Millard County's lowest point on the floor of Sevier Lake to its highest point, Mine Camp Peak in the Pahvant Range at 10,222 feet (3,116 m). All of the familiar present-day mountain ranges and valleys were formed by block faulting and volcanism during this time. Materials eroded from the uplifting mountain blocks were shed into adjacent valley blocks, which were either raised less than the mountains or actually subsided below their pre-fault elevations. Gravity data suggest that the deepest valley areas are in the Snake Valley south of Gandy, Tule Valley east of Kings Canyon, the Sevier Desert between Sugarville and Clear Lake, and in Pine and Wah Wah Valleys along the south edge of the county. In some of these locations the pre-block-fault bedrock may now lie at or below sea level. Thickness of the valley-filling alluvial, lacustrine, and volcanic deposits ranges up to several thousand feet. Volcanism was active in the Sevier and Black Rock Deserts. Most of the eruptions were of basaltic rocks, but some rhyolitic domes, flows, and ash falls also formed.

Event Interval IX 17 Ma-45 Ma

Millard County was an area of low relief (probably less than 1,000 feet [300 m]) with no major mountains. Its paleostreams drained eastward from the continental divide in eastern Nevada. The principal deposits laid down in the county are ash-flow tuffs that were erupted from calderas outside the county in the Marysvale volcanic field to the south, the Drum Mountains to the north, the Indian Peaks area astride the Utah-Nevada line to the southwest, and the Windous Butte caldera to the west in central Nevada. The Tunnel Spring Tuff is the only eruptive deposit of this age that had its source caldera within Millard County. The probable location of this caldera is concealed by younger deposits in the desert east of Crystal Peak (Steven, 1989).

Event Interval VIII 45 Ma-55 Ma

No deposits of this part of Eocene time have been identified in western Millard County. It was undergoing erosion by eastward-flowing streams that deposited their sediments in a large lake in eastern Utah whose western shoreline was near Richfield. These sediments make up the Green River Formation, which is widely exposed in the Uinta Basin.

Event Interval VII 55 Ma-70 Ma

Streams draining eastward off highlands of the Sevier mountain belt, in western Millard County and Nevada, ponded along the east edge of Millard County in the Canyon, Pahvant, and Valley mountains area. A large lake stretched eastward into the Uinta Basin and freshwater lacustrine limestone, shale, sandstone, and conglomerate were deposited in Millard County. These deposits make up the upper part of the Canyon Range Conglomerate, and the Flagstaff and North Horn Formations.

Event Interval VI 70 Ma-130 Ma

The Sevier mountain belt rose in western Millard County and eastern Nevada as a result of convergence of the North American plate and Farallon plate along the west coast. The continental drainage divide was in eastern Nevada. Synorogenic Upper Cretaceous conglomerate in the Canyon Range was deposited over folded Paleozoic and Precambrian strata, which were thrust tens of miles eastward over Triassic and Jurassic strata during the Sevier orogeny. The eastern limit of thrust deformation in central Utah is east of Millard County and is concealed beneath Sanpete Valley and the Wasatch Plateau. See figure 53 for the timing of thrusting and deposition of synorogenic sedimentary rocks.

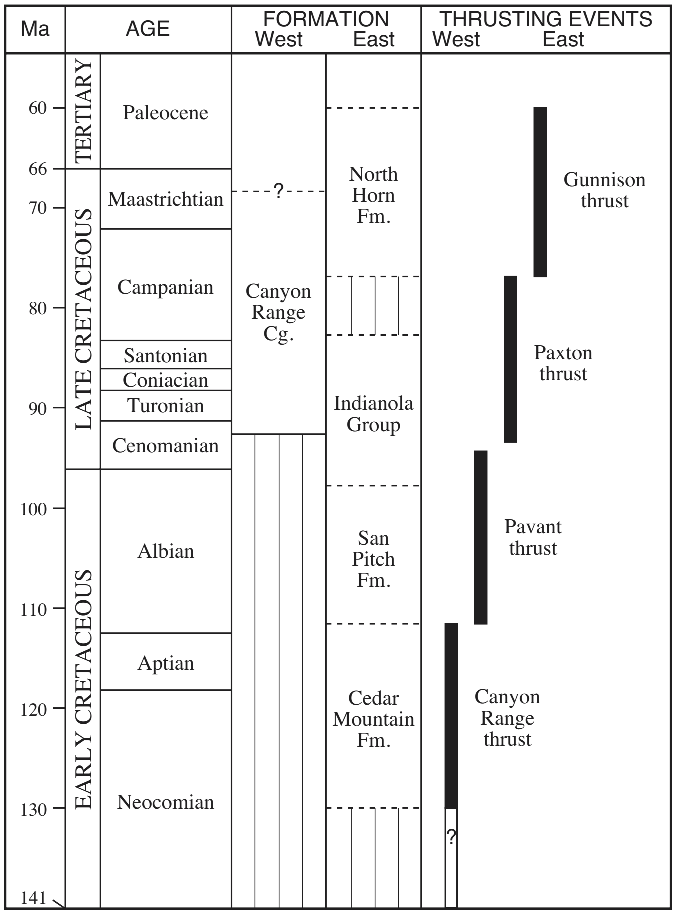


Figure 53. Age of thrusting in central Utah as determined by DeCelles and others (1995) by palynological dating of sedimentary formations produced by each thrusting event. Sedimentary record is preserved in the San Pitch Mountains east of Millard County. Lower age limit of the San Pitch Formation is from Waanders in Lawton and others (1997, p. 54).

Event Interval V 130 Ma-190 Ma

The Jurassic Notch Peak quartz monzonite stock (170 Ma) was intruded into Cambrian strata in central Millard County, and a small diorite plug (141 Ma) cut through Mississippian strata in western Millard County. Cretaceous and Jurassic granitic intrusive bodies are common in eastern Nevada and northwestern Utah and represent early or pre-Sevier orogenic activity. This interval of time is not represented by any other rocks in Millard County (chart 7, appendix C).

Event Interval IV 190 Ma-240 Ma

Navajo Sandstone (Lower Jurassic), now exposed along the west side of the Pahvant Range, once extended westward across Millard County as part of an enormous coastal eolian sand-dune sheet that covered most of Utah when the state lay near sea level. It was removed from central and western Millard County when that area was elevated and eroded during the Sevier orogeny (time interval VI). Similarly, the non-marine Chinle Formation (Upper Triassic), mostly volcanic ash, sandstone, and fossil-wood-bearing conglomerate, now exposed along the Pahvant Range, formerly extended westward, but suffered the same fate as the Navajo Sandstone.

Event Interval III 240 Ma-1,000 Ma

The Lower Triassic Thaynes and Moenkopi Formations (chart 7, appendix C) are the only Mesozoic deposits now found in both eastern and western Millard County. These are the youngest marine deposits in Millard County. The Thaynes Formation is mostly gray sandy limestone that was deposited in shallow offshore marine waters. The Moenkopi Formation is largely red mudstone and siltstone deposited on near-shore tidal flats. An erosional unconformity separates these Lower Triassic deposits from the Permian marine strata upon which they rest. Permian and older Paleozoic marine deposits accumulated to a thickness of about 6 miles (10 km) in western Millard County, and to about one-half that thickness in the east side of the county. Deposits were mostly limestone and dolomite laid down in coastal-shelf marine waters. Low-lying lands lay to the east; westward the sea deepened. Intracontinental sea levels dropped several times during the Paleozoic Era, enough to leave small gaps in Millard County's rock record of deposition during the late Permian, late Pennsylvanian, late Devonian, early Devonian-late Silurian, Early Silurian-Late Ordovician, middle Ordovician, and early Cambrian-late Precambrian.

Paleozoic strata in western Millard County contain superb fossil assemblages of Middle and Late Cambrian, Early Ordovician, and Mississippian ages. The other portions of the Paleozoic rock column also contain marine fossils, but less abundantly.

An unfossiliferous Late Proterozoic (latest Precambrian) sequence of clastic rocks, about a mile (1.6 km) thick, directly underlies the Lower Cambrian Prospect Mountain Quartzite. These rocks mark a new phase of continental shelf subsidence in western North America. The continent is believed to have extended farther westward in Middle Proterozoic time, but a rift developed in what is now western Nevada, and a western, now unknown, part of the continent drifted away, leaving the raw edge of continental crust to slowly cool and subside. This subsidence accommodated the deposition of the thick stack of Upper Proterozoic to Lower Triassic shallow-water marine sediments found in Millard County today. This cumulative deposit is called, by some geologists, a miogeosyncline (Armstrong, 1968b), or alternatively, a miogeocline.

Event Interval II 1,000 Ma-1,600 Ma

This time interval is not represented by rocks in Millard County and was probably an interval of erosion. Because of argon loss, the 1,100 Ma K-Ar age reported from well 81-5 (appendix A) is probably younger than its actual age.

Event Interval I 1,600 Ma-1,800 Ma

Millard County's oldest rock is the banded gneiss exposed in the Mineral Mountains. It was metamorphosed from pre-existing rock, probably sedimentary, about 1,750 Ma, in Early Proterozoic time. This gneiss is about the same age as gneiss and schist found in the Wasatch Mountains and in the subsurface of southeastern Utah. Such rocks are believed to underlie all of western Utah and eastern Nevada, but they are exposed at the surface in only a few places.

STRATIGRAPHY OF THE BEDROCK MAP UNITS

by Lehi F. Hintze

Millard County's bedrock has been subdivided into more than 150 map units (packages of similar rocks traced on geologic maps) which range from Precambrian rocks that were metamorphosed 1,750 million years ago (abbreviated Ma in this bulletin where numbers are isotopic or fission-track ages) to lava flows that are only several hundred or thousand years old. The rocks that have attracted the most attention are Cambrian and Ordovician marine deposits in the House and Confusion Ranges where these strata contain an unusually complete fossil record of life on Earth between 540 and 440 million years ago. This bulletin summarizes both the rock and the fossil records as written in the "book of stone" in Millard County and transcribed by geologists into map, figure, and text descriptions.

Because many of the bedrock map units are of limited areal extent, and to consolidate local nomenclature, Millard County was subdivided into 11 areas (figure 51), within which a limited number of map unit names are used. The stratigraphic columns for these areas are columns 1-11 in appendix C. Thicknesses shown on these columns were summarized from published detailed measured sections and other publications, where available, but others have been estimated for this bulletin from map measurements or using other approximate methods. The degree of accuracy is implied by the number of significant figures (non-zeros) shown. Correlation charts that show the relative ages of the various map units are charts 1-8 (appendix C). Maps that show the areal distribution of exposures of bedrock of the several time periods are included within the discussion of each period. Surficial deposits in Millard County are discussed later in this bulletin under the headings "Quaternary-Pliocene Deposits" and "Quaternary Sedimentary Deposits."

Precambrian

Introduction

Precambrian rocks are exposed in four mountain ranges in Millard County as shown in figure 54. The Canyon Mountains (columns 1 and 2, appendix C) and the northern San Francisco Mountains (column 5) have large areas that display an upper Precambrian sedimentary sequence consisting of, in ascending order, the Pocatello, Blackrock Canyon, Caddy Canyon, Inkom, and Mutual Formations. The upper part of the same sequence is found on the north edge of Millard County along the east side of the Drum Mountains (column 6) where outcrops are the south tip of more extensive exposures to the north in Juab County. A small outcrop of banded gneiss is exposed on the west side of the north end of the Mineral Mountains (column 4). It is the oldest rock exposed in the county.

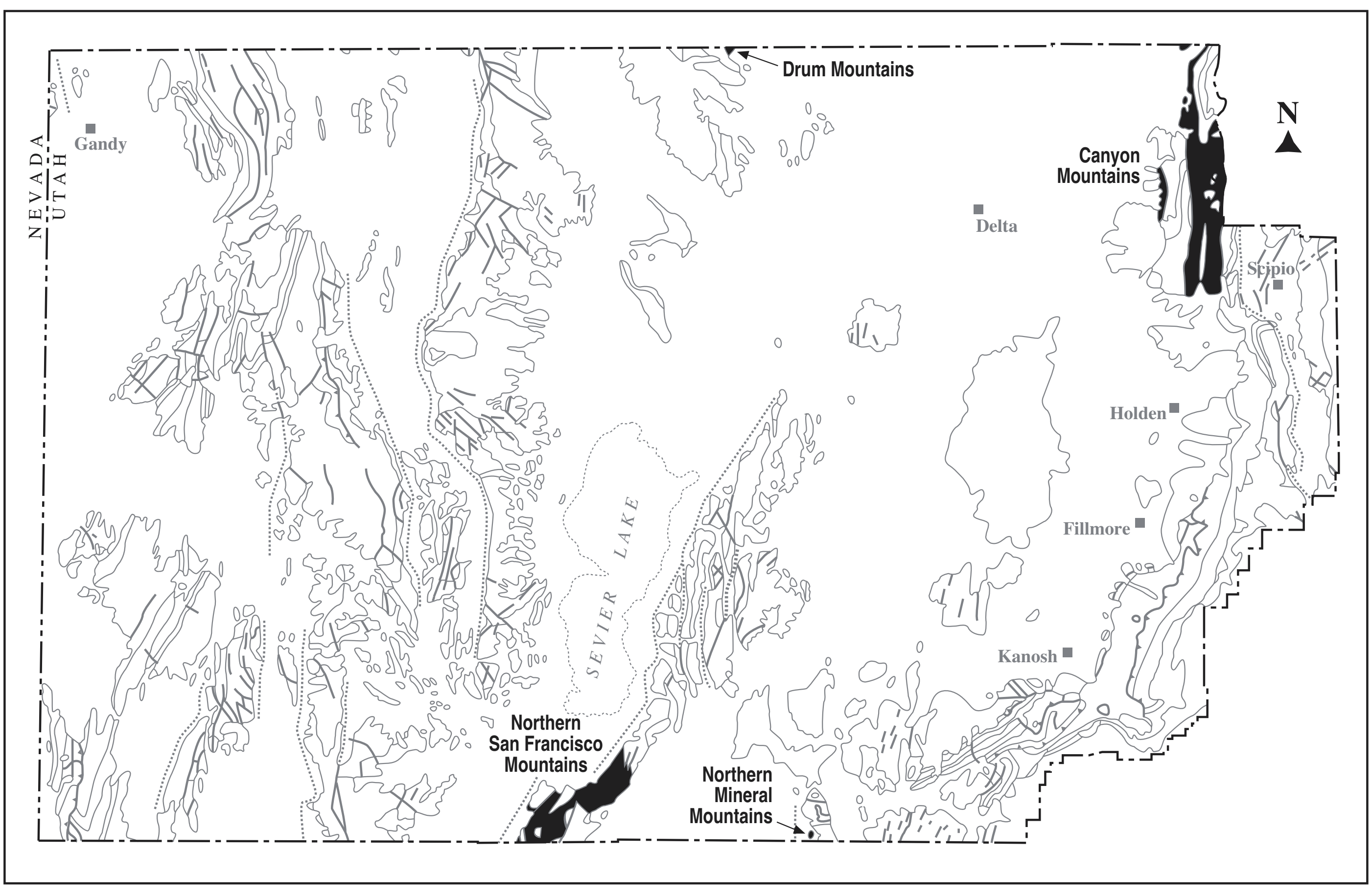


Figure 54. Precambrian outcrops in Millard County.

Banded Gneiss (p€g)

The banded gneiss unit is the oldest rock exposed in the Mineral Mountains (column 4, appendix C). Scattered exposures along the west side of the range extend for 10 miles (16 km) southward into Beaver County from the lone exposure in southern Millard County. Nielson and others (1978) and Sibbett and Nielson (1980) described the rock as banded gneiss that is typically fine- to medium-grained with coarse-grained leucocratic layers composed of subequal amounts of quartz and K-feldspar, with minor biotite and plagioclase. Dark layers are composed predominantly of biotite, plagioclase, and quartz with minor hornblende and K-feldspar. Rounded zircon grains and apatite are common accessory minerals.

The compositional banding may represent original sedimentary bedding. Individual layers are 0.4 to 4 inches (1-10 cm) thick in a typical outcrop. More mafic zones and more felsic zones are a few feet to more than 100 feet (~ 1-30+ m) thick. Biotite is the most abundant mafic mineral in the dark layers and zones, and is accompanied in places by a minor amount of hornblende.

Schistosity is well to poorly developed and generally parallels the banding. Small-scale isoclinal folds are present in the gneiss. In exposures in Beaver County, the banded gneiss is locally associated with metaquartzite and sillimanite schist. Because the Precambrian gneiss was intruded by Tertiary granitic rocks, it yields Tertiary isotopic ages with potassium-argon methods (Nielson and others, 1986). However, on the basis of lead isotope ratios, Stacey and Hedlund (1983), Aleinkoff and others (1986), and Bowring and Karlstrom (1990) concluded that the original age of the gneiss in the Mineral Mountains is 1,750 million years and that the gneiss is part of the widespread basement rock in Utah, Arizona, and Colorado that consists of metamorphic rocks of about that same age.

Precambrian gneiss is also present in subsurface in Millard County. Royse (1993) showed a K-Ar age of 1,635 Ma for granitic gneiss in the 82-1 drill hole (appendix A) about 20 miles (32 km) to the northeast of exposures in the Mineral Mountains. A Precambrian gneiss was reported in drill hole 81-5 in the Valley Mountains and a sample was K-Ar dated at 1,100 Ma (appendix A). But, I consider this rock to be older (~1,750 million years old), the age having been "reset" by the thermal event noted by Lee and others (1980) in eastern Nevada.

Upper Precambrian Sedimentary Sequence

Upper Precambrian sedimentary rocks in Millard County were first described by Christiansen (1952) in the Canyon Mountains, and by Woodward (1968) in the northern San Francisco ("Beaver") Mountains. They numbered, but did not name, their mapped stratigraphic units. Crittenden and others (1971) reviewed the upper Precambrian sequence in southeastern Idaho, stated that its nomenclature could be extended into northern Utah, and suggested that it might possibly be traced as far south as the San Francisco Mountains along the axis of a northerly trending late Precambrian depositional trough. Woodward (1972) was the first to actually apply the southeastern Idaho (Pocatello area) stratigraphic nomenclature to upper Precambrian strata in the Canyon and San Francisco Mountains.

Christie-Blick (1982) redefined the upper Precambrian stratigraphy in the Sheeprock Mountains in central Utah and suggested that all rocks exposed in the Canyon Mountains stratigraphically below the Inkom Formation might be correlated with the Caddy Canyon Quartzite of southeastern Idaho. Holladay (1984) rejected Christie-Blick's suggestion and used the following Idaho-derived terminology for his Canyon Mountains map units, in ascending order: Pocatello Formation, Blackrock Canyon Limestone, Caddy Canyon Quartzite, Inkom Formation, and Mutual Formation, the last a term from the Wasatch Range near Salt Lake City.

Two units, the Blackrock Canyon Limestone and the Inkom Formation, are especially useful in subdividing the thick upper Precambrian sedimentary sequence. The Blackrock Canyon Limestone is unique in that it contains Proterozoic limestone. The lithology of the limestone is different in appearance from most Paleozoic carbonate units as it contains unusual silty pelletoidal limestone beds that weather to a sponge-like surface. The Inkom Formation consists of slate, argillite, and siltstone, and lacks the dominant quartzite component that makes up most of the upper Precambrian sequence. The Inkom's few hundred feet of fine-grained sediments generally form recessive valleys or slopes between the more resistant quartzite formations, and is therefore topographically distinctive within the Precambrian sequence.

Pocatello Formation (p€p): This formation, predominantly a quartzite, has been mapped in the Canyon Mountains (column 1, appendix C) and in the northern San Francisco ("Beaver") Mountains (column 5). In both areas the base of the formation is covered, so its total thickness in Millard County is unknown. Woodward (1968, 1972) described the Pocatello Formation in the northern San Francisco Mountains as 970 feet (300 m) of light-gray, thick-bedded, medium- to coarse-grained quartzite with a few hematitic slate beds near the top. In thin section, the quartzite is almost entirely quartz grains with interstitial sericite and chlorite. Trace amounts of feldspar, hematite, chert, zircon, tourmaline, and apatite are present. The quartz clasts are cemented by quartz overgrowths; the original grains are outlined by thin hematite coatings. Lemmon and Morris (1984) remapped Woodward's (1968) Precambrian units but did not remeasure the Pocatello Formation.

In the Canyon Mountains (column 1, appendix C), the Pocatello Formation was identified by Woodward (1972) as the lowest three units of Christiansen's (1952) measured section. Millard (1983) and Holladay (1984) both mapped the Pocatello Formation in the Canyon Mountains, but Holladay (1984) examined the most extensive exposures and provided the most comprehensive description of the formation. Holladay (1984) subdivided the Pocatello Formation into a lower shale member, a middle quartzite member, and an upper siltstone and shale member. Total exposed thickness of the Pocatello Formation in the Canyon Mountains is about 2,600 feet (800 m). The section is truncated below by the Canyon Range thrust fault and represents only the upper part of the Pocatello Formation of northern Utah and southern Idaho as described by Crittenden and others (1971). The upper limit of the formation is placed at the base of the lowest limestone of the Blackrock Canyon Limestone.

The lower shale member is non-resistant and forms a strike valley. Exposures are poor and consist mostly of brownish-gray to olive gray soil. Holladay (1984) estimated its thickness as about 600 feet (180 m). The lower portion is in fault contact with younger rocks; the top of the member is placed at the base of the lowest resistant quartzite bed of the middle quartzite member. Sussman (1995), in restudying part of Holladay's map area, questioned the identity of the rocks that Holladay assigned to the lower Pocatello.

The middle quartzite member is a very light-gray quartzite that weathers grayish orange to moderate brown. It is noticeably lighter gray than the Caddy Canyon or Cambrian quartzites with which it might be confused. In addition, it is distinguished by small angular cavities on weathered surfaces. These cavities are produced by weathering of limonite- and hematite-cemented quartz grains and are pervasive throughout this member. Near its base the member includes a quartzite pebble conglomerate bed. Throughout, the middle quartzite member includes cross-bed sets up to 10 inches (20 cm) thick. The member is resistant and forms a prominent ridge on the west side of the Canyon Mountains. The member is 1,312 feet (400 m) thick.

The upper shale and siltstone member consists of interbedded phyllitic shale and siltstone with thin beds of quartzite. In Holladay's (1984) map area in the northern part of the Canyon Mountains, the member is about 770 feet (230 m) thick and is apparently overlain by a thin-bedded, fine-grained quartzite that apparently thickens southward from 8 feet (2.5 m) in Holladay's area to 400 feet (122 m) in the central part of the Canyon Mountains where it was measured by Christiansen (1952) as his Precambrian unit 3. Christiansen's underlying shale and quartzite unit 2 is 640 feet (195 m) thick, making a total thickness of 1,040 feet (317 m) for the upper Pocatello in the central Canyon Mountains. Millard (1983) reported that this upper part of the Pocatello Formation is 760 feet (248 m) thick in the southern Canyon Mountains and consists mostly of olive-gray siltstone interbedded with yellowish-gray, thick-bedded, fine-grained, well-sorted quartzite. A phyllitic shale bed 85 feet (26 m) thick is intercalated in the middle of this quartzite.

In the Canyon Mountains the Pocatello Formation varies from north to south in the proportion of quartzite, siltstone, and shale. The greater thickness of the formation exposed to the north is not indicative of an original depositional pattern because the base of the formation is nowhere exposed in Millard County. Correlation of the Pocatello subunits from north to south in the Canyon Mountains is not well defined because no unified study of the formation throughout the range has been done.

Blackrock Canyon Limestone (p€b): This formation includes all of the carbonate deposits that are present in the Precambrian sequence in Millard County. It is exposed both in the Canyon Mountains (column 1, appendix C) and in the northern San Francisco Mountains (column 5). In the Canyon Mountains the formation is best exposed on the north side of Whiskey Creek, from where A.W. Millard Jr. (1983, unpublished notes) reported the following section beneath the Caddy Canyon Quartzite:

Unit No.	Description	Thickness Feet	Meters
4.	Limestone, olive-gray, weathers light gray, oolitic to pisolitic, massive, forms cliff.	60	18
3.	Quartzite, grayish-orange, fine-grained, thin-bedded, with interbeds of siltstone and shale, forms slope.	154	47
2.	Limestone, medium-gray, contains oolitic beds, massive forms ledges and cliffs, includes a 6-foot (2-m) bed of orange-gray quartzite 42 feet (13 m) below the top; locally fractured with white secondary calcite forming veinlets.	119	36
1.	Limestone, grayish-red, weathers grayish-orange, coarsely crystalline, thin-bedded, with thin interbeds of siltstone and fine-grained sandstone; limestone locally includes "algal" stromatolites 2 inches (5 cm) across and 6 inches (15 cm) high; contact with underlying Pocatello Formation is indistinct and is placed at the lowest limestone bed in the section.	225	68
	Total measured thickness of Blackrock Canyon Limestone	558	169

Millard (1983) included photographs of the algal (likely microbial) stromatolites, and micrographs of oolites and pisolites found in the Blackrock Canyon Limestone. Christiansen (1952) measured the Precambrian section on the ridge north of Oak Creek in the central part of the Canyon Mountains; his units 4-7 are the Blackrock Canyon Limestone, for which he obtained a total thickness of 610 feet (186 m). Holladay (1984) reported a thickness of only 150 feet (45 m) for the Blackrock Canyon Limestone at Wild Horse Canyon in the north end of the Canyon Mountains.

Although Christie-Blick (1982) suggested that the Blackrock Canyon Limestone in central Utah might be equivalent to part of the Caddy Canyon Quartzite of southeastern Idaho, Smith and others (1994), using isotopic chemostratigraphic analysis, found that the Blackrock Canyon Limestone of the Canyon Mountains is isotopically similar in its oxygen-18 and carbon-13 content to the Blackrock Canyon Limestone in its type area in southeastern Idaho.

In the northern San Francisco Mountains the Blackrock Canyon Limestone was mapped by Lemmon and Morris (1984), who divided the formation into three members. The lower member is interbedded gray to pale-green, calcareous argillite and quartzite with minor lenses and thin beds of brown-weathering arenaceous limestone or dolomite. The member is 500 to 660 feet (145-200 m) thick. The middle member is limy argillite with at least one thick bed, and one or more thinner beds of blue-gray dense limestone or gray hydrothermally altered dolomite locally replaced by iron-oxide minerals. This unit forms the top of the Blackrock Canyon Limestone in much of the northern San Francisco Mountains. Thickness of the middle member is 33 to 165 feet (10-50 m). The upper member is chiefly green argillite, red and green siltstone, and green quartzite, with some minor marble beds. Thickness of the upper member is 0 to 165 feet (0-50 m).

The Blackrock Canyon Limestone is found about 15 miles (24 km) south of Millard County in the southern Wah Wah Mountains where Abbott and others (1983) reported that it is 625 to 820 feet (190-250 m) thick and is interbedded sand-streaked limestone and dolomite, quartzite, micaceous sandstone, and phyllite. This is the southwesternmost known occurrence of the Blackrock Canyon Limestone.

Caddy Canyon Quartzite (p€c): In its type area in southeastern Idaho, the Blackrock Canyon Limestone is overlain by the Papoose Creek Formation composed of green interbedded siltstone and quartzite. The Papoose Creek is overlain by the Caddy Canyon Quartzite, a thick light-colored orthoquartzite with subordinate beds of argillite and siltstone. Woodward (1972) suggested that the Papoose Creek Formation could be identified in the Canyon Mountains and northern San Francisco Mountains. But geologic mappers in the Canyon Mountains (Millard, 1983; Holladay 1984) found it too difficult to identify a consistent horizon in the transitional zone between the upper, and lower, siltier part of the Papoose Creek-Caddy Canyon sequence, and chose to call the entire interval the Caddy Canyon Quartzite. As such, the Caddy Canyon Quartzite in Millard County consists of a lower quartzite that is silty and thin bedded, and an upper quartzite that is mostly clean, well sorted and forms massive ledges and cliffs. The lower contact of the Caddy Canyon Quartzite is with the uppermost limestone of the Blackrock Canyon Limestone. The upper contact is placed at the base of the thick sequence of phyllitic olive shale of the Inkom Formation.

In general appearance, the lower part of the Caddy Canyon forms ledges and slopes made up of siltstone and thin-bedded pale-orange quartzite. The upper part forms prominent cliffs of grayish-orange-pink, coarse-grained quartzite with some interbeds of pebbly conglomerate. A.W. Millard Jr. (1983, unpublished notes) measured the following section of Caddy Canyon Quartzite in the central Canyon Mountains on the north side of Whiskey Creek:

Unit No.	**Description**	**Thickness Feet**	**Thickness Meters**
4.	Quartzite and pebble conglomerate, grayish-orange-pink, weathers pale to moderate red, coarse-grained, massively bedded, forms cliffs; grains irregularly shaped, mostly quartz, some feldspar; grades into unit 3.	820	248
3.	Quartzite, mostly very pale-orange, with some beds moderate brown and light-olive-gray, medium-grained, medium to massively bedded, forms talus slopes in lower half, ledges and cliffs above; grains are mostly well-sorted subrounded quartz.	495	150
2.	Phyllitic siltstone and quartzite interbedded, poorly exposed; quartzite is grayish-orange to dark-yellowish-orange, very thin- to thin-bedded.	223	68
1.	Phyllitic siltstone and quartzite, very poorly exposed, chips of siltstone and quartzite in soil suggest thin bedding; quartzite is orangish-gray, silty.	392	119
	Total measured thickness of Caddy Canyon Quartzite	1,930	585

Christiansen (1952) reported 1,685 feet (557 m) for the thickness of his units 8 and 9, which probably represent the Caddy Canyon Quartzite as measured along the ridge north of Oak Creek in the central Canyon Mountains.

In the northern San Francisco Mountains, Lemmon and Morris (1984) described the Caddy Canyon Quartzite as 265 to 300 feet (80-100 m) of buff, light-pink, or light-gray, thick-bedded, medium- to coarse-grained quartzite with conglomerate, siltstone, and argillite in the upper 50 feet (15 m). Twenty-five miles (40 km) to the southwest Abbott and others (1983) reported that the combined Caddy Canyon-Papoose Creek interval is 2,250 feet (680 m) thick in the southern Wah Wah Mountains. The considerable difference in thicknesses reported from the San Francisco and Wah Wah Mountains is probably related to thrust faults present in both areas.

Inkom Formation (p€i): The Inkom Formation consists of fine-grained clastic deposits a few hundred feet thick that contain almost none of the quartzite beds that cause the units above and below the Inkom to form high topography. Hence the Inkom Formation forms easily traceable valleys and saddles between the ridge-forming Mutual Formation and Caddy Canyon Quartzite. The Inkom is a key bed for the field geologist mapping Precambrian strata in western Utah.

Because of its non-resistant nature, the Inkom is in most places covered with talus, soil, and vegetation. Good exposures are scarce. The most complete exposure of the Inkom in the Canyon Mountains is in Lyman Canyon in the northeast quarter of section 17, T. 17 S., R. 3 W. where it was described by A.W. Millard Jr. (1983, unpublished notes) as follows:

Unit No.	**Description**	**Thickness Feet**	**Thickness Meters**
4.	Phyllitic shale, light-olive-gray, with few thin beds of dusky red very fine-grained quartzite; quartzite percentage increases upwards grading into overlying Mutual Formation; unit forms a slope.	105	33

Unit No.	Description	Thickness Feet	Thickness Meters
3.	Phyllitic shale, light-olive-gray, fissile, forms slope and low ledges.	50	15
2.	Silty shale, light-olive-brown, fissile, laminated, contains few small mica flakes, forms slope.	100	30
1.	Siltstone, light-olive-gray, laminated to very thin-bedded, forms slope; sharp topographic contrast with resistant beds of Caddy Canyon Quartzite beneath.	20	6
	Total thickness of Inkom Formation	275	84

In the northern part of the Canyon Mountains, Holladay (1984) reported that the Inkom Formation is 300 feet (90 m) thick along Fool Creek; Higgins (1982) measured 308 feet (93 m) of Inkom in Leamington Canyon a few miles north of Millard County.

In the northern San Francisco Mountains, the Inkom Formation was mapped by Lemmon and Morris (1984) and they described it as 460 to 530 feet (140-160 m) of purplish-red, arenaceous, phyllitic argillite, with some thin and thick zones of olive-green argillite and quartzite. The southwesternmost occurrence of Inkom Formation is in the southern Wah Wah Mountains. Abbott and others (1983) reported that the Inkom there is known only from drill holes where its maximum thickness is about 230 feet (70 m).

Mutual Formation (p-Ꞓm): Although reddish-purple quartzite is the dominant lithology of the Mutual, the formation also includes interbeds of variegated red and green shale in its type area in the Wasatch Range where it was named by Crittenden and others (1952). They chose to recognize its mixed lithologic composition by giving it the title Mutual Formation rather than that of its dominant lithology, quartzite.

Within the mostly quartzitic Precambrian and basal Cambrian sequence described here, the most distinctive aspect of quartzite in the Mutual Formation is its red color. In the nomenclature of the Rock Color Chart (Geological Society of America, 1948), its color ranges from light grayish red to dark grayish red or purplish black. This contrasts with the white, yellow or brown tones of other Precambrian quartzites and the lighter pink or yellow shades of basal Cambrian quartzites.

In Millard County the Mutual Formation is exposed in the Canyon Mountains (columns 1 and 2, appendix C), the northern San Francisco Mountains (column 5), and the Drum Mountains (column 6). In the Canyon Mountains the Mutual Formation was mapped by Higgins (1982), Millard (1983), and Holladay (1984). Higgins (1982) reported that, in Leamington Canyon at the north end of the range (figure 32), the Mutual is about 1,600 feet (490 m) thick and consists mostly of reddish-purple quartzite and metaconglomerate. In the north-central part of the range, Holladay (1984) divided the Mutual Formation into two members: a lower quartzite member about 1,650 feet (500 m) thick, and an upper siltstone and quartzite member that ranges in thickness from 250 feet (75 m) at Leamington Pass to 825 feet (250 m) at Wild Horse Canyon 2 miles (3 km) to the south. Holladay's (1984) map shows that the Mutual Formation is present on both the Canyon Range thrust plate, and incompletely exposed on the underlying younger Pavant thrust plate. Millard (1983) reported 1,750 feet (530 m) of Mutual Formation in the south-central part of the Canyon Mountains, and also described a measured section of Mutual Formation 2,263 feet (690 m) thick that he suggested had been partially repeated by faulting.

Forty miles (64 km) west of the Canyon Mountains, the Mutual Formation is exposed on the east flank of the Drum Mountains (column 6, appendix C) where it was mapped by Dommer (1980). He reported that the Mutual there is a red grit and pebble conglomerate about 3,000 feet (915 m) thick. Dommer described a measured section of the lower third of the formation where it is exposed above the Inkom Formation in southern Juab County about 1 mile (1.6 km) north of the Millard County line.

Lemmon and Morris (1984) mapped the Mutual Formation in the northern San Francisco Mountains (column 5, appendix C) where they found it to be about 2,100 feet (635 m) thick, and made up of pink to dark-purplish-red, medium-bedded, coarse-grained, locally cross-bedded quartzite that contains a few beds of argillite. Abbott and others (1983) mapped the southwesternmost known exposures of Mutual Formation in the southern Wah Wah Mountains in north-central Beaver County. There they found the Mutual to be 1,197 feet (365 m) thick and composed of rocks similar to those in the San Francisco Mountains.

Cambrian

Introduction

Cambrian strata are exposed in most of the mountain ranges in Millard County, as shown in figure 55. The part of the North American continent that was to become Utah was vastly different in Cambrian time from what it is today. At that time there were no Rocky Mountains, and the state lay at or slightly below sea level. The equator crossed the state in what is now a north-south direction. Western Utah was covered by shallow seas something like today's coastal waters off the Bahamas or the Texas-Louisiana Gulf Coast. Low-lying lands lay east of Utah, and the marine water deepened westward in Nevada (Rowell and others, 1979; Hintze, 1988a). Microenvironments that developed on this continental shelf were locally favorable for abundant marine life, and for preservation of this life as fossils. It is our good fortune that House Range rocks include many such sites in vertical succession. Paleoenvironmental reconstructions have been made for several of the fossil-bearing rock formations in the House Range and these are summarized under the section on Cambrian lithologic units.

Cambrian Fossil Life in Western Utah

Strata in the House Range are world famous for two reasons. First, the trilobite *Elrathia kingii* is found in the Wheeler Shale near Antelope Spring in a rare mode of fossilization that has reinforced the creature's bug-like body to the extent that specimens weather out, or can be cracked out, of the

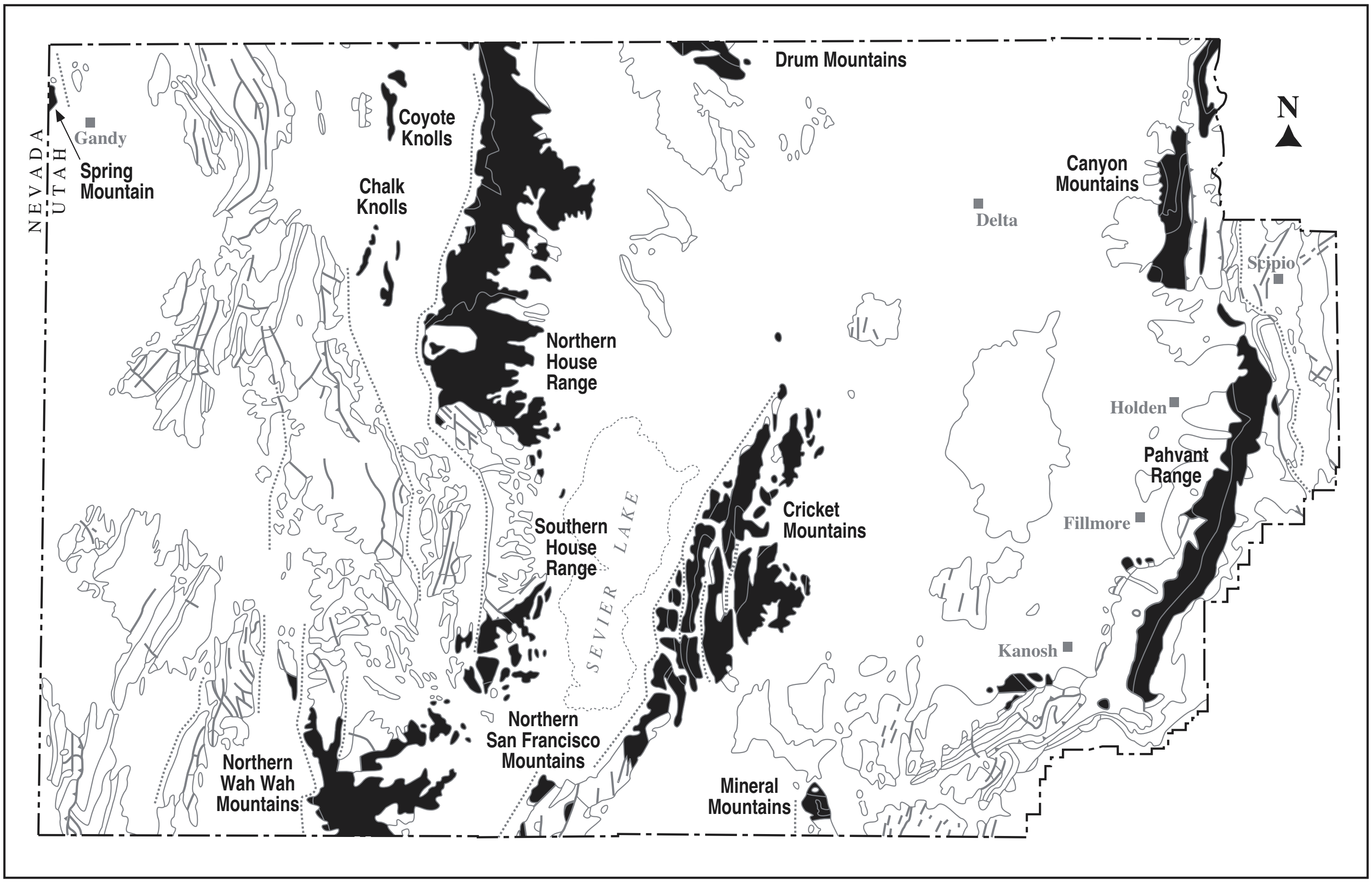


Figure 55. Cambrian outcrops in Millard County.

enclosing rock as whole trilobites that range from dime-size to silver dollar-size. Hundreds of thousands of trilobites have been obtained from the Antelope Springs locality by both amateur and commercial collectors and given or sold to universities, museums, and rock shops worldwide, so that *Elrathia* from the House Range is, without doubt, the trilobite most likely to be found in any fossil display anywhere. Second, Cambrian rocks in the House Range contain trilobites and other fossils at many levels throughout more than 8,000 feet (2,500 m) of strata, as shown on column 7 (appendix C). This enables paleontologists to follow the course of animal evolution here through Cambrian time. In fact, the Cambrian sequence in the House Range has become the most important fossil-bearing reference section for Middle and Upper Cambrian biostratigraphy in western North America.

Because of the special significance that the House Range Cambrian fossil record has to our knowledge of the evolution of early multicelled organisms, the various fossil groups that are represented in the House Range are discussed separately below. Two kinds of fossils, trilobites and, in the Upper Cambrian, conodonts, have proven especially useful as guide fossils in Cambrian rocks because they are both abundant and evolved into many distinctive species during the 25 million years represented by the fossiliferous rocks in the House Range. Other organisms are of interest in giving us a view of the evolving ecosystems of Cambrian time, but because of their scarcity, or their slowness to change through time, they are not as useful as guides to time as are the conodonts and trilobites. In the following pages the fossil groups are presented in the order of their apparent abundance; trilobites are first, followed by brachiopods, sponges, and the other organisms.

Trilobites: Although prehistoric Pahvant Ute Indians may have used *Elrathia kingii* as amulets (Taylor and Robison, 1976)(figure 56), the first recorded discovery of trilobites at Antelope Spring was made in 1859 by Henry Engelmann (in Simpson, 1876, p. 329). Meek (1876) described the fossils collected by Engelmann on Simpson's expedition. G.K. Gilbert, aware of Engelmann's discovery, was the next geologist to visit the House Range. Gilbert (1875, p. 167) measured 2,300 feet (700 m) of Cambrian strata near Antelope Spring. The fossils he collected there were reported by Walcott (1884, 1886) as *Acrothele subsidua, Ptychoparia Kingi, P. Housensis*, and *Asaphiscus Wheeleri* (his spelling and capitalization).

Charles Doolittle Walcott (born 1850, died 1927) was a giant in the development of our knowledge of Cambrian fossils and their containing strata, not only in the House Range, but throughout North America and in some foreign lands. Walcott first visited the House Range for two weeks in 1903 and returned for another two weeks in 1905 to measure the entire Cambrian section and to make extensive fossil collections. Walcott (1908a, d) named the Howell, Dome, Swasey, Wheeler, Marjum, Weeks, Orr, and Notch Peak Formations in the House Range, and described many of their trilobites (Walcott, 1908b, 1916a-b, 1925) and brachiopods (Walcott

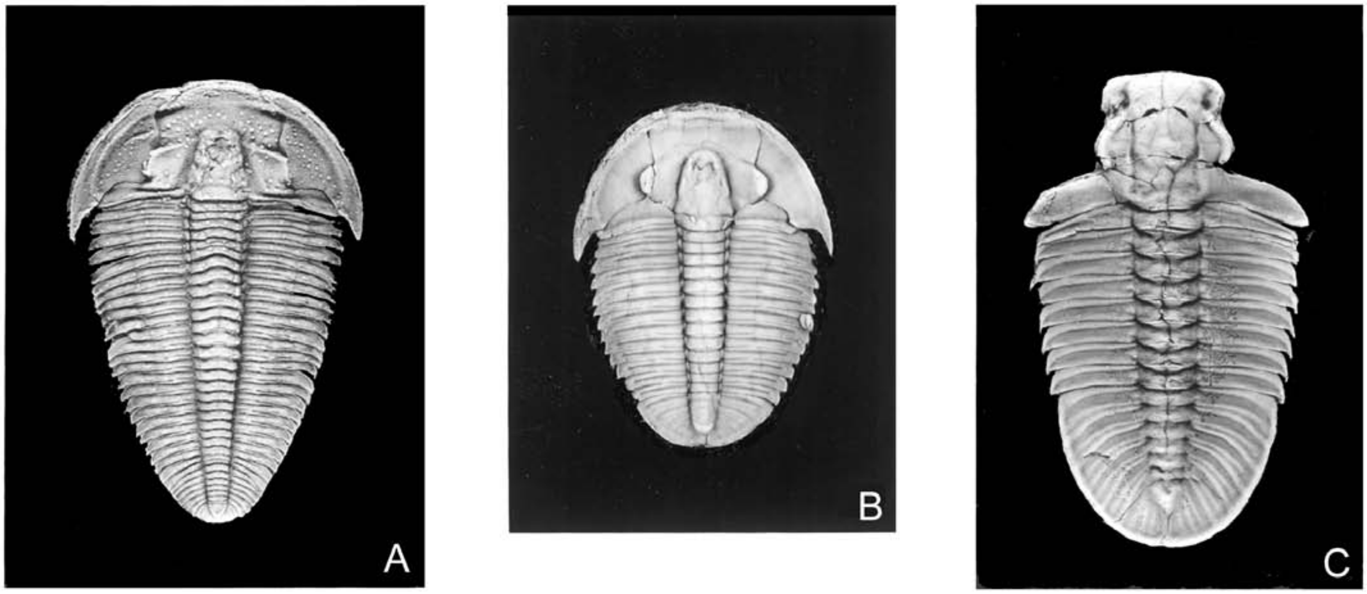


Figure 56. *Trilobites from the Wheeler Shale in the House Range: A, Holotype of* Alokistocare harrisi *Robison, X1.4; B,* Elrathia kingii *(Meek), X1.1; C,* Bathyuriscus fimbriatus *Robison, X0.9, free cheeks missing.*

1908c, 1912a-b). Walcott's assistant, Charles Resser, finished Walcott's House Range work by describing two Upper Cambrian trilobites from the Weeks Formation (Resser, 1942). Palmer (1954) redescribed the following species from the House Range: *Asaphiscus wheeleri* (Meek), *Bolaspidella housensis* (Walcott), *Elrathia kingii* (Meek), *Olenoides nevadensis* (Meek), and *Peronopsis interstrictus* (Walcott). Bright (1959) made a detailed study of *Elrathia kingii* (Meek).

Richard Ashby Robison, with family roots in Fillmore, Utah, was the next person to make major contributions to House Range paleontology. Beginning with his master's thesis (Robison, 1960a) and followed by his Ph.D. dissertation (Robison, 1962), Robison brought Utah trilobites and their utility as guides to geologic time and paleoenvironments into the modern era of paleontology with several important publications (Robison 1964a, 1967, 1971,1976, 1982, 1984a-b; Robison and Hintze, 1972). He and other trilobite specialists (Rowell and others, 1982) have established the Cambrian trilobite zonation scheme shown on chart 1 (appendix C). In addition, he has written many other significant papers on non-trilobite Cambrian organisms and Cambrian stratigraphy and paleoecology, which are cited later in this section. Robison taught paleontology at the University of Utah and, later, at the University of Kansas, and several of his graduate students (Oldroyd, 1973; Randolph, 1973; White 1973; Kopaska-Merkel, 1983; Vorwald, 1983; Rees, 1984, 1986; Beebe, 1990) have done research on Millard County Cambrian rocks and fossils. Professor Robison kindly furnished the photographs of the Cambrian fossils illustrated in this bulletin.

Another Utahn, Michael E. Taylor, described Upper Cambrian trilobites, some of which came from the southern part of the House Range, for his unpublished dissertation (Taylor, 1971). Palmer (1965) described and illustrated 10 Upper Cambrian trilobite species, half of them new, from the Orr Formation in the House Range in his regional study of Pterocephaliid trilobite fossil zones. Palmer (1971) summarized the distribution of Cambrian strata and their trilobite zonation in the Great Basin and presented his correlation of Cambrian rocks in the House Range with other significant localities in the western United States. Palmer and Taylor both worked for the U.S. Geological Survey as paleontologists specializing in Cambrian trilobites.

As noted by Hintze and Robison (1987), the House Range is a magnet, drawing trilobite lovers, amateur and professional, from everywhere. Almost every day, during decent weather, trilobite seekers can be found at Antelope Spring, combing the Wheeler Shale for fossils. Of all the non-commercial collectors, none have been more usefully productive than the Gunther family of Brigham City, Utah. Realizing that, beyond the fun of finding fossils, there is new scientific information to be gained in the discovery of previously undescribed organisms. Gunther family members have spent months on end in the House Range, quarrying through the shaly limestones of the Wheeler Shale and Marjum Formation, and carefully recording the stratigraphic location of each of their finds. They have donated thousands of specimens to universities and museums. Also, they have seen to it that unusual new finds were called to the attention of professional paleontologists who could describe the new species. Family members have provided the public with a book of trilobite pictures available for House Range fossils (Gunther and Gunther, 1981) and have popularized responsible amateur collecting (Gunther and others, 1993). These efforts were rewarded by having several fossil species named after them. In 1984, they received the first Harrell L. Strimple collector's award from the world's largest professional organization of paleontologists, the Paleontological Society.

Commercial mining of trilobites began in the late 1960s by Robert Harris of Delta, Utah, who discovered that a 2-foot (60-cm) zone near the top of the Wheeler Shale yielded the most abundant and best preserved specimens. Accordingly, his workers have strip-mined that zone, following it across several small fault blocks near Antelope Spring. Fortunately for Harris and other commercial collectors, the best trilobite mining localities are on state-owned sections where fossil mining is allowed by permit. Harris and other permit-holders have mined hundreds of thousands of trilobites from these beds over the past 30 years. After the trilobites are sorted, cleaned, and graded, a few of them are sold to tourists in the rock shops in Delta, but most are wholesaled to dealers, and find their way into rock shops, museums, and educational institutions all over the world.

Brachiopods: After trilobites, brachiopods are the next most abundant fossils in Cambrian strata in Utah. Walcott (1886, p. 40) identified the brachiopod *Acrothele subsidua* (White) from the fossil collection made in 1871-72 at Antelope Spring by Gilbert (1875). Walcott (1912a-b) provided comprehensive descriptions and illustrations of brachiopods from all of the Cambrian formations in the House Range, except the Prospect Mountain Quartzite, collected during his field work in 1903 and 1905. He assigned House Range brachiopods to 10 genera and a number of species (Walcott, 1912 a-b), adding one more species in Walcott (1924).

Cambrian brachiopods have never attained much popularity with non-specialists because they are only exciting to look at microscopically. Most are of the hingeless phosphatic type and appear, to the unaided eye, like small dark inkspots in the rock. Despite their abundance and wide stratigraphic distribution, they are not commonly used as guides to geologic time, but are more helpful as paleoenvironmental indicators (Rowell and Brady, 1976; McGee, 1978). Professor A.J. Rowell, at the University of Kansas, and others have performed studies involving brachiopods in western Utah (Rowell, 1966, 1976, 1986; Rowell and Henderson, 1978; Rowell and Caruso, 1985), and have described some species that had escaped Walcott's attention. The latest work is by Popov and others (2002).

Sponges: Separated sponge spicules are quite common in shaly Cambrian rocks in western Utah, appearing as 1/4 - inch (6-mm) cross-bars of stars, or as bundles of hairs on weathered surfaces. These are the disarticulated parts of a geometric network of spicules that formed the body framework of most Cambrian sponges (figures 57 and 58). Entire sponge specimens are usually found only by quarrying shaly limestone beds and splitting them to reveal fresh bedding surfaces. Left to the weather, sponge specimens commonly deteriorate. Spicules can also be found when limestones are dissolved with acid.

Walcott (1920) included descriptions and pictures of four sponge species from the Wheeler and Marjum Formations in the House Range in his comprehensive account of Middle Cambrian sponges. A more thorough investigation of sponges in the House Range began with Rigby (1966) and has continued with subsequent papers (Rigby, 1969, 1976, 1978, 1981, 1983, 1986; Rigby and Church, 1990). Rigby was aided in his studies by the efforts of the Gunther family, mentioned above. The Gunthers opened quarries for the special purpose of obtaining sponges, and spent several months splitting their way through successive rock layers in the central House Range to obtain the magnificent collection of sponge specimens described by Rigby in his papers. In addition to his work on sponges of the House Range, Professor Rigby (1986) updated Walcott's (1920) descriptions of Middle Cambrian sponges from the famous Burgess Shale of British Columbia and has thereby revised our understanding of the evolution of sponges (Rigby, 1976, 1981).

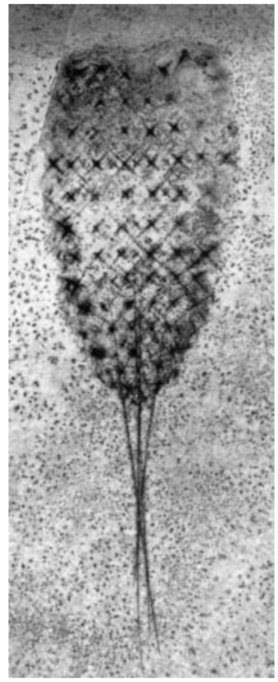


Figure 57. Diagonella cyathiformis *(Dawson & Hinde); Marjum Formation, House Range; X2.8.*

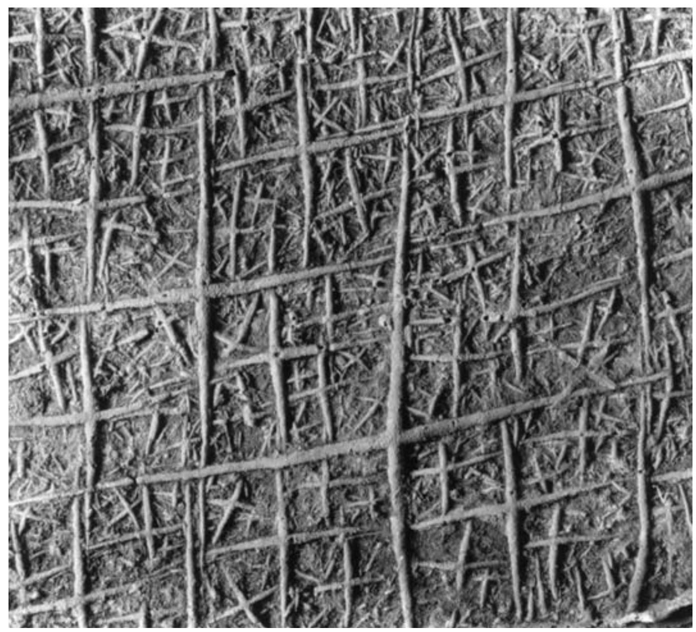


Figure 58. *Rubber cast of spicule fabric in wall of* Protospongia hicksi *Hinde; Marjum Formation, House Range; X5. Photo provided by J. Keith Rigby.*

Fossils not commonly found or collected: Although trilobites, brachiopods, and sponges are the fossils most commonly collected in the House Range, a number of other kinds of fossils have been obtained there that round out our picture of the floral and faunal systems that existed in Utah's shallow seas during early Paleozoic time. Some of these fossils, such as tubes and trails of burrowing organisms, are fairly common but are not exciting enough in appearance to attract most people's attention. Others (radiolarians and conodonts) are microscopic and demand laboratory work to be seen. Some are soft-bodied and thus are preserved only rarely under very special conditions. At a marvelous site in the Burgess Shale, great numbers of soft-bodied Cambrian organisms were discovered in 1910 by Charles D. Walcott high on a mountainside in the Canadian Rockies. Walcott (1910, 1911a-c, 1912a-b, 1919, 1920, 1931) described most of the organisms he and his team recovered from the quarry. Collecting there is now off-limits except when specifically authorized by the Canadian government. They allowed the quarry to be reopened in 1966 and 1967, and Harry Whittington and his associates redescribed many of Walcott's unusual fossils. Their work radically revised some of Walcott's biological assignments and they recognized that several Burgess Shale organisms might belong to unique phyla (Whittington, 1985). The story of the contrasts between Walcott's interpretations and those of Whittington's team is delightfully recounted in Stephen Jay Gould's book "Wonderful Life" (Gould, 1989) and in a short illustrated article by Gore (1993).

The point of the above discussion of the Burgess Shale is to emphasize the importance of continuing finds of soft-bodied and other organisms in western Utah. Robison (1991) listed the diverse biotas preserved in the Wheeler Shale and Marjum Formation in the House Range and Drum Mountains. They include cyanobacteria, algae, radiolarians, sponges, cnidarians, brachiopods, mollusks, worms, arthropods including trilobites and crustaceans, echinoderms, animals of problematic assignments (typically soft bodied), trace fossils, and conodonts as discussed below.

Cyanobacteria and algae: Robison (1991) listed four genera of cyanobacteria (blue-green "algae") or possible cyanobacteria from the Wheeler Shale and Marjum Formation, including *Epiphyton*, *Girvanella*, *Morania*, and *Renalcis*. Representative species were illustrated by Rees (1984), and Conway Morris and Robison (1988). These organisms have little value in geologic age determination, but are useful in determining paleoenvironments, generally indicating shallow marine shelves. True algae are represented by *Margaretia* (figure 59) and *Yuknessia* (Conway Morris and Robison, 1988).

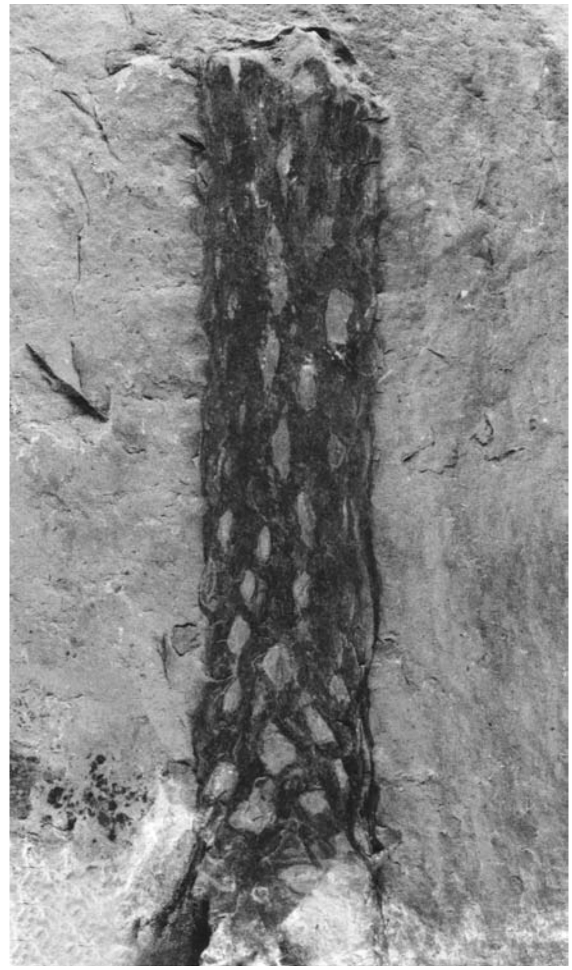


Figure 59. *Fragment of compressed axis of* Margaretia dorus *Walcott (Chlorophyta); Wheeler Shale, House Range; X1.2.*

Radiolarians: These microscopic siliceous organisms have not received much study in Utah's Cambrian strata. However, White (1986) reported specimens from the Wheeler Shale in the Drum Mountains, and they could likely be found in other places if acid residues from various Cambrian stratigraphic levels were processed and searched.

Cnidarians: These are coelenterates characterized by stinging cells. Three genera possibly represent this group in western Utah. *Scenella* was found in the Chisholm Formation in the Drum Mountains (Babcock and Robison, 1988). Willoughby and Robison (1979) named *Cambromedusa* from the Wheeler Shale, and Conway Morris and Robison (1988) identified the medusoid *Cambrorhytium* from the Marjum Formation.

Mollusks: Mollusks listed from the Wheeler Shale and Marjum Formations in western Utah include hyolithids, monoplacophorans, and stenothecoids. Ubaghs and Robison (1985) reported *Hyolithes* spp.; Robison (1964a) identified *Latouchella* and *Stenothecoides*; Vorwald (1983) and Rees (1984) identified the monoplacophoran *Pelagiella* from the Wheeler Shale.

Worms: Most worms found in the Wheeler Shale and Marjum Formation are priapulids (Walcott, 1911c; Conway Morris 1977; Conway Morris and Robison, 1986, 1988), including the burrowing *Ottoia* and the tube-dwelling *Selkirkia* genera. Vorwald (1983) listed another worm, *Hylolithellus* sp., as part of the upper Wheeler Shale biota in the Drum Mountains. Robison (1991, figure 6) illustrated some representative specimens.

Non-trilobite arthropods including crustaceans: Resser (1931) described a merostome crustacean from the Marjum Formation and named it *Beckwithia typa* after Frank A. Beckwith, the newspaper publisher in Delta, Utah, who sent the specimen to him. Robison and Richards (1981) described and illustrated two species of the crustacean genus *Perspicaris*? from the Wheeler Shale and Marjum Formations in the House Range. Robison (1991) listed 12 genera of arthropods of uncertain class assignment from the Wheeler Shale and Marjum Formation of western Utah and presented photographic illustrations of eight of them, four of which are reproduced here (figures 60-63). Robison (1990) described *Cambropodus* as the earliest-known uniramous arthropod. Other kinds are more fully described in Robison and Richards (1981), Gunther and Gunther (1981), Briggs and Robison (1984), and Conway Morris and Robison (1988). The non-trilobite arthropods are an especially interesting group of ancient marine animals. Some are large, some have bizarre shapes, one apparently fed on trilobites, and one may be the ancestor of terrestrial myriapods and insects.

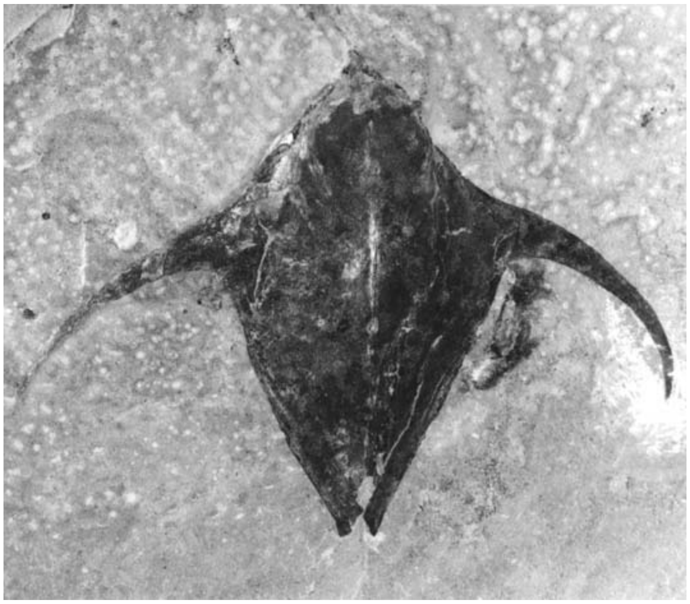


Figure 60. Pseudoarctolepis sharpi *Brooks Caster; Wheeler Shale, House Range; X0.85; as depicted in Robison (1991).*

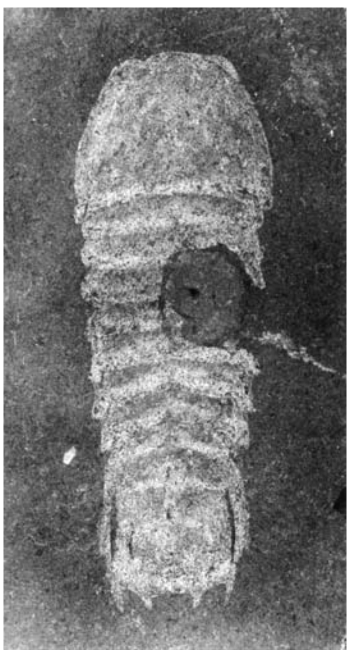


Figure 61. Mollisonia *sp. with an undetermined acrotretide brachiopod on its trunk; Wheeler Shale, House Range; X3; as depicted in Robison (1991).*

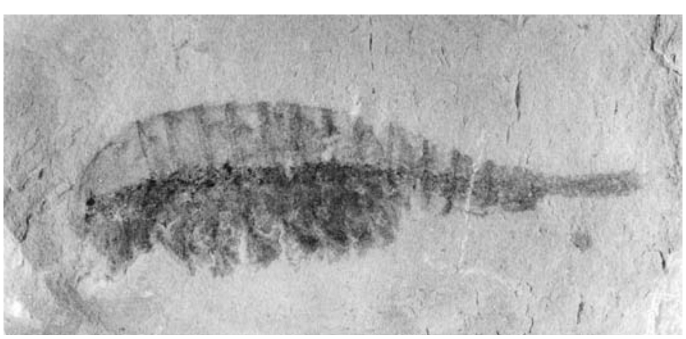


Figure 62. *Laterally compressed body of* Alalcomenaeus *cf.* cambricus *(Simonetta); Wheeler Shale, House Range; X2; as depicted in Robison (1991).*

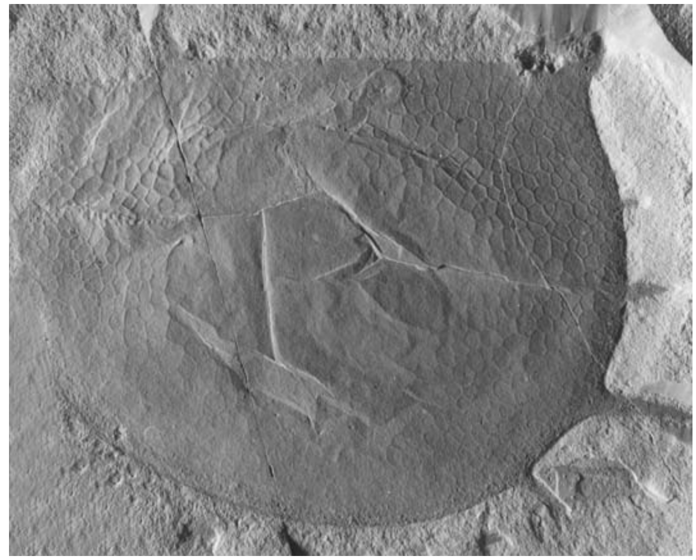


Figure 63. *Holotype left valve of* Tuzoia guntheri *(Robison & Richards); Marjum Formation, House Range; X1; as depicted in Robison (1991).*

Echinoderms: Echinoderms are scarce in most Cambrian strata in western Utah. Robison (1965) was the first to describe a species, *Gogia spiralis* (figure 64), from the Wheeler Shale and Marjum Formation in the House Range. Subsequently, Ubaghs and Robison (1985, 1988) and Sprinkle (1985) described new homalozoan echinoderms, eocrinoids, and edrioasteroids from western Utah. Because of their rarity, any echinoderm found in Cambrian strata should be called to the attention of professional echinoderm experts who can evaluate its significance and add it to the short list of known occurrences.

Animals of problematic assignment: Some fossils found in the Wheeler Shale and Marjum Formation in the House Range are not clearly assignable to major groups of organisms. Following Robison (1991), I list four genera in this category. *Anomalocaris* is the largest known Cambrian animal (Briggs and Robison, 1984) and may have preyed on trilobites (Vorwald, 1982; Babcock and Robison, 1989). *Chancelloria* was described by Walcott (1920) and Rigby (1978) as a sponge. Its disarticulated parts resemble tiny starfish. Bengtson and Missarzhevsky (1981) reassigned *Chancelloria* to a new class of organisms. *Eldonia*, formerly placed with the echinoderms, was reassigned as "phylum undetermined" by Conway Morris and Robison (1988). *Aysheaia* (figure 65), originally described by Walcott (1911c) as an annelid worm, and discussed by Robison (1985) as an onychophoran, has been reassigned by various specialists to three different groups. Photographs of these four genera were presented by Robison (1991), who discussed each briefly.

Conodonts: These microscopic tooth-like structures have become among the most useful indicators of geologic age within Paleozoic strata. Because they are made mostly of apatite, a phosphatic mineral, they can be dissolved out of carbonate rocks with acetic or formic acid. Paleontologists who specialize in conodont identification have learned that conodonts are widespread in carbonate rocks and that they rapidly evolved into many different species during Paleozoic time. Now that species' age ranges have been established through much carefully documented stratigraphic collecting,

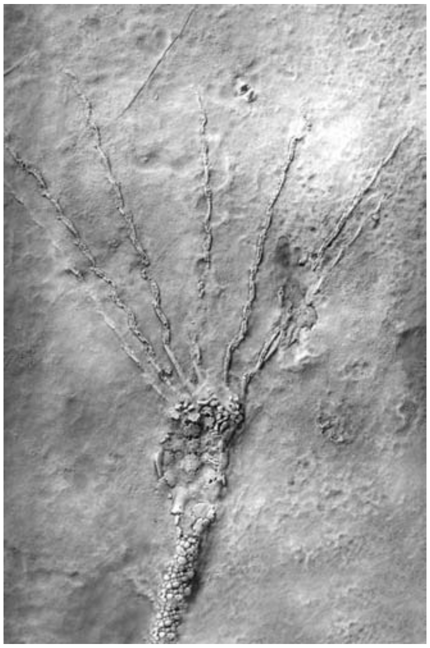


Figure 64. *Holotype of* Gogia spiralis *Robison; Wheeler Shale, Wheeler Amphitheater, House Range; X1.3.*

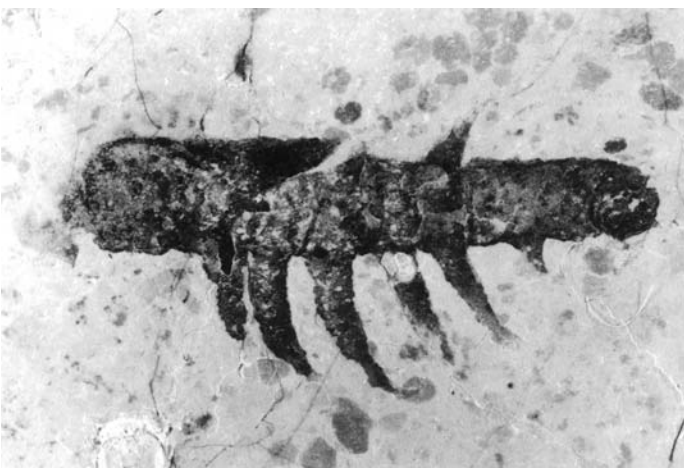


Figure 65. *Incomplete holotype of* Aysheaia prolata *Robison (phylum Onychophora) on bedding surface with several* Morania fragmenta*, a questionable blue-green alga; Wheeler Shale, House Range; X2.8.*

conodont zonations permit incredibly precise age determinations for certain parts of the Paleozoic rock record.

Conodonts make their earliest appearance in Utah in Middle Cambrian strata in the Canyon Mountains, and are especially useful in the uppermost Cambrian strata in the House Range, the Notch Peak Formation (figure 66). They were intensively studied by Miller (1969, 1978, 1980, 1984, 1987, 1988; Stitt and Miller, 1987) and his conodont results are included in Hintze and others (1988) and in Ross and others (1997). Many of the new species named by Miller (1969) from the House Range have subsequently been found worldwide in Upper Cambrian strata.

Conodonts and trilobites are found together in the upper part of the Notch Peak Formation in the House Range in such closely spaced stratal intervals as to make this a potential locality for the selection of the paleontological "golden spike" between the Cambrian and Ordovician Periods as discussed below.

Trace fossils: These are burrows, tracks, and trails made by marine organisms. They may be found in most Cambrian formations in western Utah. Uppermost beds in the Prospect Mountain and Tintic Quartzites commonly contain *Skolithos* tubes. These are vertical burrows 0.1-0.2 inches (2-5 mm) in diameter and up to 12 inches (30 cm) long (figure 67). They are also common in some quartzite beds in the Pioche and Ophir Formations. Silty and shaly beds in the Pioche and Ophir Formations are commonly laced with abundant tracks and trails; some can be recognized as trilobite tracks and trilobite resting spots.

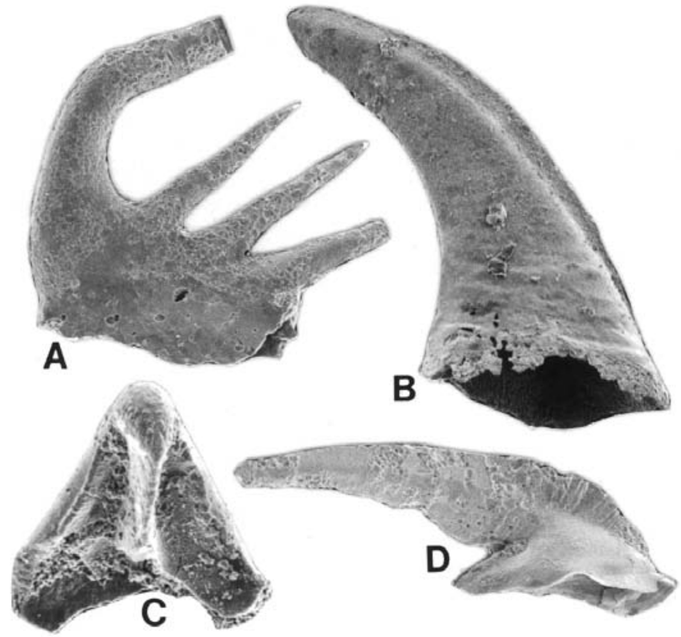


Figure 66. *Conodonts from the Lava Dam Member of the Notch Peak Formation, greatly magnified. Fossils collected by J.F. Miller; photomicrographs by M.M. Craig, Southwest Missouri State University Electron Microscopy Laboratory: A,* Cordylodus proavus *Müller, X143; B,* Proconodontus muelleri *Miller, X55; C,* Fryxellodontus inornatus *Miller, X100; D,* Cambrooistodus minutus *(Miller), X88.*

Figure 67. Skolithos *tubes in the Ophir Formation, Pahvant Range. Pen is 5 inches (13 cm) long.*

Many limestone and dolomite beds throughout the Cambrian carbonate sequence in western Utah have a characteristic "mottled" appearance, which has been ascribed to the burrowing of carbonate muds by marine organisms. Such beds are described as "bioturbated." Geologists who specialize in trace fossils have assigned names to the various patterns of burrows, tracks, and trails. Trace fossils are useful in interpreting paleoenvironments.

Cambrian-Ordovician Boundary

To standardize the boundaries of each geologic system, such as the Cambrian System, an international body of geologists, called the International Union of Geological Sciences, has established subcommissions that include paleontologists to select the fossil groups best suited for worldwide correlation within each geologic system. Setting the boundary between two systems involves paleontologic specialists familiar with the faunas of each system. Therefore, a subcommittee is ordinarily selected to recommend the best point in the succession of fossils, and the best location where that succession is displayed, to drive the "golden spike" to define the boundary between two systems.

The International Working Group on the Cambrian-Ordovician Boundary was established in 1974 under the auspices of the International Union of Geological Sciences, and its members met in various countries to examine potential stratotype boundary sections. In 2000, the global stratotype for the boundary between the Cambrian and Ordovician systems was designated at Green Point in Newfoundland. The same boundary is identifiable in Millard County in the Lava Dam Member of the Notch Peak Formation (Ross and others, 1997).

On columns 1 and 7 (appendix C) the Cambrian is divided into three parts: upper, middle, and lower. The trilobite zones that are used to define these subdivisions are given on chart 1 (appendix C). Pre-1950 Cambrian authors commonly used the terms Croxian, Albertan, and Waucoban for upper, middle, and lower respectively, but the boundaries between them were poorly defined and the names fell into disuse. Palmer (1998) proposed new names for Cambrian Series, resurrecting Waucoban for the lower, a new name, Lincolnian, for the middle, and a new name, Millardian, for the upper. He defined these subdivisions on the basis of trilobite species extinctions. The interested reader is referred to Palmer's paper for the series boundaries' definitions.

Lithologic Units in Western and Central Millard County and in the Canyon Range Thrust Plate

Names and age comparisons of all Cambrian rock formations in Millard County are shown on the Cambrian correlation chart (chart 1, appendix C). The stratigraphic columns (columns 1-10, appendix C) show formation names, map symbols, thicknesses, primary references, and other pertinent information. The 1:100,000 scale of the geologic maps that cover Millard County is too small to show many of the thin formations individually. They have been combined with adjacent units on the maps, and the combined map symbol is shown on the map explanations and on the stratigraphic columns. Each formation is discussed separately in the following sections.

Two sets of names are employed for Cambrian strata in Millard County. The most widely used nomenclature was established in the House Range by Walcott (1908a, d) and modified somewhat by later stratigraphers. It is applied to the very thick miogeosynclinal Cambrian strata in western Utah (Hintze, 1988a). The other nomenclature has been extended southward from the Tintic mining district, where it was established by Loughlin (1919) to apply to the generally thinner Cambrian sequence in the transitional area between the miogeosyncline of western Utah and the platform of eastern Utah. In the following pages the House Range nomenclature, used for western and central Millard County, is described first, followed by the Tintic district nomenclature, under the heading "Lithologic Units of Eastern Millard County."

Prospect Mountain Quartzite (Ꞓpm): Walcott (1908a, d) extended this name into the House Range from central Nevada, where it had been used by Hague (1883) for the oldest rocks exposed in the Eureka mining district. The name has subsequently been widely used in western Utah and Nevada for the thick quartzite at the base of the Cambrian sequence, as discussed by Hintze and Robison (1975). In Millard County the Prospect Mountain Quartzite is prominently exposed in the northern House Range (column 7, appendix C), the Drum Mountains (figure 20 and column 6), the Cricket and northern San Francisco Mountains (column 5), and the Canyon Mountains (column 1). The base of the formation is not exposed in the House Range, but at the other localities mentioned above it is underlain by the upper Precambrian Mutual Formation. Thickness of the Prospect Mountain Quartzite ranges from 2,760 feet (835 m) on the Canyon Range thrust plate, as measured by Higgins (1982), to 4,000± feet (1,200± m) in the Drum Mountains (Dommer, 1980), to 7,300 feet (2,210 m) as estimated by Lemmon and Morris (1984) in the northern San Francisco Mountains. The latter figure may be overestimated by as much as 3,000 feet (1,000 m) because no other Prospect Mountain thickness of this magnitude has been reported from this part of Utah. The nearest exposed section, in the Wah Wah Mountains in northern Beaver County, was reported by Abbott and others (1983) to be about 4,000 feet (1,200 m) thick.

The Prospect Mountain Quartzite is mostly a monotonously uniform, medium- to coarse-grained, pinkish-gray to light-brownish-gray quartzite that weathers reddish-brown. It commonly shows small-scale cross-bedding and includes thin beds of grit and quartz-pebble conglomerate. It lacks thick beds of argillite, but includes a few very thin beds of micaceous or phyllitic silty sandstone that weather greenish gray. Dalrymple and others (1985) speculated that the absence of shale in Cambrian orthoquartzite is best explained as a result of prolonged eolian action on the barren (prevegetation) cratonic sand source area. In the northern San Francisco Mountains the Prospect Mountain Quartzite includes a dark-greenish-gray to bluish-black basalt flow, 15 to 50 feet (5-15 m) thick, about 1,600 feet (500 m) above its base (Lemmon and Morris, 1984). The flow is chloritized and epidotized to the extent that attempts to obtain an isotopic age from it have not been successful. Abbott and others (1983) reported the same flow, or a similar one, about 1,100 feet (335 m) above the base of the Prospect Mountain Quartzite in the Wah Wah Mountains, about 25 miles (40 km) southwest of the San Francisco Mountains. Cambrian basalt has not been found elsewhere in Millard County, but Morris and Lovering (1961) reported basalt in adjacent Juab County in the Tintic Quartzite of the East Tintic Mountains.

The Prospect Mountain Quartzite has not attracted intensive study, probably because of its lack of fossils and generally monotonous lithology. It may one day yield an important story to a student of sandstones. Breaking the formation into regionally recognizable subunits is unlikely because, except for the local basalt flow, there are no apparent key beds within the formation that can be traced.

Pioche Formation (€p): Walcott (1908a) named the Pioche Formation, designated a type locality near Pioche, Nevada, and identified the formation as part of the Cambrian sequence in the House Range. Deiss (1938) coined the name "Tatow limestone" for the mixed lithologies above his Pioche that Walcott tentatively had called "Spence shale and Langston limestone," terms from northern Utah. Hintze and Robison (1975) established the current nomenclature by reassigning the carbonate-bearing Tatow as the upper member of the redefined Pioche Formation, and the carbonate-free shale and siltstone above the Prospect Mountain as the unnamed lower member of the redefined Pioche Formation. This usage has been applied in the House Range (column 7, appendix C), the Drum Mountains (column 6), and the Cricket Mountains (column 5). The Pioche Formation has not been subdivided in the Canyon Range thrust plate near Leamington where Higgins (1982) reported it to be 750 feet (228 m) thick.

Lower member: This member of the Pioche Formation is chiefly dark-brown phyllitic quartzite with interbeds of green shale and siltstone. The quartzite is fine- to medium-grained, thick- to medium-bedded in the lower part, and medium- to thin-bedded towards the top. Vertical *Skolithos* tubes, about the diameter and length of a drinking straw (figure 67), are common in quartzite beds in the middle of the lower member and suggest a shallow marine environment. Tracks made by trilobites, and horizontal burrows and trails as much as 1.6 inches (4 cm) wide made by soft-bodied creatures are abundant in many shale and siltstone beds (Magwood and Ekdale, 1993). These trace fossils in the lower Pioche member are not surpassed in richness, abundance, or diversity in any other part of the Cambrian sequence in western Utah. However, body fossils are scarce in the lower member. Robison and Hintze (1972) described four genera of Early Cambrian trilobites from the middle part of the lower Pioche in the House Range. These are the oldest metazoan body fossils known from Utah. Fragments of olenellid trilobites have been collected by the author from the lower member of the Pioche Formation in the Drum and Cricket Mountains. The trilobites at each locality are preserved as impressions in dark quartzite beds and in many places are associated with *Skolithos* tubes.

Lee and others (1980) noted that detrital muscovite mica from the lower Pioche in the House Range yielded a K-Ar radiometric age of 1,242 million years, similar to late Precambrian ages obtained from other detrital micas recovered from Lower Cambrian clastic rocks in nearby White Pine County, Nevada.

The dark blackish-brown color of many quartzite beds in the lower member is given by iron oxides. In the Cricket Mountains the lower member of the Pioche contains a hematite-rich ironstone layer 3 to 6 feet (1-2 m) thick about 160 feet (50 m) above the base of the formation. Its distribution in the Cricket Mountains is shown on geologic maps by Hintze (1984) and its occurrence as an iron deposit was noted by Bullock (1970).

The lower member is 360 feet (110 m) thick in the Drum Mountains, 420 feet (128 m) thick in the House Range, and 660 to 760 feet (200-230 m) thick in the Cricket Mountains. Below is a description of the lower member as measured by the author in May 1974 on the north side of the mouth of Marjum Canyon (figure 18), beginning at the lowest exposures on the west face of the House Range in SE1/4 NE1/4 section 16, T. 18 S., R. 14 W. A prominent orange-weathering dolomite bed several feet thick marks the base of the Tatow Member here, directly above the non-carbonate rocks of the lower member. The base of the lower member is not exposed here.

Unit No.	Description	Thickness Feet	Thickness Meters
14.	Quartzite, coarse- to medium-grained, weathers dark-brown, uneven platy parting, ledges.	25	7.6
13.	Quartzite, medium-grained, weathers brown, with 30 percent interbeds of micaceous green quartzitic siltstone.	77	23.5
12.	Quartzite and micaceous siltstone interbedded in equal proportions, trace fossils abundant on bedding surfaces, forms slope.	93	28.4
11.	Quartzite and siltstone similar to unit 12 but with *Skolithos* tubes in quartzite layer.	15	4.6
10.	Quartzite, medium-grained, weathers light-brown to dark-brown, *Skolithos* common, forms ledges.	21	6.4
9.	Quartzite, tan, interbedded with with green micaceous siltstone in 2 to 4 inch (5-10 cm) layers, forms slope.	15	4.6
8.	*Olenellus*-bearing quartzite, weathers brown, contains *Skolithos* tubes, forms ledges.	4	1.2
7.	Quartzite, medium-grained, silty, interbedded with micaceous siltstone, forms ledges.	24	7.3
6.	Quartzite, light-pinkish-gray, very coarse-grained, forms cliff.	6	1.8
5.	Quartzite, pinkish-gray, medium- to coarse-grained, cross-bedded, with 20 percent interbeds of green micaceous siltstone.	32	9.8
4.	Quartzite, pink, with 50 percent interbeds of green micaceous siltstone, forms ledges.	23	7.0

Unit No.	Description	Thickness Feet	Meters
3.	Siltstone, green, micaceous, forms slope.	45	13.7
2.	Quartzite, silty, brown, ledge-forming, with 40 percent interbedded micaceous quartzitic siltstone.	27	8.2
1.	Quartzite, pink, ledge, lowest exposure along wash.	3	0.9
	Total exposed thickness of lower member of Pioche Formation	410	125

Unit 1 in the above measured section may or may not be the top of the Prospect Mountain Quartzite. The section at Marjum Canyon is presented here because it is the one that is most visited. Deiss (1938) measured the lower member of the Pioche about 1.5 miles (2.4 km) north of Marjum Canyon, where he recorded its thickness as 265 feet (80.7 m). He may have placed his basal Pioche contact too high, and strata that he included in the Prospect Mountain Quartzite would now be regarded as lower Pioche. I measured an excellent section, where the Pioche Formation is underlain by more than 2,000 feet (600 m) of exposed Prospect Mountain Quartzite, on the west face of the House Range in SW1/4 SE1/4 section 30, T. 15 S., R. 13 W. (Hintze, 1981b). There the lower member is 420 feet (128 m) thick.

Tatow Member: Deiss (1938) named the "Tatow limestone" and designated its type section 1.5 miles (2.4 km) north of the mouth of Marjum Canyon in the House Range (figure 68). Hintze and Robison (1975) in emending its name to the Tatow Member of the Pioche Formation noted that, despite Deiss' description, only a small part of the unit is carbonate and the rest is chiefly tan calcareous quartzite with interbeds of phyllitic shale. However, the Tatow does include the lowest appearance of carbonate rock in the Cambrian of western Utah, and thereby constitutes an easily recognizable rock unit. The lower boundary is placed at the base of the lowest limestone bed, and the upper boundary is placed where slope-forming calcareous sandstone of the upper Tatow is overlain by the massive cliff-forming Howell Limestone. Some of the carbonate beds in the Tatow Member weather to a distinctive burnt-orange color that make the Tatow Member easy to identify from a distance.

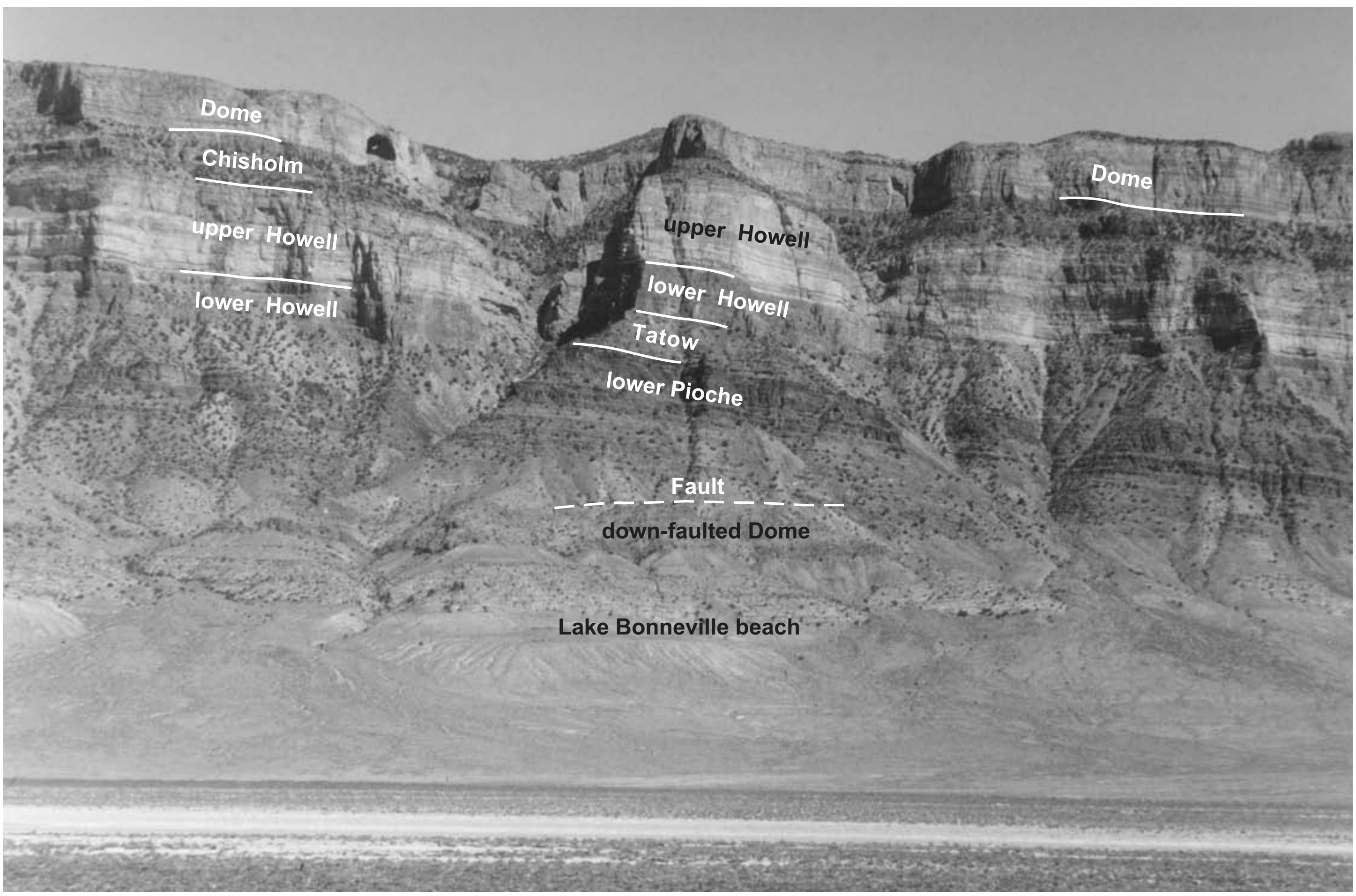


Figure 68. *Cambrian strata on the west face of the House Range west of Delta, Utah. Upper cliff with cave is Dome Limestone; tree-covered bench beneath it is shaly Chisholm Formation; light-banded cliff underneath Chisholm is upper member of Howell Limestone with dark Millard Member at its base. Shale slope beneath Howell cliffs is Tatow Member of the Pioche Formation; below that are dark ledges of quartzites in the lower member of the Pioche Formation. Light- and medium-gray bedrock at the base of the slope is down-faulted Swasey Limestone, Whirlwind Formation, and Dome Limestone. Light terrace near base of slope is Lake Bonneville beach deposit. White fine-grained Lake Bonneville deposits of Tule Valley show in foreground.*

Limestone beds in the upper 30 feet (10 m) of the Tatow Member in the House Range contain *Albertella* Zone trilobites, representing early Middle Cambrian time (chart 1, appendix C). In the Cricket Mountains the trilobites *Mexicella*, *Paralbertella*, and *Volocephalina*, representing early Middle Cambrian time, were reported from 6 feet (2 m) above the base of the Tatow Member by Hintze (1984). The boundary between Lower Cambrian and Middle Cambrian rocks, as defined by trilobite zones, is within the Pioche Formation at about the lithologic boundary between the lower member and the Tatow Member.

Deiss (1938) recorded a thickness of 165 feet (50.3 m) for the Tatow Member at his measured section 1.5 miles (2.4 km) north of Marjum Canyon. The section of Tatow at Marjum Canyon, described below, totals 178 feet (54 m). In the Cricket Mountains the Tatow is 82 to 115 feet (25-35 m) thick, and in the Drum Mountains it is 55 feet (17 m) thick. The Tatow Member has not been recognized as a separate unit to the east in the Pahvant Range and Canyon Mountains, although orange-weathering carbonate beds, like those in the Tatow, occur locally in the lower part of the Middle Cambrian strata in those ranges.

The following section of the Tatow Member was measured near the base of House Range bedrock exposures 0.35 miles (0.55 km) north of Marjum Canyon by L.F. Hintze and Blaine Willes in July 1960. The Tatow Member is conformably overlain here by a dark-gray limestone cliff of the Millard Member of the Howell Formation (figure 68).

Unit No.	**Description**	**Thickness Feet**	**Thickness Meters**
12.	Sandstone, calcareous, brownish-gray, thin- to medium-bedded, with some interbeds of thin-bedded limestone and quartzite, forms slope at base of Millard Member cliff.	35	10.7
11.	Limestone, medium-gray, forms ledge.	3	0.9
10.	Quartzite, brownish-gray, thin-bedded, with thin interbeds of greenish-gray phyllite and siliceous limestone.	71.5	21.8
9.	Limestone, medium-gray, coarse-grained, contains trilobite fragments, forms low ledge.	2	0.6
8.	Quartzite, grayish-brown, phyllitic, thin-bedded with some cross-bedding, forms ledges.	10.5	3.2
7.	Phyllitic shale, light-greenish-gray, thin-bedded, with interbeds of thin-bedded medium-gray limestone, poorly exposed except in upper half, forms slope.	8	2.4
6.	Limestone, medium-gray, mottled with grayish-brown and dark-gray splotches, upper 2 feet (0.6 m) contains pisolitic “algal” spheres, forms low ledge.	5.5	1.7
5.	Quartzite, brownish-gray, fine-grained, forms slope.	10	3.0
4.	Limestone, moderate brown, siliceous, forms upper half of the lowest prominent ledge in the Tatow here.	6.5	2.0
3.	Quartzite, moderate-brown, fine-grained, forms lower half of the lowest Tatow ledge.	6	1.8
2.	Covered; float suggests phyllitic shale.	18	5.5
1.	Dolomitic limestone, moderate-brown, massive, coarsely crystalline, forms low ledge.	2	0.6
Total thickness of Tatow Member of Pioche Formation		178	54.2

The Tatow Member here rests conformably on light-greenish-gray, papery, micaceous, siliceous phyllitic shale, which is more than 50 feet (15 m) thick and poorly exposed.

Dome, Chisholm, and Howell Formations, undivided (€dh): On the 1:100,000-scale geologic maps of Millard County, the Howell Limestone, Chisholm Formation, and Dome Limestone are shown as a combined map unit. They are described separately below and illustrated on figure 68. In the Wah Wah and Beaver Lake Mountains in Beaver County, the Peasley Limestone, a carbonate equivalent to the upper Chisholm Formation, is included within this unit. The Chisholm may or may not be present in the northern Mineral Mountains. Formations in this map unit are structurally thinned in the Beaver Lake and Mineral Mountains.

Howell Limestone: Although Walcott (1908a, d) named the Howell, his description of the formation inadvertently included down-faulted portions of younger Cambrian strata, which later geologists (Deiss, 1938; Robison, 1960b) assigned to other units. Hintze and Robison (1975) reviewed the history of changes in Howell nomenclature leading to the present usage, which divides the Howell Limestone into two members: a lower, Millard Member, and an upper member that has not been given a formal name. Deiss (1938), in his emendation of Walcott's work, described the type section of the Howell as consisting of a lower portion (the part now called Millard Member), which he measured 1.5 miles (2.4 km) south of Marjum Canyon, and an upper portion (including both the upper Howell and the Chisholm Formation of present usage) measured on the north side of Marjum Canyon.

<u>Millard Member:</u> Wheeler (1948) named the Millard limestone in the House Range by elevating the basal 281 feet (86 m) of Howell Limestone, as described by Deiss (1938), to separate formational rank. Robison (1960b) later reduced the Millard to member status. The Millard Member is the dark-gray lower part of the cliff-forming Howell Limestone; it stands in conspicuous color contrast to the light-gray upper member. It is an easily distinguishable map unit within the House Range, Cricket Mountains, and Wah Wah Mountains,

but is not readily separated from the upper Howell as a map unit in the Drum Mountains (figure 20; column 6, appendix C) or the Canyon Mountains (column 1).

Noncarbonate residues decrease abruptly from about 60 percent in the Tatow Member of the Pioche Formation in the House Range to an average of about 5 percent in the Millard Member (Hintze and Robison, 1975, table 2). In the Millard Member, fine-grained detrital quartz and very small quartz crystals compose most of the insoluble fraction, with clay minerals and traces of mica and ferromagnesian minerals making up the rest.

Oncolites of probable *Girvanella* microbial origin are abundant in the Millard Member. Comminuted fossil debris is common in some beds, but identifiable macrofossils are rare. Deiss (1938) reported rare *Zacanthoides* trilobite heads about 100 feet (30 m) above the base of the member in the type section north of Marjum Canyon, and Hintze and Robison (1975) reported mixed *Albertella-Glossopleura* Zone trilobite collections from the lower part of the member in Marjum Canyon, along with rare occurrences of *Gogia* (eocrinoid), *Indiana*? (ostracode), *Coreospira* (gastropod), and *Scenella* (monoplacophoran).

The following section of the Millard Member was measured on the north side of Marjum Canyon by L.F. Hintze and Blaine Willes in July 1960. The Millard Member here is conformably overlain by the upper member of the Howell Limestone.

Un`it No.	Description	Thickness Feet	Thickness Meters
5.	Limestone, medium-dark-gray, fine-grained, forms massive ledge at top of Millard Member with narrow bench at base of overlying upper member of Howell.	60	18.3
4.	Limestone, medium-dark-gray, fine-grained, locally mottled with bioturbation burrows, few beds with “algal” oncolites, forms steep slope.	150	45.7
3.	Limestone, medium-dark-gray, medium-grained, “algal” pisolites and oncolites abundant in upper 15 feet (5 m).	25	7.6
2.	Limestone, medium-dark-gray, fine- to medium-grained, nearly unbedded but locally thick-bedded to massive, some beds mottled by bioturbation, includes some poorly preserved oncolites and pisolites, forms steep slope.	45	13.7
1.	Limestone, medium-dark-gray, medium-grained, forms massive cliff without apparent bedding.	30	9.1
	Total thickness of Millard Member of Howell Limestone	310	94.5

The Millard Member is 200 to 250 feet (60-75 m) thick in the Cricket Mountains (column 5, appendix C) and 180 feet (55 m) thick in the Wah Wah Mountains (Hintze, 1974e) a few miles south of the Millard County line.

Upper member: Robison (1960b) emended Deiss' (1938) definition of the Howell Limestone by applying the name Chisholm Formation to its uppermost 219 feet (66.8 m) of slope-forming, fossiliferous limestone and shale. As thus restricted, the Howell Limestone forms massive cliffs with a light-weathering upper member and a lower dark-weathering Millard Member.

The upper member is fine-grained, and apparently formed mostly from finely divided lime mud. White calcite blebs, common in some beds, may be a secondary product of the calcification of dolomite. Microbial pisolites and laminated microbial structures are rare, and other fossils have not been reported from the upper member in the House Range. Samples from the upper member, taken at about 10-foot (3-m) intervals, yielded an average 3.8 percent insoluble residue (Hintze and Robison, 1975). Fine-grained quartz constitutes most of the residues, with clay dominant in a few samples. Mica and ferromagnesian minerals make up less than one percent of the residues.

For a bed-by-bed description of the upper member of the Howell Limestone see Deiss (1938, p. 1136-7), who found the upper member to be 334.5 feet (102 m) thick at Marjum Canyon in the House Range. The upper member is 100 to 165 feet (30-50 m) thick in the Cricket Mountains, and 190 feet (58 m) thick in the Wah Wah Mountains (Hintze, 1974e) a few miles south of Millard County.

Chisholm Formation: Robison (1960b) extended the name Chisholm from Pioche, Nevada where this shale and interbedded limestone unit had been named by Walcott (1916b). The Chisholm Formation, as mapped in the House Range (Hintze, 1974d, 1980a, 1981a-b), consists of three main parts: the lowest quarter is a slope-forming, thin-bedded, trilobite-rich limestone with interbedded olive shale and siltstone; the middle half is a dark-gray ledge-forming limestone, pisolitic in its lower half and bearing *Glossopleura* trilobite coquinas in some beds in its upper half; the top quarter is an olive fissile shale that forms a slope beneath the overlying Dome Limestone. Deiss (1938) described a measured section of Howell Limestone in Marjum Canyon in the House Range (figure 69); the upper 219 feet (66.8 m) of his Howell Limestone is actually the Chisholm Formation. In the course of sampling Cambrian limestones for insoluble residue content, I remeasured the Marjum Canyon section and got a thickness of 216 feet (65.8 m). The middle limestone beds in the Chisholm averaged only 3.7 percent insolubles, mostly clay rather than quartz (Hintze and Robison, 1975).

Oldroyd (1973) documented 25 species of trilobites from the Chisholm of the House Range and Drum Mountains; *Glossopleura*, *Alokistocare*, and *Zacanthoides* are the most commonly represented genera. Each trilobite species shows a strong preference for particular environments. The various rocks in which they are found represent a variety of shallow marine shelf-lagoon and near-sea-level shoal environments. Oldroyd (1973) recorded a thickness of 290 feet (88 m) of Chisholm in Marjum Canyon. His uppermost limestone unit is part of the Dome Limestone as mapped by Hintze (1974d).

The Chisholm Formation is 219 feet (66.8 m) thick in the

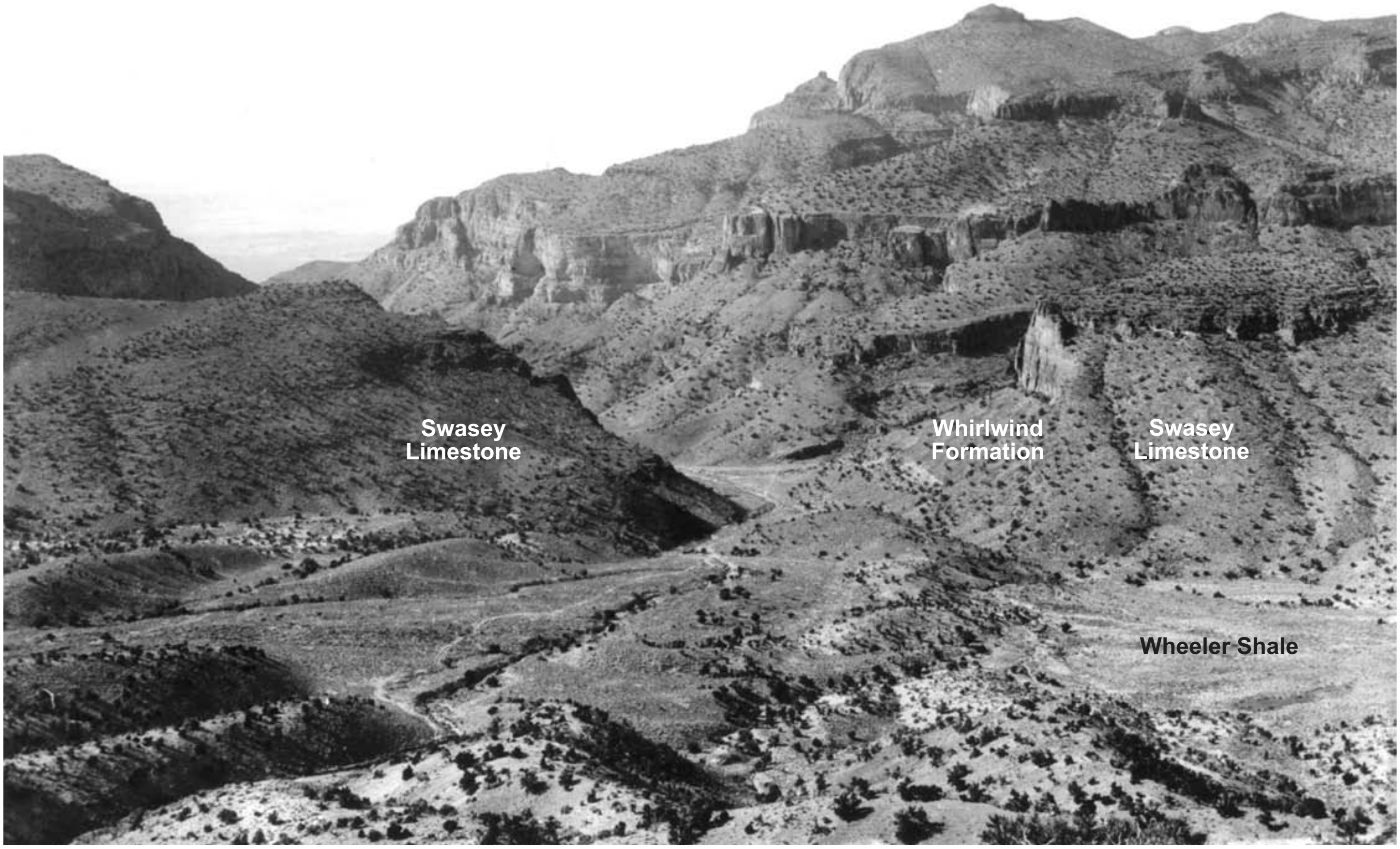


Figure 69. *Photograph, looking northwest down Marjum Canyon, taken by G.K. Gilbert, U.S. Geological Survey geologist, in 1901. Mormon wagon trail down the canyon later was followed by U.S. Highway 6, a graded road which was frequently washed out by cloudburst floods. Route 6 was moved south 15 miles (24 km) and paved in the early 1950s. East-dipping Middle Cambrian strata exposed in the canyon (older to younger) are the Howell, Chisholm, Dome, Whirlwind, and Swasey Formations; because of faulting and folding (see Hintze, 1974d), labeling all the strata is not practical. Photo from U.S. Geological Survey Field Records Library, Denver, Colorado.*

H ouse Range, 247 feet (75 m) thick in the Canyon Mountains, 165 to 265 feet (50-80 m) thick in the Cricket Mountains, 205 feet (62.5 m) thick in the Drum Mountains, and 40 to 80 feet (12-24 m) thick in the Wah Wah Mountains just south of the Millard County line.

Dome Limestone: Walcott (1908a, d) named this formation in the House Range and his designation has remained unchanged. The Dome Limestone is a massive cliff-forming limestone between two slope-forming shaly limestone formations, so it is easy to recognize. Deiss (1938) described 310 feet (94.4 m) of Dome Limestone in Marjum Canyon. Other measurements of the Dome in the House Range by Hanks (1962) and Hintze (1974d) gave thicknesses of 330 feet (100.5 m) and 320 feet (97.5 m), respectively.

In the House Range the lowest fifth of the Dome Limestone is a medium-dark-gray fine-grained limestone with thin silty clay accumulations on bedding surfaces spaced a few inches apart, giving it a layered appearance on its massive cliff face. The middle three-fifths of the Dome is mottled medium-gray to light-gray-weathering, fine- to medium-grained, massive, cliff-forming limestone that includes a few reddish-gray clayey limestone horizons. Oolites and traces of small-scale cross-bedding can be seen in some places, suggesting deposition as a granular lime mud. The upper fifth of the Dome includes some cross-bedding sets 6 inches (15 cm) thick, within the medium-dark-gray, medium-grained, locally argillaceous, massive cliff-forming limestone. Samples of Dome Limestone, taken at 10-foot (3-m) intervals through the formation (Hintze and Robison, 1975), show that insoluble residues average only 1.8 percent. Clay forms most of the residue, but finely divided quartz is the chief constituent in about one-third of the samples. A trace of ferromagnesian minerals was noted in samples from the upper two-thirds of the formation.

Fossils are rare in the Dome Limestone. However, Oldroyd (1973) reported collecting the trilobites *Ehmaniella*, *Kootenia*, *Mexicella*, *Poliella*, and *Spencella*, indicative of the *Ehmaniella* Zone, from 60 feet (18 m) above the base of the Dome. The Dome is 310 to 330 feet (94.4-100.5 m) thick in the House Range, 230 to 330 feet (70-100 m) thick in the Cricket Mountains, 300 to 365 feet (90-111 m) thick in the Drum Mountains, 181 feet (55 m) thick in the Canyon Mountains, and 280 to 310 feet (85-94.4 m) thick in the Wah Wah Mountains just south of Millard County.

Wheeler, Swasey, and Whirlwind Formations, undivided (€ww): On the 1:100,000-scale geologic maps of Millard County, the Whirlwind Formation, Swasey Limestone, and Wheeler Shale are shown as a combined map unit. They are discussed separately below. The type locality for several of Walcott's Middle Cambrian formations is shown on figure 69. Whirlwind is shown on the 1:100,000-scale geologic maps of Millard County separately (Cw) in the Cricket Mountains.

Whirlwind Formation (€w): Robison (1960b) proposed the name Whirlwind for the shaly slope-forming lower part of Walcott's (1908a) Swasey Limestone, restricting Swasey to the cliff-forming upper part. The following Whirlwind section was measured on the north side of Marjum Canyon in section 14, T. 18 S., R. 14 W., by L. F. Hintze and Blaine Willes in July 1960:

Unit No.	Description	Thickness Feet	Thickness Meters
5.	Limy shale, light-olive-gray, with 10-20% interbeds of medium-gray thin-bedded limestone, some beds of which are coquinas of *Ehmaniella* trilobite parts, and others are beds of intraformational conglomerate.	54	16.4
4.	Limestone, dark-gray, silty, medium-bedded, forms prominent ledges in middle of Whirlwind slope.	28	8.5
3.	Shale, papery, weathers grayish-orange-pink, forms slope below unit 4.	11	3.4
2.	Shaly limestone, medium gray, weathers light-brownish-gray, thin-bedded, platy, contains a few trilobite impressions, forms slope.	39	11.9
1.	Limy shale, light-brownish-gray, weathers readily to form silty soil slope; rests conformably on upper part of cliff-forming Dome Limestone.	15	4.6
	Total thickness of Whirlwind Formation	147	44.8

Kopaska-Merkel (1983, 1988) examined the paleontology and depositional environments of the Whirlwind Formation in the Canyon, Drum, House, and Wah Wah ranges, measuring three sections in the Drum Mountains in great detail. He concluded that Whirlwind sediments were deposited in a shallow shelf basin, or lagoon, which was protected from the open ocean on the west by carbonate banks. Water depth during accumulation of the upper and lower shaly deposits ranged from 25 feet (8 m) to about 100 feet (30 m). The middle limestone was deposited when the sea became shallower, allowing lime mud banks to encroach into the lagoonal area. Whirlwind body fossils are strikingly undiverse. Most of them belong to a single trilobite genus, *Ehmaniella*. Others include a single genus of inarticulate brachiopod and rare hyolithids. Trace fossils are limited to trails, vertical "U"-tubes, and burrow-filling fecal pellets. Whirlwind waters were probably of moderately high salinity, very warm, and possibly oxygen-poor. Sundberg (1990) studied trilobites of the *Ehmaniella* biozone in the House Range, Drum Mountains, and other localities in western Utah and eastern Nevada. Sundberg (1994) described trilobites from the Dome, Whirlwind, and Swasey Formations naming 9 new genera and many new species and subspecies of Middle Cambrian trilobites from his *Ehmaniella* Biozone, which he divided into four subzones.

The Whirlwind Formation is 147 feet (44.8 m) thick in the House Range, 145 feet (44 m) thick in the Canyon Mountains, 137 feet (42 m) thick in the Drum Mountains, and 99 feet (30 m) thick in the Wah Wah Mountains.

Swasey Limestone: Walcott (1908a, d) named the Swasey Limestone, recognizing a lower and upper part. Robison (1960b) restricted the Swasey to the upper cliff-forming part of Walcott's original Swasey Limestone and proposed the name Whirlwind for the lower part. The restricted Swasey Limestone is remarkably pure limestone, bounded above and below by shaly units. Hintze and Robison (1975) noted that samples taken at 10-foot (3-m) intervals through the Swasey averaged 1.8 percent insoluble residue that is mostly clay or very fine-grained quartz. Swasey Limestone is mostly medium to dark gray, locally mottled, finely to coarsely crystalline, thick bedded to massive, cliff forming, and includes many oolitic and some pisolitic beds. Descriptions of measured sections of Swasey Limestone in the House Range are found in Deiss (1938), Hanks (1962), and Caldwell (1980).

Caldwell (1980) studied the sedimentary petrology of the Swasey Limestone in five measured sections in the House Range, and a section each in the Drum Mountains and the Canyon Mountains. He found that the lower half of the Swasey is composed of lime mudstone, which reflects deposition in a quiet-water lagoon. Most of the upper Swasey is an oolitic grainstone that was deposited on a migrating underwater dune complex on the continental side of a gently sloping platform. The uppermost 3 to 10 feet (1-3 m) of Swasey is a bioclastic packstone that was deposited in very shallow waters. Thus, Swasey Limestone records a progressive shallowing of the marine environment in Millard County during the time of its deposition.

Fossils are common only in the uppermost few feet of the Swasey Limestone and occurrence is sporadic. A diverse fauna of 31 species of non-agnostid trilobites was described by Randolph (1973) from the upper Swasey in the Drum Mountains. Termed the *Glyphaspis* fauna, it includes *Parkaspis*, *Tonkinella*, *Pagetia*, *Zacanthoides*, *Dorypyge*, and several new genera. The *Glyphaspis* fauna has been found in many ranges in the eastern Great Basin and makes a useful marker for correlation. White (1973) concluded that the *Glyphaspis* fauna probably lived along the seaward sides of shallow-water shoals. The Swasey Limestone is about 250 feet (76 m) thick in the House Range, 180 feet (55 m) thick in the Drum Mountains, 440 feet (140 m) thick in the Wah Wah Mountains, and 614 feet (186 m) thick in the Canyon Mountains. It is not recognized as a separate unit in the Cricket Mountains, where it forms the lower part of the "limestone of Cricket Mountains" map unit.

Wheeler Shale: This formation, named by Walcott (1908a) and limited to a relatively small area in western Utah, is world-famous for its trilobites. Beautifully preserved specimens of *Elrathia kingii*, from the upper part of the Wheeler Shale at Wheeler Amphitheater in the House Range, are distributed in fossil collections wherever trilobites are on display. The Wheeler Shale was described and/or discussed by Deiss (1938), Robison (1962, 1964b), White (1973), Hintze and Robison (1975), McGee (1978), Grannis (1982), Vorwald (1983), Rogers (1984), and Rees (1986). Its distribution in the House Range was mapped by Hintze (1974d, 1980a, 1981a-b). Fossils from the Wheeler Shale, the reason for the widespread interest in the formation, have been described by many paleontologists, as discussed earlier in this report under the heading "Cambrian Fossil Life in Western Utah." Pictures of many of its common fossils are in Gunther and Gunther (1981).

Figure 70. *Wheeler Amphitheater in the House Range is surrounded by thick-bedded ledges and cliffs of the Marjum Limestone; view roughly to north. The bowl of the amphitheater is underlain by the less-resistant Wheeler Shale whose thinner beds form the low outcrops in the lower half of the photo. Fossils occur throughout all layers of rock shown above but are mined commercially only from an especially fossiliferous layer about 2 feet (0.7 m) thick. Rockhounds from all over come here to collect trilobites and are welcome, except in the commercially operated pits.*

Figure 71. Ptychagnostus gibbus *(Linnarsson); basal Wheeler Formation, House Range; X6 (Robison, 1982).*

The basal beds of the Wheeler, at its type locality in the Wheeler Amphitheater (figure 70), are composed of slope-forming, laminated, argillaceous limestone with an agnostid-rich trilobite fauna characterized by *Ptychagnostus gibbus* (figure 71) and abundant phosphatic brachiopods. The contact with the underlying Swasey Limestone is an abrupt change in rock type, from pure limestone to shaly limestone, and locally may show a boundary surface with relief of 6 inches (15 cm). The upper part of the Wheeler Shale includes a few thin ledge-forming limestone beds (figure 44); its fauna is dominated by the trilobites *Elrathia* and *Asaphiscus*, which occur with the considerable variety of other fossils discussed earlier in this report. Bed-by-bed descriptions of the Wheeler Shale and its fossils in the House Range are found in Robison (1962), who reported its thickness as 487 feet (148 m) at Marjum Pass. Insoluble residues from samples taken at 20-foot (6-m) intervals in the Wheeler here (Hintze and Robison, 1975) range from 10 to 70 percent. Clay is the most common constituent with finely divided silica making up less than one-fourth of the residue.

The maximum thickness of Wheeler Shale, 910 feet (277 m), is found in the Drum Mountains (figure 21). The best exposures are in Juab County, within a mile (1.6 km) of the Millard County line. The Wheeler in the Drum Mountains is composed of a lower shale 280 feet (85 m) thick, a middle limestone 505 feet (154 m) thick, and an upper shale 125 feet (38 m) thick (White, 1973; Grannis, 1982; Vorwald, 1983; Hintze and Oviatt, 1993). The only other occurrence of Wheeler Shale in central Utah is in the Canyon Mountains (column 1, appendix C) where Higgins (1982) reported 100 feet (30 m) of Wheeler that contained the conodont *Hertzina* and trilobites representative of the *Ptychagnostus gibbus* Zone, which is found in the lowest one-fifth of the Wheeler Shale in the House Range. Rowell and Rees (1981) plotted the distribution of Wheeler-type basinal lithologies in northwestern Utah and eastern Nevada.

The Wheeler interval is represented by the Eye of Needle Limestone in the Wah Wah Mountains (column 9, appendix C) and a portion of the Limestone of Cricket Mountains in the Cricket Mountains (column 5). These limestones were deposited on a carbonate shelf, whereas the Wheeler Shale was deposited in the House Range embayment, a gulf of deeper water that lay northwest of the carbonate bank. The line of demarcation between the carbonate shelf and the House Range embayment extends southwestward across Nevada in such a straight line that Rees (1986) suggested it was fault controlled. The varied environments in the House Range embayment adjacent to the carbonate platform (which is commonly barren of fossils) range from deep basin (Rogers, 1984) to various slope and shelf conditions, and gave rise to the remarkable abundance and diversity of Cambrian fossils found in the Wheeler Shale.

Upper and Middle Cambrian strata, undivided (€um): In the Canyon Range thrust plate, the thin Wheeler Shale at the north end of the Canyon Mountains is overlain by about 1,600 feet (490 m) of undivided Upper and Middle Cambrian limestone and dolomite. Lithologies are typical of this part of the Cambrian sequence in western Millard County and include unfossiliferous, massive, mottled gray limestone, white laminated dolomitic boundstone, and dark-gray dolomite flecked with small blebs or rods of white dolomite. A thin olive-gray shale crops out in SE1/4 NE1/4 NW1/4 section 17, T. 15 S., R. 3 W. This shale contains a few thin interbeds of intraformational limestone conglomerate and one coarse-grained limestone, which contain sparse trilobite fragments from the lower Upper Cambrian *Crepicephalus* Zone, suggesting that the upper few hundred feet (<100 m) of this unit may be equivalent to the lower part of the Orr Formation in the House Range. Cretaceous synorogenic clastic deposits unconformably overlie the uppermost Cambrian strata here.

Eye of Needle, Swasey, and Whirlwind Formations, undivided (€ew): On the Wah Wah Mountains North geologic map the Whirlwind Formation, Swasey Limestone, and Eye of Needle Limestone are shown as a combined map unit in the Wah Wah Mountains (Hintze and Davis, 2002a). Each formation is discussed separately herein.

Eye of Needle Limestone: As noted by Wheeler (1948), the Wheeler Shale is conspicuously absent from the Cambrian sequence in the Wah Wah Mountains. Its place above the Swasey Limestone is occupied by a massive cliff-forming limestone that was given the name "Eye of Needle" by Hintze and Robison (1975). It is composed almost entirely of light-gray massive limestone, locally mottled, with darker gray bands, and containing, in its middle one-third, small rods or tubes filled with white calcite, called fenestral fabric. The contact between the Eye of Needle Limestone and the adjacent formations is conformable and transitional. The formation is unfossiliferous and has been correlated with the Wheeler Shale solely on its position in the lithostratigraphic sequence. It is as much as 240 feet (80 m) thick in the Wah Wah Mountains but has not been mapped elsewhere. It is not completely exposed in Millard County but its type section is along state Highway 21 about 5 miles (8 km) south of the county line in Beaver County.

Marjum or Pierson Cove Formation (€mp): On the 1:100,000-scale geologic maps of Millard County the Marjum and Pierson Cove Formations have the same map symbol (Hintze and Davis, 2002a-c), because the Marjum Formation is present in only a small area in the central House Range. They are discussed separately below.

Marjum Formation: The Marjum Formation was named by Walcott (1908a, d); Robison (1964b) reviewed the history of usage of the name and recommended that it not be extended beyond the House Range because typical Marjum lithologies are replaced by different rock types in equivalent sequences elsewhere. As thus restricted, the Marjum Formation is even more limited in areal extent than the underlying Wheeler Shale. The Marjum occurs only in the central House Range north and south of Marjum Pass, and in nearby Wheeler Amphitheater (figures 44 and 81), from which its exposures wrap around the flanks of Swasey Peak. Both the Marjum Pass and the Wheeler Amphitheater sections were measured and described in detail, along with their fossils, by Robison (1962, 1964a, 1971, 1982).

Although these two sections are only 10 miles (16 km) apart, their lithologic sequences are quite different. Brady and Koepnick (1979) suggested that Marjum Formation exposures in the central House Range provide one of the few opportunities in the Great Basin to follow a platform-to-basin transition in nearly continuous exposure. The Marjum Formation grades from an interbedded shale and limestone basinal sequence, in the Marjum Pass section, to more diverse types of shale and carbonate lithologies representing transition out of the basin, through slope and into platform conditions in the Wheeler Amphitheater-Swasey Peak sections. The term basin, as used here, does not refer to oceanic deeps, but to slightly deeper waters than found in adjacent places on the continental platform or the platform-to-basin slope. Rees (1986) ascribed the origin of the trough of deeper water in which the Marjum was deposited to a paleofault that extended from the House Range embayment southwesterly through Nevada.

Detailed descriptions of the various types of limestone and shale present in the Marjum Formation, and the environments of deposition inferred from them, can be found in Brady and Koepnick (1979), Rees (1984, 1986), and Rogers (1984). The Marjum Formation is abundantly fossiliferous. Robison (1962, 1964a, 1982) summarized previously published paleontological work and added modern descriptions of fossils, mostly trilobites (figure 72), from the Wheeler and Marjum Formations. Gunther and Gunther (1981) presented illustrations of many fossils from the Marjum Formation.

Figure 72. Modocia typicalis *(Resser); lower Marjum Formation, House Range; X4 (Robison, 1964a).*

Robison (1962, summarized in 1964b) presented bed-by-bed descriptions of Marjum lithologies and fossils for four sections in the central House Range. He recorded the following thicknesses of the Marjum Formation: 1,413 feet (436 m) at Rainbow Peak; 1,362 feet (415 m) at Marjum Pass; 1,145 feet (349 m) at Wheeler Amphitheater; and 531 feet (162 m) at Swasey Peak. The striking reduction in thickness between the Wheeler Amphitheater and Swasey Peak sections is related to the passage of Marjum lithologies into dolomite atypical of the Marjum, as noted by Brady and Koepnick (1979). Hintze (1981b) mapped the roughly 500 feet (150 m) of dolomite that caps Swasey Peak as the lower (dolomite) part of the Trippe Limestone (see column 7, appendix C), and it is shown as Trippe Limestone (€lw) on the Tule Valley geologic map (Hintze and Davis, 2002c).

Pierson Cove Formation: The Pierson Cove Formation was established by Hintze and Robison (1975) to include the unfossiliferous non-shaly carbonate beds that are the temporal equivalent of all except the topmost part of the Marjum Formation, as shown on chart 1 (appendix C). Predominant lithology in the Pierson Cove is dark-gray dolomitic lime mudstone. The next most common is massive, fine-crystalline, medium-gray limestone, in some places containing small rods or tubes filled with white calcite (fenestral fabric). Least common, but nonetheless conspicuous, is yellowish-gray, laminated, dolomitic, microbial boundstone that forms thin white bands in the mostly dark-gray sequence.

The Pierson Cove Formation is virtually unfossiliferous except for the laminated microbial boundstone, and the trace-fossil bioturbation trails that give the mottled appearance to many lime-mudstone beds. Kepper (1974, 1976) suggested variable salinity conditions as a cause for an antipathetic relation between trilobite and algal abundance. Apparently, "algae" (likely cyanobacteria) flourished in shallower, warmer, and more saline waters than did trilobites, which favored the slightly deeper water marine environment and limy clay mud-bottom deposits.

Bond and Kominz (1991) and Bond and others (1991) speculated on Earth's orbital forcing of peritidal cyclic sedimentation, using the Pierson Cove Formation and Trippe Limestone as examples.

The Pierson Cove Formation is about 1,200 feet (370 m) thick at the north end of the House Range (Hintze, 1980a), 800 feet (243 m) thick in the Drum Mountains (Dommer, 1980; Hintze and Oviatt, 1993), and 1,441 feet (439 m) thick in its type section in the Wah Wah Mountains (NE1/4 section 23, T. 26 S., R. 16 W.) as described below.

Unit No.	Description	Thickness Feet	Thickness Meters
30.	Limestone, medium-gray, medium-grained, with thin interbeds of laminated dolomite; forms ledges, lithologies transitional to basal Trippe Limestone that forms dolomite slopes above.	74	22.6
29.	Dolomite, yellowish-gray, laminated, forms slope.	9	2.7
28.	Limestone, dark-gray, medium-grained, with mottled dolomitic limestone bioturbated zones, forms ledges.	33	10.1
27.	Dolomite, yellowish-gray, laminated, interbedded with medium-gray, granular limestone, forms slope.	7	2.1
26.	Limestone, medium-dark-gray, mottled with light-olive-gray bioturbated dolomitic zones, uneven and poorly marked bedding, few horizons with tubes and blebs filled with white calcite; forms cliffs.	348	106.1
25.	Dolomite, yellowish-gray, very fine-grained, laminated boundstone, interbedded with medium-gray, very-fine-grained limestone that comprises 60 percent of unit. Rip-up clast layers common. Forms slopes and ledges less steep than adjacent units.	103	31.4
24.	Limestone, dark-gray, mottled with olive-gray dolomitic zones, bioturbated, forms ledges.	15	4.6
23.	Limestone, medium-gray with tubular blebs and rods of white calcite comprising 10 percent of rock, massive ledge.	25	7.6
22.	Limestone, dark-gray, mottled with brownish-gray dolomitic zones, forms ledges.	35	10.7
21.	Covered, laminated dolomite in soil, forms slope.	25	7.6
20.	Limestone, dark-gray, mottled with brownish-gray dolomitic limestone, forms cliffs and ledges.	49	14.9
19.	Limestone, similar to unit 18 but with prominent 10-20 cm partings; forms bench.	8	2.4
18.	Limestone, dark-gray, mottled with brownish-gray dolomitic zones, probably bioturbation features; includes rods and blebs filled with white calcite in few blebs, forms cliffs. Bedding marked by faint parting and stylolitic cracks 20-200 cm apart.	130	39.6
17.	Limestone, dark-gray, medium-grained, mottled with irregular light-gray zones transverse to faint bedding, few stylolitic cracks; forms cliffs.	25	7.6
16.	Dolomite, yellowish-gray, laminated boundstone, with 30 percent interbeds of very-thin-bedded medium-gray limestone, forms prominent light slope at base of cliff-forming upper Pierson Cove.	43	13.1
15.	Limestone, dark-gray, banded with dark-brownish-gray dolomite comprising 40 percent of unit, thin-bedded, forms ledges.	35	10.7
14.	Limestone, medium-gray, thin-bedded, nonresistant.	13	4.0
13.	Limestone, dark-gray, with brownish-gray mottled zones of dolomite, medium-grained, forms ledges.	210	64.0
12.	Limestone, light-gray, fine-grained, massive.	13	4.0
11.	Limestone, medium-dark-gray, medium-grained, mottled with brownish-gray dolomitic areas, probably bioturbated, forms cliff with units 12 and 13.	40	12.2
10.	Limestone, medium-gray, medium-grained, very thin-bedded, forms slope zone.	38	11.6
9.	Limestone, dark-gray, medium-grained, mottled with brownish-gray dolomite fillings in burrow or bioturbation pathways. Forms cliffs prominent on air photos.	47	14.3

Unit No.	Description	Thickness Feet	Thickness Meters
8.	Dolomite, yellowish-gray, fine crystalline, thin-bedded to laminated, slope forming.	20	6.1
7.	Dolomite, yellowish-gray, with 20 percent interbeds of medium- to light-gray limestone, laminated or with low-relief "algal" heads in some horizons, forms slope.	40	12.2
6.	Dolomite, yellowish-gray, laminated, slope forming.	30	9.1
5.	Limestone, medium-gray, fine-grained, massive.	6	1.8
4.	Dolomite, medium-gray, mottled, bioturbated.	2	0.6
3.	Dolomite, yellowish-gray, laminated boundstone, slope.	10	3.0
2.	Dolomite, dark-gray, fine-grained, mottled.	3	0.9
1.	Limestone, medium-gray, thin- to to medium-bedded, forms slope above top of Eye of Needle massive cliffs.	5	1.5
	Total thickness of Pierson Cove Formation	1,441	439.2

Limestone of Cricket Mountains (Ꞓcm): This informal designation was used by Hintze (1984) for a carbonate sequence in the Cricket Mountains that is equivalent to the combined Pierson Cove Formation, Eye of Needle Limestone, and Swasey Limestone of other areas as shown in chart 1 (appendix C). Hintze (1984) found no reliable way of subdividing this thick and somewhat heterogeneous map unit that would accord with the usage of formation names in adjacent ranges. The limestone of Cricket Mountains consists mostly of unfossiliferous, dark-gray, fine-grained limestone and silty limestone, commonly mottled with irregular patterns of brownish-gray dolomitic limestone that represent bioturbation of the limy mud. Light-gray, thin-bedded to laminated, dolomitic boundstone occurs sparsely in the upper two-thirds of the formation in discontinuous beds up to 10 feet (3 m) thick. The limestone of Cricket Mountains was defined as all strata between the *Ehmaniella*-bearing Whirlwind Formation and the *Eldoradia*-bearing Trippe Limestone. It is about 1,970 feet (600 m) thick.

Lamb Dolomite and Trippe Limestone, or Weeks Limestone (Ꞓlw): The combined Trippe Limestone and Lamb Dolomite, and, roughly, the lateral equivalent, the Weeks Formation (chart 1 and column 7, appendix C), have the same map symbol on the 1:100,000-scale geologic maps of Millard County. They are discussed separately below.

Weeks Limestone: The name Weeks was applied by Walcott (1908a, d) to a sequence of fossil-bearing platy silty limestones in the central House Range. Robison (1964c) and Hintze and Robison (1975) reviewed the usage of the name and recommended that the name Weeks be applied only at its type section because typical Weeks lithologies are replaced in equivalent sequences elsewhere by mostly unfossiliferous shelf carbonate rocks (chart 1, appendix C). As such, the Weeks Limestone follows the Marjum Formation and the Wheeler Shale in having an areal distribution limited to the House Range embayment, a paleotrough of Middle and Late Cambrian time where the seaway was slightly deeper than on adjacent shallow shelves. Most of the Weeks Limestone is dark-gray, fine-grained, thin-bedded, silty limestone that weathers to orange- or yellowish-brown platy talus. Insoluble residue, mostly finely divided silica, makes up 20 percent of the rock (Hintze and Robison, 1975).

Beebe (1990) studied the trilobite faunas and depositional environments of the Weeks Limestone. It was deposited in a marine environment that became progressively shallower upward in the sequence. Basal beds of laminated lime mudstone and skeletal wackestone and packstone were deposited in deep open-shelf environments. Unfossiliferous lime mudstone in the upper Weeks was deposited in a shallow, subtidal, restricted-shelf environment. Transitional strata include peloidal-packstone to grainstone, ooid-grainstone, and silty lime-mudstone. The shallowing-upwards sequence of the Weeks Limestone records the final filling of the House Range embayment.

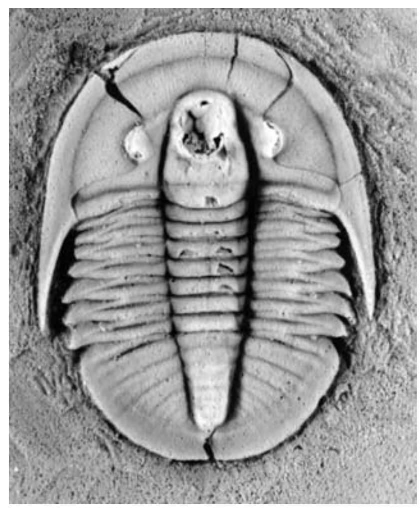


Figure 73. Cedaria minor *Walcott; upper Weeks Limestone, House Range; X5 (Beebe, 1990).*

The lower 164 feet (50 m) of the Weeks contains the abundant agnostoid trilobite *Lejopyge calva* that Robison (1964b) showed to be late Middle Cambrian in age. The upper part of the Weeks contains *Cedaria* (figure 73), *Tricrepicephalus*, and other trilobites usually regarded as typical of the lower Upper Cambrian. Beebe (1990) identified 18 species of trilobites from the Weeks Limestone. He suggested that even the upper part of the Weeks might be Middle Cambrian in age, but that, because of the uncertainty in the age range of some agnostoid trilobites, the position of the Middle-Upper Cambrian boundary in the Weeks Limestone has not been resolved (Peng and Robison, 2000, p. 41).

Deiss' (1938) measured section of the Weeks Limestone gave a total thickness of 1,940 feet (591 m), but he included about 700 feet (213 m) of the overlying Orr Formation in what he called Weeks. The upper and lower contacts of the Weeks are somewhat gradational and, near the Notch Peak granitic intrusion, obscured by thermal metamorphism. As mapped (Hintze, 1974d), the Weeks is about 1,200 feet (366 m) thick.

Trippe Limestone: This formation was defined in the Deep Creek Range, Utah by Nolan (1935) who noted that although mottled limestone makes up most of the formation, "the most striking parts of the formation are the finely laminated white or cream-colored beds." These white laminated beds are now called boundstone by geologists and are characteristic of the lower member of the Trippe. Hintze and Robison (1975) noted that extension of the name Trippe Limestone into areas beyond the Deep Creek Range was facilitated by recognition of the regional extent of an *Eldoradia* trilobite-bearing unit. This unit is the Fish Springs Member, which makes up the uppermost one-sixth of the Trippe. The combination of boundstone-bearing strata in the lower Trippe and ubiquitous *Eldoradia*-bearing intraformational conglomerate at the top has enabled widespread recognition of the Trippe Limestone as a mappable unit in western Utah.

<u>Lower member:</u> The interbedded dark-gray mottled lime mudstone and nearly white laminated dolomitic boundstone that characterize the lower member of the Trippe Limestone are widely distributed in western Utah. Kepper (1972, 1976) interpreted the boundstone as deposited by algae [cyanobacteria] in very shallow peritidal marine waters. The mottled mudstone was deposited in the somewhat deeper water sublittoral environment. Thus, water depth fluctuated slightly repeatedly during deposition of the Trippe. The lower member is barren of body fossils; it contains only the boundstone deposited by "algae" and the mottled structures made by burrowing organisms. A well-exposed reference section of the lower member of the Trippe Limestone, measured by L.F. Hintze in the western foothills of the Wah Wah Mountains in NE1/4 section 12, T. 26 S., R. 16 W. (Hintze, 1974e) is given below:

Unit No.	Description	Thickness Feet	Thickness Meters
16.	Limestone, dark-gray, mottled, with 20 percent interbeds of light-gray laminated dolomitic boundstone, forms slopes with some ledges.	100	30.5
15.	Dolomite, yellowish-gray, laminated boundstone, with 10 percent interbeds of thin-bedded limestone in upper third.	17	5.2
14.	Limestone, dark-gray, with few thin horizons of yellowish-gray laminated boundstone, forms massive cliff.	85	25.9
13.	Dolomite, yellowish-gray, laminated with interbeds of dark-gray and brownish-gray limestone, forms ledges.	90	27.4
12.	Limestone, dark-gray, mottled and striped with brownish-gray dolomite, forms cliff.	35	10.7
11.	Limestone, dark-gray, capped with 30 cm light, laminated dolomitic boundstone, cyclic.	11	3.4
10.	Limestone-dolomitic boundstone cycle, basal two-thirds is dark-gray bioturbated lime mudstone, capped with 1 m yellowish-gray laminated dolomitic boundstone.	9	2.8
9.	Limestone, dark-gray, uneven bedding, grading into laminated dolomitic boundstone in top 1 m, forms ledges.	7	2.1
8.	Dolomite, yellowish-gray, laminated boundstone, forms low ledges.	21	6.4
7.	Limestone, mottled dark-gray, medium-grained, ledge.	2	0.6
6.	Dolomite, medium-gray, laminated, ledge.	5	1.5
5.	Dolomite, dark-gray, with laminated zones.	5	1.5
4.	Dolomite, yellowish-gray, laminated limestone, interbedded with medium-gray, thin-bedded, dolomitic limestone, forms low ledges.	38	11.6
3.	Limestone, medium-gray, mas-, sive concentric "algal" structures of 60 cm diameter are poorly defined.	6	1.8
2.	Dolomite, yellowish-gray, laminated boundstone, forms slope.	25	7.6
1.	Limestone, dark-gray, striped with yellowish-gray dolomitic layers, thin-to medium-bedded, forms low ledges above cliffs of Pierson Cove Formation.	50	15.2
	Total thickness of Trippe Limestone, lower member	506	154

The lower member of the Trippe Limestone is 520 feet (158 m) thick in the northern House Range, 384 feet (108 m) thick in the Drum Mountains, and 660 to 760 feet (200-230 m) thick in the Cricket Mountains.

<u>Fish Springs Member:</u> The Fish Springs Member of the Trippe Limestone was named by Hintze and Robison (1975), who designated units 1 to 5 of Nolan's (1935) type section of the Trippe in the Deep Creek Range as the type section. A well-exposed, easily accessible and very fossiliferous section in the Fish Springs Range was recognized by Hintze and Robison (1975) as the best reference section.

The Fish Springs Member is readily apparent in this part of the Cambrian sequence in western Utah because it is shaly and forms recessive topography amid more resistant carbonate units. The lower two-thirds of the Fish Springs Member is olive-green shale interbedded with equal amounts of thin-bedded medium-gray limestone, of which one-third is flat-pebble intraformational conglomerate that commonly contains disarticulated parts of the trilobite *Eldoradia*. The upper one-third of the Fish Springs Member is dark-gray, thin-bedded, mottled limestone, which forms low ledges, and medium- to dark-gray, thin-bedded, silty limestone, which forms slopes at the base of the more resistant carbonate formation above. The Fish Springs Member contains rock types that resemble those in the Middle Cambrian Whirlwind Formation and, like the Whirlwind, its fauna consists almost entirely of only one trilobite species. As noted by Hintze (1974f), the trilobite *Eldoradia* is indeed a welcome signpost in the middle of a thick sequence of otherwise barren carbonate strata.

The Fish Springs Member is 320 feet (98 m) thick in the northern House Range, 70 feet (21 m) thick in the Drum Mountains, 100 feet (930 m) thick in the Cricket Mountains, and 115 to 135 feet (38-45 m) thick in the Wah Wah Mountains.

Lamb Dolomite: Nolan (1935) first described the Lamb Dolomite in the Deep Creek Range, Utah, and Staatz and Carr (1964) extended usage of the name eastward to the Dugway Range in Juab County. Dommer (1980), mapping in the Drum Mountains, and Hintze (1981c), mapping east of Wheeler Amphitheater in the House Range, divided the Lamb into two informal members, a lower dark-gray pisolitic to oncolitic dolomite, and an upper light-gray to nearly white dolomite. The Lamb Dolomite is equivalent to the Wah Wah Summit Formation in southern Millard County (chart 1, appendix C).

Lower member: Dommer (1980) described the lower member in the Drum Mountains as consisting of a basal cliff-forming oncolitic and pisolitic brown dolomite 82 feet (25 m) thick, overlain by 203 feet (61.9 m) of medium-gray, coarsely crystalline dolomite. Hintze (1981c) described the lower member in the eastern House Range as consisting of 262 feet (80 m) of medium-dark-gray, fine- to medium-crystalline, medium-bedded to massive, cliff-forming dolomite. A thin-bedded limestone at the base of the lower member is abundantly fossiliferous and contains the trilobites *Modocia* and *Bolaspidella* and the phosphatic brachiopods *Micromitra* and *Lingulella*. Fossils have not been reported elsewhere from the Lamb Dolomite.

Upper member: Dommer (1980) described the upper member in the Drum Mountains as consisting of 340 feet (103.6 m) of light-grayish-brown to nearly white coarsely crystalline dolomite. Hintze (1981c) described the upper member in the eastern House Range as consisting of 190 feet (58 m) of banded light- and dark-gray coarsely crystalline dolomite that forms a light-toned bench above the darker cliffs of the lower Lamb Dolomite. The upper member is unfossiliferous.

Wah Wah Summit and Trippe Formations, undivided (€wt): The Wah Wah Summit Formation and Trippe Limestone are shown as a combined map unit in southern Millard County and northern Beaver County on the 1:100,00-scale geologic maps of Millard County (Hintze and Davis, 2002a; Hintze and others, 2003). They are discussed separately herein. The formations in this map unit are structurally attenuated in the northern Mineral Mountains and their identification is therefore uncertain.

Wah Wah Summit Formation: In the southern House Range, Cricket Mountains, and the Wah Wah Mountains, the interval represented elsewhere by the Weeks Limestone and the Lamb Dolomite is called the Wah Wah Summit Formation (chart 1, appendix C), so named by Hintze and Robison (1975) because rocks typical of the Weeks and Lamb are not found in southern Millard County. Two subunits, informally designated ledgy (lower) and white marker (upper) members, are mapped there (Hintze, 1974a, e, 1984).

Ledgy member: The ledgy member forms ledges and cliffs that rise steeply above the slope formed by the Fish Springs Member of the Trippe Limestone. The lower two-fifths of the ledgy member consist mostly of light-gray, fine-grained, massive limestone interbedded with dark-gray mottled limestone and dolomite. The remainder of the ledgy member is mostly mottled dolomitic limestone, with pisolites common in the lower half. These rocks are unfossiliferous except for the pisolitic microbial structures.

The ledgy member is 550 feet (168 m) thick in the southern House Range (Hintze, 1974a), 410 feet (125 m) thick in the Cricket Mountains, and 825 feet (251.5 m) thick in its type section, described below, in NE1/4 section 23, T. 25 S., R. 16 W., in the Wah Wah Mountains.

Unit No.	Description	Thickness Feet	Meters
12.	Limestone, medium-dark-gray, medium-grained, some beds mottled with brownish-gray dolomite, increasing upwards to give a brownish overall cast to this ledge-forming unit, a few thin beds of light-gray, fine-grained dolomite near base.	130	39.6
11.	Limestone, medium-dark-gray, mottled with light-olive-gray dolomite, bioturbated, forms ledge.	65	19.8
10.	Limestone, medium-dark-gray, medium-grained contains 60 percent beds of pisolites, other beds are mottled; thick-bedded, forms ledges.	180	54.9
9.	Limestone, medium-dark-gray, medium-grained, with brownish-gray dolomitic partings, contains about 10 percent pisolitic layers, medium- to thick-bedded, forms ledges.	45	13.7
8.	Limestone, medium-dark-gray, medium-grained, with mottled dolomite in irregular channels or bioturbated pathways, several pisolitic layers near top, forms the most prominent dark cliff in the middle of the Wah Wah Summit Formation.	60	18.3
7.	Limestone, light-gray, fine-grained, contains some small white calcite blebs or tube fillings, forms massive ledges and rounded cliffs.	88	26.8
6.	Dolomite, yellowish-gray, sugary texture, ledge.	7	2.1
5.	Limestone, medium-dark-gray, medium- to coarse-grained, with	80	24.4

Unit No.	Description	Thickness Feet	Meters
	yellowish-gray partings, unevenly bedded, forms rounded cliffs and ledges.		
4.	Limestone, light-gray, fine-grain, ed, some dark layers, contains small, white calcite rods in a few horizons, massive, forms rounded cliffs.	115	35.1
3.	Limestone, dark-gray, mottled with olive-gray dolomite, upper half contains pisolites, forms ledge.	33	10.1
2.	Covered slope, probably thin-bedded, dark limestone.	12	3.7
1.	Limestone, dark-gray, mottled with irregular light-brownish-gray dolomite in both bedded and transverse zones, oolitic and pisolitic in upper half, forms basal ledge.	10	3.0
Total thickness of ledgy member		825	251.5

White marker member: This member forms the most conspicuous band of light strata in the entire Cambrian sequence in the Wah Wah Mountains, Cricket Mountains, and southern House Range (figure 19). It consists of light-gray, laminated, dolomitic limestone beds that make up about one-third of the member, interbedded with thin-bedded, mottled, limestone beds. It forms a slope between the underlying ledgy member and the overlying cliffs of the Big Horse Limestone Member of the Orr Formation. It is 164 to 230 feet (50-70 m) thick in the Cricket Mountains (Hintze, 1984), 170 feet (52 m) thick in the southern House Range (Hintze, 1974a), and 157 feet (47.8 m) thick in its type section in NE1/4 section 23, T. 25 S., R. 16 W., in the Wah Wah Mountains, as described below.

Unit No.	Description	Thickness Feet	Meters
19.	Limestone, light-gray, fine-grained, stromatolitic, contains 10 percent interbeds of yellowish-gray laminated dolomite.	30	9.2
18.	Limestone, as unit 19, but with 30 percent interbedded laminated dolomite.	35	10.7
17.	Limestone, light-gray, fine-grained, stromatolitic.	7	2.1
16.	Limestone, light-gray, interbedded with yellowish-gray laminated dolomite boundstone in 30 cm beds, forms slopes.	20	6.1
15.	Limestone, light-gray, "algal" heads at base, forms ledge.	5	1.5
14.	Limestone, light-gray, with interbedded laminated dolomite, forms slope.	10	3.1
13.	Limestone, light-gray, fine-grained, massive ledge.	3	.9
12.	Limestone, light-gray, with interbeds of yellowish-gray dolomitic boundstone, forms slope.	5	1.5
11.	Limestone, medium-light-gray, fine-grained, massive ledge.	4	1.2
10.	Limestone, light-gray, with interbeds of yellowish-gray laminated dolomite, forms slope.	5	1.5
9.	Dolomite, yellowish-gray, with interbeds of dark-gray limestone in 30 cm beds.	6	1.8
8.	Limestone, medium-gray, mottled, bioturbated, massive ledge.	8	2.5
7.	Dolomite, yellowish-gray, laminated boundstone.	2	0.6
6.	Limestone, dark-gray, mottled ledge.	2	0.6
5.	Limestone, dark-gray, mottled with brownish-gray interbedded with yellowish-gray, laminated dolomite.	4	1.2
4.	Limestone, dark-gray, mottled with brownish-gray, fine-grained, bioturbated, forms ledge.	3	0.9
3.	Dolomite, yellowish-gray, laminated boundstone.	1	0.3
2.	Limestone, medium-dark-gray, medium-grained, ledge.	3	0.9
1.	Dolomite, yellowish-gray, laminated boundstone, forms slope.	4	1.2
Total thickness of white marker member		157	47.8

Orr Formation: Walcott (1908a, d) named the Upper Cambrian Orr Formation in the central House Range. Hintze and Palmer (1976) subdivided it into five members which are, in ascending order, the Big Horse Limestone Member, Candland Shale Member, Johns Wash Limestone Member, Corset Spring Shale Member, and Sneakover Limestone Member (figure 74). These members also can be recognized in the Cricket Mountains in Millard County, and in the Fish Springs Range in Juab County. The Johns Wash Limestone Member is absent in the southern House Range and Wah Wah Mountains so that the Candland and Corset Spring Members merge into one mappable unit termed the Steamboat Pass Shale Member. In the Drum Mountains the Candland and Johns

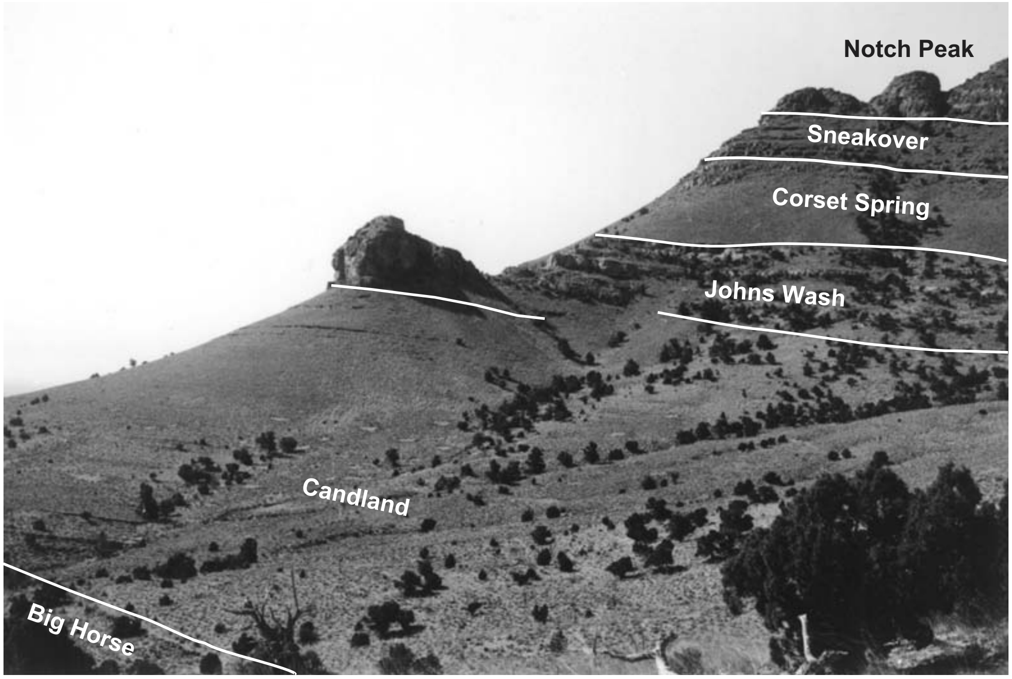


Figure 74. Upper members of the Orr Formation in the type section on Orr Ridge in the House Range (Hintze and Palmer, 1976), view roughly northeast. Top of the Big Horse Member barely shows in the lower left corner of the photo; broad slope in lower half of photo is fossiliferous Candland Shale Member; knob and ledgy outcrops above that are Johns Wash Limestone Member; Corset Spring Shale Member forms smooth slope above Johns Wash and below stair-step ledges of the Sneakover Limestone Member; ragged cliffs in the upper right corner are basal Notch Peak Formation.

Wash Members merge into one mappable unit named, informally, the light purple member (Dommer, 1980).

Trilobites representing eight of the standard North American assemblage zones have been identified within the Orr Formation (chart 1, appendix C). The Big Horse Limestone Member includes the upper *Cedaria* and *Crepicephalus* Zones; the Candland Shale Member contains the *Aphelaspis*, *Dicanthopyge*, *Prehousia* and low *Dunderbergia* Zones; the Johns Wash Limestone Member is barren but occupies the upper *Dunderbergia* Zone interval; the Corset Spring Shale Member contains the lower *Elvinia* Zone; and the Sneakover Limestone Member includes the upper *Elvinia* and *Taenicephalus* Zones.

Palmer (1965) proposed that five of the above zones (*Aphelaspis*, *Dicanthopyge*, *Prehousia*, *Dunderbergia*, and *Elvina*) collectively constitute a biostratigraphic unit called the "pterocephaliid biomere." To identify the boundaries of this biomere it is necessary to find trilobites representing the *Aphelaspis* and *Elvinia* Zones within the formations studied. Fortunately, trilobites of this age are common enough in strata in the eastern Great Basin to permit the biomere to be traced within a variety of rock types, thus enabling regional analyses of paleoenvironments such as those made by Koepnick (1976) and Lilley (1976). Although trilobites are common, and in places abundant, they have not been sought by amateur or commercial fossil collectors in the pterocephaliid biomere because their size and/or preservation limits their attractiveness as display specimens. Most are small, disarticulated, and not silicified.

Big Horse Limestone Member (€ob): This basal member of the Orr Formation forms massive cliffs that stand in marked contrast to the slope-and-ledge topography of the rest of the Orr. Lohmann (1976, 1977) recognized that four interfingering cycles of deposition of two kinds of limestone complexes make up the Big Horse Member: (1) a platform-margin high-energy-environment complex, composed of oolitic grainstone, "algal" boundstone, and skeletal and oncolitic packstone and grainstone; and (2) a deep-shelf low-energy-environment complex composed of burrowed wackestone, nodular mudstone, and laminated mudstone. The low-energy complex makes up more than half of the Big Horse in its type section in the House Range. Osleger (1991a-b), Osleger and Read (1991), and Drummond and Wilkinson (1993) discussed the cyclic stacking patterns of Big Horse carbonate units as possibly resulting from eustatic sea-level change caused by cyclic changes in Earth's orbital motions.

Hintze and Palmer (1976), in defining the Big Horse Limestone Member, noted that its base commonly is marked by the abrupt appearance of bioclastic or ooidal limestone above generally unfossiliferous strata below. The Big Horse Limestone Member is 715 feet (217.9 m) thick in its type section in the House Range, 660 feet (201 m) thick in the Cricket Mountains, and 660 to 700 feet (201-213 m) thick in the Wah Wah Mountains.

Upper members, undivided (€ou): The various upper members of the Orr Formation (figure 74) form a combined map unit on the 1:100,000-scale geologic maps of Millard County. They are discussed separately below. Saltzman and others (1998), using carbon-13 isotope data from the upper Orr Formation in the House Range and Wah Wah Mountains, identified significant variations in carbon-13 ratios that they interpreted to represent significant global changes in sea level, climate, or tectonics that triggered a series of extinctions of trilobite faunas in middle Late Cambrian time.

Candland Shale Member: Olive shale is interbedded with medium-gray, thin-bedded, fossiliferous calcisiltite and calcarenite throughout this member in its type section in the House Range. Dark disarticulated trilobite parts and black phosphatic brachiopods show prominently on weathered limestone platy talus from this unit, making it easy to identify. The Candland Shale Member was probably deposited in quiet water below wave base. Some of the interbedded limestones may have been derived from an adjacent shelf-margin environment. Palmer (1971) noted that the Candland Shale Member was deposited in an outer detrital belt that extended from western Utah to central Nevada.

The Candland Shale Member is 412 feet (125.6 m) thick in its type section in the House Range, and about 165 feet (50 m) thick in the Cricket Mountains. In the southern House Range and Wah Wah Mountains it merges with the Corset Spring Shale Member to form the Steamboat Pass Shale Member.

Johns Wash Limestone Member: Drewes and Palmer (1957) named the Johns Wash Limestone in the southern Snake Range, Nevada. Hintze and Palmer (1976) included it as a member of the Orr Formation in the House Range, Utah, where it is a ledge- and cliff-forming unit between the slope-forming Candland and Corset Spring Shale Members. As such it is easily traced on topographic maps (Hintze, 1974d) and on aerial photographs.

Rees and others (1976) found that the Johns Wash Limestone Member in the House Range is made up of five principal types of limestone: (1) bioclastic limestone consisting of thin-bedded fossiliferous or mottled wackestone; (2) oolitic limestone consisting of cross-bedded oolitic intraclastic grainstone; (3) stromatolitic limestone consisting of diverse types of "algal" stromatolites in an oolitic matrix; (4) pelletoidal limestone consisting of light-gray burrowed oolitic grainstone and pelletoidal packstone; and (5) fenestral limestone consisting of extensively bored and burrowed light-gray mudstone and packstone. These rocks are interpreted to represent deposition on a broad platform on which an oolite shoal separated a shallow-water lagoon from a more open-marine expanse to the west. Landward (east) of the lagoon, the fenestral limestones accumulated on an open tidal flat. Westward progradation of these environments resulted in the superposition of the various types of limestone which make up the regressive sequence displayed by the Johns Wash Limestone Member.

The Johns Wash Limestone Member is 140 to 330 feet (43-100 m) thick in the central House Range (Rees and others, 1976), and about 100 feet (30 m) thick in the Cricket Mountains. The Johns Wash Limestone in the Cricket Mountains falls within the *Elvinia* Zone and is thus younger than in the House Range, where it is within the *Dunderbergia* Zone.

Corset Spring Shale Member: The Corset Spring Shale was defined by Drewes and Palmer (1957) in the southern Snake Range, Nevada. Hintze and Palmer (1976) included it as a member of the Orr Formation in the House Range, Utah where it forms a slope or bench between more resistant limestone members. Shale beds in the Corset Spring Member are generally brighter green and contain fewer limestone interbeds than those of the Candland Shale Member. The Corset Spring Shale Member is generally not as fossiliferous as the Candland Member in western Millard County, but it yields *Housia* and other trilobites that place it in the *Elvinia* Zone.

McClure (1978) measured six sections of Corset Spring Shale Member in the central House Range. He found that the lower three-fourths of the member is composed of interbedded shale and limestone, which he ascribed to deposition under variable energy conditions in a shallow sea. Influx of terrigenous mud from an eastern source dominated over in-place accumulation of carbonate most of the time. The upper one-fourth of the Corset Spring Member is mostly pelletal wackestone that McClure (1978) suggested was deposited in a protected shallow lagoon in quiet water. The sparsity of fossils in this part of the member suggests a stressed environment, possibly of high salinity.

The Corset Spring Shale Member is 130 to 170 feet (40-52 m) thick in the central House Range (McClure, 1978), and about 40 feet (12 m) thick in the Cricket Mountains. In the southern House Range and Wah Wah Mountains it merges with the Candland Shale Member to form part of the Steamboat Pass Shale Member.

Steamboat Pass Shale Member: The Johns Wash Limestone Member is absent in the southern House Range and Wah Wah Mountains and the Candland and Corset Spring Shale Members merge to form the Steamboat Pass Shale Member, as mapped by Hintze (1974a, e) and defined by Hintze and Palmer (1976). The Steamboat Pass Shale Member in this area was studied by Lilley (1976), who collected fossils and described the lithologic details in four measured sections. The lower one-half to two-thirds of the Steamboat Pass Member is thin- to very thin-bedded, bioclastic, pelleted packstones and wackestones interpreted to have been deposited in an open-shelf environment. The upper part of the Steamboat Pass Member is a sequence of shale and limestone conglomerate that accumulated in a terrigenous-shelf environment that received clastic materials from the east.

The Steamboat Pass Shale Member is 175 to 190 feet (53-58 m) thick in the southern House Range and 265 feet (81 m) thick in the Wah Wah Mountains (figure 75).

Sneakover Limestone Member: The Sneakover Limestone Member, the uppermost member of the Orr Formation, was named by Hintze and Palmer (1976) in the central House

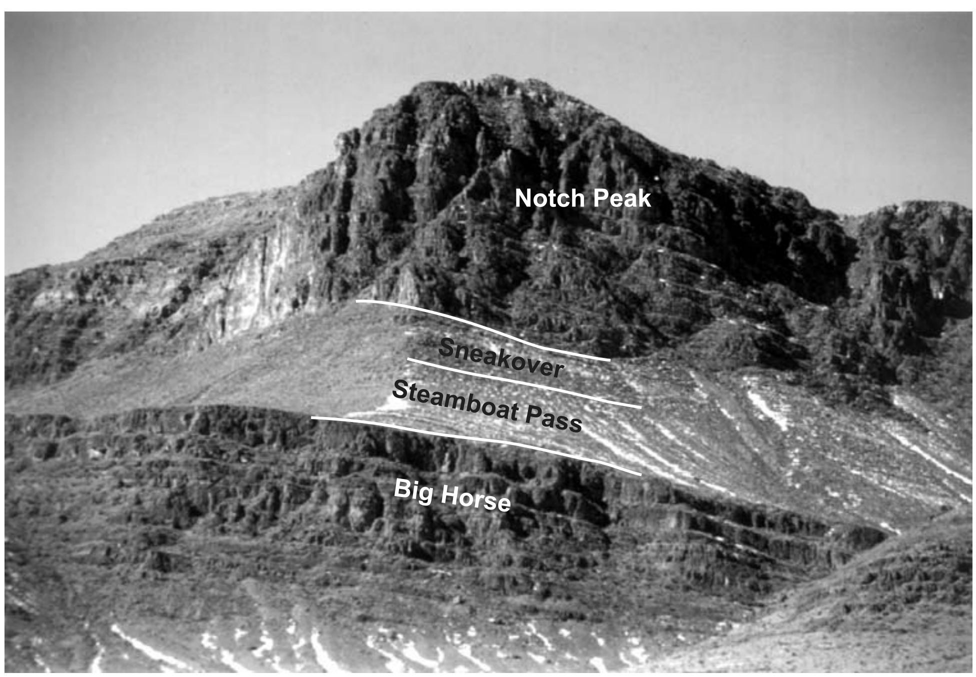


***Figure 75.** Upper Cambrian formations looking roughly west near Lawson Cove Reservoir in the Gray Hills at the northeast end of the Wah Wah Mountains (Hintze and Palmer, 1976). Big Horse Limestone Member of the Orr Formation forms the lower ledgy cliffs; smooth slope in middle of photo is Steamboat Pass Shale Member; stair-step ledges below massive cliffs are Sneakover Limestone Member of the Orr Formation; massive cliffs are Notch Peak Formation.*

Range. It is a consistently recognizable map unit in many ranges in western Utah where it occurs as ledge-forming outcrops beneath the cliffs of the Notch Peak Formation and above the slopes of the shaly members of the Orr Formation (figure 75). The Sneakover Member is mostly medium-gray calcisiltite and calcarenite with pinkish and purplish-gray silty partings. It forms ledges 2 to 4 feet (0.6-1.2 m) high and commonly contains well-preserved disarticulated trilobites and brachiopods of the *Elvinia* Zone. Echinoderm fragments and sponge spicules are also common.

McClure (1978) studied the Sneakover in six sections he measured in the central House Range. He classified the lowest 15 feet (5 m) of the member as an echinoderm grainstone and the remainder as a fossiliferous wackestone that represents deposition on a low-relief open shelf just below normal wave base. Brady and Rowell (1976) suggested that the subtidal carbonate blanket represented by the Sneakover Member extended over a very large area in western Utah and eastern Nevada during middle to late *Elvinia* Zone time.

The Sneakover Limestone Member is 185 feet (56.4 m) thick in its type section in the central House Range, about 100 feet (30 m) thick in the Cricket Mountains, and 150 to 170 feet (45-56 m) thick in the southern House Range and Wah Wah Mountains.

Notch Peak Formation (O-Єn): Walcott (1908a, d) named the Lower Ordovician-Upper Cambrian Notch Peak Formation in the central House Range (figure 76). Hintze and others (1988) subdivided it into three mappable members. In ascending order, these are the Hellnmaria, Red Tops, and Lava Dam Members. All members are limestone or dolomite; the Red Tops consists of thin-bedded, bioclastic, lime grainstone, whereas the other members are massive fine-grained cherty limestone or dolomite. Both the Hellnmaria and Lava Dam Members include beds of large stromatolites in their upper parts.

A few trilobites representing the *Taenicephalus* and *Idahoia* Zones have been obtained from the Hellnmaria Member. The Red Tops Member contains trilobites of the *Saukiella junia* Subzone of the *Saukia* Zone. The Lava Dam Member contains faunas of the *Saukiella serotina* Subzone of the *Saukia* Zone, the Lower Ordovician *Eureka apopsis* Zone and the *Missisquoia depressa* and *Missisquoia typicalis* Sub-

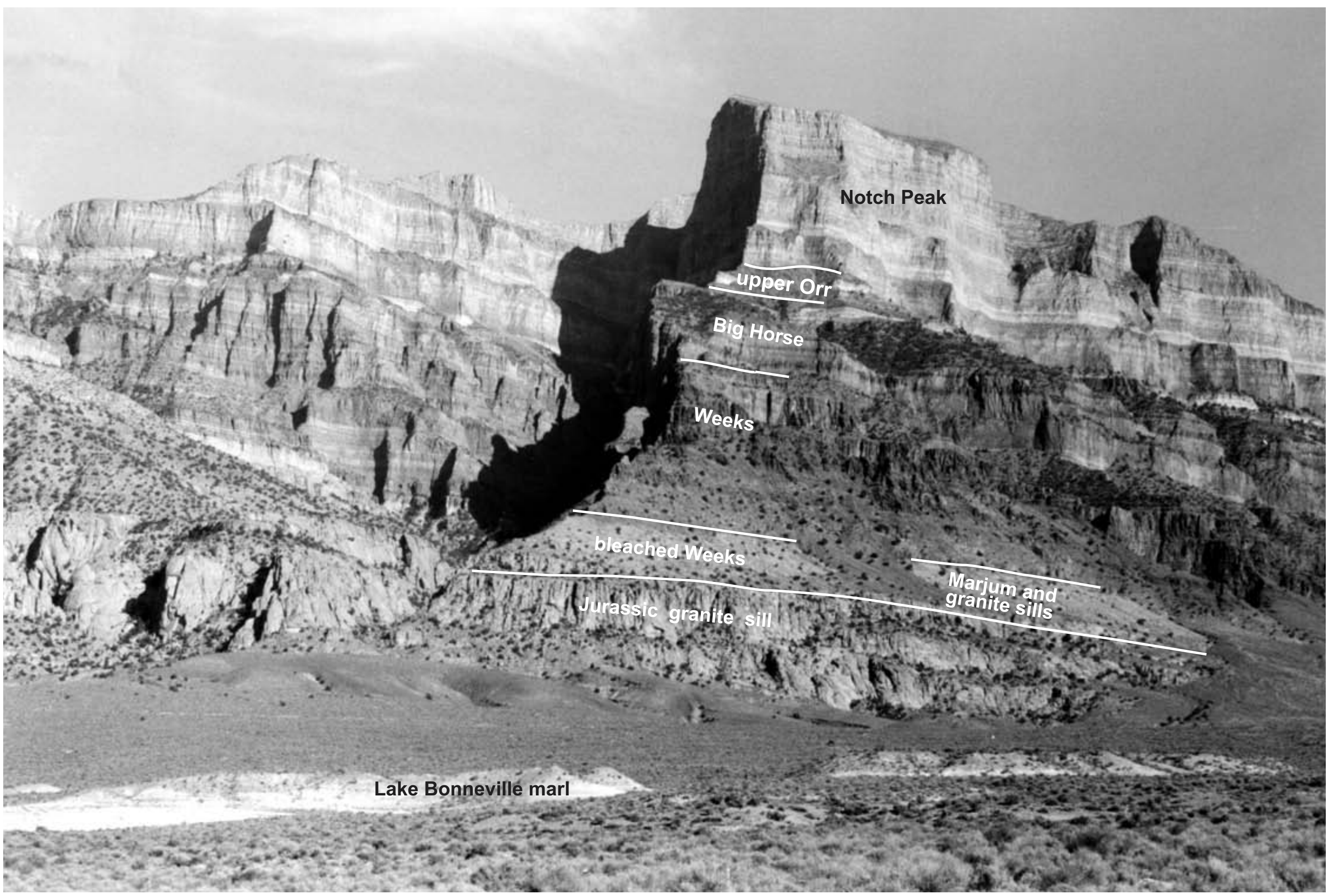


Figure 76. Notch Peak, sometimes called Sawtooth, is not quite the highest peak in Millard County, but it is surely the most distinctive. At 9,654 feet (2,943 m), its jagged profile, on the top of the House Range in the west-central part of the county, can be identified from most parts of the area. Its sheer north face (in shadow on the photo above) drops nearly vertically for 1,500 feet (457 m), probably the highest free-fall in Utah. The top of Notch Peak is composed of the youngest Cambrian strata. Its base includes tabular igneous intrusions (sills) of Jurassic granite; the main Notch Peak intrusion forms a light-colored, brushy slope on the left side of the photo. Heat and fluids from the granite, which was emplaced at depth 170 million years ago, bleached and altered some of the normally gray limestone beds to snowy white marble bands that can be seen part way down from the top. White beds in the foreground are marly clays that were deposited in Lake Bonneville when western Utah valleys were occupied by the Ice Age lake about 30,000 to 12,000 years ago. View is to the east-northeast.

zones of the *Missisquoia* Zone, and the *Symphysurina brevispicata* Subzone of the *Symphysurina* Zone. Two conodont zones and 7 subzones are recognized in the Red Tops and Lava Dam Members of the Notch Peak Formation. These, and their associated trilobite zones, are shown on chart 2 (appendix C).

The Notch Peak Formation forms massive cliffs wherever it is exposed in western Utah (figure 14) and eastern Nevada. Its correlative units, such as the Nopah Formation of southern Nevada, the Ajax Dolomite of central Utah, and the St. Charles Formation of northern Utah, have similar dolomite/limestone lithologies and form equally rugged topography.

Hellnmaria Member: The Hellnmaria Member is characteristically a chert-bearing limestone or dolomite that forms massive cliffs and ledges. In its type section in the House Range, the member is entirely limestone; in the Fish Springs Range, just north of Millard County, the same interval is almost entirely dolomite; in other areas it is partly limestone and partly dolomite. There is no reason to believe that Mesozoic or Cenozoic thermal metamorphism produced the dolomitization. It was probably produced by slight varia-tions in temperature, water depth, and salinity at the time of deposition or shortly thereafter.

The Hellnmaria Member was subdivided on The Barn geologic map (Hintze, 1974a) into three map units on the basis of locally traceable variations in lithology, color, and topographic expression. The lower map unit of The Barn subdivisions can be extended southward into the Wah Wah Summit quadrangle (Hintze, 1974e) as well. None of these subdivisions is recognized elsewhere.

Biostratigraphically significant fossils are rare in the Hellnmaria Member. Microbial stromatolites form reefs locally, and the mollusk *Matthevia* is locally common in the middle of the Hellnmaria, but neither of these has age-diagnostic value. The Hellnmaria has yielded some conodonts (Hintze and others, 1988) but these, too, are rare and undiagnostic. Trilobites are rare in the member. A trilobite fauna assigned to the *Taenicephalus* Zone was collected near the base of the Hellnmaria Member, and an assemblage assigned to the *Idahoia* Zone was collected from the member (Hintze and others, 1988).

The Hellnmaria Member is 1,203 feet (366.7 m) thick in its type section southeast of Notch Peak, 999 feet (304.5 m) thick in the southern House Range, and 1,340 feet (404.4 m) thick at Lawson Cove in the Wah Wah Mountains. Only the basal 100 feet (30 m) is preserved in the Cricket Mountains.

Red Tops Member: The Red Tops Member consists mostly of thin-bedded, bioclastic, lime grainstone that forms beds less resistant than the more massive members above and below. Its light brown weathered color also contrasts with the predominantly gray color of the adjacent members.

The Red Tops Member contains trilobites of the *Saukia* Zone and conodonts of the *Proconodontus muelleri* Zone, the *Eoconodontus notchpeakensis* Subzone, and the lower part of the *Cambrooistodus minutus* Subzone of the *Eoconodontus* Zone (chart 2, appendix C).

The Red Tops Member is found throughout the House Range; it is 140 feet (42.7 m) thick in its type section. It is 131 feet (39.3 m) thick in the southern House Range, but only 50 feet (15.2 m) thick in the northern Wah Wah Mountains (Hintze and others, 1988).

Lava Dam Member: The Lava Dam Member is entirely limestone, and some of its beds are composed of crowded microbial stromatolite heads 8 to 15 inches (20-40 cm) across and as much as 2 feet (60 cm) high. Other beds contain nodular chert. In most places the member forms resistant cliffs and ledges that contrast topographically with lower ledges and rounded slopes of the overlying Pogonip Group.

Bed-by-bed collecting of conodont and trilobite faunas from the Red Tops and Lava Dam Members has enabled recognition of the faunal zones shown on chart 2 (appendix C). A reference section for the Lava Dam Member in the southern House Range in sections 6 and 7, T. 23 S., R. 13 W., has been identified as the best place in the United States to trace these faunal zonations across the Cambrian-Ordovician boundary. The zonations found here are of great interest to paleontologists. Detailed lists of the fossils and their zonal significance were presented in Hintze and others (1988) and Ross and others (1997). Professor James F. Miller of Southwest Missouri State University and Dr. Michael E. Taylor of the U.S. Geological Survey have been instrumental in identifying and describing the conodonts and trilobites, respectively, in this key stratigraphic section.

The Lava Dam Member is 364 feet (110.9 m) thick in its type section in the House Range south of Notch Peak, 254 feet (77.4 m) thick in the Lava Dam reference section in the southern House Range, and 437 feet (133.2 m) thick in the northern Wah Wah Mountains.

Lithologic Units in Eastern Millard County

In general, the western Millard County Cambrian rock units, named in the House Range, represent a thick sequence of strata that was deposited farther west of the Cambrian shoreline than the thinner Tintic sequence exposed in eastern Millard County. Although most of the same lithologies are represented, they make up different mappable packages of rock, each of which is best described in its own depositional setting. Because all Paleozoic rocks in eastern Millard County have been carried several tens of miles eastward on late Cretaceous and early Tertiary thrust plates, they are fractured and locally brittly attentuated.

Tintic Quartzite (€t): The name Tintic was first used by Tower and others (1900) on geologic maps of the Tintic mining district. Loughlin (1919) restricted its usage to the basal Cambrian quartzite, but it remained for Morris and Lovering (1961) to describe the unit in detail. In the mining district it is an unfossiliferous, vitreous, light-colored quartzite that is about 2,500 feet (760 m) thick and includes a basalt flow, as much as 40 feet (12 m) thick, about 980 feet (300 m) above its base. The lower one-fourth of the Tintic Quartzite contains many interbeds of quartz pebble conglomerate; the upper Tintic grades into sandstones near its contact with the overlying Ophir Formation. The Tintic Quartzite is, in most respects, similar to the Prospect Mountain Quartzite as described earlier in this bulletin. I choose to apply the name Tintic to the parautochthonous Cambrian quartzite beneath the Canyon Range thrust in eastern Millard County, 30 miles (48 km) south of the Tintic mining district, because the Cambrian formations overlying the Tintic Quartzite are also better described using Tintic district nomenclature, and it seemed best to not mix terminologies from the different suites.

In the Canyon Mountains the Tintic Quartzite is a pinkish-orange-gray, dense, vitreous quartzite that weathers pale reddish brown. Quartz pebble conglomerate and small-scale cross-bed sets are common. It is about 3,000 feet (900 m) thick but is so structurally deformed beneath the Canyon Range thrust (Sussman, 1995) that an accurate thickness has not been obtained in the Canyon Mountains. In the southern Pahvant Range, George (1985) estimated it to be about 3,300 feet (1,000 m) thick. Because all Paleozoic rocks in eastern Millard County have been carried by thrusting from the west into their present location, they are fractured and faulted. There are no unbroken sections of Tintic Quartzite from which a complete thickness measurement can be obtained.

Ophir Formation (€op): The Ophir Formation was named by Loughlin (1919) for a 400-foot (120-m) thick sequence of shale and interbedded sandstone and limestone in the Tintic mining district. The name was introduced into the Canyon Mountains by Christiansen (1952) and it was mapped there by Holladay (1984). It was also mapped in the southern Pahvant Range by Hickox (1971), Davis (1983), and George (1985). Some of these authors used the western Utah name, Pioche, for the Ophir Formation, probably because both the Pioche and Ophir are the first units of mixed lithologies above a basal Cambrian quartzite. However, as shown on chart 1 (appendix C), the Ophir Formation is younger than the Pioche, and is in fact, equivalent in age to the Howell, Dome, Chisholm, and Whirlwind Formations of the House Range, as dated by the *Glossopleura* and *Ehmaniella* trilobites found in the Ophir. I therefore chose to use Ophir Formation for this unit in the southern Canyon Mountains and the Pahvant Range, where it is present within the Pavant thrust plate. Chart 1 shows that the names of the House Range sequence can be properly applied only to those Cambrian strata in the Canyon Mountains that are part of the Canyon Range thrust plate, as exposed near Leamington.

Because the Ophir Formation is less resistant than adjacent formations, it forms covered slopes and strike valleys wherever it occurs in the Canyon Mountains and Pahvant Range. The only place in the Canyon Mountains where the complete Ophir Formation is fairly well exposed is at the head of Limekiln Canyon on the Oak City North 7 1/2-minute quadrangle in an unsurveyed part of T. 16 S., R. 4 W. L.F. Hintze measured the section described below in October 1990. The beds are overturned at the base of the section, which begins at UTM coordinates 4360800 meters N-391860 meters E. The section was followed northeastward 0.25 miles (0.4 km) across the saddle at the head of Limekiln Canyon and ended on the west flank of hill 8763, where vertical outcrops of massive dolomitic limestone overlie the uppermost Ophir beds conformably.

Unit No.	Description	Thickness Feet	Thickness Meters
10.	Limestone, medium-gray, thin-bedded *Ehmaniella*-bearing calcisiltite and intraformational conglomerate beds interbedded with light-olive-gray shale; non-resistant, forms light-brown band on aerial photographs. Unit is equivalent to Whirlwind Formation of the House Range.	110	33.5
9.	Limestone, bluish-gray, medium- to thick-bedded, forms ledges and low cliffs. Equivalent to upper part of Dome Limestone of House Range.	60	18.3
8.	Limestone, medium-bluish-gray, thin-bedded, forms slope. Equivalent to lower part of Dome Limestone of House Range.	100	30.5
7.	Limestone, light-bluish gray, thin-bedded, contains *Glossopleura* trilobites and oncolites in a few beds, forms a slope.	70	21.7
6.	Shale, olive-gray, forms bottom of saddle at summit. Units 6 and 7 are partial equivalents to Chisholm Formation of the House Range.	80	24.4
5.	Limestone, medium-gray, thin-bedded, forms slope.	20	6.1
4.	Shale, olive-gray, not micaceous, forms chippy slope.	30	9.1
3.	Quartzite, white to brown, thick- to medium-bedded, forms ledges and low cliffs, *Skolithos* tubes common.	120	36.6
2.	Quartzite, greenish-gray to reddish-brown, with 20% interbeds of non-micaceous silty argillite, *Skolithos* tubes in some beds.	240	73.2
1.	Sandy siltstone, tan to olive, thin bedded, forms slope, some thin- to medium-bedded quartzite interbeds, not micaceous. Does not contain trace-fossil tracks or trails. Contact with underlying Tintic Quartzite is conformable. Tintic is light-pinkish-gray, medium- to thick-bedded, and forms ledges and cliffs.	250	76.2
	Total thickness of Ophir Formation	1,080	329.2

Partial sections of the Ophir Formation are exposed in faulted and folded slices in several places along the west side of the Pahvant Range, but the most complete section I know of was measured by George (1985) in the Fillmore 7 1/2-minute quadrangle. The base of the section is in SE1/4SW1/4 section 7, T. 22 S., R. 4 W., on the southwest flank of Halfway Hill. George included the upper part of the Ophir within his Cambrian limestone map unit. The Ophir conformably underlies his Cambrian dolomite map unit. A summary of George's field notes (S.E. George, written communication, 1985; then at Brigham Young University) follows:

Unit No.	Description	Thickness Feet	Thickness Meters
7.	Limestone, dark-bluish-gray, silty, slightly dolomitic, thin to thick uneven bedding, few oolitic and pisolitic beds, forms ledges.	74	22.5
6.	Interbedded limestone and shale; limestone is light-brownish-gray to dark-bluish-gray, thin-bedded, some beds silty, some layers of intraformational conglomerate; shale is olive-green, papery; forms slopes; probably equivalent to Whirlwind Formation of the House Range.	108	33
5.	Upper one-half of unit is similar to unit 7; lower one-half is similar to unit 6; forms ledges and slopes; probably equivalent to Dome Limestone of House Range.	182	55.5
4.	Limestone, medium-bluish-gray, weathers greenish-brown, some beds of *Glossopleura* trilobite hash; interbeds of olive-green shale and few thin beds of calcareous orange sandstone, forms slopes.	30	9
3.	Dolomitic limestone, weathers orangish-brown, thick-bedded, forms prominent ledge.	5	1.5
2.	Interbedded limestone, sandstone, and shale; limestone is dark-bluish gray, thin bedded, with oolitic, pisolitic, and oncolitic beds, some intraformational conglomerate beds, and some bioclastic beds that contain *Glossopleura* trilobite hash and *Chancelloria* star-shaped spicules; sandstone is brownish green, medium grained, glauconitic, and thin bedded; shale is olive green, papery. Unit forms ledgy slope.	79	24
1.	Interbedded phyllitic shale, siltstone, and quartzite; shale is olive green, slightly micaceous; siltstone is argillaceous, brownish green, thin bedded, some beds show burrows and trails; quartzite is fine to medium grained light to dark purple, orangish brown, or light to dark green, thin to medium bedded, glauconitic, cross-bedded in some layers, and contains *Skolithos* tubes and burrows and trails in some layers; lithology similar to lower member of Pioche Formation in the House Range: conformable on underlying Tintic Quartzite.	370	113
	Total Thickness of Ophir Formation	848	258.5

Hickox (1971) restricted his Ophir Formation map unit to the non-limestone part of the Ophir, essentially unit 1 of the above section. At Mountain Sheep Canyon in the Pahvant Range he found this unit to be 336 feet (102 m) thick. Hickox (1971) mapped the upper interbedded limestone and shale part of the Ophir Formation as his "lower limestone unit," which he found to be 522 to 621 feet (159-189 m) thick in the central Pahvant Range. A very accessible partial section of the Ophir Formation was described by Davis (1983) at Eightmile Point near an I-15 freeway off-ramp in section 5, T. 24 S., R. 6 W., on the Sixmile Point 7 1/2-minute quadrangle. There, Davis (1983) found 193 feet (59 m) of limestone-free lower Ophir, which he called Pioche Shale, overlain by 315 feet (96.1 m) of *Glossopleura*-bearing upper Ophir Formation, which he called Tatow Member, and followed upward by Cambrian rocks undivided.

Upper and Middle Cambrian carbonate rocks, undivided (Єum): Most geologists who have mapped the thick sequence of post-Ophir Middle and Upper Cambrian strata in the southern Canyon Mountains and Pahvant Range have applied the formation names that were established for this interval in the Tintic mining district by Loughlin (1919). These units' names are, in ascending order, Teutonic, Dagmar, Herkimer, Bluebird, Cole Canyon, Opex, and Ajax. The top of the Cambrian is well defined by the contrast in lithology between the Upper Cambrian Ajax Dolomite and the unique lithologies of the Lower Ordovician Pogonip Group. Beneath the Ajax Dolomite, the Upper Cambrian Opex Formation contains *Crepicephalus* trilobite-bearing bioclastic limestone beds that permit it to be readily identified. Separating Middle Cambrian strata between the Opex and the Ophir is problematic for geologic mappers because these strata are about 1,500 to 2,700 feet (450-820 m) thick and made up of several limestone and dolomite lithologies that are interlayered repeatedly throughout the section. Conspicuous beds such as the Dagmar Dolomite, a white laminated boundstone, serve very well as key mapping beds in the Tintic district. But similar laminated boundstones are common within the upper Middle Cambrian sequences in eastern Millard County, and there is no means of tracing the Dagmar for 40 miles (66 km) southward under cover of younger rocks from the Tintic district into eastern Millard County.

The *Ehmaniella* trilobite-bearing shaly limestone at the top of the Ophir Formation can be found everywhere the upper Ophir is exposed, so it identifies a consistent base to the sequence of post-Ophir strata. Only one geologist has reported finding time-diagnostic fossils from within the upper Middle Cambrian sequence: Lautenschlager (1952) found *Eldoradia* trilobites in a 14-foot (4-m) shale bed 30 feet (9 m) below the top of his Cole Canyon Dolomite in Shingle Mill Canyon east of Fillmore. This bed is not much help in subdividing the post-Ophir Middle Cambrian because it is so near the top of the sequence. Nonetheless, it is a widely occurring key trilobite horizon (Morris and Lovering, 1961; Hintze, 1974f) that geologists should look for in future work.

Geologists mapping in the southern Canyon Mountains have not subdivided post-Ophir Cambrian strata. Christiansen (1952) estimated a thickness of 4,750 feet (1,450 m) of undifferentiated Cambrian and Ordovician limestone and dolomite. Millard (1983) measured 2,800 feet (855 m) of Middle and Upper Cambrian carbonate rocks, mostly dolomite, in Oak Creek Canyon, but he made no formational identifications and found no fossils. Millard's reported thickness is too small. Post-Ophir Cambrian strata in Oak Creek Canyon are at least 3,200 feet (975 m) thick; I collected trilobites of the *Crepicephalus* Zone from yellowish-weathering bioclastic limestone beds about 2,400 feet (730 m) above the top of the Ophir near a small adit visible from the road low on the hillside north of Oak Creek, 0.4 miles (0.6 km) west of the confluence of North Walker Creek and Oak Creek.

Lautenschlager (1952) used all of the Tintic district Cambrian formational names except the Ajax Dolomite on his map of the central Pahvant Range, and he presented measured sections giving a thickness of about 2,400 feet (730 m) for the post-Ophir Cambrian strata. His geologic map is not on a topographic base, so it is not possible to accurately transfer his formation boundaries to modern 1:24,000-scale maps and thus ascertain, in detail, what he did. However, it seems certain that the Tintic district names he used in the Pahvant Range are not direct equivalents of their namesakes in the Tintic district, so we have not perpetuated his subdivisions on the Delta and Richfield 1:100,000-scale geologic maps (Hintze and Davis, 2002b; Hintze and others, 2003). The same is true of Tucker's (1954) mapping. However, the west half of Tucker's area was remapped by Hintze (1991i) and Michaels and Hintze (1994), and their Upper and Middle Cambrian nomenclature and subdivisions are here used in the northern Pahvant Range as discussed below.

Hickox (1971) used the Tintic district names Ajax Dolomite and Opex Formation in the central Pahvant Range, but he declined to use any other post-Ophir formal names and instead mapped a lower "dolomite unit" 410 to 730 feet (125-222 m) thick and an upper "limestone unit" 1,500 to 2,000 feet (450-600 m) thick.

Davis (1983) mapped 1,066 feet (325 m) of dolomite and boundstone that he called "Pierson Cove Formation" in the Dog Valley Peak 7 1/2-minute quadrangle southwest of Kanosh. His description of the "Pierson Cove" suggests that it might be the Cole Canyon Formation in Tintic district terminology. He did not report finding any fossils. These likely Middle Cambrian rocks are included in unit Ꞓum on the Richfield geologic map (Hintze and others, 2003).

In addition to the general lack of fossils, four other factors inhibit the study of post-Ophir Cambrian strata in the Pahvant Range: cover, indistinct topographic expression, structural deformation, and poor accessibility. Middle Cambrian strata are mostly present at high elevations in the Pahvant Range where colluvial cover is extensive and vegetative cover equally so. A continuously exposed stratigraphic sequence is rare. Internal structural deformation of Cambrian units is pervasive; all are fractured, and many are distorted by minor folds and faults too small to show on 1:24,000-scale geologic maps. Unlike the House Range, where Cambrian strata form an alternating cliff-and-slope topography by which individual formations can be easily recognized, the Cambrian carbonates in the Pahvant Range show no such conspicuous topographic differentiation. Also, color differences are masked by vegetative and colluvial cover. In addition, the better sections are accessible only by hiking some distance. No one has yet deemed the Upper and Middle Cambrian carbonate rocks of the Canyon Mountains and Pahvant Range to be interesting enough to attract study of the details of their stratigraphy, paleontology, or depositional environment. They are important, nevertheless, as the easternmost exposed Cambrian strata in central Utah to which subsurface Cambrian rocks in eastern Utah may be compared.

Herkimer, Dagmar, and Teutonic Formations, undivided (Ꞓht): These names come from the Tintic mining district, where the formations were described in detail by Morris and Lovering (1961). In the Pahvant Range the best exposed, least distorted, and most readily accessible section of these rocks is in the Scipio Pass 7 1/2-minute quadrangle (Michaels and Hintze, 1994). In the Tintic district the Dagmar is a conspicuous white dolomite bed 60 to 100 feet (20-30 m) thick that separates the Herkimer and Teutonic Formations, which are gray look-alike limestones. In the Scipio Pass quadrangle the Dagmar interval locally consists of two to four white dolomite beds, 10 to 20 feet (3-6 m) thick, separated by thicker gray limestone beds. Because the Dagmar Dolomite does not constitute a mappable unit in the Scipio Pass quadrangle, Michaels and Hintze (1994) grouped the three formations together as an undivided entity, retaining the combined Tintic district nomenclature to indicate approximate correlation with the strata named there.

The upper and lower parts of this undivided unit are dark- to medium-gray limestone, mottled with blebs and stringers of light-olive-gray silty dolomite. Mottling in the gray limestones probably was formed by bioturbation of lime muds by burrowing organisms living in the shallow waters of the Cambrian sea. The lower part of the undivided unit also includes oolitic and oncolitic structures. In the lower beds *Glossopleura*-zone trilobites are associated with oncolites.

The white Dagmar-type dolomite beds in the middle of this undivided unit are laminated microbial mats (figure 77). Heads 12 inches (0.3 m) high are present near the top of the undivided Herkimer-Dagmar-Teutonic unit (figure 78). The alternating thin to very thick beds in the lower part of the

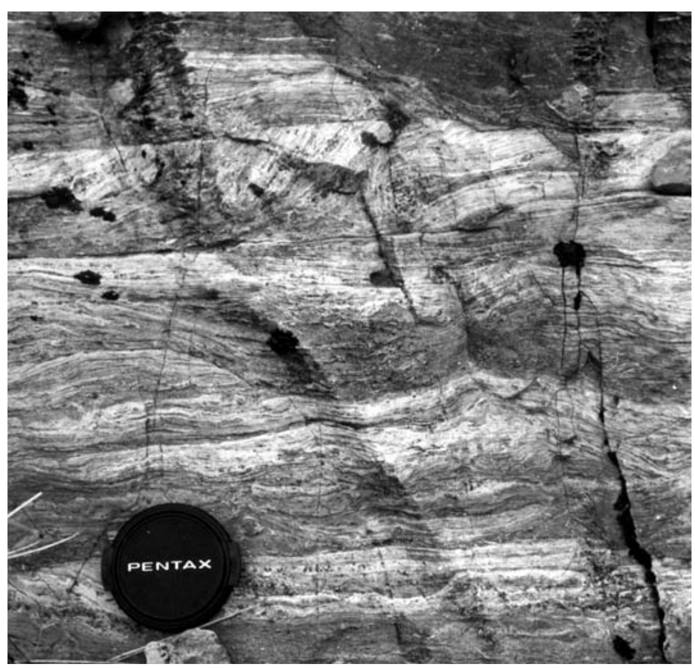


***Figure 77.** Laminated dolomite from the middle part of the Herkimer, Dagmar, and Teutonic map unit. The laminae were produced by cyanobacteria that lived in shallow marine waters. The wave patterns were produced shortly after deposition when the carbonate mud was soft and easily reworked. Lens cover for scale is 2 inches (5 cm) in diameter.*

Figure 78. "Algal" stromatolite heads from the uppermost part of the Herkimer, Dagmar, and Teutonic map unit. Lens cover for scale is 2 inches (5 cm) in diameter. The "algae" were likely cyanobacteria.

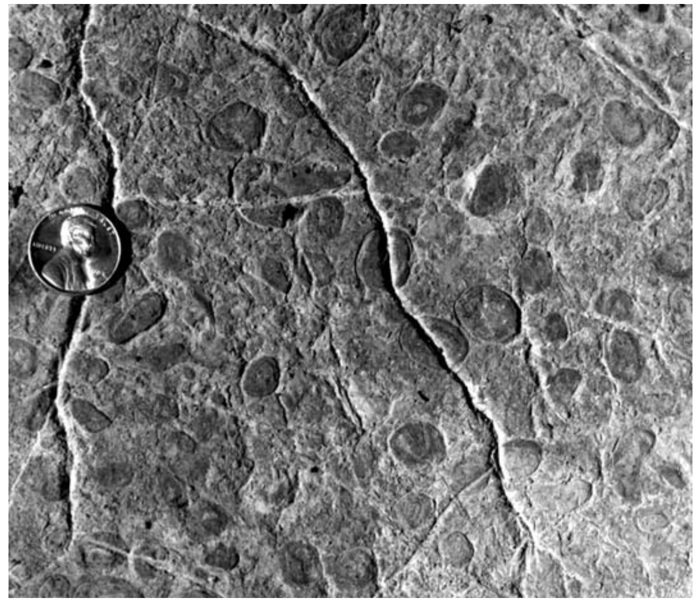


Figure 79. "Algal" oncolites in the Opex Formation. Similar oncolites are common in the bottom of the Herkimer, Dagmar, and Teutonic map unit. The "algae" were likely cyanobacteria.

Herkimer-Dagmar-Teutonic unit form ledgy terraced slopes that are commonly covered with talus or colluvium. The upper part (Herkimer equivalent) is very thick bedded and forms a steep slope with massive ledges.

Michaels and Hintze (1994) included a detailed measured section of the undivided Herkimer-Dagmar-Teutonic map unit. It is 994 feet (303 m) thick but the base of the unit is not exposed.

Cole Canyon and Bluebird Dolomites, undivided (Єcb): These formation names come from the Tintic mining district (Morris and Lovering, 1961), where the Bluebird Dolomite is characterized by small white dolomite rods interspersed in a dark-gray dolomite matrix. These were called "twig-shaped bodies" by Morris and Lovering (1961). In the Pahvant Range this sequence is best exposed in the Scipio Pass 7 1/2-minute quadrangle (Michaels and Hintze, 1994) where the undivided dolomitic Cole Canyon and Bluebird (Єcb) map unit is easily identified because it contains no limestone, which is the principal rock type of the underlying and overlying map units. The undivided Єcb map unit is made up of three interbedded rock types. The Bluebird-type dolomite is most common near the base of the map unit but is also interbedded with other dolomites throughout. The second common rock type is medium-light-gray to very light-brownish-gray, thick-bedded, fine-grained dolomite that weathers to massive ledges and low cliffs. The third rock type is medium-gray to light-brownish-gray, medium-grained, thick-bedded dolomite that weathers to ledges that have a mottled gray appearance. The undivided Cole Canyon and Bluebird map unit is 536 feet (163.5 m) thick. Lautenschlager (1952) reported finding the trilobite *Eldoradia* in a thin shale bed near the top of the Cole Canyon Dolomite.

Opex Formation (Єox): This formation is made up of very thin- to very thick-bedded shaly and bioclastic limestone, with thin interbeds of dolomite, shale, and sandstone. The limestone is generally medium gray, with pink or yellow silty partings. Some limestone is oolitic and oncolitic (figure 79), and the formation includes a few beds of intraformational conglomerate. Some of the bioclastic limestone beds in the lower third of the Opex Formation yielded trilobite fragments identified by R.A. Robison at the University of Kansas (written communication, 1985) as *Blountia* sp., *Tricrepicephalus* sp., and *Kingstonia* sp., indicative of either a late Middle or an early Late Cambrian age. Other trilobite fragments, from just beneath the Ajax Dolomite, were identified by Robison as *Saratogia*? sp., and may represent the *Idahoia* trilobite Zone of middle Late Cambrian age. The Opex Formation is 671 feet (204.5 m) thick in the Scipio Pass quadrangle (Michaels and Hintze, 1994). Hickox (1971) measured the Opex Formation just west of Big Spring in upper Corn Creek in the Joseph Peak 7 1/2-minute quadrangle, where it is 389 feet (119 m) thick.

Ajax Dolomite (Єa): The Ajax Dolomite consists mostly of dolomite beds that range from light to dark gray. The basal 130 feet (40 m) is medium-gray to light-brownish-gray dolomite that weathers light olive gray, and contains microbial stromatolites 6 to 8 inches (15-20 cm) high. The upper Ajax Dolomite is mostly thick bedded and forms steep slopes, ledges, and cliffs. Chert is not common in most exposures, but it is locally abundant. The Ajax, which in the Scipio Pass 7 1/2-minute quadrangle is entirely dolomite, is easily distinguished from the less resistant, predominantly limestone units above and below it. Here, the Ajax Dolomite is 966 feet (295 m) thick (Michaels and Hintze, 1994). Hickox (1971) measured the Ajax Dolomite 0.4 miles (0.6 km) east of Big Spring in upper Corn Creek in the Joseph Peak 7 1/2-minute quadrangle where it is 696 feet (212 m) thick and includes 116 feet (30 m) of limestone about 150 feet (45 m) below its top.

Ordovician

Introduction

Ordovician strata are exposed in several ranges in Millard County, as shown in figure 80. Exposures in the south-

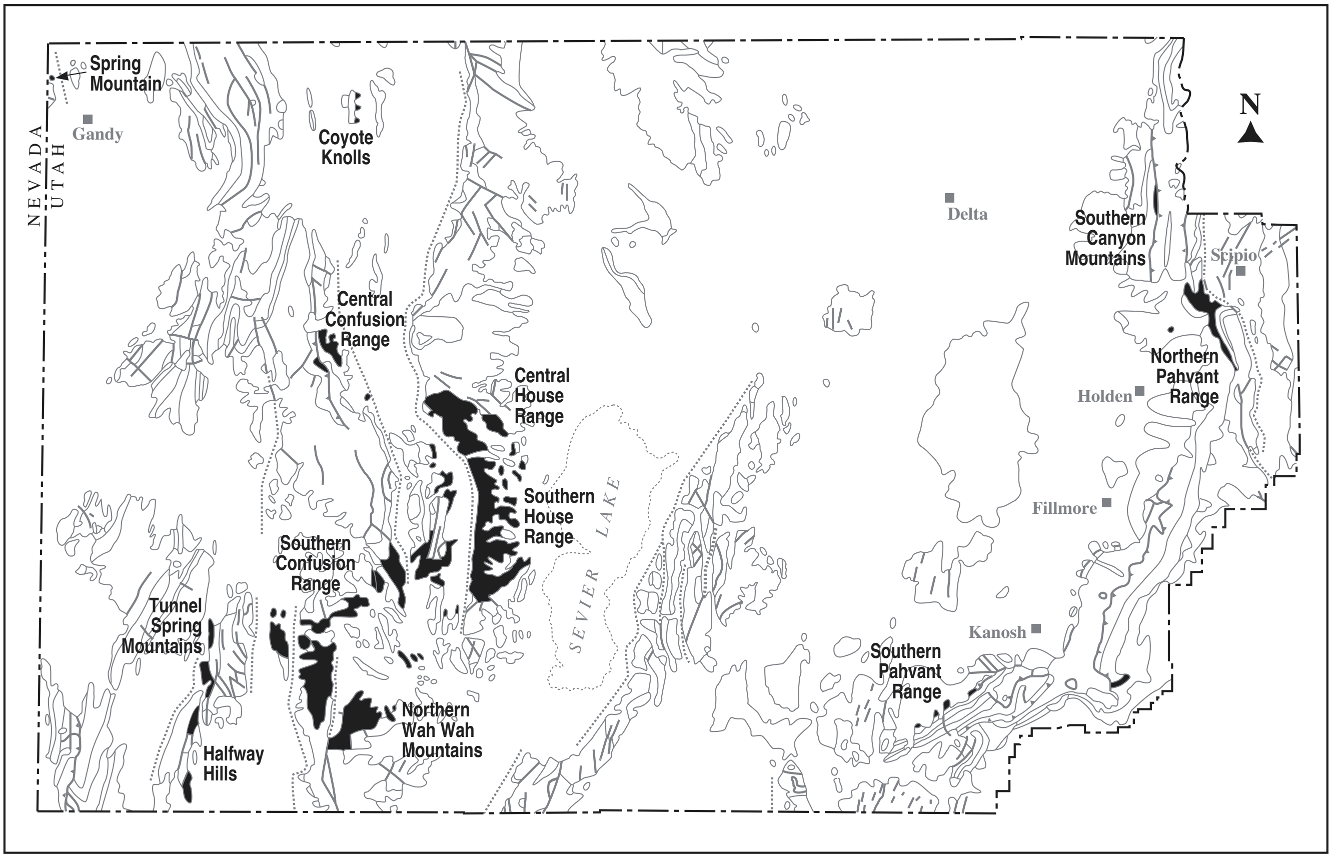


Figure 80. Ordovician outcrops in Millard County.

ern part of the Confusion and House Ranges are world famous because they contain an exceptionally continuous record of life in Early Ordovician time (Hintze and others, 1972). The names applied to Ordovician formations in the county are shown in chart 3 (appendix C), and descriptions of these rock units follow the section "Ordovician Fossil Life in Western Utah."

Collecting Ordovician trilobites in Millard County has never attained the popularity of collecting Cambrian trilobites in the Wheeler Amphitheater of the House Range because whole specimens of Ordovician trilobites are scarce. Ordovician rocks contain many disarticulated and wave-worn parts of fossils (figure 81), and these are treasures of information for the paleontological specialist. However, as a source for display fossils, Ordovician rocks are generally disappointing. Nonetheless, among paleontologists, the 3,500 feet (1,070 m) of Ordovician limestones and shales in the southern Confusion Range, Barn Hills, and southern House Range (figure 80), near Jack Watson's abandoned homestead at Ibex (figure 82), are renowned because they contain the most diverse assemblage of Lower Ordovician fossils in North America, and perhaps in the world (Hintze, 1987).

Exactly who first noticed the fossil beds near Ibex is not known. The area in which they are found has been used as winter range for sheep and cattle since the late 1800s, and herders could hardly fail to have seen the fossils. These fossil beds were likely known to Jack Watson, an English immigrant who homesteaded at Ibex, and established a post office there in 1898 (Kelsey and Kelsey, 1992; Kelsey, 1997). He called the place Ibex, using a European name for the desert

Figure 81. Weathered rock surface from the lowest part of the Kanosh Shale near Ibex showing disarticulated pliomerid trilobites and other wave-worn fossils; magnification about X1.4.

Figure 82. Jack Watson's Ibex ranch as photographed by University of Utah Professor Ferdinand F. Hintze on May 10, 1931; view roughly to south. Fossil Mountain is the peak at the right edge of the picture.

antelope. Watson homesteaded at Ibex because the Ordovician quartzite there contains a series of small natural potholes (which he enlarged with small dams) that retain water throughout most of the summer in wet years. The Ibex potholes were the only water source within 25 miles (40 km) in any direction, so by locating on them Watson could use the surrounding desert to support his small herd of cattle. In addition, he had discovered a small steep-walled valley nearby that forms a natural cattle enclosure that he called "the barn." Watson was forced to leave Ibex by the great drought of 1934. He lost his arm in 1936 because of an injury sustained at the U.S. Government's Ibex Well on the playa lake 5 miles (8 km) northeast of Ibex, and his homestead shacks lay abandoned until about 1950, when they burned (figure 83). The names "Ibex" and "The Barn" have been retained on all current U.S. Geological Survey maps of the area, and Watson's water catchments can still be seen but are no longer used.

The abundant Ordovician fossils near Watson's homestead were first publicized by Frank Beckwith. Frank Ashel Beckwith arrived in the newly founded town of Delta, Utah about 1910 as cashier of its first bank. Beckwith's chief enthusiasm was not in banking, but in roaming the deserts of Utah with his friend, Charles Kelly (figure 84), and collecting fossils and Indian artifacts (Beckwith, 1947). It was Beckwith who named the hills west of Ibex "Fossil Mountain" (Kelly, 1944) and, in the 1920s, led University of Utah geology professor Frederick J. Pack and his students to Fossil Mountain to collect Ordovician fossils (written communication from Beckwith to L.F. Hintze, March 29, 1948). Beckwith took Charles E. Resser (figure 46), Curator of Paleontology, U.S. National Museum (part of the Smithsonian Institution in Washington, D.C.), to Fossil Mountain in 1930, and he also sent several boxes of Ordovician fossils, including disarticulated trilobites, brachiopods, ostracodes, and cephalopods, from Fossil Mountain to the National Museum. Among the fossils from Beckwith's shipment, only the brachiopods were described by paleontologists at the museum. Ulrich and Cooper (1936, 1938) listed *Anomalorthis lonensis*, *Anomalorthis utahensis*, and *Orthis michaelis* as having come from "Smooth Canyon, a mile west of Ibex post office, Confusion Range, Utah," but they failed to mention the donor's name.

I was the next person to describe fossils from Ibex. My father, Ferdinand F. Hintze, was Professor of Geology at the University of Utah, and in 1931 he took his paleontology students to Ibex to collect Ordovician fossils while Jack Watson was still living there (figure 85). In 1947, while I was a graduate student at Columbia University and was casting around for a thesis project, my father took me to Ibex. We spent two days measuring the Ordovician rocks near Fossil Mountain and making collections of fossils at successive points in our

Figure 84. *Frank Beckwith Sr. (left) and Charles Kelly, about 1940 (Jane Beckwith collection).*

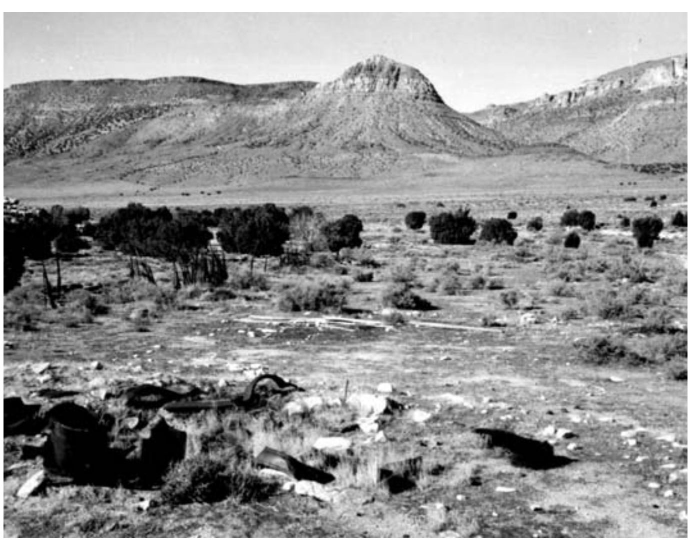


Figure 83. *Fossil Mountain looking southwest from Watson's Ibex ranch in October 1987. Body parts from Watson's old automobiles are scattered in the foreground.*

Figure 85. University of Utah paleontology class with Jack Watson (center) at Ibex, May 10, 1931. Photo taken by Professor Ferdinand F. Hintze whose 1928 Buick carries a milk can for drinking water from Antelope Spring. Students are Harold Wright, Norma Fairbanks, Helen Potter, and Jerry Aderton.

measured section. These collections formed the basis for my master's thesis at Columbia University, under the direction of Professor Marshall Kay (Hintze, 1948), wherein I made preliminary identifications of nine trilobite genera, three brachiopods, two ostracodes, and some gastropods, nautiloids, cystoids, and a receptaculitid. I returned to Ibex in 1948 and 1949, measured and described the Ordovician strata in greater detail and collected more fossils for my doctoral dissertation at Columbia (Hintze, 1951, 1952).

Concurrently with my work in Millard County, Reuben J. Ross, Jr., a doctoral student at Yale University, was doing similar work on Lower Ordovician rocks in northeastern Utah. Upon sharing notes, we found that we had many previously undescribed fossils in common, and because Ross' interests were paleontologic and mine were stratigraphic, we agreed that he should publish his trilobite descriptions first (Ross, 1951), and I would follow with descriptions of those trilobites that he had not already described (Hintze, 1952). Together we established a sequence of trilobite zones (chart 3, appendix C) in Lower Ordovician strata in Utah that has become a standard for comparison of rocks of this age with those of similar age in many parts of the world. Ibex has been established as the best area to designate as a reference section, and I proposed that the name "Ibexian" be used as the time-stratigraphic series designation for all strata of this age in North America (Hintze, 1982). This proposal received strong support from a number of paleontologists (figure 86) (Ross and others, 1997; Sweet and Tolbert, 1997), and the name "Ibexian" has begun to replace the old term "Canadian" as the series name for North American lower Ordovician rocks, as shown on chart 3. Publications of the many paleontologists who have described fossils from Ordovician strata near Ibex are listed below under the several headings of fossil groups.

Ordovician Fossil Life in Western Utah

Diversity is the word that expresses the difference between Ordovician fossil assemblages found near Ibex compared with those that are common in Cambrian beds in the House Range. Many groups of Ordovician marine animals are represented: trilobites, conodonts, brachiopods, graptolites, cephalopods, gastropods, echinoderms, sponges, ostracodes, bryozoa, pelecypods, corals, microbial organisms (cyanobacteria), and trace fossils. A few groups are present in abundance throughout the rock column, and these, particularly trilobites, graptolites, conodonts, and brachiopods, are the most useful as guides to time and the successive Ordovician stages represented near Ibex. Chart 3 (appendix C) shows the names of the conodont, graptolite, and trilobite zones. Other groups are helpful in supporting age assignments and in interpreting the environments that attracted the marvelous diversity of organisms now represented in the shallow-water marine deposits of early (Ibexian) and middle (Whiterockian) Ordovician age near Ibex. Jaanusson (1979) provided a comprehensive summary of world-wide Ordovician fossil faunas.

Trilobites: Trilobites can be found throughout the Pogonip Group near Ibex, and they form the main basis for the initial fossil zonation of these beds (Hintze, 1952). The most remarkable aspect of their occurrence near Ibex is that trilo-

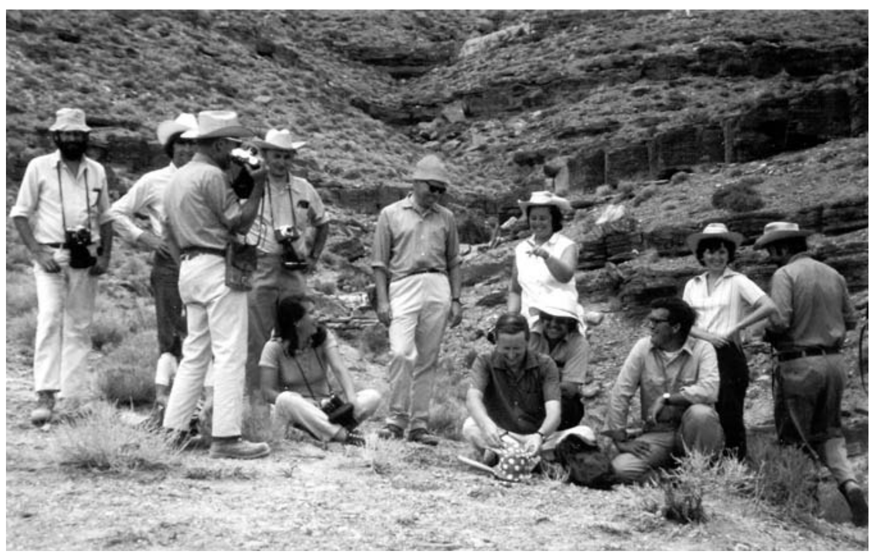


Figure 86. TIGBOE- Third International Great Basin Ordovician Excursion, July 26, 1972, at the base of the Wah Wah Limestone J-section, near Ibex. This group of Ordovician paleontologists came from all over the world to examine the Ordovician strata in western Utah and Nevada. The trip was organized by Dr. Reuben J. Ross, Jr., (left foreground, facing group) to familiarize the international paleontological community with the marvelous lower Ordovician stratigraphy in the Great Basin. The 1972 group, only half of whom are in this picture, included paleontologists from museums and universities in England, Wales, Scotland, Norway, Sweden, Russia, France, United States, and Australia. Dr. Ross was Chairman of the International Subcommission on Ordovician Stratigraphy and during the past three decades he has conducted many similar groups of paleontologists and biostratigraphers to Ibex to examine and collect Ordovician rocks and fossils. That Ordovician stratigraphy in the Great Basin has become so well known internationally is due, in large measure, to publications and field excursions of the "Mr. Ordovician" of his era, Dr. Reuben J. Ross, Jr. He has brought literally hundreds to a knowledge of Ibex.

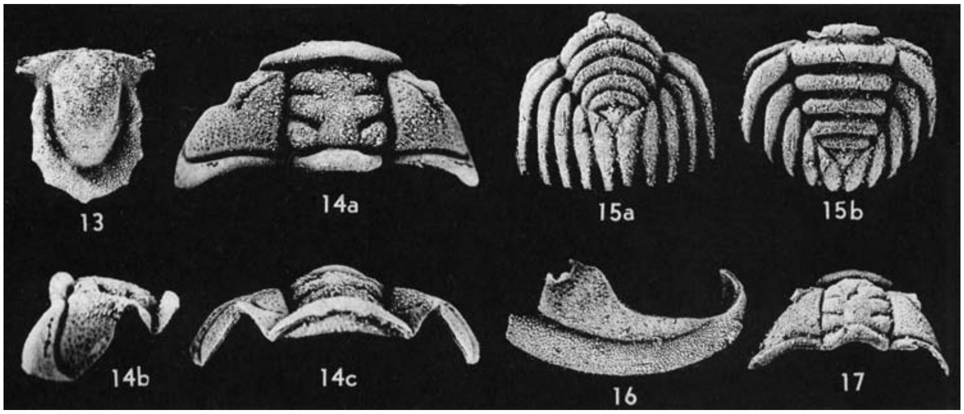


Figure 87. *Disarticulated silicified parts of the trilobite* Hintzeia aemula*; Fillmore Formation, zone G-1, Ibex (from Hintze, 1952): 13, hypostome, X5; 14, cranidium, top, side, and front views, X4; 15, pygidium, rear and top views, X5; 16, free cheek, X5; 17, cranidium, X3.*

Under the column labeled "Shelly Fossil Zones," chart 3 (appendix C) gives the names of the fossils that are used to designate each zone. All of the fossils listed are trilobites except those typical of zone O (*Eofletcheria-Oepikina*), zone L (*Paralenorthis-Orthodiella*), and zone K (*Hesperonomiella*). Zone K is a very thin zone made up of a coquina of shells of the small brachiopod *Hesperonomiella minor*, but some zones are several hundred feet thick and are characterized by a number of fossils, not merely the one that gives the zone its name. Zones G-1 (*Hintzeia celsaora*) and F (*Rossaspis superciliosa*) bear my name and that of Reuben Ross, the paleontologist who

Figure 88. Hintzeia *cf.* aemula*; Fillmore Formation, zone H, Ibex; X3. Whole specimens are rare near Ibex.*

bites are selectively silicified throughout most of the Lower Ordovician stratigraphic section, which is 2,300 feet (700 m) thick. Other fossils near Ibex are rarely silicified, even though they occur in the same beds as the trilobites. Many of the trilobites near Ibex are small and have complicated spiny shapes, and they would be very difficult to extract from the enclosing rock if they were not silicified. The silicification permits one to dissolve the limy matrix away with hydrochloric or acetic acid and to recover a residue rich in trilobite debris (figures 87-89). Selective silicification of trilobites in Lower Ordovician rocks occurs in a narrow belt that extends from near Logan, Utah, across Millard County southwestward to Pioche, Nevada (Hintze, 1953). That the silicification occurred during Ordovician time, as a chemical reaction controlled by temperature, salinity, and the susceptibility to replacement of the organic portion of the trilobite's chitinous shell, is suggested by the observation that the Logan-Ibex-Pioche trend follows the alignment of the Ordovician shoreline-shelf trend of that time (Hintze, 1953).

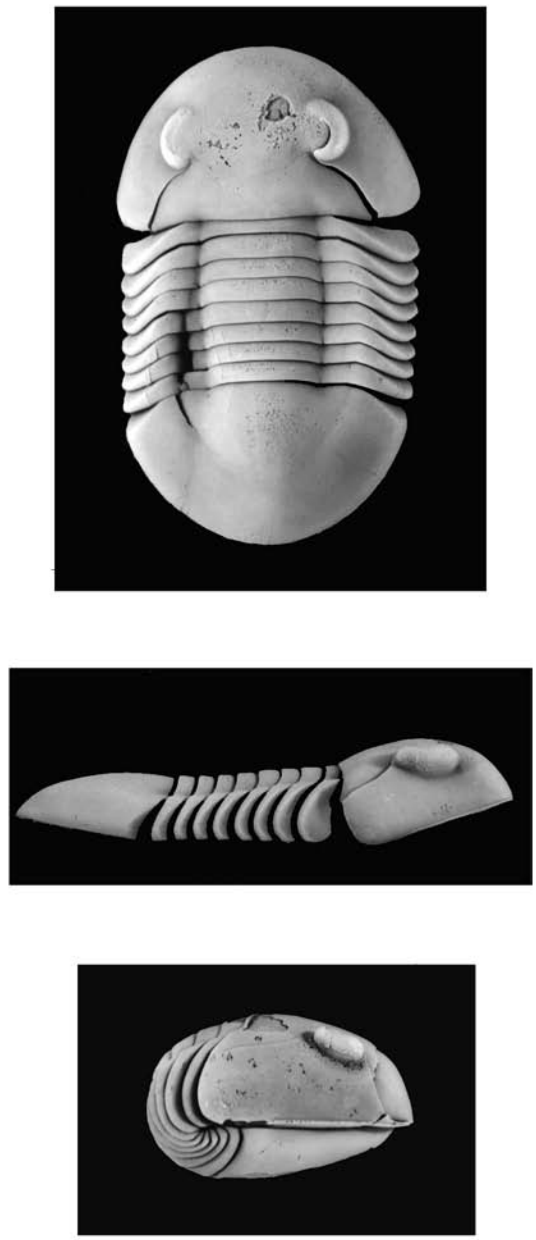


Figure 89. Presbynileus ibexensis*; Fillmore Formation, zone I, Ibex; X3. Bottom, enrolled specimen; X3.*

originally defined the zones. Lest the reader think that we named these zones after ourselves, it should be noted that my original designation for zone G-1 was *Protopliomerops celsaora*, and that for zone F was *Protopliomerops superciliosa*. Harrington (1957) coined the names *Hintzeia* and *Rossaspis* in his reclassification of pliomerid trilobites, and he reassigned the species to these genera.

Ross (1951) and Hintze (1952) initially identified more than 100 trilobite species and about half that many genera. Seventy percent of the Utah trilobites are still known only from western North America. The remaining 30 percent have been recognized elsewhere. In addition to the Ross-Hintze lettered zones B to O, chart 3 (appendix C) shows the *Missisquoia* and *Eurekia apopsis* zones at the base of the Ordovician. These zones were discussed by Taylor (in Hintze and others, 1988), and were further elucidated in Ross and others (1997). Important additional descriptions of Ordovician trilobites from the Ibex area were made by Demeter (1973), Terrell (1973), Young (1973), Fortey and Droser (1996), and Adrain and others (2001). Demeter (1973) described pliomerid trilobites from zones D through H. Terrell (1973) added new information about trilobites from zones D and E, and Young (1973) described an unusually diverse trilobite assemblage obtained from a 5-inch (13-mm) bed in zone H in the upper part of the Fillmore Formation. Fortey and Droser (1996) described 20 species of trilobites from zone L in the Juab Limestone. McCormick (1999) suggested that the trilobite genus *Carolinites* Kobayashi 1940, found near Ibex, is a useful fossil for testing microevolutionary patterns, having statistically valid change patterns in a lineage with excellent stratigraphic control.

Range charts showing the stratigraphic distribution of trilobites in the Ibexian portion of the Pogonip Group were published in Ross and others (1997). Although similar range charts have not been published for the Whiterockian zones L through O, the stratigraphic listing of fossil collections by Hintze (1951, 1952) shows the ranges of trilobites in these zones. Range charts for Whiterockian trilobites and other fossils in Nevada were given by Ross and Ethington (1992).

In summary, the remarkable occurrence of silicified trilobites throughout most of the Pogonip Group near Ibex has enabled recognition of successive trilobite zones that are useful as a comparative standard for determining the relative ages of Lower Ordovician trilobites elsewhere in the world.

Conodonts: For closely spaced vertical occurrence within the Pogonip Group near Ibex, conodonts are the only fossil group other than trilobites that forms a near-continuum (figure 90). Miller (1969, 1978) described conodonts from Upper Cambrian and basal Ordovician strata of the House Range (figure 91). Ethington and Clark (1971) presented the results of their reconnaissance collecting, showing that conodonts occur almost continuously through 2,700 feet (800 m) of Ordovician strata near Ibex. Ethington (1978, 1979) followed with more information and an overview, and Ething-

FORMATIONS		TRILOBITE ZONES	
Eureka Quartzite			
Crystal Peak Dolomite		O	*?Phragmodus flexuousus*
Watson Ranch Quartzite			
Lehman Formation		N	*Paraprioniodus costatus* *Chosonodina rigbyi* *Histiodella holodentata*
Kanosh Shale		N	*Histiodella sinuosa*
Kanosh Shale		M	*Histiodella altifrons* *Multioistodus auritus*
Juab Limestone		L	*Tripodus laevis*
Wah Wah Limestone		J	*Reutterodus andinus*
Fillmore Formation	Calathium member	I	*Reutterodus andinus*
Fillmore Formation	Calcarenite member	H	*Reutterodus andinus* / *Oepikodus communis*
Fillmore Formation	Brown slope and ledge member	G-2	*Oepikodus communis* / *Acodus deltatus - Oneotodus costatus*
Fillmore Formation	Light-gray ledge mbr	G-2	*Acodus deltatus - Oneotodus costatus*
Fillmore Formation	Shaly siltstone slope member	G-1	*Acodus deltatus - Oneotodus costatus*
Fillmore Formation	Ledge-forming limestone member	F	*Macerodus dianae*
Fillmore Formation	Ledge-forming limestone member	E	"Low diversity interval"
Fillmore Formation	Ledge-forming limestone member	D	"Low diversity interval"
House Limestone		C	*Rossodus manitouensis*
House Limestone		B	*Cordylodus angulatus* *Iapetognathus* *Cordylodus lindstromi* *Cordylodus intermedius*
Notch Peak Formation		Mi	*Cordylodus proavus*
Notch Peak Formation		Ea	*Eoconodontus*
Notch Peak Formation		Ss	*Eoconodontus*
Notch Peak Formation		Sj	

Figure 90. *Conodont zones near Ibex compared with trilobite zones. Zone boundaries coincide at only a few horizons, but the degree of zonation is similar. For ranges of individual species see Ross and others (1997) and Ethington and Clark (1981).*

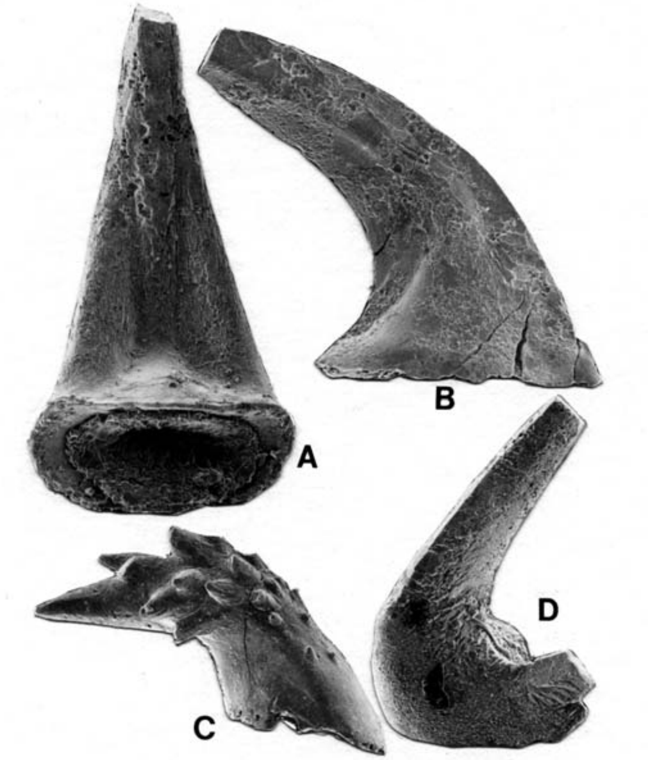


Figure 91. *Conodonts from the House Limestone, greatly magnified. Fossils collected by J. F. Miller; photomicrographs by M. M. Craig, Southwest Missouri State University Electron Microscopy Laboratory: A,* Aloxoconus iowensis *(Furnish), X122; B,* Paltodus *new species, X122; C,* Hirsutodontus simpex *(Druce and Jones), X94; D,* Iapetognathus *new species, X188.*

ton and Clark (1981) gave a detailed taxonomic and biostratigraphic study of conodonts (figures 92 and 93) that had been keyed into the trilobite-bearing measured sections of Hintze (1951, 1973a). Range charts for conodonts in the Ibexian Series are found in Ross and others (1997), from which the Ibexian conodont zone names were derived. Whiterockian conodont zones shown in chart 3 (appendix C) are from Ethington and Clark (1981). Supplementary information on Whiterockian conodont distribution in Nevada may be found in Ross and Ethington (1992).

Comparison of conodont zones and shelly fossil zones on chart 3 (appendix C) shows that each subdivides the Ibexian and Whiterockian series into 15 to 17 time intervals of unequal length. The chart also shows that conodont and shelly fossil zone boundaries seldom fall at the same time line in the stratigraphic succession. Thus, taken together, the trilobite and shelly fossil zones may permit a more refined subdivision and correlation within Ordovician time than either zonal system used separately.

Persons unfamiliar with the wonderfully useful conodont fossil should be aware that these microscopic tooth-like structures are too small to be identified without magnification. They are freed from their carbonate rock matrix using acetic or formic acid, and paleontologists who specialize in their identification can determine the ages of the Paleozoic rocks that contain them with precision similar to that shown on chart 3 (appendix C). In addition, the preserved color of the conodont gives an indication of how high a temperature that fossil was subjected to during its history of burial. Con-

Figure 92. *Lower Ordovician conodonts from the lower middle part of the Fillmore Formation near Ibex. Note the relatively simple form of conodonts of this age. Photographs from Ethington and Clark (1981); magnifications range from X27 to X55; listed clockwise starting at upper left: 1,* Drepanodus arcuatus, *drepanodontiform element; 2,* Drepanoistodus basiovalis, *drepanodontiform element; 3,* Acodus deltatus, *prioniodiform element; 4,* Scolopodus rex, *large element; 5,* Drepanoistodus basiovalis, *suberect element; 6,* Drepanoistodus basiovalis, *oistodontiform element; 7, ?*Paltodus jemtlandicus, *oistodontiform element; 8,* Oneotodus costatus*; 9,* Drepanodus arcuatus, *oistodontiform element.*

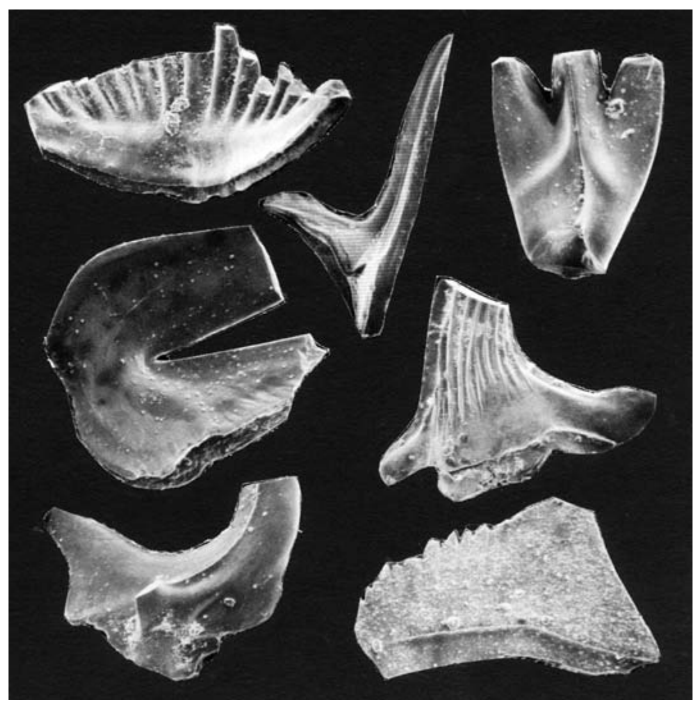


Figure 93. *Middle Ordovician conodonts from the Kanosh Shale and Lehman Formation near Ibex; magnifications range from X22 to X45; listed clockwise starting at upper left: 1,* Chosonodina rigbyi*; thin flexed blade; 2,* Pterocontiodus cryptodens, *acodiform element; 3,* Dischidognathus primus*; 4,* Pteracontiodus cryptodens*; 5,* Histiodella sinuosa, *elongate blade; 6,* Multioistodus auritus, *distacodiform element; 7,* Oistodus multicorrugatus, *noncostate cordylodiform element.*

odont Color Alteration Index (CAI) (Epstein and others, 1977) values of about 3.0 are typical of conodonts from the Ibex area. They have been altered to a dark brown or brownish black color by burial temperatures of several hundred degrees Celsius.

For an extended discussion of each of the Ibexian conodont zones and a listing of their conodonts, refer to Ross and others (1997).

Brachiopods: Next to trilobites and conodonts, articulate (hinged) brachiopods are the most widely distributed fossils in the Pogonip section near Ibex. Except for *Shoshonorthis* (originally *Orthambonites*) *perplexus* in the Crystal Peak Dolomite, none of the brachiopods is silicified.

Jensen (1967) recognized 25 species of brachiopods in Ordovician strata near Ibex, as shown in figure 94. Brachiopods are most abundant and useful in the Whiterockian part of the section near Ibex, where they can be correlated with brachiopod occurrences known in southern Nevada (Ross and Ethington, 1992). The sequence of appearance of brachiopods near Ibex is slightly different from that in the type Whiterockian of central Nevada. For example, *Orthidiella* occurs as the lowest Whiterockian fauna in Nevada, but it is found in Utah above the appearance of *Anomalorthis*, and in Nevada *Anomalorthis* appears above *Desmorthis*; near Ibex the reverse is true.

Salmon (1942) named a new genus and species of brachiopod, *Kirkina millardensis*, for a fossil collected in 1896 by A.O. Kennedy from an unknown locality Kennedy designated as "Point of Rocks, Millard County, Utah." Hintze (1952, p. 23) assigned the collection to zone N on the basis of an associated trilobite, but the whereabouts of "Point of Rocks" is still unknown.

Jaanusson and Bassett (1993) gave new generic names to three Ibexian brachiopods. *Orthambonites subalata* became *Paralenorthis subalata*, and *Orthambonites michaelis* (figure 95) and *Orthambonites perplexus* were assigned to the new genus *Shoshonorthis*.

Inarticulate (hingeless) brachiopods, although common in the Pogonip Group near Ibex, have not been pursued systematically by anyone. Inarticulate brachiopods are commonly not good guides to the age of the rocks in which they occur because they evolved slowly through geologic time. They are more valuable for paleoenvironmental interpretation than for indicators of the ages of the rocks that contain them.

Graptolites: Graptolites are colonial marine organisms characterized by an organic exoskeleton that has many small leaf-like or sawtooth shapes. They commonly occur in black shales where they form an important group of Ordovician guide fossils. Near Ibex they occur as resinous impressions on olive shales that are interbedded with other lithologies in the Pogonip Group (figures 96-98). Braithewaite (1976) searched Pogonip rocks near Ibex for graptolites and delineated seven zones, as shown on figure 99. He identified 45 species from 13 genera and, because of the exceptional translucent preservation of graptolites near Ibex, he was able to make valuable contributions to knowledge of graptolite ontogenetic development.

Graptolites that occur in black shale sequences are traditionally interpreted to have been floating marine organisms of worldwide distribution whose remains were deposited on the deep seafloor. The environment through most of the Pogonip Group near Ibex is mostly conspicuously nearshore shallow-shelf, an environment in which graptolites are not

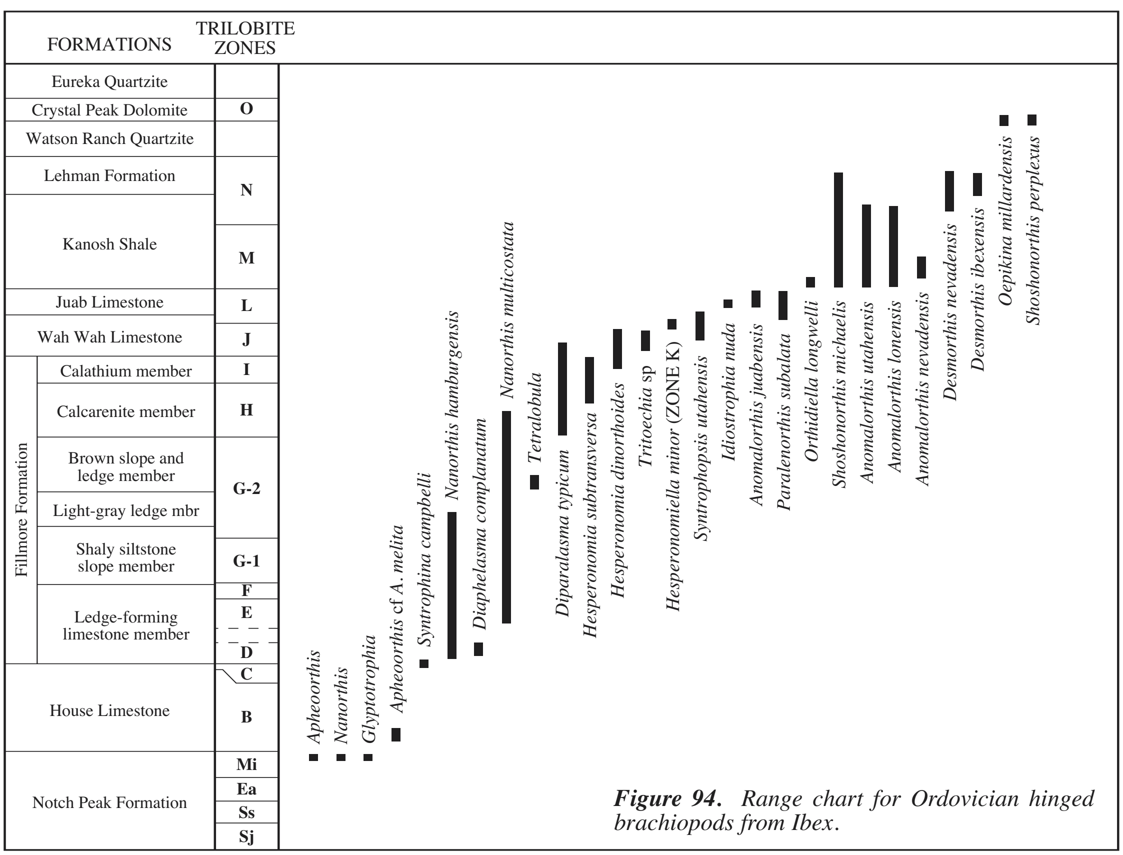


Figure 94. *Range chart for Ordovician hinged brachiopods from Ibex.*

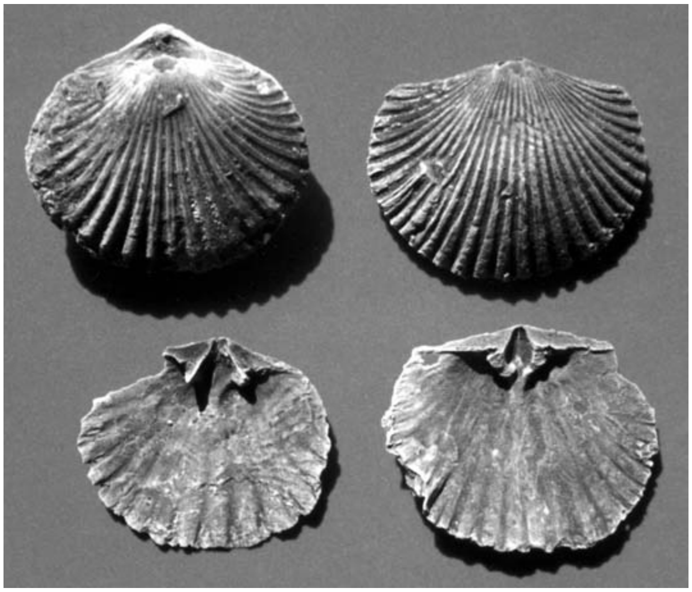


Figure 95. Shoshonorthis michaelis*; Kanosh Shale; X1.9.*

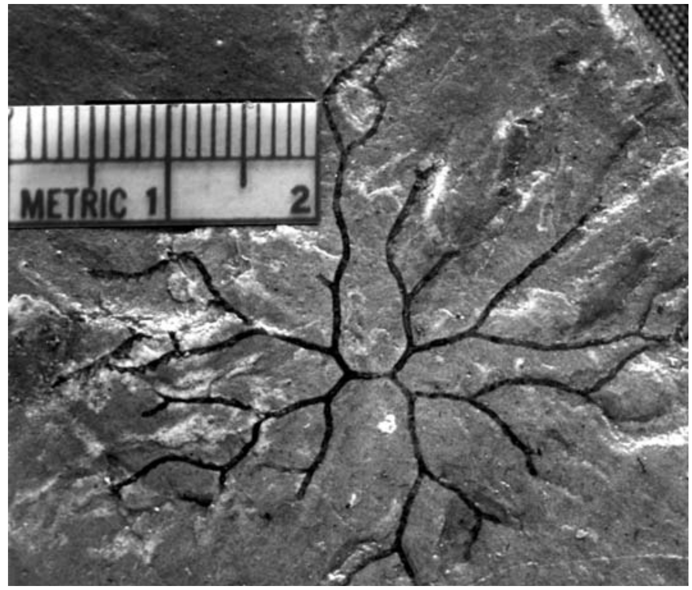


Figure 96. Clonograptus flexilis*; Fillmore Formation (Braithwaite, 1976, plate 3).*

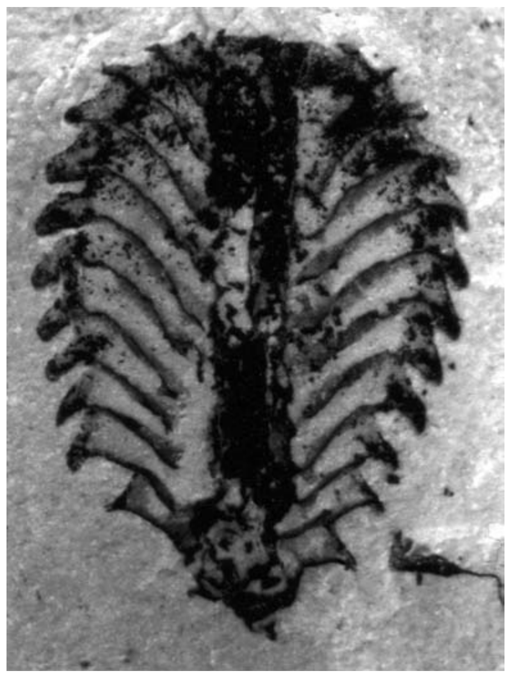


Figure 97. Phyllograptus anna*; upper Wah Wah Limestone (Braithwaite, 1976, plate 7); X10.*

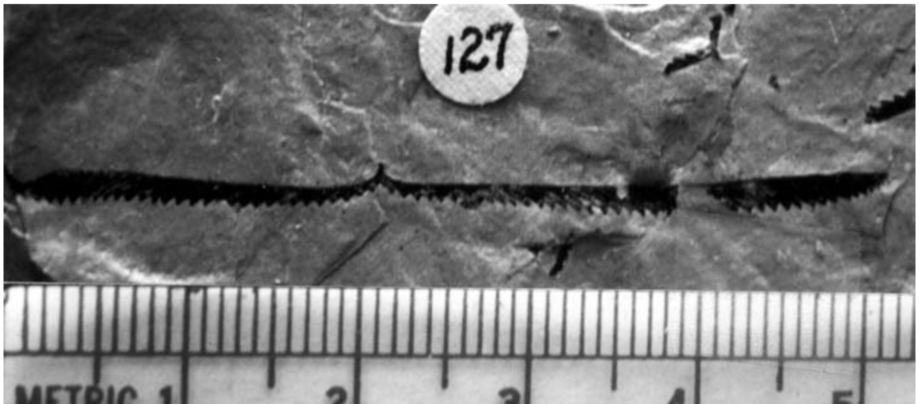


Figure 98. Didymograptus nitidus*; Juab Limestone (Braithwaite, 1976, plate 7).*

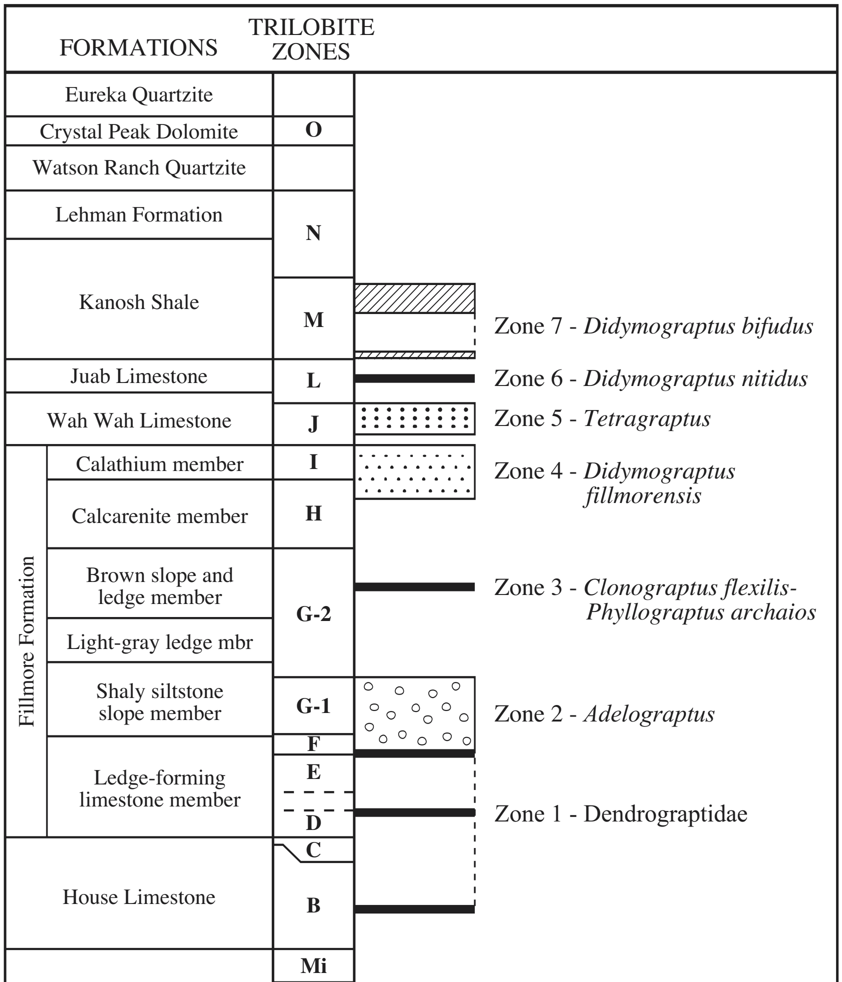


Figure 99. *Range chart for Ordovician graptolites from Ibex; graptolite zones defined by Braithewaite (1976).*

commonly found. Thus, there are gaps in the graptolite record near Ibex. Braithwaite (1976) noted that the provinciality of his collections made it difficult for him to correlate his graptolite zones with those from deep-water sequences, especially with the standard British graptolite zones (see Ross and others, 1982). The Marathon region in Texas contains an Ordovician graptolite sequence (Berry, 1960) from which conodonts have been obtained (Bradshaw, 1969; Bergstrom and Cooper, 1973). Unfortunately, conodonts have been reported from only a small part of the lower Ordovician sequence in Texas so they provide only a partial means of correlation. The conodont *Tripodus laevis* (chart 3, appendix C) occurs in both the Marathon area and near Ibex in zone L, the horizon that bears *Didymograptus nitidus* at the base of the Whiterockian. Perhaps additional work in the Marathon region will elucidate other graptolite correlations in the Pogonip Group near Ibex.

J.F. Miller and others (1999) reported the discovery of well-preserved earliest Tremadocian graptolites in the lower House Limestone near Ibex. The graptolites are above the base of the *Iapetognathus* conodont zone and below the base of the *Cordylodus anagulatus* conodont zone. The graptolites are 10 feet (3 m) above a bed containing the trilobite *Jujuyaspis borealis*, and other diagnostic species.

Cephalopods: Rousseau H. Flower (born 1913, died 1988) was, in the latter part of his life, the world's leading expert on Ordovician cephalopods, having studied them in most of their important field occurrences and in many museum collections in all parts of the world. He spent several weeks near Ibex in the mid-1960s, carefully searching the entire Pogonip Group for his beloved cephalopods. Collecting Ordovician cephalopods is not an easy task. Most of them are shaped like a long tapered pipe, which may be as much as several inches in diameter and up to a few feet in length. Commonly they are encased in a bed of solid limestone from which they can be extracted only by vigorous work with a sledgehammer and chisels. Dr. Flower shipped hundreds of pounds of cephalopod-bearing rocks to his laboratory in Socorro, New Mexico, where he sawed sections through the rocks to make his identifications.

Unfortunately, Flower died before completing descriptions of much of the material he collected near Ibex. He personally described several Pogonip cephalopods from Whiterockian zone N (Flower 1968a-b). His students, April Gil and Stephen Hook, completed the descriptions of cephalopods from Whiterockian zone L (Gil, 1988) and Ibexian zone J (figure 100) (Hook and Flower, 1977). The

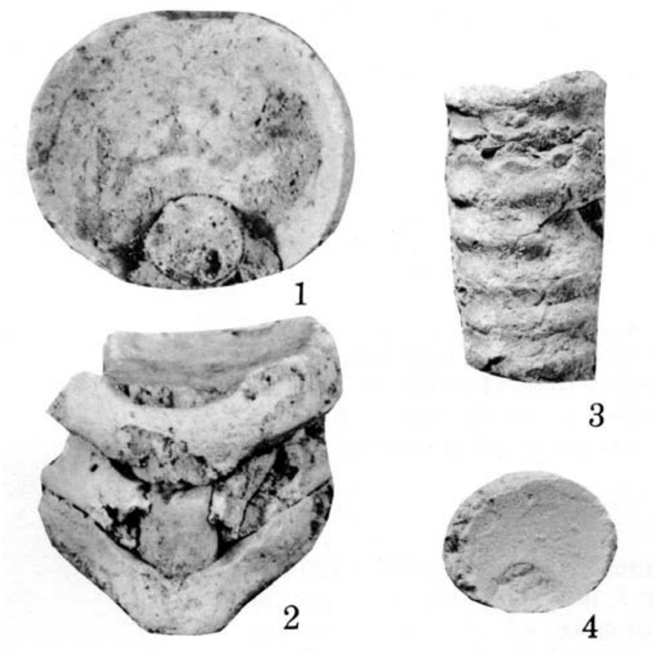


Figure 100. Catoraphiceras ibexense*: 1, anterior view, venter down, X4.8; 2, ventral view, X4.8; 3, ventral view, X1.9; 4, anterior view, venter down, X1.9.*

remainder of the identifications summarized below were transmitted to me in a voluminous series of letters from Flower in the late 1960s.

Flower found that the cephalopods in the Pogonip Group near Ibex occur chiefly at five levels in the section, in trilobite-brachiopod zones D, E, J, K, and N. In his correspondence, he identified the oldest cephalopod zone as his "First Endoceroid" zone, in the upper part of zone D, and listed the genera *Proendoceras*, *Manitouoceras*, *Aphetoceras*, and *Clitendoceras* as enabling correlation with the Cooks Formation of the El Paso group, part of the Manitou of Colorado, the Goodwin of Nevada, the lower Gorman of central Texas, the Roubidoux of Missouri, the Fort Ann of New York, and the Longview of Virginia.

His "First Pilocerid" horizon occurs in zone E near Ibex. From this zone he identified the genera *Clitendoceras*, *Dartonoceras*, *Bisonoceras*, *Bassleroceras*, and *Campbelloceras*, and stated that these genera are also found in the El Paso, Manitou, and Garden City Formations. Flower's collecting in zones F, G, and H near Ibex yielded a few baltoceratids and protocycloceratids of limited correlation value. Dattilo (1993) showed a coiled nautiloid, *Tarphyceras*, from zone G-2. Flower found that zone I produced a few specimens, including *Cyclostomiceras*, similar to forms from the Fort Cassin of New York, the Smithville of Arkansas, and the Scenic Drive Formation of El Paso, Texas.

Cephalopods from zone J were well documented by Hook and Flower (1977) who described 20 species, mostly new, of cephalopods assigned to the orders Ellesmeroceratida, Endoceratida, Tarphyceratida, and Michelinoceratida. They pointed out that the Wah Wah Limestone near Ibex and the Florida Mountains Formation in New Mexico are the only places in North America that have yielded large, well-preserved cephalopod faunas of latest Ibexian age.

Cephalopods from the Juab Limestone were described by Gil (1988), who recognized 11 species assigned to the genera *Cyptendoceras*, *Williamsoceras*, *Rossoceras*, *Evansoceras*, and *Cameroceras*. Flower (1968a-b) described *Juaboceras braithwaitei*, also from the Juab. Gil (1988) pointed out that Juab (zone L) cephalopods differ substantially from those common in the underlying Wah Wah Limestone in that Michelinoceratida and Ellesmeroceratida, dominant in the upper Ibexian zone J, are minor constituents in zone L, which is dominated by Endoceratida, especially the characteristic Whiterockian genera *Rossoceras* and *Williamsoceras*.

Zone M of the Kanosh Shale has as its most common cephalopod a species of *Rossoceras* similar to those in the *Palliseria* gastropod zone of the Antelope Valley limestone in central Nevada. Rousseau Flower personally identified a number of partial specimens of *Rossoceras* collected by the author from the Kanosh Shale, but none of those was formally described.

Flower (1968a-b, 1971) identified 5 species of cephalopods from zone N near Ibex. *Adamsoceras lehmanense* and *Wutinoceras davisi* (Flower, 1968a) are orthoconic (straight, tubular) forms and *Plectolites costatus* and *Litoceras adamsi* (Flower, 1968b) are coiled cephalopods. Flower noted that similar cephalopods are found in the sponge beds at Ike's Canyon in central Nevada. Flower (1971) described *Kiotoceras quadratum* from the Oil Creek Limestone in Oklahoma and noted that it also occurs in zone N near Ibex.

Zone O in the Crystal Peak Dolomite has yielded fragmentary cephalopod remains, not well enough preserved to be usefully identified. In summary, although cephalopods are localized in relatively few parts of the Pogonip Group near Ibex, those present have enabled Flower to correlate the Lower and Middle Ordovician strata near Ibex with rocks of similar age elsewhere in North America.

Gastropods: Snails are fairly common in Pogonip rocks near Ibex, but they are mostly preserved as steinkerns, the hardened mud that filled the hollow interior of the shell. Because this type of preservation gives only the general form of the gastropod (right or left-coiling, high or low-spiraling), it is not possible to give more than general generic identification to most gastropods near Ibex. None is silicified, and only rarely do any specimens preserve external shell markings or ornamentation.

Dr. Ellis L. Yochelson, a gastropod expert now retired from the U.S. National Museum in Washington, D.C., originally identified gastropods collected by the author near Ibex (Hintze, 1979). The revised names shown on figure 101 were provided by Dr. David M. Rohr of Sul Ross State University at Alpine, Texas. Dr. Rohr is currently studying the Ordovician gastropods of western North America, and has reexamined the collections from Ibex.

Yochelson and Jones (1968) described an unusual gastropod operculum (a lid that some gastropods have to close their aperture) which they named *Teiichispira*. It is a distinctive horn-shaped operculum that occurs in the Wah Wah Limestone near Ibex and is readily identified by its fibrous internal structure and great elongation. *Teiichispira* has been identified in late Ibexian and early Whiterockian (middle Arenig) strata in Alabama, Tasmania, Malaysia, Australia, western Canada, and northern Utah, and appears to be a use-

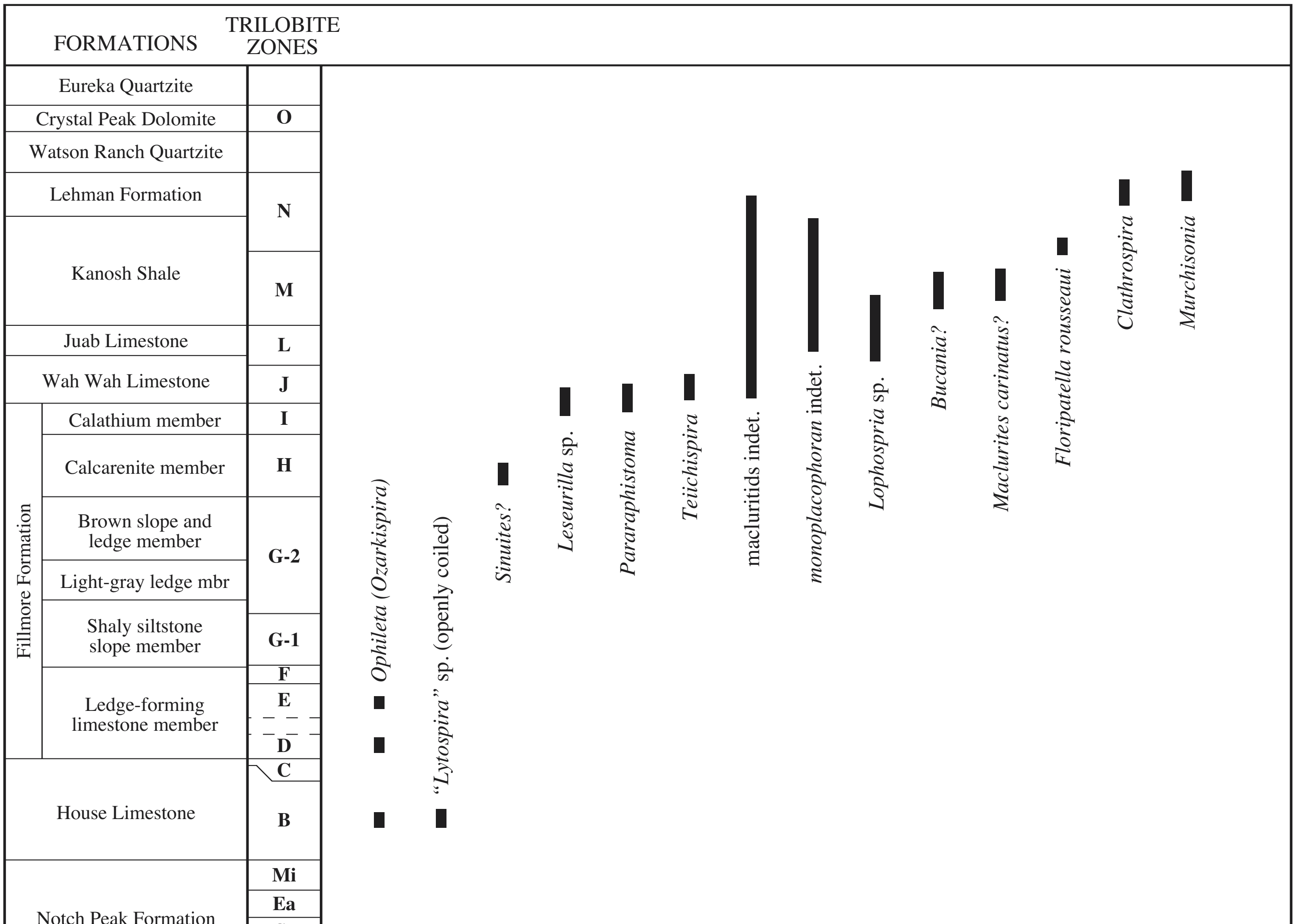


Figure 101. *Range chart for Ordovician gastropods from Ibex.*

ful guide fossil to rocks of this age. Yochelson (1988) described a new genus of conical gastropod, which shows a horseshoe-shaped muscle scar, as *Floripatella rousseaui*. It occurs in the Whiterockian Kanosh Shale near Ibex and is the oldest known example of the gastropod superfamily Patellacea.

Dattilo (1993) showed three typical gastropod steinkerns, which he identified as *Loxonema*, *Macluritella*?, and *Seelyia*? from zone G-2, incidental to his study of environments of deposition in the Fillmore Formation.

Because of Professor Rohr's continuing interest in Ordovician gastropods in western North America, I can hope that he or one of his students may continue to improve our knowledge about gastropods near Ibex and increase their potential for correlation and age determination. But until additional collecting yields external impressions of shell ornamentation, gastropods will have limited value in age determination near Ibex.

Echinoderms: This group of marine animals, which includes modern starfish, sea biscuits, and sea lilies, appeared in Cambrian time, and diversified substantially during early and middle Ordovician time (Guensburg and Sprinkle, 2001), as represented by the considerable variety of forms found in the Pogonip Group near Ibex, including eocrinoids, cystoids, crinoids, edrioasteroids (figure 102), and starfish (figure 103).

The echinoderm skeleton consists of plates of calcite, which are interlocked in some instances, or held together by living tissue in other instances. Most Ordovician echinoderms fall into the latter category, so that, upon the death of the animal, the platy skeleton became disarticulated and the loose calcite plates became scattered. Limestones that include a conspicuous percentage of echinoderm plates are common at many levels in the Pogonip Group near Ibex. Unfortunately, individual plates seldom provide sufficient information to enable specific identification of an echinoderm. So, despite the evidence of the abundance of echinoderms in the Pogonip Group, the present record of echinoderms near Ibex resulted from careful searching and the occasional fortuitous finding of articulated specimens.

Figure 104 shows the names of echinoderms reported from Ibexian and Whiterockian strata in western Utah (Sprinkle and Guensburg, 1997). *Cheirocystella antiqua* (Paul, 1972), a cystoid, is the oldest echinoderm listed. In addition to *Hybocrinus*, described by Lane (1970), and *Pogonipocrinus antiquus*, described by Kelly and Ausich (1978, 1979), informally named echinoderms of Ibexian age were collected and identified by Sprinkle and Guensburg (1997).

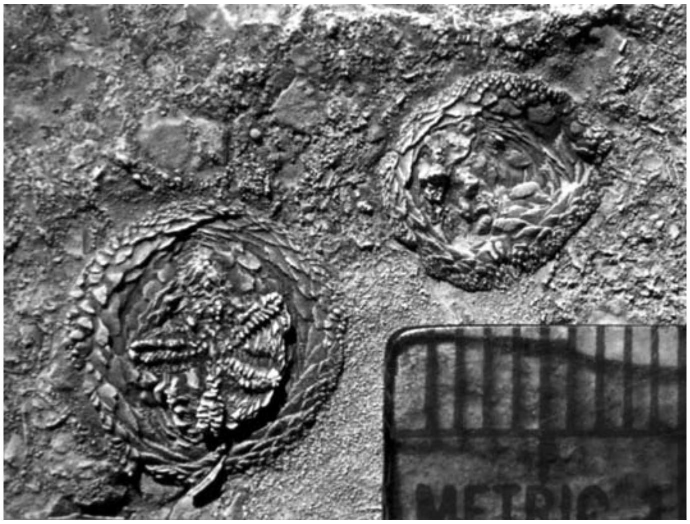


***Figure 102**. Edrioasteroid from the Lehman Formation near Ibex.*

***Figure 103**. Starfish from the Kanosh Shale near Ibex.*

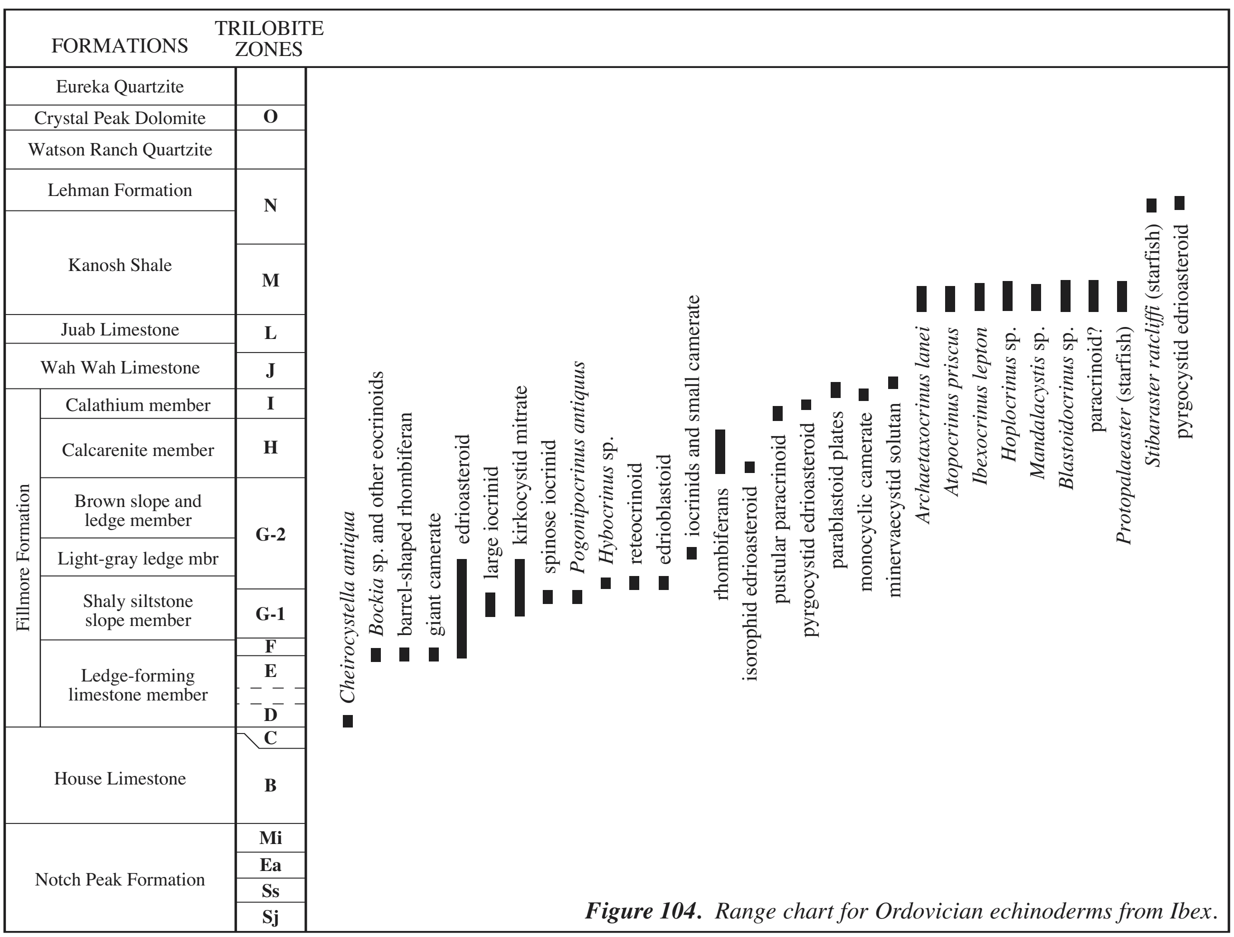


***Figure 104.** Range chart for Ordovician echinoderms from Ibex.*

The formally named Whiterockian echinoderms were described by Lane (1970), Lewis (1981), Lewis and others (1987), Wilson and others (1992) and Blake and Guensburg (1993).

Most recent echinoderm discoveries near Ibex are the result of field work by James Sprinkle and Thomas E. Guensburg (Guensburg and Sprinkle, 1990, 1992a, 1994; Sprinkle and Guensburg, 1997). They collected mainly from the Fillmore Formation and found that two distinct echinoderm assemblages are present in different lithologies of the Fillmore, implying that the type of substrate was an important factor in the diversification of echinoderms during the Ordovician radiation (Sprinkle and Guensburg, 1997; Guensburg and Sprinkle, 1992a-b, 2001). Crinoids dominate the Fillmore echinoderm fauna and are found almost exclusively on hardgrounds developed on sponge-stromatolite mounds, flat-pebble conglomerates, and grainstones, along with less common edrioasteroids and eocrinoids, as noted by Dattilo (1988, 1993). In contrast, other echinoderm groups, such as mitrate stylophorans and rhombiferans, are found primarily in micrites, shales, and limy siltstones that originated as soft substrates.

Study of echinoderms from the well-dated Pogonip Group near Ibex has yielded important new information on the effect of paleoenvironments on the evolution of this interesting group of marine animals.

Sponges: Sponges occur at only a few stratigraphic horizons near Ibex apparently because favorable conditions were attained only temporarily in the high-energy shallow-water environment represented by the clastic limestones that constitute most of the Ordovician section near Ibex. Sponges seemed to enjoy an association with algae and quasi-algal organisms, and together they formed patch reefs at certain horizons. The identifications shown in figure 105 were provided by Professor J.K. Rigby, who is describing the sponge fauna. Rigby (1962, 1965, 1971) established a preliminary sponge zonation based on his collections from Ibex. He plans a comprehensive treatment of Ordovician sponges in the near future.

Church (1974), a student of Rigby, described Lower Ordovician patch reefs within the Fillmore Formation near Ibex and noted that stromatolitic microbial cyanobacteria stabilized the substrate providing a base for an anthaspidellid sponge reef framework that harbored other organisms. Dattilo (1993), also Rigby's student, illustrated an *Anthaspidella* sponge from zone G-2 in connection with his study of environments of deposition of the Fillmore Formation.

Ostracodes: Ostracodes are bivalved crustaceans that are abundant in the upper part of the Pogonip Group near Ibex. They are generally dark brown or black there and range in size from a pinhead to a small bean, which they somewhat resemble. White (1874) described *Leperditia bivia* from upper Pogonip strata in Nevada, and this name had appeared in U.S. Geological Survey lists as a common guide fossil to the upper Pogonip wherever it was found in the Great Basin. It remained for Berdan (1976, 1988) to show that upper Pogonip beds contain large and varied faunas of ostracodes, most

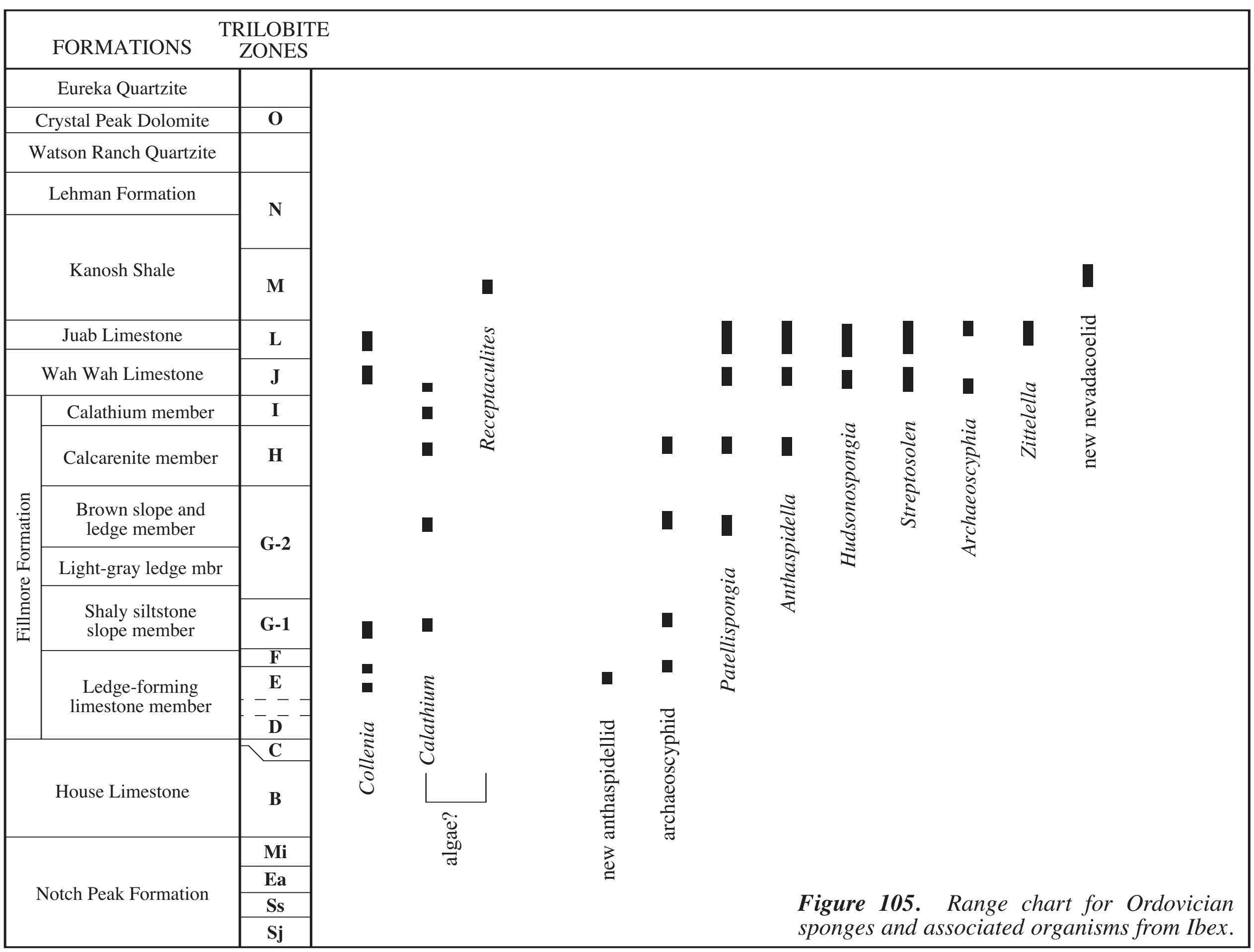


Figure 105. *Range chart for Ordovician sponges and associated organisms from Ibex.*

of whose names are shown on figure 106. The oldest ostracodes near Ibex are small leperditellids from the upper part of the Fillmore Formation and in the Wah Wah Limestone (Hintze, 1979). Because their precise location in the section is not known, they have not been described by Berdan. The lowest ostracode shown on figure 106, *Tirisochilina juabaria*, occurs with *Leperditelloides dolabrata*, *Ningulella*? sp., and *Ectoprimitioides*? sp. in what Berdan (1988) calls ostracode assemblage I. *Tirisochilina* has also been found in Middle Ordovician beds in Oklahoma, New York, Vermont, and Quebec (Berdan, 1976).

The Kanosh Shale contains two distinct ostracode assemblages. The older, assemblage II, is characterized by *Hintziella* (figure 107), which is abundant up to 130 feet (40 m)

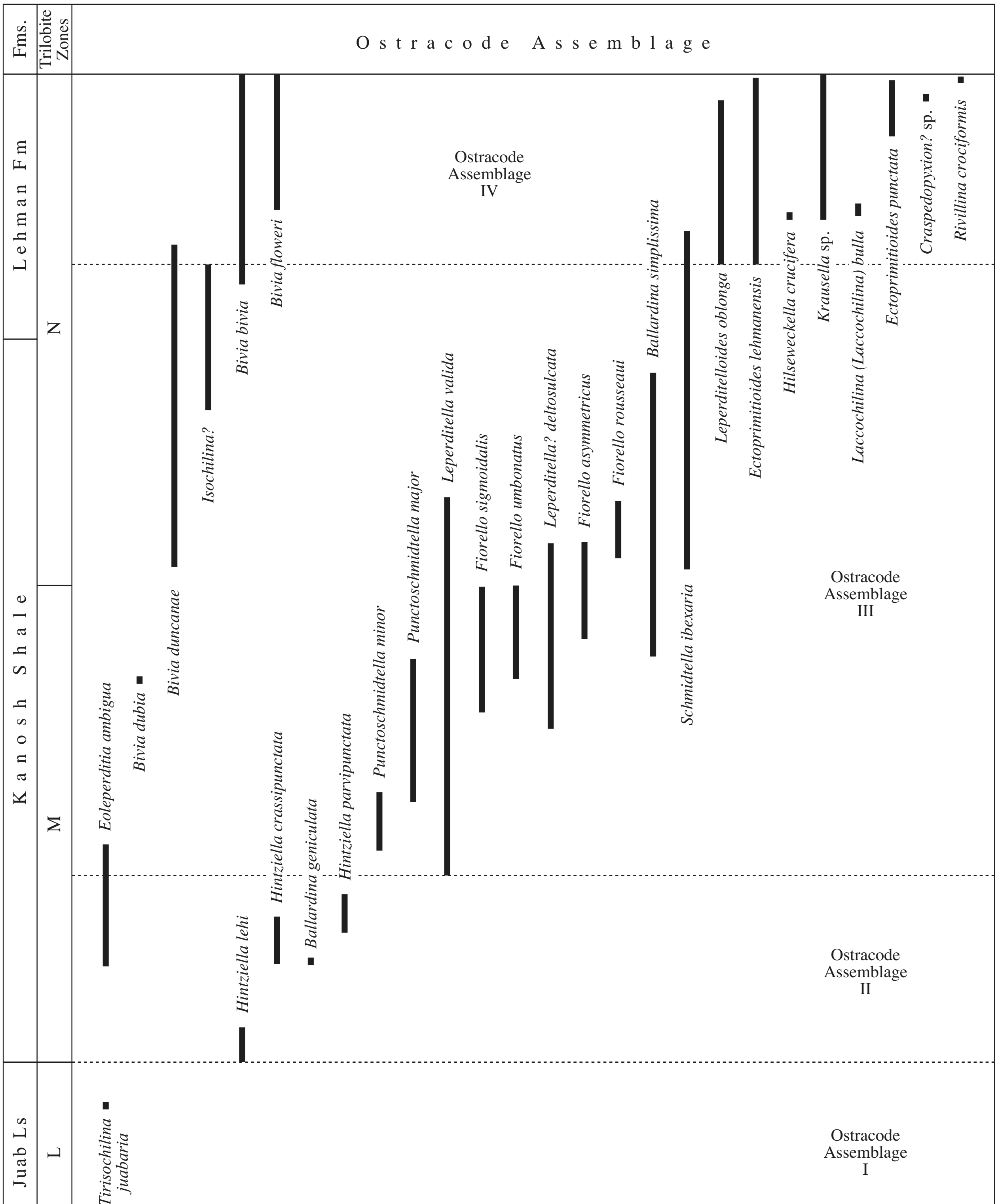


***Figure 106.** Range chart for Ordovician ostracodes from Ibex; assemblages defined by Berdan (1988).*

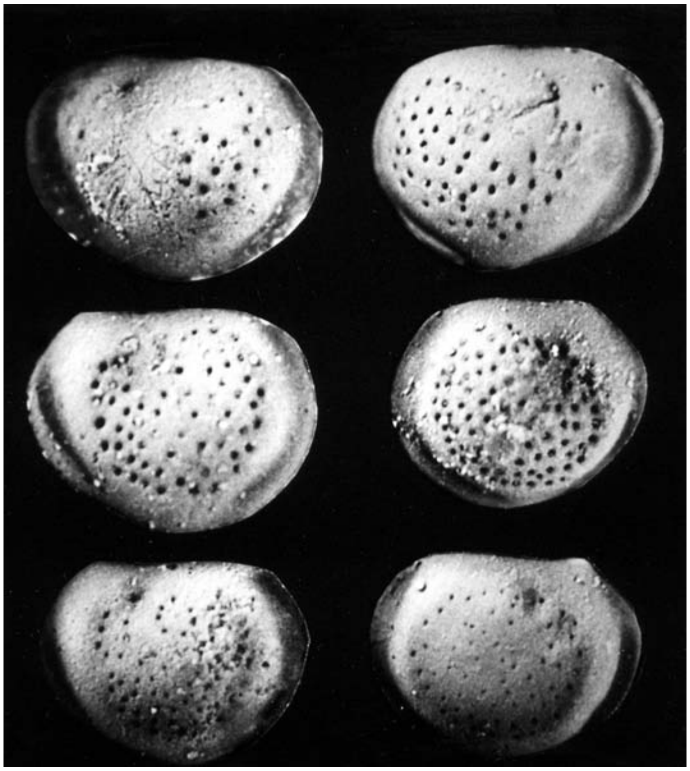


Figure 107. *Three species of* Hintziella *from the lower Kanosh Shale showing right and left valves; X25: upper,* H. lehi*; middle,* H. crassipunctata*; lower,* H. parvapunctata.

above the base of the Kanosh. Within 20 feet (6 m) this fauna is replaced by assemblage III, with an association of *Leperditella valida* (figure 108) and species of *Punctoschmidtella* and *Fiorello*. In the transition between assemblages III and IV, only *Schmidtella ibexaria*, *Bivia bivia*, and *Bivia duncanae* overlap the boundary.

Bivia floweri, which appears in the Lehman Formation, extends into the Crystal Peak Dolomite (above the top of figure 106).

Now that the ranges of various ostracodes were documented by Berdan (1976, 1988) near Ibex, where the age of the upper Pogonip is well constrained by other fossil groups, ostracodes should be more useful as guides to dating lower and middle Ordovician strata in the Great Basin and elsewhere.

Bryozoa: Hinds (1970) documented the Bryozoa and bryozoan-like organisms near Ibex, as shown in figure 109. He recognized six species, all new, but because of scarcity and poor preservation he named only two formal species. The Bryozoa near Ibex are most like those in the Oil Creek and McLish Formations of Oklahoma.

Pelecypods: Pelecypods are scarce in the Utah Ordovician, and none have been found well enough preserved for more than generic assignment. *Modiolopsis* is the most common form. It occurs in mats of thin, crushed shells in the upper Kanosh Shale and Lehman Formation. Pelecypod identifications shown in figure 109 were provided by Dr. John Pojeta, paleontologist at the U.S. Geological Survey, Washington, D.C.

Corals: Corals make their appearance near the top of the pre-Eureka rocks near Ibex, as shown in figure 109. They are

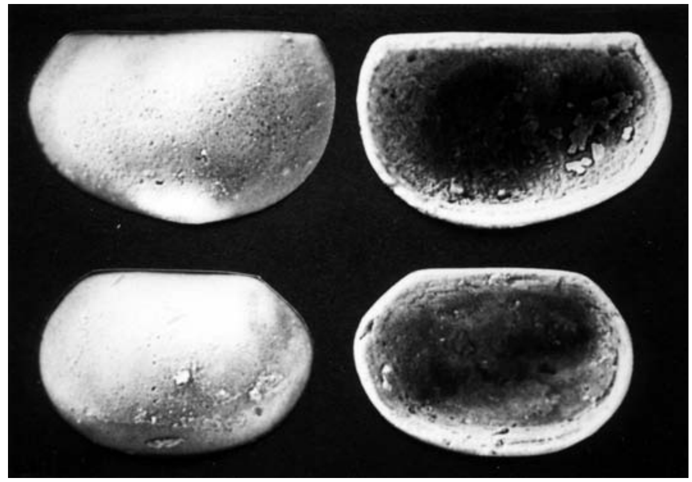


Figure 108. Leperditella valida *from the middle and upper part of the Kanosh Shale; clockwise from upper left: left valve exterior, left valve interior, right valve interior, right valve exterior; X11.*

some of the oldest corals known. *Lichenaria*, the oldest, occurs as small, thumbnail-size specimens in the Lehman Formation. *Eofletcheria* (figure 110) forms bedded masses up to 1.5 m (5 feet) thick in the Crystal Peak Dolomite. These forms were described by Rigby and Hintze (1977).

Algae: Encrusting algae, in association with sponges, were important in the development of algal-bound lime mudstone mounds and hardgrounds. These algae show little distinct structure but develop into sponge-algal patch reefs a few feet high and several feet in diameter. These are found locally, mostly in the Fillmore Formation and Wah Wah Limestone.

Calathium and *Receptaculites* (figure 111), whose distributions are shown on figure 105, are distinctively ("garden hose" and "sunflower cup") shaped organisms of problematic affinity, classed as sponges by some paleontologists, and as algae by others. Church (1991) described a new species of *Calathium* from the Fillmore Formation near Ibex.

The problematical alga *Nuia* occurs locally in the Wah Wah Limestone near Ibex within a bed of *Girvanella*-bound oncoids (Ross and others, 1988).

Trace fossils: Fucoidal markings are the most conspicuous trace fossils in Ordovician strata near Ibex and are common on sandstone bedding surfaces in the Kanosh Shale, Lehman Formation, and Watson Ranch Quartzite.

In his study of depositional environments of part of the Fillmore Formation, Dattilo (1993) showed the deposit-feeding trace *Chondrites*, braided burrows in shale, and spreite burrows in calcarenite, and he noted two trace fossils attributed to trilobites, *Rusophycus* and another trail. Trace fossils in Pogonip rocks in Millard County have received scant attention because in most lithologies there they are neither abundant nor obvious.

Benner and Ekdale (1999) noted that macroborings in the Fillmore Formation near Ibex demonstrate that the macroboring behavioral strategy was firmly established in the earliest stages of the great Ordovician diversification in the marine biosphere.

Summary of fossil documentation: Half of the 14 groups of Ordovician fossils discussed above have been collected and described thoroughly enough so that their zonation potential has been assessed, and description of major blocks of

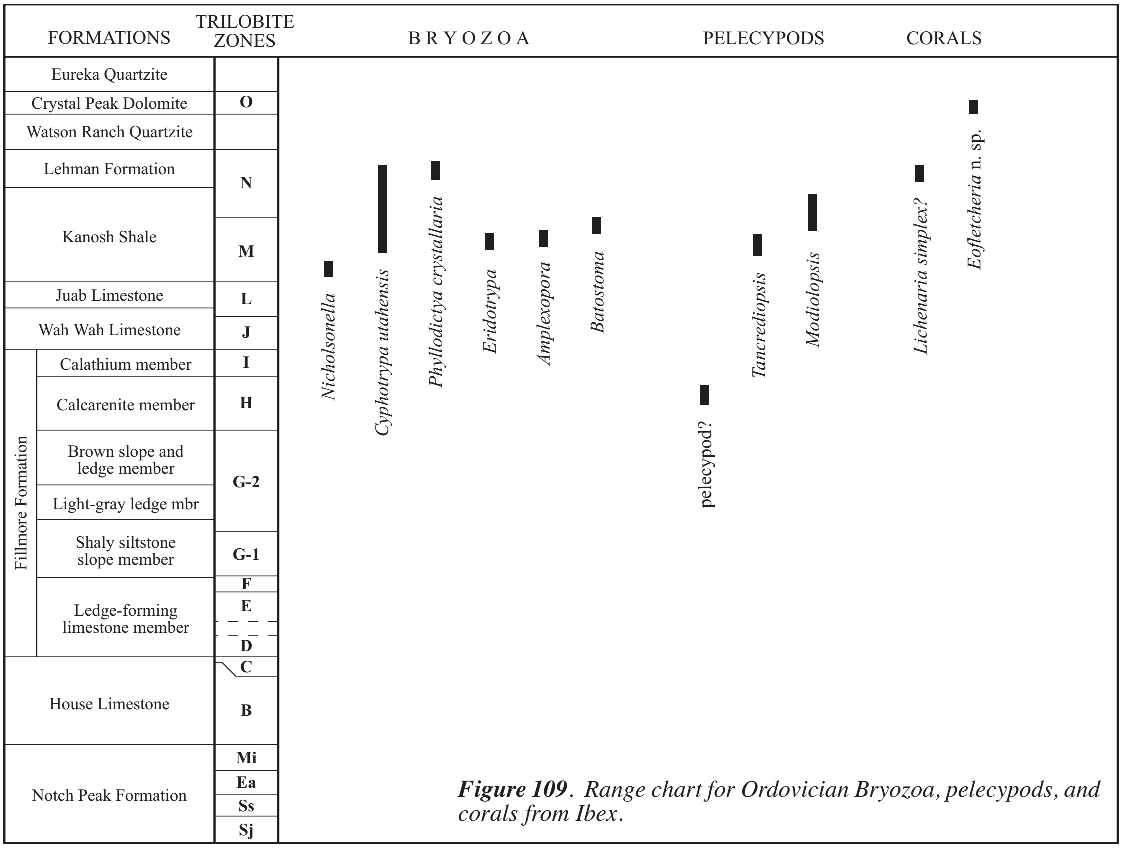


***Figure 109**. Range chart for Ordovician Bryozoa, pelecypods, and corals from Ibex.*

***Figure 110**.* Eofletcheria*, an ancient coral from the Crystal Peak Dolomite near Ibex.*

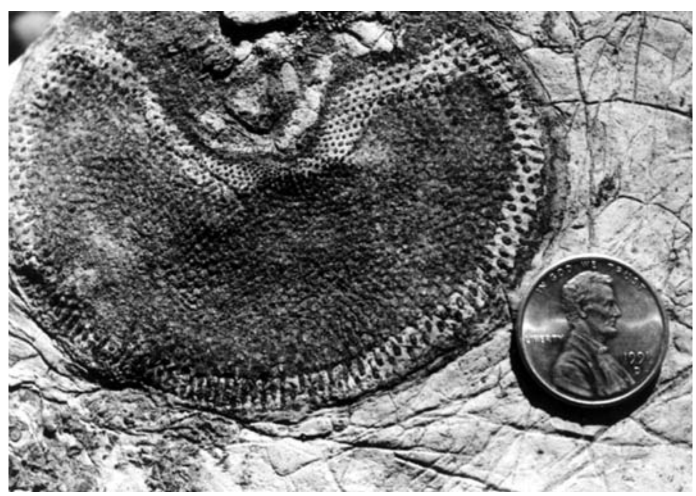


***Figure 111**.* Receptaculites*, the "sunflower" fossil, found in the Kanosh Shale in Millard County.*

new finds is not likely, although some new data are to be expected. These groups include trilobites, conodonts, brachiopods, graptolites, ostracodes, bryozoa, and corals. The remaining seven groups have been partly described and additional significant data are to be expected as follows:

(1) Cephalopods from the Fillmore Formation were collected by Rousseau Flower but never described. Whether his collections at the New Mexico Bureau of Mines and Mineral Resources in Socorro are in such condition that someone could proceed with the study of material already collected, or whether the cephalopods of the Fillmore Formation would need to be recollected, remains to be seen.

(2) Gastropods have never been systematically collected near Ibex. The present identifications are from materials collected incidently to other field work. Considering the importance of gastropods in Ordovician strata in the midcontinent area, a better knowledge of their occurrence near Ibex would be useful.

(3) Echinoderms are actively being pursued by Dr. James Sprinkle at the University of Texas in Austin, and Dr. Thomas Guensburg at Rock Valley College in Rockford, Illinois. These paleontologists, specialists in echinoderms, will likely add substantially to the documentation of this group near Ibex in the near future.

(4) Sponges were collected by Dr. J. Keith Rigby of Brigham Young University three decades ago, and, although he has provided preliminary identifications of his material, the detailed descriptions remain to be published.

(5) Pelecypods are in much the same status as gastropods, except that they are much less abundant in Pogonip rocks. Someone with interest and determination could increase our data base. The present collections have been obtained incidental to other studies.

(6) Microbial organisms have been noted in the Pogonip Group near Ibex only by their acting as a binding agent for sponge-microbial patch reefs and hardgrounds. *Calathium*, a problematical alga, is a reef-forming organism that occurs consistently at the zone I level in Pogonip Group rocks in many locations in Utah and Nevada, and was described by Church (1991). Microbial oolites, oncolites, pisolites, and laminated boundstones are almost completely absent in the Pogonip Group near Ibex.

(7) Trace fossils have not been documented systematically in Ordovician strata in western Utah, but much potential exists. Dattilo (1993) found several kinds of trace fossils in the Fillmore Formation, and an even greater variety likely exists in upper Pogonip rocks and the overlying Ordovician formations. Trace fossil study would lead to a better understanding of environments of deposition of Ordovician strata in Millard County.

Lithologic Units

Names of Ordovician formations in Millard County are shown on chart 3 (appendix C) where age comparisons are made, and on columns 2, 3, 7, 8, 9, and 10 (appendix C), where map symbols, thicknesses, primary references, and other pertinent data are shown for the various locations where Ordovician strata are exposed. The 1:100,000 scale of the geologic maps of Millard County is too small to show thin formations individually (Hintze and Davis, 2002a-c; Hintze and others, 2003). They have been combined with adjacent units, and the combination map symbol is shown on the explanation and on the stratigraphic columns. However, each formation is discussed separately in the following section.

Pogonip Group (Op) in eastern Millard County: "Pogonip limestone" was used originally to include all limestones and dolomites between the Cambrian Dunderberg shale and the Ordovician Eureka quartzite in the White Pine mining district of eastern Nevada. As use of the name spread throughout the Great Basin, the tendency was to restrict Pogonip to the Ordovician (see Sharp, 1942, for a referenced review of the term). Hintze (1951) elevated Pogonip to group rank and defined its subdivisions near Ibex in western Utah.

In eastern Millard County (columns 1 and 3, appendix C) a combination of poor exposure and complex structure has hindered subdividing the Pogonip on geologic maps, even though most of its characteristic formational units can be locally recognized (Hintze, 1951). Pogonip strata are partially exposed in road cuts along Interstate Highway 15 from the bottom of the hill southwest of the town of Scipio to the summit of Scipio Pass (Michaels and Hintze, 1994). There, the basal Pogonip formation, the House Limestone, is medium-gray, slightly cherty, fine-grained limestone that forms ledges and cliffs at the summit of Scipio Pass. Hintze (1951) reported 271 feet (82.5 m) of House Limestone near here. The middle part of the Pogonip Group (identified as Fillmore Limestone, Wah Wah Limestone, and Juab Limestone by Hintze, 1951), is characterized by thin-bedded intraformational conglomerate interbedded with thin beds of silty limestone, shaly limestone, shale, and bioclastic limestone. This interval is exposed in all the roadcuts along the freeway from the summit of Scipio Pass to the lowest exposures to the northeast at the base of the hill. Scipio Pass, which separates the Canyon Mountains from the Pahvant Range, has developed geologically as a low divide because of the soft, nonresistant nature of the thin-bedded Pogonip rocks that the highway follows over the pass area. Hintze (1951) reported 1,046 feet (317 m) of middle Pogonip near the pass.

The upper part of the Pogonip Group is olive shale with thin beds of limestone that commonly contains ribbed brachiopods about the size of a penny (figure 95). This shale forms slopes beneath the resistant Eureka Quartzite. It is exposed in road cuts along I-15 in Baker Canyon about 6 miles (10 km) north of Cove Fort. Thickness of the Pogonip Group in eastern Millard County ranges between 1,125 and 1,684 feet (343 and 513 m) (columns 3 and 2, respectively, appendix C).

Pogonip Group in western Millard County: Excellent exposures, lack of structural complexity, and abundant fossils have made the Pogonip Group near Ibex in western Millard County a mecca for Ordovician biostratigraphers (Hintze, 1987). On the 1:100,000-scale geologic maps of Millard County, the Pogonip Group has been separated into three map units: House Limestone, Fillmore Formation, and

Upper Pogonip Group as shown in chart 3 (appendix C) and on columns 7-10 (appendix C). In western Millard County the Pogonip Group is nearly 3,500 feet (1,067 m) thick, more than twice as thick as in the eastern part of the county.

House Limestone (Oh): The House Limestone is a medium-gray, silty (quartz), sparsely cherty, finely crystalline limestone, generally lacking stromatolitic deposits, that occurs in beds mostly between 2 and 4 feet (0.6-1.3 m) thick. It erodes to ledges less massive than those of the underlying Notch Peak Formation but more resistant than those of the overlying Fillmore Formation (figure 112). A brown-weathering quartz sandy limestone more than 20 feet (6 m) thick occurs near the middle of the formation near Ibex. Silicified *Symphysurina* Zone trilobites are common on bedding surfaces, particularly in the upper third. The uppermost 15 feet (5 m) consist of a massive limestone ledge with a 2-foot (0.6-m) coquina of brachiopods and trilobites (*Syntrophina* and *Paraplethopeltis*) at its base.

Descriptions of measured sections of House Limestone are published in Hintze (1951, 1973a). Stratigraphic faunal lists and fossil ranges are given in Hintze (1952), Ross and others (1997), and in this bulletin (figures 90, 94, 99, and 101). The House Limestone is about 500 feet (150 m) thick in western Millard County and a little more than half that thick near Scipio Pass, as noted above.

Fillmore Formation (Of): This formation includes all beds between the prominent ledge at the top of the House Limestone and the prominent ledges at the base of the Wah Wah Limestone. It is medium-gray, mostly thin-bedded, silty, intraformational conglomerate and calcisiltite, interbedded with thin beds of light olive shale. It is generally nonresistant and, except at the base, includes only a few ledge-forming beds 3 to 6 feet (1-2 m) thick, which are commonly sponge-microbial reef limestones. Near Ibex the Fillmore was divided into six informal members (Hintze, 1973a), which are described below, beginning with the oldest member. Measured sections are published in Hintze (1973a). Stratigraphic faunal lists and fossil ranges are given in Hintze (1952), Ross and others (1997), and in this bulletin (figures 90, 94, 99, 101, 104-106, and 109).

Basal ledge-forming limestone member: This is the most resistant member of the Fillmore Formation, not quite so resistant as the House Limestone, but more so than the overlying Fillmore members (figure 113). It is mostly medium-gray, thin- to medium-bedded, silty calcisiltite, with some beds of intraformational conglomerate and some sponge-microbial reef beds. Its lowest 94 feet (29 m) contains unsilicified *Leiostegium* and *Kainella* zone D trilobites. The interval from 180 to 390 feet (55 to 119 m) contains silicified *Tesselacauda* zone E trilobites, as described by Terrell (1973). The upper 100 feet (30 m) contains silicified trilobites of *Rossaspis* zone F. The member is 485 feet (148 m) thick near Ibex (Hintze, 1973a).

Slope-forming shaly siltstone member: Silty limestones and calcareous siltstones make up most of this member, which has an olive-gray fissile shale horizon in the middle. Thin-bedded intraformational conglomerate comprises less than 40 percent of the member. From afar this member looks like a silvery gray slope, easily distinguished from the more resistant members above and below. The *Rossaspis* trilobite zone F continues into the lowest 5 feet (1.5 m) of this member. Trilobites of *Hintzeia* zone G-1 are present throughout the next 250 feet (76 m), and the upper 65 feet (20 m) contains silicified trilobites of the *Protopliomerella* zone G-2. The member is 320 feet (98 m) thick near Ibex (Hintze, 1973a).

Light-gray ledge-forming member: This member is mostly medium-gray, thin-bedded, calcareous siltstone with interbeds of intraformational conglomerate, and calcilutite, which forms ledges, giving the member a cyclic ledge-slope aspect (figure 114). The entire member is somewhat more resistant than the Fillmore members above or below it. Silicified trilobites of the *Protopliomerella* zone G-2 occur throughout the member. Stratigraphic faunal lists are given in Hintze (1952), and fossil ranges are presented in Ross and others (1997). The member is from 180 to 194 feet (55 to 59 m) thick near Ibex (Hintze, 1973a).

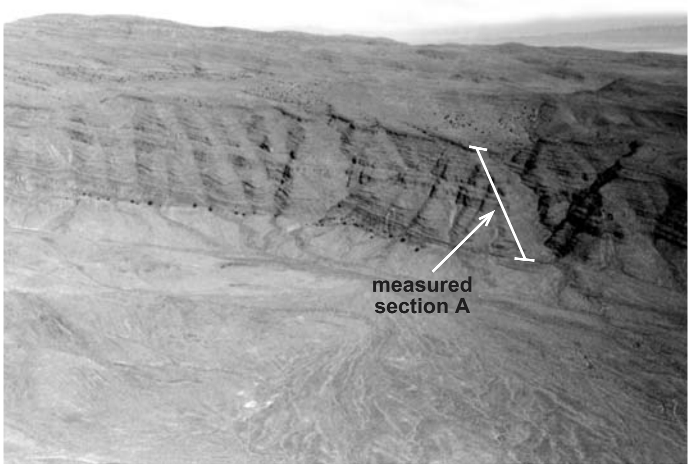


Figure 112. Aerial view of House Limestone on the west side of the House Range just north of Skull Rock Pass. Measured section A of Hintze (1973a) is on spur of ridge just left of small canyon on right side of picture. Juniper-bearing ledge that caps the hill is uppermost House Limestone. Darker ledge in middle is a limy sandstone.

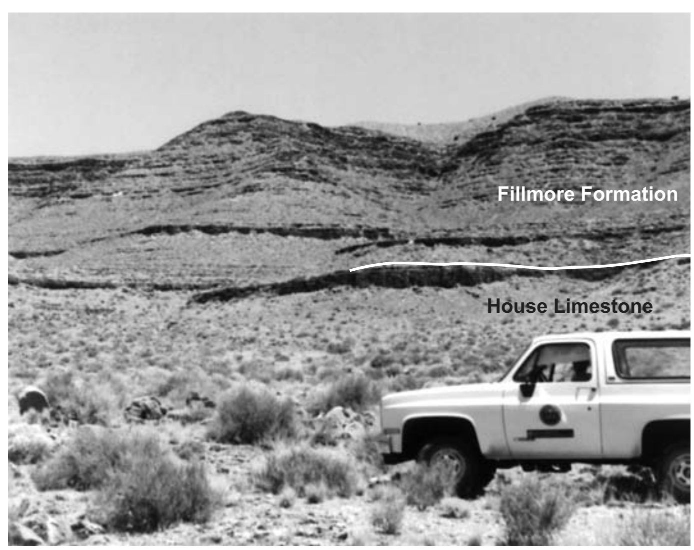


Figure 113. View looking east at measured section C of Hintze (1973a), located 4 miles (6 km) south of Ibex Well in the southern House Range. The lowest ledge above the vehicle is the uppermost ledge of the House Limestone. All ledges above that in this picture belong to the lowest member of the Fillmore Formation.

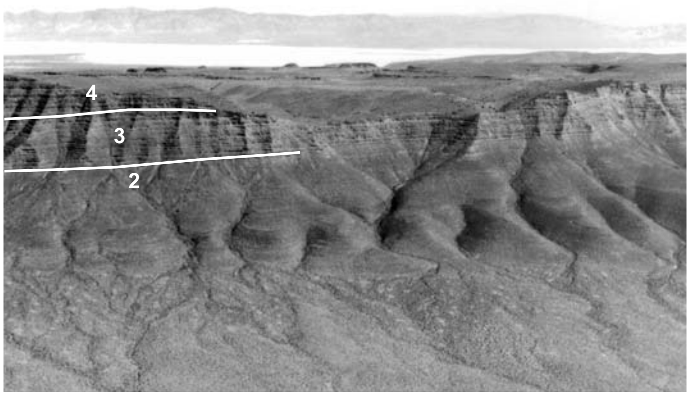


Figure 114. *View looking east at the southern House Range where members of the Fillmore Formation are exposed in the Mesa section of Hintze (1973a), located 2 miles (3 km) south of Ibex Well. Uppermost unit is the brown slope and ledge member at the left top in the picture (4); continuous band across picture is the light-gray ledge-forming member (3); rounded exposures in lower hillside is slope-forming shaly siltstone member (2). Sevier Lake and Cricket Mountains in the distance. Dark rocks capping hill in middle distance are reddish-brown Tertiary ash-flow tuffs in the Needles Range Group (28-31 Ma).*

Figure 115. *Intraformational conglomerate, a distinctive rock that typifies the Fillmore Formation, but is also present less commonly in other members of the Pogonip Group. Its pebbles are silty limestone that was ripped up from a muddy tidal flat while still unconsolidated and redeposited near the original site of deposition.*

Brown slope and ledge member: This member is made up almost entirely of brownish-gray, thin- to medium-bedded, intraformational conglomerate (figure 115), the flat pebbles of which are commonly made of calcareous siltstone in a less silty calcareous matrix. The most distinctive beds within the member are widely spaced ledge-forming calcilutite beds, which can be used to correlate horizons within the member from place to place near Ibex. All but the uppermost 13 feet (4 m) of the member contain silicified trilobites of the *Protopliomerella* zone G-2. *Trigonocerca typica*, zone H, trilobites are found in the top of the member. The member is 324 feet (99 m) thick near Ibex (Hintze, 1973a).

Calcarenite member: Medium- to light-gray calcarenite (coarse granular limestone), the dominant type of rock in this member, is interbedded with thin-bedded intraformational conglomerate, calcisiltite, algal hardgrounds, and shale (figure 116). The member weathers to low ledges and slopes. Trilobites of *Trigonocerca typica* zone H are common as silicified fragments and disarticulated parts in clastic limestones throughout the member. The member is 310 feet (94 m) thick near Ibex (Hintze, 1973a).

Calathium calcisiltite member: The tubular spongelike fossil *Calathium* ("*Receptaculites elongatus*" of Hintze, 1951) forms a conspicuous 10-foot (3-m) reef at the base of this member. Church (1991) described a new species, *Calathium yersini*, from this member and noted that it is among the earliest of receptaculitids. The remainder of the member consists mostly of light-yellowish-gray, thin-bedded, silty calcisiltite, calcareous siltstone, and shale that forms low ledges and slopes beneath the more massive ledges of the overlying Wah Wah Limestone (figure 117). Except for the uppermost 3 feet (1.0 m), which carries J zone fossils, the rest of the *Calathium* calcisiltite member bears silicified trilobites of *Presbynileus ibexensis* zone I. Hintze (1973a) described measured sections of this member near Ibex, where it is 170 feet (52 m) thick. Fossil lists and range charts can be found in Hintze (1952) and Ross and others (1997).

Figure 116. *Interbeds of limestone and shale in the middle Fillmore Formation as exposed in highway road cuts near Skull Rock Pass. Hammer is 12 inches (0.3 m) long. The thickness of shale interbeds in the Fillmore is usually underestimated because the shale weathers and becomes covered with loose slabs of silty limestone and intraformational conglomerate.*

Upper Pogonip Group (Opu): The small scale (1:100,000) of the geologic maps of Millard County does not allow showing the Lehman Formation, Kanosh Shale, Juab Limestone, and Wah Wah Limestone separately; they have been combined under the symbol Opu. They are described separately below, and are shown separately on more detailed geologic maps of western Millard County that are listed in the sources of geologic mapping.

The Pogonip Group in western Millard County is too thick to be exposed in a single unbroken section. The House Limestone and Fillmore Formation are exposed in the south-

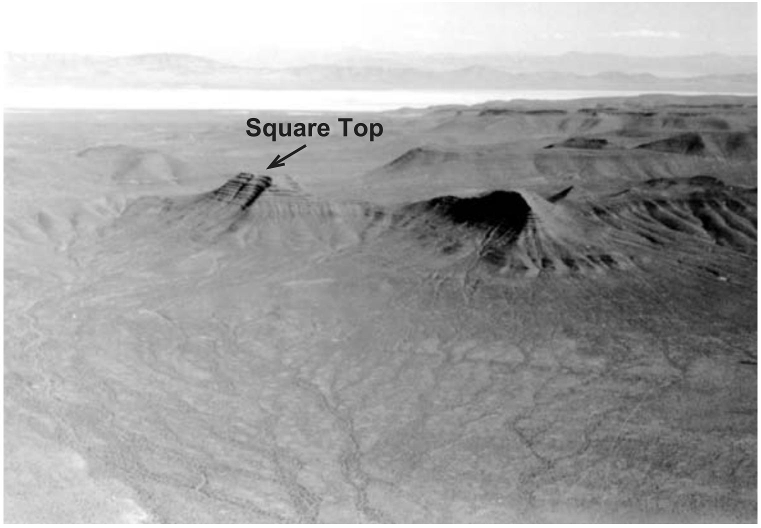


Figure 117. Aerial view looking east at upper members of the Fillmore Formation exposed at the Square Top measured section of Hintze (1973a), located about 3 miles (5 km) southeast of Ibex Well; view roughly to east. The nearly horizontal strata here lie on the axis of a broad east-west syncline in the southern House Range. Square Top is capped by the lowest ledges of the Wah Wah Limestone, beneath which the Calathium *calcisiltite member and most of the calcarenite member are well exposed. Sevier Lake and the Cricket Mountains are in the distance.*

ern House Range east of Ibex Well. Upper Pogonip Group formations are exposed from Fossil Mountain southward (figure 118), west of Watson's Ibex ranch. The two areas duplicate most members of the Fillmore Formation as described by Hintze (1973a).

Wah Wah Limestone: In contrast to the slope-forming topographic expression of the underlying Fillmore Formation, the Wah Wah Limestone forms a series of ledges. It is chiefly a quartz-silty calcisiltite with interbeds of thin-bedded calcarenite and intraformational conglomerate and a few beds of light olive fissile shale (figure 119). A few small sponge-microbial patch reefs, described by Wyatt (1979), are present near Ibex. A *Hesperonomiella minor* brachiopod coquina (zone K) forms an easily identifiable marker horizon 2 feet (0.6 m) thick, 215 feet (66 m) above the base of the formation. Silicified trilobites of *Pseudocybele nasuta* zone J are abundant below the *Hesperonomiella* bed and were listed by Hintze (1952) and Ross and others (1997). Measured sections are presented by Hintze (1951, 1973a). The Wah Wah Limestone is 258 feet (79 m) thick in its type section (Hintze, 1973a).

Juab Limestone: The Juab Limestone is a medium-gray, medium-bedded, ledge-forming calcisiltite that includes

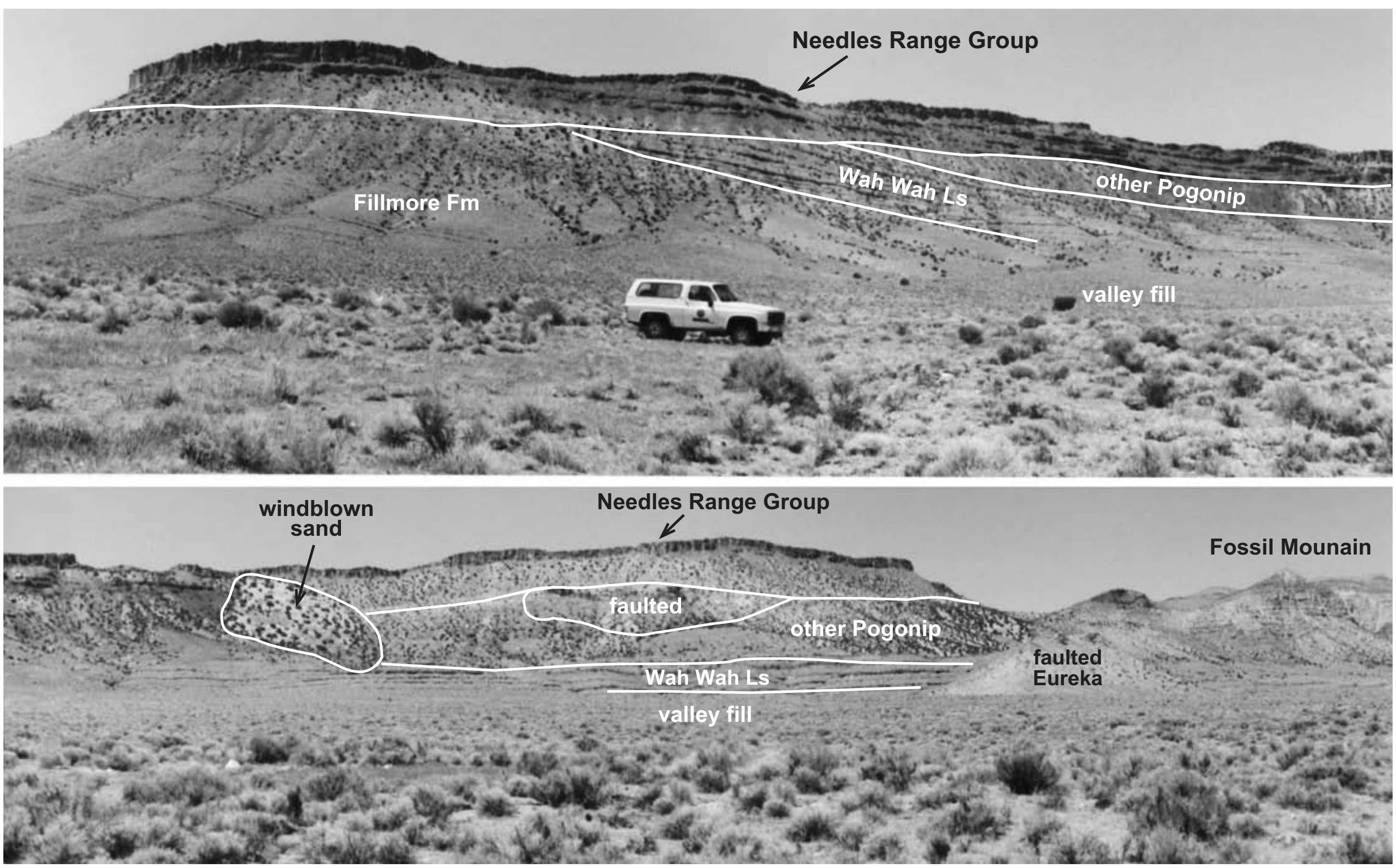


Figure 118. Panoramic views looking southwest (upper) and northwest (lower) from Warm Point showing angular unconformity between nearly horizontal Oligocene volcanic rocks (Needles Range Group) and tilted Ordovician strata. Lowest beds at left side of upper picture are Fillmore Formation of measured section G of Hintze (1973a). Five prominent tilted ledges above are the Wah Wah Limestone, which crosses the middle of the lower picture and appears to be cut off by a down-faulted block of Eureka Quartzite. Other Pogonip Group formations are above the Wah Wah Limestone and are also complicated by faulted blocks. Measured section J of Hintze (1973a) is just left of the hill of quartzite. Fossil Mountain, section K of Hintze (1973a), is at the right side of the lower picture (see figure 120).

Figure 119. Wah Wah Limestone at the base of J section of Hintze (1973a).

a few thin beds of graptolite-bearing shale (figure 120). Its color contrasts with the brownish-gray aspect of the Wah Wah Limestone. Its trilobites are not silicified and were studied by Fortey and Droser (1996) who described species of the following genera: *Psephostenaspis*, *Goniotelina*, *Ectenonotus*, *Petigurus*, *Pseudoolenoides*, *Kanoshia*, *Pseudomera*, *Madaraspis*, *Punka*, *Uromystrom*, *Isochrotoma*, *Kawina*, and *Carolinites*. Its most characteristic fossil is *Paralenorthis subalata*, a coarse-ribbed brachiopod about the size of a dime. Fossil lists and fossil range charts are presented in Hintze (1952) and Ross and others (1997). The description of its type section near Ibex (Hintze, 1973a) gives its thickness as 157 feet (48 m).

Kanosh Shale: Dark olive shale characterizes this formation, making it the most easily recognized part of the Pogonip. The shale includes interbeds of other rock types that were used by Hintze (1973a) to subdivide the formation near Ibex into five informal members as listed below.

The Kanosh Shale is abundantly fossiliferous. Some of the thin-bedded limestones are coquinas of brachiopods, ostracodes, echinoderms, and other fossils (figure 81). The lower 370 feet (113 m) contains fossils of the *Pseudoolenoides dilectus* zone M, and the upper Kanosh and all of the Lehman Formation have fossils of the *Pseudoolenoides acicaudus* zone N. Fossil names and ranges are listed in Hintze (1952) and Ross and others (1997). McDowell (1995) summarized the depositional history of the Kanosh Shale. The Kanosh Shale is 564 feet (172 m) thick near Ibex.

Lower olive shale and calcarenite member: This is a dark olive-gray shale with interbeds of thin-bedded fossiliferous calcarenite. This member commonly forms a slope. Brachiopods, ostracodes, and trilobites are abundant in the limestone but rare in the shale. Fossils are not silicified. The member is 105 feet (32 m) thick.

Silty limestone member: This member consists of interbeds of thin-bedded calcisiltite, calcarenite, calcareous shale, and intraformational conglomerate. It forms a steeper slope than do the adjacent members. It is 40 feet (32 m) thick.

Upper olive shale and calcarenite member: This member is similar in lithology to the lowest Kanosh member, except that thin-bedded calcarenite becomes the dominant lithology towards the top of this member. It is 141 feet (43 m) thick.

Sandstone and shale member: Orange-weathering, fine-grained, calcareous sandstones are the most distinctive beds in this member, although they constitute less than 20 percent of the entire thickness. The sandstone beds range from 1 to 4 feet (0.3-1.3 m) thick and are interbedded with fissile olive shale and fossiliferous thin-bedded calcarenite. The member is 137 feet (42 m) thick.

Calcisiltite member: This is a light-gray silty calcisiltite with nodular bedding. It includes about 5 percent interbeds of fissile shale, and several interbedded thin beds of fossiliferous calcarenite in its upper third. The top of the member is placed at the base of the massive quartzite ledge, about 10 feet (3 m) thick, that forms the base of the Lehman Formation near Ibex. The calcisiltite member is 141 feet (43 m) thick.

Lehman Formation: This formation consists of interbeds of bluish-gray fossiliferous calcisiltite and calcilutite, brownish-gray sandstone and quartzite, and light-olive gray dolomitic limestone and dolomitic sandstone, in beds ranging in thickness from a few inches to a few feet. Orthid brachiopods and large bean-shaped ostracodes are abundant in some beds. Fossils are not silicified but include trilobites, bryozoans, gastropods, pelecypods, and, more rarely, cephalopods and corals. Faunal lists are presented in Hintze (1952). Descriptions of measured sections are given by Hintze (1951, 1973a). The Lehman Formation ranges in thickness from 168 feet (51 m) at Crystal Peak, 10 miles (16 km) southwest of Ibex, to 220 feet (67 m) near Ibex (Hintze, 1973a).

Eureka, Crystal Peak, and Watson Ranch Formations, undivided (Oew): The 1:100,000 scale of the geologic maps of Millard County does not allow the Eureka Quartzite, Crystal Peak Dolomite, and Watson Ranch Quartzite to be shown separately, so they have been combined under the map symbol Oew (figures 120-122). They are described below, and are shown separately on the more detailed geologic maps of western Millard County that are listed in the sources of geologic mapping. The Watson Ranch and Crystal Peak Formations are not recognized in eastern Millard County but their time-equivalent strata are included in the upper part of the undivided Pogonip Group (Michaels and Hintze, 1994). Ketner (1968) postulated a northern source for Ordovician quartzites in Nevada and Utah.

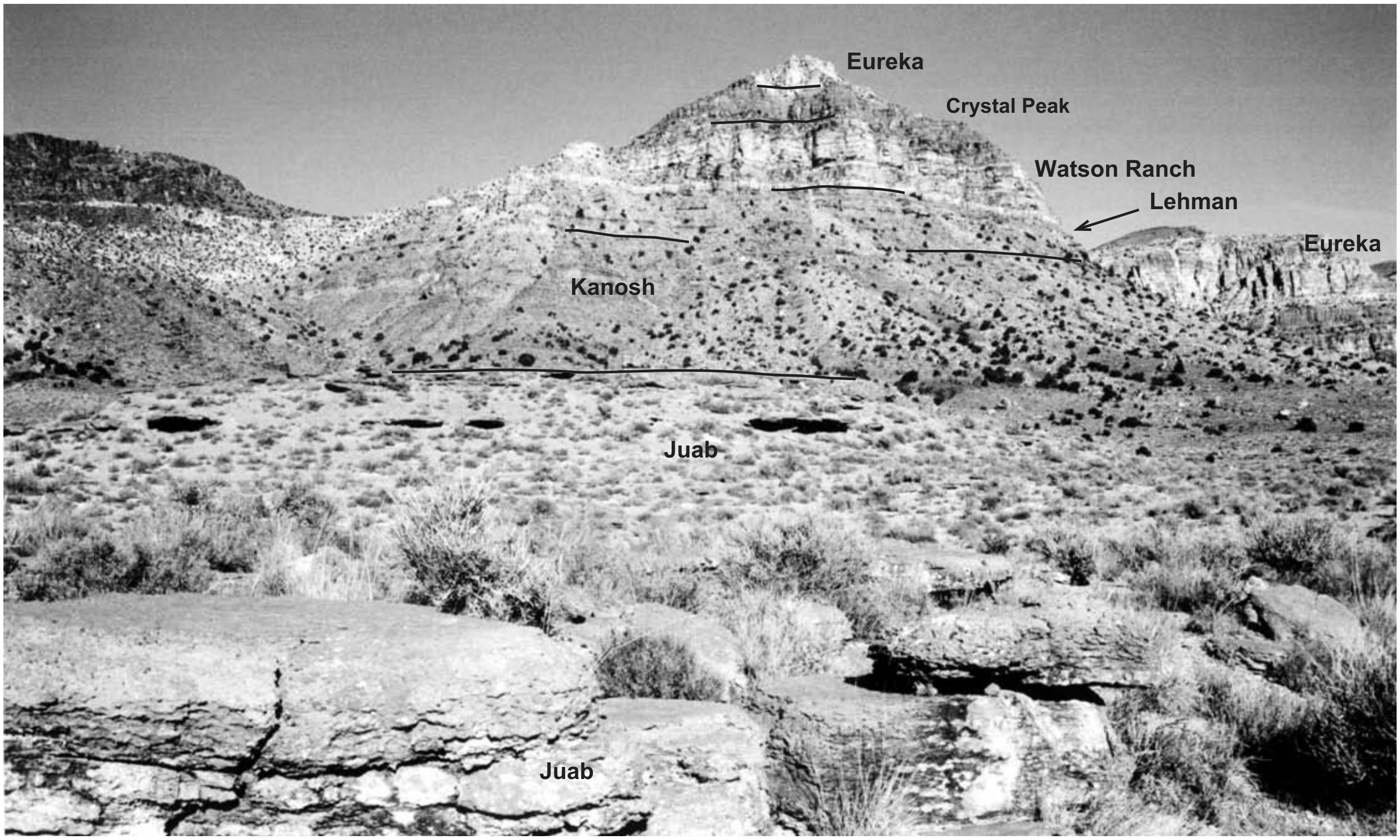


Figure 120. View looking roughly northwest at Fossil Mountain near Ibex in the southern Confusion Range. Ordovician Juab Limestone ledges in foreground. White peak top is Eureka Quartzite; gray ledges beneath are Crystal Peak Dolomite; light ledges beneath are Watson Ranch Quartzite; slopes to base of hill are Lehman Formation and Kanosh Shale.

Watson Ranch Quartzite: This is a light-gray, thin-to thick-bedded, generally vitreous quartzite that weathers reddish-brown and is locally cross-laminated. Contacts with both overlying and underlying formations are gradational; the Watson Ranch Quartzite includes a few interbeds of fossiliferous limestone of Lehman aspect near its base. Webb (1956) described the Watson Ranch Quartzite in western Millard County and showed the following thicknesses: 243 feet (74 m) near Ibex; 205 feet (62 m) at Crystal Peak; and 191 feet (58 m) west of Tule Valley.

Crystal Peak Dolomite: This finely crystalline, medium-gray dolomite weathers light-olive-gray and occurs in beds about a foot (0.3 m) thick. Locally, thin beds of blue-gray limestone and light-gray quartzite are interbedded with the dolomite. Silicified brachiopods identified by Jensen (1967) as *Orthambonites perplexus* (but now reassigned to the genus *Shoshonorthis*) are found in a thin zone in the lower 6 feet (2 m) of the formation; *Eofletcheria* corals (figure 110) are common in the upper third of the formation (Rigby and Hintze, 1977). Topographically, this formation usually forms a bench between more resistant quartzites. Webb (1956) described the Crystal Peak Dolomite in western Millard County and showed the following thicknesses: 85 feet (26 m) near Ibex; 89 feet (27 m) at Crystal Peak; and 61 feet (19 m) west of Tule Valley.

Eureka Quartzite: The light-orangish-brown cliffs of Eureka Quartzite stand out in prominent contrast to the gray colors of adjacent carbonate strata, making it easily identifiable from a distance. The Eureka is a medium- to fine-grained orthoquartzite and quartz sandstone, vitreous in part, white to light gray where unweathered, medium- to thick-bedded, and cliff-forming. Spherical pockmarks, about one-half inch (1 cm) in diameter, are numerous and characteristic of this formation. The upper and lower few feet are gradational into adjacent units. Webb (1956, 1958) interpreted this to be a transgressive beach sand. The Eureka is 535 feet (163 m) thick near Ibex, 563 feet (172 m) thick at Crystal Peak, and 380 feet (116 m) thick in the Confusion Range 20 miles (32 km) northwest of Ibex.

Eureka Quartzite in eastern Millard County (Oe): In eastern Millard County the Eureka Quartzite is composed of a lower light-gray, silty quartzite that weathers to light shades of pink, orange, or brown, and an upper white quartzite. Both parts form light-colored, resistant cliffs that contrast markedly with the darker Ordovician units above (Ofh) and below (Op). The quartzite is medium to coarse grained, and locally shows minor cross-bedding. Millard (1983) reported thicknesses of 63 feet (19 m) for the lower Eureka, and 161 feet (49 m) for the upper part as measured on the southeasternmost part of the Canyon Mountains; Michaels and Hintze (1994) reported thicknesses of 80 feet (24 m) for the lower part and 100 feet (30 m) for the upper part of the Eureka on the northwesternmost part of the Pahvant Range just east of Scipio Pass. Thicknesses in the southern Pahvant Range are 150 to 180 feet (45-55m) (column 3, appendix C). Tucker (1954) measured thicknesses of 236 and 394 feet (72 and 120

m) in the northern Pahvant Range.

Ely Springs Dolomite (Oes): In a regional stratigraphic study of Upper Ordovician through Middle Silurian dolomites in the eastern Great Basin, Budge and Sheehan (1980a-b) recommended that the Upper Ordovician dolomite near Ibex be called Ely Springs Dolomite, a name derived from southeastern Nevada. They recognized four members in the Ely Springs near Ibex: (1) a lower member, 31 feet (9 m) thick, characterized by frosted quartz sand grains suspended in a dolomite matrix, representing deposition on the disconformity above the Eureka Quartzite, and called the "Ibex Member;" (2) a dark-gray, finely crystalline, ledge- and cliff-forming dolomite 156 feet (48 m) thick, called the "Barn Hills Member;" (3) an interlayered light- and dark-gray, thin- to thick-bedded dolomite 231 feet (70 m) thick, called the "Lost Canyon Member;" and (4) an upper dark-brownish-gray, finely crystalline, lam-inated, thick-bedded to massive cliff-forming dolomite 134 feet (41 m) thick called the Floride Member, a name from the Thomas Range, Utah (Staatz and Carr, 1964). Dr. W. Britt Leatham, conodont paleontologist at California State University, San Bernardino, has reexamined Ely Springs Dolomite localities in the Great Basin that were studied by Budge and Sheehan (1980a-b); he stated (telephone communication, April 1994) that only the Floride Member can be accurately traced regionally. Therefore, the lower three members of Budge and Sheehan (1980a-b), Harris and Sheehan (1996, 1997), and Sheehan and Harris (1997) might be regarded as local informal units. In the above paragraph they are, therefore, shown in quotes. Budge and Sheehan (1980b) reported finding poorly preserved low-spired gastropods, pelmatozoan fragments, and dolomitized brachiopods, corals, and cephalopods in the Ely Springs Dolomite near Ibex. Hintze (1974a) reported the horn coral *Streptelasma* and the colonial coral *Paleofavosites* from the Floride Member near Ibex. Thickness of the Ely Springs is 552 feet (168 m) near Ibex (figures 121 and 122), and between 345 and 630 feet (105-192 m) elsewhere in western Millard County, as shown in columns 8 through10 (appendix C).

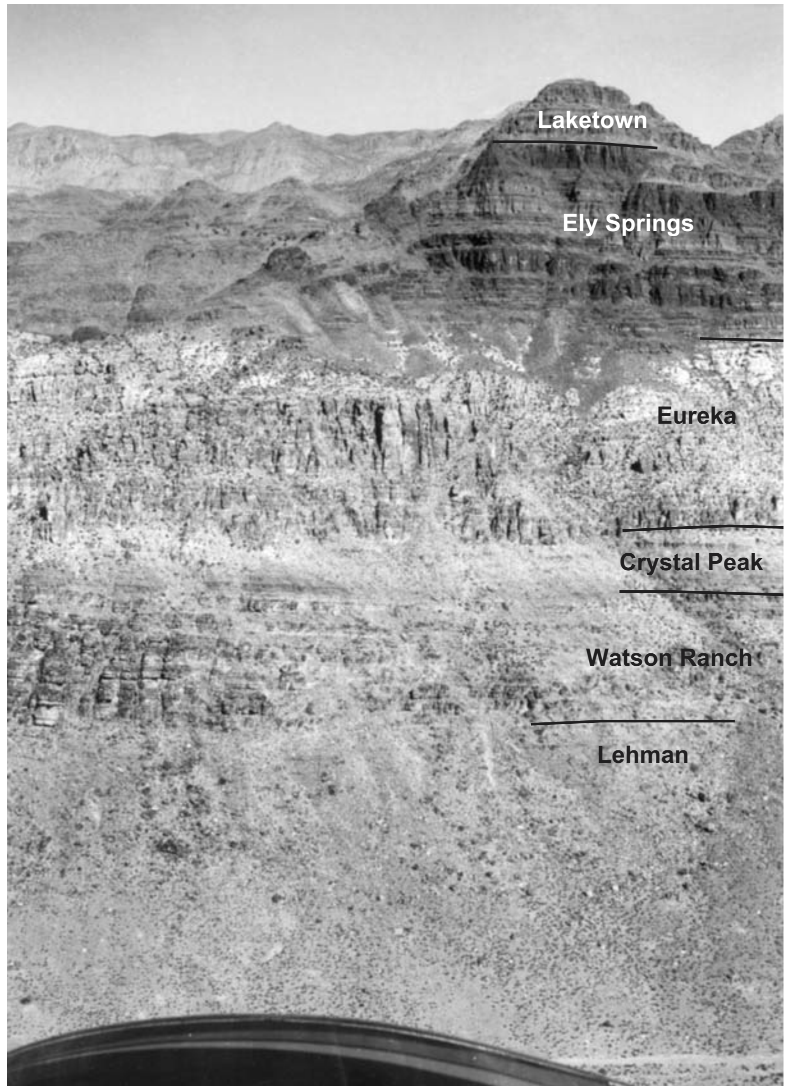


Figure 121. *Recessive, partly covered slope across the middle of the picture is the Crystal Peak Dolomite. Ledges below it are Watson Ranch Quartzite; Lehman Formation is mostly covered by quartzite talus in the bottom third of the picture. Eureka Quartzite forms cliffs above the Crystal Peak slope and grades upward to white slope below black ledges of the Upper Ordovician Ely Springs Dolomite. This is an aerial view looking north at the Camp section of Hintze (1973a) in the Barn Hills, about 2 miles (3 km) east of Watson's Ranch at Ibex.*

Fish Haven Dolomite (Ofh): Millard (1983) and Michaels and Hintze (1994) applied the name Fish Haven, from northern Utah, to Upper Ordovician dolomite in the southern Canyon Mountains and the northern Pahvant Range (column 1, appendix C). No special stratigraphic studies have been made of, nor definitive fossils reported from, the Fish Haven in eastern Millard County, so its age is uncertain. Michaels and Hintze (1994) presented a measured section near Scipio Pass that described the lower part of the Fish Haven Dolomite as medium-dark-gray to brownish-gray, fine-grained dolomite that weathers light-gray to light-olive-gray, thick-bedded, ledge-forming dolomite. These geologic mappers arbitrarily placed the boundary between the Fish Haven and Laketown Dolomites at the horizon at which the dolomite becomes cherty. Thus defined, the Fish Haven Dolomite here generally lacks chert, and Laketown Dolomite is cherty.

The Fish Haven Dolomite is 261 feet (79 m) thick in the northern Pahvant Range (Michaels and Hintze, 1994) and 138 feet (42 m) thick in the southern Canyon Mountains (Millard, 1983). In both places the Fish Haven Dolomite is locally extensively brecciated, so the difference in thicknesses given above is likely the result of tectonic thinning related to Mesozoic deformation.

Silurian-Ordovician

Ordovician-Silurian Transition

The lack of sandstone and shale in Upper Ordovician and Silurian strata in western Utah, and their dolomitic makeup suggests that they were deposited in the warm, shallow waters of an epicontinental sea that covered western North America. Utah lay at the equator and the closest

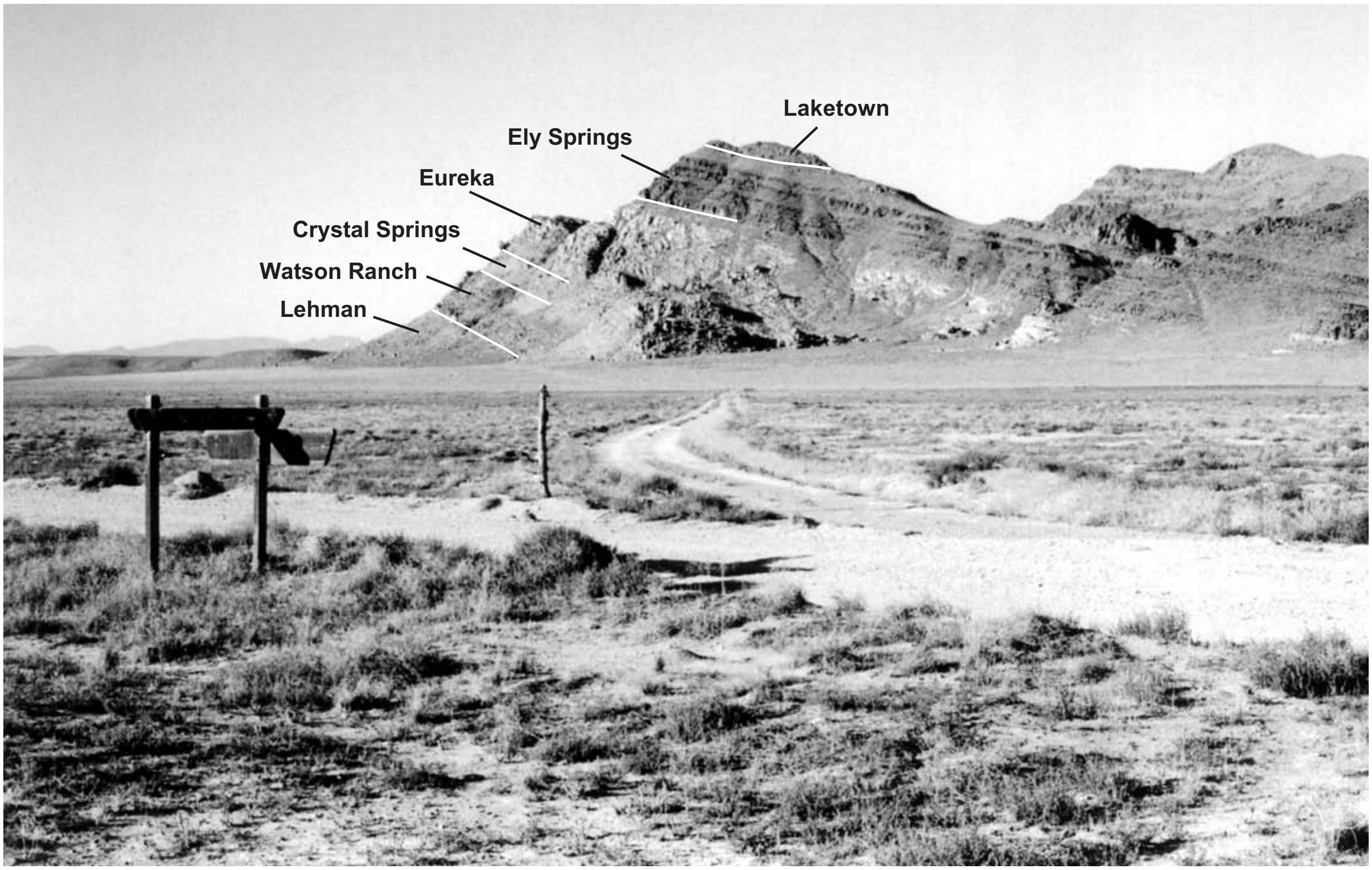


Figure 122. *Middle Ordovician Eureka–Crystal Peak–Watson Ranch Formations beneath the Upper Ordovician Ely Springs Dolomite, a profile view of the preceding photograph, looking west from 1.3 miles (2 km) south of the Ibex Well.*

mountains were far distant in what is now eastern North America (Hintze, 1988a). Given the similarity of upper Ordovician and Silurian dolomites in Utah, it would seem that they might represent continuous deposition. But, as shown in chart 3 (appendix C), a time interval of non-deposition occurred at the Ordovician-Silurian boundary. This gap is documented by the fossil record of mass extinction of Ordovician species and their later replacement by a Silurian fauna. Budge (1966) and Sheehan (1971) documented the changes in coral and brachiopod faunas across the Ordovician-Silurian boundary in the Great Basin. Leatham (1988) noted that Late Ordovician conodont faunas are typically impoverished in the Great Basin, with low diversity and sparse occurrence. Conversely, lowermost Silurian conodonts are fairly diverse and moderately common.

The Ordovician extinction coincided with a period of extensive glaciation in Africa and South America that resulted from worldwide cooling and that produced draining of the epicontinental seaways. Sheehan (1988) reviewed this phenomenon and presented an extensive reference list of publications pertinent to it.

Lithologic Units

Laketown and Fish Haven Dolomites, undivided (SOu): Because geologic mappers have found no consistent basis for separating Laketown from Fish Haven Dolomites in the southern Pahvant Range, Davis (1983) opted to apply the old term Bluebell Dolomite, used in the Tintic mining district for dolomites of Ordovician, Silurian, and Devonian age (Loughlin, 1919; Morris and Lovering, 1961). Because no Devonian strata are present in Davis' "Bluebell," the term "Laketown and Fish Haven Dolomites, undivided" is used in this bulletin. Davis (1983) described the strata as a dark-gray, cherty dolomite that contains laminated chert, algal boundstone, and sparse rugose corals. He reported a 566-foot (172.5 m) thickness, but Crosby's (1959) estimate of 1,000 feet (300 m) seems more reasonable.

Laketown and Ely Springs Dolomites, undivided (SOu): This unit was used only in the vicinity of Mile-and-a-Half Canyon in the Confusion Range (Tule Valley geologic map; Hintze and Davis, 2002c) where the geology is complex due to thrust fault "slivers" along the Kings Canyon thrust.

Silurian

Introduction

Silurian strata are exposed in several mountain ranges as shown on figure 123. Silurian stratigraphy is Utah's simplest: it consists of one lithology, dolomite, assigned mostly to one formation, the Laketown Dolomite, as shown on chart 3 (appendix C) and columns 1, 8, 9, and 10 (appendix C). In

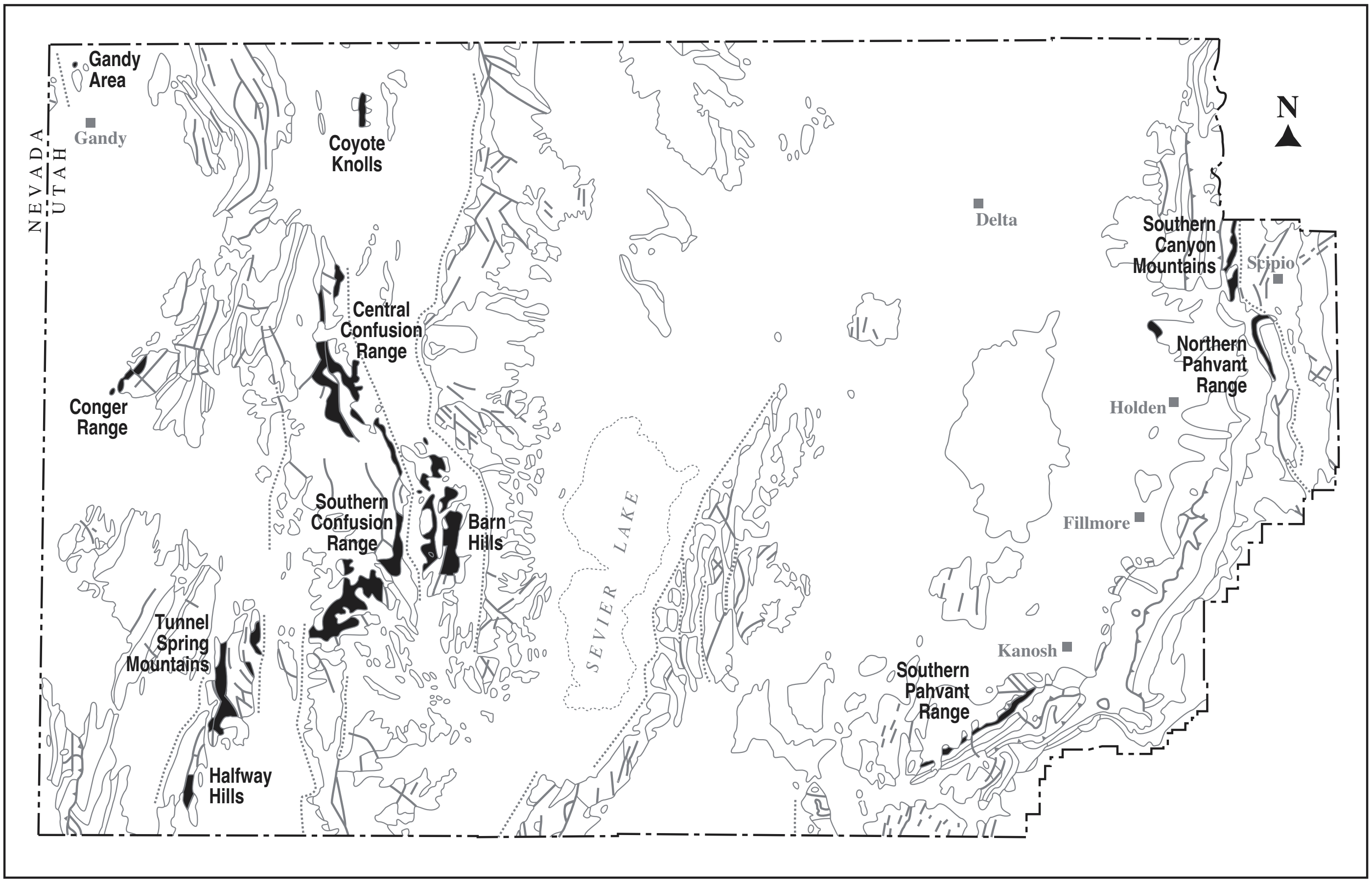


Figure 123. Silurian outcrops in Millard County.

contrast to the abundance of fossils in Cambrian and Ordovician strata in western Utah, Silurian dolomites contain fewer fossils, and most of those are poorly preserved (Sheehan and Harris, 1997). Locally, some corals and brachiopods are well preserved by silicification, but the limited marine environment represented by the dolomite was not conducive either to sustaining or to preserving many life forms.

Laketown Dolomite (Sl)

The Laketown Dolomite was named in northeastern Utah where it is generally a light-gray dolomite. In western Utah the dolomite is color-banded, ranging from dark-brownish-gray to light-gray, and including orange-pinkish-gray bands in its upper part (figure 124). Staatz and Carr (1964) mapped four separate formations within the Laketown interval in the Thomas and Dugway ranges north of Millard County. These map units were reduced in rank to members of the Laketown Dolomite on maps by Dommer (1980) and Hintze (1980b). Rush (1956) and Budge and Sheehan (1980a-b) proposed six different members of the Laketown Dolomite in western Utah, based on stratigraphic and petrologic studies, but the mappability of these units has never been demonstrated, and they are not perpetuated herein. The Laketown has not been subdivided in this study.

In the Confusion Range (columns 8 and 9, appendix C) the Laketown Dolomite is about 1,000 feet (300 m) thick. Its lower half is a dark-gray, sparsely cherty, medium to finely crystalline dolomite that weathers dark-brownish-gray and forms ledges capped by a 100-foot (30 m) cliff. The lower half of the Laketown commonly bears poorly preserved corals, dasycladacean algae, and the brachiopods *Virgiana* and *Pentamerus* in thin zones, about 200 feet (61 m) and 400 feet (122 m), respectively, above the base of the formation.

The lower part of the upper half of the Laketown contains two prominent pinkish-gray marker beds. The lower one is about 30 feet (10 m) thick and is separated from the upper, 125-foot (38-m) thick, pinkish-gray horizon by 110 feet (34 m) of dark dolomite. The upper quarter of the Laketown Dolomite contains as much as 20 percent bedded chert nodules in some beds, but averages about 5 percent chert. The uppermost 80 feet (24 m) of Laketown contains a well-preserved silicified brachiopod-coral fauna (figures 125 and 126) (*Howellella*, *Douvillina*, *Zeleophyllum*) described by Waite (1956).

Measured sections of Laketown Dolomite are given in Budge and Sheehan (1980b). The Laketown Dolomite is 920 to 1,100 feet (280-335 m) thick in the northern and central Confusion Range, about 1,000 feet (300 m) thick in the southern Confusion Range, and 1,560 feet (474 m) thick in the Tunnel Spring Mountains.

In eastern Millard County the Laketown Dolomite forms massive cliffs on the southeast end of the Canyon Mountains (Millard, 1983) and the north end of the Pahvant Range (Michaels and Hintze, 1994). At these locations it is a medium- to dark-gray, thick-bedded, cherty dolomite that contains

Figure 124. *Silurian Laketown Dolomite in the Barn Hills 50 miles (80 km) west of Delta Utah; view roughly to west. Light gray rocks capping the hills from photo center to right edge are Sevy Dolomite. Banded rocks below are all Laketown Dolomite. Hill just beyond playa is down-faulted block of upper Laketown. Upper Ordovician Ely Springs Dolomite forms darkest ledges at base of hill in the right quarter of the photo.*

Figure 125. Howellella pauciplicata *Waite; Laketown Dolomite.*

Figure 126. *Favosites, the "honeycomb" coral; Laketown Dolomite.*

sparse poorly preserved brachiopods and horn corals. Millard (1983) measured 1,092 feet (333 m) of Laketown, and Michaels and Hintze (1994) measured 832 feet (254 m) of Laketown.

Devonian

Introduction

Devonian strata are widely exposed in western Millard County (figures 127 and 128) where they are more than 5,000 feet (1,525 m) thick. They are absent in central Mil-

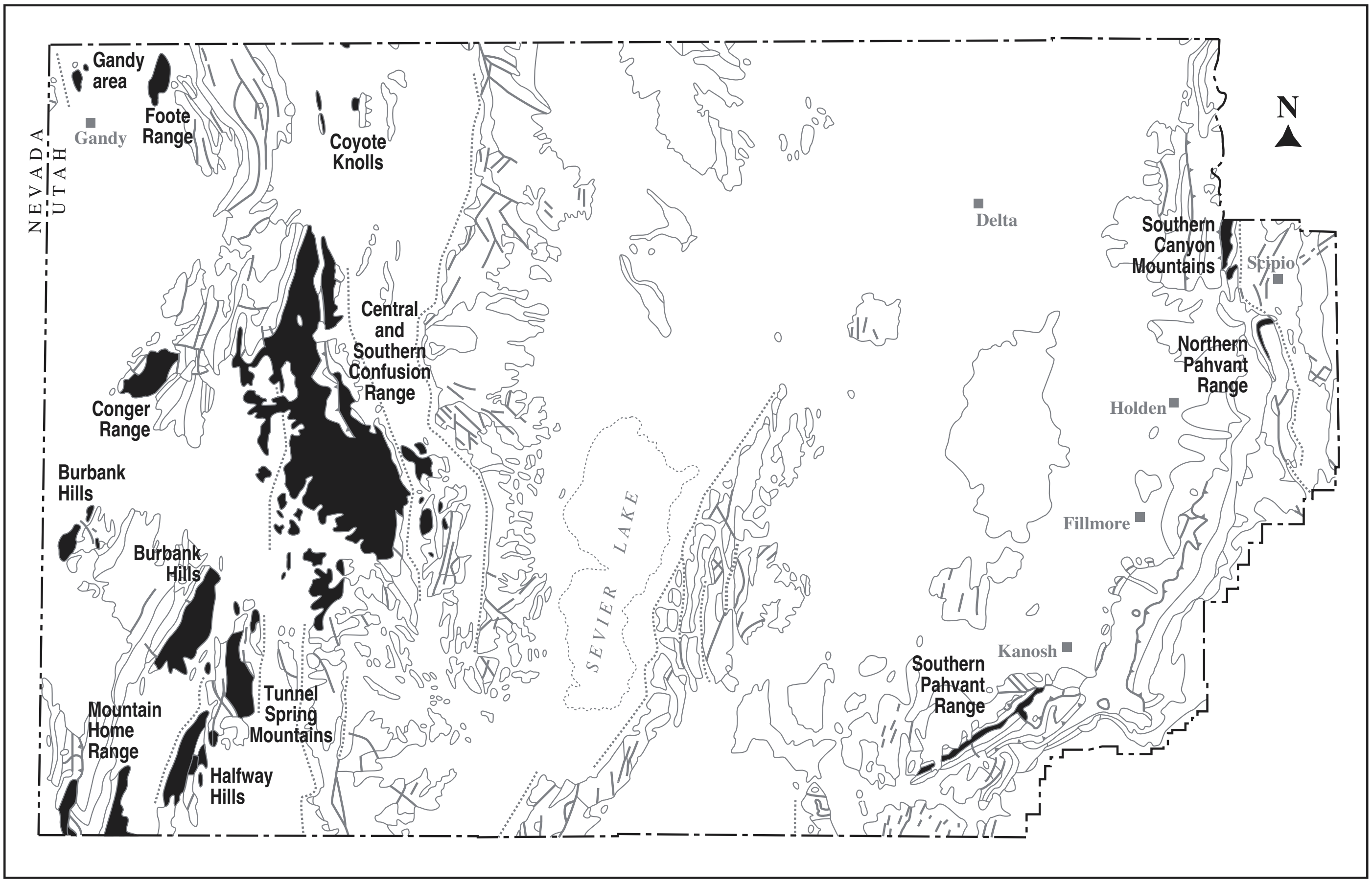


***Figure 127**. Devonian outcrops in Millard County.*

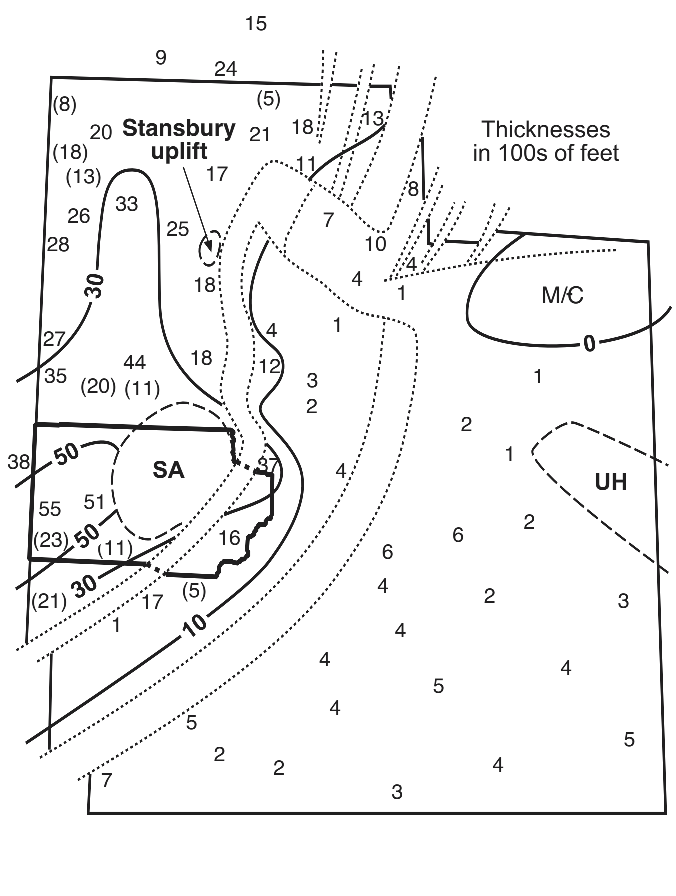


***Figure 128**. Distribution and thicknesses of Devonian rocks in Utah; numbers in parentheses indicate location where the rocks are only partially preserved, and gaps and distortion in map are due to post-Devonian folding and faulting (modified from Hintze, 1988a). Millard County outline is bold. In west-central Utah, these strata follow the typical early Paleozoic pattern: thin in eastern Utah, but thousands of feet thick in western Utah. Devonian rocks are chiefly dolomite and limestone, but quartz sandstone and silty shale beds appear in the upper Devonian as a result of the Stansbury uplift in Utah and the Antler orogeny in Nevada. SA shows the location of the Sevier Arch, a Mesozoic positive area from which Devonian strata were removed. UH shows the Uncompahgre Highland, a late Paleozoic uplift. Mississippian rocks rest unconformably on Cambrian strata (M/Є) in the eastern Uinta Mountains area.*

lard County, having been removed by erosion during Late Mesozoic time from an uplifted area called the Sevier arch (Harris, 1959). In eastern Millard County, Devonian strata are present above the Pavant thrust in the Canyon Mountains where they are 3,240 feet (1,065 m) thick (column 1, appendix C). In the southern Pahvant Range, Devonian strata are present in a deformed belt beneath the Pavant thrust where they are 1,635 feet (448 m) thick (column 3).

Chart 4 (appendix C) shows the names applied to Devonian strata in Millard County. Three names are widely used: Sevy Dolomite, Simonson Dolomite, and Guilmette Formation. Changing conditions of deposition in Late Devonian time produced different kinds of deposits as reflected in the Upper Devonian lithologic nomenclature on chart 4.

Devonian Fossil Life

Except for the Sevy Dolomite, fossils are common in Devonian strata. Stromatoporoids are probably the most easily noticed fossils in the Simonson and Guilmette Formations. They come in two shapes: the most common form looks like tangles of spaghetti (figure 129), and a larger form that looks like fossilized brussels sprouts. The latter has attracted the interest of petroleum geologists, because in Alberta, Canada, this kind of stromatoporoid forms porous reef rocks that contain oil. Certain horizons in the Middle and Upper Devonian strata bear corals, brachiopods, bryozoans, and cephalopods that have been used in the past as guides to the age of Devonian rocks. But in the last few decades, microscopic tooth-like conodont fossils (figure 130) have become the most definitive fossil with which to assign age to the Devonian strata. Chart 4 (appendix C) shows 33 conodont zones that permit determining the age of Devonian strata almost to the nearest one million years, according to Sandberg and others (1997).

Figure 129. Amphiora*, the "spaghetti" stromatoporoid, common enough in upper Devonian carbonates to serve as a useful means of telling them from similar rocks of Cambrian age in areas of structural complexity.*

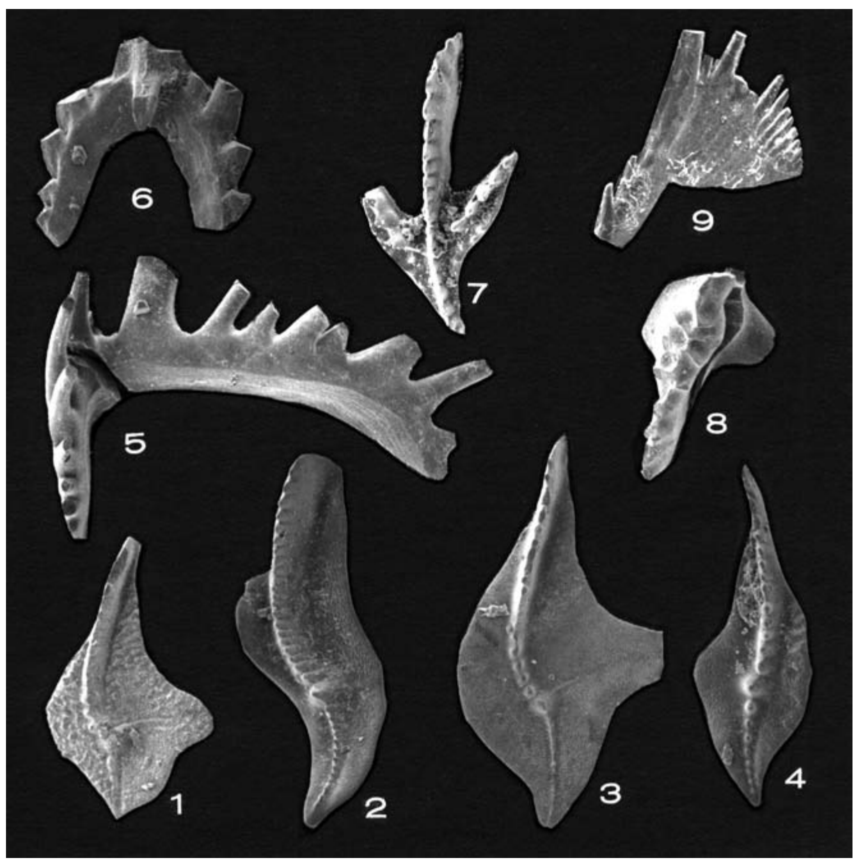


Figure 130. *Photomicrographs of typical Devonian conodonts. Photos and identifications furnished by Professor Scott Ritter, Department of Geology, Brigham Young University, about X40: 1, 2, 3, 4, 9,* Palmatolepis*; 5, 6, unidentified ramiform conodonts; 7,* Ancyrodella*; 8,* Icriodus.

Lithologic Units

Sevy Dolomite (Dsy): The Sevy (pronounced <u>see</u>vee) Dolomite was named by Nolan (1935) in the Deep Creek Range in western Utah. Osmond (1954, 1962) detailed its extent throughout 100,000 square miles (259,000 km^2) in California, Nevada, Utah, and Idaho, where it unconformably(?) overlies Silurian dolomite (figures 5 and 131) and is overlain by middle Devonian dolomite.

In Millard County the Sevy is easily recognized by its uniform light-gray color, regular bedding in beds up to about 2 feet (0.6 m) thick, and its fine-grained faintly laminated texture. In its uppermost part it includes scattered thin horizons of rusty-weathered frosted quartz sand grains of wind-blown origin that commonly float as thin seams or individual grains in the dolomite matrix.

Fossils are completely lacking in most Sevy exposures, but Davis (1983) reported fragments of fish from a thin bed about 100 feet (30 m) above the base of the Sevy in the southern Pahvant Range. Elliott and Johnson (1997) collected

Figure 131. Silurian-Devonian contact exposed along U.S. Highway 6-50 in Kings Canyon; view down canyon to the east. Fossiliferous Silurian Laketown Dolomite forms the dark cliffs; overlying light ledges are unfossiliferous Sevy Dolomite, regionally assigned to the Lower Devonian.

fish fragments from this locality and reported the following fish types: two pteraspids, two cyathaspidids, a cephalaspid, a placoderm, and an acanthodian. Ilyes and Elliott (1992) traced the Devonian fish horizon from Utah to Death Valley, California, and concluded that the fish probably lived in brackish estuaries during a brief part of Emsian (Early Devonian) time.

Osmond (1954) described a 1,600-foot (488-m) thick measured section of Sevy Dolomite near U.S. Highway 6-50 at the head of Kings Canyon in the Confusion Range (figure 132), and this has become the standard reference section for the Sevy in western Millard County because it appears to be unfaulted, or nearly so. Detecting faults within the Sevy Dolomite is difficult because the formation is so homogeneous that faults within the formation may go unnoticed. Hose (1966) summarized the lithologic content of Sevy Dolomite in the southern and central Confusion Range and gave 1,300 feet (396 m) as a representative thickness there. In the southern Pahvant Range (column 3, appendix C) the Sevy is 710 feet (216.5 m) thick (Davis, 1983).

Simonson Dolomite (Ds): The Simonson Dolomite was named by Nolan (1935) in the Deep Creek Range in western Juab County, Utah. Osmond (1954) detailed lithologic aspects and petroleum potential of the Simonson from a score of measured sections in western Utah and eastern Nevada. Osmond's (1954) description of the Simonson at the head of Kings Canyon near U.S. Highway 6-50 has become the standard reference section for the Simonson Dolomite in western Millard County. Osmond (1954) recognized four informal members of regional extent within the Simonson Dolomite: (1) a basal, tan, coarsely crystalline, cliff-forming dolomite, 59 feet (18 m) thick at Kings Canyon; (2) a lower alternating gray- and brown-striped, heterogenous dolomite, 582 feet (177 m) thick at Kings Canyon; (3) a brown, cliff-forming, biostromal dolomite, 49 feet (15 m) thick at Kings Canyon; and (4) an upper alternating gray- and brown-striped, heterogenous member, 239 feet (73 m) thick at Kings Canyon.

Hose (1966) summarized Simonson stratigraphy in the Confusion Range in Millard County and noted that the Simonson thins northward, averaging about 660 feet (201 m) thick. Hose (1966) noted that the brown cliff-forming member averages about 40 feet (12 m) thick and contains abundant gastropods, cephalopods, stromatoporoids, and sparse brachiopods in its upper part. The upper alternating member, averaging about 200 feet (61 m) thick in the northern Confusion Range, contains *Cladopora*, *Syringopora*, *Favosites*, *Thamnopora*, *Alveolites*, *Atelophyllum*, *Atrypa*, *Paracyclas*, *Productella*, and "*Martinia*." The upper 10 feet (3 m) yielded the guide brachiopod *Stringocephalus*.

The Simonson Dolomite is about 660 feet (200 m) thick in the Burbank Hills, 540 to 700 feet (165-213 m) thick in the Confusion Range, and 185 feet (56 m) thick in the southern Pahvant Range.

Lower Guilmette, Simonson, and Sevy equivalents, undivided (Dss): Millard (1983) reported a thickness of about 2,720 feet (830 m) for a light-gray sequence of Devonian dolomites, which he called "Sevy" on the northeast side of the Canyon Mountains. This thick sequence of Sevy-like dolomites probably includes the temporal equivalents of the Sevy, Simonson, and lower Guilmette Formation, but the sequence is unfossiliferous. The overlying 774 feet (236 m) of brown sugary dolomite (Dgu) is probably equivalent to the upper part of the Guilmette Formation of western Millard County.

Guilmette Formation (Dg, Dgu, Dgw, Dgm, Dgb): The Guilmette Formation was named by Nolan (1935) in the Deep Creek Range of western Juab County, Utah, and the name has since been widely applied to 2,000 to 3,000 feet (600-900 m) of dolomite, limestone, and, in its upper part,

Figure 132. Sevy Dolomite forms gentle slopes with low ledges, looking southward from milepost 24 on U.S. Highway 6-50 at the head of Kings Canyon.

sandstone in western Utah and eastern Nevada. Geologic mappers have subdivided the Guilmette locally into informal members, some of which are thick enough to show on the 1:100,000-scale maps of the County (units Dgu, Dgw, Dgm, Dgb; Hintze and Davis, 2002a-c; Hintze and others, 2003). Because these members are restricted in their occurrence, the discussion below deals with them separately in the four areas in Millard County in which they occur.

In eastern Millard County (columns 2 and 3, appendix C), dark-gray, stromatoporoid-bearing dolomite is present beneath the Devonian Cove Fort Quartzite in the Canyon Mountains (Dgu) (Millard, 1983) and southern Pahvant Range (Dg) (Davis, 1983), where it is 774 and 575 feet (236 and 175 m) thick, respectively. These thickness are markedly thinner than the equivalent Guilmette strata in western Millard County. The dolomite includes thin lenticular beds of quartz sand and sandy dolomite. Millard (1983) called this unit "Simonson," but it is probably better included in the Guilmette. Diagnostic fossils have not been collected from the Guilmette Formation in eastern Millard County, but conodonts could likely be obtained from some of its beds.

In the Confusion Range (columns 8 and 9, appendix C), Hose (1966) recognized four unmapped units within the Guilmette (Dg) near Little Mile-and-a-Half Canyon, in ascending order:

(1) A basal 650 feet (198 m) of dark-gray, fine-grained limestone that is locally a breccia formed by solution collapse at some period before or during the deposition of the overlying Guilmette units.

(2) A 700-foot (213-m) thick, dark-gray, locally mottled and argillaceous, thin- to medium-bedded limestone that includes some dolomite beds.

(3) An 800-foot (244-m) thick sequence of fine- to medium-grained, medium- to dark-gray dolomite that weathers light olive gray to brownish black and includes a few beds of light-gray coarse-grained dolomite. Stromatoporoids of both the "worm-like" *Amphipora* type, and the concentric spheroidal *Stromatopora* type, are abundant, and corals, bryozoans, and brachiopods are present locally in unit 3.

(4) 450 feet (137 m) of mostly thin-bedded, medium-gray limestone that includes beds of dolomite and several beds of brown-weathering quartzite as much as 3 feet (1 m) thick.

Fossils are common in the upper unit of the Guilmette and include *Tenticospirifer*, *Productella*, *Atrypa*, *Spirifer*, *Hypothyridina*, *Manticoceras*, *Thamnopora*, and *Alveolites*. Biller (1976) made conodont collections from the upper 534 feet (163 m) of the Guilmette in Little Mile-and-a-Half Canyon to enable correlation of these rocks with standard conodont zonation schemes. Sandberg and others (1997) updated these assignments.

Larsen and others (1988) described the repeated depositional cycles in the upper 2,000 feet (600 m) of the Guilmette Formation in the central Confusion Range (figure 133). They noted that shallowing-upwards transgressive-regres-

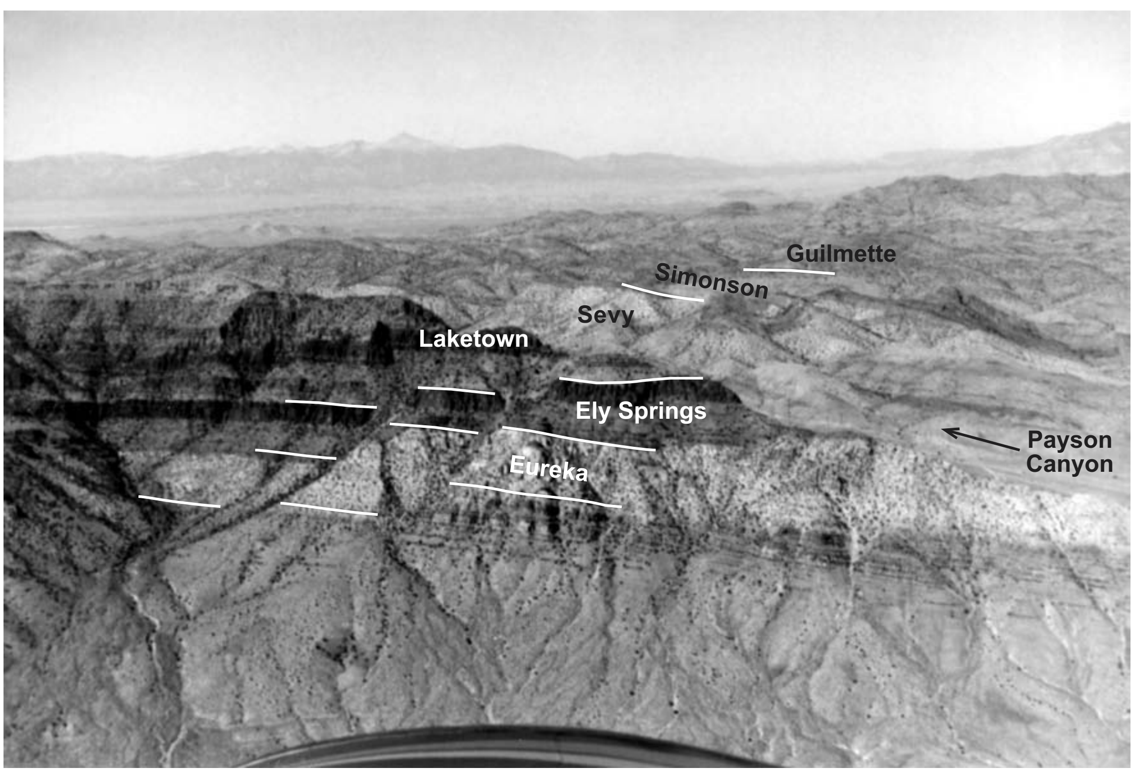


Figure 133. Aerial view of the Confusion Range looking westward from Tule Valley across Payson Canyon. Canyon and structural geologic complications in the canyon are mostly obscured. Light cliffs in foreground are Eureka Quartzite; dark bands above are Upper Ordovician Ely Springs Dolomite and Silurian Laketown Dolomite; low topography beyond Laketown in light-gray Sevy Dolomite; medium-gray hills in mid-distance are Simonson and Guilmette Formations on the east limb of the Confusion Range synclinorium. Thicknesses of stratal units are given in column 8 (appendix C).

sive cycles average 36 feet (11 m) thick in the upper Guilmette. Lithofacies indicate that the depositional environment generally deepens upsection.

The thickest deposits of Guilmette Formation in Utah are in the Burbank Hills (column 10, appendix C) where it has been divided into a lower breccia member (Dgb), middle member (Dgm), and West Range Limestone Member (Dgw). The lower member of the Guilmette is a limestone breccia 330 to 660 feet (100-200 m) thick and is similar to the basal breccia described in the Confusion Range discussion. The lowest 300 feet (91 m) of the middle member include a basal 150 feet (46 m) of thick-bedded, dark-gray dolomite that contains sparse silicified brachiopods, overlain by 150 feet (46 m) of silty, red-weathering, thin-bedded, slope-forming dolomite that includes a few ledges as much as 2 feet (0.6 m) thick of dark-gray dolomite. Biller (1976) described in detail the remainder of the middle member of the Guilmette Formation and the lower 387 feet (118 m) of the West Range Limestone Member. He measured the uppermost part of the middle member twice, not recognizing he had crossed a fault. So the total middle member is 2,958 feet (902 m) thick (Hintze, 1997d). The West Range Limestone Member is mostly fossiliferous, thin-bedded, medium-gray limestone interbedded with calcareous siltstone, shale and quartz-sandy limestone, and is 860 feet (260 m) thick near Big Jensen Pass (Hintze, 1997d). Biller (1976, plate 1) showed the entire thickness of the West Range Limestone Member as 633 feet (193 m) on his regional correlation plate, which was taken from an unpublished stratigraphic section measured by C.A. Sandberg, F.G. Poole, and E.J. Biller of the U.S. Geological Survey. Sandberg and others (1989) showed that the West Range Limestone Member in the Burbank Hills contains the *Palmatolepis rhomboidea* and *P. crepida* conodont zones and is, therefore, equivalent in age to the lower member of the Pilot Shale in the Confusion Range, as shown on the Devonian correlation chart (chart 4, appendix C).

The base of the Guilmette Formation is not exposed in the Mountain Home Range (column 11, appendix C) and the Wah Wah Mountains North geologic map only shows two subdivisions of the Guilmette Formation in this range (Dgw, Dgm), as well as the undivided Guilmette (Dg)(Hintze and Davis, 2002a). Hintze (1986a) and Hintze and Best (1987) mapped three units within the Guilmette here: a lower member, a middle sandstone member, and an upper West Range Limestone Member. The lower member is at least 1,300 feet (400 m) thick, consisting mostly of dark- to medium-gray, coarsely crystalline, medium- to thick-bedded dolomite and limestone, with several interbeds of brown-weathering quartzite, as much as 10 feet (3 m) thick, in the upper 550 feet (170 m). Stromatoporoids resembling spaghetti are common in both limestone and dolomite beds. The overlying sandstone member is about 130 feet (40 m) thick, light-brownish-gray, fine-grained, dolomitic sandstone, with about 20 percent interbeds of sandy dolomite. The lower and sandstone members comprise the middle member map unit (Dgm) on the Wah Wah Mountains North geologic map (Hintze and Davis, 2002a). The West Range Limestone Member (Dgw) is 260 to 400 feet (80-120 m) thick and consists of brachiopod-bearing bluish-gray, thin-bedded, shaly limestone with a few thick-bedded, ledge-forming beds.

Cove Fort Quartzite (Dc): Crosby (1959) named the Cove Fort Quartzite in the southern Pahvant Range where it is 85 to 160 feet (26-49 m) thick and consists of a basal yellowish-gray clean quartzite, overlain by quartzite interbedded with limestone and dolomite.

The Cove Fort Quartzite was mapped by Millard (1983) in the Canyon Mountains where it is at least 250 (77 m) thick and consists of thin-bedded, pale-orange sandstone and sandy dolomite interbedded with thick-bedded, light-grayish-orange-pink, fine-grained quartzite.

Although sandstone and quartzite beds, some of which are as thick as the Cove Fort Quartzite, are found in the upper part of the Guilmette Formation in western Millard County, the name Cove Fort has not been used there because the Guilmette clastics are older than the Cove Fort Quartzite as shown on chart 4 (appendix C).

Biller (1976) measured 79 feet (24 m) of limestone above the Cove Fort Quartzite in the southern Pahvant Range and identified conodonts from it that are equivalent in Devonian age to those in the Pinyon Peak Limestone of the Tintic mining district in Juab County (see column 3, appendix C). On the Richfield 1:100,000-scale geologic map (Hintze and others, 2003) this interval is included in the Redwall Limestone as done by Davis (1983).

Mississippian-Devonian

Pilot Shale (MDp)

The Pilot Shale was named by Spencer (1917) in the Ely mining district, Nevada, and has subsequently been identified in many parts of eastern Nevada and western Utah. The Pilot Shale is found in the Mountain Home Range (column 11, appendix C), Burbank Hills (column 10), and the Confusion Range (column 8), but does not extend into eastern Millard County. Only a small part of the formation is actually shale; most of it consists of yellow- and orange-weathering, thin-bedded, silty limestone with thin interbeds of shale, siltstone, sandstone, and limestone. It is less resistant than the Guilmette Formation beneath and the Joana Limestone above, so it forms strike-valleys and covered slopes wherever it occurs.

Hose (1966) described Pilot Shale occurrences in the Confusion Range where it ranges from about 700 feet (215 m) to as much as 830 feet (250 m) thick, and consists mostly of siltstone and dolomite siltstone. Sandberg and others (1988, 1997) described an unusual partial section of Pilot in the Coyote Knolls (figure 134) just east of the Confusion Range where the formation is mostly turbiditic siltstone and sandstone with thin interbeds of limestone. Sandberg and others (1980) listed conodont faunas and identified the unconformities within the Pilot Shale. Sandberg and others (1989) identified conodonts that show that the lower member of the Pilot Shale in the Coyote Knolls and the Confusion Range is equivalent to part of the upper Guilmette Formation, including its West Range Limestone Member, in the Burbank Hills as shown on chart 4 (appendix C). Sandberg and Poole (1992) summarized the tectonic and environmental conditions related to the Antler Orogen in central Nevada that controlled the deposition of the Pilot Shale. Giles (1994), and Giles and Dickinson (1995) reviewed the work of the authors named above.

In the Burbank Hills, the Pilot Shale is 511 feet (156 m) thick (Biller, 1976, plate 1) and is composed mostly of thin-

Figure 134. *View eastward within Coyote Knolls towards the House Range; the knolls are located in Tule Valley just east of the Confusion Range. Resistant dark beds holding up the hogback are uppermost Guilmette Formation carbonates. The thin-bedded, light-colored strata on the backslope are sandstones of the Pilot Shale as described by Sandberg and others (1988). White outcrops in the foreground and to the east in Tule Valley are Quaternary Lake Bonneville deposits.*

bedded calcareous siltstone and shale in its lower two-thirds; its upper one-third is thin-bedded silty limestone and limestone. Gutschick and Rodriquez (1979) have described the biota of the upper part of the Leatham Member.

In the Mountain Home Range, the Pilot Shale was mapped by Hintze (1986a) and Hintze and Best (1987). It is 360 feet (110 m) thick and consists of thin-bedded siltstone and silty limestone.

Mississippian

Introduction

Mississippian strata are exposed in three ran-ges in western Utah (col-umns 8, 10, and 11, ap-pendix C) where Paleozoic and Triassic rocks are preserved in the large late Mesozoic synclin-orium that extends ac-ross western Millard County in a northeaster-ly trending arc from the Mountain Home Range on the south to the northern Confusion Range on the north. Mississippian strata, which once covered central Millard County, were removed during Cretaceous time over the Sevier arch, and are, therefore, not present in the subsurface of this part of the county (figure 135). Mississippian limestone is present in the southern Pahvant Range (column 3). Figure 135 shows that Mississippian deposits, mostly limestones, are widely distributed in Utah and are generally thicker in western Utah than to the east.

Distribution of the Lower Mississippian Joana and Redwall Limestones is shown on figure 136. The Lower Mississippian Joana Limestone is part of a carbonate blanket deposit that is widely distributed in western North America and is known by such names as Madison Limestone in Montana and Wyoming, Lodgepole Limestone in Idaho and northern Utah, Gardison Limestone in central Utah, Leadville Limestone in Colorado, Redwall Limestone in Arizona and southern Utah, and Monte Cristo Limestone in Nevada.

The Chainman Formation is shown separately on figure 137 in order to emphasize the fact that the Chainman, regarded as a potential source rock for oil, is not present in eastern Millard County. The non-carbonate deposits within the Chainman Formation were derived from erosion of an orogenic highland area that formed in middle and late Mississippian time in central Nevada.

Mississippian Fossil Life in Western Utah

The Chainman Formation in western Millard County is notably fossiliferous and has yielded many kinds of marine invertebrates to professional paleontologists and amateur collectors. Those fossils most useful as guides to time include conodonts, ammonoids, corals, and foraminifera, as shown on chart 5 (appendix C). However, brachiopods are present in great variety and abundance, crinoid columnals are also abundant, and blastoids, gastropods, bryozoans, pelecypods, and trilobites are all present in the Chainman Formation. In some localities, particularly in the Jensen Member, these fossils weather free from their shaly matrix and are easy to collect. Because of the abundance and variety of fossils in the Chainman Formation of western Millard County, many fossil species have been identified or described as discussed below. The area has been studied by paleontological specialists concerned with establishing the Mississippian-Pennsylvanian boundary in the eastern Great Basin (Webster and others, 1984).

Conodonts: Studies in the past two decades by Charles A. Sandberg of the U.S. Geological Survey have resulted in the establishment of the 16 conodont zones for the western United States as shown on chart 5 (appendix C) (Poole and Sandberg, 1991). The microscopic tooth-like conodont fossil (figure 138) has become one of the most useful time indicators in Paleozoic strata, supplementing the microscopic foraminiferal (foram) zones of Mamet and Skipp (1970), the

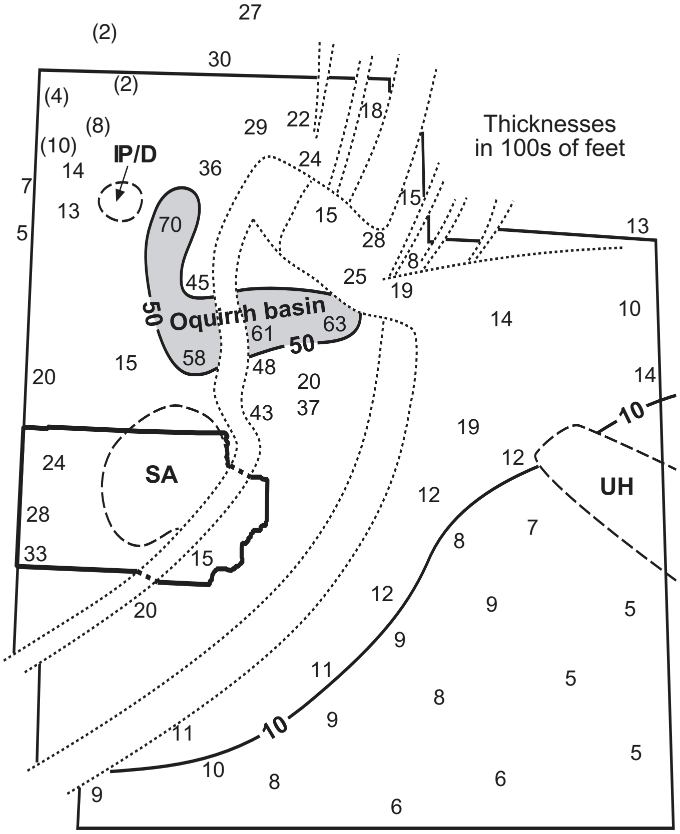


Figure 135. Distribution and thicknesses of Mississippian rocks in Utah; numbers in parentheses indicate locations where the rocks are only partially preserved, and gaps and distortion in map are due to post-Mississippian folding and faulting (modified from Hintze, 1988a). Millard County outline is bold. These rocks, mostly limestones, show a change in thickness pattern from that of earlier Paleozoic deposits because the late Paleozoic Oquirrh basin made its first appearance. Mississippian rocks are as much as 7,000 feet (2,100 m) thick in the basin and include deposits representing the entire span of Mississippian time, one of the most complete records of this interval in North America. SA indicates the Sevier arch, a late Mesozoic positive area. IP/D on the map indicates the area in the Newfoundland Mountains where Mississippian rocks are absent between Devonian and Pennsylvanian strata. UH indicates the Pennsylvanian Uncompahgre Highland.

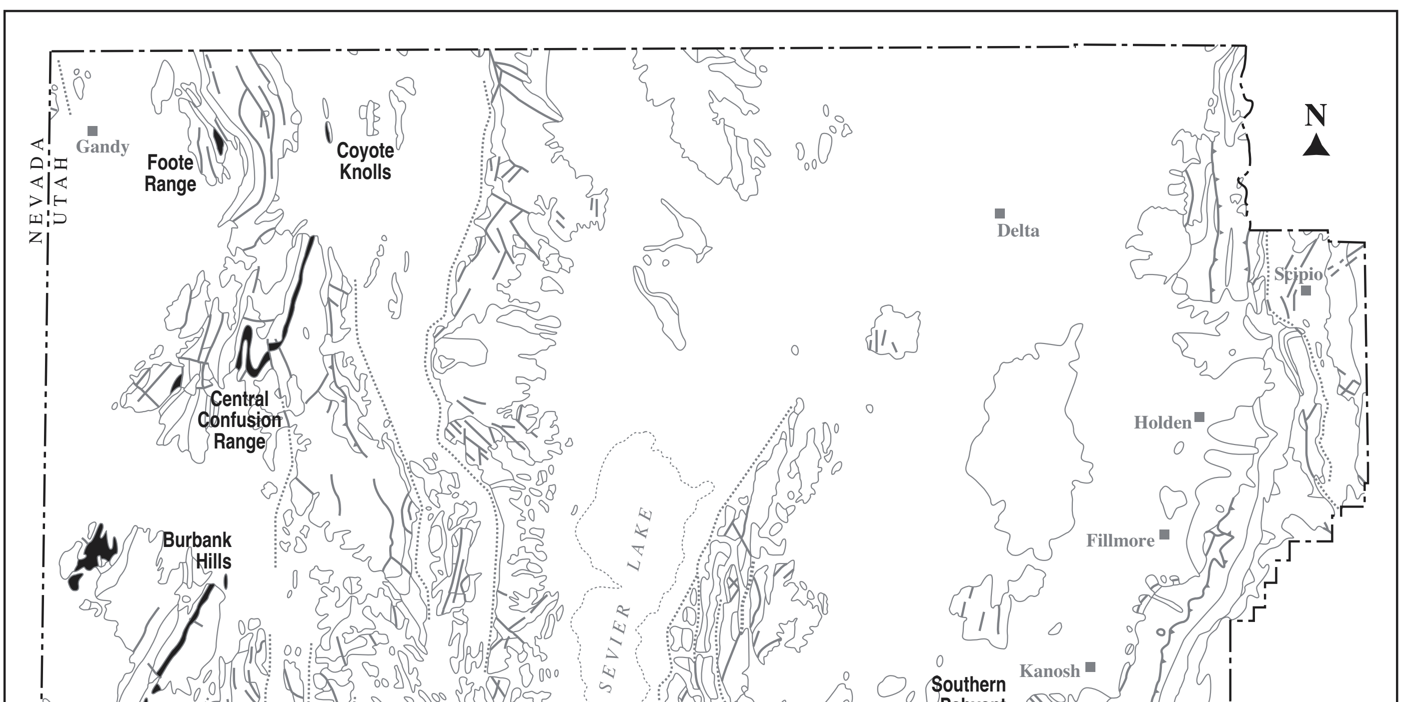


***Figure 136.** Lower Mississippian (Joana-Redwall) outcrops in Millard County.*

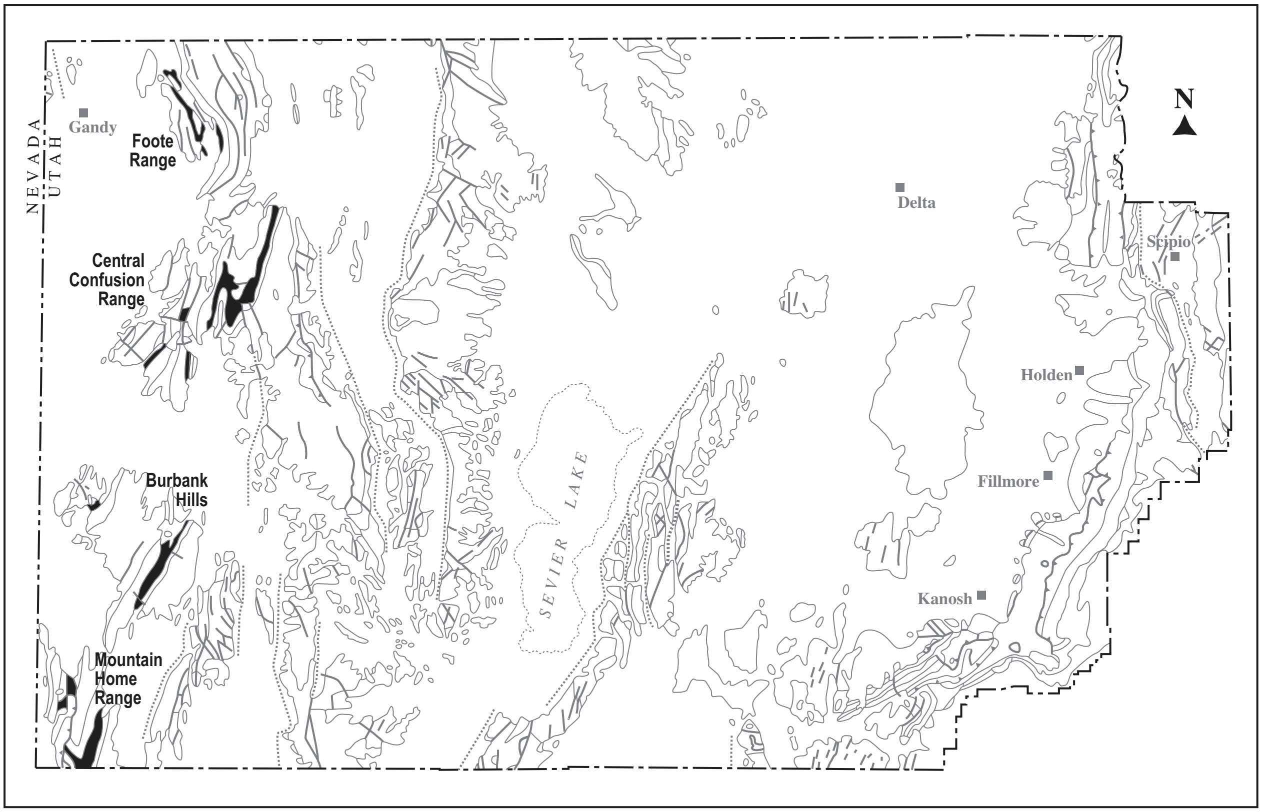


Figure 137. *Upper Mississippian (Chainman) outcrops in Millard County.*

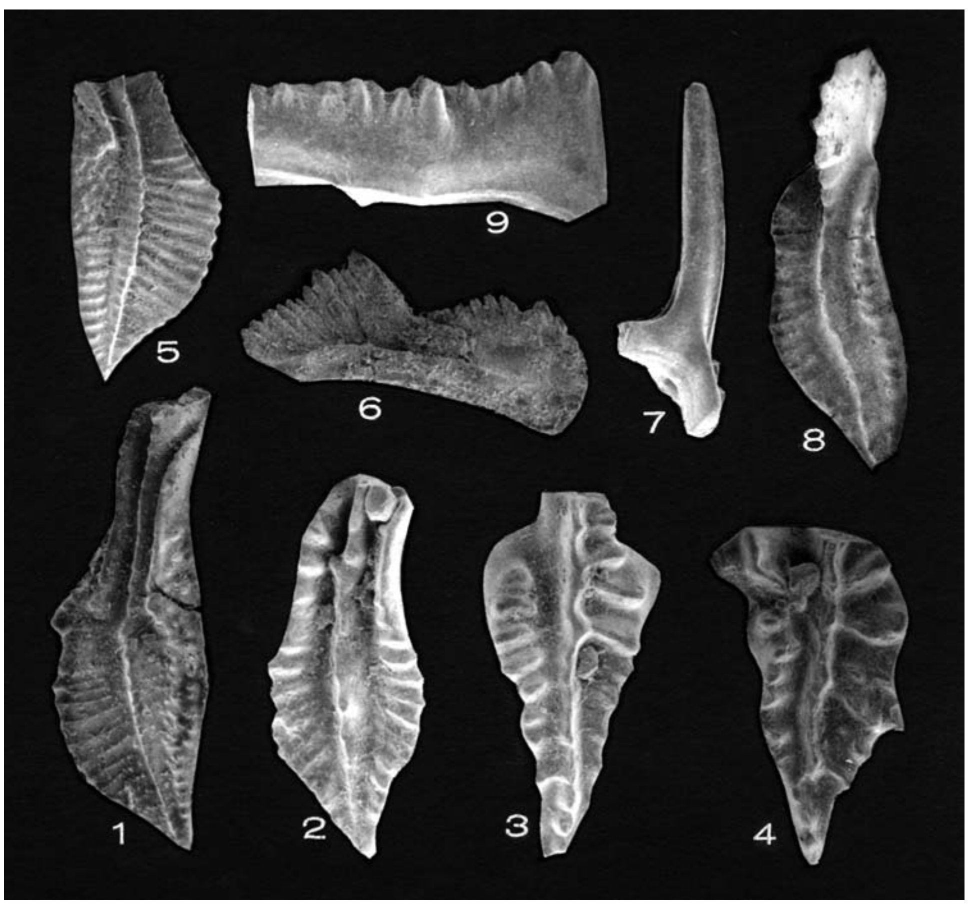


Figure 138. *Photomicrographs of typical Mississippian conodonts. Photos and identifications furnished by Professor Scott Ritter, Department of Geology, Brigham Young University, about X40: 1,5,6,* Siphonodella*; 2,8,* Polygnathus*; 3,4,* Pseudopolygnathus*; 7,* Ligonodina*; 9,* Bispathodus.

coral zones of Sando and Bamber (1985), and the ammonoid zones of Gordon (1984). Conodonts are recoverable from carbonate rocks from which they can be separated by using acetic or formic acid to dissolve the rock. Newman (1980) described conodonts from the Joana Limestone in the Mountain Home Range in his reconnaissance study of Lower Mississippian conodont biostratigraphy in Utah and Nevada. Goebel (1991) used conodonts identified by C.A. Sandberg for time control in her study of the Joana Limestone in western Utah and eastern Nevada. Tynan (1980) described conodonts in his detailed zonation study of conodont biostratigraphy of the Chainman Formation in the Needle (Mountain Home) Range, Burbank Hills, and Confusion Range.

Foraminifera: Calcareous microscopic foraminifers are valuable for intercontinental correlation because they are widely dispersed in shelf carbonates. Mamet and Skipp (1970) proposed foram zones 7-19, shown on chart 5 (appendix C), for correlation of Mississippian rocks in western North America. Brenckle (1990) reviewed the application of foram zones in the central United States as compared to occurrences in Europe and concluded that calcareous foraminifers provide at least seven possible levels for intercontinental correlation. Brenckle (1990) presented photographs of representative foram specimens.

Corals: Sando and Bamber (1985) recognized six numbered zones and eleven lettered subzones of corals in west-central North America on the basis of associations of selected genera and subgenera of restricted range; the boundaries are marked by first or last appearances or by changes in abundance of these selected taxa. Corals are widely distributed in shallow-water carbonate rocks because of their free-swimming larval stage. Geochronometric resolution of Mississippian coral zones compares favorably with that of zonations based on free-swimming foraminifers, conodonts, and cephalopods. Corals, being macroscopic, can often be identified in the field with a hand lens, but like all fossils, the accuracy of the identification depends on the expertise of the identifier. Most corals must be thin-sectioned for proper identification.

Sando and Bamber (1985) identified the four coral genera listed on chart 5 (appendix C) from the Joana Limestone in the Confusion Range. They also listed the corals *Amplexizaphrentis*, *Barytichisma*?, and *Michelinia* from zone V in the Chainman Formation in the Burbank Hills (figure 139). Unfortunately no systematic, stratigraphically controlled collection of corals has been made from the widely exposed fossil-bearing Mississippian rocks in western Millard County, so Sando and Bamber's (1985) coral zones can only be applied there indirectly by correlation with Mississippian strata in central Utah, near Provo, that were well documented in their work. Sando (1990) reviewed the suitability of Mississippian corals for global stratigraphic correlation and concluded that 11 groups of genera are cosmopolitan enough to be of use in intercontinental work.

Cephalopods: Because they moved freely in open ocean waters, cephalopods are widely distributed; and because their form evolved rapidly through time, they make good guides to time. Ammonoid cephalopods (figure 140) have been grouped into seven zones in the upper Chainman Formation as shown on chart 5 (appendix C). The species named on chart 5 are those selected by Gordon (1984) to represent each zone

Figure 139. Amplexizaphrentis *(upper right) and other horn (rugose) corals from the Jensen Member of the Chainman Formation in the Burbank Hills.*

Figure 140. Goniatites multiliratus*, a Mississippian ammonoid cephalopod from the Chainman Formation at Skunk Spring, Confusion Range. Collected and photographed by Kevin Bylund, X2.7.*

of cephalopods, which may be made up of 10 to 20 ammonoid and other cephalopod species. Flower and Gordon (1959) described belemnites from the Chainman Formation in the Burbank Hills. Mackenzie Gordon Jr. was in the process of preparing a U.S. Geological Survey Professional Paper on the cephalopods of the Chainman Formation in west-central Utah at the time of his death, and it is hoped that his work will be published posthumously.

Kullmann and others (1990) reviewed the potential of Mississippian ammonoids for international correlation and recognized 16 zones. The Chainman ammonoids belong within their upper eight zones.

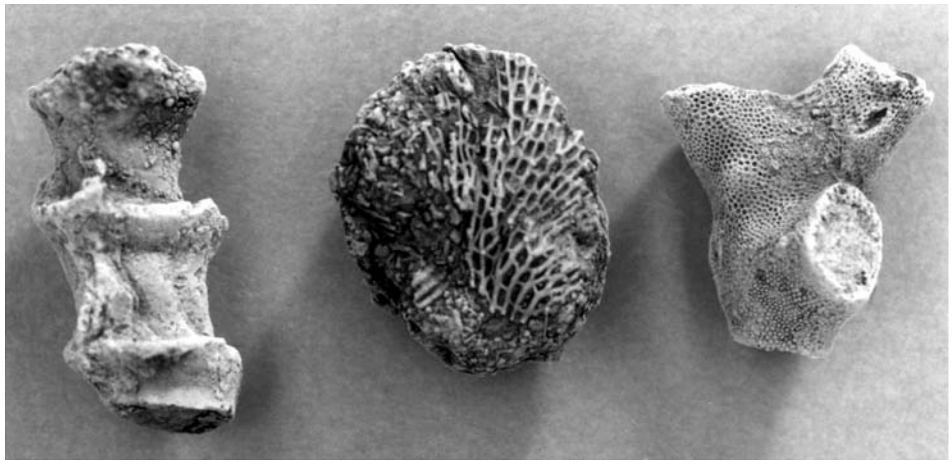


Figure 141. *Bryozoans from the Jensen Member of the Chainman Formation in the Burbank Hills; left to right,* Archimedes *sp.,* Fenestella *sp.,* Anisotrypa *sp., X2.*

Gastropods: Gordon and Yochelson (1987), in their definitive work on Late Mississippian gastropods of the Chainman Formation in western Millard County, recognized 37 genera and subgenera including 79 species, of which 32 are new. They grouped these gastropods into eight assemblages, which they equated with established ammonoid and foraminiferal zones. Most of their publication is devoted to illustrating and describing the new species, but they also give stratigraphic distribution and geographic localities with faunal lists for their numerous collections. Until this monographic work was published, almost nothing was known of Late Mississippian gastropods in the western United States.

Bryozoans: Karklins (1986) described 18 species of bryozoans, which he assigned to 15 genera, from the upper Camp Canyon, Willow Gap, and Jensen Members of the Chainman Formation in the Burbank Hills (figure 141) and Confusion Range of western Millard County. As noted by Karklins (1986), until his monograph, there had been very little published concerning Upper Mississippian bryozoans of the western United States, although bryozoans of this age are fairly well documented from Illinois, Kentucky, and Indiana.

Development and dispersal of bryozoan faunas was made possible by shallowing of the marine waters and establishment of carbonate deposition in western Utah during late Chainman time. The bryozoans studied by Karklins (1986) were collected over a period of years, beginning in 1960, by Mackenzie Gordon Jr. of the U.S. Geological Survey as part of the Survey's project to study the Mississippian and Pennsylvanian biostratigraphic framework in western Utah and adjoining areas. Karklins' (1986) monograph provides a standard of reference to which future finds of Upper Mississippian bryozoans in western North America may be compared.

Pelecypods: Gordon (1984, figure 1, p. 75), without giving names of genera, indicated that 78 species of pelecypods had been collected by the U.S. Geological Survey in its study of Chainman Formation faunas in western Millard County. Apparently none of this material has yet been described, nor have the pelecypod genera and species names yet been published. Because Gordon died, the author asked John Pojeta Jr., pelecypod paleontologist with the U.S. Geological Survey in Washington, D.C., to furnish information about the Utah Chainman pelecypod collections of the U.S. Geological Survey. His list of pelecypods is table 1. All samples were collected from the upper part of the Chainman Formation and the lowermost beds of Ely Limestone at the north end of the Foote Range in or near section 31, T. 15$\frac{1}{2}$ S., R. 17 W., as shown on the 1:24,000-scale geologic map by Hose and Ziony (1963). In Mississippian rocks, pelecypods are not much used as guides to time; they are more useful as indicators of depositional environment.

Brachiopods: Brachiopods are among the most abundant and conspicuous fossils in the Chainman Formation, espe-

Table 1. *Pelecypods in Chainman Formation in western Millard County (John Pojeta, Jr., U.S. Geological Survey, written communication, April 21, 1998).*

Pelecypods attached to the seafloor by a horny holdfast	
Pectinacea (scallops)	Mylinidae
Aviculopecten	*Myalina*
Streblochondria	*Septimyalina*
Streblopteria	*Posidoniella*
Posidonia	
Pteriacea	Mytilacea
Leptodesma	*Volsellina*
Pelecypods attached just beneath the seafloor	
Pinnacea	
Aviculopinna	
Pelecypods that burrowed within marine sediments	
Palaeotaxodonts	Trigoniaceans
Palaeoneilo	*Schizondus*
Phestia	
Nuculopsis	
Nuculanella	Crassatellaceans
Paleoyoldia	*Astartella*
Anomalodesmatans	Permophorids
Wilkingia	*Permophorus*
Edmondia	
Cardiomorpha	

cially in the Willow Gap and Jensen Members (figure 142). Gordon (1984) gave the total number of brachiopod species from the Chainman Formation in western Utah as 116, with 84 coming from these upper two members. Unfortunately, Gordon never published a complete list of Chainman brachiopods, but did conclude that only one brachiopod species, *Rhipidomella nevadensis*, is useful as a zone fossil. All other species are either too long-ranging in time, or too similar to other species to be readily identifiable, to be useful as time-stratigraphic guides. Dutro and others (1979) recognized seven brachiopod assemblage zones in their survey of paleontological zonation of the Mississippian System in the United States, based chiefly on collections made in the type Mississippian in the upper Mississippi Valley region. The only zone with a type area in the western United States that was included is the *Rhipidomella nevadensis* Zone, proposed by Sadlick (1965) from the upper Chainman Formation of western Utah.

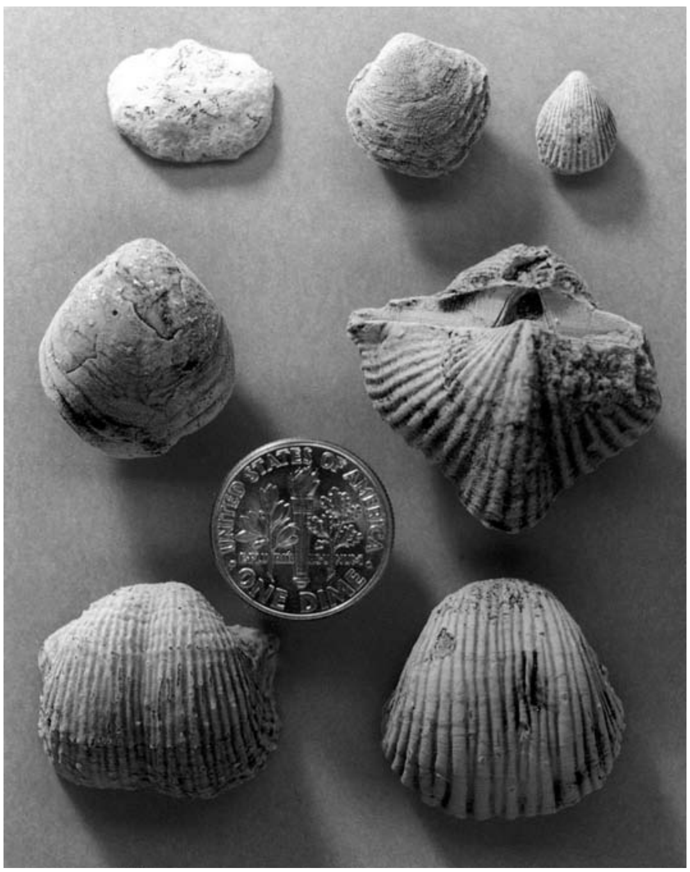


Figure 142. *Brachiopods from the upper part of the Chainman Formation in the Burbank Hills. Clockwise from the upper left:* Chonetes granulifer, Cliothyridina sublamellosa, Eumetria costata, Spirifer occidentalis, Dictyoclostus portlockianus *var.* crassiostatus, Dictyoclostus portlockianus, Composita *sp.*

Bacon (1948) and Rush (1951) identified a few Mississippian brachiopods in their reconnaissance studies of the stratigraphy of the Confusion Range and Burbank Hills, but the most complete listing of Mississippian brachiopods from the Chainman Formation is that of Sadlick (1965). Sadlick listed specific and generic names of 33 brachiopods from the Chainman Formation in western Utah: 3 from the Needle Siltstone Member, 16 from the Camp Canyon Member, 11 from the Willow Gap Member, and, surprisingly, only 3 from the Jensen Member, which has a prolific brachiopod fauna. Generic names of the brachiopods listed in Sadlick's manuscript are given below under the summary of each lithologic unit. Sadlick (1965) noted the long-ranging, non-time-diagnostic nature of most Mississippian brachiopods, but discussed at some length the value of the single species, *Rhipidomella nevadensis*, as a guide to time.

Brachiopods weather free from their shaly matrix in the upper Chainman members at several locations in the Mountain Home Range, Burbank Hills, and Confusion Range, where they have been collected not only by professional paleontologists, but also by geology students and other amateur collectors.

Crinoids: Crinoid stem columnals are common in some beds in the Chainman, but crinoid heads, the critical identifying portion, have not been reported. Some of the crinoid columnals are large, about the diameter of a quarter dollar (figure 143). They weather free of the shaly matrix in the upper Chainman members.

Plants: Sadlick (1965) reported a Visean plant, *Adiantites*? sp., from the Needle Siltstone Member, and *Rhodea* and *Asterocalamites* from the Camp Canyon Member. Gordon (1984) showed that six unnamed algae had been collected by the U.S. Geological Survey from the upper Chainman in western Utah.

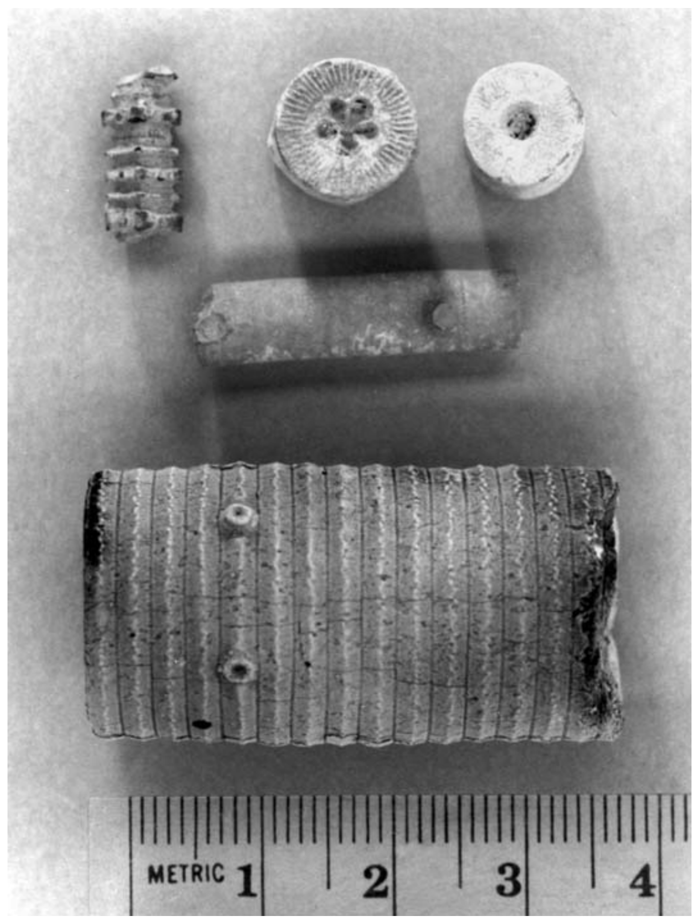


Figure 143. *Crinoid stem columnals from the upper Chainman Formation in the Burbank Hills. All are side views except upper center and right, which are top views. Some crinoid stems attained a length of a few feet, made up of stacks of individual columnals, some of which supported smaller branch stems. These are the most common fossil fragments found in Mississippian strata in Utah.*

Summary of fossil documentation: Of the nine fossil groups listed above, only the conodonts, gastropods, and bryozoans have been adequately identified and described from Mississippian strata in western Utah. Many of the cephalopods have been described by various authors, but the monographic zonal summary manuscript that Mackenzie Gordon Jr. of the U.S. Geological Survey was preparing at the time of his death has not yet become available. Although common in some limestones, few corals have been specifically identified or described from this area. The same is probably true of foraminifera, pelecypods, and brachiopods. Plants and crinoids have not been commonly reported, and none have been described from this area.

Lithologic Units

Names of Mississippian formations in Millard County are shown on columns 3, 8, 10, and 11 (appendix C), where map symbols, thicknesses, primary references, and other pertinent data are shown. The 1:100,000 scale of the geologic maps of Millard County is too small to show most lithologic units individually. They have been combined, and the map symbol representing the combination is shown on the map explanation, the stratigraphic columns, and within this text. Each unit, however, is discussed separately in the following section.

Pilot Shale (MDp): General features of the Pilot Shale were outlined in previous pages under the heading Mississippian-Devonian. Sandberg and others (1980) showed that the upper 174 to 197 feet (53-60 m) of Pilot Shale at Little Mile-and-a-Half Canyon in the Confusion Range (figure 144) are Early Mississippian (Kinderhookian) in age on the basis of conodonts of the *Siphonodella duplicata* Zone. Poole and Sandberg (1991) indicated that minor erosional unconformities bound the Mississippian portion of the Pilot both above and below its upper member as shown on chart 5 (appendix C). The upper member of the Pilot is overlain by the Joana Limestone.

Joana Limestone (Mj): The Joana Limestone was named by Spencer (1917) after the Joana mine near Ely, Nevada. Usage of the name has spread throughout western Utah and eastern Nevada where it is a massive, resistant, ledge- and cliff-forming unit between the underlying slope-forming Pilot Shale and the overlying valley-forming Chainman Formation. The Joana is the partial equivalent of the Redwall Limestone of the Grand Canyon area in Arizona and the Monte Cristo Limestone of southern Nevada, and may or may not be equivalent to part of the Redwall Limestone mapped in the southern Pahvant Range (see section on Redwall Limestone).

Joana Limestone was mapped in the Mountain Home Range by Hintze (1986a) and Hintze and Best (1987) where it is a massive bluish-gray, cliff-forming limestone 460 feet (140 m) thick. The limestone contains 5 to 10 percent chert nodules that occur in some lower beds but are most common in the upper part of the formation. Olive-gray dolomite is included as mottled zones in about 15 percent of the Joana beds. About one-third of the Joana in the Mountain Home Range is coarse-grained bioclastic limestone that is made up of sand-size fossil debris that includes a few whole horn corals and colonial corals. The limestone has an aromatic smell when split with a hammer.

In the Burbank Hills the Joana Limestone is 520 to 560 feet (160-170 m) thick (Hintze, 1997d). The basal Joana unit is a calcareous quartz sandstone as much as 16 feet (5 m) thick. Of the limestone that makes up most of the formation,

__Figure 144.__ Aerial view looking roughly northeast of the cuesta formed by the cliff-forming Joana Limestone in the Confusion Range just east of Conger Mountain near Little Mile-and-a-Half Canyon. Road above the airplane wing follows the strike valley (Ledger Canyon) developed on the non-resistant Pilot Shale; road on left (west) side of Joana cuesta follows the non-resistant Chainman Formation down Camp Canyon. Joana Limestone is offset by a cross-fault in the left foreground. Ridges of Ely Limestone are visible west (left) of Camp Canyon in the distance. Hills on right side of the Pilot Shale strike valley are Devonian Guilmette Formation. Tule Valley is the white area in the right distance.

the lowest one-fifth is a coarse-grained, bioclastic, massive, medium-gray limestone that contains as much as 10 percent nodular chert; crinoid, brachiopod, and other invertebrate fossil debris makes up much of the rock, and both solitary and colonial whole corals are scattered throughout. The remainder of the Joana, mostly exposed on the backslope of the Joana hogback or cuesta, forms alternating ledges and slopes reflecting the less massive, thick-bedded character of the limestone, and deposition of the Joana as cyclic repetitions of coarse- and fine-grained clastic limestones. Chert nodules make up as much as 15 percent of the Joana Limestone in its upper 130 feet (40 m). Sandberg (in Biller, 1976, figure 2) lists Kinderhookian conodonts from the base of Joana Limestone in the Burbank Hills.

At Little Mile-and-a-Half Canyon in the central Confusion Range (figure 144), the Joana is 255 feet (78 m) thick and is massive coarse- to fine-grained bioclastic limestone. Brown-weathering bedded chert nodules make up about 15 percent of the rock from 20 to 25 feet (6-8 m) above the base and in the uppermost 30 feet (9 m). The chert is enclosed mostly in fine-grained limestone. Bacon (1948), Sandberg and others (1980), and Goebel (1991) record a pinkish quartzite bed as much as 6 feet (2 m) thick at the base of the Joana in the Confusion Range. This is overlain by about 6 to 9 feet (2-3 m) of thin-bedded nodular limestone, from which Bacon (1948) reported the following fossils of Kinderhookian age: *Camarotoechia*, *Cleiothyridina*, *Composita trinuclea*, *Productus elegans*, *Spirifer platynotus*, *Echinocrinus*?, *and Platycrinites*.

The Joana Limestone thins markedly northward in the Confusion Range and is entirely absent between the Pilot and Chainman Formations at Granite Mountain, just north of the Millard-Juab county line.

Goebel (1991) examined the Joana Limestone throughout its extent in western Utah and eastern Nevada with the objective of relating changes within the makeup of the Joana to events that occurred in the Antler orogenic system in central Nevada. She noted that all of the Joana Limestone in Millard County belongs to her eastern facies belt, far removed from the center of orogenic activity in Nevada. Goebel (1991) divided the Joana into two parts based on conodonts. Her lower Joana Limestone contains *Siphonodella crenulata* - *Siphonodella isosticha* zone conodonts; her upper Joana includes *Gnathodus typicus* conodonts. Goebel's (1991) lower Joana Limestone includes: (1) a basal quartz arenite, a few feet thick; (2) an overlying wavy-bedded, argillaceous, fossiliferous wackestone, a few feet thick; and (3) a capping crinoidal-peloidal wackestone to packstone that makes up most of the lower Joana, and is several tens of feet thick and forms massive cliffs. Biota noted in thin sections from this wackestone-packstone unit include crinoid, brachiopod, bryozoan, and molluscan debris, and conodonts, foraminifers, and ostracodes.

Goebel's (1991) upper Joana Limestone in western Utah is made up of four cycles of repeated lithologies which, when completely developed, include from the base upwards: (1) fossiliferous wackestone to packstone deposited in subtidal open marine waters; (2) oolitic grainstone formed in sand shoals; (3) crinoidal-peloidal grainstone deposited either in peritidal lagoons or shallow subtidal sand flats; and (4) thin-bedded calcareous mudstone deposited in intertidal lagoons. Skeletal debris identified in thin section in the wackestone to packstone facies includes fragments of echinoderms, brachiopods, molluscs, foraminifers, rugose corals, sponge spicules, and, rarely, bryozoans.

Goebel's (1991) dissertation is the most comprehensive regional study of the Joana Limestone made to date. Although it does not include bed-by-bed descriptions of her studied sections, it does include a number of photographs of thin sections of rocks showing various textures and fossil constituents.

Chainman Formation (Mc): The Chainman Shale was named by Spencer (1917) from the Chainman mine 2 miles (3 km) west of Ely, Nevada, and the name has subsequently been widely used in eastern Nevada and western Utah. Sadlick (1965), in his comprehensive study of the Chainman in western Utah, recommended that, in Utah, because of the heterogeneity of its component rocks, it is better to call it a formation rather than a shale, and I do so herein. Sadlick (1965) proposed names for five members of the Chainman Formation in western Utah, in ascending order: Needle Siltstone Member, Skunk Spring Limestone Member, Camp Canyon Member, Willow Gap Limestone Member, and Jensen Member. He designated a type section and presented a detailed measured section for each member's type section, thus fulfilling the requirements for official acceptance of his proposed members except for one condition: his dissertation was never formally published. Despite this deficiency, Sadlick's names for members of the Chainman have been used in subsequently published studies of Chainman rocks and fossils in western Utah, and I herein also use Sadlick's member names for the Chainman Formation in western Utah.

An additional member, not recognized by Sadlick (1965), was added to the bottom of the Chainman sequence by Sandberg and Gutschick (1984). This Delle Phosphatic Member is shown on maps by Hintze (1986a) and Hintze and Best (1987), who showed all Chainman members as separate map units in the northern Mountain Home (Needle) Range. Hintze (1997a-d) also showed each member separately in the Burbank Hills. Unfortunately, the U.S. Geological Survey 1:24,000-scale Miscellaneous Investigations Maps of Richard K. Hose and his associates do not show the Chainman members separately in the Confusion Range (figure 145) (see geologic map index on the Tule Valley geologic map for names of co-authors and dates of publication; Hintze and Davis, 2002c), the type area for some of the members. But, most members can be recognized in the field in the Confusion Range without too much difficulty (column 8, appendix C). The Chainman Formation ranges in thickness between 1,600 and 1,800 feet (490-550 m) in the Confusion Range.

<u>Delle Phosphatic Member:</u> Sandberg and Gutschick (1984) recognized the widespread distribution of a Mississippian phosphatic interval, correlatable by conodonts, which they called the Delle Phosphatic Member. This name is derived from the southern Lakeside Mountains west of Salt Lake City. They noted its presence as a member in several formations, including the Chainman Formation. Hintze (1986a) and Hintze and Best (1987) mapped two units within this member in the Mountain Home (Needle) Range: a lower recessive siltstone unit 40 to 65 feet (13-20 m) thick, and an upper ledge- and cliff-forming limestone member 80 to 110 feet (25-35 m) thick. The limestone unit does not extend north of the Mountain Home Range. In the Burbank Hills the

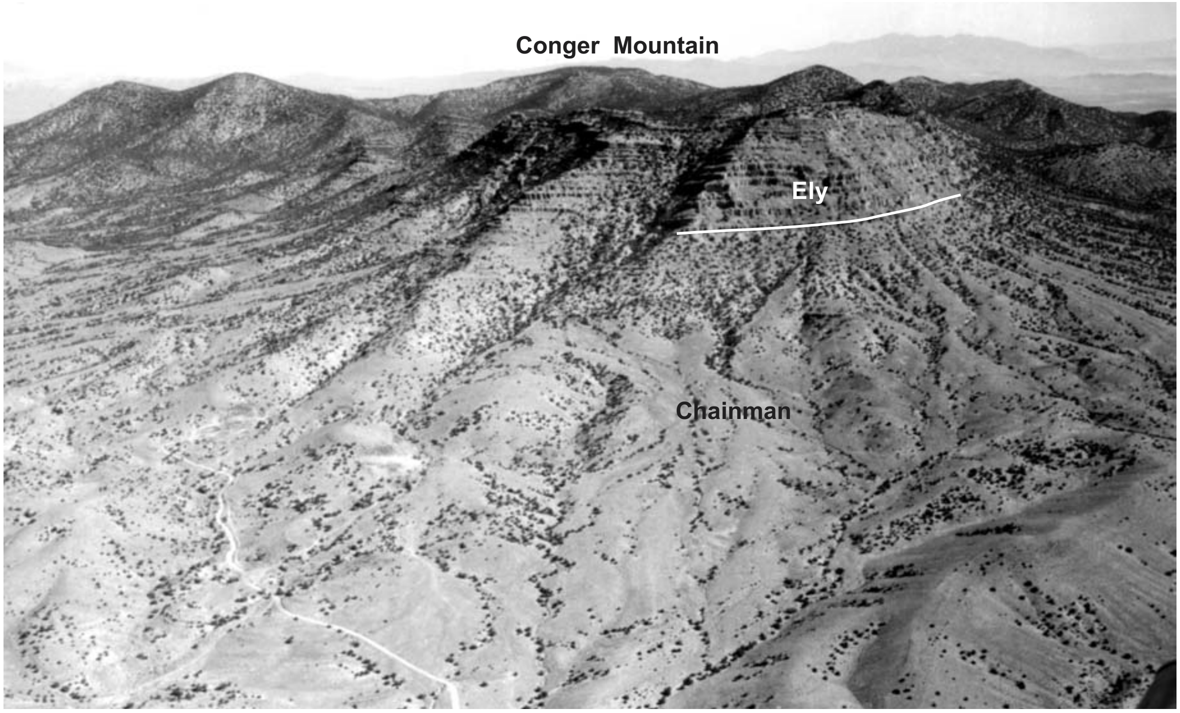


Figure 145. *Chainman Formation, in foreground, wraps around west, south, and east sides of Conger Mountain on the axis of the Confusion Range synclinorium. Only the upper half of the Chainman is included in this aerial view northward. Top of the Chainman Formation is marked by the lowest ledges of the Ely Limestone. Conger Mountain itself exposes only the basal Mississippian-Pennsylvanian portion of the Ely Limestone, which typically forms large stair-step ledges of repeated lithologies indicating cyclic deposition in shallow marine water. Note the gentle opposed dips in Ely Limestone that define the axis of synclinorium, here called the Conger Mountain syncline. The road in the lower left corner of the picture leads to Conger Spring.*

Delle Phosphatic Member is 0 to 80 feet (0-24 m) thick (Hintze, 1997a-d). The Delle Phosphatic Member has not been mapped separately in the Confusion Range. Sandberg and others (1980) reported 16 feet (5 m) of Delle near Skunk Spring in the central Confusion Range; it apparently thins northward and has not been identified in the northern Confusion Range.

Sandberg and Gutschick (1984) interpreted the Delle to have been deposited in a deeper water sediment-starved basin, but Nichols and Silberling (1990; Silberling and Nichols, 1991) suggested that certain sedimentologic features indicate that the Delle may have been deposited on a shallow shelf. Sandberg and others (1991a-b) responded to this suggestion with a reaffirmation of their original concept of deeper water deposition.

<u>Needle Siltstone Member:</u> Sadlick (1965) named this member for the location of its type section in the Needle Range, the northern part of which is now shown on maps as the Mountain Home Range. The Needle Siltstone Member was identified without question by Sadlick (1965) only in western Utah where it thins progressively northward from its type section. There it is a gray, calcareous siltstone that weathers light brownish gray, is mostly thin bedded, and includes 10 percent fine-grained sandstone interbeds and minor shale. Sadlick (1965) reported its thickness in the type section as 550 feet (168 m) but Hintze (1986a) measured as much as 600 feet (180 m) in his mapping of the Mountain Home Range. Sadlick (1965) reported the Needle Siltstone as 315 feet (96 m) thick in the Burbank Hills. Sandberg and others (1980) reported 167 feet (51 m) of Needle at Skunk Spring in the central Confusion Range. Sadlick (1965) identified the brachiopods *Sartenaeria*, *Orbiculoides*, and *Quadratia* from two thin beds in the type section and interpreted the depositional environment of the Needle Siltstone as neritic marine and low energy.

<u>Skunk Spring Limestone Member:</u> Sadlick (1965) named this member for the location of its type section near Skunk Spring in the central Confusion Range. It is a medium-gray, slightly silty, fine-grained limestone that is thick bedded in its lower part, becoming thin bedded at the top. The Skunk Spring Limestone Member forms a conspicuous ledge that is generally found throughout Chainman Formation exposures in Millard County. It is about 6 feet (2 m) thick in the Mountain Home Range, 0 to 6 feet (0-2 m) thick in the Burbank Hills, and 5 to 16 feet (2-5 m) thick in the Confusion Range. Sadlick (1965) identified the horn coral *Amplexizaphrentis* in growth position as a rare fossil constituent of the Skunk Spring Limestone Member and concluded that the limestone probably was deposited in low-energy shallow marine water in an outer sublittoral environment.

<u>Camp Canyon Member:</u> Sadlick (1965) designated the type section of this member in Camp Canyon, a strike valley that follows the member's belt of outcrop on the east side of Conger Mountain in the central Confusion Range. The Camp Canyon is the thickest member of the Chainman Formation and was specified to include all beds between the Skunk Spring and the Willow Gap Limestone Members. As such the member is made up of a variety of rock types, including black shale, silty shale, calcareous siltstone, and fine-grained limestone. Hintze (1986a) mapped three units within the Camp Canyon Member in the Mountain Home Range, needing them to resolve structural complexities on the west flank

of that range. His basal black shale unit, about 400 feet (120 m) thick, is a grayish-black to dark-brown, recessive shale with 20 percent interbedded dark-gray, thin-bedded limestone and minor siltstone. Locally, near its base, it contains large limestone concretions, some of which bear goniatite cephalopods. The middle Camp Canyon unit is a clayey limestone, about 300 feet (90 m) thick, that is dark gray on fresh surfaces, but weathers to light gray or pale yellowish brown. It includes some silty limestone and shale beds, and forms low ledges and blocky talus slopes. Some beds contain brachiopods, pelecypods, and gastropods. Hintze's (1986a) top member of the Camp Canyon is a rusty-weathering limestone that is about 650 feet (200 m) thick. On fresh surfaces it is a dusky-yellowish-brown, finely crystalline, locally cross-laminated limestone that weathers moderate-reddish-brown to light brown; it forms slopes and ledgy slopes, and contains scattered nodules of chert.

The lower black shale unit can be recognized in the Burbank Hills where it is 320 feet (98 m) thick. The upper Camp Canyon in the Burbank Hills is an undivided unit of clayey and silty limestone 670 feet (203 m) thick (Hintze, unpublished notes).

The Camp Canyon Member has not been subdivided on geologic maps of the Confusion Range, although it would probably be feasible to do so. In his description of the type section of the Camp Canyon Member near Skunk Spring, Sadlick (1965) divided it into a lower part 294 feet (90 m) thick that is mostly shaly deeper water deposits, and an upper part 668 feet (204 m) thick that is mostly shallower water siltstone and calcisiltite. Sandberg and others (1980) measured the same section and recorded a thickness of about 1,050 feet (320 m) for the Chainman interval between the Skunk Spring and Willow Gap Members. They also concluded that the Camp Canyon interval represents deposition in deeper water at the base and shallower water at the top. Webster and others (1984) published a summary diagram of the Chainman Formation at Granite Mountain, just north of the Millard County boundary, which indicated a thickness of about 770 feet (235 m) for the Camp Canyon interval there, indicating that the Camp Canyon thins towards the north in Millard County. Because post-Mississippian erosion removed these strata in central Millard County, as shown on figure 135, the depositional pattern to the east is not known. Sadlick (1965) discussed the nature of Chainman deposition westward towards the Antler orogenic belt in central Nevada.

Sadlick (1965) noted that, although fossils are not especially abundant in the Camp Canyon Member, it contains a variety of taxa, including a succession of index goniatite cephalopods that he placed in the following zonation, oldest first: (1) prolecantid zone; (2) *Goniatites* cf. *crenistria*; (3) *Goniatites multiliratus* (figure 140); (4) *Goniatites granosus*; and (5) *Cravenoceras hesperium*. Gastropods are fairly common in the Camp Canyon Member, from which 25 species were described by Gordon and Yochelson (1987). Sadlick (1965) noted that brachiopods are the next most common fossils in the Camp Canyon and are usually represented by the species *Sartenaeria carbonifera* and unnamed lingulids. Other brachiopods present are *Orbiculoidea*, *Anthracospirifer*, *Rhipidomella*, *Neochonetes*, *Ovatia*, *Duartea*, *Quadratia*, *Neospirifer*, *Brachythyris*?, and *Inflatia*. Pelecypods and the corals *Amplexizaphrentis* and *Faberophyllum* also occur in the Camp Canyon Member. Karklins (1986) recorded only two bryozoans, *Polypora* and *Tabulipora*, from the Camp Canyon Member.

<u>Willow Gap Limestone Member:</u> Sadlick (1965) named this member after the location of its type section at Willow Gap near Skunk Spring in the central Confusion Range. The Willow Gap Member forms prominent ledges and strike ridges between the less resistant Camp Canyon and Jensen Members. At its type section the Willow Gap is 352 feet (107 m) thick and is predominantly medium- to light-gray calcisiltite and calcarenite with minor shale and siltstone interbeds. In the Mountain Home Range the Willow Gap Limestone Member is 260 to 360 feet (80-110 m) thick (Hintze, 1986a). In the Burbank Hills, the Willow Gap Member is about 300 feet (90 m) thick at the southeast edge of the range but pinches out in Jensen Wash 2 miles (3.2 km) north of Little Jensen Pass, and is thus absent from the type section of the overlying Jensen Member (Hintze, 1997d). This pinch-out appears to be localized to the northeastern Burbank Hills area, because I believe the Willow Gap is present to the north throughout the length of the Confusion Range, although it has not been shown separately on geologic maps of the range.

The Willow Gap Limestone Member contains a varied marine invertebrate fauna. Its ammonoids belong to the *Cravenoceras hesperium* zone. Gordon and Yochelson (1987) described 28 species of gastropods and Karklins (1986) described 13 species of bryozoans from the Willow Gap Member. Sadlick (1965) listed the following brachiopod genera from the Willow Gap: *Anthracospirifer*, *Spirifer*, *Neospirifer*, *Sartenaeria*, *Inflatia*, *Productus*, *Diaphragmus*, *Echinochonchus*, *Antiquatonia*, *Flexaria*, and *Ovatia*. Large solitary horn corals, the tubular *Caninia nevadensis* and the expansive *Caninia excentrica*, are present in upper beds of the member. Crinoid columnals are abundant.

Sadlick (1965) noted that limestone beds in the Willow Gap are lenticular and that low-angle cross-bedding and the clastic makeup of the limestones suggest deposition in shallow water lime-sand banks.

<u>Jensen Member:</u> Sadlick (1965) named the Jensen Member after its type locality in Jensen Wash in the Burbank Hills. In his description of the type section, Sadlick indicated that the Jensen Member is underlain by 235 feet (72 m) of Willow Gap Member. However, in mapping the geology of the Big Jensen Pass 1:24,000-scale quadrangle, I found that the Willow Gap Limestone Member pinches out about 2 miles (3 km) south of the type area of the Jensen Member (Hintze, 1997d). The strata that Sadlick (1965) described at this location under the heading "Willow Gap Member" are not at all like the typical Willow Gap elsewhere in Millard County. In the Jensen Wash section only one-tenth of his "Willow Gap" strata are limestone; most are siltstone and shale, and are better assigned to the Camp Canyon Member. As a limestone unit, the Willow Gap is not present at the type locality of the Jensen Member. Whether the Camp Canyon-like strata that Sadlick (1965) described there are the temporal equivalent of the type Willow Gap in the Confusion Range, or whether rocks representing Willow Gap time are simply missing, is not clear. Given the lenticular form of most Willow Gap limestone beds, Willow Gap time may be represented by Camp Canyon-like deposits at the Jensen Wash locality.

In its type locality at Jensen Wash, Sadlick (1965) described the Jensen Member as consisting of 470 feet (143

m) of calcareous siltstone and shale with a few interbeds of calcarenite and sandstone. The Jensen Member stands out from other parts of the Chainman Formation because of its general reddish- or orangish-brown weathered outcrops. Webster and others (1984) listed the *Adetognathus unicornis* conodont zone fossils from the upper Jensen Member at the type locality. Gordon (1984) noted the diversity of fossils found in the Jensen Member, including foraminifera, corals, bryozoans, brachiopods, pelecypods, gastropods, and ammonoid cephalopods.

Gordon (in Gordon and Yochelson, 1987) remeasured Sadlick's type section of the Jensen Member and gave its thickness as 583 feet (178 m), some 25 percent greater than recorded by Sadlick. Both Sadlick and Gordon identified the same fossil horizon (Sadlick's fossil locality 2-11) at the base of the Jensen Member and listed a number of gastropods and a few ammonoids from this place. Gordon and Yochelson (1987) also listed seven gastropod species from a 56-foot (17-m) thick fossiliferous shale sequence some 110 feet (34 m) below the top of the Jensen Member.

In the Mountain Home (northern Needle) Range Hintze (1986a) noted that the Jensen Member ranges in thickness from 260 to 400 feet (80-120 m). Gordon and Yochelson (1987) listed five gastropod species from the Jensen Member there, along with the ammonoid *Richardsonites merriami*. The unit also contains abundant brachiopods and, locally, belemnites and blastoids.

At Skunk Spring, in the central Confusion Range, Sadlick (1965) showed 183 feet (56 m) of Jensen Member and noted the presence of the key brachiopod *Rhipidomella nevadensis* in its upper part. Sandberg and others (1980) showed a thickness of 190 feet (58 m) for the same section and identified the conodont zone *Adetognathus unicornis* as being prevalent throughout the Jensen Member here.

The Jensen Member thins northward in the Confusion Range and is about 100 feet (30 m) thick at Granite Mountain just north of the Millard-Juab county line (Webster and others, 1984).

Redwall Limestone (Mr): Davis (1983) mapped the Redwall Limestone in the southern Pahvant Range and described an overturned measured section of Redwall in sections 28 and 29, T. 24 S., R. 6 W., as follows:

Basal unit A is interbedded medium-gray, medium- to thin-bedded sandy dolomite and crinoidal limestone that contains scattered rugose corals. It is 387 feet (118 m) thick and is probably the Whitmore Wash Member of the Redwall as described by McKee and Gutschick (1969) in northern Arizona, and equivalent to the Dawn Limestone Member of the Monte Cristo Limestone of southern Nevada (Hewett, 1931). Biller (1976) listed conodonts from the lowest 33 feet (10 m) of the Redwall Limestone here, and showed the underlying 79 feet (24 m) of limestone is actually Devonian. These Devonian strata are included in the Redwall on the Richfield 1:100,000-scale geologic map (Hintze and others, 2003), as done by Davis (1983).

Unit B is a dark-gray, fine-grained, cherty limestone with abundant fossil hash, mostly crinoidal, and a few solitary corals. It generally forms massive ledges and cliffs and is 623 feet (190 m) thick. Davis (1983) found a small ammonoid, *Beyrichoceras*?, in this unit, dating it as Osagean. Unit B correlates with the Thunder Spring Member of the Redwall of Arizona, and the Anchor Limestone Member of the Monte Cristo Limestone of southern Nevada.

Unit C is a calcareous sandstone with thin interbeds of limestone and dolomite aggregating 535 feet (163 m) in thickness. A 25-foot (8-m) thick limestone bed near its top contains abundant colonial corals and some horn corals. This unit is equivalent to the combined Mooney Falls and Horseshoe Mesa Members of the Redwall of northern Arizona (McKee and Gutschick, 1969); the Bullion, Arrowhead, and Yellowpine Members of the Monte Cristo Limestone of Nevada (Hewett, 1931); and the Deseret Limestone of north-central Utah.

Total thickness of the Redwall Limestone in the southern Pahvant Range is 1,545 feet (471 m). Welsh (1976) recorded a subsurface thickness of 1,400 feet (427 m) of Mississippian strata in the Sunset Canyon well in the central Pahvant Range and used the north-central Utah terms Fitchville, Gardison, and Deseret in the well log. Sandberg and Gutschick (1984) published a columnar section of the basal part of the Deseret Limestone (unit C of Davis, 1983) at Dog Valley Peak in the southern Pahvant Range wherein they recognized the Delle Phosphatic Member as being 164 feet (50 m) thick.

The Redwall Limestone in the southern Pahvant Range is important because it is the southeasternmost surface exposure of Mississippian strata in Utah. Because the Redwall terminology is widely used in well logs in southeastern Utah, it has been adopted here as representative of what may be found in those wells. In their map of the Beaver Lake Mountains in Beaver County, Lemmon and Morris (1984) used the Nevada term "Monte Cristo Limestone" for Mississippian strata that are commonly called Redwall Limestone in Utah.

Pennsylvanian

Introduction

Figure 146 shows the distribution of exposures of Pennsylvanian rocks in Millard County. The Callville Limestone in the southern Pahvant Range is the only formation in the county that is entirely Pennsylvanian in age (chart 6, appendix C). The Ely Limestone in western Millard County is mostly Pennsylvanian, but it also includes Permian strata in its upper part and Mississippian strata at its base. The Ely is discussed under the heading "Permian-Pennsylvanian-Mississippian."

Chart 6 (appendix C) shows the age ranges of the fossils most useful in dating Pennsylvanian and Permian strata. Foraminifera (forams), one-celled animals the size of a small grain of wheat, are useful in the Pennsylvanian and lower Permian (figure 147). Conodont (figure 148) age ranges are shown by arrow brackets on chart 6. Corals, brachiopods, bryozoans, and other marine invertebrates are common in Pennsylvanian and Permian strata, but are not as readily used for detailed age determination as microscopic foraminifera and conodonts.

Callville Limestone (IPc)

Welsh (1972, 1976, 1979) recommended extending usage of the name Callville from southern Nevada and Utah into the Pahvant Range for the Pennsylvanian strata there. In his regional analysis, based on fusulinid and conodont age determinations, Welsh found that the Callville rests discon-

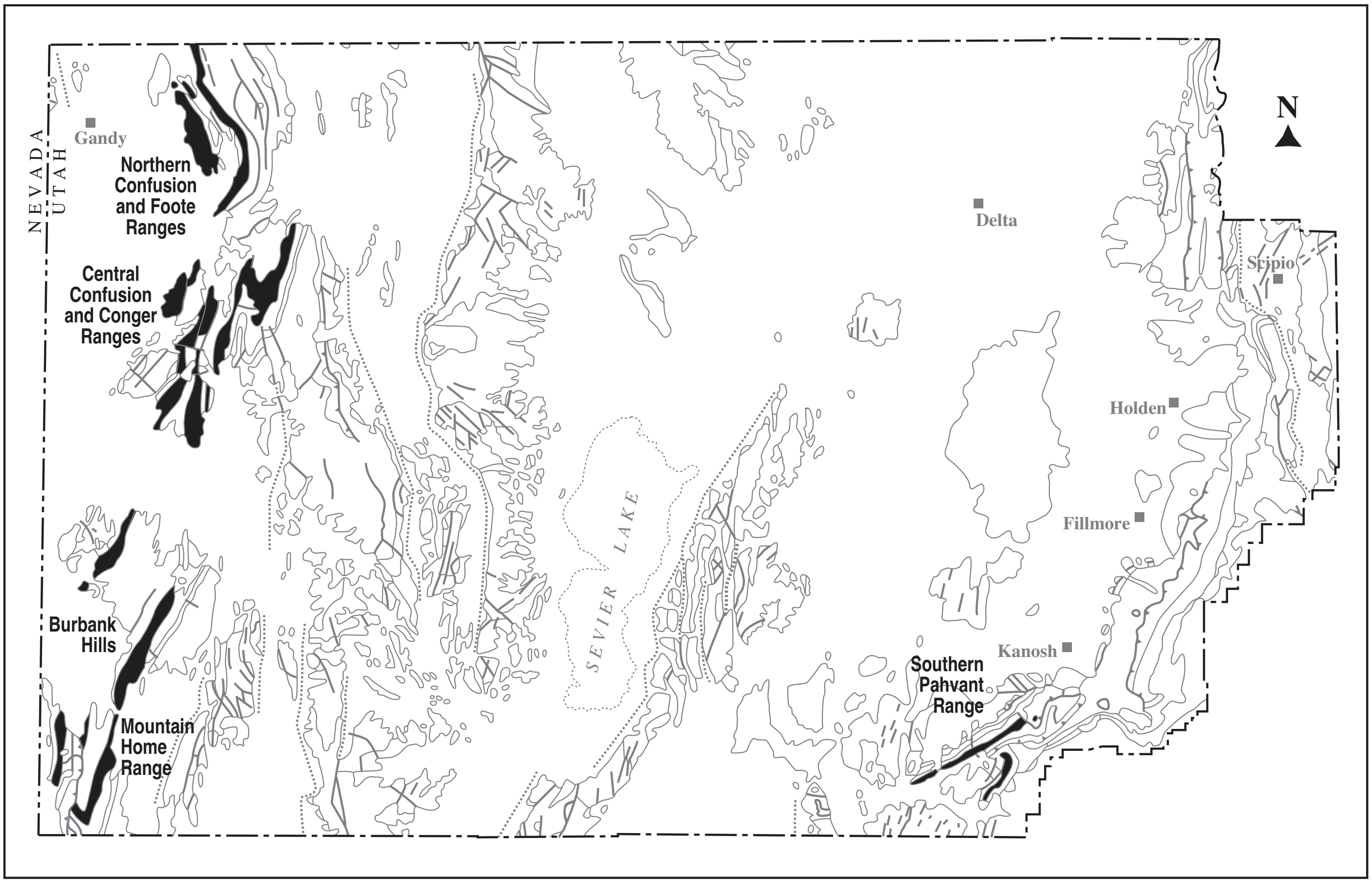


Figure 146. *Pennsylvanian outcrops in Millard County.*

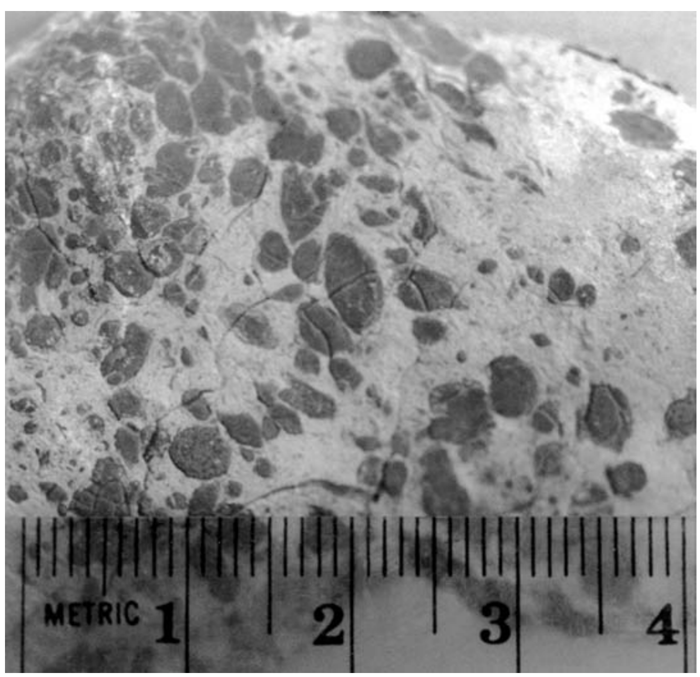


Figure 147. *Foraminifera tentatively identified by C.A. Ross as* Triticites californicus *or* T. cellamagnus *from the upper Ely Limestone in the Burbank Hills, latest Pennsylvanian or earliest Permian in age. The fossils are poorly preserved, having been crushed and recrystallized; they occur abundantly in a 30-foot (10-meter) thick zone in the upper Ely throughout western Millard County.*

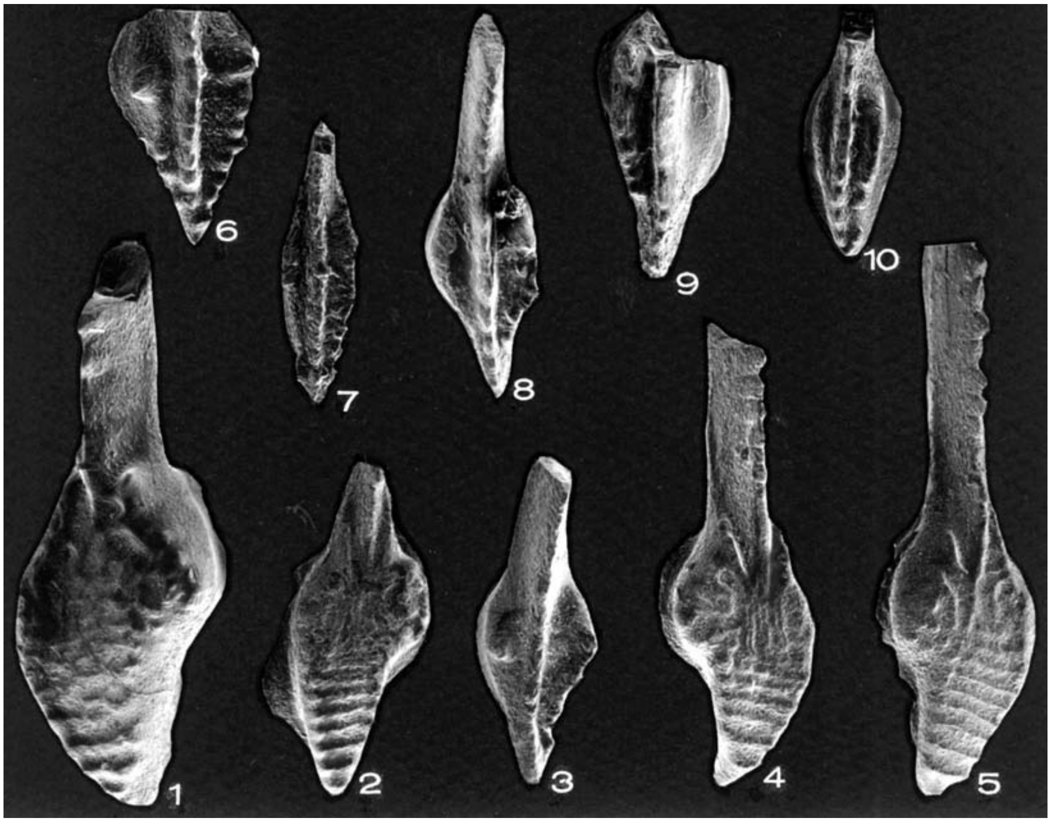


***Figure 148.** Photomicrographs of typical Pennsylvanian conodonts. Photos and identifications furnished by Professor Scott Ritter, Department of Geology, Brigham Young University, about X40: 1-2, 4-5,* Idiognathodus*; 3, 6-10,* Neognathodus.

formably on the Mississippian Redwall Limestone, and that Missourian-age deposits are absent within the Callville in southwestern Utah, as shown on chart 6 (appendix C).

The Callville Limestone was mapped in the southern Pahvant Range by George (1985) and Davis (1983). R.L. Davis (unpublished) measured the well-exposed section on the west side of Dog Valley Peak. There the Callville consists of medium- to light-gray, fine- to medium-grained, medium- to thick-bedded, cherty, interbedded dolomite and limestone. It includes a 10-foot (3-m) thick, fine-grained, pinkish-gray sandstone near its top, and thinner interbeds of sandstone in its lower one-third. It is 538 feet (164 m) thick on Dog Valley Peak. Welsh (1976) logged 290 feet (88 m) of Callville in the Sunset Canyon well in the central Pahvant Range.

Permian-Pennsylvanian-Mississippian

Ely Limestone (PIPMe)

Lawson (1906) named the Ely Limestone in eastern Nevada and Hose and Repenning (1959) showed that, in western Millard County, the Ely ranges in age from Late Mississippian to Early Permian. Bissell (1964) proposed that the Permian portion of the Ely in the Confusion Range be called the Ferguson Mountain Formation, but his suggestion has never been adopted by geologic mappers in Millard County because there is no practical way to recognize the age difference in the field since both the Pennsylvanian and Permian portions of the Ely are similar cherty limestones. The approximate position of the base of the Permian in the Ely is marked by the widespread appearance of large (1/4 inch [1/2 cm]) fusulinids that are abundant enough locally to be shown as a fossil zone on a geologic map (Hintze, 1986a). St. Aubin-Hietpas (1983) identified these as *Pseudoschwagerina* but C.A. Ross (written communication, December 2, 1987) tentatively called them *Triticites californicus* (figure 147). Bissell (1962), in a regional stratigraphic study, recommended that the name Riepe Spring Limestone be applied to the Permian portion of the Ely in the Mountain Home (northern Needle) Range and the Burbank Hills, but mappers have chosen not to use Riepe Spring as a map unit because the basis of its distinction from the Ely is entirely paleontologic rather than lithologic.

The basal part of the Ely is identified as Mississippian on the basis of the contained guide brachiopod, *Rhipidomella nevadensis*, and other Late Mississippian fossils. But it is also distinguishable lithologically from the Pennsylvanian-Permian part of the Ely by being almost entirely chertless, and is shown as a separate lower Ely unit on maps by Hintze (1986a) and Hintze and Best (1987).

Throughout western Millard County, as elsewhere, the Ely Limestone is easily recognized at a distance by its repetitive "stair-step," ledge-slope outcrops (figure 149), a product of its deposition under repeated cyclic conditions. Hose and Repenning (1959) noted that its limestones are commonly bioclastic, consisting of fragments of echinoids, brachiopods, crinoids, corals (figures 150 and 151), and foraminifera, as well as calcareous mud pellets and oolites.

***Figure 149.** Stair-step ledges of the Ely Limestone at the south end of the Conger Range, looking north from U.S. Highway 6, about 9 miles (15 km) east of the Nevada border.*

Figure 150. Barbouria *sp. horn corals in a muddy matrix are found in vast numbers 540 to 550 feet (165-168 m) above the base of the Ely Limestone in the Foote Range (Hose and Repenning, 1959).*

Figure 151. *Geology students returning from gathering horn corals from the shaly swale in which they occur in the lower Ely Limestone in the Foote Range. Hose and Repenning (1963) and Hose and Ziony (1963) show the extent of the coral bed on their geologic maps. Students in the center distance are on the coral bed.*

Silica is present not only in thin sandstone and siltstone interbeds but also as chert, in bedded nodules that range considerably in size and shape but are present throughout the formation, except at its base. Hose and Repenning (1959) noted that the Ely is 1,850 feet (564 m) thick near Skunk Spring in the central Confusion Range, and about 2,000 feet (610 m) thick in the northern Confusion Range. The Mississippian part of the Ely is about 60 feet (20 m) thick at Skunk Spring, and 200 feet (60 m) thick at Granite Mountain at the north end of the range (Webster and others, 1984). The Permian portion of the Ely is 350 feet (107 m) thick at Skunk Spring, and thins to about 100 feet (30 m) thick in the northern Confusions.

The Ely Limestone in the Mountain Home Range and Burbank Hills was described in detail by St. Aubin-Hietpas (1983) and mapped by Hintze (1986a; 1997a-d). In the Burbank Hills and the Mountain Home Range the chertless Mississippian part of the Ely is 200 feet (60 m) thick and the cherty Pennsylvanian-Permian part is about 2,500 feet (762 m) thick. St. Aubin-Hietpas' section in the Burbank Hills is incomplete because of faulting, but her described section totals about 2,600 feet (800 m) thick. St. Aubin-Hietpas (1983) contains the most complete analysis available for the Ely Limestone in western Millard County; she summarized the Ely's lithologic makeup, fossil content, and likely environments of deposition, and presented photographs of several of its common fossils.

Permian

Introduction

Figure 152 shows the distribution of exposures of Permian rocks in Millard County. Formation names, map symbols, thicknesses, general lithologies, and other information are shown on columns 3, 8, 10, and 11 (appendix C). Nomenclature for Permian rocks in the southern Pahvant Range is that generally applied to the thin platform sequence in southern Utah and adjacent areas in Arizona and Nevada. Names for the Permian rocks in western Millard County are those generally applied in western Utah and adjacent Nevada. Correlation of the two nom-enclatures is shown on chart 6 (appendix C). Paleontologic stratigraphers who have studied the Permian sequence regionally are inclined to split Permian strata into more named units than is practicable for geologic mappers. Different usages, inherent in the stratigraphic versus the mapping approach, are summarized in the discussions below. The sequence in western Millard County is given first, followed by the southern Pahvant Range sequence.

Conodants (figure 153) and fusulinids (figure 154) are the best fossils for definitive dating, but certain Permian limestones also contain abundant marine macrofossils as mentioned in the unit de-scriptions below.

Lithologic Units in Western Millard County

Arcturus Formation (Pa): Spencer (1917) named the Arcturus Formation at Ely, Nevada and it has been subsequently identified widely in the eastern Great Basin. Hose and Repenning (1959) adopted the name in their discussion of the stratigraphy of the Confusion Range and described its most complete and least structurally disturbed exposures in the northern part of the range. There the Arcturus Formation consists of poorly indurated, yellowish-gray, calcareous and dolomitic, fine-grained sandstone, and sandy limestone. The sandstone grains are mostly quartz with minor feldspar, tourmaline, and zircon. The Arcturus is generally medium to thin bedded and forms low topography. It includes a few limestone beds that persist throughout the northern Confusion Range and also includes thin gypsum beds at several horizons, but most commonly in the upper part. Fossils are rare in the Arcturus, but Hose and Repenning (1959) listed a small molluscan and bryozoan fauna from a limestone bed in

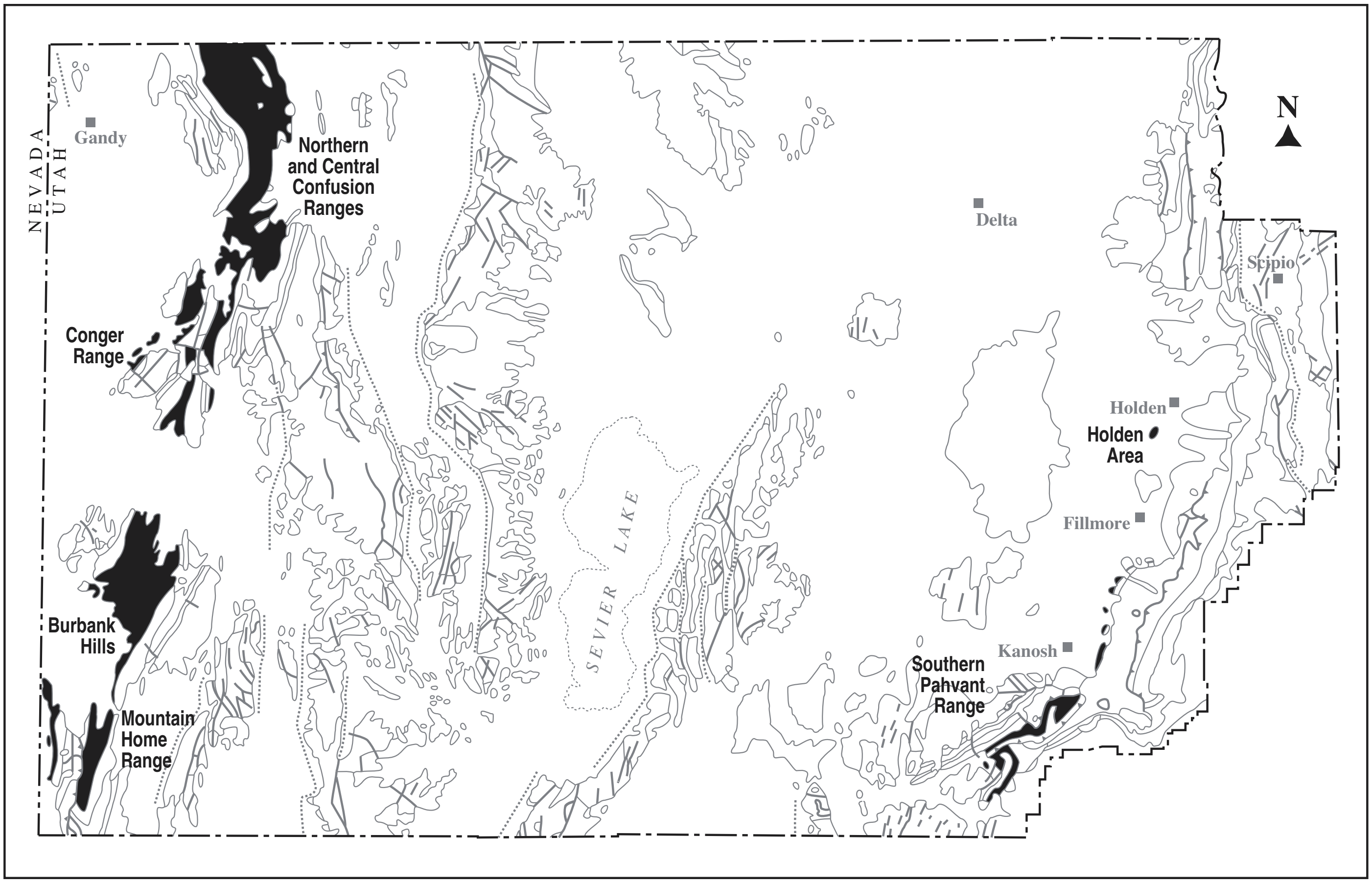


Figure 152*. Permian outcrops in Millard County.*

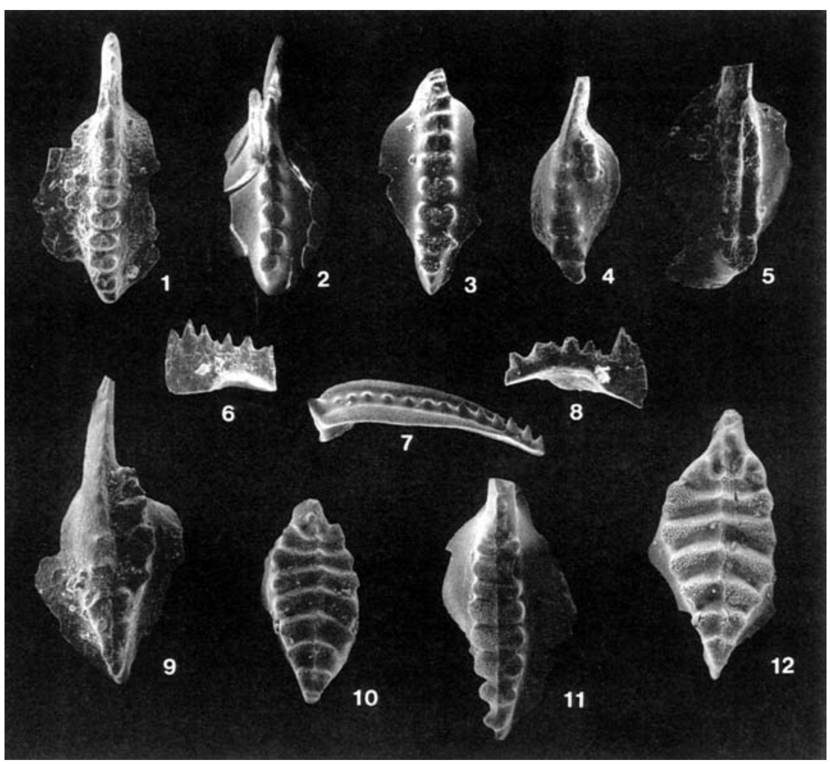


Figure 153*. Lower Permian conodonts from the Riepetown Formation (age equivalent of the lower Arcturas Formation). Photos and identifications furnished by Professor Scott Ritter, Department of Geology, Brigham Young University, about X37: 1-6, 8, 10-12,* Sweetognathus *spp.; 9,* Rabeignathus *sp.; 7,* Mesogondolella *sp.*

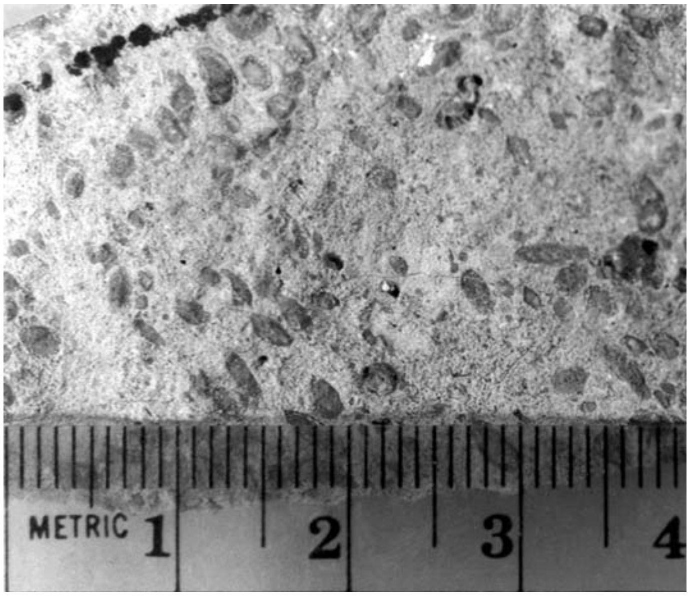


Figure 154. Lower Permian fusulinids from the upper Ely Limestone in the Burbank Hills, identified by C.A. Ross (written communication, 2 December 1987) as Schubertella *cf.* S. kingi, Triticites *sp.,* Schwagerina *cf.* S. aculeata*, S*chwagerina bellula*, and* Pseudofusulina *cf.* P. attenuata.

the upper part of the Arcturus that date the formation as Early Permian. The Arcturus is more than 2,700 feet (820 m) thick in the northern Confusion Range according to Hose and Repenning (1959); but these strata are highly deformed, so this thickness may not be accurate.

Bissell (1964) proposed elevating the Arcturus to a group that includes the Ferguson Mountain, Pequop, and Loray Formations in the Confusion Range, but his nomenclature has not been used on geologic maps in Millard County and probably does not have mapping practicability there.

The Arcturus is exposed in the central Burbank Hills where Hintze (1988b) estimated it to be 2,500 feet (760 m) thick. The top of the Arcturus is not preserved in either the Burbank Hills or the Mountain Home Range where Hintze (1986a) estimated its thickness as more than 2,300 feet (700 m). In both ranges the Arcturus is yellowish-gray-weathering, unfossiliferous, sandy dolomite or dolomitic sandstone.

Kaibab Limestone (Pk): Newell (1948) transferred the Grand Canyon name Kaibab into western Utah on the basis of identifying Kaibab brachiopods in this limestone in the Confusion Range. Hose and Repenning (1959) listed 10 typical Kaibab brachiopods found in the upper part of the Kaibab in the Confusion Range and noted that the Kaibab there is 480 feet (146 m) thick and consists mostly of massive, light-gray to yellowish-gray, cherty, bioclastic limestone capped by a 75-foot (22-m) thick bed of yellowish-gray dolomite. In western Millard County the Kaibab Limestone is found only in the central and northern Confusion Range where its maximum thickness is about 600 feet (180 m).

Plympton Formation (Pp): Hose and Repenning (1959) defined the Plympton Formation and presented measured sections of its type locality in the northern Confusion Range. The Plympton consists mostly of dolomite and chert that Hose and Repenning noted could be differentiated into five distinctive lithologic zones: the lowest zone, 20 to 25 feet (6-8 m) thick, consists predominantly of dark-gray bedded chert with a few thin beds of yellowish-gray dolomite; the second zone, 110 to 115 feet (34-35 m) thick, consists of yellowish-gray, cherty dolomite; the third zone, 115 feet (35 m) thick, consists of interbedded chert and dolomite; the fourth zone, 125 feet (38 m) thick, consists of dense, yellowish-gray, cherty and siliceous dolomite; the fifth and top zone is about 310 feet (94 m) thick and includes interbeds of dolomite, chert, carbonate breccia, sandstone, siltstone, and gypsum. The Plympton is unfossiliferous. Its aggregate thickness in the Confusion Range is 690 feet (210 m).

Gerster Limestone (Pg): Nolan (1935) named the Gerster in the Gold Hill mining district of western Utah, and Hose and Repenning (1959) applied the name to strata in the northern Confusion Range where the Gerster consists almost entirely of light-brownish-gray, ledge-forming bioclastic limestone interbedded with yellowish- or brownish-gray, slope-forming shaly limestone. The Gerster Limestone is abundantly fossiliferous, characterized by the *Punctospirifer pulcher* brachiopod fauna. The bioclastic limestone includes fragments of brachiopods, bryozoans, echinoids, crinoids, and gastropods. It is about 1,100 feet (335 m) thick in the northern Confusion Range.

Lithologic Units in Eastern Millard County

Pakoon Dolomite (Ppk): McNair (1951) named the Pakoon in northern Arizona, and Welsh (1972, 1976) extended its use into southwestern Utah. Both Davis (1983) and George (1985) mapped the Pakoon Dolomite in the southern Pahvant Range, but Davis' area contains the only complete sequence. There the base of the Pakoon is marked by a 50-foot (15-m) thick chert pebble conglomerate resting disconformably on the Callville Limestone. The remainder of the formation is mostly light-grey, cherty, sandy dolomite with a few thin interbeds of limestone. The Pakoon Dolomite is 445 feet (136 m) thick on the west side of Dog Valley Peak. Welsh (1976) reported 200 feet (61 m) of Pakoon Dolomite in the Sunset Canyon well in the central Pahvant Range.

Queantoweap Sandstone (Pq): McNair (1951) named the Queantoweap in northern Arizona, and Welsh (1972, 1976) extended its use into southwestern Utah. Both Davis (1983) and George (1985) mapped the Queantoweap Sandstone in the southern Pahvant Range, but Davis' map area contains the only complete exposures. There the Queantoweap is pinkish- or brownish-gray, fine-grained, cross-bedded, quartz sandstone that is variably cemented with calcite and locally friable. Davis (1983) reported a thickness of 817 feet (249 m) on Dog Valley Peak. Welsh (1976) recorded 290 feet (88 m) in the Sunset Canyon well (well 60-1, appendix A) near Meadow in the central Pahvant Range.

Kaibab Limestone (Pk): Darton (1910) named the Kaibab Limestone in northern Arizona and the term has been used in various ways in southeastern and southwestern Utah. Both Davis (1983) and George (1985) mapped the Kaibab in the southern Pahvant Range, but Davis' area contains the only completely exposed sequence, which he described as three units. The basal 330 feet (100.5 m) consists mostly of light-gray, fine-grained, cherty dolomite that includes about 70 feet (21 m) of fine-grained sandstone in its upper part. Welsh (1972, 1976) correlated this basal unit with the Toroweap Formation of northern Arizona. Davis' middle unit is 454 feet (138.3 m) of medium- to brownish gray, fine- to coarsely crystalline, thin- to medium-bedded, cherty, fossiliferous limestone. This middle limestone correlates with the Fossil Mountain Member of the Kaibab Limestone in northern Arizona. Davis' upper unit is 376 feet (114.5 m) of cherty, sandy dolomite and dolomitic sandstone. It correlates with the Harrisburg Member of the Kaibab of northern Arizona and part of the Plympton Formation of the Confusion Range. Davis (1983) and George (1985) included the Toroweap within their Kaibab map unit because they said there was no feasible way to trace the Kaibab and Toroweap separately in the field. Also, typical Toroweap lithologies are not present in their map areas. Total thickness of the Kaibab map unit in the southern Pahvant Range is 1,160 feet (353 m). Welsh (1976) reported 590 feet (180 m) of Kaibab-Toroweap in the Sunset Canyon well in the central Pahvant Range.

Cherty Dolomite near Holden (Pc): Column 2 (appendix C) shows this map unit, which is exposed 2 miles (3 km) southwest of the I-15 freeway offramp south of Holden. It forms a low narrow outcrop, surrounded by plowed fields, about a mile (1.6 km) west of the freeway, which it parallels for half a mile (0.8 km). It had not been mapped previous to this study (Hintze and Davis, 2002b).

The rock is predominantly light-gray, fine- to medium-grained, medium-bedded dolomite that contains bedded nodules of light-brown-weathering chert that makes up 10 to 50 percent of individual beds. Bedding strikes generally N. 30° E. and the rocks are folded, with both eastward and westward dips ranging to as much as 80 degrees. The rocks are fractured and silicified along fracture zones. Most beds contain no fossils, but one locality near the north end has a few small crinoid columnals. Several rock samples were processed for conodonts but only one sample yielded one fragment of a long-ranging late Paleozoic form. The amount of chert in the rocks suggests that they are Permian and, if so, may be a continuation of the Permian Kaibab rocks exposed in the Pahvant Range foothills south of Fillmore as mapped by George (1985).

This isolated outcrop is something of an enigma that must be taken into consideration in interpreting the Pahvant Range - Sevier Desert structural transition zone as discussed in a later section of this bulletin.

Triassic

Introduction

Triassic rocks in Millard County are exposed in the northern Confusion Range and the Pahvant Range (figure 155). Those in the Confusion Range (column 8, appendix C) are geosynclinal marine deposits of the Lower Triassic Thaynes Formation. Triassic strata in the Pahvant Range (column 3) are shelf deposits of the shallow-marine Lower Triassic Moenkopi Formation and the non-marine Upper Triassic Chinle Formation (chart 7, appendix C).

Triassic Fossil Life

Marine Lower Triassic strata contain many kinds of invertebrate fossils such as crinoids, gastropods, sponges, pelecypods, and brachiopods, but only two kinds, ammonites (figure 156) and conodonts (figure 157), have been used much for age correlation. Ammonites, an ancient relative of the modern chambered nautilus, have long been used as guides to time. Because they swam freely in the open ocean,

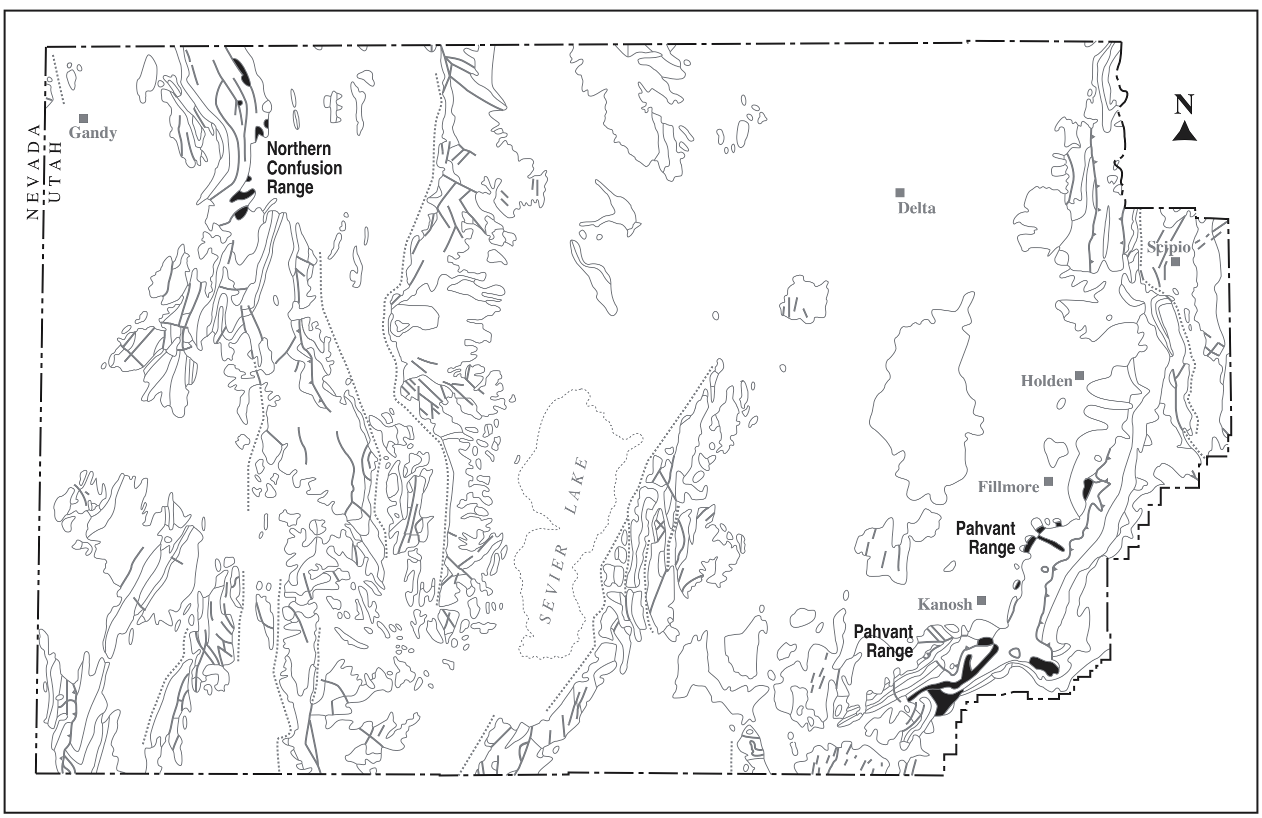


Figure 155. Triassic outcrops in Millard County.

Figure 156. Ussurites hosei*, a Lower Triassic (Spathian) ammonite from the Thaynes Formation, Cowboy Pass, Confusion Range; collected and photographed by Kevin Bylund; X0.9 magnification.*

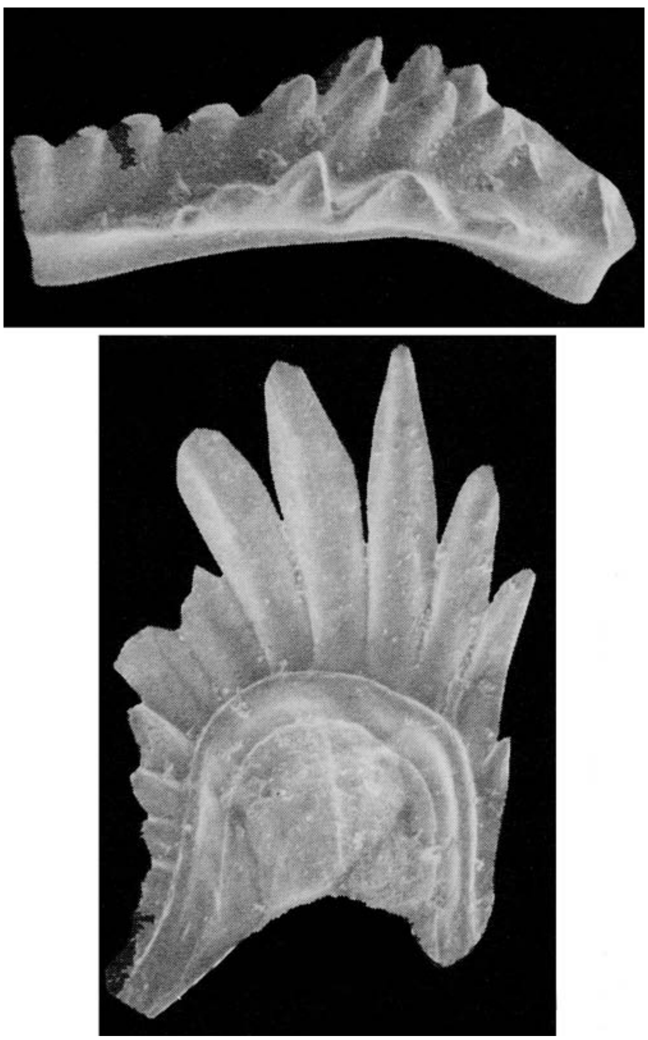


Figure 157. Lower Triassic conodonts (from Clark and others, 1979): top, Neogondolella milleri*, upper Smithian, X120; bottom left,* Parachirognathus ethingtoni*, middle Smithian, X67.*

they attained widespread distribution; because their suture pattern changed rapidly through time, a number of sequential ammonite zones can be recognized in Triassic deposits (Clark, 1957). Triassic conodonts, microscopic tooth-like fossils, were first described from the Great Basin by Muller (1956). Since that time they have proven to be even more useful than ammonites (see following paragraph), because they are more widely distributed in Lower Triassic marine strata. Conodonts became extinct in Triassic time, but ammonites continued to diversify and serve as useful guide fossils until the end of the Mesozoic.

Several biostratigraphers have proposed conodont zonation schemes for the Lower Triassic in the western United States as summarized by Carr and others (1984) and Clark and Carr (1984). Early zonation schemes, such as Sweet and others (1971), had many separate zones to include the various conodont assemblages found in a variety of environments. Clark and Carr (1984) combined some of the zones to produce the eight numbered zones shown in table 2, below. Lower Triassic zone names proposed by Sweet (1988) use the same number system but substitute a few different species names to represent certain zones.

***Table 2.** Lower Triassic conodont zones of Clark and Carr (1984), listed youngest (8) to oldest (1).*

8.	*Neogondolella timorensis*
7.	*Neospathodus homeri*
6.	*Neospathodus collinsoni*
5.	*Neospathodus triangularis*
4.	*Neospathodus waageni*
3.	*Neospathodus dieneri*
2.	*Neospathodus kummeli*
1.	*Hindeodus typicalis*

Recognition of conodont zones enabled Collinson and others (1976) to establish the magnitude of the unconformity between Permian and Triassic rocks in the Great Basin where the lowest three zones listed above are generally missing.

Conodont zones were correlated with earlier established ammonite zones by Collinson and Hasenmueller (1978). Conodont zones 4 and 5 are approximately equivalent in age to the *Meekoceras gracilitatis* ammonite zone; conodont zones 6 and 7 equate with the *Columbites-Tirolites* ammonite beds.

Lithologic Units

Thaynes Formation (TRt): Hose and Repenning (1959) established the usage of the Park City, Utah area term, Thaynes, in the Confusion Range and recognized seven rock sequences within the Thaynes Formation in western Millard County. The lowest 30 to 50 feet (9-15 m) is light-olive-gray and pinkish-gray, thin-bedded, porcellanous limestone that weathers to brownish-gray slabs that clink when walked on or struck with a hammer. The second 190 to 210 feet (58-64 m) is mostly olive-gray to yellowish-gray fissile claystone with thin interbeds of limestone, some of which contain ammonites. The third 310 feet (94 m) is calcareous claystone that is generally poorly exposed. The fourth 300 feet (91 m) is reddish-gray shaly claystone with interbeds of limestone as much as 16 feet (5 m) thick. Nearly all these limestones contain the fossil pelecypod, *Aviculopecten*. The fifth 330 feet

(101 m) consists of interbedded shaly claystone, fine-grained sandstone, and fine- to coarse-grained limestone that contains abundant terebratulate brachiopods in the lowest quarter of the unit. The sixth 230 feet (70 m) is covered, no rock exposed. The seventh and highest 525 feet (160 m) is yellowish-gray claystone and siltstone with interbeds of olive-gray limestone.

Regional studies of the Thaynes Formation in the Utah-Nevada-Wyoming-Idaho area show that the seven rock sequences reflect differing water depths associated with transgressions and regressions of seas over the western United States during Early Triassic time. Thaynes exposures in the Great Basin are widely separated. Northwest of the Confusion Range the nearest exposures of the Thaynes Formation are at Currie, Nevada, about 90 miles (144 km) away. Dubiel and Johnson (1994) summarized the Thaynes at Currie as being composed of alternating marine-shelf limestone and offshore marine shale and siltstone, generally similar to the Thaynes Formation in the Confusion Range. Pisera and others (1996) described fossil sponges from the Thaynes Formation in the Confusion Range.

Total thickness of the Thaynes Formation in the Confusion Range is 1,935 feet (590 m) (Hose and Repenning, 1959).

Moenkopi Formation (TRm): The Moenkopi Formation is widely exposed in southern and eastern Utah and adjacent states where its variations have been traced by several authors (for example, Stewart and others, 1972b; Blakey, 1974; Dubiel, 1994; Paull and Paull, 1994). But no regional stratigraphers have included the Pahvant Range exposures of Moenkopi in their discussions despite the fact that they are the northwesternmost exposures of Moenkopi known. The Moenkopi Formation in the Pahvant Range was mapped by Davis (1983) and George (1985). The best exposed section of Moenkopi is in section 34, T. 24 S., R. 6 W. and was described by R.L. Davis (unpublished field notes, 1983, then at Brigham Young University) as follows:

Unit No.	**Description**	**Thickness Feet**	**Meters**
27.	Slope covered with debris from Shinarump cliffs above.	190	58.0
26.	Siltstone, mostly reddish-brown but with some greenish-gray beds, calcareous, shaly, forms slope.	112	34.0
25.	Covered slope, Shinarump talus.	33	10.0
24.	Covered slope, red soil suggests mudstone.	108	33.0
23.	Covered slope. Units 23-27 may represent upper red member of Moenkopi of southern Utah.	79	24.0
22.	Sandstone, yellowish- to orangish brown, fine-grained, calcareous, ripple-marked, forms low ledges and slopes.	15	4.5
21.	Dolomite, light-olive-gray, weathers dark olive gray, sandy, thin- to medium-bedded, some cross-bedding, interbeds of thin-bedded, tan, calcareous sandstone.	60	18.3
20.	Limestone, light-brownish-gray, bioclastic, thin-bedded, forms ledge, contains abundant *Pentacrinus* and brachiopod fragments.	16	5.0
19.	Sandstone, dolomitic, brownish-gray, fine-grained, thin-bedded, contains ripple marks and rip-up mud clasts.	42	12.8
18.	Limestone, similar to unit 20.	10	3.0
17.	Sandstone, similar to unit 19.	57	17.5
16.	Limestone, similar to unit 20.	15	4.5
15.	Sandstone, reddish-gray, weathers reddish-brown, thin-bedded, forms flagstone-covered slope.	93	28.5
14.	Limestone and dolomite, medium-gray, finely to coarsely crystalline, thin- to medium-bedded, bioclastic with crinoid and brachiopod fragments, includes some thin sandstone interbeds, forms platy talus slope. Units 14-22 may be equivalent to the Shnabkaib Member of the Moenkopi in southern Utah.	30	9.0
13.	Sandstone, light-reddish-gray, fine-grained, calcareous, thin-bedded, ripple marks on some surfaces, with a few thin interbeds of red shale and gray limestone.	128	39.0
12.	Limestone, light-brownish-gray, sandy, with some reddish-gray, thin sandstone interbeds, forms ledgy slope.	55	16.8
11.	Interbedded limestone and sandstone. Limestone is brownish-gray, thin-bedded, bioclastic; sandstone is dark-reddish-brown, calcareous, thin-bedded, forms platy talus-covered slope.	74	22.5
10.	Similar to unit 11, better exposed.	84	25.5
9.	Interbedded sandstone, siltstone, and limestone. Sandstone and siltstone is reddish-gray, thin-bedded; limestone is medium-gray bioclastic with shell fragments and intraformational limestone clasts. Unit forms debris-covered slope. Units 9-13 may be equivalent to the middle red member of the Moenkopi of southern Utah.	212	64.5
8.	Interbedded limestone, shale, and siltstone. Limestone is brownish- to bluish-gray, fine-grained, thin-bedded, ledge-forming, and includes abundant coquinas of the	180	54.8

Unit No.	Description	Thickness Feet	Meters
	ammonite *Meekoceras*. Shale and siltstone interbeds are olive-gray, thin-bedded, and form slopes. Nine ammonite-bearing beds within this unit total about 20 feet (6 m) thick. This unit may be equivalent to the Timpoweap Limestone Member of the Moenkopi in southern Utah, and the Sinbad Limestone Member in eastern Utah (Hintze, 1988a).		
7.	Interbedded dolomitic siltstone and shale. Siltstone is olive-gray, thin-bedded, forms low ledges; shale is olive-gray, papery, forms covered slopes.	27	8.3
6.	Interbedded thin-bedded limestone and papery shale.	52	15.7
5.	Limestone, olive-gray, thin-bedded, silty, some bedding surfaces show worm-trail trace fossils, others show ripple marks, forms ledgy slope.	49	15.0
4.	Limestone, light-gray, light-brown, and pinkish-brown, thin- to thick-bedded, forms ledges, some beds oolitic, some bioclastic, forms ledgy slope.	20	6.0
3.	Interbedded siltstone and sandstone, reddish-brown, calcareous, thin-bedded, some ripple marks and cross-beds, some papery shale in talus, forms slope.	116	35.5
2.	Interbedded siltstone and sandstone, similar to unit 3 but better exposed.	7	2.0
1.	Pebble conglomerate, siltstone, and sandstone, interbedded. Conglomerate is gritty and contains limestone and chert pebbles. Siltstone and sandstone similar to unit 3.	12	3.8
	Total thickness of Moenkopi Formation	1,876	572

The Shell Oil Company Sunset Canyon exploration well in the central Pahvant Range penetrated more than 2,000 feet (600 m) of Triassic rocks in the upper part of the hole, but the thickness of the Moenkopi is unclear from well logs (appendix A, well 60-1).

Chinle Formation: The Chinle Formation is widely exposed in southern and eastern Utah and northern Arizona where its characteristics were summarized by Stewart and others (1972a) and Dubiel (1994). However, no regional stratigraphers have studied the Chinle in the Pahvant Range; its description there was done by Davis (1983) and George (1985), who mapped two Chinle members, a thick basal sandstone and conglomerate, the Shinarump Conglomerate Member, and a thin mudstone and siltstone sequence that they designated, informally, as the upper member of the Chinle Formation. It is probably equivalent to the Petrified Forest Member of southern Utah and Arizona.

Shinarump Conglomerate Member (Ŧcs): Although this unit is regionally called a conglomerate, in the Pahvant Range it is mostly coarse sandstone and grit. Within the Pahvant Range it varies considerably in thickness. In section 17, T. 22 S., R 4 W., George (1985) measured 177 feet (54 m) of Shinarump sandstone. In section 30, T. 24 S., R. 5 W., Davis (1983) measured 566 feet (172.5 m) of Shinarump, which he described in unpublished notes as follows:

Unit No.	Description	Thickness Feet	Meters
8.	Sandstone, coarse-grained, tan to white, cross-bedded, forms ledges, contains few thin interbeds of gritstone up to 3 feet (1 m) thick, sparse fossil wood fragments.	166	50.5
7.	Gritstone, coarse, weathers brownish-gray, cross-bedded, forms ledge.	8	2.5
6.	Sandstone and gritstone, tan, includes some pebbles of quartzite and fossil wood fragments, large cross-beds, forms cliffs.	34	10.5
5.	Gritstone and sandstone, tan, iron-stained, includes one thin bed of quartzite pebble conglomerate with a sandstone matrix, forms ledges.	20	6.0
4.	Pebble conglomerate and gritstone, gray, mostly quartzite and chert clasts, subangular to subrounded, some fossil wood fragments.	13	4.0
3.	Sandstone, coarse grained to gritty, cross-bedded, light-gray, iron stained, forms ledges.	54	16.5
2.	Gritstone and pebble conglomerate, gray, with red, brown, gray, black, and orange quartzite and chert pebbles, some fossil wood fragments, forms ledges.	25	7.5
1.	Sandstone, gritstone, and pebble conglomerate, with clasts of quartzite and chert, some cross-bedding, some fossil wood fragments, poorly cemented, poorly exposed. Contact with underlying Moenkopi Formation not exposed, covered by Shinarump talus and debris.	246	75.0
	Total thickness of Shinarump Conglomerate Member	566	172.5

A fluvial depositional environment is indicated for the Shinarump because of the cross-bedding within units and lens-shaped channel form of many beds. Fossil wood fragments are common; the largest petrified log segment found was 20 inches (50 cm) in diameter and about the same length.

Dubiel and Johnson (1994) presented a paleogeographic map of the Shinarump fluvial system that shows the major drainage trending from southeastern Utah towards northwestern Utah and northeastern Nevada. Cross-bedding direction measurements have not been reported from the Pahvant Range exposures, so it is not presently known what such measurements might indicate about paleodirection of stream flow in this part of Utah.

Upper member (T̶Rcu): The upper member consists of interbedded sandstone, siltstone, mudstone, and shale that contains calcareous and hematite nodules. Davis (1983) reported a thickness of 86 feet (26 m) of upper Chinle above the Shinarump in the measured section described above. George (1985) measured the upper member in two places in the Fillmore 7 1/2-minute quadrangle and found that its thickness ranges from 183 to 192 feet (55.5-58.5 m). The better exposed of the two sequences is located in Meadow Creek in the NE1/4 NE1/4 section 20, T. 22 S., R. 4 W., and is summarized as follows from George's unpublished notes:

Unit No.	Description	Thickness Feet	Thickness Meters
3.	Interbedded mudstone, shale, and siltstone. Mudstone is dark-reddish-purple to light-red with green blotches, irregular bedding and weathers to crumbly slope. Shale is brownish-red and greenish-gray, papery. Siltstone is similar to mudstone in color, bedding and weathering.	74	22.5
2.	Interbedded sandstone and shale. Sandstone is fine-grained, calcareous, grayish-purple, green, and yellowish-brown, thin- to medium-bedded, with some cross-laminations. Shale is purple, red, and green, papery and contains minor small-pebble conglomerate interbeds. Basal 30 feet (9 m) of this unit has abundant hematite nodules up to 6 inches (15 cm) in diameter with botryoidal surfaces. Middle part of unit contains abundant petrified wood fragments. Upper two-thirds of unit contains abundant purple and green septarian nodules. Unit generally forms a colluvium-covered slope.	84	25.5
1.	Interbedded sandstone, siltstone, and shale. Sandstone is fine-grained, purple with green blotches, thin- to medium-bedded, cross-bedded. Siltstone is purple, laminated to thin-bedded, cross-bedded. Shale is purple and green, papery. Unit forms slope with sharp contact with underlying ledges of Shinarump Conglomerate Member.	25	7.5
	Total thickness of upper member of Chinle Formation	183	55.5

Dubiel and Johnson (1994) presented a paleogeographic map of the Late Triassic Petrified Forest fluvial system, of which the upper member is likely a part, that shows Chinle streams draining towards the northwest across central Utah.

Jurassic

Introduction

The only Jurassic sedimentary deposit exposed in Millard County is the Navajo Sandstone, a deposit of unfossiliferous wind-blown sand that covered all of Utah except its northwest corner in Early Jurassic time. Other Jurassic rocks in Millard County are the Middle Jurassic quartz monzonite intrusive stock in the House Range and a very small intrusive diabase plug in the Burbank Hills (chart 7, appendix C; figure 158).

Lithologic Units

Navajo Sandstone (Jn): The Navajo Sandstone is extensively exposed along the west side of the Pahvant Range from Fillmore to the south end of the range. Between Fillmore and Kanosh it is overlain structurally by Cambrian quartzite at the base of the Pavant thrust plate. South of Kanosh it is overlain unconformably by Tertiary sedimentary and volcanic rocks as shown on the Richfield 1:100,00-scale geologic map (Hintze and others, 2003). The top of the Navajo Sandstone is nowhere exposed in Millard County.

The Navajo Sandstone is a brownish-red, fine-grained, eolian, cross-bedded sandstone; its quartz grains are frosted, well rounded, and variably cemented with calcite. The Navajo forms prominent ledges and cliffs and is generally fractured and shows joint sets. Locally, the Navajo is white, particularly near the top of its exposures or locally, along fractures. Because its top in the Pahvant Range is a structural surface, its exposed thickness varies considerably. Lautenschlager (1952) calculated a thickness of 2,019 feet (615 m) in the South Fork of Chalk Creek; Crosby (1959) measured 1,742 feet (531 m) in the southern Pahvant Range; Hickox (1971) estimated a thickness of about 1,800 feet (550 m) on the ridge between Walker and Meadow Creeks; and Davis (1983) estimated a thickness of 1,130 feet (345 m) in the Red Ridge 7 1/2-minute quadrangle south of these other localities. Original depositional thickness of the Navajo Sandstone in eastern Millard County was probably at least 2,000 feet (600 m) as judged from regional thickness trends of the Navajo in Utah (Hintze, 1988a).

Notch Peak Quartz Monzonite (Jg): Because the Notch Peak stock is the only large Jurassic pluton in west-central Utah, it has attracted a variety of studies related to determining the Mesozoic and Cenozoic history of mineralization and deformation in the area (figure 17). Gehman (1958) presented the first geologic map and detailed discussion of this granitoid intrusion in the central House Range. Tungsten was mined during World War II from the contact metamorphic aureole in Cambrian carbonate rocks that roof the intrusion. Armstrong and Suppe (1973) reported a K-Ar age of 143 Ma for the intrusion; this was later revised to 170 Ma (Ren and others, 1989). Hintze (1974d) showed the Notch Peak intrusion on his 1:48,000-scale geologic map of the Notch Peak quadrangle, as well as a small undated diorite dike in rocks

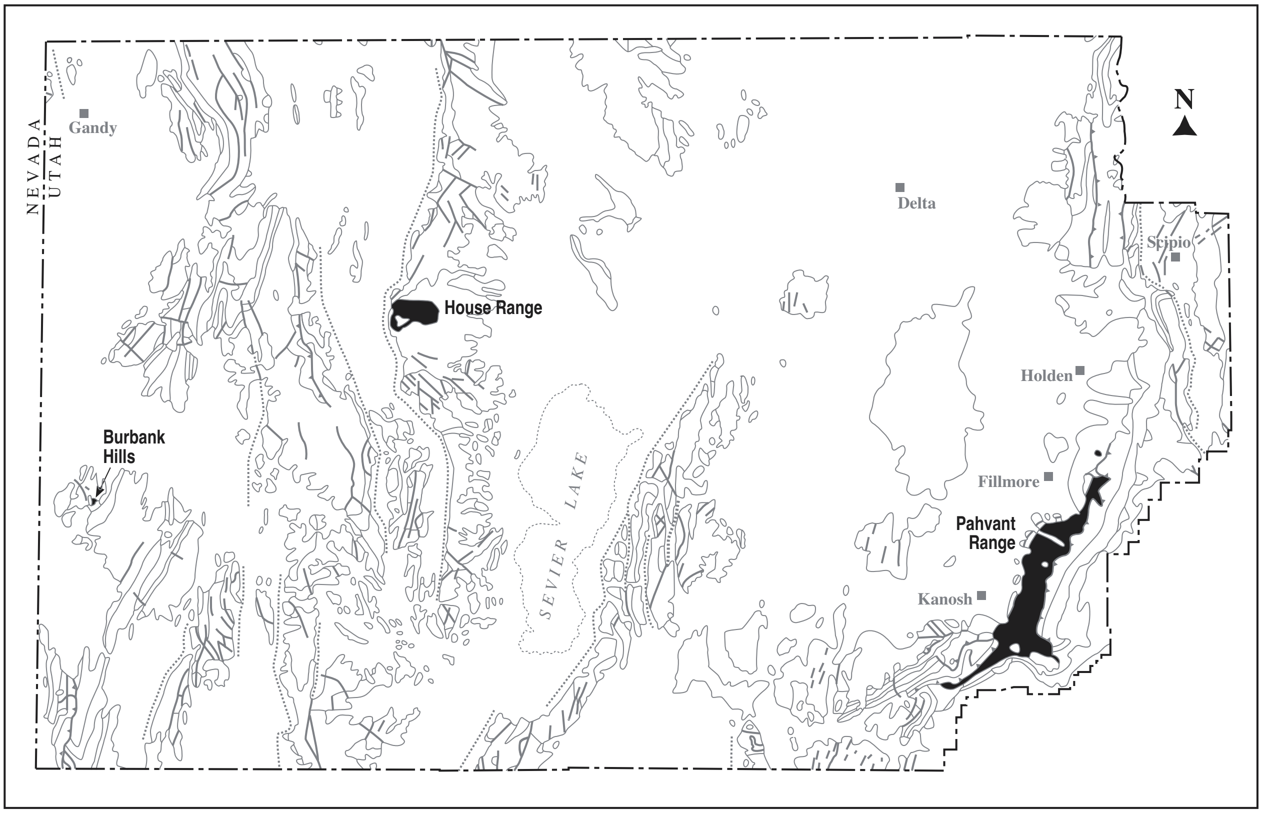


Figure 158. Jurassic outcrops in Millard County.

near the intrusion. Whether the dike is Jurassic or Tertiary in age is not known, but it is identified on the Tule Valley geologic map as Tid (Hintze and Davis, 2002c).

Gehman (1958) described the main body of the intrusion as a coarsely crystalline porphyritic quartz monzonite and noted that diopside-rich monzonite forms isolated masses along the contact of the intrusion with the Cambrian country rocks, and that hornblende granite occupies the central part of some sills that extend from the main body. Aplite (rock containing smaller feldspar crystals than the main body) dikes and sills show a wide variation in grain size and composition, and cut both the main body of the intrusion and, in places, extend into the adjacent sedimentary rocks. Gehman (1958) also described the contact metamorphic skarns, where massive garnet (none of gem quality) has replaced some of the metamorphosed sedimentary rocks.

Petersen (1976) studied the geochemistry of the tungsten deposits in the contact metamorphic skarn and tactite zones, and described relationships at eight of the individual tungsten mines and prospects. Hover-Granath and others (1983) focused on contact metamorphic effects in the Upper Cambrian Big Horse Limestone Member of the Orr Formation and used the development of certain contact metamorphic minerals to estimate the temperature at which the metamorphism occurred (450-600 degrees C), assuming an overburden pressure of about 2 kbar.

Nabelek and others (1986) reported on the origin of reverse zoning and petrogenesis of the Notch Peak intrusion. Ren and others (1989) used microfractures in quartz grains from the Notch Peak intrusion and other later igneous rocks to determine the paleostress history of this part of the Great Basin. Labotka and others (1988a-b) studied fluid infiltration and effects of contact metamorphism on limestone and shale in the Big Horse Member of the Orr Formation. Novick and Labotka (1990) examined fluid inclusions in rocks around the Notch Peak intrusion. Ferry and Dipple (1992) and Cui and others (2002) studied fluid flow in the rocks metamorphosed by the intrusion. Todd (1990) used the bleaching of Cambrian limestone adjacent to the Notch Peak intrusion to determine the composition of the metamorphic fluids responsible for bleaching, and concluded that the fluid was more than 90 percent water. Allmendinger and Miller (1991) studied microstructures around the Notch Peak and other Jurassic intrusions in western Utah and eastern Nevada to put limitations on the nature of Jurassic and Cretaceous tectonic movements in that area.

Campbell and Labson (1989) said that magnetotelluric soundings at Notch Peak suggest that the exposed granite extends only to a depth of about 3,500 feet (1 km) where it overlies at least 18,000 feet (5 km) of Precambrian and/or Paleozoic strata. They concluded that the Jurassic granite is either a laccolith or, more likely, that it was truncated at depth by a low-angle Cretaceous or Tertiary fault. Magnetotelluric data indicate another intrusive body at greater depth, offset about 1 to 3 miles (2-5 km) to the south of the exposed granite.

Diabase plug in the Burbank Hills (Jd): A rocky pile, measuring about 30 feet (9 m) in diameter, of large, exfoliated, brown-weathering boulders surrounded by Mississippian Chainman Formation is the exposed remains of an uppermost Jurassic diabase plug that I found while mapping for this study (Hintze, 1997a). It is located in section 11, T. 22 S., R.

19 W., 0.7 mile (1.1 km) southwest of Red Pass on the Burbank Pass 7 1/2-minute quadrangle. A K-Ar age of 141.4 ± 3.1 Ma was determined for the rock by Dr. Paul E. Damon (written communication, February 23, 1988) in his Isotope Geochemistry Laboratory at the University of Arizona. The rock is hard and dense. On fresh surface it is black and has a finely crystalline texture.

Granitic intrusive rocks of Late Jurassic and Early Cretaceous age are fairly widespread in eastern Nevada and northwestern Utah (Allmendinger and Miller, 1991), but this is the first reported occurrence of a Jurassic mafic rock in west-central Utah.

Early Eocene-Paleocene-Cretaceous

Introduction

Beginning in the Middle Jurassic and extending into Paleocene time, Millard County was subjected to tectonic events associated with mountain building in western Utah and eastern Nevada; the affected terrain is called the Sevier orogenic belt and the events are part of the Sevier orogeny. The Jurassic Notch Peak quartz monzonite stock was intruded into the disturbed belt, and during Late Cretaceous and Paleocene time compressive forces pushed thick sheets of Precambrian, Paleozoic, and lower Mesozoic strata tens of miles southeastward in a succession of thrust movements. During Late Cretaceous time sediments eroded from the Sevier orogenic highland were shed eastward, covering Utah from eastern Millard County eastward. Most of these Cretaceous deposits in eastern Utah were laid down on marshy coastal plains or in shallow marine waters. The Canyon Mountains and Pahvant Range (figure 159) contain major exposures of coarse conglomerates and other alluvial rocks deposited on the west side of the Cretaceous coastal plain and at the east edge of the Sevier highland (figure 53).

Vandervoot and Schmitt (1990) described the Cretaceous to early Tertiary paleogeography in eastern Nevada just west of Millard County and listed the localities that have deposits of this age. There, Cretaceous to Eocene terrestrial sediments are mostly conglomerates and sandstones with lesser limestones and, locally, landslide megabreccia. Deposition was restricted to local basins and preserved stratal thicknesses range from 0 to about 3,300 feet (0-1,000 m). Similar sediments may have been deposited in Millard County, but were later eroded from ranges or are concealed in the basins in the county.

Exposed Cretaceous rocks in Millard County are mostly unfossiliferous. Their age is constrained by the dated rocks that overlie and underlie them, and by geologic structures they cover and are cut by, as well as by their interpreted equivalency to fossiliferous Cretaceous strata in central Utah. The only deposits in Millard County that are believed to be entirely Cretaceous are the Canyon Range Conglomerate (chart 7; columns 1 and 2, appendix C), the conglomerate in the Mineral Mountains (column 4), the tectonic melange at the base of the Pavant thrust (column 5), and breccia in the House Range (column 7). The tectonic breccia in the Halfway Hills (column 10) may have formed either during Cretaceous Sevier deformation or later in Tertiary time. The North Horn Formation is latest Cretaceous in its lower part

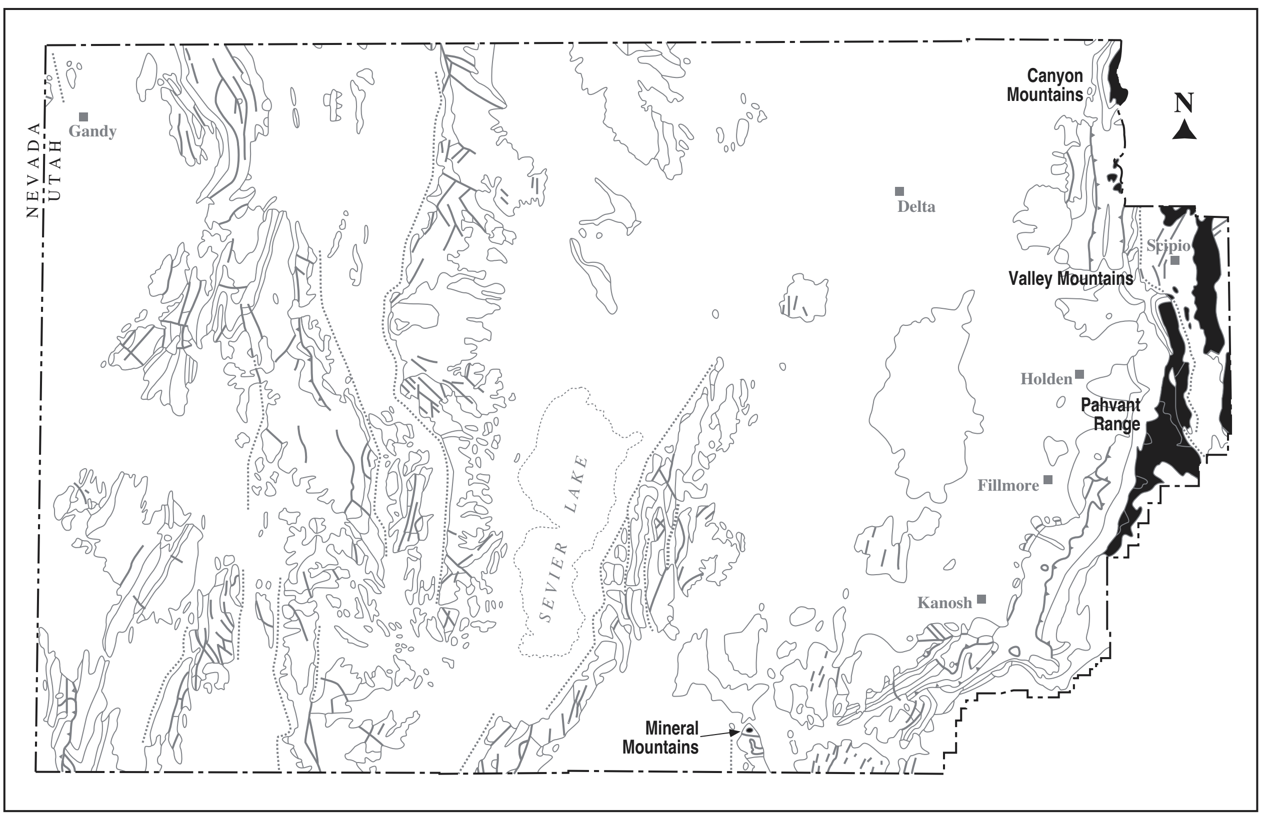


Figure 159. Paleocene and Cretaceous (pre-Flagstaff Formation) outcrops in Millard County.

and Eocene in its upper part, based on dinosaur and other fossil remains found in central Utah (Lawton and others, 1993).

Lithologic Units

Tectonic melange beneath Pavant Thrust (Ktm): Hickcox (1971) mapped "thrust slices" at the base of the Pavant thrust at four locations along the base of the range front between Fillmore and Kanosh and identified in them rocks ranging from Mississippian to Jurassic. Reexamination of the outcrops that he mapped as Jurassic Twin Creek Limestone indicates that they are mostly a mixture of Triassic Moenkopi Formation lithologies. Because of the incoherence of rocks found in most of the thrust slices, it is probably more useful to designate them as a melange (mixture of various rocks) (column 3, appendix C), rather than to give them a formation designation which might suggest less structural deformation than the rocks show.

Melange wedges represent rocks, chiefly of late Paleozoic and Triassic age, that were dragged along beneath the Pavant thrust plate as it overrode the Navajo Sandstone. Thickness varies from zero to several hundred feet. Internal structures, such as might identify direction of movement of the thrust plate, have not been reported.

Breccia and mylonite along tear faults in the House Range (Kbm): Northwest-trending tear faults in the House Range have locally produced zones of breccia in Cambrian quartzite and mylonite in Cambrian limestone as much as 30 feet (9 m) wide (Hintze, 1981a-b). Northwest-trending tear faults are conspicuous features in several ranges in west-central Utah (Hintze, 1980d). Hintze (1978) showed that the tear faults are related to zones of tectonic attenuation in lower Paleozoic strata, especially well displayed in the northern part of the House Range and in the Fish Springs Range in Juab County. The attenuation-tear faulting relationship was likely produced during Sevier orogenic contraction (Hintze, 1978).

Canyon Range Conglomerate (Kc): The coarse bouldery deposits in the Canyon Mountains area that accumulated along the east margin of the overthrust belt (figures 32 and 53) have been assigned various names by successive geologists. Christiansen (1952) called them "Indianola group(?)," taking the name from an area in Sanpete Valley, 30 miles (50 km) to the east. The type Indianola is early Late Cretaceous (Campanian to Cenomanian) according to Fouch and others (1983), and is more sandstone and shale than conglomerate. Armstrong (1968a) deemed Indianola to be an inappropriate name, both lithologically and temporally for the Canyon Mountains deposits and termed them "Canyon Range fanglomerate." He suggested that, despite the lack of fossils or other age control, the Canyon Range fanglomerate might be a lateral equivalent of the Paleocene and Eocene Flagstaff Limestone of central Utah. Stolle (1978) made a detailed study of these coarse clastic deposits on the east side of the Canyon Mountains near Fool Peak, about 10 miles (16 km) north of Scipio Pass. Stolle (1978) called these rocks the Canyon Range formation (informal name) and concluded that its lower conglomeratic part was likely equivalent to the Upper Cretaceous Price River Formation and the Cretaceous-Paleocene North Horn Formation to the east. The upper part of Stolle's (1978) Canyon Range formation includes fluvial sandstone and some lacustrine limestone. He correlated this upper part with the North Horn Formation and the Flagstaff Limestone.

Holladay (1984) mapped part of the northern Canyon Mountains where the Canyon Range Conglomerate is extensively exposed and he divided it into three map units: lower member, middle member, and upper member. Holladay's lower and middle members were mapped and remeasured by Lawton and others (1997, 2003) who called them the "hanging wall assemblage" of the Canyon Range Conglomerate as discussed below. The more than 3,900-foot (1,200+ m) thick upper member of Holladay's (1984) Canyon Range Formation is better designated as the North Horn Formation. All of this unit, as mapped by Holladay (1984), is located east of the Millard County-Juab County line where it is overlain by the Flagstaff Formation, which is shown on Holladay's (1984) geologic map as "Red beds of Wide Canyon."

Lawton and others (1997, 2003) presented a new map and descriptions of the Cretaceous and lower Tertiary conglomerate units in the Canyon Mountains. They recognized a lower sequence of conglomerate units that they called the "footwall assemblage," which is exposed between Little Oak Canyon and Cow Canyon on the southeast flank of the Canyon Mountains. They divided it into seven map units about 1,700 feet (520 m) thick in aggregate and consisting of interlayered quartzite-, carbonate-, and mixed-quartzite-carbonate-clast lithologies (column 1, appendix C). Lawton and others' (1997, 2003) reported it to be Albian in age, older than previously thought (compare to figure 53).

Lawton and others' (1997, 2003) upper Canyon Range Conglomerate (figure 160), called the "hanging wall assem-

__Figure 160.__ Canyon Range Conglomerate in Leamington Canyon is a boulder conglomerate with abundant clasts from Caddy Canyon, Mutual, Prospect Mountain, and Pioche Formations. The conglomerate is steeply inclined, but less so than the upper Precambrian and lower Cambrian strata which it overlies unconformably. See Lawton and others (1997, stop 5) for map and explanation.

blage," is exposed in the northeastern part of the Canyon Mountains near Wild Horse Peak. Their units Kcm4 through Kcq8, thought to be Cenomanian through Campanian in age, total 2,770 feet (844 m) in thickness. Unit Kcq8 is overlain by a mixed-clast conglomerate that is probably equivalent to the uppermost Cretaceous part of the Tertiary-Cretaceous North Horn Formation.

In the north end of the Pahvant Range, Michaels and Hintze (1994) reported 792 feet (241 m) of Canyon Range Conglomerate along the east side of the Scipio Pass 7 1/2-minute quadrangle. Lawton and others (1997, 2003), who worked from Chokecherry Creek northward in the central and northern Pahvant Range, concluded that the Cretaceous conglomerates there (figure 161) range in age from late Albian to Campanian; they assigned the following names to stratal units in ascending order: basal conglomerate, Pavant sandstone, Noon Rock conglomerate, and Chokecherry conglomerate. They (2003) described the Chokecherry conglomerate in Chokecherry Canyon as dominantly quartzite-boulder conglomerate and sandstone that rest directly on Cambrian carbonate rocks. The aggregate Canyon Range Conglomerate thickness is estimated to be up to about 3,100 feet (950 m), and the Canyon Range Conglomerate is not exposed south of Meadow Creek in the central Pahvant Range. In the central Pahvant Range, Lautenschlager (1952) reported 70 to 550 feet (21-168 m) of "Price River conglomerate" and measured 866 feet (264 m). Lawton and others (1997, 2003) recommended that the name “Price River” be abandoned for Cretaceous strata in the Pahvant Range.

Conglomerate of Mineral Mountains (Kcg): Liese (1957) mapped and described outcrops of conglomerate at the north end of the Mineral Mountains. He identified them as Cretaceous in age based on comparison with conglomerates of similar structural position in the Canyon Mountains. The conglomerate is composed mostly of pebbles and cobbles of gray limestone with lesser amounts of gray quartzite, tan sandstone, and black chert clasts, cemented in a matrix of sandy limestone that is generally gray but locally reddish-brown; the conglomerate is massive and forms ledgy outcrops. Liese reported that it is 112 feet (34 m) thick.

Walker and Bartley (1992) reported that their mapping showed that the conglomerate in the Mineral Mountains is present beneath Cambrian quartzites that were thrust over the conglomerate during the Late Cretaceous (see figure 4 in Coleman and others, 1997). Note, however, that Walker and Bartley showed Liese’s conglomerate outcrops as Tertiary and that their subthrust conglomerates were not mapped by Liese. Because the age of the “Tertiary” conglomerate is uncertain, all these conglomerates are shown as Cretaceous on the Richfield 1:100,00-scale geologic map (Hintze and others, 2003).

North Horn Formation (TKn): Eastern Millard County includes the westernmost exposures of the North Horn Formation, a predominantly clastic unit that was spread across central Utah during the last phases of Late Cretaceous to Eocene Sevier mountain-building activity. The formation was deposited in nonmarine environments that included alluvial fans and various stream-channel, flood-plain, and freshwater lake settings. Its deposits are mostly clastics that range in coarseness from conglomerate to mudstone, but stream-laid sandstone is probably its most common component in eastern Millard County. During North Horn deposition, northeastern Millard County was apparently the locus of a large eastward-flowing stream system that deposited several thousand feet of sandstone and associated clastics in a foreland basin in central Utah that was tectonically subsiding during the deposition.

The North Horn Formation was examined in great detail by Lawton and others (1993) in the San Pitch Mountains, about 20 miles (30 km) east of Millard County. Through geologic mapping and stratigraphic observations, including stream-flow (direction), palynomorph, and magnetostratigraphic studies, Lawton and others (1993) showed that the North Horn Formation ranges in age from Campanian (Late Cretaceous) to Ypresian (Eocene) and was deposited contemporaneously with local thrust-fault deformation in the San Pitch Mountains. Lawton and others (1993) and Talling and others (1995) also showed that the upper North Horn (Eocene and Paleocene) contains limestone tongues of the Flagstaff Formation. No similar detailed study has yet been published on North Horn deposits in Millard County, but Lawton and others (1997, 2003) showed that the upper part of their Canyon Range Group in the Canyon Mountains is partly time equivalent to the North Horn Formation in the northern Pahvant Range and San Pitch Mountains.

Christiansen's (1952) geologic map shows North Horn Formation in the low hills 5 miles (8 km) north of Scipio where he estimated that its interbedded siltstones, sandstones, and conglomerates could be as thick as 3,500 feet (1,070 m). However, some of the beds that Christiansen included in the lower part of the North Horn Formation there are now regarded as part of the Canyon Range Conglomerate. Tucker (1954) mapped North Horn strata on the east side of the Pahvant Range and the west side of the Valley Mountains near Scipio and described the North Horn as mostly well-bedded, medium- to coarse-grained, yellowish-gray, calcareous sandstone that includes

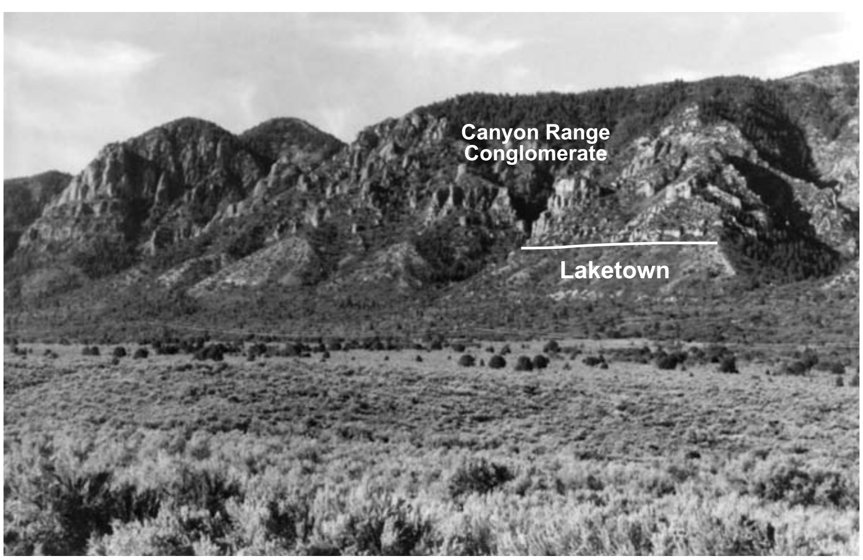


Figure 161. East side of the northern Pahvant Range as viewed from mile 38 on U.S. Highway 50. Strata at base of range are Silurian Laketown Dolomite. Cliffs above are Canyon Range Conglomerate subunits as discussed by Lawton and others (1997, 2003).

interbeds of shale, siltstone, pebble conglomerate, and sandy limestone. Tucker (1954) measured the North Horn Formation on the west side of the Valley Mountains in the south half of section 24, T. 20 S., R. 2 W., found it to be 2,680 feet (817 m) thick, and estimated that 500 feet (150 m) more at the base was not exposed. Lawton and others (1997, 2003) suggested that some of the uppermost conglomerates that Tucker mapped as "Price River Conglomerate" in the Pahvant Range may be partial age equivalents of sandstone in the lower North Horn Formation in the Valley Mountains. The Delta and Richfield 1:100,000-scale geologic maps show most of the strata formerly mapped as "Price River" in the northern and central Pahvant Range as Canyon Range Conglomerate (Kc) (Hintze and Davis, 2002b; Hintze and others, 2003).

Lautenschlager (1952) mapped the cental Pahvant Range and described what he mapped as North Horn Formation as predominantly buff to brown sandstone and siltstone with interbeds of gray and tan shale, fewer interbeds of purple and red siltstone and gray conglomerate, and limestone near the top of the unit. He measured 3,270 feet (997 m) of North Horn Formation and 866 feet (264 m) of "Price River Conglomerate" (Canyon Range Conglomerate) in the central Pahvant Range 10 miles (16 km) east of Fillmore. The exact location of Lautenschlager's traverse is uncertain because the name "Rock Creek," which he used to describe the traverse, is shown on the 1961 Mt. Catharine 7½-minute quadrangle in a different location than his route must have followed to get across the Price River and North Horn units shown on his geologic map, which was plotted on an uncontrolled planimetric base. He probably went up the North Fork of Chalk Creek, with the bottom of his section located where the Cretaceous conglomerate (Kc) rests unconformably on Cambrian limestone.

Based on reconnaissance mapping with Grant Willis (Utah Geological Survey) for the Richfield 1:100,000-scale geologic map (Hintze and others, 2003), we placed the upper North Horn contact lower in the section than Lautenschlager (1952) did. We restrict the North Horn to dominantly yellowish-gray sandstone and mudstone, and assign gray to medium reddish-brown, cobble to boulder conglomerate, and overlying reddish conglomerate, sandstone, mudstone, and limestone in the upper part of his unit to the lower red member of the Flagstaff Formation (Tflr). The restricted North Horn is about 2,500 feet (760 m) thick at Lautenschlager's measured section (North Fork Chalk Creek) and thins southward to about 2,000 feet (600 m) near the South Fork of Chalk Creek. About 2 miles (3 km) to the south on Hans Ridge, we calculated a thickness of about 1,400 feet (430 m) using stratal dip, outcrop width on map, and topography. About 3 miles (5 km) farther south, at the crest of White Pine Peak ridge, Willis (unpublished) mapped only a few thin outcrops of restricted North Horn Formation; it appears to pinch out 1 to 2 miles (1.6-3 km) to the south. The North Horn either pinches out or is concealed by the overlying Flagstaff Formation to the south, intertongues with the Flagstaff, or it grades southward into interbedded conglomeratic sandstone and pebble to cobble conglomerate more typical of the lower Flagstaff Formation in the Pahvant Range.

Thickness figures given above make it clear that our restricted North Horn Formation thins drastically towards the south in the central Pahvant Range. This is reflected in the outcrop pattern on the Richfield 1:100,000-scale geologic map (Hintze and others, 2003). The North Horn Formation is not exposed in the southern Pahvant Range and it is likely that not much was ever deposited in this area. However, additional detailed geologic studies will be required to resolve the age(s) of the conglomeratic beds and to place them in the correct formation(s).

Tectonic breccia in western Millard County (TKbr): Three types of breccia are present in western Millard County. Brecciated masses of Devonian, Silurian, and Upper Ordovician dolomite and Ordovician Eureka Quartzite were mapped by Best and Hintze (1980a), Hintze (1981d), and Hintze (1997d) in the Halfway Hills (figure 162) and Tunnel Spring Mountains (figure 12). The breccias are as much as 0.35 miles (0.56 km) wide and several miles long. Age of the brecciation is not known. It may have been caused by contractional forces during the Mesozoic Sevier orogeny, or by extensional stretching during early Tertiary time. Oligocene volcanic rocks in the same area show no such brecciation.

Breccias mapped by Hintze and Best (1987) in the Devonian Guilmette Formation and Mississippian Joana Limestone on the west side of the Mountain Home Range, mostly in Beaver County (also TKbr on the Wah Wah Mountains North geologic map; Hintze and Davis, 2002a), are most likely Tertiary in age and are related to north-south-trending, Basin and Range faulting.

Breccias in Precambrian rocks in the San Francisco Mountains are up to 0.3 miles (0.5 km) wide and 1.5 miles (2.4 km) long (Hintze and others, 1984). This brecciation could be as old as Precambrian or as young as late Cenozoic, but the strike-slip offset across the breccia implies it was formed during the Sevier orogeny.

Breccia of Cat Canyon (Tbr): This unit consists of gray Cambrian limestone and dolomite fragments, ranging from sand to boulder size (figure 163) but predominantly pebble size, that are thoroughly cemented with carbonate. This breccia is probably an indurated talus or rockslide rubble and

Figure 162. *Tectonic breccia exposed in road cuts where State Highway 21 crosses the west side of the Halfway Hills. Hammer is 11 inches (28 cm) long.*

Figure 163. *Breccia of Cat Canyon in the southeast Cricket Mountains. Pen is 5 inches (13 cm) long.*

overlies, with angular unconformity, tilted Cambrian strata in the Cricket Mountains (post-Sevier orogeny). It forms a resistant cap rock as much as 165 feet (50 m) thick (Hintze, 1984).

Flagstaff Formation (Tf): Millard County includes the westernmost exposures of the Flagstaff Formation (figure 164), an interbedded limestone and clastic unit that was deposited in the southwestern (Flagstaff) arm of Paleocene-Eocene Lake Uinta, which was centered in the ancestral Uinta Basin (Stanley and Collinson, 1979; Franczyk and others, 1992). Strata in the Pahvant Range were deposited in an alternating alluvial plain (fans and streams), shallow lake, and distributary delta setting. Overbank and subaerial carbonates are common and lacustrine deposits less so (Willis, 1994). Lawton and Weiss (1999) noted that intraclastic, sandy, fossiliferous dolomite, evidence of rootlet churning and bioturbation, evaporite mineral pseudomorphs, and nodules formed in soils, suggest that carbonate muds and calcareous silts of the Flagstaff were often exposed to subaerial weathering during deposition of the formation. Boulder and gravel conglomerates were deposited in river channels flowing mainly to the southeast. Local gypsum beds indicate occasional hypersaline environments.

Regional analyses of the Flagstaff Formation by LaRocque (1960), Schneider (1967), and Stanley and Collinson (1979) covered areas mainly east of Millard County. Schneider (1967) presented a detailed measured section of the Flagstaff near Richfield totaling 1,907 feet (582 m) and recognized four principal rock types: calcisiltite (silty limestone), calcilutite (fine-grained limestone), argillaceous calcilutite (muddy fine-grained limestone), and sandstone and conglomerate. He found that calcisiltite makes up more than half of the Flagstaff Formation, that calcilutite makes up one-quarter of

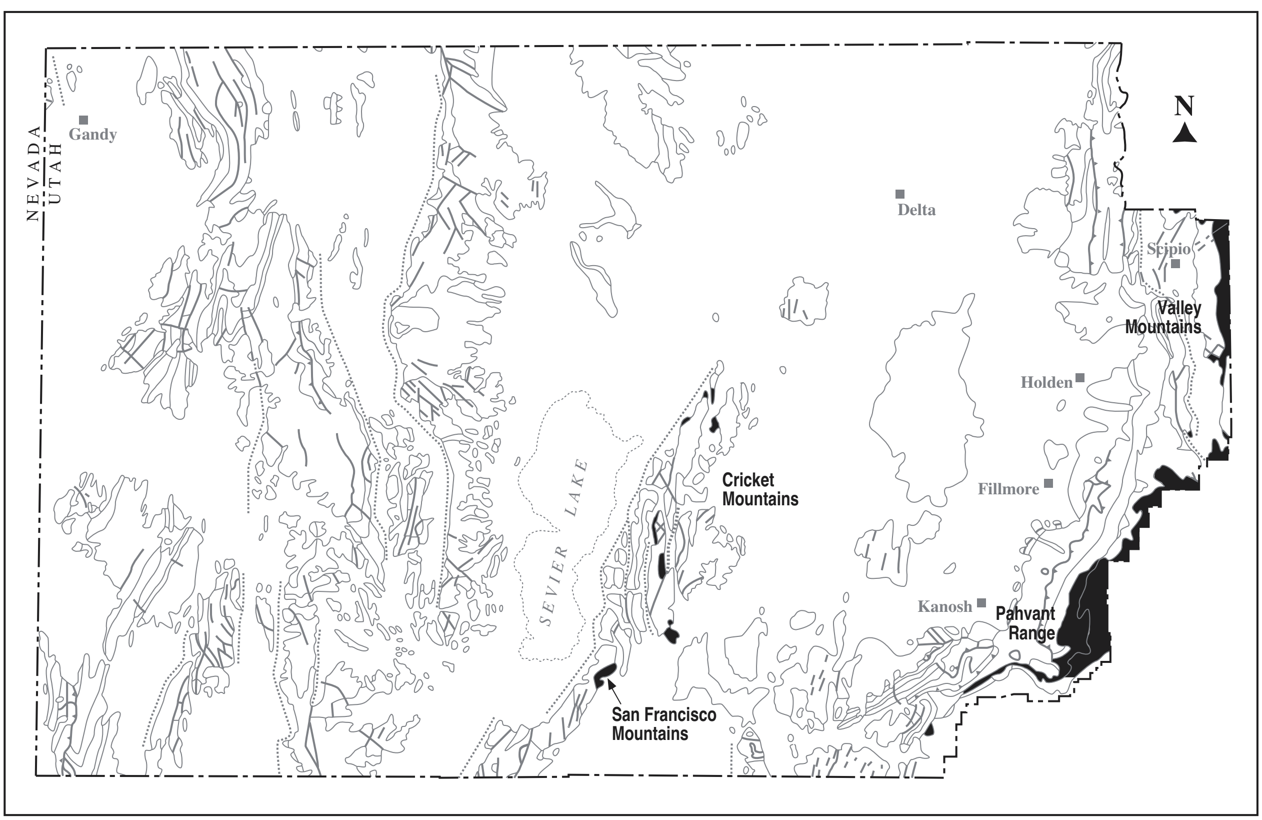


Figure 164. *Flagstaff Formation (Late Paleocene-Eocene) outcrops in Millard County.*

the upper and lower parts of the formation but is absent in its middle, that argillaceous calcilutite comprises 20 percent of the middle Flagstaff and a smaller percentage of the upper and lower Flagstaff, and that sandstone and conglomerate make up one-sixth of the lower Flagstaff and decreases in percentage markedly in the middle and upper Flagstaff. Exposures of the Flagstaff Formation in Millard County (figure 164) have probably been neglected because the formation is incomplete in the San Francisco and Cricket Mountains, and in the Pahvant Range and Valley Mountains only the lower part of the formation is present within the county. The formation in its entirety is exposed on the east side of the Pahvant Range in Sevier County.

The Flagstaff Formation becomes increasingly conglomeratic to the southwest; conversely, limestone and fine-grained clastic beds decrease. As a result, the conglomeratic Flagstaff Formation in eastern Millard County contrasts strikingly with the more typical carbonate-dominated strata in Sevier and Sanpete Counties, Utah.

I checked all areas of Flagstaff in that part of the Valley Mountains that are within Millard County and concluded that the thickest, most accessible, and best exposed section of Flagstaff is located just east of Interstate I-15 beginning in the SE1/4 section 16, T. 17 S., R. 2 W., Juab County, and extending northeastward for 1.2 miles (1.9 km) across section 15. In this measured section, described below, the top of the Flagstaff is not exposed and the basal conglomerate of the Flagstaff overlies yellow calcareous sandstones of the North Horn Formation.

Unit No.	Description	Thickness Feet	Thickness Meters
18.	Limestone, interlayered pink and gray, hackley fracture, contains algal fragments, forms ledges.	60	18
17.	Limestone, medium-gray, hackley fracture, ledgy.	20	6
16.	Bentonitic mudstone, white, forms slope.	15	5
15.	Limestone, light-gray, nodular; forms cliff.	30	9
14.	Clayey limestone, partly bentonitic, light-gray, forms slope.	100	30
13.	Interbedded bentonitic clay and sandy pebble conglomerate, forms slope and low ledges.	70	21
12.	Bentonitic mudstone, pinkish white, forms slope.	20	6
11.	Pebble conglomerate, 60% limestone, 40% quartzite clasts in sandy matrix, forms ledges.	25	8
10.	Limestone, mottled yellow and purple, nodular, forms reddish slope	50	15
9.	Pebble and cobble conglomerate, clasts are 80% limestone, 20% quartzite, in calcareous sandy matrix; interbeds of thin-bedded nodular limestone make up 20% of this unit which caps the top of hill. Beds dip 22% northeastward.	200	61
8.	Pebble and cobble conglomerate, 70% limestone, 30% quartzite clasts. Few limestone beds containing floating pebble clasts.	15	5
7.	Clayey limestone, red, nodular, forms rubbly slope.	170	52
6.	Limestone, mostly medium gray with some yellow and purple mottled interbeds. Limestone is thin-bedded, sandy, and forms platy talus. Forms slopes and low ledges on hill capped by unit 7.	160	49
5.	Clayey limestone, mottled yellow, purple, and red, with upper 15 feet (5 m) forming blocky cap rock, unit mostly forms backslope of cuesta.	75	23
4.	Interbedded sandy limestone (70%) and conglomerate (30%), forms slopes and low ledges with a 6-inch (15 cm) bed of gray limestone at top.	60	18
3.	Pebble and cobble conglomerate capped by 2 feet (0.6 m) of clayey red paleosol.	50	15
2.	Conglomerate with 20% interbeds of thin-bedded, platy, sandy limestone, forms top of low hill.	80	24
1.	Pebble conglomerate made of 80% limestone clasts in a gray limy sandstone matrix, and with 40% interbeds of thin-bedded platy sandstone, forms lowest ledges of conglomerate above yellow calcareous sandstones of the North Horn Formation.	100	30
	Measured thickness of Flagstaff Formation (top not exposed)	1,300	395

On the east side of the Canyon Mountains in the Fool Creek Peak quadrangle, Stolle (1978) divided his informal "Canyon Range Formation" into two major units, A and B, and concluded that unit B, about 1,600 feet (500 m) thick, is mostly equivalent to the Flagstaff Formation. Holladay's (1984) map unit, "Redbeds of Wide Canyon" with an estimated thickness of 2,470 feet (750 m) is properly called Flagstaff Formation. Both Holladay's and Stolle's Flagstaff sections lie in Juab County, just a few miles east of the Millard County line.

In the Cricket Mountains, Hintze (1984) mapped three early Tertiary units, two of which are here reassigned to the Flagstaff Formation: (1) conglomerate of Red Pass, (2) limestone of Fillmore Canyon, and (3) breccia of Cat Canyon.

The oldest unit, breccia of Cat Canyon (Tbr on column 5, appendix C and shown on figure 163) has been described in previous pages.

The limestone of Fillmore Canyon is white to very light gray, locally vuggy, thin to thick bedded, and forms low hills of alternating ledges and slopes. A few layers contain small lacustrine bivalves and high-spired gastropods similar to those common in the Flagstaff Formation in central Utah. The limestone is 160 feet (50 m) thick near the head of Fillmore Canyon. The overlying conglomerate of Red Pass is well- to poorly cemented conglomerate that contains limestone, dolomite, and quartzite pebbles and cobbles in a matrix of red-weathering sandstone, siltstone, and mudstone. In the Red Pass quadrangle, the lowest 100 to 160 feet (30-50 m) is unconsolidated conglomerate in a clayey matrix; this is overlain by 82 feet (25 m) of conglomerate in a well-cemented sandy matrix. Above this is 25 feet (8 m) of algal limestone that forms a resistant ledge. This limestone contains small gastropods similar to those found in both the North Horn and Flagstaff Formations in central Utah. The uppermost 25 feet (8 m) at Red Pass consists of well-cemented, ledge-forming, limestone conglomerate.

Lemmon and Morris (1984) mapped a unit that they called "conglomerate of High Rock Pass" in the San Francisco Mountains. Field examination by the author showed that some of the outcrops so designated in Millard County are more properly assigned to other lower Tertiary formations. In particular, the large red-colored exposures at Black Rock Pass, both north and south of the Garrison-Black Rock road, are here reassigned to the Flagstaff Formation, as are smaller outcrops scattered along the east side of the range for 5 miles (9 km) to the south. The small type area of Lemmon and Morris' conglomerate unit is located just east of High Rock Pass (Thr on Wah Wah Mountains North geologic map; Hintze and Davis, 2002a) and differs markedly in lithology and color from the red conglomerates at Black Rock Pass mentioned above. The author measured the following section 1.5 miles (2.2 km) south of Black Rock Pass in sections 32 and 33, T. 24 S., R. 11 W., where the Flagstaff Formation rests unconformably on Cambrian quartzite:

Unit No.	Description	Thickness Feet	Meters
8.	Limestone, light gray, medium-bedded, forms ledges on backslope to base of hill. Valley cover above could conceal an additional 200 feet (60 m) of Flagstaff. Lemmon and Morris (1984) show a north-trending fault through here that separates this section from several hundred feet of Flagstaff conglomerates east of the fault.	15	5
7.	Interbedded pebble-cobble conglomerate (70%) and red sandstone (30%). Matrix of conglomerate is pink sandstone. Forms backslope of cuesta. Beds dip 15° east.	200	61
6.	Limestone, purple, with 60% interbeds of red sandstone, forms backslope ledges.	20	6
5.	Conglomerate, salt and pepper gray, clasts are 70% carbonate, remainder quartzite.	160	49
4.	Sandstone, red, silty, with few lenses of conglomerate.	30	9
3.	Conglomerate, salt and pepper gray, clasts are similar to unit 5.	60	18
2.	Sandstone, red, with 30% interbeds of purple freshwater limestone.	30	9
1.	Conglomerate, poorly cemented, red silty matrix. This unit rests on Cambrian quartzite and both dip about 20° eastward.	70	21
	Total thickness of Flagstaff Formation.	585	178

Willis (1994) mapped six informal members of the Flagstaff Formation in the Richfield 7 1/2-minute quadrangle and measured a total thickness of about 2,000 feet (600 m). These informal members were traced by me and Grant Willis (Utah Geological Survey) into the adjacent 7 1/2-minute quadrangles in completing the Richfield 1:100,000-scale geologic map (Hintze and others, 2003). In the White Pine Peak area, the lower red member is difficult to distinguish from, and may be partially equivalent to, the North Horn Formation, which pinches out to the south. Near Corn Creek and Spring Canyon (upper Kanosh Canyon), Flagstaff members become thinner and less distinct (the lower white member becomes a thin, indistinct bed), and members are not mapped separately to the southwest where the formation (Tf) appears to thin markedly. However, the upper Flagstaff is unconformably overlain (concealed) by younger units southwest toward Cove Fort.

Flagstaff Formation (Tf) outcrops on the Richfield 1:100,000-scale geologic map (Hintze and others, 2003), southwest from Corn Creek towards Cove Fort, are based on reconnaissance geology by Willis; previous mapping showed the outcrops as Price River and North Horn Formations. In the southern Pahvant Range mostly south of Corn Creek, Crosby (1959) identified 850 feet (260 m) of conglomerate beneath his “North Horn Formation” as "Price River Conglomerate" and described it as mostly poorly sorted, cobble to boulder conglomerate, consisting of sub-rounded clasts of Cambrian quartzite and limestone in a matrix of calcareous sand and silt. These strata are shown on Hintze and others (2003) Richfield map as Flagstaff and Aurora Formations. Crosby’s (1959) “North Horn” was only 140 feet (43 m) thick, and he described it as medium- to coarse-grained, reddish-brown sandstone, and thin-bedded, brownish-gray siltstone; his “North Horn” is shown on Hintze and others (2003) Richfield map as Flagstaff Formation and is likely part of the lower red member. Also in the southern Pahvant Range south of Corn Creek, Davis (1983) reported 1,525 feet (465 m) of “North Horn Formation,” but Willis (verbal communication) thinks that the lower 344 feet (105 m), consisting mostly of reddish-brown, poorly sorted, cobble conglomerate and coarse-grained sandstone, most likely correlates with the lower Flagstaff Formation, and the upper 1,181 feet

(360 m) of Davis' "North Horn" unit should be assigned to the Aurora Formation. These conglomeratic strata and those near Cove Fort (Aurora of Willis; North Horn of Davis, 1983) need to be examined more carefully to properly determine their age and formation assignment, because Lawton and others (1993) and Talling and others (1995) showed that the upper North Horn is the time equivalent (as young as Eocene) of the Flagstaff to the northeast.

The following member descriptions are mostly from Willis (1994).

Lower red member (Tflr): This member is interbedded, dark-reddish-brown, grayish-red, and purplish-red variably calcareous sandstone and conglomerate, and dark-reddish-brown to reddish-purple siltstone, mudstone, and sandstone that forms alternating cliffs and slopes. On the west side of the Pahvant Range, the basal beds are gray to reddish, cobble to boulder conglomerate with quartzite and carbonate clasts. Conglomerate abundance and clast size decrease eastward across the range. Most conglomerates are channel lenses that pinch out laterally. Clasts are mostly quartzite with lesser dolomite and limestone derived from Precambrian and Paleozoic terranes. Bioturbation is common to intense in both resistant and non-resistant beds. The upper contact is picked where the dominant lithology changes from dark-reddish-brown sandstone to pale-gray calcareous sandstone and sandy limestone. The color difference shows on aerial photographs.

The member ranges from less than 200 feet (60 m) thick in its southwesternmost exposures to 1,300 feet (400 m) near Leavitt Peak (north of Corn Creek) to about 600 feet (180 m) near the crest of the Pahvant Range east of Fillmore.

Lower white member (Tflw): Resistant, blocky limestone beds in the lower part of this member form the crest of the Pahvant Range for about 10 miles (16 km) between Fillmore on the west and Richfield on the east. These lower limestone beds are commonly pale-purplish gray with mottled yellowish-gray blotches; this color combination is a distinctive characteristic of the lower Flagstaff, as well as its equivalent, the Claron Formation of southwestern Utah. The limestone is silty and is interbedded with pale-gray to pale-reddish-gray calcareous mudstone, sandstone and, locally, conglomerate. The limestone beds are as much as 200 feet (60 m) thick. Less resistant, similarly colored, calcareous mudstone, siltstone, and sandstone beds form the middle part of the member as exposed on the dip slope along the east side of the Pahvant Range. Beds are commonly intensely bioturbated.

White, clayey limestone beds, locally as much as 150 feet (45 m) thick, cap the member in the Beehive Peak 7 1/2-minute quadrangle; these white beds show on aerial photographs as an easily traceable marker horizon below the middle red member.

The lower white member is as much as 700 feet (215 m) thick in the Beehive Peak and Mt. Catharine 7 1/2-minute quadrangles. It thins to 236 feet (72 m) in the northern Richfield 7 1/2-minute quadrangle (Willis, 1994). It could not be traced much farther south on the crest of the Pahvant Range. The middle red appears to directly overlie the lower red between the forks of Corn Creek; but, the lower white member, though thin, is present to the south.

Middle red member (Tfmr): The middle red member is mostly medium- to thick-bedded, medium- to dark-reddish-brown, cliff- and ledge-forming, calcareous sandstone and minor conglomerate. These coarse clastics are interbedded with slope-forming, thin-bedded mudstone, and fine-grained sandstone. The member typically forms 10- to 50-foot (3-15-m) high cliffs and ledges separated by steep slopes. Conglomerates occur as sheets and channel lenses, and are less than 10 feet (3 m) thick. Clasts range to boulder size (14 inches [36 cm]) but most are cobbles and pebbles (<6 inches [15 cm]) and are rounded to subrounded. About half the clasts are quartzite, one-third are dolomite and limestone, and the remainder are chert; all are derived from Precambrian and Paleozoic terranes in western Utah. The member is 600 feet (180 m) thick in the Richfield 7 1/2-minute quadrangle (Willis, 1994).

Middle white member (Tfmw): As described by Willis (1994), the lower part of this member is mostly slope-forming, gypsiferous mudstone with thin interbeds of ledge-forming, pale-yellowish-gray sandstone and limestone. Bedded and stringer gypsum is present in fresh exposures. Gypsum decreases southwest from the Richfield 7 1/2-minute quadrangle and this interval forms ledges similar to the upper part of the middle white member described below. The gypsiferous interval ranges between 160 and 210 feet (49-64 m) in thickness in the Richfield 7 1/2-minute quadrangle. A 10- to 20-foot-thick (3-6 m) medium-orangish-red, blocky, ledge-forming sandstone marker bed locally separates the lower gypsiferous unit from an upper unit that consists of pale-yellowish-gray to pale-pinkish gray to light-olive-gray, calcareous sandstone, sandy limestone, and, locally, conglomerate lenses that form ledges and cliffs between minor sandy mudstone slopes. This upper unit makes up most of the prominent white cliffs along the mountain front north of Richfield. It is 350 feet (105 m) thick. Total thickness of the middle white member is between 515 and 580 feet (157-177 m).

Upper red member (Tfur): The upper red member consists of dark-reddish-brown calcareous sandstone, siltstone, mudstone, and locally near the top, a lenticular conglomerate as much as 15 feet (4.6 m) thick. The member forms ledgy slopes with local cliffs. In the Richfield 7 1/2-minute quadrangle the upper red member thins from 162 feet (49 m) near Richfield to less than 50 feet (15 m) 6 miles (10 km) to the northeast; it thickens to the southwest in the Richfield 30 x 60 minute quadrangle.

Upper white member (Tfuw): The upper white member forms a steep slope beneath the resistant Green River Formation near Richfield. It is composed of pale-gray, pale-pinkish-gray, or pale-purplish-gray, interbedded, sandy to clayey limestone and calcareous mudstone, and calcareous siltstone and sandstone. It is thinner bedded and has distinctly fewer ledges than other members of the Flagstaff Formation, forming a broad slope with a few ledges. In most areas the upper contact is covered by rubble eroded from overlying formations. It is marked by a change from pale-purplish-gray muddy limestone and mudstone to pale-yellowish-orange or pale-greenish-gray mudstone of the Green River Formation. A greenish-gray, altered volcanic ash bed, which is the primary detachment surface for many of the landslides and slumps in the Richfield 7 1/2-minute quadrangle (Willis, 1994), also marks the contact. In the Richfield 7 1/2-minute quadrangle, the upper white member is 170 to 185 feet (52-56 m) thick.

Green River Formation (Tg): This formation is exposed in easternmost Millard County only over about 0.5 square miles (1.2 km^2) in the southern Valley Mountains in the Scipio Lake and Beehive Peak 7 1/2-minute quadrangles. It is more extensively exposed in adjacent western Sevier County and near Richfield (city) as described below. Only about 200 feet (60 m) of the upper part of the Green River is exposed in Millard County, where it is present in a small downfaulted block between the North Horn and Flagstaff Formations. Lithologies present in the Green River Formation as exposed in Millard County include light-brown calcareous sandstone, oolitic limestone, and cherty limestone. The unit forms well-bedded ledges in the low hills on the east side of the southern end of the Valley Mountains.

In Sevier County, the Green River Formation is composed of pale-yellowish-orange, pale-yellowish-gray, and pale-greenish-gray siliceous limestone and dolomite, calcareous fine-grained sandstone, and algal limestone (Sheliga, 1980). It is thin- to thick-bedded, generally jointed, and makes blocky outcrops. Irregular brown, white, and gray chert blebs are common and diagnostic of the upper part of the formation, which is mostly limestone and is the most resistant unit on the east flank of the Pahvant Range between Richfield and Aurora. Large algal mounds are common in the upper part of the formation. The contact with the overlying Crazy Hollow Formation is placed where dark-brownish-orange sandstone predominates. Upper Green River resistant limestone beds at least 800 feet (245 m) thick are exposed in the fault blocks on the east side of the Beehive Peak 7 1/2-minute quadrangle. Willis (1994) reported 70 to 90 feet (21-27 m) of Green River Formation in the Pahvant Range west of Richfield. To the west and south the formation thins to absence.

Pliocene-Miocene-Oligocene-Late Eocene

Introduction

By late Eocene time the Sevier orogenic highlands of western Millard County, which had been uplifted and provided sediments for the upper Cretaceous, Paleocene, and lower Eocene deposits that extended from the east edge of Millard County eastward, had been eroded to a plain with limited relief. None of the mountain ranges of present-day Millard County had yet formed. Volcanic activity commenced in late Eocene time in the Keg Mountain-Drum Mountain area just north of Millard County and deposited the volcanic rocks and their related sediments in the Little Drum Mountains area of north-central Millard County. Later, in Oligocene and early Miocene time, large volcanoes erupted in the Marysvale volcanic field just southeast of the county, in the Mountain Home and Indian Peak Ranges just south of Millard County in northwestern Beaver County, and in south-central Nevada. Thick volcanic deposits from the Marysvale and Needle Range vents extended into Millard County (columns 3 and 11, respectively, appendix C). Ash-flow tuffs from these three volcanic centers covered more distant parts of Millard County with a few hundred feet of ash that tended to fill valleys and thus flatten the topography even more than before.

About 17 million years ago, the Basin and Range topography that characterizes Millard County today began to develop. Much of western North America began to be stretched, or extended, by heat flowing upward from deep sources; uplift may have been regional or local. This process continues today and has, over the past 17 million years, produced the present landscape with basins, like the Sevier Desert and Tule Valley, divided by ranges, such as the north-trending House Range. As the rising mountain ranges underwent erosion they shed alluvial materials into the adjacent subsiding valleys which locally contained ephemeral lakes. These alluvial and lacustrine deposits now form the tangible record of this history of Basin and Range development.

This history is portrayed on the Cenozoic correlation chart (chart 8, appendix C). It shows that Paleocene and lower Eocene deposits were limited to eastern Millard County. Oligocene and lower Miocene volcanic rocks were spread sporadically across the county. Upper Miocene to Holocene sedimentary deposition has been mostly continuous in the basins (valleys), and this has been accompanied by intermittent basaltic and rhyolitic volcanism in central and eastern Millard County. Nelson and Tingey (1997) have studied this volcanism statistically on a regional scale. The following pages contain descriptions of upper Eocene through Pliocene units in three areas, each section begins with the oldest units.

Lithologic Units in Eastern Millard County

Aurora Formation (Tau): In its lower part the Aurora Formation consists mostly of poorly resistant, pale-gray to orangish-, reddish-, and yellowish-gray, bentonitic siltstone and claystone, interbedded with lesser thin- to medium-bedded, medium-gray limestone, fine-grained sandstone, and conglomerate. When fresh, the limestone is medium to dark olive green and fetid. Overall, outcrops are pale yellowish gray to white. Bentonitic clay, distinctive black biotite flakes, and volcanic clasts become more abundant in the upper part of the formation, which weathers to form spongy slopes. Gypsum stringers are common in some layers. The upper contact of the Aurora Formation is poorly exposed in the Richfield area but is mapped at the transition from beds of predominantly sedimentary components to the volcaniclastic conglomerate and sandstone of the Dipping Vat Formation, which is present locally. In Millard County, the Aurora Formation contains pale-gray, yellowish-gray, and reddish-gray, bentonitic shale, calcareous siltstone, and gray, muddy limestone, with thin beds of fine-grained sandstone and carbonate- and quartzite-clast, pebble to cobble conglomerate. It is overlain by the volcanic rocks of Dog Valley. In the Dog Valley and Cove Fort areas, Willis (unpublished mapping) reassigned most outcrops mapped by Steven and Morris (1983) as Cretaceous Price River Formation and by Davis (1983) as North Horn to the Aurora Formation, based on his correlation with his Aurora in the southern Pahvant Range. In the Cove Fort and Dog Valley areas the Aurora is typically a reddish-brown, boulder conglomerate, conglomeratic sandstone, mottled pink- to purplish-gray silty limestone and mudstone.

Willis (1988) obtained K-Ar isotopic ages of 38.4 ± 1.5, 39.6 ± 1.5, and 40.5 ± 1.7 Ma (late Eocene) from the upper part of the Aurora Formation near the town of Aurora. A sample from near Cove Fort is probably 38.42 ± 0.82 Ma (Ar/Ar single crystal biotite). The likely source for the volcanic component is the Tintic area or Drum Mountains of west-central Utah. The Aurora Formation is contemporaneous with the upper Green River Formation near Duchesne in the Uinta Basin. The Aurora Formation is 550 feet (168 m) thick in the Richfield 7½-minute quadrangle (Willis, 1994), about 900 feet (275 m) thick in the Elsinore 7½-minute quadrangle, and about 1,200 feet (360 m) thick in the Joseph Peak 7½-minute quadrangle. It thins southward from there and is 0 to 200 feet (0-60 m) thick in the Cove Fort area.

Conglomerate of High Rock Pass (Thr): Lemmon and Morris (1984) named this unit for its occurrence in the High Rock 7½-minute quadrangle. I examined the outcrops shown on Lemmon and Morris' (1984) map as conglomerate of High Rock Pass in the field, and reassigned these rocks in the Red Rock Knoll 7½-minute quadrangle to the Flagstaff Formation, as discussed earlier in this bulletin. In the type section just east of High Rock Pass, the conglomerate is an unconsolidated, unbedded bouldery deposit with a gray matrix, in contrast to the red matrix typical of the Flagstaff Formation. In its type section the restricted conglomerate of High Rock Pass may be as much as 300 feet (90 m) thick.

Horn Silver Andesite (Ths): Lemmon and Morris (1984) mapped this unit, named by Stringham (1967), in the northern San Francisco and Beaver Lake Mountains where it includes mostly clastic, gray, red, purple, and green, andesitic, dacitic, and quartz latitic rocks. The unit includes agglomerate, tuff, and volcanic conglomerate and sandstone that contain interbedded dark-colored, medium- to fine-grained andesitic lava flows that increase in thickness and number to the south. A K-Ar isotopic age on plagioclase from a vitrophyre is 31.6 ± 1.0 Ma (corrected), and another K-Ar age is about 35.0 ± 1.0 Ma (corrected) (Lemmon and Morris, 1984; Best and others, 1989c). Thickness is up to 1,600 feet (500 m) in Millard County and thicker (2,000 feet [600 m]) with more lava flows in Beaver County.

Dipping Vat Formation (Tdvt): The Dipping Vat Formation consists of light-gray to pale-bluish-gray, poorly cemented volcaniclastic sandstone, conglomerate, and reworked volcanic tuff. Conglomerate beds are poorly sorted; clasts are up to 14 inches (36 cm) in diameter, range from mostly volcanic to mostly sedimentary, and commonly include welded tuff, quartzite, limestone, and dolomite.

Willis (1986) obtained radiometric ages of about 35 Ma from the Dipping Vat Formation near the type section about 15 miles (24 km) east of Richfield. However, because the material was water-lain and was reworked, the formation may be as young as 27 million years old (age of the overlying Three Creeks Tuff Member of the Bullion Canyon Formation). The Dipping Vat Formation is not mapped in Millard County. About 600 feet (180 m) of Dipping Vat strata are exposed in a slump block in the southwestern corner of the Richfield 7½-minute quadrangle (Willis, 1994) and in the northwest part of the Elsinore quadrangle. Though it occupies the same stratigraphic position as the volcanic rocks of Dog Valley (Tdv), between the underlying Aurora Formation and the overlying Three Creeks Tuff, the Dipping Vat has a more sedimentary aspect like the Aurora Formation and at least the lower part is probably older than the volcanic rocks of Dog Valley.

Volcanic rocks of Dog Valley (Tdv): Steven and Morris (1983) gave this informal name to a heterogeneous assemblage of andesitic to dacitic rocks in the southern Pahvant Range. They include lava flows, volcanic breccia, and minor moderately welded ash-flow tuff. The lavas and breccia are typically a dark- to light-gray porphyry characterized by abundant phenocrysts of plagioclase, hornblende, biotite, Fe-Ti oxides, and locally contain clinopyroxene (Cunningham and others, 1983). Kowallis and Best (1990) reported a fission-track zircon age of 33.6 ± 2.6 Ma on a lava flow in the lower part of the volcanic rocks of Dog Valley. Near Cove Fort and on the north flank of the Marysvale volcanic field, the volcanic rocks of Dog Valley locally interlayer with the tuff of Dog Valley (Tdt) (33.6 Ma Ar/Ar). Rowley and others (2002) estimated that the volcanics of Dog Valley are up to 1,200 feet (370 m) thick on the northwest margin of the Marysvale volcanic field.

Tuff of Dog Valley (Tdt): This unit is gray, tan, and pink, moderately welded, dacitic, ash-flow tuff containing about 40 percent phenocrysts of plagioclase (andesine), hornblende, and minor biotite, with abundant flattened pumice fragments, in a matrix of devitrified glass shards. High hornblende-to-biotite ratio may be the distinguishing characteristic (Steven and Morris, 1983; Rowley and others, 2002). The tuff is mostly resistant and reddish-brown weathering. The tuff intertongues with the volcanic rocks of Dog Valley. The tuff resembles and was previously mapped as Wah Wah Springs Tuff (Tnu) (30.5 Ma K-Ar) and Three Creeks Tuff Member of the Bullion Canyon Volcanics (Tbct) (27 Ma) (Cunningham and others, 1983; Steven and Morris, 1983; Rowley and others, 2002). However, this range in ages conflicted with the physical stratigraphy. This problem was resolved for this bulletin when a sample of the tuff from near Cove Fort was dated at 33.56 ± 0.10 Ma (Ar/Ar spectrum age on biotite). The tuff is about 400 feet (120 m) thick near Cove Fort (Steven and Morris, 1983).

Volcanic rocks of Wales Canyon (Tw): These rocks are moderately resistant, red, moderately crystal-rich, intermediate-composition lava flows and densely welded ash-flow tuff exposed near Cove Fort in the southern Pahvant Range. This unit was originally described by Caskey and Shuey (1975). The unit overlies the volcanic rocks of Dog Valley (Tdv) (Steven and Morris, 1983), and locally intertongues with the Three Creeks Tuff Member (Tbct) of the Bullion Canyon Volcanics (27 Ma) in Millard County on the north flank of the Marysvale volcanic field. The unit thickness is about 440 feet (135 m) (Rowley and others, 2002).

Three Creeks Tuff Member, Bullion Canyon Volcanics (Tbct): This resistant, light-gray and light-brown, moderately to densely welded, crystal-rich, dacitic ash-flow tuff contains 40 to 60 percent phenocrysts, mostly of plagioclase, with lesser amounts of hornblende, biotite, and quartz, and trace amounts of Fe-Ti oxides and sanidine. It is widely exposed in the southern Pahvant Range where it is a key marker bed within less distinctive units of the Bullion Canyon Volcanics, a complex assemblage of stratovolcano deposits that range in composition from andesite to low-silica rhyolite. The Three Creeks Tuff is probably the most voluminous and widely distributed ash-flow tuff erupted from the Marysvale volcanic field (Steven, 1981) and was derived from a caldera east of Cove Fort (Cunningham and others, 1983). Rowley and others (1994) list the age of the Three Creeks Tuff as 27 Ma. It is 0 to 720 feet (0-220 m) thick (Rowley and others, 2002), with its maximum thickness likely east of Millard County.

Tuff of Albinus Canyon (Tac): Steven (1979a-b) named this informal unit for its occurrence in the southern Pahvant Range west of Elsinore. It is resistant, light-purplish-gray, pink, tan, reddish-brown, red, and gray, crystal-poor, densely welded, trachytic ash-flow tuff that contains a few percent phenocrysts of calcic andesine-labradorite (plagioclase), augite, and a trace of biotite in a glassy to devitrified matrix. Prominent flow structures and lineate vesicles are characteristic. In the Cove Fort area the tuff of Albinus Canyon contains almost no phenocrysts (Steven and Morris, 1983). Several thin cooling units, locally separated by thin beds of volcanic mudflow breccia, conglomerate, and sandstone, are exposed in the southern Pahvant Range, Antelope Range, and Annabella area. Rowley and others (1994) noted that the tuff of Albinus Canyon may intertongue with basaltic andesite flows (Tba) in a fashion similar to the Antimony Tuff Member of the Mount Dutton Formation (Tda). Both tuffs are about the same age, 25.3 (Tac) and 25.4 Ma (Tda), and are lithologically similar. The tuff of Albinus Canyon is considered to be erupted from a nearby caldera, now buried beneath the Sevier Valley near Joseph, that also erupted the Kingston Canyon and Antimony Tuff Members of the Mount Dutton Formation (Rowley and others, 1994). The tuff of Albinus Canyon is 0 to 650 feet (0-200 m) thick.

Granodiorite of Mineral Mountains (Tgm): This intrusive rock is exposed at the north end of the Mineral Mountains where it covers about 4 square miles (9 km^2) astride the Millard-Beaver County line. It is medium grained, and locally shows a vertical east-west foliation. It is composed of 54 percent plagioclase, 12 percent K-feldspar, 12 percent quartz, 11 percent hornblende, 9 percent biotite, 1 percent sphene, 1 percent opaque minerals, and a trace of apatite and zircon (Sibbett and Nelson, 1980). It weathers to gray, sandy grus, forming slopes generally covered with talus from the numerous porphyritic rhyolite dikes that cut the granodiorite.

Aleinkoff and others (1986) dated the granodiorite as about 25 Ma, using U-Pb and Rb-Sr isotopic studies on zircon, sphene, and thorite. Therefore, it represents the oldest phase of intrusive activity in the Mineral Mountains batholithic complex. Nielson and others (1986) presented an alkali-silica plot for rocks of the Mineral Mountains intrusive complex and noted that the granodiorite is part of an Oligocene calc-alkaline suite that contrasts with the slightly alkaline main intrusive sequence of Miocene age that makes up the main body of the Mineral Mountains batholith.

Zeolitic tuff (Tzt): The zeolitic tuff is soft, white, partially welded, crystal-poor rhyolitic ash-flow tuff containing about 10 to 30 percent lithic clasts as well as phenocrysts of sanidine and plagioclase with sparse quartz and biotite. The matrix has been almost completely converted to the zeolite mineral clinoptilolite. It may correlate with the Leach Canyon Formation (Cunningham and others, 1983; Steven and Morris, 1983), a widespread ash-flow sheet in the eastern Great Basin (dated at 24 Ma [24.6 Ma corrected]; Anderson and Rowley, 1975). It is exposed only in the Cove Fort area, where it overlies the tuff of Albinus Canyon (Tac) and intertongues with the Bullion Canyon Volcanics (Tbc). It is about 400 feet (120 m) thick (Rowley and others, 2002).

Monzonitic/latitic intrusions, Bullion Canyon Volcanics (Tbci): These rocks are moderately resistant, gray, tan, and brown, fine- to medium-crystalline, crystal-rich monzonite and quartz monzonite and their finer grained equivalents, latite and quartz latite, in plutons that are solidified magma sources of some of the younger deposits of the Bullion Canyon Volcanics. The plutons are cupolas of a large composite batholith underlying the north and central part of the Marysvale volcanic field. Near Cove Fort the porphyries cut the Three Creeks Tuff (27 Ma) and are unconformably overlain by the Osiris Tuff (23 Ma). The intrusions consist of phenocrysts of andesine-labradorite, clinopyroxene, and magnetite in a matrix of alkali feldspar and contain little or no quartz (Steven and Morris, 1983). Their K-Ar ages cluster at about 23 Ma (Cunningham and others, 1983; Rowley and others, 2002).

Osiris Tuff, outflow facies (To): The large Monroe Peak caldera in the northern Sevier Plateau was formed by the eruption of the Osiris Tuff (Rowley and others, 1994). It was named by Anderson and Rowley (1975) for a location near the town of Antimony. This unit is resistant, moderately crystal-rich, rhyodacitic, densely welded ash-flow tuff, whose lower part is orangish- and reddish-brown, and its upper vapor phase is light gray. The tuff contains phenocrysts of plagioclase (An 25), subordinate sanidine, and minor biotite, pyroxene, and Fe-Ti oxides. It forms one or two cooling units that commonly contain black basal vitrophyres. The tuff contains drawn-out pumiceous lenticules, and the upper part locally shows steeply dipping flow-foliated layers. It has been mapped in the southern Pahvant Range and near Cove Fort, as well as in Sevier County, and is as thick as 200 feet (60 m) (Steven and Morris, 1983). Its age is 23 Ma (Rowley and others, 1994).

Joe Lott Tuff Member of the Mount Belknap Volcanics (Tmj): The Mount Belknap caldera, centered on the crest of the Tushar Mountains, subsided in response to the eruption of the Joe Lott Tuff about 19 million years ago (Rowley and others, 1994). This tuff is light-gray or brownish-gray, crystal-poor, slightly to moderately welded, alkali-rhyolite ash-flow tuff containing 1 to 2 percent phenocrysts of quartz, sodic plagioclase, sanidine, and traces of biotite. It was mapped at the north edge of the Tushar Mountains near Cove Fort by Steven and Morris (1983) where it may be as much as 200 feet (60 m) thick. Its maximum thickness in Sevier County is about 400 feet (120 m).

Quartz monzonite of Mineral Mountains (Tqm): This intrusive rock forms most of the north-central Mineral Mountains in Beaver County but barely reaches across the line into Millard County. It is light gray, biotite rich, coarse grained, and weathers to massive light-brownish-gray outcrops. It intrudes Precambrian banded gneiss (p€g), hornblende granodiorite (Tgm, age about 25 Ma), and biotite and hornblende diorite (Tdm), and is intruded by most of the other Tertiary igneous rocks in the Mineral Mountains. Average composition is 41 percent microcline, 30 percent plagioclase (An 13), 20 percent quartz, 4 percent biotite, and minor sphene, apatite, zircon, and Fe-Ti oxides. Texture is xenomorphic granular. The rock is massive with few joints and weathers to rounded outcrops and grus. Near its contact with Precambrian gneiss the rock contains numerous xenoliths and shows shear foliation locally (Sibbett and Nielson, 1980). Its isotopic age is about 18 Ma (Coleman and others, 1997).

Sevier River Formation (Tse): Exposures of this formation are present on the southeast and northeast corners of the Delta and Richfield 1:100,000-scale map areas (Hintze and Davis, 2002b; Hintze and others, 2003), respectively; all are in Sevier County. These exposures are contiguous with more extensive exposures mapped by Willis (1988, 1991), who described the formation as pale-, pink-, orangish-, and greenish-gray mudstone and sandstone with lenticular conglomerate beds, the pebbles of which are similar to lithologies found in the North Horn, Flagstaff, or Green River Formations. Willis (1988, 1991) reported that the Sevier River Formation is probably more than 600 feet (180 m) thick. An ash bed in the upper part of the formation was dated by fission-track methods at 5.2 ± 0.4 Ma (Willis, 1988). Steven and others (1990) reported that a tuff layer near the bottom of the formation was dated by fission-track methods at about 15 Ma. But this dated tuff layer is near the Marysvale volcanic field and the Sevier River Formation near the volcanic field is different than exposures described above (compare with Sevier River Formation description in this bulletin under heading "Lithologic Units in Marysvale Volcanic Field, Western Sevier County").

Rhyolite porphyry dikes (Trd): These north-northwest-trending dikes extensively cut the hornblende granodiorite stock (Tgm) and quartz monzonite (Tqm) at the north end of the Mineral Mountains (Sibbett and Nielson, 1980). The rock consists of 10 to 14 percent K-feldspar in 0.08 to 0.16 inch (2-4 mm) phenocrysts, 5 to 14 percent quartz, a trace to 3 percent biotite, and a few plagioclase phenocrysts in a matrix of granophyric intergrowths. The north-northwesterly strike of the dikes reflects the east-west orientation of the least principal stress axis. The dikes have not been dated directly but their geologic relationships throughout the Mineral Mountains suggest that they represent the last products of the main intrusive sequence in the Mineral Mountains and may be 11 to 12 million years old (Nielson and others, 1986; Coleman and Walker, 1994).

Tuff of Holden (Tht): This unit was found by the author in 1991 while mapping the geology of the Holden and Fillmore 7 1/2-minute quadrangles for this bulletin. The first outcrop located was in a new excavation along North Creek in the barnyard of the ranch house shown on the Holden quadrangle in SE1/4 SW1/4 NE1/4 section 10, T. 21 S., R. 4 W. There, at creek level, about 5 feet (1.5 m) of fine-grained white tuff was exposed. Subsequent mapping in the Fillmore quadrangle located exposures in irrigation pipeline trenches then being dug by the same rancher in nearby NW1/4SW1/4 section 11. Additional exposures were also found about 2 miles (3.2 km) east of Fillmore. The largest exposure is in NE1/4 NW1/4 NW1/4 section 27, T. 21 S., R. 4 W., where thin layers of white tuff are interbedded with pink to white shaly siltstone, clay, grit, and pebble gravel. Tuff beds in all exposures are tilted eastward as much as 40 degrees. They are overlain with angular unconformity by gravels weathered from the Oak City Formation. Because of limited exposures the complete thickness of the tuff-bearing sediments could not be ascertained but perhaps 200 feet (60 m) or more may be present. The white tuff itself, where not contaminated by included sedimentary debris, is composed almost entirely of clear glass shards with less than one percent heavy minerals.

Professor Francis H. Brown (University of Utah), a geologist who specializes in identifying late Cenozoic ashfalls, analyzed samples taken from the two localities described above and reported that, on the basis of microprobe analyses, the tuff of Holden matches the Cougar Point XIII ash of the Bruneau-Jarbidge volcanic center of the Snake River Plain. This ash has been dated at 10.83 ± 0.03 Ma (F.H. Brown, written communication, December 29, 1994).

A third sample of tuff was reported by Professor Brown (written communication, February 20, 1995) as matching an ash from the Snake River Plain volcanic province that dates at about 10.5 Ma, slightly younger than the other two samples. This younger ash came from SW1/4 SE1/4 section 22, T. 21 S., R. 4 W., and represents the uppermost part of the exposed section of ash beds in the Fillmore 7 1/2-minute quadrangle.

Fool Creek Conglomerate (Tfc): Christiansen (1952) named this formation for conglomerates that he mapped locally within the Canyon Mountains and widely on its western and southern flanks. Campbell (1978, 1979), for a doctoral dissertation under Christiansen's supervision, placed the flanking deposits in a new formation, the Oak City Formation, discussed below. He retained the Fool Creek designation only for patches of conglomerate located near the crest of the range at the heads of Oak Creek Canyon and the Dry Fork of Fool Creek. Campbell designated the exposures at the head of Oak Creek Canyon as the type area for the Fool Creek Formation, but restudy by Lawton and others (1997, 2003) showed that the Oak Creek Canyon outcrops are a part of the Canyon Range Conglomerate. The remaining strata, here assigned to the Fool Creek Conglomerate, are 530 feet (160 m) thick at the head of Dry Fork. Campbell considered some exposures in Clay Spring Wash, south of Oak City, to be part of the Fool Creek Conglomerate, but a field check by the author during the preparation of this bulletin did not confirm that assignment. They are herein reassigned to the Oak City Formation.

The Fool Creek Conglomerate is composed of clasts ranging from silt to boulders 4 feet (1.2 m) in diameter. Most are rounded to subrounded quartzite clasts from Cambrian and Precambrian formations. A few limestone and siltstone clasts may have been derived from North Horn Formation outcrops east of the Canyon Mountains. The matrix is pink to red, silty, calcareous sandstone, locally showing cross-bedding. At Dry Fork, Holladay (1984) noted that limestone cobble clasts are more common than quartzite clasts in the Fool Creek Conglomerate. A small outcrop of conglomerate in section 29, T. 18 S., R. 3 W., shown as Canyon Range Conglomerate on the Scipio Pass quadrangle (Michaels and Hintze, 1994) and on the Delta 1:100,000-scale geologic map (Hintze and Davis, 2002b), might possibly be assignable to the Fool Creek.

Age of the restricted Fool Creek Conglomerate is problematic. No fossils or volcanic components are known from the Fool Creek Conglomerate. Campbell (1978, 1979) suggested that deposition of the conglomerate predated Basin and Range deformation (>17 million years ago) and he assigned it to the Oligocene. It rests unconformably on the Canyon Range Conglomerate east of the Millard County line in Juab County. It may be the intra-Canyon Mountains equivalent of the Oak City Formation, possibly of Miocene or Pliocene age (chart 8 and column 1, appendix C).

Oak City Formation (Toc): Campbell (1978, 1979) named this formation and mapped its distribution around the west and south sides of the Canyon Mountains, designating its type section in the hills just south of Oak City. The Delta and Richfield 1:100,000-scale geologic maps extend the Oak City Formation southward along the west front of the Pahvant Range to the Kanosh area (Hintze and Davis, 2002b; Hintze and others, 2003). Campbell (1978, 1979) did not recognize that large recemented masses of brecciated quartzite (Tqb) and carbonate (Tcb), which are found in the Oak City South 7$^1/_2$-minute quadrangle near the type section, are slide blocks that are part of the Oak City Formation as mapped by Hintze (1991a). As a result of Hintze's mapping, these slide blocks were studied by Hebertson (1993), who saw in the carbonate slide blocks possible oil reservoirs if such blocks were encountered in the subsurface. Morris and Hebertson (1996) discussed the diagenesis of the carbonate blocks.

The type section of the Oak City Formation designated by Campbell (1978, 1979) is hardly representative of the general makeup of the formation throughout its extent in Millard County. As generally exposed, the Oak City Formation is mostly a sandy, bouldery gravel, the internal structure of which is exposed only locally within road cuts and gravel pits where it is poorly sorted and poorly bedded and made up of subangular to subrounded clasts ranging from silt to boulder size; sand-, pebble-, and cobble-size clasts are the most common materials. Clasts are from bedrock units exposed in adjacent highlands of the Canyon Mountains and Pahvant Range. The formation represents flood and mudflow deposits that formed alluvial aprons on the west and southwest sides of the Canyon-Pahvant westward-tilted fault block. The recemented slide mass breccias (Tqb and Tcb) are intercalated within loosely cemented alluvial sediments locally. The enigma of how the quartzite breccia became thoroughly recemented with quartz, but the surrounding Oak City sediments did not, has not yet been answered.

The Oak City Formation has been uplifted since its original deposition and is currently being dissected. In the Coffee Peak 7$^1/_2$-minute quadrangle on the west side of the Pahvant Range, it extends to elevations of more than 7,400 feet (2,250 m), suggesting that its post-depositional relative uplift is probably more than 1,000 feet (330 m). The Church Mountains and Cedar Mountain are outliers of Oak City Formation that are surrounded by erosional aprons formed from their own dissection. Water erosion has cut a gully system on Oak City outcrops, has preferentially removed small silt and sand clasts, and has left residual cobble and boulder clasts to form an armor that covers hills and ridges where the formation is exposed. In the Church and Canyon Mountains, these gully courses trap eolian silt blown northeastward off the Sevier Desert floor.

Most surficial exposures of Oak City Formation show only loose carbonate cementation of the clasts. But, at a few localities, well-cemented Oak City beds are exposed. One of the best locations to see well-cemented Oak City is on the west side of the Church Hills in section 15, T. 18 S., R. 4 W. just west of hill 5512 on the Duggins Creek 7$^1/_2$-minute quadrangle. There the Oak City Formation dips eastward 15-25 degrees, and is well cemented with a pink calcareous matrix. It rests unconformably on Paleozoic carbonate rocks.

Age of the Oak City Formation was thought by Campbell (1978, 1979) to be Miocene but he had no direct evidence. During geologic mapping for this bulletin, I traced the Oak City Formation from its type area southwards along the west side of the Pahvant Range for 30 miles (48 km) into the Dog Valley Peak 7$^1/_2$-minute quadrangle. There, Oviatt (1991a) reported a bed of Cudahy Mine pumice, dated at 2.6 Ma (Oviatt, 1991a), within the Oak City Formation. Thus the upper part of the formation is Pliocene. The lower age limit of the formation is less certain because the only place where any rocks other than Paleozoic strata have been seen beneath the Oak City Formation is east of Fillmore, where the 10.5 Ma tuff of Holden appears to underlie the Oak City. Chart 8 (appendix C) shows the Oak City Formation as being equivalent in age to unnamed valley-filling alluvial and lacustrine deposits that underlie the Sevier Desert. The exact relationship of the exposed Oak City Formation and the subsurface deposits has yet to be determined. Because of its unknown subsurface extent, only the minimum surficial thickness figures of 0 to 1,500 feet (0-450 m) are here estimated.

Basalt of High Rock (Thb): This is brown-weathering, black, fine-grained flow rock containing small phenocrysts of labradorite, augite, basaltic hornblende, and minor olivine in a partly glassy groundmass. Maximum thickness is 150 feet (50 m). Age is uncertain, but may be Pliocene (Lemmon and Morris, 1984).

Rhyodacite of Coyote Hills (Tcr): Crecraft and others (1981) mapped this informal unit in the Twin Peaks volcanic field near Black Rock. At 71 percent SiO_2, it is the least silicic rock at Twin Peaks. It contains 6 to 12 percent zoned plagioclase phenocrysts, 1 to 2 percent sanidine, and rare quartz, augite, and hypersthene microphenocrysts. Groundmass makes up 87 percent of the rock and consists of plagioclase, quartz, sanidine, Fe-Ti oxides, and zircon (Crecraft and others, 1981). The rhyodacite is light gray to medium-brownish gray. Evans and others (1980) K-Ar dated the rhyodacite of Coyote Hills at about 2.7 Ma. It has an exposed volume of 0.24 cubic miles (1 km^3), and an apparent maximum thickness of about 650 feet (200 m).

Rhyolite of Cudahy Mine (Tcr): Crecraft and others (1981) mapped this informal unit which forms coalescing domes, flows, and volcaniclastic deposits of high-silica (76 percent) black obsidian and light-gray felsite and pumice. The obsidian contains traces of quartz, sanidine, plagioclase, biotite, hornblende, augite, orthopyroxene, fayalite, magnetite, and ilmenite in a 99 percent glassy matrix. The felsite matrix is devitrified and shows relict flow layering, spherulites, and lithophysae with vapor phase quartz and sanidine. Evans and others' (1980) whole rock K-Ar dates on the obsidian range from 2.63 ± 0.10 to 2.48 ± 0.12 Ma. Exposed volume is about 0.5 cubic miles (2 km^3). It has a maximum apparent thickness of about 500 feet (150 m).

Pumice from this unit was formerly mined as a lightweight cement aggregate. Some beds of black obsidian contain light-gray spherulites called “snowflakes” by rock hounds. Snowflake obsidian from this unit has been used for arrowheads by prehistoric Indians and is still in demand as ornamental stone and for jewelry.

Basalt of Lava Ridge (Tlr): This basalt forms Lava Ridge on the Black Point 7$^1/_2$-minute quadrangle. It was informally named by Crecraft and others (1981) who included it on their map. At Lava Ridge the basalt of Lava Ridge underlies the limestone of Twin Peaks, which is, in turn, overlain by the basalt of Cove Creek (column 4, appendix C). In their usage of the term "basalt of Lava Ridge" Steven and Morris (1983) combined the overlying and underlying basalts under the same name. For this bulletin we have followed the usage of Crecraft and others (1981) and have retained the name, basalt of Lava Ridge, but use it only for the basalt beneath the limestone of Twin Peaks. The Lava Ridge flow consists of olivine-normative, dark-gray basaltic andesite that is more silicic and alkalic than the next younger basalt of Cove Creek. Best and others (1980) dated the basalt of Lava Ridge at 2.5 ± 0.4 Ma; Nash (1986) reported a K-Ar date of 2.22 ± 0.57 Ma. It is as much as 200 feet (60 m) thick.

Nelson and Tingey (1997) studied regional time-transgressive basaltic volcanism in southwest Utah and identified the Black Rock Desert in Millard County as a subzone of a north-south belt of basalts that extends into northern Arizona. The basalt of Lava Ridge is the oldest of the several basaltic flows in the Black Rock Desert.

Limestone of Twin Peaks (Ttl): A new informal name is herein applied to this unit that was called "Sevier River Formation" by Zimmerman (1961), "lake limestone" by Carrier and Chapman (1981), "lacustrine sediments" by Crecraft and others (1981), "unnamed marly limestone (QTl)" by Steven and Morris (1983), and called "lacustrine limestone (QTln)" by Oviatt (1991a).

The best exposure of the limestone of Twin Peaks is in the Antelope Valley 7 1/2-minute quadrangle in NW 1/4 section 3, T. 25 S., R. 8 W. where it was described by Zimmerman under his discussion of the "Sevier River Formation," a name that is inappropriate for these strata. Because of the importance of this unit to the structural interpretation of the Cove Creek area, and the relative inaccessibility of Zimmerman's thesis, his description of the limestone of Twin Peaks is repeated here:

Unit No.	Description	Thickness Feet	Thickness Meters
18.	Limestone-arenaceous marlstone: buff to light gray colored, hard, dense, vuggy limestone; cliff former; limestone stained red to yellow; limestone varies downward into a cavernous, arenaceous marlstone; arenaceous material consists of angular to rounded quartz, limestone, rhyolite, andesite, and basalt fragments; limestone interval approximately 4 feet thick; marlstone interval approximately 5 feet thick. [Top of unit 18 is top of hill. No overlying unit here.]	9	2.7
17.	Soft marlstone: white to light gray; friable; lens of arenaceous material composed of angular to rounded fragments of quartz, limestone, rhyolite, andesite, and basalt.	2	0.6
16.	Limestone: buff; poorly consolidated; arenaceous; surficial red to yellow iron oxide staining; composition of arenaceous fragments similar to those found in unit 17.	2	0.6
15.	Soft marlstone: white to light gray; friable; arenaceous; at base of unit a gray to arenaceous lens with a flaky calcareous clay matrix; unconsolidated; composition of lens fragments similar to those of unit 17.	2	0.6
14.	Limestone: buff, hard, dense, resistant and vuggy; unit varies downward into a cavernous, arenaceous marlstone; arenaceous material similar in composition to fragments found in unit 17; limestone interval approximately 2 feet thick; marlstone interval approximately 4 feet thick.	6	1.8
13.	Cover: alluvial mantle consists of arenaceous materials mentioned in unit 17, calcareous clays, and limestone blocks from above; 2 feet to 3 feet thick arenaceous marlstone ledges appear through alluvial cover.	40	12.2
12.	Marlstone: buff to white marlstone lens 2 to 4 feet thick, alternates with thinner 1-foot thick, drab, flaky, marlstone lens throughout unit; 2-foot thick, poorly consolidated to arenaceous lens at base of unit; lens has a flaky calcareous clay matrix; root-like concretions weather out at surface of measured section; composition of angular to rounded pebble and arenaceous fragments similar to those of unit 17.	15	4.6
11.	Soft marlstone: buff to light gray; arenaceous; root-like concretions weather out at surface of measured section; angular to rounded arenaceous fragments similar in composition to those of unit 17.	3	0.9
10.	Cover: alluvial mantle of arenaceous material, calcareous clay, and limestone blocks; no exposures.	60	18.3
9.	Limestone: similar to unit 15	5	1.5
8.	Soft marlstone: drab, flaky; poorly consolidated; vertical jointed; arenaceous; angular to rounded fragments similar in composition to those of unit 17.	2	0.6
7.	Cover: similar to unit 10.	30	9.1
6.	Marlstone: buff to light gray; poorly consolidated; friable; arenaceous; vertical jointed; root-like concretions weather out at surface of measured section; pebble and arenaceous lens, light gray in color and 1 foot thick at base of unit; poorly consolidated;	3	0.9

Unit No.	Description	Thickness Feet	Meters
	angular to rounded pebble and arenaceous fragments similar in composition to fragments of unit 17.		
5.	Soft marlstone: light gray; friable; arenaceous; vertical jointed; arenaceous material similar in composition to fragments of unit 17.	2	0.6
4.	Marlstone: buff to white; friable; arenaceous; vertical jointed; arenaceous lens at base of unit, approximately 1 foot thick; lens matrix of light gray flaky calcareous clay; poorly consolidated; angular to rounded arenaceous fragments similar in composition to those fragments of unit 17.	3	0.9
3.	Marlstone: similar to unit 12.	12	3.7
2.	Marlstone: buff to light gray; arenaceous; friable; vertical jointed; pebble and arenaceous lens at base of unit approximately 2 feet thick; lens poorly consolidated, with matrix of calcareous, flaky clay; angular to rounded pebble and arenaceous fragments similar in composition to fragments of unit 17.	16	4.9
1.	Marlstone: red to pink; poorly consolidated; arenaceous; 1-foot to 5-inch thick lenses throughout unit are composed of pebble and arenaceous fragments similar in composition to fragments of unit 17.	50	15.2
Base of unit 1 rests on vesicular basalt.			
Limestone of Twin Peaks total exposed thickness		262	79.9

The limestone of Twin Peaks is generally less resistant than adjacent basalt units. The overlying basalt of Cove Creek commonly forms a surficial talus cover over areas where the limestone of Twin Peaks has slumped. The limestone does, however, form the crest of the elongate Cove Creek dome, which extends about 6 miles (10 km) in a north-northwesterly direction along the west side of the Antelope Valley 7 1/2-minute quadrangle. The dome is symmetrical, with flanking dips of up to 10 degrees on both east and west sides.

Thompson and others (1995) described two drill cores, one from the west shore of Sevier Lake, and the other from near Black Rock, that penetrated limestone that could be equivalent to the limestone of Twin Peaks.

Basalt of Cove Creek (Tcc): Crecraft and others (1981) named this informal unit in the Twin Peaks volcanic field near Black Rock. It overlies the limestone of Twin Peaks. Carrier and Chapman (1981) used the informal name "Twin Peaks basalt" for the basalt of Cove Creek, but herein I apply the Twin Peaks name to the limestone unit. The Cove Creek basalt flows consist of dark-gray olivine tholeiite that is in general less silicic and less alkalic than the slightly older basalt of Lava Ridge. The map unit includes a vent cone and adjacent flow south of the exposures of the basaltic andesite of Burnt Mountain. Crecraft and others (1981) reported major element and normative compositions for 5 samples of basalt of Cove Creek. The basalt of Cove Creek is 0 to 400 feet (0-120 m) thick, and dated at about 2.55 Ma (Crecraft and others, 1981).

Rhyolite of Mid-Dome (Trt): Crecraft and others (1981) mapped this small body of silicic rocks separately but indicated its close chemical affinity with the larger North Twin Peak and South Twin Peak rhyolite domes. On the Richfield 1:100,000-scale geologic map, we have included all three under the symbol Trt (Hintze and others, 2003). Crecraft and others (1981) reported modal compositions of a rhyolite-felsite sample from Mid-Dome and noted that, petrographically, it is similar to the more silicic portions of the rhyolite of North Twin Peak. Crecraft and others (1981) reported major element analyses and CIPW norms of 12 Twin Peaks rhyolite samples. They also compared major element concentrations versus rubidium content of Twin Peak (Trt) rhyolites with the older Coyote Hills-Cudahy Mine (Tcr) rhyolites, noting that parallelism of composition trends suggested that Trt rhyolites had evolved from the Tcr magma source. K-Ar age on sanidine is 2.51 ± 0.8 Ma (Evans and others, 1980). Thickness is estimated to be 0 to 300 feet (0-100 m).

Rhyolite of North Twin Peak (Trt): Crecraft and others (1981) mapped and described this largest dome of the Twin Peaks group. Rhyolites from North Twin Peak show enough variation in composition to cause Crecraft and others (1981) to suggest that it may consist of two discrete eruptions. In general the rock is 70 percent groundmass of quartz, feldspar, oxides, apatite, sphene, and zircon. Phenocrysts are strongly zoned plagioclase, sanidine (some more than 1 inch [3 cm] long and commonly with resorbed edges), quartz, biotite, and rarely pyroxenes. Age is about 2.4 Ma (average of two K-Ar dates on sanidine) (Evans and others, 1980). Thickness is estimated to be 0 to 600 feet (0-180 m).

Rhyolite of South Twin Peak (Trt): Crecraft and others (1981) mapped and described the rhyolite of this tallest Twin Peak. Phenocryst content ranges from 3 percent on the north margin to 20 percent elsewhere. Quartz forms rounded crystals as much as 0.16 inches (4 mm) long. Plagioclase occurs as grains 0.04 inches (1 mm) in diameter or less, and as aggregates. Sanidine forms crystals up to 0.2 inches (5 mm) long. Biotite is the only mafic phenocryst. The groundmass consists of quartz, sanidine, plagioclase, oxides, and zircon. Hematite in the groundmass gives the rock its characteristic red color. K-Ar age on sanidine is 2.35 ± 0.08 Ma (Evans and others, 1980). Thickness is estimated to be 0 to 1,000 feet (0-300 m).

Basaltic andesite of Burnt Mountain (Tbm): Clark (1977) informally named these basaltic flows, but on his map he included them with the older basalt of Lava Ridge. Steven and Morris' (1983) map showed these as separate units and identified the cinder cone from which the basaltic andesite of Burnt Mountain issued. Steven and Morris' (1983) description of map units erroneously stated that they included the basalt of Cove Creek in their Burnt Mountain map unit; actually they mapped some basalt of Cove Creek as their "basalt of Lava Ridge" map unit, and other exposures as their Burnt Mountain map unit.

The basaltic andesite of Burnt Mountain consists of black to medium-gray, fine- to medium-grained, porphyritic rock containing 20 percent phenocrysts of labradorite, with less olivine, orthopyroxene, and clinopyroxene. Flow surfaces are commonly blocky aa lava. Flows are 30 to 60 feet (10-20 m) thick and aggregate to a maximum thickness of about 500 feet (150 m). The cinder cone vent is included in the map unit. Age is 2.11 ± 0.36 Ma (Nash, 1986).

Lithologic Units in the Drum Mountains and Smelter Knolls

Pyroxene latite of Black Point (Tdr): Leedom (1974) included this as part of his pyroxene shoshonite (Ts_3) map unit, but geologic remapping of the Little Drum Pass 7 1/2-minute quadrangle for this bulletin (shown in Hintze and Davis, 2002c; Hintze, 2003), and Ar/Ar ages on volcanic rocks in the area (Shubat and Snee, 1992; Hintze, 2003) require revision of Leedom's volcanic stratigraphy. The pyroxene latite of Black Point is named for Black Point, shown on the Whirlwind Valley NW (Hintze, 1981c), the Little Drum Pass (Hintze, 2003), and Lady Laird Peak 7 1/2-minute quadrangles. The unit covers about 10 square miles (26 km^2), mostly in the southwest corner of the Lady Laird Peak 7 1/2-minute quadrangle, and forms rugged hills at the northwest end of the Little Drum Mountains. This latite appears to be the oldest volcanic rock exposed in the Little Drum-Drum Mountains area, but its relationships to adjacent volcanic units are not completely established, particularly along its northeast contact where its probable fault relationship with the Drum Mountains Rhyodacite is not clearly exposed.

As seen at Black Point, the rock is a dark-gray lava flow containing abundant plagioclase, clinopyroxene, and orthopyroxene phenocrysts in a fine intergranular to intersertal matrix of the same minerals, plus Fe-Ti oxides and glass. Phenocrysts are corroded and have conspicuous glass inclusions.

The age of the pyroxene latite of Black Point is uncertain. An Ar/Ar groundmass age of 38.80 ± 0.43 was obtained for this bulletin (see also Hintze, 2003), but the statistical measure of variation in the analysis indicates the result is suspect. Leedom (1974; written communication, October 1989) reported a K-Ar age of about 38.3 Ma (corrected) from the Lady Laird Peak quadrangle, but it is not certain what rock unit was dated. A K-Ar age determination on a plagioclase concentrate from a sample taken at Black Point, analyzed in 1989, yielded an age of 52.2 ± 3.2 Ma. The age is anomalous because no other ages this old have been confirmed for volcanic rocks in this part of Utah.

Because of the probable close relationship of the pyroxene latite of Black Point with the Drum Mountains Rhyodacite, both are shown on the Tule Valley and Delta 1:100,000-scale geologic maps under the symbol Tdr (Hintze and Davis, 2002b-c). Leedom (1974) presented analyses and descriptions of lithologic variations of his units that are within our Tdr unit. The pyroxene latite of Black Point is at least 1,000 feet (300 m) thick.

Little Drum Formation (Tld): The Little Drum Formation was named and mapped by Hintze and Oviatt (1993). In its type section on the east side of the Little Drum Mountains (figures 22 and 165) it consists of 12 informal members, half of which are tuffs and the remainder intercalated bouldery volcanic conglomerates. Fission-track zircon ages of 39.5 ± 3.5 Ma and 38.6 ± 3.1 Ma were reported by Hintze and Oviatt (1993). Ar/Ar analyses done for this bulletin produced biotite ages of 37.62 ± 0.41 and 38.62 ± 0.37 Ma near the top (unit 11) and base (unit 2) of the formation, respectively, and a hornblende age of 38.52 ± 0.60 for unit 2; though the unit 2 sample was likely altered. These ages are too old based on the younger Ar/Ar ages of the underlying Drum Mountains Rhyodacite. Alternatively, the Drum Mountains Rhyodacite does not underlie the Little Drum Formation, or the Drum Mountains Rhyodacite was emplaced over a million years and includes rocks that underlie and overlie (are younger than) the Little Drum Formation; and the dated rocks do not underlie the Little Drum Formation. Further mapping and dating are needed. Chart 8 and column 6 (appendix C) place the Little Drum Formation below the Drum Mountains Rhyodacite, revising the Tule Valley geologic map (Hintze and Davis, 2002c). The Little Drum Formation is probably com-

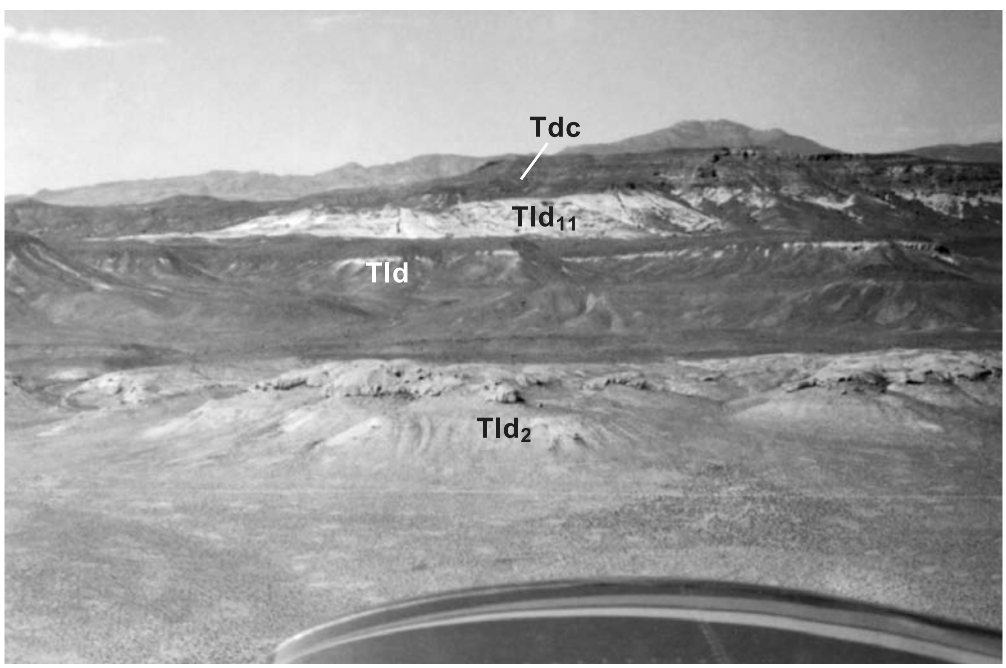


Figure 165. *Aerial view of the east face of the Little Drum Mountains. The nearest light outcrops are the oldest tuff member of the Little Drum Formation (Tld_2), probably about 38.5 million years old. Above it are other members of the Little Drum Formation (Tld). The prominent light outcrop across the upper third of the picture is the upper tuff of the Little Drum Formation (Tld_{11}; 37.6 Ma); above that is the basal ash-flow tuff (~37 million years old) and overlying units of the volcanic sequence of Dennison Canyon (Tdc).*

prised by distal deposits from volcanoes active in the Drum Mountains during late Eocene time. The formation is 1,500 to 2,325 feet (450-708 m) thick.

Drum Mountains Rhyodacite (Tdr): This formation was named by Lindsey (1979) and its type locality was rather broadly identified as being in sections 32, 33, and 34, T. 14 S., R. 11 W. in the Lady Laird Peak 7 1/2-minute quadrangle. It includes rusty-weathering, black, rhyodacite flows and breccia, with phenocrysts of intermediate to calcic plagioclase, and pyroxene in an aphanitic to glassy matrix. According to Lindsey, the rock is modally a hypersthene andesite, but chemical analyses show that the rock ranges from rhyodacite to quartz latite. Lindsey (1982) reported a single fission-track age of 41.8 ± 2.3 Ma, but this is too old. Ar/Ar ages on hornblende from Drum Mountains Rhyodacite sampled in the Little Drum Pass 7 1/2-minute quadrangle are 36.68 ± 0.22 and 36.93 ± 0.22 Ma (Hintze, 2003). Nutt and others (1996) reported Ar/Ar ages on hornblende in two samples of Drum Mountains Rhyodacite from the Drum Mountains mining district as 36.9 ± 0.1 Ma and, near the base, 37.6 ± 0.2 Ma. These ages are not much different from Ar/Ar ages Nutt and others (1996) got from Mt. Laird porphyry dikes in the area: 36.8 ± 0.19 Ma on hornblende near the Martha mine; 36.9 ± 0.1 Ma on hornblende near the Drum mine; and 36.5 ± 0.1 Ma on biotite and 37.2 ± 0.02 Ma on hornblende from the Copperhead mine (locations from C.J. Nutt, written communication, October 10, 1994). Nutt and others (1996) also noted that compositions of these igneous rocks are similar, and concluded that the Drum Mountains Rhyodacite, Mt. Laird porphyry, and Mt. Laird tuffs represent flows, intrusions, and tuffs from the same magma source. However, Nutt and others (1996) reported younger ages of the Mt. Laird Tuff as 36.3 ± 0.1 and 36.4 ± 0.1 Ma on hornblende and biotite, respectively. The Mt. Laird Tuff occurs just north of the Millard-Juab county line.

In the Smelter Knolls West 7 1/2-minute quadrangle (Hintze and Oviatt, 1993), the Drum Mountains Rhyodacite includes maroon-weathering flows and dark-green vesicular and amygdaloidal lavas that Pierce (1974) described as pyroxene shoshonite. The Drum Mountains Rhyodacite is as much as 2,000 feet (600 m) thick.

Drum Mountains intrusions (Tdi): Nutt and Yambrick (1989) mapped two small intrusions of dark-gray, finely crystalline diorite near the Drum gold mine in the Drum Mountains. The rock is predominantly composed of feldspar and hornblende, typically partially replaced by biotite. No age has been reported but it is probably younger than the Drum Mountains Rhyodacite. The larger outcrops are shown on the Delta 1:100,000-scale geologic map (Hintze and Davis, 2002b). More silicic intrusions near the mine were Ar/Ar dated at 36.0 and 36.1 Ma, but might be Mt. Laird dikes (Nutt and others, 1996).

Other small, dark-gray, finely crystalline diorite intrusions are exposed along the Millard and Juab county line; two are shown on the Tule Valley geologic map (Hintze and Davis, 2002c). The diorite contains abundant calcic plagioclase and hornblende, and lesser biotite and interstitial K-feldspar.

Altered strata (Ta): This map symbol is used for altered Cambrian and Tertiary rocks near the Drum mine; alteration includes jasperoids and silicification, argillization and bleaching, and, in Tertiary igneous rocks, sericitization. To the north in the Drum Mountains the altered strata are Cambrian rocks where the formation cannot be determined. The symbol is also used for dolomitized, iron-stained, brecciated Cambrian rocks near Sand Pass on the west side of the House Range (Hintze, 1980a, c).

Mt. Laird intrusive dikes (Timl): Between Buckhorn Canyon and Black Point, in the northwest corner of the Little Drum Pass 7 1/2-minute quadrangle (sections 20 and 29, T. 15 S., R. 11 W.), two dikes of Mt. Laird rhyodacitic porphyry cut the older volcanic rocks. A sample from one of these dikes was Ar/Ar dated for this bulletin and gave a single-crystal biotite age of 37.07 ± 0.28 Ma, but the dike cuts Drum Mountains Rhyodacite dated at 36.68 ± 0.22 (Hintze, 2003). The dikes are likely part of the Mt. Laird Tuff, a regionally extensive unit consisting of ash-flow tuff, tuff breccia, lapilli tuff, flow rocks, and hypabyssal intrusive rocks (Lindsey, 1979, 1982). Ar/Ar ages of Mt. Laird Tuff, including other Mt. Laird dikes, are listed above in the Drum Mountains Rhyodacite summary. The Buckhorn Canyon dikes are as much as 900 feet (275 m) wide and have an exposed length of 0.4 mile (0.7 km).

Volcanic sequence of Dennison Canyon (Tdc): Hintze and Oviatt (1993) proposed this name for a sequence consisting of a basal thick, pink, ash-flow tuff that is overlain by volcanic-clast conglomerate and lava flows of andesitic and latitic rocks (figures 22, 166, and 167). The basal ash-flow tuff is Pierce's (1974) "latite tuff Tt_3." It is about 500 feet (150 m) thick and forms prominent pink cliffs that extend northward for more than 5 miles (8 km) along the upper east face of the Little Drum Mountains (figure 165). The Ar/Ar age on hornblende from this tuff is 37.05 ± 0.18 Ma, with a Ar/Ar biotite age of 37.47 ± 0.19. Previously reported ages on the tuff, a fission-track age (31.3 ± 2.3 Ma on zircons) and a K-Ar age (28.5 ± 1.9 Ma on plagioclase) (Hintze and Oviatt, 1993), are probably not accurate. Another Ar/Ar age on hornblende from the Dennison Canyon is 36.66 ± 0.37 Ma on a hornblende latite (Hintze, 2003) above laharic breccia of Pierce (1974) and Leedom (1974). Pierce (1974) and Hintze and Oviatt (1993) provide petrographic descriptions of the tuff.

Pierce (1974) and Leedom (1974) mapped the units above the basal tuff in the sequence of Dennison Canyon as "laharic breccia" (their unit Tlb_2) and "interbedded flows" (Leedom's unit Tlb_2f). The "laharic breccia" immediately above the basal ash-flow tuff may better be called volcanic-clast conglomerate (figure 168). They are as much as 1,500 feet (460 m) thick and are overlain by about 500 feet (150 m) of thin hornblende andesite lava flows of local extent interbedded within additional layers of mud-flow conglomerate. The general composition is andesitic. The volcanic sequence of Dennison Canyon totals about 2,500 feet (760 m) thick in the Little Drum Pass 7 1/2-minute quadrangle. Additional mapping (Hintze, 2003) has shown the Ar/Ar-dated hornblende latite is at the top of the Dennison Canyon rocks and the capping hornblende andesite flows overlie the Red Knolls Tuff. So these capping flows and inter-bedded rocks have been placed in a new unit named after Horse Canyon in the Little Drum Pass 7 1/2-minute quadrangle and mapped separately from the volcanic sequence of Dennison Canyon by Hintze (2003). The volcanic sequence of Dennison Canyon was apparently derived from the Drum Moun-

Figure 166. The basal tuff member of the volcanic sequence of Dennison Canyon is a poorly welded tuff that weathers into small caves called tafoni, with open lace-work texture. Photograph was taken in section 20, T. 16 S., R. 10 W.

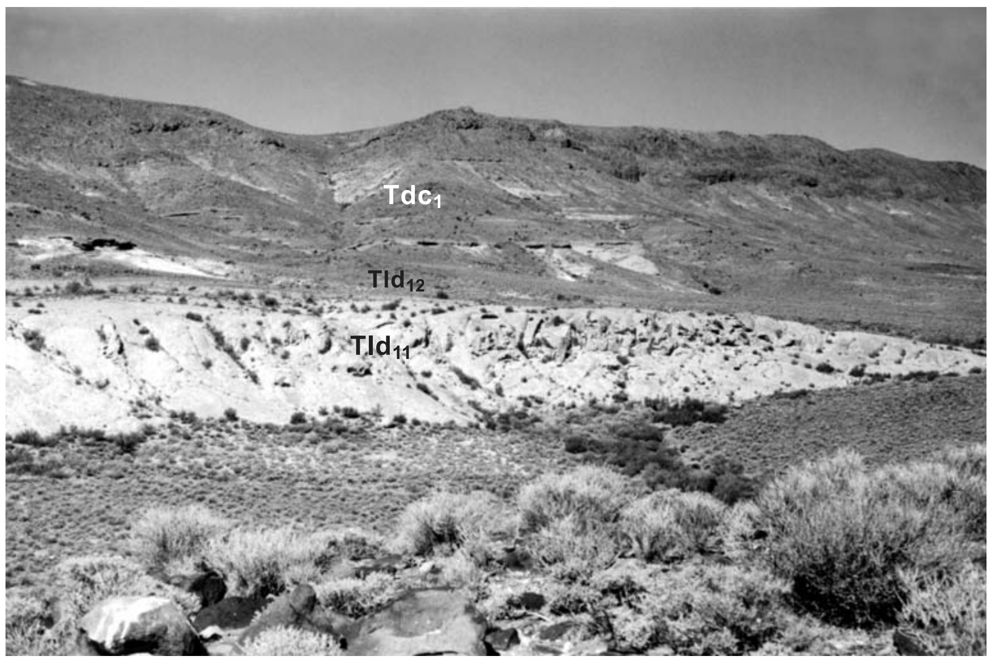


Figure 167. Nearest white outcrops are the upper tuff of the Little Drum Formation (Tld_{11}; 37.6 Ma), which is overlain by a conglomerate (Tld_{12}). Debris-covered slopes in upper half of photograph partly conceal the basal tuff of the volcanic sequence of Dennison Canyon (~37 million years old), better shown in figure 166. Top of the hill is the basal part of a sequence of bouldery volcanic debris flows that make up the thick upper part of the volcanic sequence of Dennison Canyon (~36.5 million years old). Photograph was taken on the west side of section 8, T. 16 S., R. 10 W., with view to northwest.

Figure 168. Volcanic-clast conglomerate of the volcanic sequence of Dennison Canyon. Brown, aphyric andesite is the most abundant clast type with fewer clasts of purple to gray, pyroxene- and hornblende-bearing andesite and vesicular andesite. Matrix is poorly sorted rock and mineral fragments from pulverized igneous rocks. Some layers include a few quartzite clasts. Photograph was taken in canyon for which the unit was named.

tains volcanic center and is coeval with the Drum Mountains Rhyodacite.

Red Knolls Tuff (Trk): The Red Knolls Tuff was named and mapped by Hintze and Davis (1992b) in the southern Little Drum Mountains. It is light-gray to grayish-orange-pink, crystal-rich dacite welded ash-flow tuff that contains 10 to 30 percent lithic fragments, mostly of volcanic rocks of similar composition. Phenocrysts, in decreasing order of abundance, are plagioclase, biotite, quartz, hornblende, and a trace of bright-green augite. Some layers of the tuff show abundant fiamme (dark, vitric lenses in welded tuffs, about an inch [2 cm] long, formed by collapse of hot pumice fragments). Leedom (1974) and Pierce (1974) incorrectly identified it as Needles Range Formation in the Little Drum Mountains. Hintze and Davis (1992b) presented fission-track ages on zircons from four samples of the tuff (average 31.5 ± 2.8 Ma). Ar/Ar dating of this unit (36.50 ± 0.14 Ma on biotite) has improved the chronostratigraphy of the area. The location of the source caldera of the Red Knolls Tuff is uncertain, but it may lie in the Drum Mountains area. Thickness of the tuff in its type area in the Red Knolls 7$^1/_2$-minute quadrangle is 210 feet (64 m).

Skull Rock Pass Conglomerate (Tsr): The Skull Rock Pass Conglomerate, named for said pass in the House Range, has its type section on Long Ridge (Hintze and Davis, 1992a), a low cuesta that rises slightly above the Sevier Desert floor north of Sevier Lake. The unit is an uncemented, unsorted, cobble and boulder conglomerate with a matrix of slightly clayey, silty to fine sandy, comminuted volcanic material that weathers light yellowish to reddish gray. Matrix commonly makes up 10 to 20 percent of the deposit but locally may make up to 80 percent. Clasts in the conglomerate are almost entirely of Paleozoic sedimentary rocks, mostly limestone and dolomite derived from Cambrian through Devonian units. Ordovician Eureka Quartzite boulders (figure 169) are a conspicuous constituent and locally make up to 5 percent of the conglomerate clasts. Clasts range in size from pebbles to boulders as much as 15 feet (4.6 m) long (figure 170); roundness ranges from subangular to well rounded, but subrounded clasts are most common. Igneous rocks constitute less than one percent of the megaclasts; rare boulders of Jurassic granite from the House Range, and basaltic andesite boulders from the Little Drum Mountains are present locally in the deposit. The unsorted, unstratified nature of the Skull Rock Pass Conglomerate suggests that it was deposited as mud flows or debris flows on an alluvial-fan apron. It has been mapped as far south as the San Francisco Mountains (previously mapped by Lemmon and Morris (1983) as conglomerate of High Rock Pass) and as far west as the Burbank Hills.

The Skull Rock Pass Conglomerate is dated by the volcanic rocks that occur above and below it. On Long Ridge the Skull Rock Pass Conglomerate is underlain by the 36.5 Ma Red Knolls Tuff, with no overlying unit. In the central Confusion Range (Toms Knoll), southern House Range, and Burbank Hills it is underlain by the 35 Ma Tunnel Spring Tuff (columns 8 and 9, appendix C) and overlain by 30.5 and 31 Ma tuffs in the upper Needles Range Group. This interval is also occupied by a similar unit, the conglomerate at the base of the Needles Range Group (Tnc). The Tunnel Spring Tuff needs to be Ar/Ar dated to see if these conglomerates at various locations are the same age. In its type area on Long Ridge the Skull Rock Pass Conglomerate is 320 feet (98 m) thick. It is as much as 350 feet (107 m) thick in the Burbank Hills.

Rhyolite of Whirlwind Valley (Tr): Leedom (1974) noted the occurrence of this white rhyolite at the northwest edge of the Little Drum Mountains. It is well exposed along the county road running from Joy southwestward into Whirlwind Valley, about a mile south of the Millard-Juab county line. Although Leedom (1974) called it a flow, its relationship to the adjacent older volcanic rocks (Drum Mountains Rhyo-

Figure 169. Skull Rock at Skull Rock Pass in the central House Range; view is to northwest. Notch Peak is the high point on the left side of the picture. Skull Rock is a residual boulder of Ordovician Eureka Quartzite weathered out of the Skull Rock Pass Conglomerate, an Oligocene debris-flow deposit. The source of the Eureka Quartzite is probably just to the west in the Barn Hills.

Figure 170. Skull Rock Pass Conglomerate exposed next to U.S. Highway 6-50 just east of Skull Rock Pass. Largest boulder is Ordovician Eureka Quartzite. Other boulders are mostly from Upper Ordovician, Silurian, and Devonian formations. Matrix, exposed in the road cut, is cobble- to sand-size clasts of Paleozoic rocks with local lenses of clay derived from weathered volcanic tuff.

dacite, 37 Ma) suggests that it may be an intrusive body. It exhibits distorted flow layering and is composed of microfelsitic quartz and feldspar, and devitrified glass.

Dr. E.H. Christiansen of the Department of Geology, Brigham Young University (written communication, February 12, 1992) made an X-ray fluorescence spectrometry analysis of this rhyolite as follows:

Oxides	Percentage	Element	Parts per million
SiO_2	72.80	Rb	1869
TiO_2	0.0	Sr	26
Al_2O_3	15.55	Y	141
Fe_2O_3	1.03	Zr	53
MnO	0.06	Nb	57
CaO	1.18	Ba	0
Na_2O	3.69		
K_2O	4.57		
P_2O_5	0.01		
Total	99.26		

Regarding the probable age of this rhyolite Christiansen (written communication) stated: "The rhyolite appears to be much more similar to the young (< 21 Ma) topaz rhyolites than to any older rhyolitic lava or tuff that I know of in the eastern Great Basin. It is probably a "young" lava dome. The similarity to topaz rhyolites appears in the extremely high concentrations of Rb, Y, and Nb, and in the low concentrations of Sr, Ba, and Ti. Nonetheless, I am puzzled by the relatively low concentration of SiO_2 and high concentrations of Al_2O_3; typical topaz rhyolites have 74 to 77 percent SiO_2 and less than 14 percent Al_2O_3. The hand sample looks slightly altered – perhaps to clays that could account for this chemical anomaly. Moreover, the rock has high CaO for a topaz rhyolite (0.5% is typical) – there may be some secondary calcite in the rock, although we found none within the powder analyzed. This rock has the highest Rb and lowest Zr concentrations (indicators of a high degree of differentiation) of any topaz rhyolite I have seen in the eastern Great Basin, even when compared to the mineralized Spor Mountain and Honeycomb Hills rhyolites. This rhyolite may be deserving of further investigation."

The "young" Topaz Mountain Rhyolite and rhyolite of Keg Mountain (~7 Ma) are exposed 10 to 20 miles (16-32 km) to the north in Juab County (Lindsey, 1979; Shubat and others, 1999), but neither looks like the outcrops of rhyolite of Whirlwind Valley. The rhyolite of Whirlwind Valley is more similar chemically to the rhyolite of Keg Mountain than the Topaz Mountain Rhyolite, but is still more aluminous (contains a higher percentage of Al_2O_3) (compare analysis above with appendix B in Shubat and others, 1999).

Basaltic andesite north of Smelter Knolls (Tbsk): Turley and Nash (1980) mapped this unit, which is exposed in a few small scattered outcrops on the floor of the Sevier Desert 1 to 2 miles (1.6-3.2 km) north of Smelter Knolls. The rock has a felted groundmass of plagioclase, clinopyroxene, orthopyroxene, iron and titanium oxides, and glass. Plagioclase and orthopyroxene are present as phenocrysts along with quartz. Reaction rims of orthopyroxene on the quartz indicate that the quartz was out of equilibrium with the magma under the low-pressure conditions of crystallization. Turley and Nash (1980) gave a modal analysis of the basaltic andesite and also noted that it has normal paleomagnetic polarity. The basaltic andesite was K-Ar dated at 6.1 ± 0.3 Ma (Turley and Nash, 1980). It has an apparent thickness of 0 to 30+ feet (0-10+ m).

Rhyolite of Smelter Knolls (Tr): Turley and Nash (1980) mapped and described the rhyolite domes at Smelter Knolls (figure 171) as a single rhyolite flow-dome complex 3 miles (5 km) in diameter and 0.7 cubic miles (2.2 km^3) in volume. The rhyolite is white, gray, and reddish-gray and includes local obsidian layers. Dips lessen towards the perimeter of the exposures, suggesting a central magmatic source. The rock contains 10 to 20 percent phenocrysts, including alkali feldspar, quartz, plagioclase, biotite, and Fe-Ti oxides. Minor constituents include sphene, zircon, fluorite, and allanite. Topaz and hematite are vapor-phase products found in lithophysal cavities, and topaz is present in the groundmass, which consists of quartz and alkali feldspar along with devitrified spherulites of mixed mineralogy. Turley and Nash (1980) provided a variety of chemical analyses of minerals from this rhyolite and compared it to similar rhyolites found elsewhere in western Utah. Christiansen and others (1986) compared its geochemistry to similar rocks throughout the western United States. A K-Ar age on sanidine is reportedly 3.40 ± 0.1 Ma (Turley and Nash, 1980). Based on its reversed polarity, the rhyolite could fall either into the Gilbert or the Mammoth paleomagnetic interval.

Lithologic Units in Western Millard County

Welded tuff near Gandy (Tgt): An isolated small outcrop of brown, glassy, pumice-rich, crystal-poor, densely welded tuff with less than 10 percent phenocrysts of plagioclase and about one percent biotite phenocrysts is exposed about 3 miles (4.8 km) northwest of Gandy. About a 50-foot (15 m) thickness of tuff is exposed. Its age is unknown and the nearest tuff vents in Utah are 50 miles (80 km) to the east and southeast (Drum and Tunnel Spring Mountains). The vent was more likely upwind, to the west, in Nevada, where explosive volcanism occurred in the late Eocene and Oligocene (Stewart and others, 1977). The tuff is shown as late Eocene(?) on chart 8 (appendix C).

Figure 171. Hills in the center of the picture are rhyolite domes of Smelter Knolls, which emplaced about 3.4 million years ago. Dark low crater in the foreground is attributed by Oviatt (1989) to a phreatic explosion that disrupted the 300,000-year-old tholeiitic basalt flow that is located south of the Smelter Knolls rhyolite. View is northward.

Diorite dikes in House Range (Tid): At Marjum Pass in the House Range, Hintze (1981a) mapped a northeast-trending dike up to about 3 feet (1 m) wide and 1 mile (1.6 km) long. It is olive-gray, brown-weathering, finely crystalline altered rock with chlorite and a few relict quartz phenocrysts. Its age is unknown but it may be related to late Eocene and early Oligocene volcanic rocks in the Little Drum Mountains (Leedom, 1974; Pierce, 1974). Hintze (1974d) mapped a dike of similar size, orientation, and composition about 3 miles (5 km) east of Notch Peak. Both dikes intrude Cambrian strata and are shown on the Tule Valley geologic map (Hintze and Davis, 2002c).

Tunnel Spring Tuff (Tt): Bushman (1973) named this ash-flow tuff and presented geologic maps of six small areas in the Confusion Range, Tunnel Spring Mountains, and Burbank Hills where he studied the unit. The most prominent exposure of the Tunnel Spring Tuff is Crystal Peak (figure 172), a white landmark in western Millard County. Unfortunately, by the time Bushman published his study, the name "Crystal Peak" had been preempted by an Ordovician dolomite (Webb, 1956), otherwise Bushman would have used that very appropriate name for this unit.

The Tunnel Spring Tuff is one of the oldest Tertiary units in western Millard County. Residual (paleoregolithic?) materials are present locally at its base, and had accumulated on the eroded surface of the pre-Jurassic strata upon which the tuff rests. But these residual sediments are too thin to constitute a significant map unit so they are generally mapped as the basal part of the Tunnel Spring Tuff.

The Tunnel Spring Tuff is white, crystal-rich, poorly welded, rhyolite, ash-flow tuff that contains abundant xenoliths of Paleozoic carbonate and quartzite rocks. Its most distinctive component is abundant quartz crystals that are well-formed, doubly terminated grains of coarse sand size. They weather readily from the tuff and do, in fact, form a crystal-rich sand in washes and on anthills near exposures of the tuff. Other phenocrysts include sanidine, plagioclase, and biotite which, together with the quartz, make up 27 percent of the rock. The matrix is glass shards that are partly devitrified. For the most part the tuff is unsorted, but bedding can be observed locally, the result of some slight reworking by water during deposition of the air-fall tuff.

Steven (1989) combined gravity, thickness, and clast-distribution data to support his conjecture that the source caldera for the Tunnel Spring Tuff is now buried under younger volcanic deposits in an area centered about 5 miles (8 km) east of Crystal Peak. Steven (1989) reported a K-Ar age of about 35.4 Ma for the Tunnel Spring Tuff, somewhat older than the 33.9 Ma originally reported (Hintze, 1974c; Armstrong and others, 1976)(~34.8 Ma corrected). The Tunnel Spring Tuff is about the same age as the Sawtooth Peak Tuff in western Beaver County (Best and Grant, 1987). However, the two tuffs do not appear to overlap in areal extent.

The Tunnel Spring Tuff is more than 1,000 feet (300 m) thick at Crystal Peak (figure 172), and may be the same thickness between the Burbank Hills and Tunnel Spring Mountains, but is commonly only a few tens of feet thick in outlying areas (figure 173).

Rhyolitic intrusions of Tunnel Spring Mountains (Tir): Hintze (1981d) mapped some rhyolitic plugs or domes that cover about a square mile (2.6 km^2) at the south end of the Tunnel Spring Mountains. The rock is pinkish-gray to light-gray rhyolite and quartz latite with phenocrysts of plagioclase, biotite, and quartz in an aphanitic to finely crystalline matrix. Anderson (1980) noted that this unit is intrusive into the Tunnel Spring Tuff.

Dacite of Wah Wah Cove (Twc): Hintze and others (1984) mapped this unit on the east side of the Wah Wah Mountains. It consists of a basal tuff member with local cavernous weathering, and an upper flow member. The tuff is white to reddish-gray, massive, lapilli-bearing, dacite tuff containing

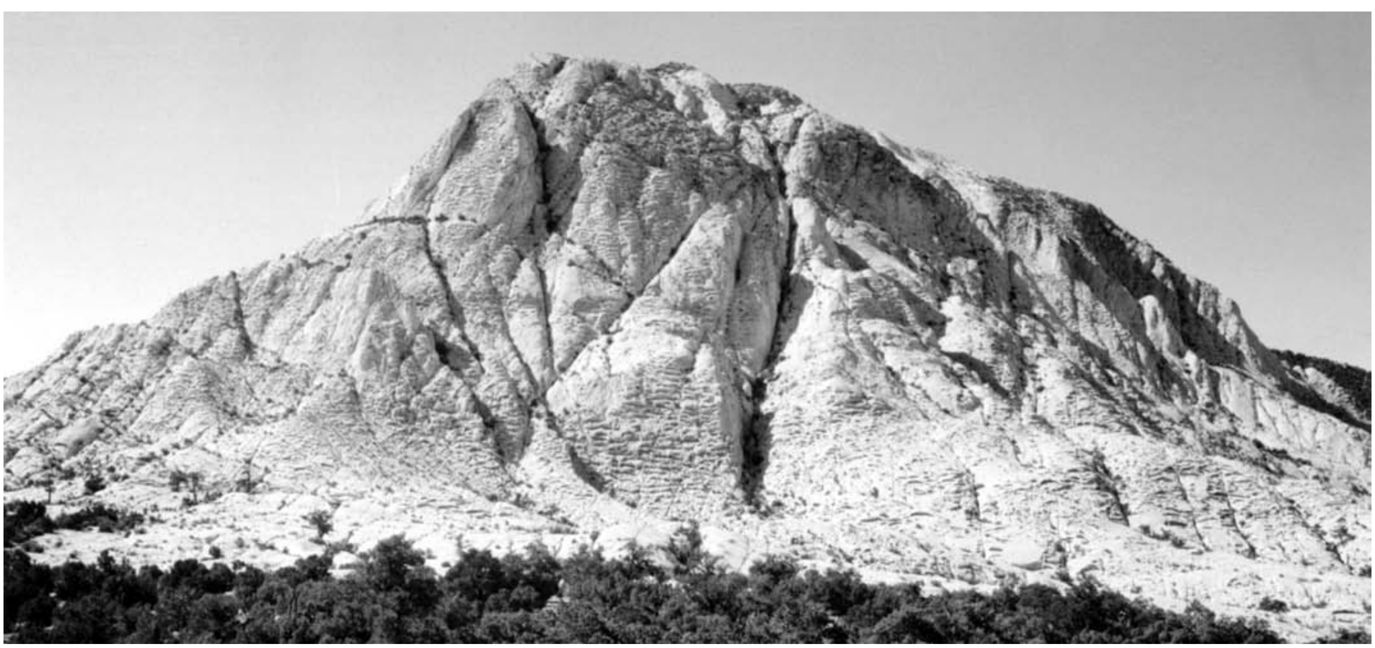


Figure 172. *Crystal Peak in the southern Confusion Range exposes a 35-million-year-old rhyolitic ash-flow tuff, rich in small, doubly terminated quartz crystals. This is an unusually thick accumulation of the Tunnel Spring Tuff, which here probably filled an east-west Oligocene paleovalley. Crystal Peak rises about 800 feet (245 m) above its base. Dwarf ponderosa pines grow in its joint crevices.*

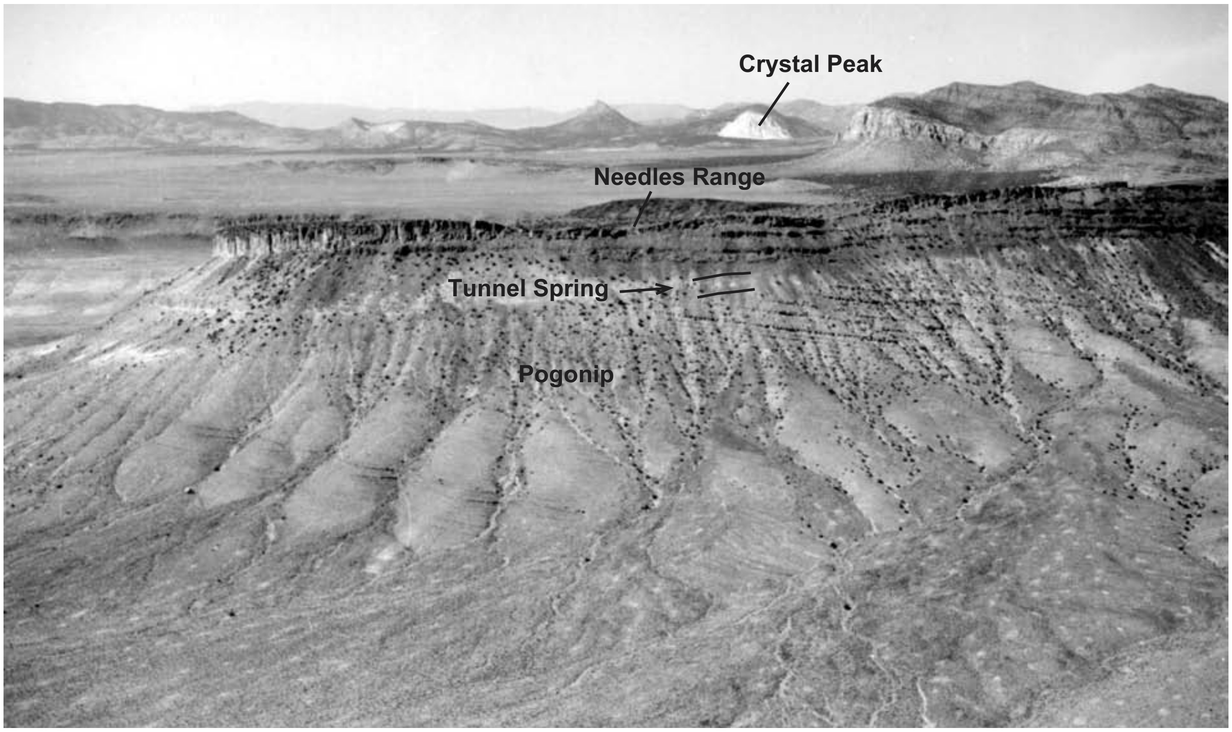


Figure 173. Aerial view westward from 2 miles (3 km) south of Ibex showing angular unconformity between inclined Ordovician strata of the Pogonip Group and nearly horizontal beds of the overlying Oligocene volcanic rocks. The thin white layer just above the unconformity is the Tunnel Spring Tuff, here quite thin as compared to its thickness at Crystal Peak, 8 miles (13 km) in the distance. Dark rocks above the Tunnel Spring Tuff on the nearest ridge are members of the Needles Range Group of volcanic rocks, about 30 million years old. Steven (1989) speculated that the source caldera for the Tunnel Spring Tuff may lie concealed beneath the desert east of Crystal Peak, in the middle left distance of this picture.

fragments of porphyritic dacite, white pumice, and broken crystals of biotite and andesine in a matrix of vitric ash. The tuff is locally more than 330 feet (100 m) thick. The flow member is a medium- to dark-gray, dense dacite porphyry with phenocrysts of andesine, biotite, hornblende, and some zones of flow breccia and vitrophyre near its base. According to Lemmon and others (1973), biotite from a flow vitrophyre gave a K-Ar age of 33.6 Ma and plagioclase from another flow gave a K-Ar age of 33.1 Ma (34.5 and 34.0 Ma corrected, respectively). Thickness of the flow rock exceeds 1,150 feet (350 m).

Sedimentary and volcanic rocks (Tsv): Hintze (1981d) mapped some small exposures of sedimentary and volcanic rocks in the Tunnel Spring Mountains that were noted by Anderson (1980). These rocks are below the welded tuffs of the Needles Range Group and might be part of the Escalante Desert Formation (lower Needles Range Group) (see Best and Grant, 1987, p. 8). Alternatively, this unit might be the time equivalent of the nearby Sawtooth Peak Formation (Tsp; 33.5 Ma; tuff) and the andesitic to rhyolitic igneous rocks at Wah Wah Summit (~33 Ma). The rocks are conglomerates, tuffaceous sandstones, and volcanic rocks of andesitic to dacitic composition. Some rocks are flow layered and range from stony to glassy in texture. They are about 300 feet (100 m) thick and form low topography. Andesite lavas up to 150 feet (46 m) thick, mapped below the Lamerdorf Tuff of the Needles Range Group just to the south in the Halfway Hills (Best and Hintze, 1980a; Hintze and Best, 1987), are also included in this unit.

Windous Butte Tuff (Twb): The Windous Butte is moderately to poorly welded, pink, rhyolite ash-flow tuff that contains quartz, plagioclase, sanidine, and biotite. It forms one of the largest sheets of ash-flow tuff in the Great Basin. Its source caldera was 100 miles (160 km) west of the Utah-Nevada line halfway between Currant and Tonopah (Best and others, 1993), so it is remarkable that a thickness of about 100 feet (30 m) of this tuff is present at the north end of the Burbank Hills in the Deadman Point 7 1/2-minute quadrangle (Hintze, 1997b). In the Burbank Hills, the Windous Butte Tuff is underlain by the Skull Rock Pass Conglomerate and overlain by the Cottonwood Wash Tuff (31 Ma). Windous Butte Tuff is known from two additional localities in Millard County. In the Conger Range it crops out near the base of Toms Knoll on the Knoll Hill 7 1/2-minute quadrangle (M.G. Best, BYU, verbal communication, January 4, 1995) where it underlies tuffs of the Needles Range Group. It is also exposed in the House Range in the Marjum Pass 7 1/2-minute quadrangle where it was mapped as dacitic ash-flow tuff by Hintze (1981a). An Ar/Ar age of 31.4 ± 0.5 Ma on plagioclase from this tuff, reported in Gregory-Wodzicki (1997), was dated by Professor W.C. McIntosh of the New Mexico Institute of Mining and Technology at Socorro and was obtained from a sample taken in the Marjum Pass quadrangle.

Lacustrine limestone and breccia (Tl): Hintze (1981a) mapped these deposits in the central House Range where they accumulated locally during Oligocene time in a southeasterly trending valley, 3 miles (4.8 km) wide, that developed on much-faulted Cambrian strata that formed the valley floor. Sidewalls of the Oligocene valley are formed of unbroken resistant Cambrian strata. The basal deposit is breccia of Cambrian dolomite and limestone fragments. The breccia is not layered, but is well cemented and massive. It represents Oligocene talus or rock avalanche deposits and is as much as 115 feet (35 m) thick. The limestone is white to pinkish- or orangish-gray, and coarsely crystalline. It is medium bedded and forms low ledges and rounded hills. Its lower third contains abundant recrystallized tubular stem or root structures; some layers contain poorly preserved fossil leaves of willow, poplar, and rush-like aspect. Gregory-Wodzicki (1997) reported the following plant genera from this limestone: *Populus, Acer* (Box elder type), *Salix*, *Rhus*, *Staphylea*, and *Ilex*. She distinguished additional forms, including one fern, that were too poorly preserved to name, and wrote that this assemblage is generally similar to the Florissant flora of Colorado. She concluded that the flora suggested a mean annual paleotemperature of 56° F (13.3°C). Freshwater gastropods, *Helix* and *Lymnaea*, are scarce. The limestone is as much as 100 feet (30 m) thick. It is overlain by an unconsolidated conglomerate that may be the lateral equivalent of the Skull Rock Pass Conglomerate, shown as such (Tsr) on the Tule Valley geologic map (Hintze and Davis, 2002c). The Windous Butte Tuff, from which an Ar/Ar age of 31.4 ± 0.5 Ma was obtained, reportedly contains clasts of this limestone (Gregory-Wodzicki, 1997), but the isolated tuff outcrop is in a wash topographically below the limestone.

Hintze (1974b) mapped a similar limestone, with no breccia, in Mile-and-a-Half Canyon in the Confusion Range where it is as much as 200 feet (60 m) thick. It is shown as Tl on the Tule Valley geologic map (Hintze and Davis, 2002c).

Conglomerate and landslide blocks (Tnc): Conglomerate beds and landslide blocks are exposed locally below and within the Needles Range Group (Hintze, 1974a, c; Hintze and Best, 1987). The conglomerates are mostly made up of pebbles, cobbles, and some boulders of Paleozoic rocks in a tuffaceous matrix. Landslide blocks are most common in the area around Crystal Peak and are made up of rootless masses of Ordovician, Silurian, and Devonian strata. The landsliding was probably triggered by Oligocene volcanic activity (Hintze, 1972). The conglomerates may represent local flood and alluvial-fan transport. These deposits are up to 500 feet (150 m) thick.

Needles Range Group: The Needles Range Group includes a sequence of ash-flow tuffs and related volcanic rocks that had their source in calderas that straddle the Utah-Nevada line south of Millard County. Distal deposits from this volcanic center are scattered throughout western Millard County (chart 8; columns 7-11, appendix C). Details of the stratigraphy, composition, and extent of these rocks are given by Best and Grant (1987) and Best and others (1989a, 1993). Best and Grant (1987) redefined the Needles Range Formation, elevating it to group status and including in that group the following units, listed in ascending order: Escalante Desert Formation, Cottonwood Wash Tuff, Wah Wah Springs Formation, Ryan Spring Formation, and Lund Formation. Only the Ryan Spring Formation is not found in Millard County. For the purposes of the 1:100,000-scale geologic maps of Millard County we show the Escalante Desert Formation by the symbol Tnl, and the Cottonwood Wash, Wah Wah Springs, Lund, and associated rocks (figures 174 and 175) by the symbol Tnu; and the

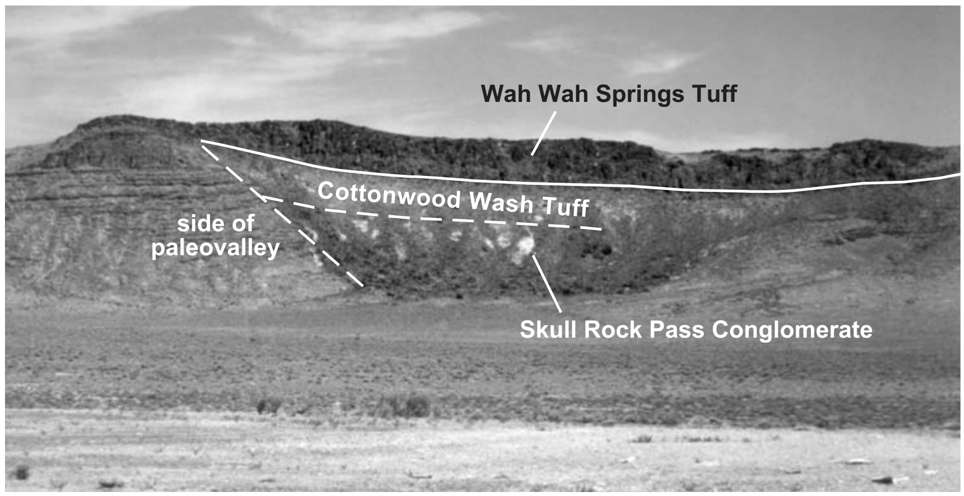


Figure 174. This feature, located in the southern House Range about 6 miles (10 km) south of the Ibex Well, is familiarly known to geologists as the "Lava Dam." This designation is not quite correct because the volcanic material that fills the paleovalley, here cut into Cambrian-Ordovician strata, is mostly ash-flow tuff. The dark ledge at the top of the "dam" is the Wah Wah Springs Formation (Tuff) of the Needles Range Group; it is underlain by dark beds of the Cottonwood Wash Tuff; the white material below that is Skull Rock Pass Conglomerate underlain by Tunnel Spring Tuff at the base.

Figure 175. Aerial view of the "Lava Dam", looking roughly east, showing the eastward extent of its paleovalley which has been truncated along its west side by the House Range normal fault. Stair-step ledges in the carbonate rocks on both sides of "Lava Dam" are the Lava Dam Member of the Notch Peak Formation (Ordovician and Cambrian). White area beyond is Sevier Lake (dry), with the Cricket Mountains on its far side.

basalt of Brown Knoll was included in the Needles Range Group, symbol Tnb. Mapping in the Confusion Range by Hose (1963b, 1965a-b, 1974b) did not identify the volcanic units by name, but the volcanic rocks that Hose mapped were field checked for this bulletin and the proper assignments, mostly Needles Range Group units, are shown on the Tule Valley geologic map (Hintze and Davis, 2002c).

Escalante Desert Formation (Tnl): Best and Grant (1987) recognized three tuff members within the Escalante Desert Formation, in ascending order: Marsden Tuff, Lamerdorf Tuff, and Beers Spring Member. The Marsden is not present in Millard County and the Lamerdorf and Beers Spring are represented in the county by small outcrops, and larger outcrops in adjacent Beaver County, in the Halfway Summit (Best and Hintze, 1980a), Tweedy Wash (Hintze, 1986a), and Mountain Home Pass and Miller Wash (Hintze and Best, 1987) 7 1/2-minute quadrangles.

The Lamerdorf Tuff is rhyolitic ash-flow tuff of various colors with 10 percent plagioclase and 2 percent biotite phenocrysts, and less than 5 percent lithic fragments. It is typically welded and locally occurs as a vitrophyre. It ranges up to 120 feet (40 m) in thickness in Millard County. Its age is about 32 Ma (Best and others, 1993).

The Beers Spring Member is greenish-gray sandstone and andesitic conglomerate. It is 0 to 30 feet (0-10 m) thick.

Cottonwood Wash Tuff (Tnu): The Cottonwood Wash Tuff is crystal-rich dacitic lapilli ash-flow tuff that contains 25 percent plagioclase, large books of biotite as much as one-quarter inch (6 mm) in diameter, sparse broken, embayed quartz crystals that are almost as large, and minor hornblende, green augite, and Fe-Ti oxides. It is found in the Mountain Home Range, Halfway Hills, Burbank Hills, and the southern Confusion Range where it generally is overlain by the somewhat similar Wah Wah Springs Tuff from which it is readily discriminated by its big biotite books. In Millard County it ranges up to 1,300 feet (400 m) in thickness. Its age is about 31 Ma (M.G. Best, BYU, verbal communication, October 1994).

Basalt of Brown Knoll (Tnb): This basaltic flow rock is found in the southern Confusion Range where it lies between the Cottonwood Wash and Wah Wah Springs Tuffs. It was first mapped by Hintze (1974a) and is given its name herein from its exposure at Brown Knoll in the Brown Knoll 7 1/2-minute quadrangle (Hintze and others, 1984). It is brown-weathering, dark-gray mafic lava flow rock that contains 10 percent phenocrysts of plagioclase, black augite, and reddish-brown olivine in a fine-grained matrix. It is as much as 250 feet (80 m) thick.

Wah Wah Springs Formation (Tnu): Best and Grant (1987) included two members within the Wah Wah Springs Formation, an outflow tuff member, and an intracaldera member. The latter member is found only within the mapped extent of the Indian Peak caldera which straddles the Utah-Nevada line south of Millard County. Therefore, the only member of the Wah Wah Springs Formation that occurs in Millard County is the outflow tuff member. As used in this bulletin, the term "Wah Wah Springs Tuff" means the same as "outflow tuff member of the Wah Wah Springs Formation." The Wah Wah Springs Tuff, together with the Windous Butte Tuff, has the distinction of being one of the most voluminous and widely dispersed ash-flow tuffs in the Great Basin. Outcrops of the Wah Wah Springs Tuff are reported 100 miles (160 km) east and west of the Utah-Nevada border, and 75 miles (120 km) north and south of Indian Peaks (Best and others, 1989a, 1993).

The Wah Wah Springs Tuff is crystal-rich dacite tuff that ranges from a porous, weakly welded, gray to light-brown tuff, to a compact, highly welded, slightly devitrified, red-brown tuff with eutaxitic white pumice lapilli, and to a black intensely welded vitrophyre. It has reversed magnetic polarity. Phenocryst content is plagioclase (andesine) (52-68%), hornblende (14-32%), biotite (in small books) (5-12%), quartz (0-11%), and pyroxene (0-4%). Thickness in Millard County ranges from 1,000 feet (300 m) in the Mountain Home Range to a few tens of feet in the northwestern part of the county. Its K-Ar isotopic age has been determined many times and Best and Grant (1987) reported its average age as 29.5 Ma. However, M.G. Best (BYU, verbal communication, October 1994) concluded that, because of its stratigraphic relationships to other Great Basin ash-flow tuffs, a better age estimate might be 30.5 Ma. Best and Williams (1997) reported the age as 30 Ma.

Lund Formation (Tnu): Small outcrops of the Lund Formation are present in the Halfway Hills in Millard County and are more extensive to the south in Beaver County (Best and Hintze, 1980a-b). Best and Grant (1987) reported an average age of about 28 Ma. The Lund Formation is light-gray, poorly welded, crystal-rich, dacitic tuff. Phenocrysts include plagioclase (20%), pale amethyst quartz up to 2.5 inches (6 cm) in diameter (8%), biotite (6%), hornblende (4%), Fe-Ti oxides (1%), and sphene (trace). Magnetic polarity is normal. The tuff is partly exposed, but appears to be up to 370 feet (113 m) thick (Best and Hintze, 1980a).

Isom Tuff (Ti): The Isom Tuff is trachydacite with multiple ash-flow tuff members and is an easily recognized marker horizon in the volcanic stratigraphy of southwestern Utah and adjacent Nevada; the age of one of its ash-flow members is 25.7 Ma. Its source caldera was near Modena, Utah (Best and others, 1993). It extends into Millard County in only one place - a small exposure is found in the Tunnel Spring Mountains overlying the Wah Wah Spring Tuff (Hintze, 1981d). It is also present in the Halfway Hills in adjacent Beaver County, where it underlies the Bauers Tuff (Tccb). There it is densely welded, vuggy, eutaxitic, crystal-poor, vitric ash-flow tuff with less than 10 percent phenocrysts, mostly plagioclase with minor Fe-Ti oxide and pyroxene. It is about 20 feet (6 m) thick.

Conglomerate and tuff of Confusion Range (Tct): Geologic quadrangle maps of the Confusion Range by Hose (1963b, 1965b, 1974b), Hose and Repenning (1963, 1964), and Hose and Ziony (1963) show five Tertiary map units labeled conglomerate, tuff and tuffaceous sandstone, tuffaceous limestone, tuff breccia, and welded tuff. Concerning these units, Hose's map legends state that their stratigraphic relations are not clear in the field because they are inferred from scattered outcrops. These Tertiary units are generally poorly consolidated and are largely covered by surficial deposits. Because these Tertiary units are unfossiliferous, the only basis for determining their age is by dating the volcanic components. For this bulletin I reexamined all of the outcrops of welded tuff shown on Hose's maps listed above and found that almost all were the Wah Wah Springs Tuff (about 30.5 Ma) of the Needles Range Group of Oligocene age, with a maximum thickness of less than 300 feet (90 m). At Toms Knoll on the Knoll Hill quadrangle (Hose, 1965b), the Wah Wah Springs Tuff is underlain by the Windous Butte Tuff and the Tunnel Spring Tuff. These older Oligocene Tuffs (31-35 Ma) have not been reported from other Tertiary localities in the Confusion Range.

At many Tertiary exposures in the Confusion Range, welded tuff of the Needles Range Group is overlain by a heterogeneous unit consisting of white, air-fall tuffs, with or without biotite flakes; tuffaceous sandstone; conglomerate with pebble, cobble, and, uncommonly, boulder clasts of mostly Paleozoic rocks, but including boulders of vesicular basalt and andesitic lava; and, locally, thin, fresh-water limestone beds. This heterogeneous unit is the conglomerate and tuff of the Confusion Range (Tct). Unit Tct occupies the same relative stratigraphic position, and has the same mountain-flank position and steep dips, as valley fill conglomerate and sandstone (Tcs), but is typically more heterogeneous. The post-Needles Range conglomerate (Tc) rests unconformably on Needles Range tuffs, like unit Tct, but dips less steeply.

Hose and his coworkers underestimated the thickness of Tertiary rocks in the Confusion Range, giving them a maximum thickness of 700 feet (210 m). Unit Tct is best exposed in stream channels such as one east of the Bishop Springs anticline (Hose and Ziony, 1963) and others on the east flank of the Confusion Range (Hose and Repenning, 1963). Tertiary strata commonly dip about 20 degrees and in some stream channels the dipping beds are exposed for nearly a mile (1.6 km); they are at least 2,000 feet (600 m) thick, and probably thicker in their covered extent beneath surficial alluvium.

Anderson (1983) remapped some of the Tertiary exposures in the Confusion Range as part of his regional study of late Cenozoic faulting. He added a number of normal faults to Hose's maps, some of them problematical. Tertiary deposits in western Utah generally rest with angular unconformity on the older rocks that have undergone Mesozoic folding and faulting. In some places in the Confusion Range the Tertiary rocks, such as unit Tct, have been preserved in down-faulted blocks surrounded by the more resistant Paleozoic strata.

The age of unit Tct is not precisely known. It is certainly younger than the Wah Wah Springs Tuff of the Needles Range Group (30.5 Ma). The most common rock type in Tct is light-gray tuff of silt-size particles; some layers contain small to very small biotite flakes. Possible source areas for rhyolitic ash include the Honeycomb Hills to the north and the Topaz Mountain area to the northeast (rhyolites erupted 6 to 10 million years ago), or erosion of Oligocene biotite-bearing ashes like those in the Needles Range Group.

Conglomerate and tuffaceous sandstone (Tcs): Thousands of feet of these valley-fill deposits are now exposed on the east flank of the House and west flank Mountain Home Ranges. These deposits may be equivalent to the conglomerate and tuff unit on the northeast flank of the northern Confusion Range (Tct) and the post-Needles Range conglomerate in and near the Burbank Hills (Tc). Unit Tcs includes sediments which, because of their steeper dips, are deemed to be older than the surficial deposits that cover most valley floors in western Millard County. No clear basis for dating these valley-fill deposits has been found; they are probably Miocene or Pliocene in age as shown on chart 8 (appendix C).

Hintze (1980c, 1981b) mapped this unit on the east flank of the House Range where it unconformably overlies Cambrian strata. The conglomerate is gray to reddish-gray, weakly consolidated pebble and cobble conglomerate and sandstone that is interbedded with a light-gray to grayish-pink latitic tuffaceous sandstone. Hintze (1980c) suggested that the tuffaceous sandstone might be the same age as one of the Tertiary (Eocene and Oligocene[?]) tuffs in the Little Drum Mountains, but no isotopic determination has actually been made on the House Range tuffaceous material. The unit dips valleyward about 10 degrees and may be as much as 1,000 feet (300 m) thick.

The thickest and most extensively exposed older valley-fill sediments in Millard County are on the west flank of the Mountain Home Range, mostly in Beaver County, and were mapped under the symbol "Tcg" by Hintze and Best (1987). These Tcs deposits consist of poorly cemented cobble, pebble, and boulder conglomerate with about 10 percent interbedded sandstone. They represent early alluvial fill of Hamlin Valley. They dip valleyward as much as 40 degrees, and have an exposed thickness of about 2,000 feet (600 m).

Deposits mapped as unit Tcs, that are almost as heterogenous as those in unit Tct, are present in the Tunnel Spring Mountains. Like unit Tct, they include conglomerate, tuffaceous sandstone, and limestone (Hintze, 1981d; units Tc, Ts, Tl); are located on range flanks and in ranges; and dip steeply (25° here). These rocks appear to be younger than the Isom Tuff. The thickness of these deposits in the Tunnel Spring Mountains is indeterminate but may be up to 1,000 feet (300 m).

Post-Needles Range conglomerate (Tc): On the west side of the Little Rough Range in the Middle Mountain 7½-minute quadrangle, Hintze (1974c) mapped a local conglomerate that rests on the Wah Wah Springs Tuff. It consists mostly of subrounded cobbles and boulders derived from nearby Devonian and Silurian dolomites, but includes some Wah Wah Springs Tuff clasts. Its matrix is limy and tuffaceous sand and silt, and it is as much as 600 feet (180 m) thick.

The same unit designation (Tc) is used in the contiguous Burbank Hills exposures, where Hintze (1997b, d) mapped oldest (fan) alluvium unconformably overlying the Wah Wah Springs Tuff. The conglomerate is overlain by younger fan alluvium. The matrix of this post-Needles Range conglomerate contains doubly terminated quartz crystals derived from the Tunnel Springs Tuff. Further work is needed to date this unit. The lack of steep dips seems to indicate it is younger than unit Tcs and might be as young as unit Ts. Thickness is unknown but may be as much as 1,000 feet (300 m) locally.

Valley-fill sediments (Ts): This smaller example of exhumed valley-fill deposits is present near Crystal Peak (Hintze, 1974c) where about 100 feet (30 m) of poorly consolidated tuffaceous sandstone is exposed. It has been shown separately on the Wah Wah Mountains North geologic map (Hintze and Davis, 2002a), because it does not dip steeply (in contrast to unit Tcs) and is not conglomeratic (in contrast to unit Tc), and may be younger than the other valley-fill deposits.

Lithologic Units of Northern Beaver County

Many of the lithologic units in Millard County, described in the preceding pages, are present in northern Beaver County. However, a few lithologic units found in northern Beaver County are not present to the north in Millard County; these units, shown on the Wah Wah Mountains North and Richfield 1:100,000-scale geologic maps (Hintze and Davis, 2002a; Hintze and others, 2003), are described below.

Sawtooth Peak Formation (Tsp): This tuff is exposed in a small area near Beers Pass in the Halfway Hills 1.5 miles (2.4 km) south of the Millard-Beaver County line (Best and Hintze, 1980a). It is a light-greenish-gray, friable, crystal-rich tuff containing quartz, plagioclase, biotite, sanidine, and olivine phenocrysts that comprise one-third to one-half the rock. Exposed thickness is about 200 feet (60 m). The Sawtooth Peak is overlain by the lower Needles Range Group and was dated (K-Ar biotite) at 33.5 ± 1.2 Ma (Best and Grant, 1987).

Andesite of Kelleys Place (Tkp): This unit is mostly a pyroclastic deposit but locally includes a few flows. The pyroclastic material is medium-grained to very-coarse-grained andesite agglomerate that includes blocks as much as 6 feet (2 m) in diameter; the matrix is gray to pink volcanic ash. Two andesite flows are locally intercalated in the agglomerate; they are dark-brown, fine- to medium-grained porphyritic andesite composed of phenocrysts of andesine, biotite, and hornblende in a dense felted matrix (Hintze, 1974e). Lemmon and others (1973) reported a K-Ar age of 32.3 Ma (~ 33.1 Ma, corrected) from hornblende from the flows. Total thickness is about 2,000 feet (600 m).

Diorite of Wah Wah Summit (Tdw): Three small porphyritic diorite intrusive bodies lie along an east-west line through Wah Wah Summit (Hintze, 1974e). The diorite is gray to brownish-gray, nonresistant rock that forms low exposures with a loose granular surface. Primary minerals are andesine, orthoclase, hornblende, biotite, and minor quartz and augite. The andesite of Kelleys Place may be the eruptive equivalent of this diorite.

Rhyolite porphyry of Wah Wah Summit (Twp): This grayish-brown, strongly welded, rhyolite ash-flow tuff contains small shattered quartz crystals in a devitrified matrix. The age is uncertain but it is thought to be younger than andesite of Kelleys Place (Hintze, 1974e). As exposed it is 0 to 100 feet (0-30 m) thick.

Rhyolite intrusive of Wah Wah Summit (Trw): This unit forms a small intrusion of light-gray, finely crystalline rhyolite, more than half of which is made of small phenocrysts of quartz and sanidine. It has not been dated but is part of the Oligocene eruptive complex in the Wah Wah Summit area (Hintze, 1974e).

Granodiorite of Beaver Lake Mountains (Tigd): Lemmon and Morris (1984) mapped several small intrusive bodies in the Beaver Lake Mountains northwest of Milford. They are mostly light- to medium-gray, medium-grained, holocrystalline rocks. Granodiorite makes up most of the intrusions. But the map unit includes quartz monzonite that forms one small stock, granite border zones, quartz diorite and monzonite occurring mostly as dike-like intrusions, and, locally, aplite dikes. The intrusive bodies were isotopically dated at 27.0 and 28.4 Ma (K-Ar hornblende) (Lemmon and others, 1973) (~27.7 and ~29.1 Ma corrected).

Jasperoid (Tj): Lemmon and Morris (1984) mapped several small jasperoid bodies in the Beaver Lake Mountains. They occur within marbleized Paleozoic carbonate rock in proximity to granodiorite intrusions. They form irregular masses of light- to dark-brown, fine-grained, silicified rock. Maximum width of the largest jasperoids is about 100 feet (30 m).

Marble (Tm): Marble has been produced by thermal and chemical metamorphism in two areas: at Wah Wah Summit (Hintze, 1974e) and in the Beaver Lake Mountains (Lemmon and Morris, 1984). The marble is light gray to white, locally blotchy or streaked, generally coarse grained, and locally dolomitic. The general absence of calc-silicate minerals and hornfels indicates the parent strata did not contain significant non-carbonate sediments. At Wah Wah Summit the parent material is Cambrian limestone and dolomite; in the Beaver Lake Mountains the parent carbonates were probably Devonian and/or Mississippian in age. Thickness is indeterminate. Age of metamorphism is that of adjacent intrusions, 28-29 Ma in the Beaver Lake Mountains and Oligocene (33 Ma?) at Wah Wah Summit.

Granitic intrusions of Frisco (Tig): The main part of this unit is located just south of the Wah Wah Mountains North map area where it forms the granodioritic Cactus stock and associated intrusive bodies near Frisco. It contains medium-sized phenocrysts of perthitic orthoclase, oligoclase-andesine, quartz, hornblende, and biotite. Biotite from this rock at the Cactus mine in the adjacent Frisco quadrangle yielded a K-Ar biotite age of 28.7 ± 0.7 Ma (Lemmon and others, 1973; Best and others, 1989c).

Syenite of Cedar Grove (Tisg): Syenite of Cedar Grove is medium- to coarse-grained, leucocratic, porphyritic to hypidiomorphic-granular rock consisting of predominant orthoclase and plagioclase, less hornblende and pyroxene, and sparse biotite. Sphene and magnetite are common accessory minerals. It cuts the gabbro porphyry (Tigp), with which it is associated, and produced propylitic alteration in adjacent Bullion Canyon Volcanics (Tbc) (Steven and Morris, 1983). Coleman and others (1997) gave an age of 23 Ma for this syenite.

Gabbro porphyry of Cedar Grove (Tigp): This unit is a dark-gray porphyritic intrusive with prominent phenocrysts of labradorite and clinopyroxene in a felted matrix of plagioclase microlites and Fe-Ti oxides grains. This intrusive cuts propylitically altered Bullion Canyon Volcanics, undivided (Tbc) (Steven and Morris, 1983).

Condor Canyon Formation, Bauers Tuff Member (Tccb): This unit is pink- to purple-gray, firmly welded ash-flow tuff with 20 percent phenocrysts of plagioclase, sanidine, and biotite in approximately equal proportions. The lower part contains light-colored pumice lapilli. This tuff came from a caldera near Caliente, Nevada and is dated at 22.7 Ma (Best and others, 1993). Its thickness in the Halfway Hills is about 20 feet (6 m).

Intrusion and gneiss complex (Tp€g): Irregular thin ridges that extend westward from the Mineral Mountains in the southwest part of the Pinnacle Pass 7 1/2-minute quadrangle contain dikes and other plutonic bodies interleaved between screens of metamorphic rocks that are believed to be

Precambrian gneisses. Sibbett and Nielson (1980) mapped individual components of the complex on their 1:24,000-scale map, but their mapping is too detailed to show at the 1:100,000 scale of the Richfield geologic map (Hintze and others, 2003). The plutonic rocks involved are the quartz monzonite (see Tqm; age about 18 Ma); the fine-grained granite (see Tgd); and other granitic and diabasic dike rocks (Sibbett and Nielson, 1980), that are not shown separately elsewhere on the Richfield 1:100,000-scale geologic map. Age of the youngest dikes involved is about 11 Ma (Nielson and others, 1986).

Diorite of Mineral Mountains (Tdm): This unit is medium-grained, equigranular, biotite hornblende diorite containing small apatite and sphene crystals. It is exposed in the northern Mineral Mountains where it intrudes foliated hornblende granodiorite (Tgm, age about 25 Ma) and is intruded by quartz monzonite (Tqm, age about 18 Ma) (Sibbett and Nielson, 1980; Coleman and others, 1997).

Syenite of Mineral Mountains (Tsm): Syenite intrudes the quartz monzonite (Tqm), and in the southwestern part of the Mineral Mountains, south of the Richfield 30′ x 60′ quadrangle, it intrudes a biotite granite stock (Sibbett and Nielson, 1980). The syenite is light gray, coarse to medium grained, and weathers to grus. Average composition is 65 percent microcline, 19 percent plagioclase (An10), 7 percent quartz, 1 to 2 percent biotite, 2 percent sphene, and accessory Fe-Ti oxides, apatite, hornblende, and zircon (Sibbett and Nielson, 1980).

Granite dikes (Tgd): Dikes of biotite granite, fine-grained granite, and leucocratic granite intrude the quartz monzonite (Tqm) in the northern Mineral Mountains. The fine-grained granite dikes cut the leucocratic and biotite granite dikes. The biotite-granite dikes are believed to be related to a biotite-granite stock in the southwestern part of the Mineral Mountains, south of the study area. The fine-grained granite dikes are actually fine to medium grained and contain 57 percent K-feldspar, 29 percent quartz, 9 percent plagioclase, 3 percent biotite, and accessory sericite and chlorite. They form brown, resistant, jointed outcrops. The biotite-granite dikes are medium grained; the related stock contains 50 percent K-feldspar, 27 percent quartz, 13 percent plagioclase, 7 percent biotite, and 3 percent accessory sphene, Fe-Ti oxides, apatite, and zircon. The leucocratic dikes cut the biotite granite and syenite (Tsm) and look similar to the biotite granite but have larger quartz crystals and less biotite. The map unit also includes minor aplite and pegmatite dikes (Sibbett and Nielson, 1980).

Microdiorite dikes (Tdd): This unit consists of dark-green to black, resistant, thin dikes with subdiabasic texture. The dikes cut the Mineral Mountains quartz monzonite (Tqm) and granite dikes (Tgd). Microdiorite dikes are composed of 40 percent andesine, 25 percent hornblende, 15 percent actinolite, 6 percent biotite, 0-6 percent K-feldspar, and 1-3 percent each of sphene, Fe-Ti oxides, apatite, orthopyroxene, and alteration minerals (Sibbett and Nielson, 1980).

Rhyolite of Gillies Hill (Trg): Rhyolite of Gillies Hill consists of lava flows and domes of light-gray to white, flow-layered rhyolite that ranges from nearly aphyric to porphyritic with abundant phenocrysts. Some flows are crystal-poor with a few phenocrysts of quartz, sanidine, plagioclase, and biotite, whereas one major flow has abundant plagioclase and biotite phenocrysts. Its fine-grained matrix ranges from dense to vesicular (Steven and Morris, 1983). A K-Ar age on sanidine from the rhyolite is 9.13 ± 0.31 Ma, with K-Ar ages from unaltered biotite of about 9 Ma (Evans and Steven, 1982). This rhyolite covers a few square miles about 6 miles (10 km) south-southwest of Cove Fort. Domes are more than 1,000 feet (300 m) high (Steven and Morris, 1983).

Lithologic Units of Marysvale Volcanic Field, Western Sevier County

The Richfield 30′ x 60′ quadrangle extends east of Millard County and the geologic map includes many map units in western Sevier County that are not present in Millard County (Hintze and others, 2003). Most of these are igneous units that originated in the Marysvale volcanic field. During the past century many geologists have mapped and remapped the complex geology of that volcanic center, the exposed history of which began about 32 million years ago in early Oligocene time, and was mostly over by middle Miocene time, 17 million years ago. A 1:100,000-scale geologic map of the central Marysvale volcanic field (Rowley and others, 2002) is the source of the geologic mapping in the southeastern part of the Richfield 30′ x 60′ geologic map, and the following descriptions of the igneous units in this area have been taken, with the permission of the authors, from the text that accompanies their colored map and from Cunningham and others (1983). Most Paleocene and Eocene sedimentary units that are exposed in Sevier County north of the Marysvale volcanic field extend into Millard County and have been discussed previously in this bulletin; the exception is the Crazy Hollow Formation, which is discussed below.

Crazy Hollow Formation (Tch): The Crazy Hollow Formation is mostly dark-brownish-orange to brownish-red, thin-bedded sandstone, siltstone, and mudstone with 20 to 30 percent interbeds of pale-grayish-orange, thick-bedded to massive, lenticular, mostly medium-grained channel sandstone and a few percent of pebble conglomerate beds.

Channel sandstone clasts are about 50 percent quartzite, 45 percent chert, carbonate, and siltstone, and 5 percent feldspar. The sandstone is friable but case-hardened, and weathers to many unusual shapes. Black chert pebbles in the conglomerate beds are diagnostic of the formation.

The contact with the overlying Aurora Formation is mapped at the change from dark-brownish-orange sandstone to pale-gray or pale-reddish-gray clayey mudstone. The Crazy Hollow Formation is 350 feet (107 m) thick just west of Richfield (Willis, 1994) but thins to absence a few miles to the southwest.

Older volcanic rocks (Tov): This unit consists of poorly to moderately resistant, light-gray, light- to dark-green, brown, and red volcanic mudflow breccia and subordinate lava flows. Flows and clasts are dacitic. The unit is exposed in the northeast part of the Annabella 7 1/2′ quadrangle, where it underlies the Three Creeks Tuff (Tbct) and overlies the Aurora Formation (Tau). It is about 660 feet (200 m) thick (Rowley and others, 1981b). In the Pahvant Range the same stratigraphic position is occupied by the lithologically similar volcanic rocks of Dog Valley (Tdv).

Quartz-latite volcanic dome and rhyodacite flow (Tql): This large volcanic dome in the Joseph Peak quadrangle is composed of resistant, gray, crystal-rich, quartz latite. The map unit includes a resistant, dark-gray, crystal-poor rhyodacitic lava flow that overlies the dome. The age of this unit is uncertain; it has been shown as older and younger than the Three Creeks Tuff Member of the Bullion Canyon Volcanics (Cunningham and others, 1983; and Rowley and others, 2002; respectively). Its maximum thickness is about 650 feet (200 m) (Rowley and others, 2002).

Crystal-poor dacitic lava flows (Tcp): These flows consist of moderately resistant, pale-gray, pale- to moderate-greenish-gray, and pale-reddish-gray, locally vesicular or amygdaloidal, aphanitic, dacitic lava flows and red volcanic mudflow breccia (Rowley and others, 1981b). They contain small sparse phenocrysts of plagioclase, pyroxene, and Fe-Ti oxides. They are exposed in the hills near Annabella. These flows have not been dated but lie between the tuff of Albinus Canyon (Tac; 25 Ma) and Three Creeks Tuff (Tbct; 27 Ma). The flows are 100 to 160 feet (30-50 m) thick.

Volcanic rocks of Signal Peak (Tsg): Volcanic rocks of Signal Peak are mostly resistant, gray, black, brown, reddish-brown, and red andesitic lava flows, flow breccia, and subordinate volcanic mudflow breccia, densely welded ash-flow tuff, and conglomerate. Lava flows are mostly crystal poor and are locally vesicular and amygdaloidal. Flows and breccia clasts contain phenocrysts of plagioclase and subordinate pyroxene, Fe-Ti oxides, and olivine in an aphanitic matrix. Most of the volcanic rocks of Signal Peak are vent-facies rocks of a clustered long-lived (middle Oligocene to early Miocene) shield volcano complex in the northern Sevier Plateau. Vent-facies and alluvial-facies rocks were separated during more detailed mapping (Cunningham and others, 1983; Rowley and others 1986). On the Richfield 30′ x 60′ geologic map (Hintze and others, 2003) the volcanic rocks of Cliff Canyon, an alluvial-facies unit that contains clasts of Three Creeks Tuff (27 Ma) and underlies the volcanic rocks of Signal Peak (Tsg) (Rowley and others, 1981a-b; Cunningham and others, 1983), is included in the Tsg map unit. The volcanic rocks of Signal Peak overlie the tuff of Albinus Canyon northeast of Annabella (Rowley and others, 1981b; Willis, 1994). The volcanic rocks of Signal Peak are as much as 2,100 feet (650 m) thick.

Basaltic andesite lava flows, Antimony Tuff Member of Mount Dutton Formation, and tuff of Albinus Canyon, undivided (Taa): See individual unit descriptions of Tba, Tda, and Tac.

Mount Dutton Formation, Antimony Tuff Member (Tda): The Mount Dutton Formation includes many map units, but only the Antimony Tuff Member is exposed in the Richfield 30′ x 60′ quadrangle. The Mount Dutton Formation is the most voluminous group of volcanic deposits in the Marysvale volcanic field. Most of its rocks are crystal-poor to aphanitic andesite or, less commonly, dacite erupted from a string of stratovolcanoes aligned along the east-striking Blue Ribbon transverse zone, whose axis is about 20 miles (32 km) south of the edge of the Richfield 30′ x 60′ quadrangle. Isotopic ages indicate a long episode of magmatism, from 30 to 21 Ma (Fleck and others, 1975; Rowley and others, 1994).

The Antimony Tuff is resistant, mostly red, densely welded, crystal-poor, trachytic ash-flow tuff intertongued within the Mount Dutton Formation and interstratified with the volcanic rocks of Signal Peak. Its source has not been found, but may be buried beneath the Sevier Valley near Joseph. It contains medium-grained phenocrysts of plagioclase and sanidine and minor pyroxene and Fe-Ti oxides, as well as drawn-out pumice lenticules. Locally it includes a basal black vitrophyre as much as 10 feet (3 m) thick. The tuff is widespread. It is best exposed in the Richfield 30′ x 60′ quadrangle in a small fault block 3 miles (5 km) east of Annabella and is 200 feet (60 m) thick. A K-Ar age of 25.4 Ma was reported (Rowley and others, 1981b; Cunningham and others 1983; Rowley and others, 1994, 2002).

Basaltic andesite lava flows (Tba): These are resistant, dark-gray and black, locally vesicular and amygdaloidal, crystal-poor, basaltic andesite lava flows that make up a relatively thin sequence in the southeastern Pahvant Range. They intertongue with the Antimony Tuff Member (Tda) and the tuff of Albinus Canyon (Tac). A K-Ar age of 21.6 Ma was reported for a flow near Joseph that overlies the tuff of Albinus Canyon (Rowley and others, 1994). These basaltic andesites probably represent flows of one or more shield volcanoes, which may underlie valley-fill deposits in Sevier Valley or occur farther east in the northern Sevier Plateau. If erupted from the Sevier Plateau, they may be part of the volcanic rocks of Signal Peak (Tsg). Maximum thickness is about 500 feet (150 m) (Rowley and others, 2002).

Bullion Canyon Volcanics (Tbc): This heterogenous sequence of rocks, ranging in age from at least 30 to 22 Ma (Miocene and Oligocene), makes up the second-most voluminous series in the Marysvale volcanic field; the roughly coeval Mount Dutton Formation is the most voluminous. The unit was originally named and mapped by Callaghan (Callaghan, 1939; Callaghan and Parker, 1961a-b, 1962a-b; Willard and Callaghan, 1962), but has been extensively revised and mapped in more detail by Rowley and others (1979), Steven and others (1979, 1990), Cunningham and others (1983), and Steven (1984). It consists of moderately resistant, tan, gray, brown, pink, light-green, and light-purple, volcanic mud-flow breccia, lava flows, flow breccia, ash-flow tuff, and fluvial conglomerate and sandstone, all of which are products of clustered stratovolcanoes or of their erosion. Lava flows are mostly crystal-rich dacite, but include local flows of fine-grained, crystal-poor, black andesite, as well as rhyodacite and quartz latite lava flows. The unit is widely distributed in the southern Pahvant Range, northern Tushar Mountains, and the Sevier Plateau in Beaver and Sevier Counties. Its maximum thickness is at least 5,000 feet (1,500 m) (Rowley and others, 2002)

Metamorphosed rock (Tm): This unit consists of calc-silicate hornfels and quartzite that is in contact with a quartz monzonite intrusion of the Bullion Canyon Volcanics (Tbci, age about 23 Ma). Rocks in this unit are thought to be metamorphosed Toroweap Formation (Lower Permian), which contains interbedded dolomite, limestone, and sandstone (Steven and Cunningham, 1979). The metamorphosed rock may be fault bounded (Rowley and others, 2002).

Volcanics of Monroe Peak caldera: The nine map units described under this heading were erupted from, deposited in, and emplaced in early Miocene time (23-21 Ma) in the largest caldera in the Marysvale volcanic field, the Monroe Peak caldera. This caldera is located northeast of the town of Marysvale and covers about 65 square miles (170 km^2) in the southeastern corner of the Richfield 30′ x 60′ quadrangle.

The caldera is mapped in detail in the southern half of the Monroe Peak and Antelope Range 7 1/2′ quadrangles (Steven and others, 1984; Rowley and others, 1988a-b, 1994, 1998).

Osiris Tuff, intracaldera facies (Toi): This phase of the Osiris Tuff includes soft to resistant, orange and tan, densely welded ash-flow tuff and lava flows(?) that are similar to the outflow facies (To) but are generally altered to clay. The unit is confined to the source Monroe Peak caldera and includes intracaldera collapse breccia derived from landslides from the caldera walls. The alteration is argillic and was caused by intracaldera intrusions (Tmpi) and the central intrusion (Tci). K-Ar age is about 23 Ma. Thickness is at least 1,150 feet (350 m) but its base is not exposed (Cunningham and others, 1983; Rowley and others, 2002).

Lava flows of Bagley Meadows (Tmpb): This is a local sequence of resistant, light- to medium-gray and pink, locally vesicular and amygdaloidal, locally flow-foliated, crystal-rich, dacitic lava flows or a volcanic dome. It contains abundant phenocrysts of plagioclase, pyroxene, sanidine, olivine, and Fe-Ti oxides. It is confined to the northern margin of the Monroe Peak caldera (Rowley and others, 1981a). Maximum thickness is about 650 feet (200 m) (Cunningham and others, 1983; Rowley and others, 2002).

Lava flows of Monkey Flat Ridge (Tmpf): This unit contains moderately resistant, reddish-brown, gray, brownish-green, and green, locally vesicular or amygdaloidal, dacitic to rhyodacitic lava flows, minor fluvial sandstone and conglomerate, and minor crystal-rich lava flows. Its maximum exposed thickness is 500 feet (150 m) (Cunningham and others, 1983; Rowley and others, 2002).

Volcanic rocks of Sage Flat (Tmpa): This unit contains reddish-brown, medium- to dark-gray, pink, black, and purplish-brown, mostly resistant and crystal-poor, andesitic lava flows and minor volcanic mudflow breccia, flow breccia, and fluvial sandstone and conglomerate. Some flows contain large phenocrysts of plagioclase, pyroxene, olivine, and minor Fe-Ti oxides. Upper parts of flows are generally scoriaceous and amygdaloidal (Cunningham and others, 1983). The unit is exposed in the northern part of the Monroe Peak caldera where these rocks are about 200 feet (60 m) thick (Rowley and others, 2002).

Lava flows of Monroe Peak (Tmpl): These are mostly resistant, gray, pink, brownish-green, and dark-green, vesicular and amygdaloidal, generally crystal-rich rhyodacitic lava flows and minor crystal-poor lava flows, flow breccia, volcanic mudflow breccia, fluvial sandstone, and airfall tuff. K-Ar age is 21.3 Ma (Rowley and others, 1988b). Maximum exposed thickness is 500 feet (150 m) (Rowley and others, 2002).

Central intrusion (Tci): This is a resistant, gray and green, porphyritic to locally equigranular, quartz monzonite to monzonite stock that exhibits a fine-grained chilled margin as wide as 200 feet (60 m). The stock is distinctive enough that it is mapped separately from other intracaldera intrusions of the Monroe Peak caldera. The stock is a possible source for some lava flows in the late intracaldera deposits of the Monroe Peak caldera (Tmpu). Isotopic age is about 22 Ma (Rowley and others, 1988a-b). The pluton was eroded and unroofed by about 19 million years ago, when it was unconformably overlain by the Red Hills Tuff Member (Tmr) of the Mount Belknap Volcanics (Rowley and others, 2002).

Sedimentary rocks (Tmps): This sedimentary unit in the Monroe Peak caldera is mostly poorly resistant, tan, gray, yellow, brown, pink, and green, thin- to medium-bedded, fine- to coarse-grained, tuffaceous sandstone and airfall tuff, with minor intertongued, crystal-poor and crystal-rich lava flows, siltstone, and conglomerate. The unit is primarily fluvial but locally contains lacustrine deposits. The rocks are commonly altered and silicified, and the maximum thickness is 200 feet (60 m) (Rowley and others, 2002).

Intracaldera rocks, undivided (Tmpu): This unit was mapped only where hydrothermal alteration precluded identification of individual units (Rowley and others, 2002) described above, and of the intrusions described below. This combined map unit includes lava flows of varied compositions, intracaldera intrusions, airfall tuff, and fluvial and lacustrine sedimentary rocks that were deposited in the Monroe Peak caldera after subsidence. The lava flows are the extrusive products of the intracaldera intrusions (unit Tmpi). These intrusions have altered and deformed the Osiris Tuff (To). Locally, large masses of bull quartz, formed as hot spring sinter and replacements, are present in the volcanic and sedimentary caldera fill (Rowley and others, 2002).

Intracaldera intrusions, undivided (Tmpi): These are resistant, tan, light-gray, and light-green, locally flow-foliated, monzonite porphyry and quartz monzonite porphyry intrusions that were the source for, and are intruded into, late intracaldera deposits of the Monroe Peak caldera (Tmpu) and the Osiris Tuff (To, Toi). Alteration related to these intrusions resulted in the Tmpu map unit. At their margins, the intrusions are finer grained and locally resemble intracaldera Osiris Tuff. Older phases of the same intrusive complex at depth were the source of the Osiris Tuff. Isotopic dates suggest an age of about 22 to 21 Ma (Rowley and others, 1988 a-b). These intrusions make up the eastern end of the east-trending Pioche-Marysvale igneous belt (Rowley, 1998).

Mount Belknap Volcanics: This unit was originally named by Callaghan (1939) and mapped by Callaghan and Parker (1961a-b, 1962a-b) and Willard and Callaghan (1962). These volcanic rocks were erupted from several calderas and other vents. The stratigraphy was revised by Cunningham and Steven (1979) and remapped by Cunningham and others (1983), Steven and others (1990), and Rowley and others (2002). These rocks are the site of uranium, molybdenum, and alunite mineralization (Steven and others, 1981; Steven and Morris, 1987; Cunningham and others, 1994, 1998a). Isotopic ages range between 21 and 12 Ma (Cunningham and others, 1998b). Mapped units are described below.

Crystal-rich volcanic domes and plugs (Tmi): These are resistant, tan, pink, and gray, flow-foliated, crystal-rich rhyolite domes and intrusive feeders for domes that have been eroded away (Rowley and others, 2002). These rocks commonly contain phenocrysts of sanidine, plagioclase, biotite, hornblende, quartz, and minor apatite, sphene, and magnetite in a devitrified or glassy matrix (Cunningham and others, 1983). They crop out along the south margin of the Antelope Range 7 1/2′ quadrangle northeast of Marysvale. Isotopic ages of these domes and plugs are about 21 Ma. The maximum thickness of the domes is about 820 feet (250 m) (Rowley and others, 2002).

Fine-grained granite (Tmf): This unit includes resistant, gray and greenish-gray, fine-grained granite and granodiorite in a stock and dikes that cut the Central intrusion (Tci) in the Central mining area, and that host some of the uranium-bearing veins of the district. The granite is exposed just inside the Richfield 30′ x 60′ quadrangle northeast of the Red Hills caldera. It contains phenocrysts of quartz, orthoclase, plagioclase, and minor biotite in a groundmass characterized by graphic intergrowths. Isotopic ages cluster at 21 to 20 Ma (Cunningham and others, 1982, 1983; Rowley and others, 1988a-b). It was emplaced within the Monroe Peak caldera and possibly is a late intrusive phase of this caldera. But it is here included within the Mount Belknap Volcanics on the basis of its similarity in composition and age (Rowley and others, 2002).

Lower heterogeneous member (Tmh): This member consists of mostly soft, gray, rhyolite volcanic domes, lava flows, and subordinate ash-flow tuff and fluvial volcanic sandstone. It is restricted to an area northwest of Marysvale that is probably the vent area. It is about 230 feet (70 m) thick (Rowley and others, 2002).

Middle tuff member (Tmm): This member is soft, light-gray and tan, poorly welded, crystal-poor, intracaldera rhyolite ash-flow tuff. It is lithologically similar to the Joe Lott Tuff Member (Tmj) and is continuous across the margin of the Mount Belknap caldera into the upper part of the Joe Lott Tuff. The thickness of the middle tuff member is up to about 1,640 feet (500 m) (Rowley and others, 2002), but is probably thinner in the map area.

Mount Baldy Rhyolite Member (Tmb): This member includes resistant, light-gray, flow-foliated, crystal-poor rhyolite lava flows and dikes that consist mostly of a fine-grained mosaic of quartz and alkali feldspar, with minor plagioclase, biotite, and hematite; contorted flow layers are common (Cunningham and others, 1983). It was derived from and deposited mostly within the Mount Belknap caldera, which is mostly south of the Richfield 30′ x 60′ quadrangle. Maximum exposed thickness of the member is about 2,600 feet (800 m) (Rowley and others, 2002).

Red Hills Tuff Member (Tmr): This is reddish-brown, reddish-tan, and light-gray, moderately resistant, crystal-poor, densely welded, rhyolite ash-flow tuff derived from the small Red Hills caldera about 3 miles (5 km) north of Marysvale (Cunningham and Steven, 1979), just south of the Richfield 30′ x 60′ quadrangle. It contains about 7 percent phenocrysts of anorthoclase, quartz, plagioclase, and minor biotite (Cunningham and others, 1983). This tuff unconformably overlies the Central intrusion (Tci). Its age is about 19 Ma, based on a K-Ar date of 18.9 Ma (Cunningham and others, 1982) and on ages of overlying and underlying units. The maximum thickness of the member is about 600 feet (180 m) (Rowley and others, 2002).

Late rhyolite dikes, stocks, and domes (Tmd): These are small, moderately resistant, gray and pink, flow-foliated, crystal-poor, glassy to aphanitic, rhyolite dikes, stocks, and volcanic domes, and lava flows erupted from scattered vents. Their isotopic age range is 19 to 14 Ma. Some domes are as thick as 330 feet (100 m) (Rowley and others, 2002).

Basalt flows in northern Tushar Mountains (Tb): These are dark-gray, black, and red, locally vesicular and amygdaloidal, olivine basalt and basaltic andesite flows, flow breccia, scoria, and ash. Isotopic ages are not reported from basalts within the Richfield 1:100,000-scale map area, but similar basalts exposed in the mountains east and west of the Piute Reservoir have K-Ar ages of 12.7 and 10.9 Ma (Best and others, 1980; Rowley and others, 1994). As noted below under unit Tse, other basalt flows in the region have been K-Ar dated at 9.2 and 7.4 Ma. The maximum thickness of this unit is about 425 feet (130 m) (Rowley and others, 2002).

Sevier River Formation (Tse): The Sevier River Formation south of Richfield is mostly moderately indurated, pale brownish- or reddish-gray sandstone, pebbly to bouldery conglomerate, mudstone, and siltstone of fluvial and locally lacustrine origin. Volcanic clasts from the Marysvale area are common in the southern outcrops and decrease northward. Local interbedded white airfall tuffs have yielded K-Ar ages of 14 and 7 Ma near the town of Sevier (Steven and others, 1979). Basalt flows that intertongue within the formation west of Sevier have K-Ar ages of 9.2 and 7.4 Ma (Best and others, 1980). An airfall tuff collected south of Marysvale has a K-Ar age of 13.6 Ma, and another tuff collected east of Annabella has a K-Ar age of 5.6 Ma (Rowley and others, 1994). Willis (1988) reported a fission-track age of 5.2 Ma in the formation near the town of Aurora. The exposed thickness of the formation is at least 330 feet (100 m) but total thickness may be two or three times that much.

QUATERNARY-PLIOCENE DEPOSITS

by Fitzhugh D. Davis

Introduction

Pre-Lake Bonneville lacustrine sediments are widely exposed on the floors of the Sevier and Black Rock Deserts (Sevier basin), including Sevier Lake. These exposed pre-Bonneville lacustrine deposits, and some other deposits in and near Millard County, are only the top of the buried Miocene and Pliocene valley-filling sediments, which, along with buried volcanic rocks, are known from a few oil exploration wells and, less directly, from geophysical surveys. Columns 4 and 5, and correlation chart 8 (appendix C) show that these pre-Bonneville lacustrine deposits of the Sevier Desert and the other deposits overlap the time boundary between the Quaternary and Pliocene at 1.8 million years ago, using the geologic time scale of Berggren and others (1995). These pre-Lake Bonneville Quaternary and Pliocene deposits are relatively well exposed in the Sevier basin because the higher elevation of the Sevier basin, compared to the basin of the Great Salt Lake Desert, meant water and sediment flowed out of the Sevier basin during the 15,000 years that late Pleistocene Lake Bonneville occupied the basins of western Utah (25,000 to 10,000 years ago). During this time, the basin of the Great Salt Lake Desert was the depository of hundreds of feet of sediments laid down on the floor of Lake Bonneville. In contrast, the higher floor of the Sevier basin accumulated only thin local shoreline sands and gravels as finer lake sediments were largely flushed northward via the Old River Bed from the Sevier basin into the basin of the Great Salt Lake Desert, where they were added to that basin's deposits.

Fine-grained lacustrine deposits of Sevier Desert (QTlf): Hintze (1984) first documented these deposits on the east side of the Cricket Mountains. Oviatt (1989, 1991a) mapped their distribution in the Sevier and Black Rock Deserts and described their lithology and fossil content. Herein we add "of Sevier Desert" to Oviatt's title for the unit and designate it, informally, as "fine-grained lacustrine deposits of Sevier Desert." Formal naming of the unit awaits its more detailed study and designation of a type section.

Fine-grained lacustrine deposits of Sevier Desert are mostly brown and light-olive-gray, calcareous, silty clay or mud that contains minor amounts of sand. They weather orangish-pink and, on color aerial photographs, are readily differentiated from the lighter tones of Quaternary surficial deposits. They are weakly cemented and weather to smooth slopes that, locally, on the east side of the Cricket Mountains, develop small solution depressions or potholes. Oviatt (1989) noted that the deposits contain an ostracode fauna which suggests that the lake water contained calcium bicarbonate, sodium chloride, and sodium sulfate with a salinity range between 500 and 2,000 parts per million. Baer and others (1968) noted that spruce pollen was common in these lake deposits. The Bishop ash, age 759,000 years B.P. (Izett and Obradovich, 1991), is found interbedded near the top of these lacustrine deposits (figures 176 and 177), and the Huckleberry Ridge ash (2.02 Ma) is present in lower beds (Oviatt, 1989). In the wave-cut low cliff along the west side of Sevier Lake, the lacustrine deposits of Sevier Desert are cut by numerous veins of gypsum (figure 177). Exposed thickness of these beds is hard to determine because of the scattered nature of the exposures, but it may be as much as 1,000 feet (300 m). Test wells were drilled into the unit in 1993 near Black Rock and on the west shore of Sevier Lake by the U.S. Geological Survey. The hole at Black Rock was 897 feet (273 m) deep. Coring began at 25.25 feet (7.7) and extended to the total depth. The strata are greenish-gray to black lacustrine mud with five thin tephra intervals (Thompson and others, 1995). The Bishop ash was identified near the top of the hole and the tentatively identified Kaena polar-

Figure 176. Exposure of fine-grained lacustrine deposits of Sevier Desert, located on the west shore of Sevier Lake near where the U.S. Geological Survey (Thompson and others, 1995) drilled a stratigraphic test hole. Thin white layer near the top is the Bishop ash, age 759,000 years.

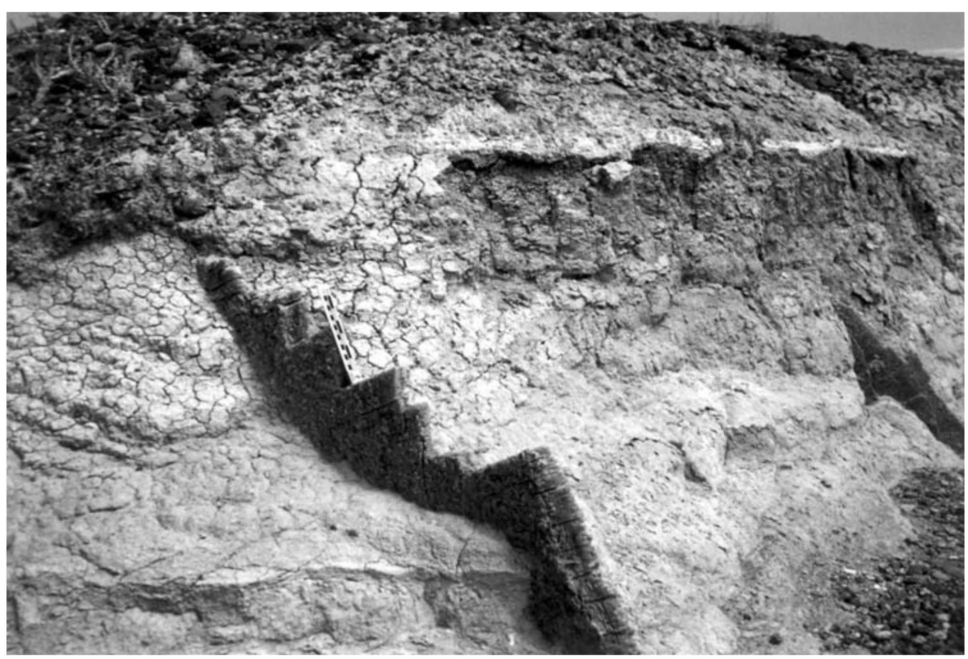


Figure 177. Close-up view of muddy fine-grained lacustrine deposits of Sevier Desert (QTlf). White layer is Bishop ash. Vertical gypsum veins that cut QTlf were exposed on the west shore of Sevier Lake by wave action that accompanied the 1983-1984 rise of Sevier Lake.

ity subchron (about 3.1 Ma) is near the bottom. The hole on the west shore of Sevier Lake was 512 feet (156 m) deep and it was all cored. The Bishop ash was identified near the top of the hole. The strata consisted of brown, gray, and green lacustrine mud to a depth of 431 feet (131 m), sand and gravel from 431 feet to 472 feet (131-144 m), and Miocene(?) tuffaceous sand from 472 feet (144 m) to total depth (Thompson and others, 1995). Kelsey (1995) noted that above 110 feet (33.5 m) the core contains more sand, indicating that the depositional environment changed from a shallow lake to a deltaic environment at about 1.25 million years ago.

Nearshore lacustrine limestone of Sevier Desert (QTln): Oviatt (1989) mapped this unit near the Provo shoreline along the northwest side of Sevier Lake (figure 178) and suggested that it may be shoreline deposits of the lacustrine deposits of Sevier Desert. In section 18, T. 20 S., R. 12 W. in the Long Ridge SW 7 1/2-minute quadrangle, the nearshore limestone of Sevier Desert is 90 feet (27 m) thick and made up mostly of light-gray limestone that contains up to 50 percent clasts of grit, pebble- and cobble-size, gray, Cambrian carbonate rocks. Some beds show small-scale cross-bedding. Only 5 percent of the lacustrine limestone beds are without included Cambrian clasts. The unit is flat-lying and forms stair-step ledges. The unit is also present to the south on the west side of Sevier Lake (Hintze and Davis, 2002a) and in the McCornick 7 1/2 minute quadrangle where 20 to 30 feet (6-9 m) are exposed (Davis, 1994).

Oviatt (1991a) erred in mapping the Tertiary limestone of Twin Peaks (Ttl, age 2.5 Ma), near Twin Peaks, as the nearshore limestone of Sevier Desert. The nearshore limestone is actually younger. Mapping done for this bulletin (Hintze and others, 2003) has revised Oviatt's mapping to show the distinction.

Quaternary-Tertiary alluvial-fan deposits (QTaf): Large alluvial fans and bajadas surround all the mountains in Millard County and have various ages. Basin-filling and alluvial-fan deposition began with the initiation of Basin and Range faulting approximately 17 million years ago. The bulk of basin-fill and alluvial-fan deposits are therefore Pliocene and Miocene in age. These Pliocene and Miocene fans are covered by variable thicknesses of younger deposits. Like other fans, unit QTaf consists of poorly sorted silt, sand, and gravel, including boulders, that were deposited by streams, debris flows, and flash floods. The exposed coarse-grained QTaf deposits grade valleyward into the upper part of the concealed, finer grained Pliocene and Quaternary basin-fill deposits. In several places, Oviatt (1992, p. 7) found a calcic soil at, or near, the top of unit QTaf that has stage IV carbonate morphology (see for example Machette, 1985a). This indicates at least an early Pleistocene age for the upper part of QTaf. He also found an interbedded ash in QTaf near Mills that was identified as the Alturas ash (4.8 Ma, early Pliocene). The unexposed lower part of QTaf is likely late Miocene in age, probably making it as old as some Tertiary valley-fill deposits (units Tcs and Ts). QTaf has been mapped on the east and west flanks of the Pahvant Range, east of the Canyon Range in Little Valley in Juab County, on the northeastern and southern margins of Round Valley (south of Scipio and extending into Sevier County), and in several areas near Cove Fort. The exposed thickness of QTaf in Round Valley ranges from 3 feet (1 m) to over 50 feet (15 m). Elsewhere the thickness may locally exceed 300 feet (90 m).

Sevier River alluvial deposits of Mills Valley (QTas): In the northeast corner of the Delta 1:100,000-scale map area, in Juab County, Oviatt (1992) mapped and described two Quaternary/Tertiary alluvial units: Sevier River sand and gravel, and basin-fill mud and sand. Oviatt's units are herein combined to form map unit QTas. Oviatt (1992) found three thin ash beds interlayered in his basin-fill unit: the Lava Creek B ash (0.62 Ma), the Bishop ash (0.74 Ma), and the Bear Creek ash (1.9 to 2.0 Ma, late Pliocene in age). Because the base of these units is not definitively exposed, their total thickness is not known. Measured sections given by Oviatt (1992) describe less than 100 feet (30 m) of exposed section, but it is likely that these deposits are thicker, at least locally, in subsurface.

Figure 178. *Nearshore lacustrine deposits (QTln) outcrops west of Sevier Lake in NW1/4 SE1/4 section 14, T. 21 S., R. 13 W. Hammer at bottom center is 12 inches (30 cm) long.*

Travertine in Canyon Mountains (QTt): Two travertine deposits are mapped on the southeastern slope of Whisky Creek (sections 4 and 9, T. 18 S., R. 4 W.) in the Canyon Mountains (Hintze, 1991a). A trench exposed about 10 feet (3 m) of the thin-bedded travertine that weathers white and light to dark gray. The travertine is tan to brownish orange on fresh fractures. Much of the travertine contains undulating, lamellar, fibrous, white calcite that is probably a secondary deposit. A 7-inch (18-cm) thick, gray, silty, pebble conglomerate is about 4 feet (1.2 m) below the top of the exposure. These travertine deposits are thought to be late Tertiary to early Quaternary in age because they are highly weathered and a thick gray soil and dense vegetation cover most of the deposits. The travertine may be related to the nearby Whisky Spring and an east-trending Tertiary normal fault that cuts through the spring and displaces Cambrian strata just east of it. Based on topographic contours, the travertine deposits may be 100 to 140 feet (30-43 m) thick. However, the deposits may drape over pre-existing topography. Some building stone has been quarried from this deposit and used for houses and stone walls in Holden.

QUATERNARY SEDIMENTARY DEPOSITS

by Fitzhugh D. Davis

Introduction

Quaternary sedimentary deposits cover a considerable part of Millard County, especially the valleys and deserts. The extensive and varied deposits include alluvial, eolian, lacustrine, deltaic, playa, spring and marsh, glacial, mass movement, mixed lacustrine-alluvial, and mixed alluvial-colluvial deposits. Most of these deposits are unconsolidated to only slightly cemented.

The Quaternary Period began about 1.8 million years ago. The Pleistocene Epoch of the Quaternary Period extended from 1.8 million to 10,000 years B.P. and can be divided into early (1.8 million to 780,000 years B.P.), middle (780,000 to 130,000 years B.P.), and late (130,000 to 10,000 years B.P.). The Holocene Epoch of the Quaternary Period comprises the last 10,000 years of earth history.

Alluvial-fan deposition continued around all the mountain ranges in the county across the Tert-iary/Quaternary time boundary. In a few places the older fan deposits (QTaf) have not been covered by younger fan deposits. Basin filling also continued in all the valleys from the Tertiary into the Quaternary. In the Sevier basin lacustrine deposition (unit QTlf) continued from late Tertiary well into middle Pleistocene time. Shallow, short-lived lakes probably occupied the Sevier basin, Tule Valley, Snake Valley, and Pine Valley from middle Pleistocene time into late Pleistocene time. Playa, alluvial-fan, and eolian deposition occurred in the valleys during arid interlacustral episodes.

In the Sevier basin, small, unmappable marl outcrops and underflow fan deposits, identified as remnants of the Little Valley Alloformation (140,000 years B.P.), have been found in the Sevier River bluff northeast of Delta (Oviatt, 1989). A few of the middle and late Pleistocene lakes in the Sevier basin, including the QTlf lake and the Little Valley lake, probably overflowed northward via the Old River Bed into the Great Salt Lake Desert drainage basin. The Sevier River flowed into the Sevier basin from Leamington Canyon; between lacustrine intervals it probably flowed due west about 15 to 20 miles (24-32 km), then veered northward to flow through the Old River Bed into the Great Salt Lake Desert basin (Oviatt, 1994; Oviatt and others, 1994b). The Beaver River became a major tributary to the basin during early middle Pleistocene time (750,000 to 500,000 years B.P.; Machette, 1985b).

Episodic erosion in the Sevier basin, probably beginning in middle Pleistocene time and extending into Holocene time, has removed an unknown amount of the lacustrine deposits of Sevier Desert (QTlf, QTln), younger sediments, and even a large part of the late Pleistocene Lake Bonneville deposits (figure 179). The thick Oak City Formation along the east flank of the Sevier basin was exhumed and highly dissected during this time. This erosional interval can be attributed chiefly to the following: (1) the Sevier basin was spreading and subsiding due to extensional faulting, and (2) the drainage divide in the Old River Bed pass was being gradually lowered due partly to faulting and partly to erosion (Oviatt, 1989). The Sevier River transported a large amount of sediment and also caused erosion through the Old River Bed. Waves and currents in the shallow overflowing lakes stirred up and carried a large amount of fine-grained sediment northward, as well as degrading the threshold area. Erosion increased gradually as the base level was lowered.

Figure 179. *A 4-foot (1.3-m) thick outcrop of Lake Bonneville "white marl" overlies an outcrop of the fine-grained lacustrine deposits of Sevier Desert (QTlf) west of the Sevier Lake playa in the NE1/4 SE1/4 section 14, T. 21 S., R. 13 W. The time interval separating the two deposits is most of middle and late Pleistocene time (more than 600,000 years).*

Lake Bonneville and Related Lakes in Western Utah

Lake Bonneville began forming in latest Pleistocene time, about 30,000 years B.P. (Oviatt and others, 1992), and evidence indicates that it was, at its highest level, the largest and deepest of the Pleistocene lakes in the interconnected valleys of western Utah. At its greatest extent the lake had a depth of just over 1,000 feet (300 m) in places and covered about 20,000 square miles (51,800 km^2) in northeastern Nevada, western Utah and southeastern Idaho (figure 180). Substantial remnants of Lake Bonneville deep-water and nearshore deposits are preserved in and on the margins of all the valleys of Millard County except Scipio, Pine, and Antelope valleys. The shorelines of the lake are notched on the mountain flanks and valley sides. The highest shoreline, the Bonneville, as well as a lower important shoreline, the Provo, are shown on the 1:100,000-scale geologic maps covering Millard County (Hintze and Davis, 2002a-c; Hintze and others, 2003); see also figure 52. Grove Karl Gilbert (1875) named the lake and made the first comprehensive scientific study of it (1890). Since Gilbert, numerous authors have reported on the chronology, deposits, and other aspects of the lake. McCoy (1987) formally described and named the Bonneville Alloformation and the Little Valley Alloformation.

As climate-induced Lake Bonneville rose in the Great Salt Lake basin (the main body), lakes began to form in the Sevier basin, Tule Valley, and probably Pine Valley at about the same time and for the same reason. The lake in the Sevier basin had a small volume compared to surface inflow and it rose fairly rapidly to 4,560 feet (1,390 m), the threshold altitude in the Old River Bed, and flowed north into the slower rising main body of Lake Bonneville. When the main body of Lake Bonneville reached the threshold altitude about 21,000-20,000 years B.P., the lakes were joined (Oviatt, 1989). Lake Tule was at a level of 4,645 feet (1,416 m) and about 240 feet (73 m) deep when water from the main body of Lake Bonneville spilled over Sand Pass, altitude 4,744 feet (1,446 m), near the north end of Tule Valley. Sack (1990) estimated that the spill-over date was about 19,500 years B.P. When the main body of Lake Bonneville reached an altitude of 4,777 feet (1,456 m) it transgressed into the Millard County part of northern Snake Valley. Unless noted otherwise, all the altitudes in this report are modern and post-date isostatic rebound of the basins.

Lake Bonneville, in all its subbasins and the main basin, gradually ascended to its highest altitude of 5,090 feet (1,552 m) (unrebounded; Currey, 1982) about 15,000 years B.P. This altitude was the low point on the Bonneville basin rim at Red Rock Pass, southern Idaho. The lake was fairly stable at this altitude for about 500 years as it formed the Bonneville shoreline and overflowed the pass. Rapid failure of the alluvial-fan threshold at Red Rock Pass about 14,500 years B.P. unleashed a tremendous flood northward into the Snake River drainage basin. Jarrett and Malde (1987) reported that the peak discharge was most likely about 33 million cubic feet per second (935,000 m^3/s) and that the flooding probably lasted at least two months. The flooding eroded the pass down to a bedrock ledge at an unrebounded altitude of 4,740 feet (1,445 m). The Provo shoreline formed at this level around the Bonneville basin as the lake continued to overflow through Red Rock Pass. In many aspects the Provo shoreline is the most notable of the Lake Bonneville shorelines in Millard County. Huge gravel barrier beaches and enclosed lagoonal deposits are present along the shoreline in many places, as well as distinctive offshore deposits of white marl.

Overflow through Red Rock Pass ceased about 14,000 years B.P. (Oviatt and others, 1992) and, due to climate, the lake began to recede from the Provo shoreline. Eventually the lake level fell below the Sand Pass threshold and the Old River Bed threshold, thus isolating Lake Tule in Tule Valley and Lake Gunnison in the Sevier basin (figure 52). The separation of Lake Bonneville and Lake Gunnison probably happened about 12,500 years B.P. Lake Tule likely receded rapidly because it had very little inflow. Lake Gunnison, however, maintained its high water level because it had large inflows from the Beaver and Sevier Rivers relative to its evaporative output. The primary Lake Gunnison shoreline remnants are shown on the 1:100,000-scale geologic maps of Millard County (Hintze and others, 2002a-c).

Lake Gunnison overflowed northward through the Old River Bed (figure 52), eroded Lake Bonneville deposits, and drained into the shrinking main body of Lake Bonneville until about 10,000 years B.P. Thereafter, surface flow through the Old River Bed ceased, and Lake Gunnison slowly receded to the present site of Sevier Lake. The Sevier and Beaver Rivers followed, flowing into the regressing Lake Gunnison.

Gilbert (1890), in his analysis of shorelines, correctly surmised that the water load of Lake Bonneville isostatically depressed the crust of the earth and that the major shorelines were formed when the crust was depressed. As the water load was removed the crust isostatically rebounded. The rebound was greatest in the center of the Bonneville basin and decreased towards the margins (Crittenden, 1963). The rebounded, present-day, altitudes of the Provo shoreline in Millard County range from 4,760 feet (1,451 m) to 4,800 feet (1,463 m). The rebounded altitudes of the Bonneville shoreline range from 5,103 feet (1,555 m) to 5,180 feet (1,579 m) in Millard County.

As previously mentioned, a lake formed in Pine Valley, western Millard County, probably about the same time that Lake Bonneville began to rise. The Pine Valley lake was an isolated, closed-basin lake. Snyder and others (1964), in their inventory of Pleistocene lakes in the Great Basin, referred to the lake as Wah Wah Lake. However, that name is inappropriate because it is not in Wah Wah Valley, and it is herein named Pine Valley Lake. Remnant beach deposits along the highest shoreline have a crestal altitude of 5,216 feet (1,590 m) in the northern part of Pine Valley. More extensive beach deposits along the most prominent shoreline have a crestal altitude of 5,200 feet (1,585 m) in the northern part of the valley also. Many faint shorelines can be seen below 5,200 feet (1,585 m) on aerial photographs in the western and northwestern parts of the valley. The sand and gravel beach deposits are fresh, unconsolidated, and have no pedogenic $CaCO_3$ morphology, which leads to the presumption that the lake was contemporaneous with Lake Bonneville and that it eventually desiccated to a playa. Pine Valley Lake, at its highest level, had a maximum depth of about 141 feet (43 m) and covered an area of about 48 square miles (124 km^2). The southern part of the lake was in what is now

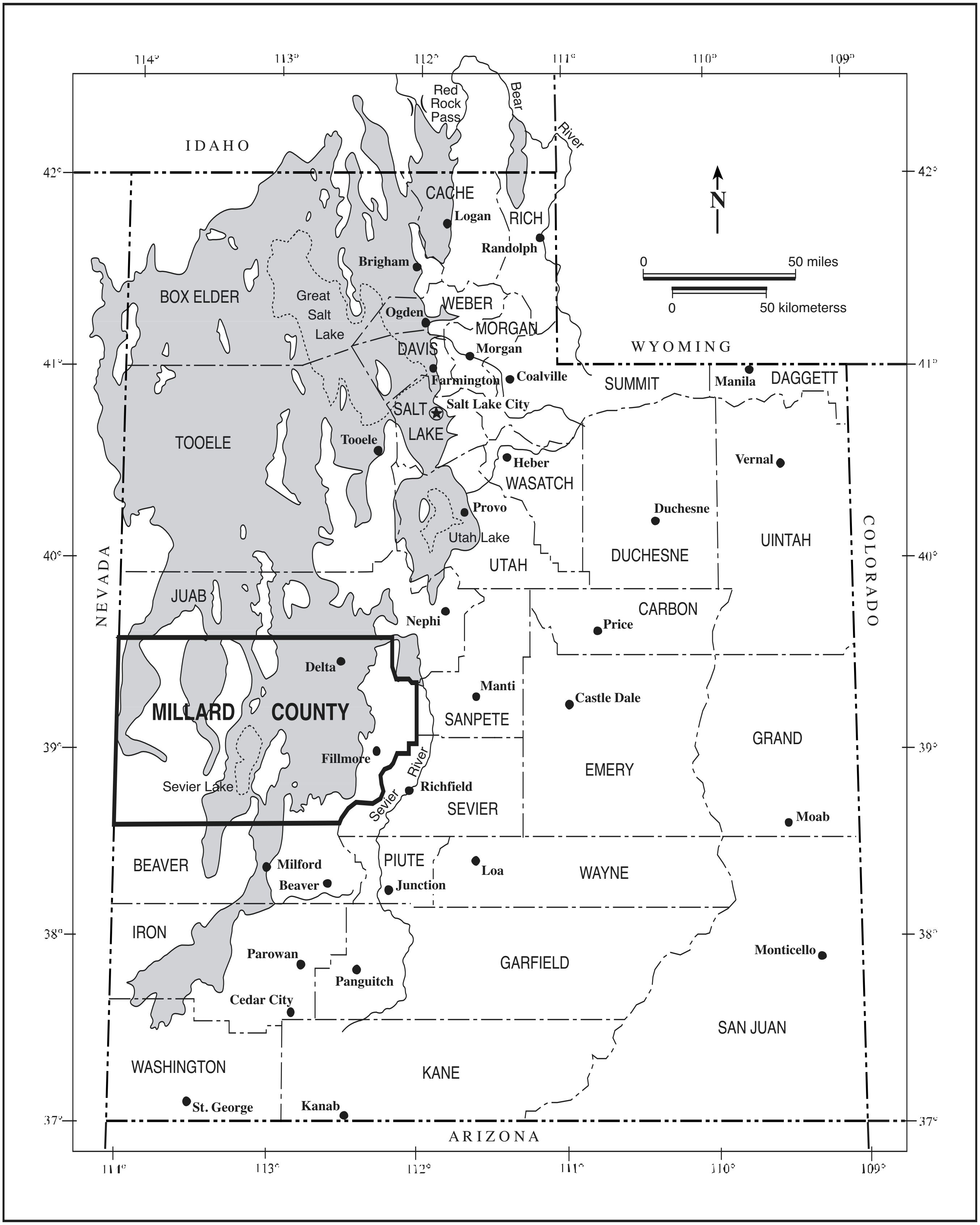


Figure 180. *Map of Lake Bonneville at its greatest extent in northeastern Nevada, western Utah, and southeastern Idaho. A large part of Millard County was occupied by the lake.*

Beaver County. The highest shoreline of the lake is shown on the Wah Wah Mountains North geologic map (PV; Hintze and Davis, 2002a).

Large mammals that lived around Lake Bonneville included mastodons, mammoths, camels, short-faced bears, musk oxen, mountain sheep, bison, mountain deer, and wolves (Nelson and Madsen, 1987). The climate was somewhat colder and wetter than now and, apparently, extensive grasslands and coniferous forests surrounded the lake. Mountain glaciation was contemporaneous with Lake Bonneville, but the peak of glacial activity preceded the peak of Lake Bonneville by several thousand years. In Millard County some of the higher reaches of the Pahvant Range were glaciated. Paleo-Indians likely migrated into Millard County 11,000 to 12,000 years B.P. (David B. Madsen, UGS, verbal communication, 1995).

Some important processes and features of the Holocene Epoch are the following. (1) The Sevier River coursed over and finally became entrenched in its large delta around the mouth of Leamington Canyon. (2) The Sevier and Beaver Rivers deposited sediments on their low-gradient alluvial fans in the Sevier basin. These large fans merge imperceptibly just northeast of the north end of the Cricket Mountains. (3) Erosion continued in parts of the Sevier basin as evidenced by the continued dissection of the lacustrine deposits of Sevier Desert (QTlf, QTln) and the accumulation and migration of numerous small and large sand dune fields. Eolian processes also are significant in Tule and Pine Valleys. (4) Alluvial-fan deposition continued around all the mountain ranges in the county. (5) Playas are prominent in the Sevier basin, Wah Wah Valley, Tule Valley, and Pine Valley.

The Quaternary sedimentary deposits in Millard County are classified mainly on the basis of their environments of deposition or origin. The Quaternary sediments were deposited in alluvial, lacustrine, deltaic, glacial, eolian, spring, and playa environments, as indicated by the first lower-case letter in the map unit symbols. Geomorphic expression denotes the origin of mass-movement deposits. The second lower-case letter in the symbols indicates other attributes of the deposits such as grain size, lithology, or geomorphic expression. Alluvial deposits have been divided into map units having distinctly different relative ages. Numeric subscripts are used, such as in the map units Qaf_1 and Qaf_2, where the subscript 2 indicates an older relative age than the subscript 1. However, many of the depositional environments, past and present, were and are coeval. Therefore, the sedimentary deposits cannot be described in chronological order. In a few places, map units are stacked so that more than one deposit can be shown. For example, Lake Bonneville lacustrine fine-grained deposits overlying pre-Lake Bonneville alluvium that overlies Quaternary-Tertiary lacustrine fine-grained deposits are mapped as $Qlf/Qal_3/QTlf$.

Alluvial Deposits

Alluvium, late Holocene (Qal_1): The youngest alluvium deposited by perennial, or recently perennial, rivers or streams has been mapped as Qal_1. Young alluvium, in channels and adjacent flood plains, is found along the Sevier River, Beaver River, Chalk Creek, Pine Creek, several other creeks in the Pahvant Range, Corn Creek, and Cove Creek in eastern Millard County; and Baker Creek and Lake Creek in western Millard County. Late Holocene alluvium also has been mapped in Scipio Valley, lower Pahvant Valley, along Round Valley Creek, and adjacent to Ivie and Willow Creeks in Round Valley in Millard County, as well as along the Sevier River in Juab and Sevier Counties.

Baker Creek originates in the Snake Range of Nevada. Except during unusually high flow, all of the water is used for irrigation in the community of Baker, Nevada. The young flood plain of the creek, however, has been mapped where it enters Snake Valley, Utah and extends northward (Hintze and Davis, 2002c). Apparently, most, or all, of the water in the creek sank into the valley fill before the water was used for irrigation because the flood plain loses its identity about 9 miles (14 km) north of Eskdale. All of the water in the Beaver River is normally used for irrigation in the Minersville and Milford areas of Beaver County. However, the Qal_1 flood plain of the river was mapped in Millard County (Hintze and Davis, 2002a; Hintze and others, 2003). Similarly, water in the Sevier River rarely reaches the Sevier Lake playa.

The alluvium deposited by these rivers and streams during the past few hundred years has been chiefly clay, silt, and sand. Gravel, however, was deposited during flood events and heavy spring runoff during melting of the winter snowpack. Qal_1 probably ranges from 0 to 20 feet (0-6 m) thick, but locally may be thicker.

Along the Sevier River in Sevier County Qal_1 consists of overbank sediments deposited in marshes and abandoned meander loops, and of channel deposits. Wind has slightly reworked some of the material. Salt and alkali crusts are common in the marshes. The flood-plain deposits grade into alluvial-fan deposits over a wide zone. The unit passes downward into older valley-fill deposits as old as Miocene that vary greatly in thickness. The late Holocene alluvium is less than 100 feet (30 m) thick (Willis, 1994). No coarse-grained sand or gravel deposits have been reported in surficial exposures along the Sevier River in near Richfield; but drill holes have encountered gravels 25 to 50 feet (7.5-15 m) below the surface (Young, 1960) and Rowley and others (1981b, 2002) mapped gravelly to bouldery channel and flood-plain deposits to the south. This Sevier River alluvium thins upstream, to the south, since Rowley and others (2002) reported it was 33 feet (10 m) thick or less.

Alluvium, middle and early Holocene (Qal_2): Older Holocene-age alluvium has been mapped in the following areas in Millard County: (1) remnants of a prominent terrace adjacent the Sevier River from Leamington Canyon to north of Delta, (2) three abandoned Sevier River channels on the Sevier River delta, (3) widespread low-gradient alluvial fans of the Sevier and Beaver Rivers in the west-central part of the Sevier Desert, (4) older remnants of Corn Creek alluvium mapped near Kanosh, (5) older remnants of Chalk Creek alluvium mapped east of Fillmore, (6) along streams near White Sage Flat, and (7) in the Pahvant Range along East Creek.

Remnants of a river terrace, 10 to 30 feet (3-12 m) above the present Sevier River flood plain, extend along the river from Leamington Canyon to north of Delta. The terrace is about 10 feet (3 m) above the present flood plain at Leamington and is about 10 to 30 feet (3-9 m) above the present flood plain 4 miles (6 km) northeast of Delta. These terrace deposits consist of tan and light-gray, calcareous silt and sandy silt that is at least 10 feet (3 m) thick.

Three abandoned Sevier River channels on the Sevier River delta were mapped as Qal_2 (Hintze and Davis, 2002b). Other channels on the delta are undoubtedly present but covered by eolian deposits. When Lake Bonneville receded from the delta, the river coursed and meandered over the delta surface for awhile before entrenching into its present valley. These old river channels can best be seen on aerial photos; they are 6 or 7 times wider than the present Sevier River channel. The channel deposits are not exposed, but they are probably silt, sand, and gravel.

Tan and light- to dark-gray sand, silt, and clay alluvium was mapped as Qal_2 by Oviatt (1989) in the large low-gradient alluvial fans of the Sevier and Beaver Rivers. The alluvium was deposited in distributary channels, natural levees, flood plains, flood-plain marshes, and oxbow lakes. The lack of debris-flow deposits is the reason Oviatt (1989) mapped these deposits as alluvium rather than alluvial fans. Lenses of sand and gravel were deposited in paleochannels and point bars. The apex of the Sevier River fan is about 2 miles (3 km) north of Delta. From the apex, the fan gently descends to the north, west, south, and southeast for distances up to 12 miles (19 km). The fan extends to the southwest for about 25 miles (40 km). Oviatt (1989) stated that the alluvium in the fan is at least 30 feet (9 m) thick at the apex and thins to nothing at its extremities. The Beaver River fan apex is in section 21, T. 20 S., R. 8 W., and fans out northward and northwestward. The alluvial thickness is unknown. The fan merges imperceptibly with the Sevier River fan in the area north of the Cricket Mountains. Oviatt (1989) reported the following radiocarbon dates on near-surface fossil shells collected from Qal_2: (1) 9,570 ± 430 yr B.P. on gastropods near the north end of the Cricket Mountains, (2) 9,345 ± 160 yr B.P. on gastropods near Gunnison Bend, (3) 5,460 ± 100 yr B.P. on shells 15 feet (4.5 m) below the ground surface north of Delta in the NE1/4 NW1/4 section 36, T. 16 S., R. 7 W., (4) 3,600 ± 85 yr B.P. on gastropods near Topaz Slough, and (5) 1,330 ± 70 yr B.P. on gastropods near the Deseret fairgrounds.

Isolated remnants of older Corn Creek alluvium were mapped as Qal_2 downstream and upstream from Kanosh (Hintze and others, 2003). Northeast of Black Rock volcano, the sand and gravel alluvium, possibly old terrace remnants, is about 15 feet (4.5 m) above alluvium mapped as Qal_1. The definite age of these Qal_2 remnants is unknown.

Alluvium, pre-Lake Bonneville (Qal_3): North of Delta, Oviatt (1989) mapped an area of pre-Lake Bonneville Sevier River alluvium as Qal_3. The ancient river alluvium is mostly covered by deep-water sediments (Qlf) of Lake Bonneville, but there are several exposures, the best of which is in a road cut in the SW1/4 SW1/4 section 25, T. 15 S., R. 7 W. The alluvium consists of lenticular sand and sandy gravel beds that contain clasts of volcanic rocks identical to those in Holocene Sevier River gravel. Only 5 feet (1.5 m) of this alluvium is exposed, so the complete thickness of Qal_3 is unknown. Oviatt (1989) reported that its age is pre-Bonneville, but post-QTlf.

Rowley and others (2002) mapped late and middle Pleistocene stream terrace alluvium in the terraces south of and an elevated terrace north of the Sevier River flood plain upstream from Elsinore in Sevier County. They didn't specifically describe the deposits, so they may be unit Qal_2 (lowest terrace above flood plains; Holocene) or Qal_3 (late and middle Pleistocene) of this bulletin. As mapped (Steven, 1979a; Rowley and others, 2002), the deposits are faulted and tilted, and appear to be up to 40 feet (13 m) thick and about 20 to 80 feet (6 to 24 m) above the flood plain. Better dating could constrain earthquake hazards. The lowest terrace deposits south of the river are shown as Qal_2 and the higher deposits, north and south of the river, are shown as Qal_3 on the Richfield 30′ x 60′ geologic map (Hintze and others, 2003).

Younger alluvial-fan deposits (Qaf_1): These are the youngest alluvial-fan deposits mapped in canyons, mountain valleys, and on alluvial fans both above and below the Bonneville shoreline. Qaf_1 consists of poorly sorted silt, sand, and pebble, cobble, and boulder gravel deposited by streams, sheetwash, debris flows, and flash floods. The valleyward component of Qaf_1 on alluvial fans may be silty sand, or silt. In the higher reaches of many canyons and in many mountain valleys the narrow widths of Qaf_1 deposits could not be mapped at the 1:100,000 scale of our geologic maps (Hintze and Davis, 2002a-c; Hintze and others, 2003). On the west side of the Cricket Mountains, the upper parts of several alluvial fans, including those at Fillmore Wash, Red Canyon, and Mine Canyon, are graded to the Bonneville shoreline at an elevation of about 5,170 feet (1,576 m). When Lake Bonneville receded from this level, the upper parts of the fans were dissected to depths of 20 to 30 feet (6-9 m), leaving two, three, or more alluvial ridges with entrenched stream channels on each side near the canyon mouths. Sheet-wash runoff, erosion, and alluviation are prevalent on the alluvial fans on both the east and west sides of Snake Valley, Whirlwind Valley, Tule Valley (figure 17), Wah Wah Valley, and other local areas. When rain falls, water and sediment gather into rills and rivulets on the steep upper slopes of fans; downslope the water and sediment merge and diverge into shallow distributary gullies and adjacent overflow areas. As the slope angle decreases farther downslope, the water velocity decreases, sediment is dropped, and the water seeps into the ground. Many gullies lose their definition near the edges of the valley floors. Pebbles and cobbles are scarce on the valley floors. Qaf_1 deposits are post-Bonneville shoreline in age (deposited in about the past 15,000 years). The deposits commonly range in thickness from 0 to 40 feet (0-12 m), but locally may exceed 60 feet (18 m) in Millard County. East of Millard County, alluvial fans are up to 165 feet (50 m) thick where they flank the Sevier River south of Richfield (Rowley and others, 1981b), but this thickness may include Pleistocene fan deposits (Qaf_2).

Older alluvial-fan deposits (Qaf_2): These deposits consist of poorly sorted silt, sand, and pebble, cobble, and boulder gravel deposited by streams, sheet wash, soil creep, debris flows, and flash floods on mostly inactive alluvial fans, and in canyons and mountain valleys above the Bonneville shoreline. Deposition of these sediments is locally active, in particular in canyons and mountain valleys, and in small and/or thin (unmappable) fans near mountain fronts. Calcic horizons, where present, are strongly to weakly developed (see for example Machette, 1985a). Gullies in Qaf_2 are commonly less than 30 feet (9 m) deep and, on alluvial fans, there are wide, fairly flat divides between tributary and sub-parallel drainages. Huge and spectacular Qaf_2 deposits are present along many of the mountain flanks in the county (figure 11 foreground, figure 181, and bright fan remnants at right on figure 196). For example, alluvial fans begin high up in the San Francisco Mountains and descend in an ever broadening, straight, smooth, 5- or 6-degree slope to the east edge of the Wah Wah Valley floor. Older alluvial fans are also present east of Millard County flanking the Sevier River and in the Beehive Peak 7 1/2′ quadrangle.

Collapse of the roof of a limestone cavern and overlying Qaf_2 has produced a large sinkhole on the east side of Snake Valley (NW1/4 NW1/4 section 8, T. 19 S., R. 18 W.). The limestone is the Ely Limestone of Permian, Pennsylvanian, and Mississippian age. The roughly circular sinkhole is approximately 150 feet (46 m) deep and has a diameter of 210 feet (64 m) at the top (figure 182). The Qaf_2 overlying the Ely Limestone is about 35 feet (11 m) thick. The age of collapse is uncertain, but likely is Pleistocene. The sinkhole is called Hole-in-the-Ground. Qaf_2 deposits are Pleistocene, mostly pre-Lake Bonneville, in age. Locally these fans are active, include Holocene deposits, and are post-Bonneville shoreline in age. The deposits range up to 200 feet (60 m), or more, in thickness.

Figure 181. *Northeast view of the huge alluvial fans (bajada) on the west side of the Confusion Range (southern part of T. 21 S., R. 16 W.).*

Figure 182. *Northeast view of the Hole-in-the-Ground sinkhole. The sinkhole is about 650 feet (198 m) east of the Bonneville shoreline and about 14 feet (4.3 m) above it. It is located 5 miles (8 km) northeast of Eskdale (Hose, 1965b).*

Lacustrine Deposits

Lacustrine marl (Qlm): Marl was deposited in offshore to deep-water environments of Lake Bonneville. Much of the marl appears to have been deposited offshore from the Provo shoreline. The marl is relatively soft and friable and much of it has been eroded away. Oviatt (1984) reported that Qlm in the Sevier Desert was deposited from about 20,000 years ago to about 12,000 years ago. Gilbert (1890) called this lacustrine unit the “white marl.”

Qlm consists of white to light-gray, fine-grained, thinly bedded to laminated marl with variable amounts of detrital sediment (figures 179 and 183). The calcium carbonate content is 20 to 80 percent and varies from lamination to lamination (Oviatt and others 1994c). In most outcrops ostracodes are numerous throughout the unit and gastropods are locally plentiful near the base and top of well-preserved outcrops. A black basaltic ash (Qva) from a Pahvant Butte hydrovolcanic eruption fell in eastern Millard County and parts of central and eastern Juab County about 15,500 years ago. The laminated ash is well preserved in the upper part of Qlm and varies from 0.04 to 120 inches (0.1 to 305 cm) thick (Oviatt, 1989). Qlm ranges from 0 to 30 feet (0-9 m) thick.

Fine-grained lacustrine deposits (Qlf): Fine-grained offshore and deep-water lacustrine sediments are extensive in Millard County. Qlf was deposited in Lake Bonneville, Lake Gunnison, Lake Tule, Pine Valley Lake, and Sevier Lake. Qlf deposits consist of tan, grayish-tan, or gray silt, sandy silt, clayey silt, and silty marl. Typically, Qlf is light-gray, calcareous, laminated silt. In places, there are laminations of fine sand. The Qlf and Qlm (marl) of Lake Bonneville are intimately mixed in many areas: both are offshore and deep-water sediments. The resultant deposits are either very calcareous light-gray silt or very silty light-gray marl. Where Qlf and Qlm are indistinguishable the deposit is mapped as Qlf. Also, eroded and reworked marl, as well as local, thin influxes of Holocene alluvial silt, have been washed into Qlf. In Pine Valley the Qlf is tan, calcareous silt that is overlain in some places by thin, pebbly alluvium. The thickness of Qlf is probably 10 feet (3 m) or less. The deposits are late Pleistocene and Holocene in age.

Lacustrine gravel (Qlg): Shore-zone gravel was deposited in Lake Bonneville, Lake Gunnison, Lake Tule, Pine Valley Lake, and Sevier Lake. Sandy gravel was deposited in beaches, embankments, offshore bars, spits, tombolos, cuspate barrier beaches (v-bars), and bayhead barrier beaches by longshore currents and wave action. Most of these deposits

Figure 183. A 10-foot (3 m) exposure of lacustrine marl (Qlm) in the west wall of a large marl pit west of Sevier Lake playa in the NE1/4 NE1/4 section 31, T. 20 S., R.12 W.

are on piedmont slopes and the adjacent and underlying alluvial fans provided much of the gravelly material. In general, Qlg consists of brown, tan, or gray, silty, fine- to coarse-grained sand and gravel (figure 184). The gravel content consistently ranges from 50 to 65 percent and commonly consists of subangular to rounded pebbles and cobbles.

The largest quantity of Qlg and the greatest variety of Qlg landforms were deposited by Lake Bonneville. The lake deposited many thick and spectacular gravel spits, shoreline embankments, and cuspate barrier beaches. These deposits are especially prominent along the Provo and Bonneville shorelines but, in places, can be found on intervening, transgressive shorelines. On the east side of Wah Wah Valley in sections 21, 27, and 28, T. 25 S., R. 13 W. there is a large, thick stack of 7 shoreline embankments from the Provo at the bottom to the Bonneville at the top. The Qlg is probably 40 feet (12 m) thick at almost any place on the stack. Near the north end of Snake Valley on the west side (sections 15 and 16, T. 15 S., R. 19 W.), a huge, cuspate barrier beach at least 60 feet (18 m) thick is on the Bonneville shoreline. The aggradational portions of the Provo, Bonneville, and other shorelines have been eroded considerably. Remnants of the Provo, Bonneville, and other aggradational shorelines typically have 2 to 18 feet (0.6-5.5 m) of beach gravel.

Figure 184. A view north in a gravel pit near the Utah-Nevada line in Snake Valley (NE1/4 SE1/4 section 13, T. 20 S., R. 20 W.). Eight feet (2.4 m) of sand and limestone gravel are exposed in this Lake Bonneville shoreline beach deposit. The altitude is 5,103 feet (1,555 m).

Pine Valley Lake, Lake Gunnison, and the ephemeral Sevier Lake have left only gravel beaches. The gravel beaches of Lake Gunnison and Sevier Lake are commonly 1 to 6 feet (0.3-1.8 m) thick. The highest Pine Valley Lake beach gravel ranges from 0 to 11 feet (0-3.4 m) thick. Beach gravel on the most prominent Pine Valley Lake shoreline ranges from 0 to 14 feet (0-4.3 m) thick (figure 185). The Qlg of Lakes Bonneville, Pine Valley, Tule, and Gunnison is late Pleistocene in age. The Qlg of Sevier Lake is Holocene in age, is lower in elevation than Qlg of Lake Gunnison, and is typically adjacent to playa mud in the lake bed.

Lacustrine sand (Qls): Lacustrine fine- to coarse-grained sand, marly sand, and pebbly sand were deposited in Lake Bonneville as beaches, spits, and offshore bars. Also, a sand spit is present between the Lake Gunnison shoreline and Sevier Lake playa in the Sevier Lake SW quadrangle. The Lake Bonneville deposits are widespread in the Sevier Desert, Black Rock Desert, Snake Valley, and to a lesser extent in Tule Valley. In Snake Valley north of Gandy, a huge sand spit about 30 feet (9 m) thick extends across the valley to the edge of Salt Marsh Lake. Farther south in Snake Valley sandy beaches were mapped west and southwest of Eskdale. In the Sevier and Black Rock Deserts, Qls appears to have been mostly deposited as offshore bars on what are now piedmont slopes. The sand was well sorted by the winnowing action of waves and longshore currents. In the southern part of the Black Rock Desert, Qls is chiefly associated with large gravel spits and barrier beaches (Oviatt, 1991a). Sack (1990) stated that Qls in Tule Valley is located about 10 to 60 feet (3-18 m) below the Provo shoreline, and usually overlies white marl (Qlm). Generally, Qls varies between 1 and 30 feet (0.3-9 m) thick.

Lacustrine carbonate sand (Qlk): Oviatt (1989) mapped lacustrine sand and pebbly sand consisting of white and light-gray carbonate pellets, carbonate-coated gastropods, and ooids as Qlk. These deposits are found west and south

Figure 185. A sand and gravel beach deposit on the most prominent Pine Valley Lake shoreline, altitude 5,200 feet (1,585 m), in the NE1/4 SE1/4 section 1, T. 25 S., R. 17 W. The view is east with the Wah Wah Mountains in the background.

of Smelter Knolls, on the west, north, and east piedmont of the Cricket Mountains, and in a large area west of Sevier Lake playa. The carbonate sands are 10 to 60 feet (3-18 m) vertically below the Provo shoreline, and in all places the Qlk overlies the white marl (Qlm). Oviatt (1989) considered that the carbonate sands were deposited offshore during the long stillstand of Lake Bonneville at the Provo shoreline when the lake was overflowing and the water was fresh but rich in calcium carbonate. Qlk generally ranges from 0 to 10 feet (0-3 m) thick.

Lacustrine lagoon deposits (Qll): White, tan, and light-gray sand, silt, clay, and marl deposited in lagoons behind gravel barrier beaches of Lake Tule and Lake Bonneville are mapped as Qll (figure 186). Sediments accumulated in the lagoons by landward slopewash and by transport in storm waves that crashed over the crests of the barrier beaches. Thin influxes of post-lacustrine alluvium are present in nearly all the lagoons. Therefore, Qll is late Pleistocene and Holocene in age. The largest lagoon deposits are behind Lake Bonneville Provo shoreline V-shaped barrier beaches. One of these, just east of Long Ridge (north of Sevier Lake playa), is over a mile (1.6 km) wide. Another large lagoon deposit, on the west side of Smelter Knolls, is a mile (1.6 km) wide and is preserved between two long barrier beaches that form a double tombolo along the Provo shoreline. The lagoon deposits are mostly less than 10 feet (3 m) thick.

Lacustrine tufa (Qlt): In northern Tule Valley, Sack (1990) mapped a thin, shorezone, lacustrine tufa (calcium carbonate) that was deposited by the shrinking Lake Tule. The tufa is white to light-gray biochemical precipitate of the calcium bicarbonate-rich water of the lake. The tufa is mostly 1 to 4 feet (0.3-1.2 m) thick and crops out on an eroded, discontinuous bench that ranges from 20 to 75 feet (6-23 m) below the Provo shoreline chiefly on the western side of the valley. Sack (1990) obtained a radiocarbon age of 13,790 ± 130 yr B.P. on the tufa.

Deltaic Deposits

Underflow-fan deposits (Qdf): The Sevier River deposited a huge delta in Lake Bonneville. The delta spreads out, fanlike, from the mouth of Leamington Canyon (figure 32) and covers over 200 square miles (518 km^2) in Millard County alone. The Beaver River also deposited a delta in Lake Bonneville, but not nearly as large as the Sevier River delta. By far the largest volume of the deltas is silt, but there also is much fine-grained sand. Oviatt (1989, 1991a) mapped and described these materials as underflow fans, which are a type of delta composed mostly of fine-grained sediment that is deposited by density currents at the mouth of a major river. The underflow-fan sediments were deposited in the deltas during both the transgressive and regressive phases of Lake Bonneville. Therefore, Qdf is a unit of the Bonneville Alloformation. The regressive phase Qdf overlies Qlm (the white marl). Both deltas are largely covered by younger deposits and both deltas are entrenched by their rivers. The best exposures of deltaic strata are in steep bluffs adjacent to the flood plains of the rivers.

The underflow-fan deposits consist of light-gray to light-brown, very thin-bedded to laminated, calcareous silt with subordinate interbedded very fine sand in very thin beds (figure 187). Cross-bedding and penecontemporaneous deformation of beds are common. Qdf ranges from 0 to 64 feet (0-20 m) thick. On the steep western front of the Sevier River delta (section 6, T. 17 S., R. 6 W.), Qdf is in thin foreset beds that are 40 feet (12 m) high. Oviatt (1991b) discussed the

Figure 186. Light-colored lacustrine lagoon deposits (right) behind the large cuspate barrier beach on the Bonneville shoreline in Snake Valley (sections 15 and 16, T. 15 S., R. 19 W.). The view is west.

Figure 187. Underflow-fan deposits in the Sevier River delta near Leamington (NE1/4 SE1/4 section 8, T. 15 S., R. 4 W. in canal cut). Hammer at bottom of photo for scale.

stratigraphy of the Sevier River delta and presented a cross section from the DMAD Reservoir to the mouth of Leamington Canyon. The cross section essentially portrays the truncation of the Little Valley Alloformation by the Bonneville Alloformation.

Deltaic sand (Qds): The lone exposure of this unit is along the I-15 frontage road in Juab County about 2.5 miles (4 km) west of Yuba Dam. It consists of 13 feet (4 m) of medium to coarse sand with some pebbles near the base, overlain by about 9.5 feet (2.9 m) of poorly sorted, fine sand. The fine sand includes a thin layer of Pahvant Butte basaltic ash (15,500 years old) near its top. Oviatt (1992) interpreted the deposit as a remnant of a small delta that formed at the margin of Lake Bonneville by overflow from a shallow Pleistocene lake in Scipio Valley.

Deltaic sand and gravel (Qdg): Deltaic sand and gravel overlie the underflow-fan deposits in both the Sevier and Beaver River deltas. The rivers carried sand and gravel to the apexes of their deltas where waves and currents in Lake Bonneville distributed and reworked the sediments.

In the Sevier River delta, Qdg consists of silty, fine- to coarse-grained sand and gravel. The strata are cross-bedded and also horizontally bedded. Clasts consist of white and purple quartzite, gray limestone, red and brown sandstone, gray conglomerate, and dark-gray igneous lithologies. The gravel is well graded (mostly pebble sized), subangular to rounded and ellipsoidal, and imbricated. Qdg is a regressive Lake Bonneville deposit.

In the Beaver River delta Qdg is both transgressive and regressive (Oviatt, 1991a). The Qdg consists of sand and chiefly pebble-sized clasts of igneous and sedimentary rocks that are well sorted. Obsidian pebbles are numerous. The strata are cross-bedded to massive. Qdg ranges from 0 to 24 feet (0-7.3 m) thick.

Deltaic mud (Qdm): Oviatt (1989) mapped a Sevier River delta at the northeastern end of Sevier Lake playa as Holocene mud. The mud is probably mostly silt and it overlies older lacustrine and playa deposits. Qdm likely ranges from 0 to 30 feet (0-9 m) thick. Because the mud delta is small, Oviatt suggested that most of the Holocene sediment transported by the Sevier River into the basin was deposited farther east in the low-gradient Sevier River fan (Qal_2).

Eolian Deposits

Eolian dunes (Qed): Morphologically well-developed, active sand dune fields are found in many areas of the county where the sand supply is abundant. Barchan, parabolic, dome, and transverse dunes, and barchanoid ridges are common, but not limited to the following largest, active dune fields: the Sevier River delta, east of Harding, northwest of Greenwood, a large area west and northwest of Beaver Ridge, northeast Pine Valley, and the central and eastern parts of northern Tule Valley. The dominant wind direction in the county is southwest to northeast. The active dunes are not stabilized by vegetation (figure 188). The dunes mostly consist of tan, well-sorted, fine-grained quartz sand, but medium- and coarse-grained sand are present in varying propor-

Figure 188. An active sand dune field in the southern part of the Sevier Desert (E1/2 section 14, T. 19 S., R. 5 W.)

tions. Gypsum dunes at White Mountain are included in unit Qed, but are elsewhere mapped separately (Qeg). Qed includes, in several places, light-gray silt dunes that are found downwind from playas and small blowout depressions. The silt contains numerous minuscule gypsum and calcite concretions as well as some fine sand. Qed ranges from 3 to 35 feet (1-11 m) in thickness.

Eolian sand (Qes): These deposits consist of eolian sand in sheets, low irregular mounds, shrub-coppice dunes, and narrow northeast-trending longitudinal ridges. These deposits, in many places, are stabilized by vegetation. The major component is silty, well-sorted, fine-grained sand, but medium- and coarse-grained sand are present in varying percentages locally. Quartz sand predominates throughout the county, but in local areas there are other primary constituents. At White Mountain (northwest of Meadow) there is abundant gypsum sand in windblown sheets and low ridges. Around Pahvant Butte and southwards to Tabernacle Hill the sand is largely black to gray basaltic ash. Typically, Qes ranges from 1 to 10 feet (0.3-3 m) in thickness.

Eolian gypsum (Qeg): Sack (1990), in northern Tule Valley, mapped chiefly gypsum sand sheets and a few chiefly gypsum sand dunes separately from other eolian sand deposits. Qeg is present in the central part of the valley and near the piedmont toe in the northeast and east-central part of the valley. Evidently, sand-sized gypsum crystals form on the surface of carbonate-rich Tule Valley basin-floor muds. Qeg is deposited downwind from the basin-floor deposits. Sack (1990) gave no thickness, but Qeg probably ranges from 1 to 10 feet (0.3-3 m) thick.

Deposits of Mixed Environments

Lacustrine and alluvial deposits, undifferentiated (Qla): These are mixed deposits on piedmont areas where pre-Lake Bonneville gravelly alluvium was reworked by waves and currents during the transgressive and regressive phases of Lake Bonneville. The resultant lacustrine sediments, in many places, are thin, extensive, and encompass small areas of virtually undisturbed alluvium. The lacustrine and alluvial gravel contacts are gradational and unmappable (see low-relief area between knolls on figure 15). On aerial photographs the chief characteristics of Qla deposits are the discontinuous shorelines grooved into the piedmont slopes. Large areas between the Bonneville and Provo shorelines are mapped as Qla. Qla generally ranges from pebbly sand and silt to sandy pebble gravel. In some favorable geomorphic settings, for example depressions and slopes adjacent to gullies, Qla is fairly thick. Adjacent to Soap Wash in the SW1/4 section 5, T. 18 S., R. 11 W., Qla is at least 12 feet (3.7 m) thick and consists of sandy, well-graded pebble gravels. In places, thin, narrow deposits of Holocene alluvium that overlie Qla could not be shown at the 1:100,000 map scale. Qla ranges from 0 to 12 feet (0-3.7 m) thick, but may be thicker in places.

Eolian and alluvial deposits, mixed (Qea): Sand and silt have weathered from volcanic rocks in the large outcrop area of the basaltic andesite of Cove Fort (Qcf) west of Cove Fort. Much of the sand and silt have accumulated along Horse Flat, in gullies, and on the lee side of ridges in the volcanic terrane. Alluvial sand has been reworked by the wind and windblown sand has been reworked by running water. The deposits are interbedded and grade into each other; they cannot be mapped separately. Small, unmappable areas of Qea have also been found on the west piedmont of the House Range and the western slopes of the Canyon Mountains. Qea generally ranges from 0 to 20 feet (0-6 m) thick.

Alluvium and colluvium, undifferentiated (Qac): This map unit is mixed alluvial and colluvial deposits that consist of fluvially reworked coarse-grained colluvium and/or alluvium with a significant colluvial component, including talus. Qac deposits are chiefly found on slopes and generally separate steeper bedrock outcrops above from alluvial or lacustrine sediments below. Qac has been mapped on the east flank of the Pahvant Range in Round Valley, and just to the south in western Sevier County; in places along the west side of the House Range and the east side of the Confusion Range in Tule Valley; in canyons of the central and southern Pahvant Range, especially on the south slope of Red Ridge; in and along the Canyon Mountains; and in the Valley Mountains. Qac ranges from 0 to 50 feet (0-15 m) thick, but locally may be thicker.

Playa Deposits

Playa mud (Qpm): Playas occupy many undrained, flat-floored depressions and undrained, flat-floored parts of desert valleys in Millard County. The playas range from about 100 feet (30 m) across to about 25 miles (40 km) long (Sevier Lake playa, figure 189). Other large playas are in Wah Wah Valley, southern Tule Valley (figure 6), Pine Valley (figure 190), and at Clear Lake. Many small playas could not be shown at the 1:100,000 map scale. Some of the small playas are undrained, flat-floored, blowout depressions (figure 28). All the playas have a tan, white, or light-gray, salty, mud crust, are barren of vegetation, and are flooded infrequently.

***Figure 189**. Looking east at the northern part of the large Sevier Lake playa. The Cricket Mountains are in the right background.*

Figure 190. *A view south into Pine Valley. The playa is the white area in the middle of the photo. The valley was occupied by a late Pleistocene lake. The Wah Wah Mountains are in the left background.*

All of the playas in the county were occupied by deep Pleistocene lakes (figure 180). The playa sediments consist of laminated, lacustrine, deep-water, silty fine sand, silt, silty marl, and clayey silt that are overlain by various thin layers of silt and clay alluvium deposited by flood water. We simply refer to these sediments as mud. The playa regime has added salt to the mud. The weathering of rocks is the principal source of salts, which are eventually brought to the playas in ground water and flood water.

The Clear Lake playa and some of the small playas in northern Tule Valley are considered "wet" playas because salts are added by ground water (springs) and by occasional surface flooding. The remainder of the playas in the county are considered "dry" playas because the chief source of salt is from the evaporation of flood water. The surface of "dry" playas is above the capillary fringe of the water table except, perhaps, during the spring.

Hampton (1978) identified halite, glauberite, thenardite, gypsum, calcite, and minor other salts in the sediments of Sevier Lake playa. Sack (1990) reported gypsum, halite, marl, and other salts in the playas of northern Tule Valley. Oviatt (1989) found halite, gypsum, and other salts in the Clear Lake playa. Gypsum and calcium carbonate are recognizable in all the playa deposits. The Sevier Lake playa sediments are the only ones that have been studied mineralogically. J.W. Gwynn (UGS, verbal communication, October 9, 1996) stated that the salty sediments in the Sevier Lake playa extend to a depth of at least 900 feet (274 m), and that the salty sediments in the Wah Wah Valley playa are 20 feet (6 m) thick, or less. The thickness of salty mud in the other playas is unknown, but is probably 20 feet (6 m) or less.

Mass Movement Deposits

Mass movements, slides and slumps (Qms): Slides and slumps in Millard County are found chiefly in mountainous areas: the Black Hills; Valley, Canyon, and Drum Mountains; southern Pahvant Range; eastern part of the Coyote Hills; northern part of the House Range; and near Cove Fort.

In the mountainous terrain between Meadow Creek, Walker Creek, and Sunset Canyon in the southern Pahvant Range, large, broken masses of Navajo Sandstone have slumped and slid downslope on the underlying, relatively easily eroded upper member of the Chinle Formation. Farther south, near the crest of the Pahvant Range, and in the canyons and on the divides of the southern tributaries to Corn Creek, huge deposits containing volcanic and sedimentary rocks have slumped and slid downslope on softer rocks. The mass movements mainly involve the Three Creeks Tuff Member of the Bullion Canyon Volcanics (Tbct) and the volcanic rocks of Dog Valley (Tdv). Sedimentary slides and slumps include masses from the Navajo Sandstone (Jn) and Moenkopi Formation (Trm).

Large slides and slumps have been mapped in the eastern Coyote Hills, principally in T. 24 S., R. 8 W. Many of the slides consist of basalt blocks and boulders from the Cove Creek basalt that failed due to undercutting of softer, underlying, slope-forming rocks of the limestone of Twin Peaks (Ttl).

In the Black Hills, Cambrian and Ordovician strata have moved downslope due to failure in shale beds of the upper Orr Formation (€ou).

Hintze (1981a-b) mapped many slides and slumps in the northern House Range, chiefly around Swasey Peak. Limestone blocks of the Dome Limestone and Marjum Formation have moved downslope on the less resistant, slope-forming Chisholm Formation (€dh) and Wheeler Shale (€ww), respectively. Only the largest slides and slumps, however, are shown on the Tule Valley geologic map (Hintze and Davis, 2002c).

East and southeast of Cove Fort in Millard County, at least four large slides and slumps are associated with rocks of the Joe Lott Tuff Member of Mt. Belknap Volcanics (Tmj) and the tuff of Albinus Canyon (Tac). On the east flank of the Pahvant Range in western Sevier County, large slides and slumps are present in the same units, as well as in the Aurora (Tau), Crazy Hollow (Tch), Green River (Tg), and upper Flagstaff (Tfur, Tfuw) Formations.

Small, isolated slides or slumps are present in many mountainous valleys in the county. Slides and slumps are Holocene to possibly middle Pleistocene in age. Slides and slumps older than middle Pleistocene have likely been almost, or totally, removed by erosion. In general, slides and slumps range from 0 to 120 feet (0-37 m) thick, but a few may be thicker.

Many large slides and slumps are also present in the Marysvale volcanic field. These Holocene and Pleistocene mass movements occurred in numerous volcanic and tuff-rich sedimentary units and are up to 250 feet (75 m) thick (Rowley and others, 2002).

Mass movements, undivided (Qmu): Deposits mapped under this symbol consist of masses of soil, sand, rock fragments, and boulders that have slowly and intermittently moved downslope, chiefly under the influence of gravity; this unit includes soil creep, slopewash, talus, and fan alluvium. Qmu has been principally mapped on the west flank of the Pahvant Range and includes blocky, boulder colluvium and talus from the Navajo Sandstone in Kanosh Canyon, colluvium and talus from the Tintic Quartzite high on the north slope of the North Fork of Chalk Creek and North Fork of Kanosh Canyon, and three areas of Qmu on the Moenkopi Formation in upper Dog Valley Creek. Southeast of Richfield (city), this unit includes talus, colluvium, and fan alluvium, mostly derived from the tuff of Albinus Canyon (Tac). Qmc ranges up to 60 feet (18 m) thick. In some places the thickness cannot be determined.

Older colluvial deposits, present on and near Bull Claim Hill southeast of Richfield (city), are included in this map unit. They consist of locally derived, moderately to poorly sorted, angular to subangular, boulder- to clay-size material. The deposits occur on low to moderate slopes as isolated, dissected, erosional remnants as much as 100 feet (30 m) thick.

Mass movements, talus (Qmt): Talus deposits consist of locally derived, poorly sorted, angular boulders with minor fine-grained interstitial material. They are the product of freeze-thaw cycles and occur at the base of cliffs, ledges, and steep slopes in mountains in Millard County. Only the larger deposits can be shown on the 1:100,000-scale geologic maps of the county. They are common in the Pahvant Range and occur mostly in association with outcrops of Tintic Quartzite (₵t), Cambrian carbonate rock (₵um), and Navajo Sandstone (Jn) on the west side of the range, as well as Tertiary Green River Formation (Tg) on the east side of the range and tuff of Albinus Canyon (Tac) near Richfield (Hintze and others, 2003). They are also mapped in the Drum Mountains and House Range on the Tule Valley geologic map (Hintze and Davis, 2002c). Thickness is less than 100 feet (30 m).

Spring and Marsh Deposits

Spring travertine (Qst): Three spring travertine deposits were mapped as Qst in the southeastern part of the Black Rock Desert (Oviatt, 1991a). The largest of these deposits, 4 miles (6 km) southwest of Meadow, is a great mass of travertine in fissure ridges accompanied by low terraces, mounds, and marsh-fill encrustations in flat, lower areas. At least 4 hot springs are present in the central and southern parts of the deposit. The linear travertine mass trends north-northeast, and is about 1.4 miles (2.2 km) long and 0.6 miles (1 km) wide. The main fissure ridge is parallel to a series of Quaternary faults just to the west. The travertine is cellular to dense and banded. On fresh fractures, much of the travertine is gray, white, and tan to yellowish brown.

Nelson and Fuchs (1987) reported that calcium carbonate, in the form of calcite and aragonite, comprises greater than 99 percent of the travertine, but gypsum, iron, and a trace of quartz are present. Both physiochemical and biochemical travertine are being deposited (Nelson and Fuchs, 1987).

Nelson and Fuchs (1987) believed that the entire travertine deposit is post-Lake Bonneville in age. Oviatt (1991a), however, found Lake Bonneville white marl overlying travertine near the southern edge of the deposit and stated that at least part of the deposit was pre-Bonneville. Oviatt (1991a) estimated that the travertine is as much as 90 feet (30 m) thick.

Two similar, but much smaller, travertine deposits were mapped in section 1, T. 24 S., R. 7 W. and section 6, T. 24 S., R. 6 W. The latter deposit straddles a northeast-trending Quaternary fault. Both deposits are about 25 feet (7.6 m) thick and consist of tan and light-gray porous travertine. Some of the travertine has thin convoluted layering. No water was issuing from these deposits in 1996.

Several small travertine mounds that range up to 18 feet (5.5 m) high are located in the vicinity of Knoll Springs and North Knoll Spring on the east side of northern Snake Valley (figure 191). Travertine is also reported at Warm Springs near Gandy (Feth and Barnes, 1979). These deposits are unmappable at 1:100,000 scale.

Other spring deposits, outside Millard County, are shown on the Richfield 30' x 60' geologic map (Hintze and others, 2003). At Roosevelt hot springs on the west flank of the Mineral Mountains in Beaver County, the spring deposits are siliceous. In Sevier County at the Monroe hot springs east of Monroe and at springs southeast of Joseph, the deposits are cellular to dense calcite.

Marsh deposits associated with springs (Qsm): Numerous marshy areas related to springs are present in the county. However, only a few are large enough to be mapped at the 1:100,000 scale. The large marsh adjacent to Twin Springs in northern Snake Valley, the marshes in the middle of northern Tule Valley, and those near Fool Creek Reservoir are the chief areas mapped as Qsm. Marsh deposits consist of gray to black organic silt, clayey silt, and sandy silt. The Tule Valley marsh deposits also tend to be carbonate-rich and saline (Sack, 1990). The thickness of Qsm is unknown, but possibly ranges from 0 to 20 feet (0-6 m).

Altered materials (Qsa): This unit consists of white, porous aggregates of opaline silica, gypsum, native sulfur, and anhydrite, and remnant quartz and cristobalite produced by mostly downward-migrating acid leaching of host rocks and surficial deposits. The alteration is related to native sulfur and

Figure 191. *This travertine mound at Knoll Springs (NW1/4 NE1/4 section 16, T. 18 S., R. 18 W.) is 15 feet (4.6 m) high and is visible on the right from the truck to the skyline.*

iron sulfide (pyrite and marcasite) mineralization that was produced by hydrogen sulfide in a geothermal system. The lack of siliceous sinter suggests the geothermal system was vapor dominated (steam rich and water poor) with little spring activity. The alteration and mineralization appears to be controlled by faults and is more extensive to the south near Sulphurdale in Beaver County. In Millard County it is located east of Cove Fort. The alteration and mineralization is in bedrock, Holocene(?) alluvial fans, and below a soil horizon in underlying alluvial fans that are likely Pleistocene in age. Bedrock hosts include Tertiary ash-flow tuff and tuffaceous siltstone, Flagstaff(?) Formation clastic rocks, Queantoweap Sandstone, and Redwall Limestone. Only the largest area of alteration in Millard County, exposed in a pit, is shown on the Richfield 30′ x 60′ geologic map (Hintze and others, 2003). The alteration is up to 105 feet (33 m) thick in this pit (R.W. Gloyn, UGS, written communication, 2002).

Glacial Deposits

Glacial till (Qgt): Glacial till is mapped in Robins Valley, Eagle Hollow, upper Maple Hollow, the upper reaches of Pharo Creek, upper Bear Canyon near White Pine Peak, and the higher parts of other small canyons in the northern part of the Pahvant Range. One or more cirques are at the heads of all these canyons. The till, including lateral and terminal moraines, consists unsorted mixtures of clay, silt, sand, and angular pebbles, cobbles, and boulders. Tucker (1954, p. 297) described the glacial features in Robins Valley as three intersecting cirques with steep upper walls and a wide till-covered valley dotted by three tiny lakes. A terminal moraine about 200 feet (60 m) high was deposited above the steep outlet canyon. This is likely the thickest till deposit in the county. Glacial till ranges in thickness from 0 to 200 feet (0-60 m). Oviatt (1992, p. 11) reported that the alpine glaciation is probably late Wisconsin (Pinedale) in age.

East of Millard County in the Monroe Peak 7 1/2′ quadrangle, till, unsorted sand and gravel in lateral and other moraines, and outwash of probable Pinedale age are present below poorly developed cirques on the north side of Monroe Peak and Glenwood Mountain, the two highest mountains in the northern Sevier Plateau. These glacial deposits are up to 100 feet (30 m) thick (Rowley and others, 1981a).

QUATERNARY VOLCANIC ROCKS

by Lehi F. Hintze

Introduction

Volcanic rocks were erupted sporadically in the Black Rock-Sevier Desert from late Miocene time until several hundred or thousands of years ago (columns 4 and 6, appendix C). These volcanic rocks are "bimodal," meaning that two contrasting rock types, basaltic and rhyolitic, were the chief products. During Quaternary time, basaltic activity has been predominant; only one small rhyolitic event has occurred in this area.

Volcanic eruptions were scattered widely in eastern Millard County. The alignment of some of them along north-south lines is interpreted as indicating that the magmas came up along concealed Basin and Range normal faults (see for example Condie and Barsky, 1972; Nelson and Tingey, 1997).

Andesite of Beaver Ridge (Qva_5): Hoover (1974) mapped and described these dark-gray, quartz-bearing, calc-alkaline flows, and noted that remnants of two vents, highly eroded volcanic necks, are preserved on the west side of Beaver Ridge. Hoover presented modal composition data for samples from the top and base of the flows. Petrographically the rock is characterized by resorbed quartz, plagioclase, and pyroxene in a hyalopilitic groundmass. The phenocrysts are small and make up less than 5 percent of the rock. Nash (1986) K-Ar dated the rock at 1.5 ± 0.2 Ma. It is about 200 feet (60 m) thick.

Basalt of Black Rock (Qvb_5): Condie and Barsky (1972) described the dark-gray basalt flows at Black Rock Station on the Union Pacific Railroad (figure 192) as composed

__Figure 192.__ Aerial view looking south of area near Black Rock. From left to right: escarpment at west edge of the basalt of Black Rock, Beaver river channel, Union Pacific Railroad track, Utah Highway 257. Ranch and reservoir at Black Rock are in the middle distance beyond the curve in the highway and railroad. Basalt of Black Rock is about 1.3 million years old.

mostly of plagioclase, with smaller amounts of clinopyroxene, olivine, and Fe-Ti oxides. The rock is generally 10 to 40 percent vesicular, and the vesicles are commonly partly filled with calcite. Most flows are not porphyritic, but some contain as much as 40 percent zoned plagioclase phenocrysts. A whole-rock K-Ar age of 0.97 ± 0.25 Ma was reported by Condie and Barsky (1972) (1.00 Ma corrected). Crecraft and others (1981) reported a K-Ar age of 1.32 ± 0.09 Ma. Maximum thickness of the flows is about 200 feet (60 m).

Basalt of Crater Bench (Qvb_5): Peterson and Nash (1980) and Galyardt and Rush (1981) mapped and described the basalt of Crater Bench. Most of this basalt shield is in Juab County where its summit crater is called Fumarole Butte. Only the southernmost tip of the shield extends into Millard County. A clay pit excavation near the Millard-Juab county line, and adjacent to the paved beryllium mine highway, has exposed the base of the basalt, which is elsewhere concealed by basalt talus. The basalt there rests on fine-grained lacustrine deposits of Sevier Desert (QTlf), which the basalt cap has protected from erosion for the past million years.

The basalt was described by Hogg (1972) as a black, finely crystalline, aphyric basaltic andesite. K-Ar ages are 0.88 and 0.95 ± 0.1 Ma (Peterson and Nash, 1980; Galyardt and Rush, 1981). At its exposed edge in Millard County it is only 20 feet (6 m) thick. Galyardt and Rush (1981) estimated that it may have a maximum thickness of 590 feet (180 m) near Fumarole Butte.

Basaltic andesite of Crater Knoll (Qck): This unit is a series of dark-gray to black, porphyritic basaltic andesite lava flows similar to the basaltic andesite of Red Knoll (Qrk), which overlies it. It contains 40 to 45 percent phenocrysts, mostly labradorite and pyroxene; its matrix is glassy to finely crystalline and contains microlites of plagioclase, pyroxene, olivine(?), and opaque minerals. Its cinder cone/vent is located 2 miles (3 km) south of the Richfield 30′ x 60′ map area about 10 miles (16 km) southwest of Cove Fort, as mapped by Clark (1977), Steven and Morris (1983), and Machette and others (1984). Only the northern tip of its lava flows extends into the Richfield 30′ x 60′ map area, and it is in Beaver County. Its thickness in the map area is less than 100 feet (30 m). K-Ar whole-rock age is 1.0 ± 0.3 Ma (Best and others, 1980).

Basaltic andesite of Red Knoll (Qrk): This unit is a dark-gray to black, porphyritic basaltic andesite to latite lava flow with a blocky scoriaceous surface underlain by dense to vesicular rock. It contains 30 to 45 percent phenocrysts, mostly labradorite and pyroxene; matrix is glassy to finely crystalline. As mapped by Steven and Morris (1983) it covers a few square miles about 8 miles (13 km) southwest of Cove Fort in Beaver County. It has not been dated isotopically, but overlies the basaltic andesite of Crater Knoll. Its cinder cone/vent is located a mile (1.6 km) south of the Richfield 30′ x 60′ map area (Machette and others, 1984). Maximum thickness is less than 200 feet (60 m).

Basalt of Mineral Mountains (Qvb_4): Sibbett and Nielson (1980) mapped a small basalt spatter cone and flow on the northeast end of the Mineral Mountains in Millard County and a spatter cone to the south in Beaver County. The basalt is dark gray and vesicular. The original form of the vent is only slightly eroded. Sibbett and Nielson (1980) suggested that it is older than 10,000 years. The K-Ar isotopic age on the basalt exposure in Millard County is 0.92 ± 0.26 Ma (Nash, 1986). The area covered by the flow is less than 0.2 square miles (0.5 km^2). The basalt flowed down the steep side of the mountain front and is, at most, 200 feet (60 m) thick.

Basalt of Beaver Ridge (Qvb_4): Hoover (1974) mapped two separate basalts on Beaver Ridge, an older flow series that he dated at about 0.9 Ma (six samples), and a younger series that he dated at about 0.5 Ma (five samples). On the Richfield 30′ x 60′ geologic map we have combined these units under the symbol Qvb_4 (Hintze and others, 2003). The older flows are diabasic basalts about 80 feet (24 m) thick; the younger basalts are about 120 feet (37 m) thick. The older basalt is made up of zoned labradorite, clinopyroxene, and olivine, about 40 percent as phenocrysts; and the remainder is groundmass along with minor apatite and Fe-Ti oxide phenocrysts. The younger basalt is made up of labradorite, olivine, and rare clinopyroxene phenocrysts in a very fine-grained to glassy groundmass of the same minerals, plus Fe-Ti oxides, apatite, and glass. Hoover (1974) presented modal composition figures for each basalt.

Basalt of Kanosh (Qvb_4): Hoover (1974) mapped this basalt field about 2 miles (3.2 km) west of the town of Kanosh. It includes a vent called the Black Rock Volcano, not to be confused with the Black Rock basalt area along the railroad about 25 miles (40 km) west of Kanosh. Hoover described the Kanosh basalt field as two large spatter-and-cinder cones, and several smaller spatter cones. Kanosh lavas are pervasively oxidized and colored red with hematite. The rock is vesicular and made up of large plagioclase phenocrysts, and small phenocrysts of olivine and clinopyroxene set in a microcrystalline matrix of the same minerals plus Fe-Ti oxides, apatite, and glass. Black Rock Volcano stands more than 300 feet (90 m) above the valley floor. Cinders and lava flows from the vents may locally be as much as 200 feet (60 m) thick. Hoover (1974) dated the basalt of Kanosh at about 0.67 Ma (average of two samples).

Rhyolite of Mineral Mountains, dome (Qvrd): A small rhyolite dome, about 0.4 miles (0.6 km) in diameter, is located just east of the hilltop called Bailey (elevation 7,918 feet) on the Pinnacle Pass 7$^1/_2$′ quadrangle in Beaver County. It is the northernmost of several rhyolite domes along the crest of the Mineral Mountains. The dome consists of tan, perlitic glass that is commonly pumiceous and brecciated and contains scattered fragments of black obsidian. The rhyolite contains several percent phenocrysts of quartz, oligoclase, alkali feldspar, biotite, and Fe-Ti oxides (Sibbitt and Nielson, 1980). Sanidine from obsidian from this unnamed northern dome yielded a K-Ar age of 0.54 ± 0.06 Ma (Lipman and others, 1978). Other rhyolite domes of the Mineral Mountains group range from this age to 0.79 Ma (Nash, 1986). These domes are believed to be the likely source of heat for the Roosevelt geothermal field located 3.5 miles (5.6 km) west of the northernmost dome.

Rhyolite of Mineral Mountains, tuff (Qvrt): Sibbett and Neilson (1980) mapped a small area covered by white to tan, weakly consolidated, airfall and/or ashflow tuff that is located about 0.5 miles (0.8 km) southeast of the dome described above. The tuff is less than 100 feet (30 m) thick. The tuff is probably a remnant of a more extensive ash deposit vented from the north dome.

Basaltic andesite of Cove Fort (Qcf): Steven and Morris (1983) mapped the cinder cone and lava flows of the basaltic andesite of Cove Fort. The rock is dark-gray to black, vesicular to dense, basaltic andesite containing small phenocrysts and microphenocrysts of plagioclase, pyroxene, magnetite, olivine, and sparse corroded quartz in a felted matrix of microlites and glass. Best and others (1980) determined its K-Ar whole-rock age as 0.5 ± 0.1 Ma. Maximum thickness is about 800 feet (250 m).

Rhyolite dome of White Mountain (Qvr_4): White Mountain is named for the white gypsum surrounding and blown up on its flanks. Its volcanic core is a small silicic lava dome that rises 150 feet (45 m) above the valley floor just east of Tabernacle Hill. The rhyolite of White Mountain is composed of black obsidian and highly devitrified felsite with spherulites and lithophysae. At the top of White Mountain the glass is frothy, almost pumiceous. Horizontal flow layers are well developed. Apparent thickness is about 120 feet (40 m). Its age is about 0.4 Ma (Lipman and others, 1978; Nash, 1986).

Basalt of Deseret, Pot Mountain, and Sunstone Knoll (Qvb_3): Shield basalt flows cap a 10-square-mile (20 km^2) black mesa about 5 miles (8 km) southwest of the town of Deseret. Condie and Barsky (1972) described the basalt as composed of nearly equal amounts of plagioclase and augite. The augite crystals are up to 0.8 inches (2 mm) long and commonly engulf smaller plagioclase crystals. Fe-Ti oxides occur as euhedral microphenocrysts and are chiefly ilmenite. Best and others (1980) reported a K-Ar age of 0.4 ± 0.4 Ma on the basalt of Deseret. Its apparent thickness is about 300 feet (95 m).

Pot Mountain (called Dunderberg Butte by Gilbert, 1890) and Sunstone Knoll are small areas of basaltic rocks near the large shield basalt of Deseret. They are probably eroded volcanic necks (figure 39). Small bodies of basaltic tuff on Pot Mountain suggest that at least one eruption there took place under water in the middle Pleistocene (Oviatt, 1989). Sunstone Knoll is so named because its basaltic rocks contain large phenocrysts of translucent labradorite feldspar, "sunstone," that gives off unusual colors in reflected light. Ages of the rocks of Pot Mountain and Sunstone Knoll have not been determined, but are probably middle and/or late Pleistocene.

Tholeiitic basalt of Smelter Knolls (Qvb_3): Turley and Nash (1980) mapped and described this basalt south of the rhyolite of Smelter Knolls. The basalt is vesicular and is mostly a microscopic intergrowth of plagioclase, clinopyroxene, olivine, Fe-Ti oxides, and glass. Olivine is the only phenocryst. Turley and Nash presented modal and chemical analyses, and CIPW norms for samples of the basalt. Its whole-rock K-Ar age is 0.31 ± 0.08 Ma (Turley and Nash, 1980). Its apparent thickness is about 60 feet (20 m). Oviatt (1989) attributed the small crater shown in figure 171 to a phreatic explosion, which happens when heat turns ground water to steam. The crater is slightly younger than the basalt flow but older than Lake Bonneville deposits.

Basaltic andesite of Cedar Grove (Qcg): Steven and Morris (1983) mapped the cinder cone and lava flows of the basaltic andesite of Cedar Grove. The rock is dark-gray to black, porphyritic, basaltic andesite that contains 30 to 45 percent phenocrysts of plagioclase, clinopyroxene, hypersthene, magnetite, and some olivine in a finely felted matrix of microlites and glass. Best and others (1980) referred to this as an andesite and dated it at 0.3 ± 0.1 Ma. Maximum thickness of the flows is about 200 feet (60 m).

Basalt of Pahvant Butte (Qvb_3): Condie and Barsky (1972) and Hoover (1974) mapped and described these oldest eruptive lavas of the Pavant Butte volcanic field. These authors noted that these basalts show a porphyritic quench fabric that is different from the other basalts in this area. Hoover showed and described this fabric in detail and suggested that it might indicate that the basalt lava erupted under a lake (see also White, 1996). Minerals in the basalt include plagioclase, clinopyroxene, olivine, Fe-Ti oxides, and apatite.

K-Ar dating of the basalt has been inconclusive; ages vary from 0.031 to 0.22 Ma with error margins on the dates as large or larger than the ages (see Condie and Barsky,1972; Hoover, (1974; Best and others, 1980). Hoover (1974) estimated that the oldest flows of Pahvant Butte basalt have a maximum age of 0.128 Ma. Maximum thickness is about 1,000 feet (300 m).

Basaltic cinders (Qvc): Basal-tic cinders were erupted from a small pre-Lake Bonneville volcanic vent about 4 miles (6.4 km) south of Pahvant Butte. The cinders are younger than the basalt of Pahvant Butte and middle or late Quaternary in age (Oviatt, 1989, p. 23); thickness is less than 30 feet (10 m).

Basaltic ash (Qva) and tuff (Qvt) of Pahvant Butte: Oviatt (1989) and Oviatt and Nash (1989) mapped the relationships between basaltic deposits from the Pahvant Butte volcano and the sedimentary deposits of Lake Bonneville. The basaltic eruptive materials from Pahvant Butte are of two main types: gray to black ash (unconsolidated deposits) and gray tuff (consolidated deposits). Some of the tuff deposits are palagonite (brown, orange, or yellow hydrothermally altered basaltic rock). Many authors, beginning with Gilbert (1890), have studied the association between the ash and tuff deposits of Pahvant Butte and the sedimentary deposits of Lake Bonneville. Their contributions were reviewed by Oviatt (1989) and Oviatt and Nash (1989). Pahvant Butte is a basaltic tuff cone (figure 193) formed during a volcanic eruption into Lake Bonneville when the lake was near its highest level, between 16,000 and 15,300 years ago (Oviatt, 1991a). The tuff deposits are found only near Pahvant Butte itself, but the ash deposits are more widely dispersed within Bonneville sediments around the Sevier Desert, and the Pahvant ash makes a very useful marker horizon within Lake Bonneville deposits. A thin bed of Pahvant Butte ash has been identified within Lake Bonneville sediments near Leamington, more than 25 miles (40 km) northeast of Pahvant Butte. Typically this ash is interbedded in the upper part of lacustrine marl and is commonly 1 to 6 inches (2.5-15 cm) thick. On the east side of Pahvant Butte this ash has been reworked by wave action.

Hoover (1974) gave petrochemical analyses of Pahvant Butte basalts and compared them with other lavas in the Black Rock-Sevier Desert area. Basaltic ash and tuff is about 600 feet (180 m) thick at Pahvant Butte.

Basalt of Tabernacle Hill (Qvb_2): Gilbert (1890), Condie and Barsky (1972), Hoover (1974), Oviatt and Nash (1989), and Oviatt (1991a) mapped and described the Tabernacle Hill basaltic lava flow and tuff cone. The Tabernacle Hill

Figure 193. *Aerial view of Pahvant Butte basaltic tuff cone showing inclined ash layers. Circle of cement posts in the lower left is the remnant of a wind-powered electric generator scam perpetrated in the early 1900s by a promoter from Los Angeles (Beckwith, 1947, p. 51).*

volcanic field consists of a nearly circular basalt flow and a central crater that is encircled by an asymmetrical tuff cone and smaller spatter or cinder cones (figure 27). The basalt flow was erupted into Lake Bonneville as indicated by lava pillows that have glass on their outer surfaces. Oviatt and Nash (1989) reported a radiocarbon age of 14,320 ± 90 years B.P. on tufa on the eastern edge of the lava flow.

Tabernacle Hill basalts are fine-grained, holocrystalline lavas with olivine and sodic plagioclase phenocrysts in a groundmass that is locally nearly opaque because of feathery, radial aggregates of clinopyroxenes produced by quenching of the lava. Hoover (1974) provided petrochemical analyses of Tabernacle Hill basalts and compared them to other basalts in the Black Rock-Sevier Desert area. Tabernacle ash is not as widely distributed as the Pahvant ash discussed above, partly because it fell into Lake Bonneville when the lake was much less extensive than it had been earlier. Thickness of basaltic deposits in the Tabernacle Hill field is as much as 200 feet (60 m).

Basalt of Ice Springs (Qvb$_1$): Gilbert (1890), Hoover (1974), Lynch (1980), and Oviatt (1991a) have studied the basalt of Ice Springs, which consists of flows that cover about 14 square miles (36 km^2) with four cinder cones near the middle of the area of flows (figure 26). Hoover (1974) noted that Ice Springs lavas have a greater glass content than other lavas in the Black Rock Desert. The rock contains only 2 percent phenocrysts and these are small euhedral crystals of olivine, plagioclase, and clinopyroxene. Hoover (1974) gave petrochemical data on the Ice Springs basalts. Lynch (1980) studied variations in chemical composition of the basalt.

The basalt of Ice Springs is estimated to be between 4,000 and 660 years old and represents the most recent volcanic activity in the Black Rock-Sevier Desert area (Valastro and others, 1972; Oviatt, 1991a). These are likely the youngest volcanic rocks in Utah. The flows may be as much as 200 feet (60 m) thick.

STRUCTURE

by Lehi F. Hintze

As outlined in previous pages in this bulletin, after late Precambrian time, Millard County underwent a long period of structural quiescence and slow subsidence during which more than 15,000 feet (4,600 m) of shallow-water marine sediments accumulated in layers unbroken by faults or folds. Marine sedimentation ceased by Late Triassic time, prior to the start of Jurassic magmatism and uplift in western Utah and eastern Nevada. The Notch Peak quartz monzonite pluton invaded the base of this thick pile of sedimentary strata in Jurassic time. Major orogenic compressive deformation of Paleozoic and lower Triassic strata during the late Jurassic, Cretaceous, and early Tertiary Sevier orogeny produced large folds in western Millard County and major thrust faults in eastern Millard County. Transport direction on these thrusts was from west to east (see figure 194 for names and locations).

Post-orogenic erosion during early Tertiary time truncated Sevier structures in western Millard County, and early Tertiary continental sediments overlapped Cretaceous and earlier Tertiary synorogenic deposits at the eastern edge of Millard County. Middle Tertiary strata are thin in Millard County and therefore do not support post-orogenic (post-Eocene) extension due to "relaxation" on Sevier folds and thrusts.

Volcanism erupted about 40 million years ago in the Drum Mountains area of Juab County and northern Millard County, and at least 35 million years ago just south of Millard County. Eruptions during the next 25 million years created volcanic deposits that accumulated to thicknesses of several thousand feet locally near vents. Widespread deposits, chiefly ash-flow tuffs from calderas outside the county, accumulated to a thickness of a few hundred feet within the county. These volcanic deposits generally rest

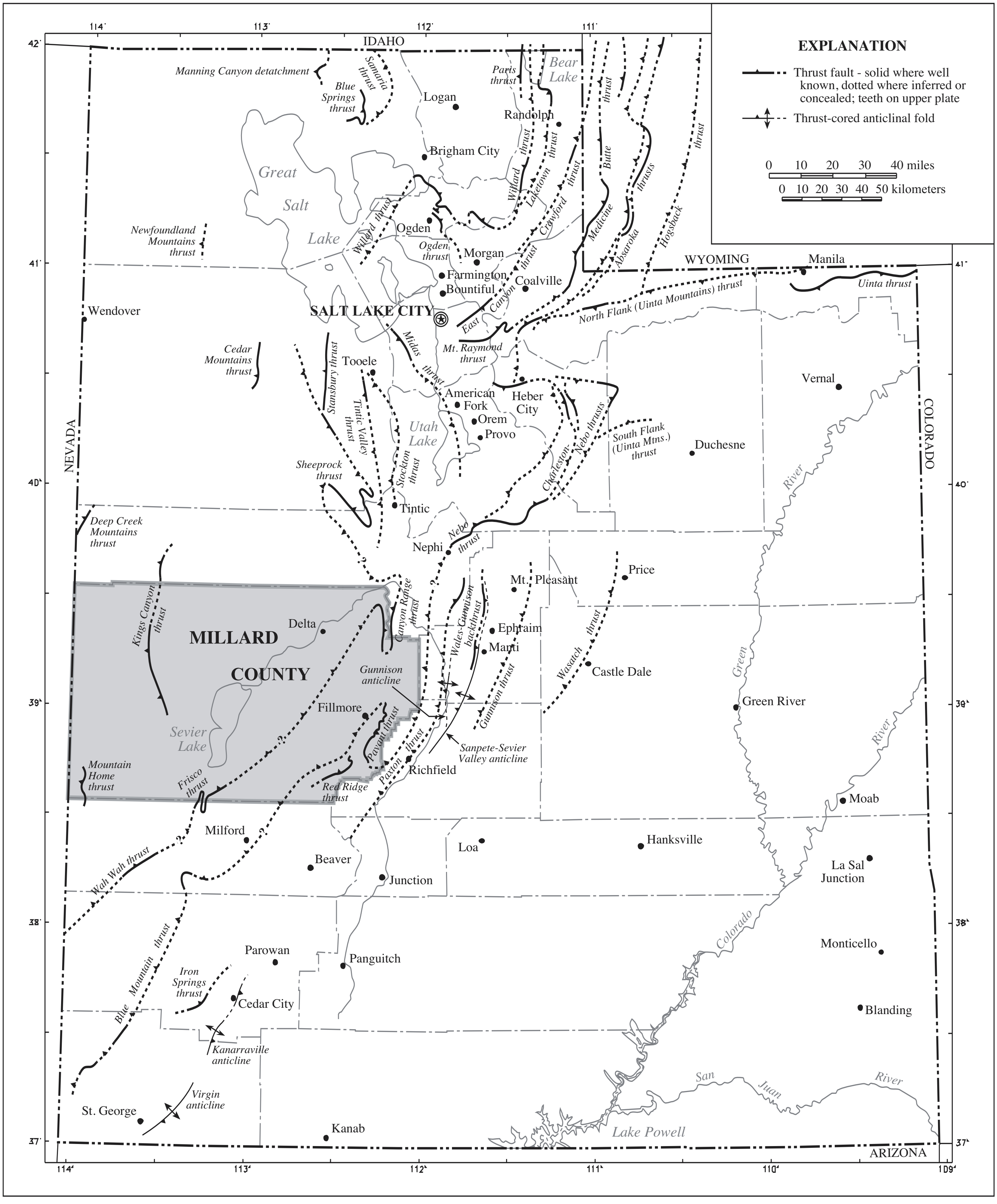


Figure 194. Major thrust faults in Utah, and thrust-cored anticlines in central and southwest Utah (modified from Willis, 2000).

with angular unconformity on folded Paleozoic strata. Thicker volcanic and sedimentary deposits (units Tct, Tcs) are present on the flanks of some mountain ranges in the county. These deposits are poorly dated, but are likely younger than 27 million years old and related to post-17 million-year-old extension.

About 17 million years ago, in response to changing relationships between the North American plate and the Pacific plate, Millard County, along with most of Utah and Nevada, entered into a time of extension (stretching) and at least relative uplift. In the process, Utah and Nevada developed a series of northerly trending major normal faults that created the tilted fault-block pattern called Basin and Range structure. Most of Millard County's present mountain ranges were formed during this late Cenozoic time of extension, and the process is continuing today. The distance between Salt Lake City and San Francisco gets greater each year by a small amount. Some volcanic activity, mostly extrusion of basalt in the Black Rock-Sevier Desert area, accompanied the Basin and Range extension.

The structural discussion that follows is divided into four sections: (1) exposed structures, (2) subsurface drill-hole and geophysical information, (3) paleotemperature indicators, and (4) regional structural interpretations and summary.

Exposed Structures

Structures exposed at the surface are shown on the 1:100,000-scale geologic maps of Millard County (Hintze and Davis, 2002a-c; Hintze and others, 2003), where map space permits. Discussion of these and a few other structures is divided into three parts: (1) pre-40 million-year-old structures formed during the Sevier orogeny, (2) Quaternary (post-1.6 million year old) and range-bounding normal faults (post-17 million year old) formed during extension, and (3) post-40 million-year-old structures and structures of indeterminate age. Ages of the structures in the first two categories are well constrained by datable rocks and sediments. Structures in the last category largely fit within the interval between 40 and 1.6 million years old, but because the ages of the rocks involved in the deformation may not give a limiting age for these structures, the last category may also include structures that are older than 40 million years.

Pre-40 Million-Year-Old Structures

Figure 195 shows the locations and names of structures that were formed before the deposition of Tertiary volcanic rocks in Millard County. Two large structural features, the Sevier arch and the Confusion Range-Burbank Hills-Mountain Home Range synclinorium, occupy two-thirds of the county's area and were formed during the Sevier orogeny. The structures east of the Sevier arch, in particular the Canyon Range and Pavant thrust faults, have substantial horizontal displacement but are not extensions of structures west of the arch, which appear to be of limited displacement and related to the folding of the syclinorium. The Sevier-age Paxton and Gunnison thrust faults are present in subsurface in eastern Millard County and farther east (see figure 194 and section on reflection seismic surveys).

Sevier arch: Harris (1959) named the Sevier arch after a high area (or culmination) was identified as a result of extensive stratigraphic work in the eastern Great Basin by Shell Oil Company's team of geologists in Ely, Nevada. Those geologists recognized the importance that the mid-Tertiary volcanic rocks play in defining pre-volcanic deformation. Harris (1959) extended his Sevier arch southwestward toward the Las Vegas area and regarded it as the source area not only for the thick Cretaceous deposits that extended from eastern Millard County eastward into Colorado, but also for the Cretaceous sandstones and shales that extended across the breadth of southern Utah. We have not restudied that portion of Harris' (1959) Sevier arch south of Millard County, but show only the arch in Millard County where rocks no younger than early Ordovician are overlain by Tertiary volcanic rocks. Welsh (1983) preferred to designate the Sevier arch in Utah by a structural geologic name, "the Canyon plate," to emphasize that its strata were transported eastward some distance in Cretaceous time.

The Sevier arch as shown on figure 195 is about 65 miles (104 km) across east-west, and 70 miles (112 km) across north-south including 10 miles (16 km) added to its northern limit in Juab County. It covers an area of about 4,500 square miles (11,700 km^2). Its east-west dimension prior to Basin and Range extension may have been somewhat less than its present width. As a result of extension, much of the Sevier arch is now a basin filled with relatively thick Miocene, Pliocene, and Quaternary rocks and deposits of the Black Rock-Sevier Desert. The Sevier Desert reflector, a feature visible on seismic data in this area, may also be the result of extension. The reflector may mark the unconformity between lower Paleozoic and Tertiary rocks (my interpretation) or may be a gently dipping normal fault (see section on Sevier Desert reflector).

Hintze (1988a) summarized the thicknesses in Utah of deposits of each period of geologic time on a series of maps that can be used to estimate the average thickness of strata removed from the Sevier arch by pre-40 million-year-old erosion; the results are shown in table 3.

Table 3. *Estimated strata removed from Sevier arch during Sevier orogeny.*

Geologic Period	Average thickness Feet	Average thickness Meters
Jurassic	500	150
Triassic	2,000	600
Permian	3,000	900
Pennsylvanian	1,200	350
Mississippian	1,500	450
Devonian	3,000	900
Silurian	1,000	300
Ordovician	3,000	900
Cambrian	500	150
Total	15,700	4,700

Cretaceous deposits that are exposed from the east side of the Sevier arch in eastern Millard County eastward into Colorado have an estimated average thickness of about 7,500 feet (2,300 m) over an area about 200 miles (320 km) east-west and 150 miles (240 km) north-south or 30,000 square miles (78,000 km^2). Comparing the estimated volume of rock eroded from the Sevier arch with the estimated volume of Cretaceous rock deposited to the east shows that the Sev-

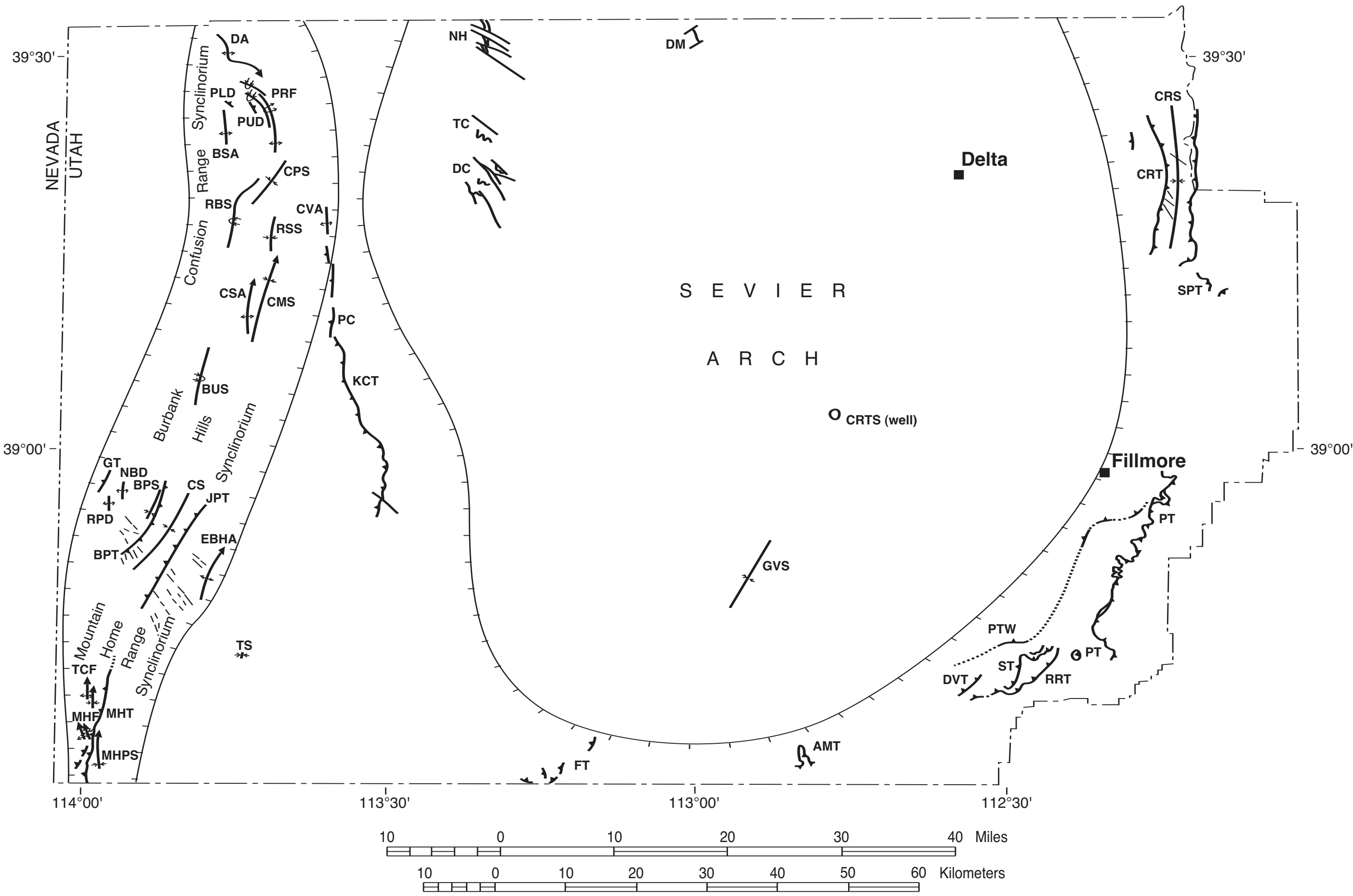


Figure 195. *Structures presently exposed in Millard County that were created by compression during the Mesozoic Sevier orogeny. See table 4 and text for names of lettered features and descriptions of all features.*

ier arch may have supplied about one-third of the Cretaceous conglomerate, sandstone, and shale deposits of central and eastern Utah.

The age of Cretaceous deposits in eastern Utah dates the time of the most active erosion of the Sevier arch as Late Cretaceous. Lower Cenozoic deposits overlapped Cretaceous rocks in eastern Millard County and extended westward over the southern part of the Sevier arch in the area of the Cricket Mountains (column 5, appendix C and GVS on figure 195). The source area for most of the thick early Cenozoic deposits in the Uinta Basin was the Uinta Mountain uplift (Hintze, 1988a), but the northern part of the Sevier arch continued to be a significant source of silt, sand, and gravel in the North Horn and Flagstaff Formations in the Pahvant Range northeast of Fillmore.

Figure 195 shows four areas on the Sevier arch (NH, TC, DC, and DM) where tear faults form boundaries of zones in which Cambrian rocks have been brittly attenuated along faults that are parallel to and nearly parallel to bedding in the rocks (figures 196 and 197). The tear faults in the House Range (DC, NH, and TC) trend northwest-southeast, while those in the Drum Mountains (DM) trend southwest-northeast. The attenuation was caused by movement of plates of strata above the zone of attenuation, which is here restricted to middle Cambrian carbonates and shales, riding eastward over and attenuating these rocks by dragging them along and smearing them out. Strata below the zone of attenuation (Lower Cambrian quartzites) are not attenuated. Attenuation of the Cambrian strata was accomplished before the middle Tertiary (late Eocene and early Oligocene) volcanic and sedimentary rocks were laid down (Hintze, 1978, 1981a; Nutt and Thorman, 1992; Nutt and others, 1996). The middle and upper Paleozoic rocks that overrode the Cambrian strata and produced the attenuation in the area of the Sevier arch were themselves removed by erosion of the Sevier arch. No relict of the kinds of structures that may have been present in these middle and upper Paleozoic rocks remains anywhere in the area of the Sevier arch as shown on figure 195. This lack of an older age limit is the reason Axen and others (1993, p. 66) attributed the attenuation in the House Range to middle Tertiary (Oligocene) extension. However, mineralization in the faults in the Drum Mountains (DM) dates the attenuation as pre-late Eocene (Nutt and others, 1996).

The Oligocene Skull Rock Pass Conglomerate, described earlier in this bulletin, unconformably overlies upper Cambrian and lower Ordovician strata on the west flank of the Sevier arch. The large size of some of its boulders of Eureka Quartzite and Upper Ordovician through Devonian dolomites (figure 169), derived from the east side of the Confusion Range synclinorium, suggests development of local areas of some topographic relief (extension) between the synclinorium and the arch in Oligocene time.

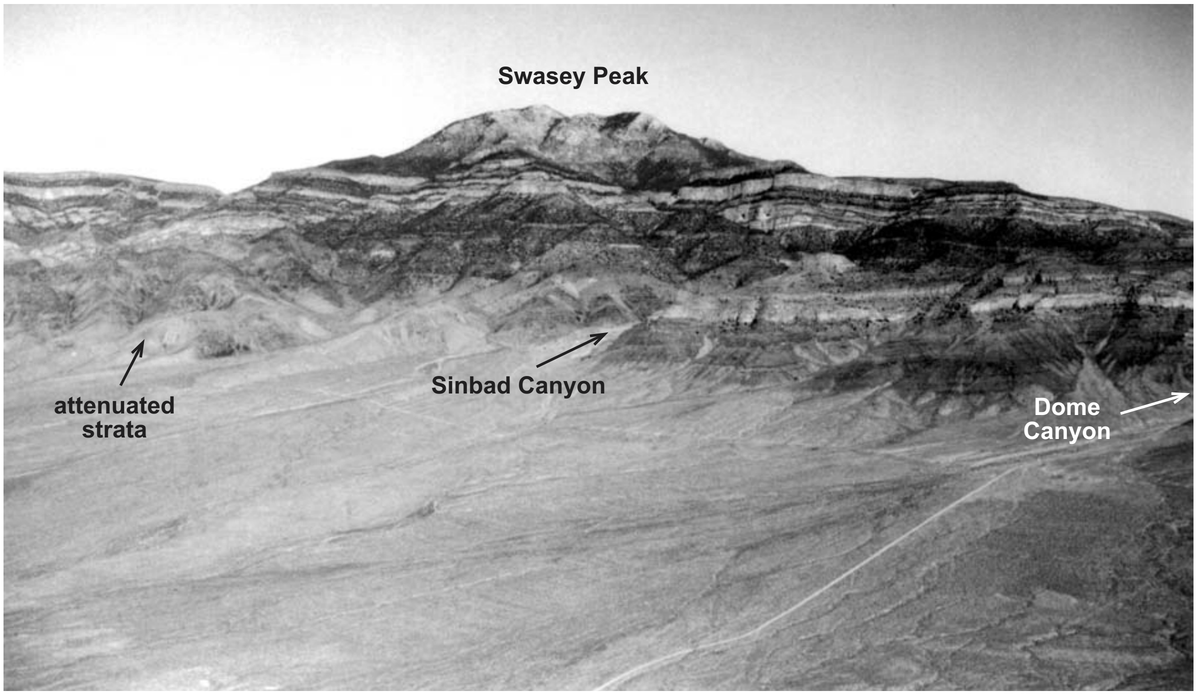


Figure 196. Aerial view of Swasey Peak, looking northeast at this highest point in the House Range, capped by Middle Cambrian Trippe Limestone (Hintze, 1981b). Road in lower right corner goes into Dome Canyon. Between Sinbad and Dome Canyons, dark strata are the Lower Cambrian Pioche Formation, which is overlain by banded cliffs of Middle Cambrian Howell and Chisholm Formations. The Howell and Chisholm along the mountain front on the left margin of the photo are so thinned by brittle structural attenuation along bedding surfaces (Hintze, 1981a) that the banding visible to the south has been destroyed and the strata are less resistant to erosion. Tear faults, which parallel the trend of Dome Canyon, offset the Cambrian strata here. Offset along these faults does not show well in this picture because its view is perpendicular to the trend of the faults.

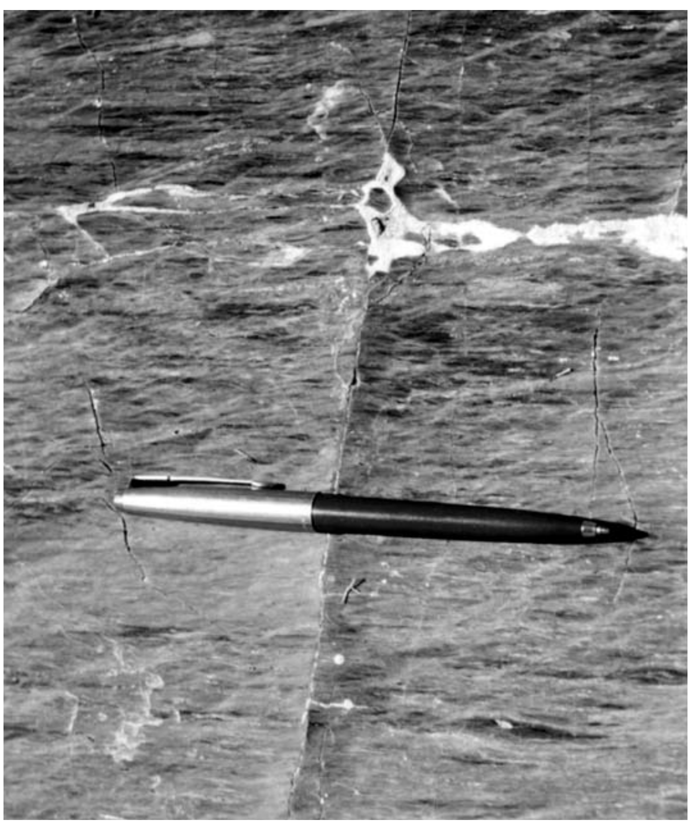


Figure 197. Mylonitized Cambrian limestone along the North Swasey tear fault (Hintze, 1981b), exposed in section 36, T. 15 1/2 S., R.13 W. Pen is 5 inches (13 cm) long.

Although this is primarily a discussion of structures exposed at the surface, information from a well drilled near the center of the Sevier arch (CRTS on figure 195) shows that the Cambrian and Precambrian strata exposed in the Cricket Mountains lie above the Canyon Range thrust (Welsh, 1983). In the well, allochthonous Precambrian strata overlie Cambrian strata that are only about 70 percent of their thickness to the west in the Cricket Mountains. Cambrian strata in the well below the thrust probably represent an in-place (autochthonous) section of normal eastward-thinning Cambrian rocks. Welsh (1983) believed the Canyon Range thrust is also exposed south of the Sevier arch in the northern Mineral and San Francisco Mountains (localities AMT and FT, respectively).

Structures on the east side of the Sevier arch: Cenozoic alluvial and lacustrine deposits conceal the east side of the Sevier arch, limiting our ability to connect the principal structures exposed in the Canyon Mountains and Pahvant Range with structures in the area of the Sevier arch.

The upper plate of the Canyon Range thrust places Cambrian and Precambrian strata, similar to rocks exposed in the House, Drum, and Cricket mountains on the Sevier arch, over Paleozoic strata on the upper plate of the Pavant thrust (figure 198). Facies of the Cambrian strata of the Pavant plate are like those in the Tintic Mountains in Juab County rather than like those exposed on the Sevier arch. Southeast-trending tear faults in the House Range at NH, TC, and DC shown on figure 195 within rocks of the Canyon Range thrust plate suggest that movement of that plate was southeastward. As exposed in the Canyon Mountains, the Canyon

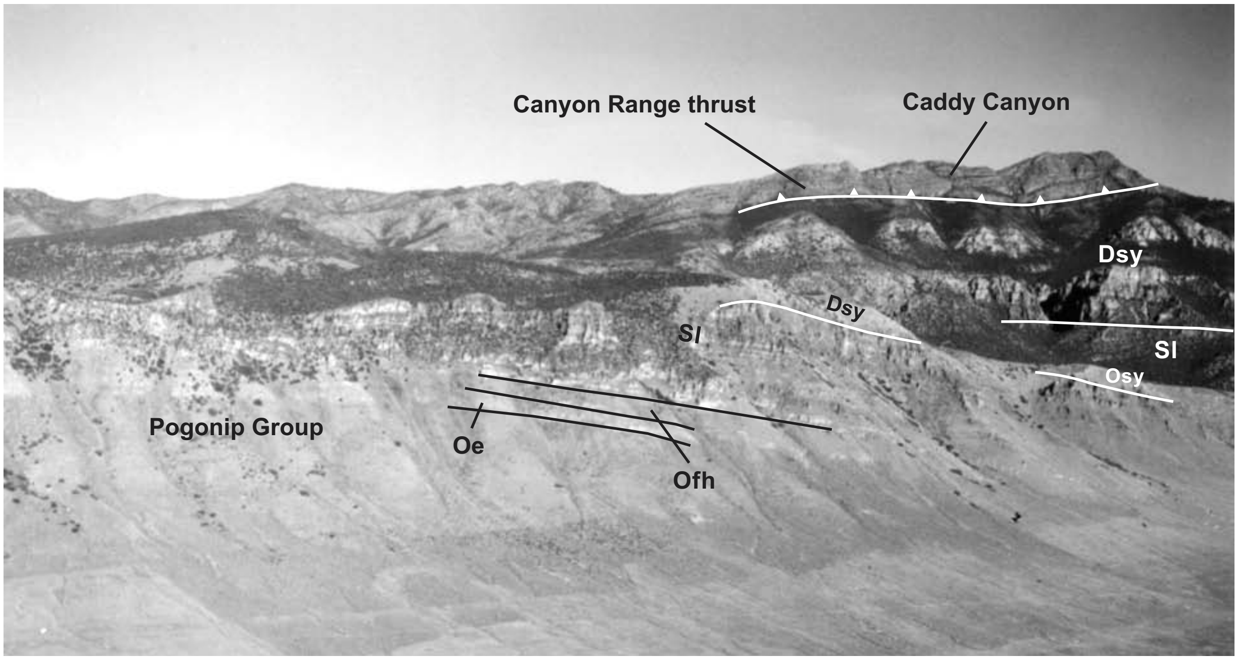


Figure 198. *Aerial view of the east side of the Canyon Mountains near Scipio. Highest cliffs are Precambrian Caddy Canyon Quartzite at the base of the Canyon Range thrust plate, which here rests on Devonian Sevy Dolomite (Dsy) that makes up light-gray cliffs. A normal fault is present in the canyon between the cliffs and the hill in the middle of the photo. This hill is composed of Ordovician strata (Pogonip Group, Eureka Quartzite [Oe], and Fish Haven Dolomite [Ofh]) and cliffs of Silurian Laketown Dolomite (Sl) capped by Sevy. Quaternary alluvial fans are present in the foreground.*

Range thrust plate (CRT) itself is folded into a well-defined asymmetrical Canyon Range syncline (CRS) with steeper dips on its west flank and poorly defined anticlines, which parallel this syncline, along its east and west sides.

The Pavant thrust fault (PT) is exposed along the Pahvant Range front between Kanosh and Fillmore, separating upright Cambrian quartzite from underlying upright Jurassic sandstone. But rocks of the Pavant plate above the thrust are exposed from Fillmore to 10 miles (16 km) north of Scipio on the east side of the Canyon Range (column 2, appendix C). The youngest strata (Devonian) on the Pavant plate in this sector are found at the northern limit of the plate's exposure. The eastward extent of the Pavant thrust is not precisely known, but it probably terminates in the subsurface beneath lower Tertiary rocks in the Pahvant Range 10 to 15 miles (15-25 km) east of its surface exposure (Royse, 1993). For nearly 30 miles (48 km) along the west front of the Pahvant Range, between Holden and Kanosh, the Pavant plate consists entirely of upright Cambrian strata that could have been thrust in from the east side of the Sevier arch.

Southeast of the Sevier arch, between Kanosh and Cove Fort, post-Cambrian Paleozoic strata are widely exposed (column 3, appendix C). Davis (1983) and George (1985) suggested that these post-Cambrian rocks, which are locally overturned and cut by minor thrust faults (DVT, RRT, ST), lie beneath the main Pavant thrust; they are in the Paxton thrust plate (Royse, 1993). Scattered small outcrops along the western base of the Pahvant Range between Meadow and Kanosh show Cambrian quartzites overthrust on upper Paleozoic and Mesozoic strata. Davis (1983) and George (1985) suggested that these intermittent exposures represented the western extension of the Pavant thrust (PTW) as it slopes westward under the Cenozoic rocks and deposits of the Black Rock-Sevier Desert.

Structures between the Sevier arch and the Confusion Range synclinorium: As drawn on figure 195, the west side of the Sevier arch is placed west of the House Range in Tule Valley just west of where Cambrian strata are exposed in the Chalk and Coyote Knolls. Although alluvial and lacustrine surficial deposits in Tule Valley prevent observation of the exact structural relationships between the Cambrian strata of the Sevier arch and the younger Paleozoic rocks in western Millard County, there is no reason to suppose that, prior to Basin and Range faulting, there was any major dislocation along the limb shared by the west side of the Sevier arch and the east side of the Confusion Range synclinorium (Hose, 1963a-b; 1977).

On the southeast side of the Confusion Range-Burbank Hills-Mountain Home Range synclinorium, Ordovician, Silurian, and Devonian strata are exposed in Basin and Range, fault-block ranges between the synclinorium and the southwest side of the Sevier arch as exposed in the southern House Range and Wah Wah Mountains. Nothing in these ranges suggests that there is any major Mesozoic dislocation of the Paleozoic strata in this transitional area. Some of the breadth of this area has been produced by extension accompanying the late Cenozoic, Basin and Range faulting. The King Canyon thrust and associated structures (KCT, PC, CVA on figure 195) are Sevier orogenic structures of small displacement.

Confusion Range-Burbank Hills-Mountain Home Range synclinorium: This remarkable structural feature extends the entire length of western Millard County. A synclinorium is defined as a composite synclinal structure of regional extent composed of lesser folds (Bates and Jackson, 1987). Hose (1977) called the northern part of it the Confusion Range structural trough. I, in extending it southward, prefer the more comprehensive term that heads this section.

The synclinorium is about 80 miles (130 km) long and 15 miles (24 km) wide in the middle, tapering at both ends. This bulletin gives names to many of its lesser structural features (figure 195) that are briefly described in table 4. I have divided the synclinorium into three portions, from north to south: the Confusion Range synclinorium, the Burbank Hills synclinorium, and the Mountain Home Range synclinorium. The southernmost structure in the Confusion Range portion is the Buckskin Hills syncline (BUS, figure 195). The Burbank Hills portion of the synclinorium contains northwest-trending faults, shown on figure 195, that are tear faults related to Sevier-age minor folding and thrusting within this part of the synclinorium.

The Mountain Home Range portion of the synclinorium includes a well-exposed thrust fault (MHT on figure 195) that Hintze (1986b) concluded was formed during the Sevier orogeny. Although Permian strata in the syclinorium are completely overturned at the northwest end of the Mountain Home Range (Hintze 1986b), strata encountered in the Outlaw #1 Federal well 1.6 miles (2.6 km) northwest of Needle Point Spring are upright. This well, in the extreme northeast part of section 1, T. 10 N., R. 70 E. (about 600 feet [200 m] west of the Utah-Nevada border), started in the Permian Arcturus Formation, penetrated 13,000 feet (3,962 m) of Paleozoic strata bottoming in the Ordovician Pogonip Group, and did not encountered any faults or folds (Shah Alam, 1990).

Relationship of the synclinorium to pre- and post-40 million-year-old structures in the Snake Range, Nevada: Exposures of bedrock in the synclinorium and those in the Snake Range, just across the state border in Nevada, are separated by the cover of surficial deposits in Snake Valley, which is 5 to 10 miles (8-16 km) wide. The geology of these two geographically parallel bedrock areas could scarcely be more different!

Because of its interesting complexity the Snake Range has been studied by a succession of geologists, beginning with Drewes (1958) who recognized younger-on-older "thrust" faults of probable late Mesozoic or early Tertiary age that brittlely attenuated the Paleozoic strata in the southern Snake Range. The Geology Department of Stanford University conducted its field course in the Snake Range for a few summers in the early 1980s under the direction of Professor Elizabeth L. Miller, and the summary below was extracted from the resulting publications (Miller and others, 1983, 1988; McGrew, 1986, 1993; Miller and Gans 1989).

Intrusive rocks were emplaced in the Snake Range-Kern Mountains-Deep Creek Mountains area during three separate thermal events of Jurassic, Cretaceous, and Tertiary age. Miller and Gans (1989) emphasized that the Cretaceous event was the most important in that it affected higher levels of the crust and was more extensive than the others. Maximum intrusion and metamorphism occurred during the Late Cretaceous (70-90 million years ago) and was accompanied by top-to-the-east layer-parallel shear. This was the same time that the erosion of the Sevier arch was furnishing sediments that covered eastern Utah so thickly.

Tertiary plutons were emplaced 39 to 35 million years ago, and were accompanied by metamorphism and decoupling of the post-Lower Cambrian strata from underlying Lower Cambrian and Precambrian quartzose strata. The Middle Cambrian through Permian strata slid downwards and eastward on a series of low-angle normal faults that merged into the Snake Range decollement, a major detachment surface. In so doing, these strata broke up into disorganized and discontinuous blocks in which the strata became thinner, stretched out and brittly extended. This type of structure is well exposed on the southeast end of the northern Snake Range where it can be seen a few miles north of U.S. Highway 6-50. As noted by Miller and others (1983), some earlier geologists surmised that the Snake Range decollement might be a Sevier-age thrust. However, Miller and others (1988, p. 676) proposed that the decollement is a late Eocene low-angle extensional structure. Both McGrew (1986) and Shah Alam (1990) presented cross sections showing the Southern Snake Range decollement extending eastward beneath the west side of Snake Valley. Reflection data on seismic line 20 presented by Shah Alam suggest that the decollement and its overlying slide blocks may extend nearly to the Nevada-Utah border. However, no firm data show that the Cenozoic decollement underlies the Confusion Range-Burbank Hills-Mountain Home Range synclinorium or that this Tertiary decoupling created the smaller structural features within the syclinorium.

The Snake Range, one of Nevada's highest ranges, extends the length of Millard County just west of the Utah state line. Young fault scarps found on both sides of the range (Dohrenwend and others, 1991a-b) support the view that it is a major Basin and Range horst, elevated in late Cenozoic time to its present imposing heights, and that the exposed structures and plutons were produced earlier at greater depths than can be seen in the adjacent synclinorium in western Millard County.

Other structures shown on figure 195: Except for the synclinorium and the arch, each structure is identified with letters and symbols on figure 195. Table 4 lists these structures, alphabetically by letter symbol, and gives their locations and other data. Major structures are discussed briefly in alphabetical order in the text. In the table and text, structures are grouped under three map location categories: 1) structures west of the Sevier arch; 2) structures on the Sevier arch; and 3) structures east or south of the Sevier arch.

1. Structures west of the Sevier arch

<u>Cedar Pass syncline (CS):</u> This is the major central fold of the Burbank Hills synclinorium. It is about 12 miles (19 km) long and 10 miles (16 km) wide. Subsidiary folds in the syncline are poorly defined because the thick Arcturus Formation, exposed broadly in the syncline, has no key beds to help outline local structures. The east limb of the syncline is cut by the Juniper Pass thrust (JPT), but extends to the east side of the Burbank Hills. The west limb of the syncline ends at the Burbank Pass thrust (BPT).

<u>Kings Canyon thrust (KCT):</u> This thrust and related structures (Payson Canyon thrusts and folds-PC and Cattlemans Valley anticline-CVA) extend for at least 20 miles (32 km) along the east side of the Confusion Range. The thrusts repeat Ordovician, Silurian, and Devonian strata. In its central part, where it crosses Kings Canyon, the thrust is a simple west-dipping surface (figures 195 and 199). Four miles (6.4 km) north of Kings Canyon the thrust is a group of splays and overturned folds in Ordovician strata. Farther north, across a transverse fault, are splays of the Payson Canyon thrusts (PC) (figure 201); these splays continue

Table 4. *Pre-40 million-year-old structures, shown on figure 195. Grouped by west of Sevier arch, on Sevier arch, and east or south of Sevier arch.*

WEST OF SEVIER ARCH

Figure Symbol	Name	$7^{1}/_{2}'$ Quadrangle(s)	Township-Range	Surface map units	Description	References
BSA	Bishop Springs anticline	Foote Range	16S -17W	Devonian	In Confusion Range synclinorium; about 6 miles (10 km) long and 1 mile (1.6 km) wide; see appendix A, well 52-1 for subsurface data	Utah Geol. Soc. (1951), Hose and Ziony (1963)
BPS	Burbank Pass syncline	Burbank Pass	21 & 22S - 18W	Permian	Located just west of larger Cedar Pass syncline (CS) in Burbank Hills synclinorium; about 4 miles (6.4 km) long and 0.5 miles (0.8 km) wide	Hintze (1997a)
BPT	Burbank Pass thrust	Burbank Pass, Cedar Pass	21 & 22S - 18 & 19W	Permian-Pennsylvanian	Axial fault of "East Burbank anticline" of Utah Geological Society (1951, plate 2); east limb of anticline was transported a short distance westward over west limb	Hintze (1997a, c)
BUS	Buckskin Hills syncline	Buckskin Hills	20S -18W	Permian	Located at south end of Confusion Range synclinorium; east flank overturned and faulted; about 4 miles (6.4 km) long and 1 mile (1.6 km) wide	Hose (1965a)
CMS	Conger Mountain syncline	Conger Mountain	18 & 19S - 17W	Permian-Pennsylvanian	In Confusion Range synclinorium; broad, north plunging, and slightly asymmetric; about 12 miles (19 km) long and 5 miles (8 km) wide; west flank is Conger Spring anticline (CSA); complicated by faults on north end	Hintze (1974b)
CPS	Cowboy Pass syncline	Cowboy Pass	17S -16 & 17W	Triassic	In Confusion Range synclinorium; north plunging and open; about 5 miles (8 km) long and 1.5 miles (2 km) wide; bounded on both flanks by faults	Hose and Repenning (1964), Hose (1977)
CS	Cedar Pass syncline	Cedar Pass, Big Jensen Pass, Dead Man Pass, Burbank Pass	22S-18W	Permian	Major and central fold of Burbank Hills synclinorium; about 12 miles (19 km) long and 10 miles (16 km) wide; Juniper Pass thrust (JPT) is in east limb	Hintze (1997a-d)
CSA	Conger Spring anticline	Conger Mountain, Cowboy Pass	18 & 19S - 17W	Devonian	In Confusion Range synclinorium; narrow and north plunging; about 10 miles (16 km) long and 2 miles (3.2 km) wide; terminated on south end by transverse fault	Utah Geol. Soc. (1951), Hose and Repenning (1964), Hintze (1974b)
CVA	Cattlemans Valley anticline	Chalk Knolls	17 & 18S - 16W	Devonian	On east flank of Confusion Range synclinorium; about 2 miles (3 km) long and narrow; along trend with and related to Payson Canyon thrusts and folds (PC)	Hose (1963b)
DA	Desolation anticline	Cockscomb Ridge, Foote Range, Big Horseshoe	15S -17W	Permian	In Confusion Range synclinorium; broad and sinuous; about 6 miles (10 km) long and 2 miles (3.2 km) wide; see appendix A, well 52-2 for subsurface data	Utah Geol. Soc. (1951), Hose and Ziony (1963), Hose and Repenning (1964), Hose (1974a)
EBHA	East Burbank Hills anticline	Big Jensen Pass	22 & 23S - 17 & 18W	Devonian	North plunging; about 6 miles (10 km) long and 3 miles (5 km) wide; cut by north-south-trending faults; truncated by normal fault on east side of Burbank Hills	Utah Geol. Soc. (1951), Hintze (1997d)

Table 4. *(continued)*

Figure Symbol	Name	$7^1/_2'$ Quadrangle(s)	Township-Range	Surface map units	Description	References
GT	Garrison thrust	Burbank Pass	21S -19W	Devonian, Mississippian	Inferred from relationship between folded Devonian Guilmette Formation on hill 5853 and Mississippian Joana Limestone on hill 5835 to east	Hintze (1997a)
JPT	Juniper Pass thrust	Cedar Pass, Deadman Point	22 & 23S - 16W	Permian	Mapped by abrupt changes in dip in Arcturus Formation, with vertical to overturned dips in hanging wall; small offset; related to folding in Arcturus in Cedar Pass syncline (CS) in Burbank Hills	Hintze (1997b-c)
KCT	Kings Canyon thrust	Bullgrass Knoll, Dowdell Canyon	18 to 20S - 15 & 16W	Ordovician, Silurian, Devonian	Located east of Confusion Range synclinorium; nearly 20 miles (32 km) long; offset is <2 miles (3 km) and dying out to north and south; varies from simple west-dipping surface to several thrusts and overturned folds	Hintze (1974b)
MHF	Mountain Home folds	Mormon Gap	25S -19W	Mississippian	In Mountain Home Range synclinorium in Mountain Home thrust plate (MHT); north-plunging anticline-syncline pair; about 2 miles (3.2 km) long and 2 miles (3.2 km) wide (figure 10)	Hintze (1986a-b)
MHPS	Mountain Home Pass syncline	Mountain Home Pass, Mormon Gap	25 & 26S - 19W	Upper Paleozoic strata	In Mountain Home Range synclinorium; north plunging and asymmetric, with steep west limb complicated by Mountain Home thrust (MHT); about 5 miles (9 km) long and 4 miles (6.4 km) wide	Hintze (1986a-b), Hintze and Best (1987)
MHT	Mountain Home thrust	Mountain Home Pass, Mormon Gap	24 to 26S - 19W	Devonian to Permian	Cuts west limb of Mountain Home Pass syncline (MHPS); offset probably <2 miles (3 km); related to folding in Mountain Home Range synclinorium	Hintze (1986a-b), Hintze and Best (1987)
NBD	North Burbank dome	Burbank Pass	21S -19W	Mississippian - Devonian	Subsidiary fold on west flank of Burbank Hills synclinorium (figure 7); nearly circular; about 1 mile (1.6 km) across	Utah Geol. Soc. (1951), Hintze (1997a)
PC	Payson Canyon thrusts and folds	Dowdell Canyon	19S -15W	Silurian, Devonian	Zone of small imbricate thrusts and tight folds (figure 201) related to Kings Canyon thrust (KCT)	Hintze (1974b)
PLD	Plympton lower decollement	Foote Range	16S -17W	Mississippian Chainman Shale	Stratigraphic horizon of structural weakness in upper Chainman; attenuated during folding of Confusion Range synclinorium; horizon traceable for 10 miles (16 km)	Hose and Ziony (1963), Hose (1977)
PRF	Plympton Ridge folds	Big Horseshoe	16S -17W	Permian	In Confusion Range synclinorium; tight, faulted, and locally overturned syncline-anticline-syncline triplet; about 7 miles (11.2 km) long and 1 mile (1.6 km) wide	Hose and Repenning (1963), Hose (1977)
PUD	Plympton upper decollement	Big Horseshoe	16S -17W	Permian Arcturus Formation	Stratigraphic horizon of structural weakness in upper gypsiferous part of Arcturus; attenuated during folding of Confusion Range synclinorium; horizon traceable for 10s of miles	Hose and Repenning (1963), Hose (1977)

Table 4. *(continued)*

Figure Symbol	Name	7½′ Quadrangle(s)	Township-Range	Surface map units	Description	References
RBS	Rattlesnake Bench syncline	North Knoll Spring, Cowboy Pass	17S -17W	Permian	On southwest side of Confusion Range synclinorium; partly overturned; about 7 miles (11 km) long and <1 mile (1.6 km) wide	Hose and Ziony (1964), Hose and Repenning (1964)
RPD	Red Pass dome	Burbank Pass	22S -19W	Devonian	Subsidiary fold on west flank of Burbank Hills synclinorium; nearly circular; about 1 mile (1.6 km) across; faulted on south end; see appendix A, well 52-1, for subsurface data	Utah Geol. Soc. (1951), Hintze (1997a)
RSS	Rattlesnake Summit syncline	Cowboy Pass	17 & 18S - 16 & 17W	Triassic and Permian	In the Confusion Range synclinorium; broad and north plunging; about 4 miles (6.4 km) long and 2 miles (3.2 km) wide; complicated by faults along its axis	Hose and Repenning (1964), Hose (1977)
TCF	The Cove folds	Mormon Gap, Tweedy Wash	14S - 19W	Mississippian	In Mountain Home Range synclinorium; narrow, tight, and rootless folds in Mountain Home thrust plate (MHT); about 2 miles (3.2 km) long and 1 mile (1.6 km) wide	Hintze (1986a-b)
TS	Tunnel Spring syncline	Tunnel Spring	24S - 17W	Ordovician	Tight syncline that involves brittle attenuation and slippage between Eureka Quartzite and adjacent rocks (figure 202)	Hintze (1981d)

ON SEVIER ARCH

Figure Symbol	Name	7½′ Quadrangle(s)	Township-Range	Surface map units	Description	References
CRTS	Canyon Range thrust, subsurface	Neels	20S - 8W	Precambrian, Cambrian	See text and appendix A, well 80-3, for details; similar thrusts occur in Canyon (CRT), Mineral (AMT), and San Francisco (FT) Mountains	Welsh (1983), Hintze (1988a)
DC	Dome Canyon tear and attenuation faults	Marjum Pass	17S -13 & 14W	Cambrian, Oligocene	Longest exposure 5 miles (8 km) long; tear faults bound brittlely attenuated strata; attenuation occurs along bedding plane faults; Windous Butte Tuff (age 31.4 Ma) rests across zone of attenuation	Hintze (1981a)
DM	Drum Mine tear and attenuation faults	Lady Laird Peak	15S -10 & 11W	Cambrian, Eocene and Oligocene	Faults localized late Eocene gold mineralization in Cambrian formations; hence, faults predate mineralization; faults don’t cut Eocene/Oligocene igneous rocks	Nutt and Thorman (1992), Nutt and others (1996)
GVS	Georges Valley syncline	Cat Canyon	22 & 23S - 9W	Cambrian, Tertiary	Located on southeast side of Cricket Mountains; broad and open fold restricted to Cambrian rocks; about 4 miles (6.4 km) long and 6 miles (10 km) wide	Hintze (1984)
NH	North House Range tear and attenuation faults	Sand Pass SE, Swasey Peak	15S -13W	Cambrian	One at least 8 miles (13 km) long; brittle attenuation along near bedding-plane faults; thickness of middle Cambrian rocks 1/3 of normal; locally, some units are eliminated	Chidsey (1978a-b), Hintze (1978, 1980c, 1981b)
TC	Trail Canyon tear and attenuation faults	Swasey Peak	16S -13 & 14W	Cambrian	Howell Limestone south of tear fault is thinned (attenuated) compared to north of fault; ~3 miles (5 km) long; horizontal slickensides present along tear fault	Hintze (1981b)

Table 4. (continued)

EAST OR SOUTH OF SEVIER ARCH

Figure Symbol	Name	$7^{1}/_{2}'$ Quadrangle(s)	Township-Range	Surface map units	Description	References
AMT	Antelope Mountain thrust	Pinnacle Pass	25S - 9W	Lower Cambrian over Middle Cambrian	See text for details; Prospect Mountain Quartzite thrust over structurally thinned and metamorphosed limestone as well as Cretaceous(?) conglomerate; age of thrusting uncertain	Leise (1957), Welsh (1983), Coleman and others (1997)
CRT; CRS	Canyon Range thrust; Canyon Range syncline	Oak City North, Fool Creek Peak, Williams Peak	16 to 18S - 3 to 4W	Precambrian, Paleozoic, and Cretaceous	See text for details; thrust and rocks above and below thrust were folded into syncline in Cretaceous during movement on younger and underlying Pavant thrust	Christiansen (1952), Millard (1983), Holladay (1984), Lawton and others (1997)
DVT	Dog Valley Mountain thrusts	Dog Valley Peak	24S - 6W	Mississippian and Devonian	Local fault zone below Pavant thrust; small offset; overturned Devonian strata overlie similarly overturned Mississippian strata; some Devonian strata cut out or brittlely attenuated	Davis (1983)
FT	Frisco thrust	Frisco Peak, High Rock	25 & 26S - 12 & 13W	Precambrian, Cambrian, Ordovician	Precambrian quartzite overlies structurally thinned and metamorphosed Paleozoic strata; Welsh (1983) correlated with the Canyon Range thrust (CRTS, CRT)	Hintze and others (1984), Lemmon and Morris (1984)
PT	Pavant thrust	Mt. Catharine, Fillmore, Sunset Peak, Joseph Peak	21 to 24S - 4 to 5W	Cambrian over Jurassic	Upright Cambrian quartzite overlies upright Jurassic sandstone; extends eastward beneath Tertiary rocks	Hickox (1971), Davis (1983), George (1984)
PTW	Pavant thrust, west extension	Fillmore, Kanosh, Dog Valley Peak	22 to 24S - 4 to 6W	Paleozoic over Mesozoic	Cambrian quartzite overlies upper Paleozoic and Mesozoic rocks in isolated exposures; extends west beneath valley fill in Black Rock Desert	Davis (1983), George (1984)
RRT	Red Ridge thrust	Red Ridge, Dog Valley Peak	24S-5 & 6W	Jurassic to Permian	Located beneath the Pavant thrust; overturned Triassic and Permian strata overlie upright Jurassic through Permian strata; offset <1.2 miles (2 km)	Davis (1983)
SPT	Scipio Pass thrust	Scipio Pass	18S-3W	Ordovician	Local thrust (older-over-younger rocks) within Pavant thrust plate	Michaels and Hintze (1994)
ST	South Mountain thrust	Red Ridge	24S-5W	Permian to Mississippian	Located beneath the Pavant thrust; overturned Mississippian limestone overlie overturned Permian strata of the Red Ridge thrust plate; small offset	Davis (1983)

northward to where the thrust dies out near the Cattlemans Valley anticline (CVA). Displacement on the thrust system is no more than about 2 miles (3 km) and it dies out northwards and southwards. The thrusts and folds are subsidiary structures on the east side of the Confusion Range synclinorium.

Mountain Home thrust (MHT): Devonian to Permian strata are thrust over strata of similar age on the steep, west limb of the asymmetric Mountain Home Pass syncline (MHPS) (figure 200). Displacement on the thrust is probably less than 2 miles (3 km), but the steep limb is completely faulted out in the northern Mountain Home Range. Thrust faulting is related to folding of strata in the Mountain Home Range synclinorium.

Plympton lower decollement (PLD): Hose (1977) identified a stratigraphic horizon of structural weakness in the upper part of the Chainman Shale and called it a decollement, in which attenuation of the Chainman occurred during folding of the Confusion Range synclinorium. Hose and Ziony (1963) speculatively traced its extent for more than 10 miles (16 km) under alluvial cover, but as shown on figure 195, actual exposure of the zone of attenuation is very limited.

Plympton upper decollement (PUD): Hose (1977) identified a stratigraphic horizon of structural weakness in the upper gypsiferous part of the Arcturus Formation, and called it a decollement, in which attenuation of the Arcturus occurred during folding of the Confusion Range synclinorium. Hose

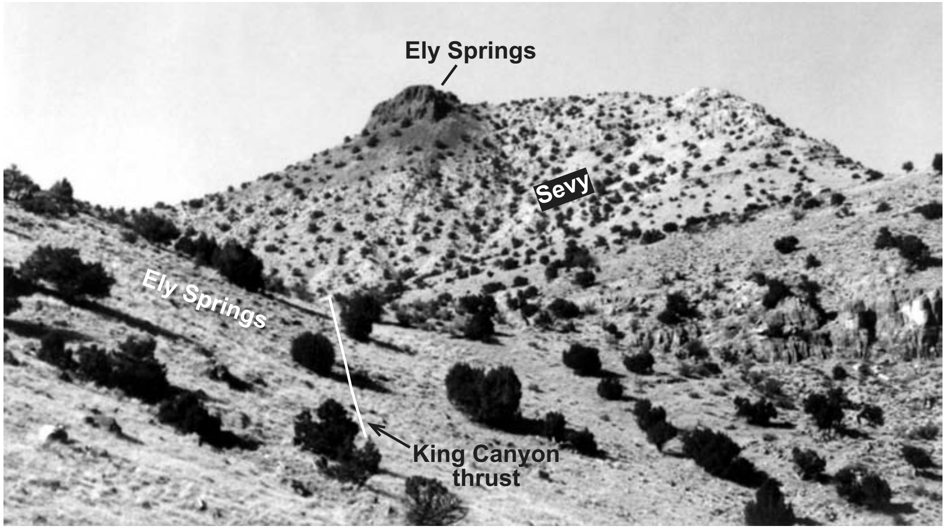


Figure 199. Dark outcrop on skyline is a klippe of Ordovician Ely Springs Dolomite, on the upper plate of the Kings Canyon thrust, resting on Devonian Sevy Dolomite of the lower plate. This klippe can be seen north of U.S. Highway 6-50 in Kings Canyon.

Figure 200. Nearest outcrops are overturned brecciated quartzite beds in the upper part of the Devonian Guilmette Formation exposed along the road west of Mountain Home Pass near the trace of the Mountain Home thrust (Hintze and Best, 1987). View is roughly to the east.

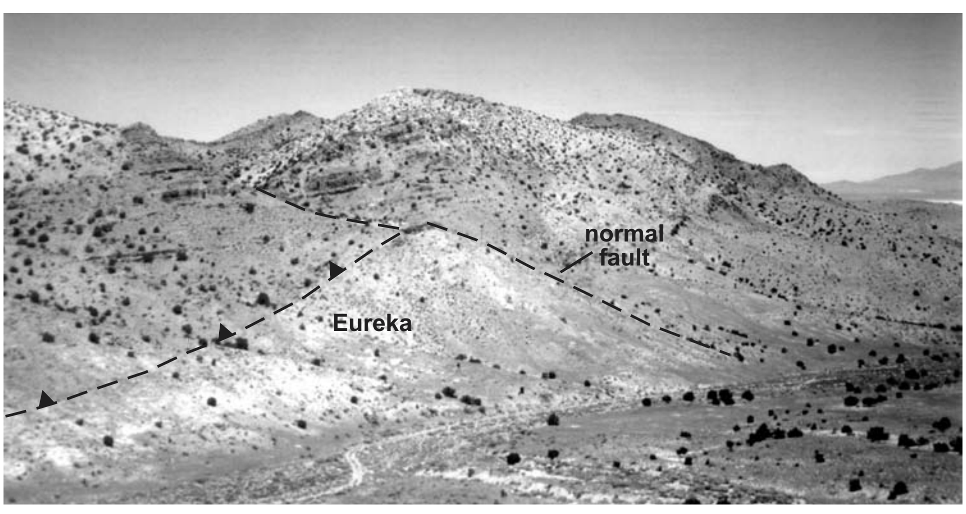


Figure 201. This northerly view of the west side of Payson Canyon in the Confusion Range shows complexly folded and thrust-faulted strata related to the Kings Canyon thrust, a thrust of small displacement east of the Confusion Range synclinorium. Light outcrops are Ordovician Eureka Quartzite. Dark outcrops are Upper Ordovician and Silurian dolomites.

speculatively traced its extent throughout several $7^1/_2$-minute quadrangles in the central Confusion Range area but as shown on figure 195, it is actually exposed in only limited outcrops in the Big Horseshoe (Cowboy Pass NW) $7^1/_2$-minute quadrangle (Hose and Repenning, 1963) in the Confusion Range synclinorium.

2. Structures on the Sevier arch

Canyon Range thrust, subsurface (CRTS): In the Cominco-American well (appendix A, well 80-3), drilled near the center of the Sevier arch in 1980 to a depth of 13,193 feet (4,021 m), Upper Precambrian strata are present under Tertiary deposits at depths between 2,480 and 8,390 feet (756-2,557 m). At 8,390 feet (2,557 m) the Canyon Range thrust separates the Precambrian Pocatello Formation from the underlying Upper Cambrian Notch Peak Formation. Cambrian strata be-neath the Notch Peak are in orderly succession to the top of the Lower Cambrian Prospect Mountain Quartzite at a depth of 13,020 feet (3,969 m). The Cambrian carbonate-shale sequence in this well is only 70 percent as thick as the same interval exposed in the adjacent Cricket Mountains. This subsurface, lower-plate, Cambrian section is likely an in-place (autochthonous) section of the normal eastward-thinning Cambrian sequence, while the Cricket Mountains section is a thicker Canyon Range plate sequence thrust in from the west.

This occurrence of the Canyon Range thrust near the center of the Sevier arch bridges the distance between the Canyon Mountains and fragmented exposures of similar thrust relationships at the north end of the Mineral Mountains (locality AMT) and the San Francisco Mountains (locality FT) as noted by Welsh (1983).

Dome Canyon tear and attenuation faults (DC): These tear faults in the House Range on the Sevier arch trend southeasterly. The longest ex-posure is about 5 miles (8 km). The tear faults bound an area within which Cambrian strata are brittlely attenuated along bedding plane faults (figure 196). Competency of Cambrian strata in the zone of attenuation is reduced and the topographic relief is accordingly subdued. The Windous Butte Tuff (age 31.4 Ma) rests across the zone of attenuation. See Hintze (1978) for discussion of these structures; dating of similar structures, the Drum Mine tear and attenuation faults (DM), is discussed by Nutt and others (1996).

North House Range tear and attenuation faults (NH): Southeast-trending tear faults (figures 195 and 203), one at least 8 miles (13 km) long, separate zones of brittly attenuated Cambrian strata from intact sections. Chidsey (1978a) and Hintze (1981b) showed that attenuation on near bedding-plane faults (figures 196 and 203) reduced the thickness of six middle Cambrian formations by about one-third on average; locally, some formations were entirely eliminated structurally. See Hintze (1978) for a discussion of these structures; the age of similar structures at the Drum Mine (DM figure 195) is discussed by Nutt and others (1996).

3. Structures east or south of the Sevier arch

Antelope Mountain thrust (AMT): This thrust places Lower Cambrian Prospect Mountain Quartzite over structurally thinned and metamorphosed (marbleized) Middle Cambrian limestone as well as Cretaceous(?) conglomerate at the north end of the Mineral Mountains. Displacement on the thrust must be at least 3 miles (5 km) (Coleman and others, 1997). Coleman and others (1997) showed that the thrust is folded into an open, east-plunging antiform, and considered the folding to be related to the emplacement of the middle Tertiary Mineral Mountains batholith rather than to the Mesozoic Sevier orogeny. Welsh (1983) correlated this thrust with the Canyon Range thrust.

Canyon Range thrust (CRT): Precambrian strata of the Canyon Range thrust plate (figure 198) overrode Paleozoic strata during Neocomian and Aptian (earliest Cretaceous) time. The Canyon Range thrust was folded in Late Aptian and Albian time into the Canyon Range syncline (CRS) (figure 33), during its piggyback transport on the underlying Pavant thrust plate (Lawton and others, 1997). Lawton and others (1997) also discussed relationships between the Canyon Range thrust and the syn- and post-thrust Canyon Range conglomerates, which may range in age from Turonian to Paleocene (figure 53). During late Cretaceous time the Canyon Range thrust was reactivated and overrode synorogenic deposits a short distance. Sussman and Mitra (1993) compared micro-deformational characteristics of quartzites from the Canyon Range and Sheeprock thrust sheets (see figure 194 for locations) and concluded that the Canyon Range sheet had been deformed at a shallower depth.

Cambrian stratigraphy of the Canyon Range thrust plate is similar to that exposed in the Cricket, Drum, and House ranges, and differs from strata of the same age in the subjacent Pavant thrust plate, which is similar to that exposed in the Tintic mining district in Juab County. My subjective estimate of the relative displacement between the Canyon Range and Pavant plates, based on the facies differences in their original Cambrian offshore continental-shelf stratigraphy, is 20 miles (32 km).

Quaternary and Range-Bounding Normal Faults

The Quaternary structures discussed below are normal faults that cut either unconsolidated Quaternary sediments or Quaternary basalt flows. Preliminary regional inventories of fault scarps in unconsolidated sediments in Millard County were made by Anderson and Bucknam (1979), Anderson and Miller (1979), Bucknam and Anderson (1979a), Dohrenwend and others (1991a-b), Ertec Western (1981), and Hecker (1993). Oviatt (1989, 1991a, 1992) and Hintze and Oviatt (1993) mapped Quaternary faults in portions of eastern Millard County, and Piekarski (1980) measured slope angles of the House Range fault scarp. Fitzhugh Davis (Utah Geological Survey) mapped Quaternary deposits and faults in Millard County for this bulletin (Hintze and Davis, 2002a-c; Hintze and others, 2003).

Figure 204 shows the locations of not only the Quaternary faults in Millard County, but also the major Basin and Range faults that have produced the present landscapes of Millard County through intermittent activity during the past 17 million years. Many of the Quaternary fault scarps, like that of the House Range, are clearly related to continued Quaternary movement along the adjacent major Basin and Range faults. However, the swarm of faults in the Sevier Desert, extending from the Deseret basalt faults to the Cove Fort basalt faults (figure 204), appear to be related to extension and volcanism within this broad valley area. A major, subsurface, Basin and Range, normal fault, called the "western basin-bounding fault," was identified on seismic records by Planke and Smith (1991). It is approximately located on figure 202 extending north-south across eastern Millard County.

The main reason for particular interest in Quaternary and range-bounding faults is that scarps produced during past earthquakes are evidence for the likely locations and magnitudes of future earthquakes. In western Utah, scarps produced by fault rupture require an earthquake of at least magnitude 6.0 to 6.5 (Arabasz and others, 1992). The major Basin and Range faults, shown with the dotted line pattern on figure 204, are not discussed below, except in those few places where Quaternary surface rupture (scarps) is indicated with solid lines. Fortunately, Millard County has a low population density, so that, should an earthquake occur, the loss of property and lives would likely be small.

Table 5 is a list of the exposed Quaternary faults shown on figure 204. It gives their names, locations, and other data. Each Quaternary fault group is discussed briefly in the same order in the text following the table. Table 6 is a list of major Basin and Range normal faults that are shown on figures 204 and 206 that do not offset Quaternary deposits at the surface. Concealed traces of the faults (dotted on figures) are constrained by the Quaternary-bedrock contacts along range fronts, steep gravity gradients that mark the margins of basins and ranges, and, locally, by seismic data and surface scarps.

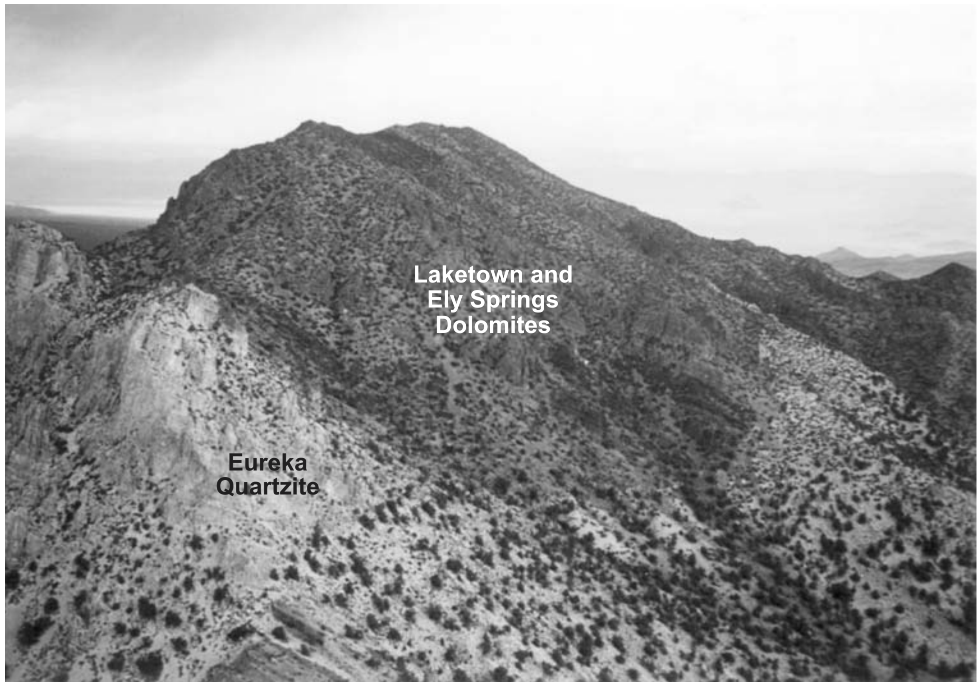


Figure 202. *Aerial view northward of Tunnel Spring Mountain in section 4, T. 24 S., R. 17 W., showing a faulted syncline. Light outcrops are Middle Ordovician Eureka Quartzite. Dark outcrops are Upper Ordovician Ely Springs Dolomite and Silurian Laketown Dolomite.*

Figure 203. *Light outcrop is Cambrian Wheeler Shale, here pinching out structurally in the northern House Range near Tatow Knob. Strata are offset along southeast-trending tear faults, and thinned by near-bedding-plane, younger-over-older brittle attenuation faults (Hintze, 1980c).*

Beaver Ridge faults: These scarps in the basalt and andesite of Beaver Ridge (ages 0.5 and 1.5 Ma, respectively) are overlain by fine-grained Lake Bonneville deposits (Oviatt, 1991a). These scarps have several different heights and may have multiple ages. Larger scarps are not overlain by Lake Bonneville deposits and latest surface rupture may be younger than Lake Bonneville. Also, a fault south of the Beaver Ridge volcanics appears to cut fine-grained Lake Bonneville sediments. Farther south, a longer fault appears to be covered by Lake Bonneville deposits. Scarps are less than 0.25 to 3 miles (0.4-5 km) long.

Black Rock basalt faults (BR): Two erosionally modified scarps with as much as 100 feet (30 m) of vertical offset cut the Black Rock basalt (ages 1.0-1.3 Ma). The scarps are only about 1.25 miles (2 km) long. Oviatt (1991a) depicted three faults as covered by pre-Lake Bonneville alluvial deposits;

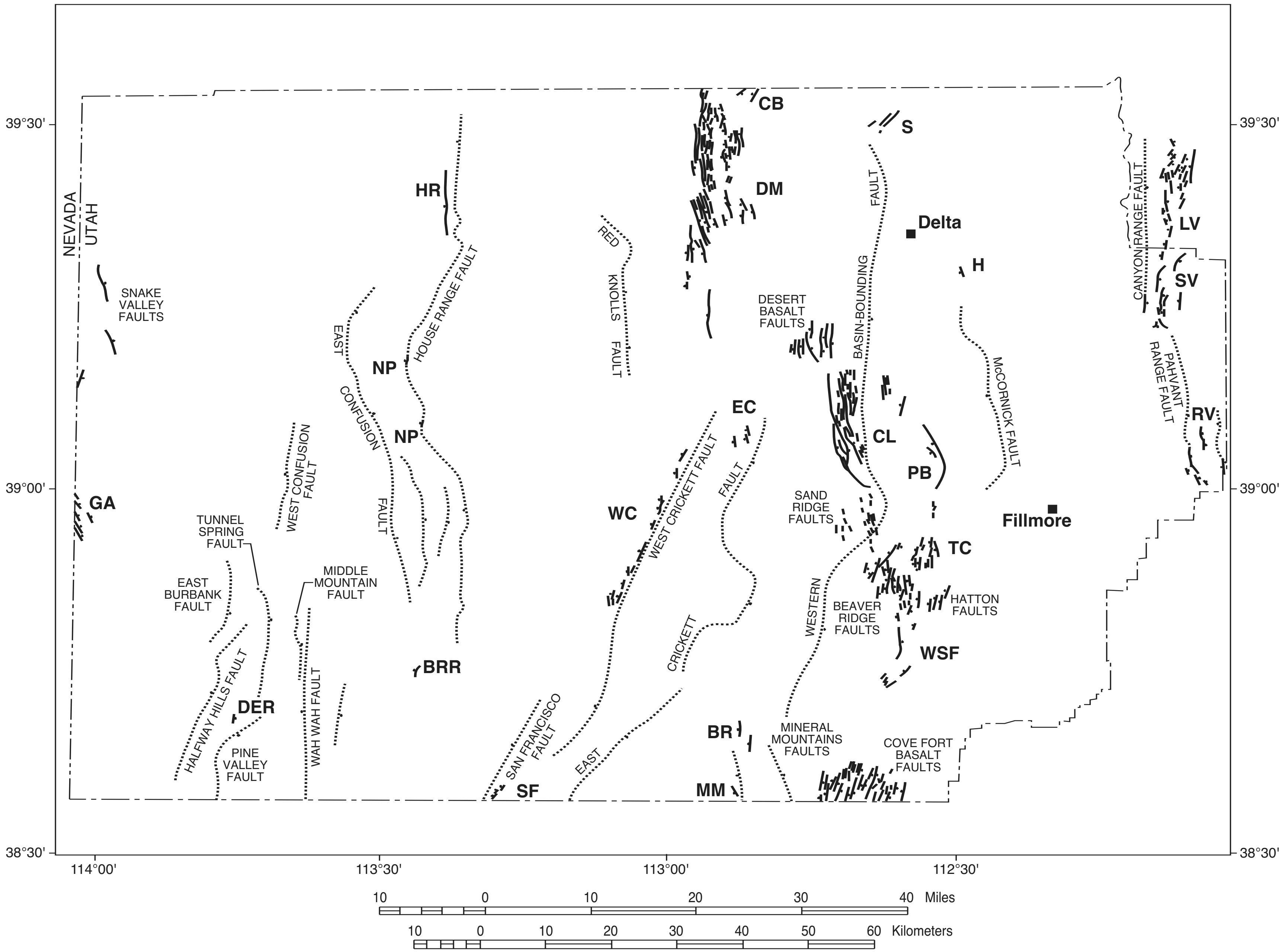


Figure 204. *Quaternary and range-bounding normal faults in Millard County. Solid lines show fault scarps that offset Quaternary basalts and deposits. Dotted lines show the trace of concealed Basin and Range normal faults that bound range blocks formed during late Cenozoic time, and are used as reference lines on figure 206. See tables 5 and 6 and text for names of lettered faults and descriptions of all faults.*

Table 5. *Quaternary faults, shown on figure 204.*

Figure Symbol	Name	7½′ Quadrangle(s)	Township-Range	Age	Surface map units	References
written out	Beaver Ridge	Tabernacle Hill, Black Point, Sixmile Point, Sand Ridge	22 & 23S - 6 & 7W	mid to late, or latest, Pleistocene	cut basalt and andesite of Beaver Ridge (0.5 & 1.5 Ma), overlain by Lake Bonneville fines; may cut Lake Bonneville deposits	Oviatt (1991a); this bulletin
BR	Black Rock basalt	Antelope Spring	25S - 9W	Pleistocene	cut basalt of Black Rock (1.0-1.3 Ma), covered by Lake Bonneville deposits	Oviatt (1991a), this bulletin
BRR	Black Rock road	Fifteenmile Point, Warm Point	24S - 14W	Pleistocene	cuts pre-Lake Bonneville alluvial fan in northwest Wah Wah Valley	Hintze and Davis (2002a), this bulletin
written out	Canyon Range	Fool Creek Peak, Williams Peak	16 to 18 S - 3W	≤ latest Pleistocene	cut post-Lake Bonneville alluvial fans	Oviatt (1992)
CL	Clear Lake	Clear Lake, Sunstone Knoll, Pahvant Butte North, Pahvant Butte South	19 to 21S - 6 to 8W	Holocene	cut Lake Bonneville fines and Holocene playa mud, covered by active dunes	Oviatt (1989), and Bucknam and Anderson (1979a), Crone and Harding (1984)
written out	Cove Fort basalt	Cinder Crater, Cove Fort	25 & 26S - 7W	mid to late(?) Pleistocene	cut basaltic andesite of Cove Fort (0.5 Ma), cuts and covered by pre-Lake Bonneville alluvium	Steven and Morris (1983), this bulletin
CB	Crater Bench	Fumarole Butte	15S - 9W	≤ latest Pleistocene	cut post-Lake Bonneville alluvium	Oviatt and others (1994b)
written out	Deseret basalt	Pot Mountain, Sunstone Knoll	18 & 19S - 8W	mid or late Pleistocene	cut basalt of Deseret (0.4 Ma), covered by Lake Bonneville fines	Oviatt (1989)
DER	Desert Experimental Range	Tunnel Spring	24S - 17W	Pleistocene	cut pre-Lake Bonneville alluvial fans	Hintze and Davis (2002a), this bulletin
DM	Drum Mountains	Drum Mtns. Well, Smelter Knolls West, Smelter Knolls East, Clay Knolls	15 to 18S - 9 & 10W	Holocene (2,300 to 9,000 years old)	cut post-Lake Bonneville alluvium, age based on scarp profiles	Hintze and Oviatt (1993), also Bucknam and Anderson (1979a-b), Oviatt (1989)
EC	East Cricket	Neels	20S - 9W	≤ latest Pleistocene	cuts pre-Lake Bonneville alluvial fan, at least one covered by Lake Bonneville deposits; two may cut Lake Bonneville shorelines	Bucknam and Anderson (1979a), Hintze (1984), Oviatt (1989); this bulletin
GA	Garrison	Garrison	21S - 20W	≤ latest Pleistocene	cut post-Lake Bonneville alluvium	this bulletin, Hintze and Davis (2002a), also Ertec Western (1981), Dohrenwend and others (1991a)
H	Harding	Harding	17S - 6W	Holocene	cut post-Provo shoreline Lake Bonneville deposits and not covered by inactive eolian sand	Hintze and Davis (2002b), this bulletin
written out	Hatton	Sixmile Point	22 & 23S - 6W	Holocene(?)	cut mostly Holocene alluvium	Oviatt (1991a), this bulletin
HR	House Range	Swasey Peak NW, Swasey Peak SW	16 & 17S - 14W	late Pleistocene	cut Provo shoreline, covered by post-Lake Bonneville alluvial fans	this bulletin, also Piekarski (1980), Bucknam and Anderson (1979a)
LV	Little Valley	Scipio North, Mills	15 to 17S - 2W	≤ latest Pleistocene	cut post-Lake Bonneville alluvial fans	Oviatt (1992), this bulletin, also Bucknam and Anderson (1979a)

Table 5. *(continued)*

Figure Symbol	Name	$7^1/_2{}'$ Quadrangle(s)	Township-Range	Age	Surface map units	References
MM	Mineral Mountains	Pinnacle Pass	25 & 26S - 9W	Pleistocene or Holocene(?)	cut pre- and likely post-Lake Bonneville alluvial fan	Hintze and others (2003), this bulletin, Sibbet and Nielson (1980)
NP	Notch Peak	Notch Peak, Hell n' Moriah Canyon	19 & 20S - 14W	late Pleistocene	cut Lake Bonneville deposits, covered by post-Lake Bonneville alluvial fans	this bulletin, also Sack (1990)
PB	Pahvant Butte	Pahvant Butte South	20 & 21S - 6W	latest Pleistocene and(?) Holocene	cut basalt of Pahvant Butte (0.17 Ma), overlain by Lake Bonneville deposits, covered by basalt of Ice Springs (<4 ka)	Oviatt (1989, 1991a)
written out	Pahvant Range	Scipio South, Scipio Lake	18 to 20S - 2W	Holocene	cut Holocene alluvium on south end	Oviatt (1992)
RV	Round Valley	Scipio South, Scipio Lake	19 to 21S - 2W	≤ latest Pleistocene	cut post-Lake Bonneville alluvial fans	Oviatt (1992)
written out	Sand Ridge	Sand Ridge, Tabernacle Hill	21S - 7W	≤ latest Pleistocene	cut Lake Bonneville deposits, concealed(?) by Holocene sand dunes	Oviatt (1991a)
SF	San Francisco	Frisco Peak	26S - 13W	Pleistocene	cut pre-Lake Bonneville alluvial fans	Anderson and Bucknam (1979), Hintze and Davis (2002a), this bulletin
SV	Scipio Valley	Scipio South, Scipio North	17 & 18S - 2 & 3W	Holocene	cut post-Lake Bonneville alluvium, age based on freshness of scarp	Oviatt (1992), also Bucknam and Anderson (1979a)
written out	Snake Valley	Gandy SW, Hole In The Ground, Baker	17 to 19S - 19W	≤ latest Pleistocene	cut post-Lake Bonneville alluvial fans	Ertec Western (1981), Hintze and Davis (2002c) this bulletin
S	Sugarville	Rain Lake	15S - 7W	≤ latest Pleistoce	cut post-Provo-shoreline Lake Bonneville deposits	Oviatt (1989), Oviatt and others (1994b), this bulletin
TC	Tabernacle Crater	Tabernacle Hill	22S - 6W	latest Pleistocene	cut basalt flows (14,400 yrs old), and covered by Lake Bonneville fines	Hoover (1974), Oviatt (1991a), Hintze and others (2003), this bulletin
WC	West Cricket	Red Pass, Sevier Lake NE, Headlight Mtn.	20 to 24S - 10 & 11W	≤ latest Pleistocene	cut post-Lake Bonneville alluvial fans	Hintze and Davis (2002a), this bulletin, Oviatt (1989), also Anderson and Bucknam (1979), Hintze (1984)
WSF	White Sage Flat	Sixmile Point Dog Valley Peak	23 & 24S - 7 & 8W	late Pleistocene or Holocene(?)	truncated by Bonneville shoreline, cut pre-Lake Bonneville alluvium, and likely cut Lake Bonneville deposits	Anderson and Bucknam (1979), Hintze and others (2003), this bulletin, also Oviatt (1991a)

Table 6. *Basin and Range faults (post-40 million years ago, probably post-17 million years ago and likely pre-Quaternary) shown on figures 204 and 206.*

Figure Symbol	Name	7½′ Quadrangle(s)	Township-Range	Age	Surface map units	References
written out	East Burbank	Deadman Point, Big Jensen Pass	22 & 23S - 17 & 18W	Oligocene or younger	range front; Paleozoic-Oligocene fault contact	Hintze (1997b, d), Anderson (1980), this bulletin
written out	Halfway Hills	Tunnel Spring, Halfway Summit	24 & 25S - 17 & 18W	Oligocene or younger	range front; gravity gradient	this bulletin, figure 215
HH on fig. 206	Halfway Hills	Halfway Summit, Tunnel Spring	25 & 26S - 18W	Oligocene or younger	cut upper Needles Range Group (30.5 & 31 Ma) "in range"	Best and Hintze (1980a), Hintze (1981d)
written out	Tunnel Spring	Big Jensen Pass, Middle Mountain	22 & 23S - 17W	concealed Basin and Range faults	range front	Hintze (1997d), this bulletin
written out	Pine Valley	Pine Valley Hardpan N, Tunnel Spring, Halfway Summit	24 to 26S - 17W	concealed Basin and Range faults	gravity gradient on west side of valley	Steven and others (1990), figure 215
written out	Middle Mountain	Middle Mountain	22 & 23S - 8 & 9W	concealed Basin and Range faults	range front	this bulletin
written out	Wah Wah	Middle Mtn., Pine Valley Hardpan N & S	23 to 26S - 16W	concealed Basin and Range faults	west side of range-gravity gradient; range front not abrupt	this bulletin, figure 215
WW on fig. 206	east Wah Wah	Grassy Cove	24 & 25S - 15 & 16W	concealed Basin and Range faults	range front	Hintze (1974e), this bulletin
CP on fig. 206	Crystal Peak	Crystal Peak	23S - 15W	Oligocene or younger	concealed 33 Ma caldera; exposed fault cuts upper Needles Range Group (30.5 Ma)	Steven (1989), this bulletin; see also Hintze (1974c)
written out	West Confusion	Conger Mtn., Thompson Knoll, Pyramid Knoll	19 to 21S - 16 & 17W	concealed Basin and Range faults	range front; not apparent on seismic lines CO Utah 1 and SB1	Hintze (1974b-c)
written out	East Confusion	Dowdell Cyn., Bluegrass Knoll, Hell N' Moriah Cyn., The Barn	18 to 22S - 14 & 15W	concealed Basin and Range faults	range front, gravity gradient; not on seismic line CO Utah 1 and SB1	Hintze (1974a-b, d), Hose (1963b), figure 215
BH on fig. 206	Barn Hills	Hell N' Moriah Canyon, The Barn	20 to 22S - 14W	concealed Basin and Range faults	Quaternary- bedrock contacts, some "in range"	Hintze (1974a, d)
written out	House Range	Sand Pass, Swasey Peak NW & SW, Notch Peak, Hell N' Moriah Cyn., Skull Rock Pass, Burnout Cyn., Red Tops	15 to 23S - 13 & 14W	concealed Basin and Range faults	range front, gravity gradient, seismic line CO Utah 1	figure 215, Hintze (1974d, 1981a-b), this bulletin
written out	Red Knolls	Red Knolls, Long Ridge	17 to 19S - 11W	Oligocene or younger	Tertiary-Quaternary contact, minor offset; not apparent on seismic line CO Utah 1	Hintze and Davis (1992a-b)
LD on fig. 206	Little Drum	Lady Laird Peak, Little Drum Pass	15 & 16S - 10 & 11W	Oligocene or younger	cuts Tertiary volcanic rocks (36.5 & 37 Ma); longest is near range front	this bulletin

Table 6. *(continued)*

Figure Symbol	Name	$7^{1}/_{2}'$ Quadrangle(s)	Township-Range	Age	Surface map units	References
written out	West Cricket	Red Pass, Sevier Lake NE, Headlight Mtn., Red Rock Knoll, Iron Mine Pass	19 to 25S - 9 to 12W	concealed Basin and Range faults	gravity gradient, range front	figure 215, Case and Cook (1979)
written out	East Cricket	Neels, Borden, Cruz	19 to 23S - 8 & 9W	concealed Basin and Range faults	gravity gradient on east; range front on west.	gravity-Case and Cook (1979), figure 215
written out	East Cricket (south)	Cat Canyon, Red Rock Knoll, High Rock	24 to 26S - 10 to 12W	concealed Basin and Range faults	gravity gradient extending south to east side of San Francisco Mountains	Steven and others (1990), figure 215
CM on fig. 206	Cricket Mtns	Red Pass, Candland Spring, Cat Canyon, Sevier Lake NE, Headlight Mtn.	20 to 24S - 9 to 11W	concealed Basin and Range faults	Quaternary-bedrock contacts "in range"; cut Paleocene Flagstaff Fm.	Hintze (1984), this bulletin
written out	San Francisco	Brown Knoll, Iron Mine Pass, Frisco Peak	24 to 26S - 12 & 13W	concealed Basin and Range faults	gravity gradient	this bulletin, figure 215
written out	Mineral Mountains	Antelope Spring, Pinnacle Pass	25 & 26S - 9W	concealed Basin and Range faults	gravity gradient and range front	figure 215, Steven and others (1990)
CC on fig. 206	Cove Creek	Antelope Valley, Antelope Spring, Black Point	23 to 25S - 7 & 8W	Pliocene	cut basalt of Cove Creek (2.5 Ma) and basaltic andesite of Burnt Mtn. (2.1 Ma)	Crecraft and others (1981), Zimmerman (1961), this bulletin
DV on fig. 206	Dog Valley	Cove Fort, Dog Valley Peak	24 to 26S - 6 & 7W	Miocene or younger	cut Three Creeks Tuff (27 Ma) and Joe Lott Tuff (19 Ma)	Steven and Morris (1983), this bulletin
written out	McCornick	McCornick, The Sink	18 to 21S - 5 & 6W	concealed Basin and Range faults	seismic line Mc2	Davis (1994); see also McDonald (1976), Mitchell and McDonald (1987), this bulletin
MG on fig. 206	Maple Grove	Scipio South, Scipio Lake, Beehive Peak	20 & 21S - 2 & 2.5W	Quaternary offset to SE outside county	Quaternary contact with Cretaceous and Tertiary	this bulletin; to southeast-Anderson and Bucknam (1979)
VM on fig. 206	Valley Mountains	Scipio North, Scipio South, Scipio Lake	17 to 20S - 2W	concealed Basin and Range faults	Quaternary contacts with Cretaceous/ Tertiary "in range"	this bulletin, Oviatt (1992)

two faults that cut these deposits are shown on the Richfield 1:100,000-scale geologic map (Hintze and others, 2003). The northern of these two faults appears concealed by Lake Bonneville deposits. Degradation of the scarps suggest that they are tens of thousands of years old.

Black Rock road fault (BRR): Mapping by Fitzhugh Davis for this bulletin (Hintze and Davis, 2002a) shows a fault scarp about 1 mile (1.6 km) long in pre-Lake Bonneville alluvial-fan deposits in northwestern Wah Wah Valley. The fault crosses the Garrison-Black Rock road. This mapping did not substantiate the faults previously shown to the west off the north end of the Wah Wah Mountains (see Ertec Western, 1981).

Canyon Range fault: Oviatt (1992) showed this fault as cutting post-Lake Bonneville alluvial fans on its south end, with a roughly 0.6-mile-long (1 km) trace. The concealed trace is poorly defined and the south scarp may connect with a fault to the north that separates Cretaceous (Kc) from younger Cretaceous and Tertiary (TKn) strata, rather than swinging to a northeast trend.

Clear Lake faults (CL): This fault zone is at least 12 miles (19 km) long and 3 miles (5 km) wide; it is 6 miles (10 km) wide if scarps with similar trend and geologic setting east of Clear Lake are included. It may also include the Sand Ridge scarps to the south. Maximum scarp height is 9.8 feet (3 m) (Oviatt, 1989). Individual scarps are about 0.3 to 4.5 miles (0.5-7.5 km) long. Oviatt (1989) discussed evidence suggesting that subsidence along the Clear Lake fault zone may have been related to withdrawal of magma beneath Pahvant Butte. In particular, the 15,000-year-old Bonneville shoreline on Pahvant Butte is 56 feet (17 m) lower than its regional norm, giving a measure of the amount of subsidence since the shoreline was formed. Oviatt (1989) reported that faults in the Clear Lake zone cut Lake Bonneville deposits and Holocene playa deposits, and showed them as both cutting and concealed by Holocene sand dunes. Scarps are covered by active sand dunes (Bucknam and Anderson, 1979a). The Clear Lake fault zone is visible as offset of near-surface reflectors on seismic lines published by McDonald (1976), Mitchell and McDonald (1987), Planke and Smith (1991, figure 4), and in the short line published by Crone and Harding (1984) (Mc 3, MM line 1, PS 4, and CH 2, respectively, on figure 209). Because the near-surface reflectors and sand dunes are younger than the igneous rocks in the area, the scarps are not solely due to magma withdrawal.

<u>Cove Fort basalt faults:</u> Scarps ranging up to 100 feet (30 m) high and up to 3 miles (4.8 km) long cut the basaltic andesite of Cove Fort (age 0.5 Ma), and both cut and are concealed by pre-Lake Bonneville alluvium.

<u>Crater Bench faults (CB):</u> Most of this Holocene fault zone is to the north in Juab County, where it cuts the basalts of Crater Bench (age about 0.9 Ma; Peterson and Nash, 1980; Galyardt and Rush, 1981), and also cuts post-Lake Bonneville alluvial fans below the Provo shoreline (Oviatt and others, 1994b).

<u>Deseret basalt faults:</u> Scarp heights on these faults range up to 50 feet (15 m) (Oviatt, 1989), and length ranges up to 3.5 miles (5.6 km). Oviatt (1989) reported that faults cut the basalt of Deseret (age 0.4 Ma) and are pre-Lake Bonneville in age.

<u>Desert Experimental Range fault (DER):</u> Mapping by Fitzhugh Davis for this bulletin (Hintze and Davis, 2002a) shows a fault scarp about 1 mile (1.4 km) long in pre-Lake Bonneville alluvial-fan deposits in northwestern Pine Valley (east flank of Tunnel Spring Mountains).

<u>Drum Mountains faults (DM):</u> Hintze and Oviatt (1993) summarized the present knowledge concerning this Holocene fault zone (figure 205). The zone is 25 miles (40 km) long and up to 7 miles (11 km) wide. Scarps are from 2.4 to 24 feet (0.7 to 7.3 m) high. Estimates of the age of faulting range between 2,300 and 9,000 years ago, based on scarp morphology, but no radiocarbon dates have been obtained. Trenching across the faults has been limited to one shallow cut. This 9-foot-deep (3 m) trench (Hintze and Oviatt, 1993), on a scarp that appears to be only 4.2 miles (7 km) long, revealed a 12-foot (3.7 m) offset (Crone, 1983). From a seismic survey (Crone and Harding, 1984; line CH1 figure 209), the fault zone contains more faults than just those visible as surface scarps. Seismic line SB-1 (Smith and Bruhn, 1984) shows this zone vaguely.

<u>East Cricket faults (EC):</u> These scarps show maximum offset of 50 feet (15 m) (Bucknam and Anderson, 1979a) and are about 0.6 miles (1 km) long. Oviatt (1989) reported the scarps are covered by thin Lake Bonneville gravel, and Bucknam and Anderson (1979a) reported the scarps were modified by Lake Bonneville. One scarp has these characteristics, but two appear to cut shorelines between the Provo and Bonneville levels of Lake Bonneville. Therefore, the scarps may predate Lake Bonneville or two may postdate the Bonneville shoreline. The concealed trace of the range-bounding East Cricket fault, shown east of the scarps on figure 204, is from Case and Cook (1979); they located it on the basis of a steep gravity gradient on the east flank of the Cricket Mountains. Steven and others (1990) inferred a concealed fault based on gravity data (steep gradient) along the east flank of the Cricket Mountains south of that of Case and Cook (1979).

<u>Garrison faults (GA):</u> Low scarps extend northwestward for 4 miles (6.4 km) in Utah from near Garrison to the Nevada border, and about another mile (1.6 km) into Nevada (this bulletin; Hintze and Davis, 2002a; see also Ertec Western, 1981; Dohrenwend and others, 1991a). Some scarps are shown as Holocene by Dohrenwend and others (1991a). Maximum scarp height is about 3 feet (1 m). The faults cut Holocene fine-grained alluvium. Mapping by Fitzhugh Davis for this bulletin (partly shown in Hintze and Davis, 2002a) shows some scarps cut post-Lake Bonneville alluvial fans and are up to 0.75 miles (1.2 km) long.

Figure 205. *One of the Drum Mountains fault scarps of Holocene age, located in section 35, T. 15 S., R. 10 W. The down-to-the-east scarp is left of the vehicle. The scarp was nearly vertical at the time it was created, but several thousand years of erosion since then has modified it to the slope of about 12° seen here.*

Hatton faults: Oviatt (1991a) stated that these faults cut Lake Bonneville deposits, and he depicted them as cutting post-Lake Bonneville (mostly Holocene) alluvial mud. They are up to about 1.2 miles (2 km) long.

Harding fault (H): North of Harding, mapping by Fitzhugh Davis for this bulletin (Hintze and Davis, 2002b) shows a scarp about 1 mile (1.5 km) long in post-Provo-shoreline, fine-grained Sevier River deltaic deposits of Lake Bonneville (Qdf). The scarp is not concealed by, and appears to cut, vegetation-stabilized sand (Qes) of Holocene age.

House Range faults (HR): Piekarski (1980) measured 20 profiles across the House Range scarps, which cut Lake Bonneville shorelines that are developed on older alluvial fans. Average slope of the fans is 7 degrees, while average scarp slope is 12 degrees. Average displacement is 4.6 feet (1.4 m). Piekarski estimated that the scarps are 12,000 to 15,000 years old based on their erosional degradation and cutting of Lake Bonneville sediments. Scarps cut the Provo shoreline but are concealed by post-Lake Bonneville alluvial fans. Discontinuous scarps form a line about 6 miles (10 km) long that is probably rupture from a single event. Gravity data help constrain the trace of the concealed portion of the fault zone. Seismic data from line CO Utah 1 (figure 209) show offset of near-surface reflectors where it crosses this fault zone. Seismic line SB-1 (Smith and Bruhn, 1984) doesn't image this fault zone well.

Little Valley faults (LV): Only the south end of this fault zone is located in Millard County, but the zone continues northward for 10 miles (16 km) into southern Juab County, paralleling the trend of the Canyon Mountains fault (figure 206). Maximum vertical offset is 25 feet (8.2 m) (Bucknam and Anderson, 1979a). Oviatt (1992) showed two of the scarps as cutting post-Lake Bonneville alluvial-fan deposits, while the rest are older. In contrast, Bucknam and Anderson (1979a) concluded that the scarps were produced by one earthquake more than 15,500 years ago, because their field relationships showed that the scarps are slightly older than the Bonneville highstand of Lake Bonneville.

Mineral Mountains faults (MM): Mapping by Fitzhugh Davis for this bulletin (simplified in Hintze and others, 2003) showed a northwest-trending scarp about 1 mile (1.6 km) long in pre- and, likely, post-Lake Bonneville alluvial-fan deposits on the northwest margin of the range. The scarp may be mantled by, rather than having cut, post-Lake Bonneville alluvium. A steep gravity gradient is also present on the west side of the Mineral Mountains and Steven and others (1990) showed several north-trending concealed faults based on gravity data. They also showed a similar concealed fault on the east side of the range but aligned it with the range front rather than the gravity gradient. Sibbet and Neilson (1980) mapped several Quaternary faults near the eastern range front in Beaver County. Smith and Bruhn (1984) and Smith and others (1989) showed a gently (10°) west-dipping normal fault on the west flank of the range, but their seismic reflector/fault might be the contact between Cenozoic basin-fill and the igneous and metamorphic rocks exposed in the Mineral Mountains (well 79-3, appendix A).

Notch Peak faults (NP): These faults were first noted by Ertec Western (1981), but appear less continuous in the field and on aerial photographs than their mapping depicts. A single scarp is present near Painter Spring that appears to cut Lake Bonneville deposits and part of a post-Lake Bonneville alluvial fan. The continuous feature just to the south (shown by Ertec Western) appears to be a shoreline(s) rather than fault scarps. Fault scarps are present farther south at the mouth of Hell n' Moriah Canyon. These scarps cut Lake Bonneville deposits between the Provo and Bonneville shorelines, and are concealed by post-Lake Bonneville alluvial fans. Sack (1990) reported the scarp on the north side of the fan head has a height of 5.2 feet (1.6 m).

Pahvant Butte faults (PB): Oviatt (1989, 1991a) reported that the faults that cut the basalt of Pahvant Butte (age 0.17 Ma) are locally overlain by Lake Bonneville deposits, and covered by the basalt of Ice Springs (≤ 4,000 years old). Oviatt (1989) also showed one fault, about 6.6 miles (11 km) long, as concealed by Holocene sand dunes; this fault is exposed and is partly the contact between dunes and inactive eolian sand on the Delta 1:100,000-scale geologic map (Hintze and Davis, 2002b). Oviatt (1989) also depicted an exposed fault 1.8 miles (3 km) long with a northeast trend as cutting the basaltic ash of Pahvant Butte (15,500 years old).

Pahvant Range fault: This fault hugs the east base of the Pahvant Range for at least 13 miles (20 km) and juxtaposes Tertiary and Cretaceous bedrock with Quaternary alluvial deposits (figure 30). The fault is discontinuously exposed. Bucknam and Anderson (1979a) were noncommittal on the age of the scarps, but noted (their table 2) that the scarps are post-Bonneville highstand and have a maximum surface offset of at least 23 feet (7 m). They and Oviatt (1992) used different names for different portions of this fault zone. Oviatt (1992) reported that the youngest scarps along the base of the range cut Holocene alluvium (for example his locality O) and have steep, vegetation-free slopes.

Round Valley faults (RV): Fault scarps are present in Round Valley east of the Maple Grove fault zone (figure 206) and along the west base of the Valley Mountains bedrock. The scarps along the Valley Mountains juxtapose Tertiary and Cretaceous bedrock with Quaternary alluvial deposits. Oviatt (1992) showed some of the faults as cutting post-Lake Bonneville alluvial-fan deposits with scarps up to 1 mile (1.6 km) long. Bucknam and Anderson (1979a) used the name "Maple Grove" for part of this fault zone and the Pahvant Range fault zone to the north. Therefore the location of their maximum surface offset of 40 feet (12 m) is not known.

Sand Ridge faults: These scarps cut Lake Bonneville deposits and are concealed by Holocene sand dunes (Oviatt, 1991a). These scarps are probably a southern extension of the Clear Lake fault zone (Oviatt, 1991a). Because this zone may be part of the Holocene Clear Lake fault zone and the dunes are active, the Sand Ridge scarps may be Holocene. Scarps appear to be about 0.6 to 3 miles (1-5 km) long within a zone about 4.5 miles (9 km) long and 4 miles (6.4 km) wide. These faults are visible as offset of near-surface reflectors on a seismic line published by McDonald (1976) (Mc 20 on figure 209). This fault zone is probably the western basin-bounding fault shown by Planke and Smith (1991, figure 3), though the location and length of the line they show (PS-2 on figure 209) is uncertain.

San Francisco faults (SF): Anderson and Bucknam (1979) traced a discontinuous line of degraded fault scarps for 8 miles (13 km) along alluvial fans on the west flank of the San Francisco Mountains. The scarps may be as high as 30 feet

(10 m) (Anderson and Bucknam, 1979). Their degree of erosional modification suggests that they are tens of thousands of years old (Anderson and Bucknam, 1979). Ertec Western (1981) reported the zone is 22 miles (35 km) long with scarp heights up to 41 feet (13 m). The scarps they traced are mostly in Beaver County; mapping by Fitzhugh Davis showed that in Millard County scarps cut pre-Lake Bonneville alluvial-fan deposits (Hintze and Davis, 2002a). Scarps mapped for this report are only about 0.25 miles (0.4 km) long. The location of the concealed trace on figures 204 and 206 is constrained by the bedrock-Quaternary contact and steep gravity gradient along the west side of the San Francisco Mountains (east side of Wah Wah Valley low).

Scipio Valley faults (SV): Bucknam and Anderson (1979a) reported two periods of scarp formation in northern Scipio Valley, pre-Holocene and Holocene, the younger being a steep scarp locally superimposed on the other. This young scarp has a maximum surface offset of 9 feet (2.7 m), while the older scarps locally have surface offset of greater than 33 feet (>10 m) (Bucknam and Anderson, 1979a). Other faults in Scipio Valley are shown by Oviatt (1992) as cutting post-Lake Bonneville alluvial-fan and alluvial (stream) deposits, and from less than 0.25 to 2 miles (<0.4-3.5 km) long. The fault zone is about 8.5 miles (14 km) long.

In northern Scipio Valley, numerous linear features are shown as a dot-dash pattern on the Delta 1:100,000-scale geologic map (Hintze and Davis, 2002b). Bjorklund and Robinson (1968) described elongate sinkholes in alluvium along some of these features. They attributed collapse on these elongate traces to fault and fracture trends in bedrock under the alluvium. These features are not mapped as faults because no offset is present at the surface and piping has occurred, so these features may be due to problem soils.

Snake Valley faults: These faults were first noted by Ertec Western (1981). Mapping by Fitzhugh Davis for this bulletin showed three scarps that cut post-Lake Bonneville alluvial-fan deposits discontinuously for about 13 miles (20 km); individual scarps are 2.4 to 3.5 miles (4-6 km) long (partly in Hintze and Davis, 2002c). Maximum scarp height is reportedly 8 feet (3.7 m) (Ertec Western, 1981). Seismic data published in Hauser and others (1987, figure 3; CO Nevada 5 on figure 209) and McCarthy (1986, figure 3; location not published so not on figure 209) show offset of near-surface reflectors indicating the northern part of this fault zone is in Nevada in the subsurface. The south end of the Snake Valley fault zone is not readily apparent on seismic line CO Utah 1 (figure 209) (see Allmendinger and others, 1986). However, two offsets of near-surface reflectors are vaguely apparent on seismic line SB-1 (see Smith and Bruhn, 1984, figure 12), that follows the same route as this portion of CO Utah 1. A detailed location of the line is not shown in Smith and Bruhn (1984), so the locations of the offsets are not known.

Sugarville faults (S): Oviatt (1989) showed these faults as cutting Lake Bonneville deposits and from less than 0.25 to 2.2 miles (<0.4-3.7 km) long. Later, Oviatt and others (1994b) reported that they are post-Lake Bonneville in age. Dames and Moore (1978) trenched the two longer faults, which form a graben, and another fault to the northwest. They found offset was greater than trench depth, 12.5 and 10 feet (3.8 and 3 m), on the fault forming the southwest side of the graben and the fault northwest of the graben, respectively. Trench logs show two or three episodes of faulting on the fault to the northwest, with about 3.3 feet (1 m) of offset across one fault.

Tabernacle Crater faults (TC): Oviatt (1991a) reported that these faults cut the 14,300-year-old basalt flows of Tabernacle Hill, and showed them as cutting and overlain by fine-grained deposits of Lake Bonneville. Mapping by Fitzhugh Davis for this bulletin (simplified in Hintze and others, 2003) shows the faults as covered by only these fine-grained deposits. Fault scarps are less than 0.25 to 1.6 miles (0.4-2.7 km) long.

West Cricket faults (WC): The scarps on the north end of the zone are up to 6 feet (2 m) high (Oviatt, 1989) and a mile (1.6 km) long. Scarps extend discontinuously for 22 miles (35 km) along the west flank of the Cricket Mountains. Ertec Western (1981) reported scarp heights up to 8 feet (2.4 m) in the zone. Scarps are less than 0.25 to 1.2 miles (0.4-2 km) long. Oviatt (1989) noted that the faults on the north end of the zone cut lacustrine and alluvial gravels (Qla) above and below the Provo shoreline. Mapping by Fitzhugh Davis for this bulletin showed that scarps cut Lake Bonneville shorelines above, and including, the Provo shoreline, as well as parts of some post-Lake Bonneville alluvial-fan deposits (Hintze and Davis, 2002a). The scarps are therefore latest Pleistocene and Holocene in age. The location of the concealed portion of the fault zone is from a gravity interpretation by Case and Cook (1979).

White Sage Flat faults (WSF): Anderson and Bucknam (1979) reported that scarps in this fault zone are truncated by the Bonneville shoreline and have a maximum surface offset of 43 feet (13.2 m). The faulting therefore predates the Bonneville shoreline and hence is older than 15,000 years. Several of their "faults" are not shown on the Richfield 1:100,000-scale geologic map (Hintze and others, 2003), because they are not visible on the ground or on aerial photographs used for our mapping. A lineament that is colinear with the largest fault scarp (east-northeast trending) is visible and is shown on our map. The faults mapped are shown as covered by mixed lacustrine and alluvial deposits (Qla) by Oviatt (1991a), and the youngest age of these deposits is uncertain (see Oviatt, 1991a). Mapping by Fitzhugh Davis for this bulletin (simplified in Hintze and others, 2003) shows the faults cut the Tertiary Oak City Formation and Quaternary alluvial and lacustrine units, as young as Lake Bonneville age, that overlie the Oak City. Scarps are up to 1.5 miles (2.4 km) long.

Post-40 Million-Year-Old Structures and Structures of Uncertain Age

Figure 206 shows predominantly normal faults that mostly had offset between 40 and 17 million years ago. However, because the ages of the rocks that are faulted may not give a limit to the age of displacement, some of these faults may be older than 40 million years and be Sevier age. A few of them may be strike-slip or tear faults, also of Sevier age. Others are normal faults that are younger than 17 million years old, but their origin is uncertain and may be due to igneous activity.

Table 7 is a list of the faults, in symbol alphabetical order, shown on figure 206. It gives a name, by area, to groups of these faults, identifies the 7 1/2-minute (1:24,000-scale)

Table 7. Post-40 million-year-old structures and structures of uncertain age, shown on figure 206.

Figure Symbol	Name	$7^1/_2'$ Quadrangle(s)	Township-Range	Age	Surface map units	References
BE	Burbank Hills East	Big Jensen Pass	23S-17W	Devonian strata	uncertain	Hintze (1997d), Anderson (1980)
BH	Barn Hills	The Barn, Hell n' Moriah Canyon	21 & 22S - 14W	Ordovician to Devonian strata	likely late Cenozoic Basin and Range faults	Hintze (1974a, d)
BW	Burbank Hills West	Burbank Pass	22S-19W	Devonian and Mississippian strata	most likely related to late Mesozoic tectonism	Hintze (1997a)
CC	Cove Creek	Antelope Valley, Antelope Spring Black Point	23 to 25S - 7 & 8W	Pliocene basalt and lacustrine deposits	formed due to late Cenozoic volcanic activity and local uplift (2-3 Ma), or late Cenozoic Basin and Range faulting	Zimmerman (1961), Crecraft and others (1981), Oviatt (1991a)
CK	Coyote Knolls	Coyote Knolls	16S-15W	Paleozoic strata	likely late Cenozoic Basin and Range faults	Hose (1963a)
CM	Cricket Mountains	Red Pass, Neels, Sevier Lake NE, Candland Spring, Borden, Cruz, Headlight Mtn., Cat Canyon	20 to 23S - 9 & 10W	Cambrian and Paleocene formations	formed during late Mesozoic tectonism and/or late Cenozoic Basin and Range faulting	Hintze (1984)
CP	Crystal Peak	Crystal Peak, King Top	21 to 23S - 15W	Ordovician-Devonian strata, Tertiary volcanics	likely late Cenozoic Basin and Range faults	Hintze (1972, 1974c)
CR	Confusion Range	numerous, see Tule Valley map (Hintze and Davis (2002c)	15 to 19S - 17 & 18W	Middle and Upper Paleozoic strata	formed during late Mesozoic tectonism and/or late Cenozoic Basin and Range faulting	Hose (1977)
DV	Dog Valley	Cove Fort, Dog Valley Peak	24 to 26S - 6 & 7W	Paleozoic-Mesozoic strata and Miocene volcanics	likely late Cenozoic and might be partly Quaternary faulting; but northeast-trending faults might be older than 40 Ma	Zimmerman (1961), Steven and Morris (1983), Davis (1983)
HH	Halfway Hills	Halfway Summit, Tunnel Spring	25 & 26S - 18W	Paleozoic strata and Oligocene volcanics	formed during early Tertiary and/or late Mesozoic tectonism	Best and Hintze (1980a), Hintze (1981d)
HC	House Range, central	Hell n' Moriah, Canyon, Skull Rock Pass	19 & 20S - 13 & 14W	Cambrian strata	formed during late Mesozoic tectonism and/or late Cenozoic Basin and Range faulting	Hintze (1967, 1974d)
HN	House Range, northern	Swasey Peak, Marjum Pass, Miller Cove, Notch Peak, Whirlwind Valley	16 to 19S - 12 to 14W	Cambrian strata	most likely are late Cenozoic Basin and Range faults, but some may have formed during late Mesozoic tectonism	Hintze (1974d, 1981a, c)
HS	House Range, southern	Burnout Canyon, Red Tops	21 to 23S - 13W	Cambrian-Ordovician strata, Tertiary volcanics	most likely are late Cenozoic Basin and Range faults, but some may have formed during late Mesozoic tectonism	Hintze (1974a)
LD	Little Drum	Little Drum Pass, Lady Laird Peak	15 & 16S - 10 & 11W	Tertiary volcanics	likely late Cenozoic Basin and Range faults	Hintze (2003), this bulletin
MC	Meadow Creek	Sunset Peak, Fillmore, Mt. Catharine	21 to 23S - 3 to 5W	Jurassic Navajo and Tertiary Oak City strata	mass-movement scarps and/or late Cenozoic Basin and Range faults	Hintze (unpublished mapping, 1992), this bulletin
MG	Maple Grove	Scipio Lake	20S-2W	Cretaceous-Paleocene strata	late Cenozoic Basin and Range faults that might have Quaternary offset	Oviatt (1992)
MH	Mountain Home	Mountain Home Pass, Mormon Gap	24 & 25S - 19W	Paleozoic strata	formed during late Mesozoic tectonism and/or late Cenozoic Basin and Range faulting	Hintze (1986a-b), Hintze and Best (1987)

Table 7. (continued)

Figure Symbol	Name	7½′ Quadrangle(s)	Township-Range	Age	Surface map units	References
MM	Middle Mountain	Middle Mountain	22S-16W	Paleozoic strata	uncertain	Hintze (1974c)
SFM	San Francisco Mountains	Frisco Peak, High Rock, Iron Mine Pass	25 & 26S - 12 & 13W	Precambrian-Cambrian strata	could be as old as Precambrian or as young as early Tertiary, but strike-slip offset implies late Mesozoic tectonism	Hintze and others (1984), Lemmon and Morris (1984), this bulletin
SM	Spring Mountain	Spring Mountain	15S-19W	Paleozoic strata (concealed)	likely related to the early Tertiary Snake Range decollement	Hintze (unpublished mapping, 1994), this bulletin
SW	Sand Wash	Crystal Peak	23S-15W	Paleozoic strata	uncertain	Hintze (1974c)
TS	Tunnel Spring Mountains	Tunnel Spring, Big Jensen Pass	23 & 24S - 17W	Paleozoic strata, Tertiary volcanics	due to early Tertiary and/or late Cenozoic Basin and Range faulting	Hintze (1981d), Anderson (1980, 1983), Hintze (1997d)
VM	Valley Mountains	Scipio North, Scipio South, Scipio Lake	17 to 20S - 2W	Cretaceous-Paleocene strata	formed during late Mesozoic-early Tertiary tectonism and/or late Cenozoic Basin and Range faulting	Oviatt (1992), Anderson and Barnhard (1992), Witkind (1994), Peterson (1997)
WW	Wah Wah Mountains	Wah Wah Summit, Wah Wah Cove, Grassy Cove, Fifteenmile Point	24 to 26S - 14 to 16W	Cambrian strata	uncertain	Hintze (1974e)

quadrangles and townships and ranges where they are exposed, tells the ages of the rocks cut by the faults, and cites the geologic references to their occurrence. Each named fault cluster is discussed briefly in the same order in the text following the table.

Burbank Hills east faults (BE): The solid lines on figure 206 indicate nearly vertical, north-striking normal faults that collectively downdrop Devonian strata a few hundred feet parallel to the concealed range-bounding normal fault on the east side of the Burbank Hills (East Burbank fault, table 6; dotted line). A northeast-striking, high-angle, Basin and Range normal fault (table 6 - East Burbank fault) through Cowboy Pass (see bar and ball) truncates these faults and downdrops Oligocene volcanic rocks against the Devonian strata of the Burbank Hills (Anderson, 1980); so, the age of the faults shown only on figure 206 is uncertain.

Barn Hills faults (BH): These high-angle normal faults, mostly down-to-the-east, repeat the Paleozoic section in several north-south-trending fault blocks (figure 6). Because nearby dotted faults with similar trends and relationships on figure 206 are probably concealed Basin and Range normal faults near Quaternary-bedrock contacts (table 6), the exposed faults are likely late Cenozoic Basin and Range faults.

Burbank Hills west faults (BW): Folded Paleozoic strata are cut by apparently normal faults of short length and small displacement. The faults are of indeterminate age but most likely are adjustment faults related to late Mesozoic folding of the strata.

Cove Creek faults (CC): Eruptions of basalt flows and rhyolite domes dated at 2 to 3 Ma were accompanied by local doming and gravity displacement. Faults in the Cove Creek area appear to have formed concurrently with the volcanic activity and local uplift rather than being Basin and Range normal faults. Oviatt (1991a) presented a contour map that estimated the local uplift at more than 1,000 feet (300 m). Alternatively, these are Basin and Range normal faults (CC, table 6).

Coyote Knolls faults (CK): These are high-angle normal faults of relatively small offset in Paleozoic strata, and were probably formed during late Cenozoic Basin and Range faulting, although no direct way of dating the exact age of the faulting is available.

Cricket Mountains faults (CM): In the Cricket Mountains, Cambrian strata dip predominantly eastward about 20° and are repeated by dominantly down-to-the west normal faults that trend in directions mostly similar to the range-bounding East and West Cricket faults (dotted on figures), but some are truncated by these range-bounding faults. All faults appear to be dip-slip normal faults, with one exception: in section 7, T. 22 S., R. 9 W. in the Candland Spring 7½-minute quadrangle, a near-vertical, fault-bounded zone with uncertain movement transects gently dipping rocks. Cambrian strata are not metamorphosed or significantly brecciated along faults. Paleocene Flagstaff Formation conglomerate, breccia, and lacustrine limestone rest unconformably on Cambrian strata and are displaced by the Basin and Range faults that cut the Cambrian rocks. Prior to Basin and Range faulting, Cambrian strata appear to have been nearly flat-lying. However, the Cricket Mountains are on the Sevier arch and could have been normal faulted prior to Basin and Range faulting, either during the Sevier orogeny or in the Tertiary. Basin and Range faulting is believed to have begun about 17 million years ago and continues into the present, as indicated by the

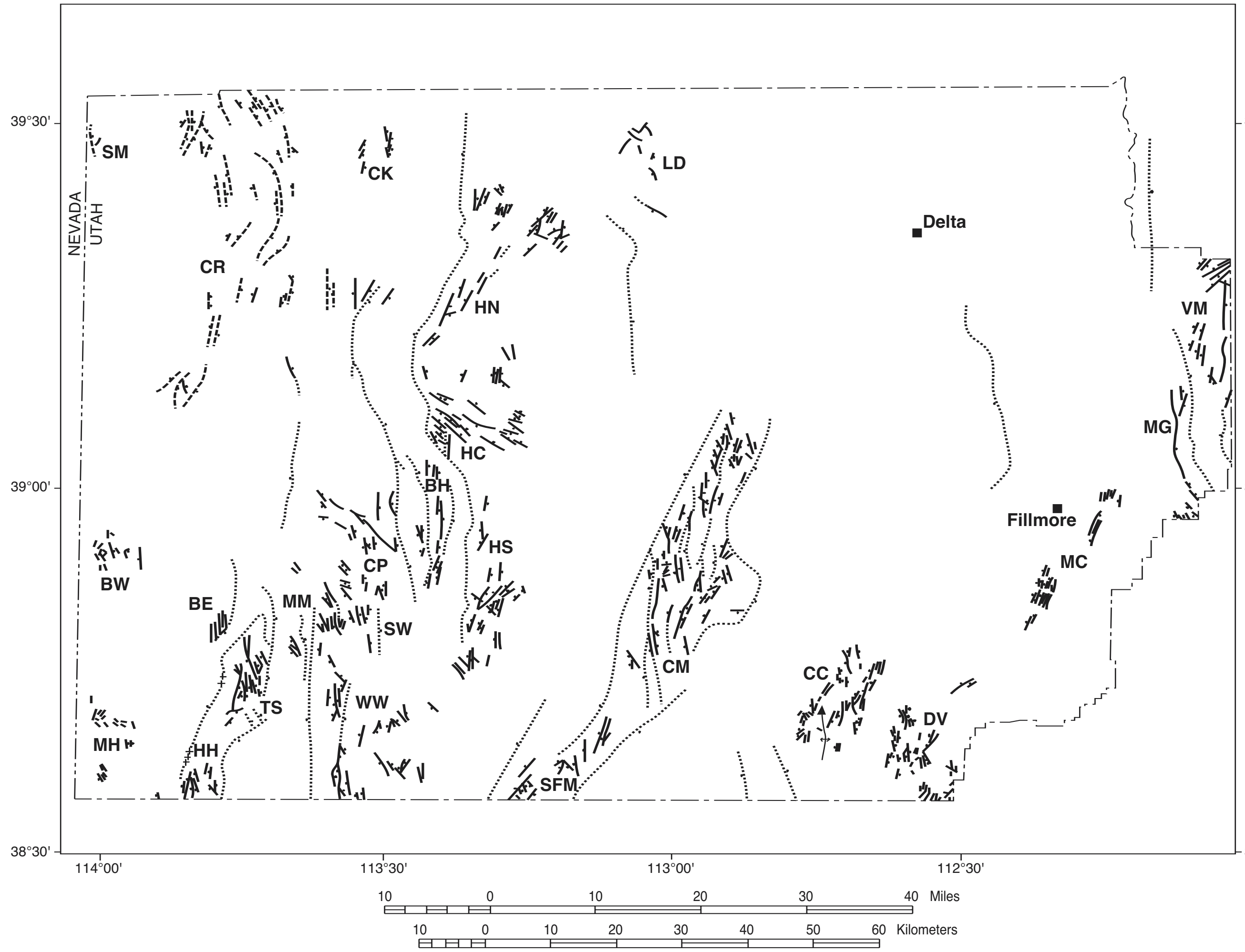


Figure 206. Post-40 million-year-old structures and faults of indeterminate age in Millard County. See table 7 and text for names and descriptions of lettered faults. Range-bounding faults are shown as dotted lines for reference.

Basin and Range faults that cut Lake Bonneville deposits on the west side of the Cricket Mountains (table 6- West Cricket). Dotted faults on figure 206 are concealed normal faults near the Quaternary-bedrock contact (see table 6).

Crystal Peak faults (CP): Most of the short, less than 2 miles (3.2 km) long, high-angle faults in this area are likely late Cenozoic Basin and Range faults. The 5-mile-long (8 km) northwesterly trending fault in the southern Confusion Range south of King Top Peak might be a pre-40 million-year-old strike-slip fault.

In the vicinity of Crystal Peak a number of megaslide blocks of Ordovician and Silurian strata rest upon the Oligocene Tunnel Spring Tuff (age 35.4 Ma) (Hintze, 1972; Steven, 1989). Steven (1989) suggested that this tuff was explosively ejected from a caldera a few miles east of Crystal Peak. A north-south-trending fault cuts later Oligocene volcanic rocks (age 30.5 Ma) in this area (CP, table 6).

Confusion Range faults (CR): Hose (1977) showed that many of the principal normal faults in the Confusion Range are coeval with Sevier-age folding and thrusting within the Confusion Range synclinorium and hence pre-Basin and Range. The 1:24,000-scale geologic maps from which Hose (1977) simplified the structural pattern for his structural analysis, and from which figures 195 and 206 were derived, show that the trend of most of the normal faults in the Confusion Range parallels the trend of the synclinorium. But, later Basin and Range faults have a similar north-south trend and movement may have taken place during both time intervals.

Dog Valley faults (DV): Normal faults in this area cut Paleozoic, Mesozoic, and Miocene rocks. Age of faulting is likely late Cenozoic and might be partly Quaternary but cannot be identified as such because the area lacks surface offset of Quaternary units (DV, table 6). Most fault trends are roughly north-south similar to Pliocene faults in the Cove Creek area (CC), and Quaternary faults in the Black Rock Desert and in basalt near Cove Fort (figure 204). The northeasterly trending faults, north of the main cluster, are in Paleozoic and Mesozoic rocks near Sevier-age structures (figure 195) and might be older than 40 million years old.

Halfway Hills faults (HH): Down-to-the-west, high-angle, normal faults repeat the upper Needles Range Group (age 30.5 Ma) south of Halfway Summit. North of Halfway Summit, pervasive normal faults on Warm Cove Ridge brecciate and attenuate the Ordovician strata (TKbr), but do not cut the upper Needles Range Group (figure 207). Devonian dolomite is brecciated (TKbr) in a zone more than 100 feet (30 m) wide along the Halfway Hills fault on the west side of the

Figure 207. *View roughly to the north of Ordovician, Silurian, and Devonian strata repeated in thrust, attenuation, and normal fault blocks on Warm Cove Ridge in the Desert Range Experimental Station; faulting is so complex that strata can not be labeled.*

range (figures 162 and 204). This brecciated zone can be followed intermittently northeastward along the west side of Antelope Valley for about 10 miles (16 km).

Central House Range faults (HC): These are southeasterly trending normal faults that Hintze (1967) pointed out are likely antithetic to the main House Range fault. However, they trend in the direction of Sevier-age tear faults, and might have undergone two types and time intervals of movement. In contrast to attenuation faults of similar trend at the north end of the House Range (figure 195), these faults do not bound zones of attenuation within the Cambrian stratal sequence.

Northern House Range faults (HN): These are high-angle normal faults of relatively small displacement. They are probably internal adjustment faults related to Basin and Range extension and tilting of the House Range along the main House Range fault along the west side of the range, but some could be Sevier age.

Southern House Range faults (HS): These are high-angle, normal faults that cut Cambrian and Tertiary rocks, and have relatively small displacement within the Cambrian strata. Most are probably late Cenozoic Basin and Range faults of small offset like those in the Barn Hills (BH). The few northeasterly and southeasterly trending faults might possibly be strike-slip faults of the late Mesozoic Sevier orogeny.

Little Drum faults (LD): Hintze's unpublished geologic mapping (simplified in Hintze and Davis, 2002c) shows that these faults offset the Drum Mountains Rhyodacite (age 37 Ma or older) and the younger volcanic sequence of Dennison Canyon (age also 37 Ma). The longest fault is down to the southwest into Whirlwind Valley and may offset the still younger Red Knolls Tuff (age 36.5 Ma); it is probably a range-bounding fault (LD, table 6).

Meadow Creek faults (MC): Hintze's unpublished geologic mapping for this bulletin (simplified in Hintze and others, 2003) shows that most of these down-to-the-valley "faults" occur on the steep west front of the Pahvant Range where jointed Navajo Sandstone blocks have crept downslope because of the incompetency of the underlying Chinle Formation. The displacement is primarily a result of gravity-induced mass movement. The large cluster of features southwest of the label "MC" on figure 206 is intimately associated with mass movements (see Hintze and others, 2003). However, the features are included here because the cluster northeast of Fillmore cuts the Oak City Formation and may be Basin and Range normal faults. The cluster just to the south, though near Chinle exposures which are prone to landsliding, might also be Basin and Range normal faults; both clusters near Fillmore are shown as normal faults on Hintze and others (2003).

Willis (1994) noted similar features in the Flagstaff Formation along the Elsinore fault zone north of Richfield. He described them as keystone blocks, with open fractures and forward rotation, that were produced by gravity deformation (mass movement) after being cut by steeply dipping normal faults.

Maple Grove faults (MG): Oviatt (1992) suggested that some displacement on the Maple Grove high-angle Basin and Range normal fault occurred in late Pleistocene and Holocene time coeval with movement on the Pahvant Range fault to which it is subparallel. However, no Quaternary scarps are present and the faults cut only Cretaceous and Paleocene rocks. To the southeast, in Sevier County, Quaternary offset has occurred on the Red Canyon fault (Anderson and Bucknam, 1979) which is colinear with the longest Maple Grove faults (MG, table 6).

Mountain Home faults (MH): These short faults with small displacement are likely strike-slip adjustment faults coeval with folding and thrusting during the late Mesozoic Sevier orogeny. But like other faults in pre-Cenozoic strata in the ranges in Millard County, late-Cenozoic Basin and Range dip-slip movement may have occurred along some faults.

Middle Mountain faults (MM): The trend of normal faults within this range mimics apparent trends of concealed range-bounding Basin and Range faults. Ordovician strata on the west side of Middle Mountain and on Cat Knoll are brecciated and attenuated. This is the north end of a zone of this type of deformation ("Tectonic breccia" map unit, TKbr) that extends southward through the Tunnel Spring Mountains (TS) and Halfway Hills (HH) into the Sawtooth Peak 7 1/2-minute quadrangle in Beaver County (Best and Hintze, 1980b).

San Francisco Mountains faults (SFM): These normal faults in Precambrian and Cambrian rocks are subparallel and perpendicular to the bounding faults on the west side of the range and are concealed by the unfaulted Tertiary Conglomerate of High Rock Pass. The faults include a wide breccia zone (TKbr) with strike-slip offset that could be as old as Precambrian, but the strike-slip offset implies a Cretaceous age.

Spring Mountain faults (SM): These isolated outcrops lie between the Confusion Range synclinorium and the Snake Range decollement structures. Most of the Paleozoic rocks in local low hills near Spring Mountain have been brecciated, but this brecciation did not affect the small outcrop of Oligocene volcanic rocks in the same area. A concealed fault of uncertain age separates the larger exposures (Hintze unpublished mapping simplified in Hintze and Davis, 2002c). The structures on Spring Mountain are probably related to the Snake Range decollement (Tertiary) because some of the Cambrian carbonate rocks have been metamorphosed.

Sand Wash fault (SW): This concealed fault appears to offset Ordovician rocks (Hintze, 1974c) and has the same trend as a post-40 million-year-old fault (see CP, tables 6 and 7) less than 1 mile (1.6 km) to the west. Therefore, the age of the fault is uncertain.

Tunnel Spring Mountains faults (TS): Late Cenozoic normal faults on the southeast flank of the Tunnel Spring Mountains repeat the Devonian strata, producing a localized apparent extension of as much as 70 percent (Anderson, 1980, 1983). There is likely a concealed, low-angle, listric, normal fault surface upon which the domino-like blocks have moved downslope.

On the northwest foothills of the Tunnel Spring Mountains the major Basin and Range bounding fault is characterized by breccia zones in Paleozoic rocks (map unit TKbr) that are as much as 50 feet (15 m) wide (figure 12). Concealed faults, dotted on figure 206, appear to offset but do not brecciate Oligocene volcanic rocks.

Valley Mountains faults (VM): These high-angle normal faults displace the North Horn (Cretaceous) and Flagstaff (Paleocene) Formations both within the Valley Mountains and along their west margin. The west margin fault (dotted on figure 206), paired with the east frontal fault of the Pahvant Range (also dotted), bound the graben of Round Valley. Anderson and Barnhard (1992) concluded that faulting here was entirely dip-slip.

Wah Wah Mountains faults (WW): These high-angle, northerly trending, normal faults offset Cambrian strata, but are apparently concealed by Tertiary volcanic rocks 34 million years old and younger. The longest is a concealed range-front fault at the Quaternary-bedrock contact (table 6) in the north-central part of the range. They are likely small Basin and Range extensional faults, but could be between 40 and 17 million years old.

Selected Deep Exploration Wells in and Adjacent to Millard County

Deep wells drilled since 1952 have yielded structural and stratigraphic information that supplements geologic observations at the surface and improves our understanding of the geology of Millard County. Wells drilled in the Sevier Desert area have been particularly revealing of stratigraphic data nowhere exposed at the surface and only partly suggested by geophysical data. Well locations are shown on figure 208 and more data on the wells are in appendix A.

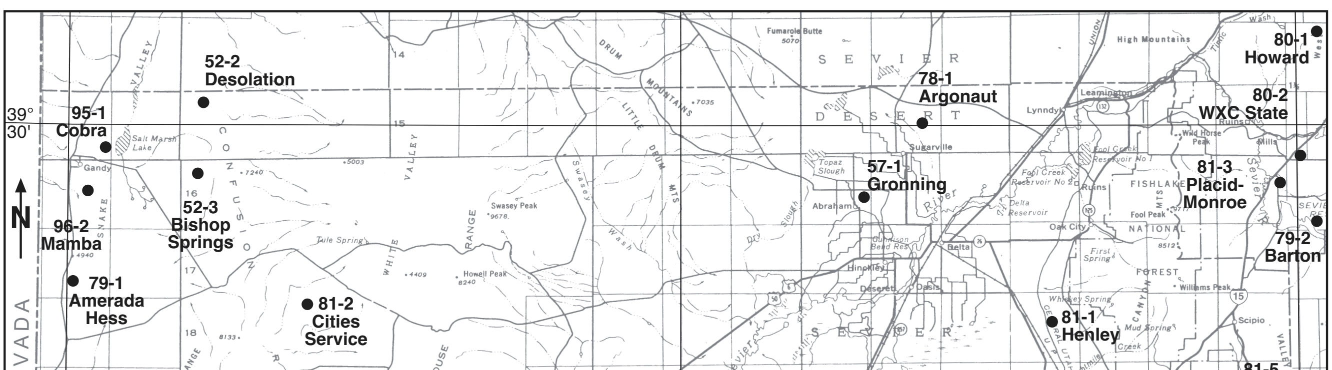


Figure 208. Location of selected deep exploration wells in and adjacent to Millard County. Numbers indicate the year in which each well was completed (for example 1979 = 79-); also shown is the name by which the well is commonly known. See appendix A for detailed data.

Table 8 is a list of selected wells pertinent to interpreting geological relationships in Millard County. This is not a comprehensive list of Millard County wells; additional well records are contained in Hansen and Scoville (1955), Helymun and others (1965), Kerns (1987), and in files at the Utah Department of Natural Resources, Division of Oil, Gas and Mining. Many of the wells documented herein were logged by the late Dr. John E. Welsh, a stratigrapher from Salt Lake City who worked in the Great Basin for 40 years, and who contributed geologic interpretations to this bulletin which he made by personal examination of drill cuttings, core samples, and electric or other logs where available (see appendix A for details).

Readers are advised that lithologic and mud logs are interpretive; well loggers attempt to compare the small chips of rock and rare core samples taken from a well with rock sequences observable in surface exposures near the well site. In some instances, comparable surface rocks are not exposed and the well samples must be dated or otherwise identified solely on the basis of examination of the cuttings. Cuttings are generally available unless the well encountered subsurface cavities or fracture zones and lost its ability to recover samples. In this case the only means of estimating the kind of rock being drilled is by means of various electric, radioactive, or mechanical logging systems that provide data from instruments lowered into the well on a cable. Well logging is an art whose accuracy depends a great deal on how familiar the well logger is with rocks exposed at the surface that are of the same age as those encountered in the well. Samples from some Millard County wells are housed in the Utah Geological Survey Core Research Center in Salt Lake City (appendix A).

Summary of Geologic Relationships in Wells

Wells drilled in and near Millard County are discussed below in three areal groupings that contain wells with similar geologic relationships: (1) the western group includes all wells west of the House Range; (2) the central group includes the following wells in the Sevier Desert -Argonaut (78-1), Gronning (57-1), Pavant Butte (81-7), Cominco (80-3), Hole-in-Rock (81-4), Meadow (82-1), and Acord (79-3); and (3) the eastern group includes all other wells shown on figure 208.

Table 8. Selected deep exploration wells, shown on figure 208. Listed by age beginning with the oldest well in 1952.

Well No.	Name on figure	Operator
52-1	Burbank	Standard Oil of California
52-2	Desolation	Standard Oil of California
52-3	Bishop Springs	Gulf Oil; Tiger Oil in 1980
56-1	Baker Creek	Shell Oil Company
57-1	Gronning	Gulf Oil Company
60-1	Sunset Canyon	Shell Oil Company
68-1	Pyramid	Pyramid Oil & Gas
75-1	Bridger	Bridger Petroleum Company
76-1	Anschutz-Monroe	Anschutz-Williams Energy
78-1	Argonaut	Argonaut Energy
78-2	Caroline Hunt	Hunt Energy Corporation
78-3	Cove Fort	Union Oil Company
78-4	Cove Fort-Sulphurdale	Union Oil Company
79-1	Amerada Hess	Amerada Hess Corporation
79-2	Barton	Placid Oil Company
79-3	Acord	Phillips Geothermal
80-1	Howard	Placid Oil Company
80-2	WXC State	Placid Oil Company
80-3	Cominco	Cominco American Inc.
80-4	Ensign	Commodore Resources Corp.
81-1	Henley	Placid Oil Company
81-2	Cities Service	Cities Service Oil Company
81-3	Placid-Monroe	Placid Oil Company
81-4	Hole-in-Rock	Arco Oil and Gas Company
81-5	WXC-USA	Placid Oil Company
81-6	Antelope Valley	American Quasar Petroleum
81-7	Pavant Butte	Arco Oil and Gas Company
81-8	Horse Heaven	American Quasar Petroleum
82-1	Meadow	Arco Oil and Gas Company
82-2	Outlaw	Commodore Resources Corporation
82-3	Paxton	Placid Oil Company
95-1	Cobra	Balcron Division-Equitable Energy
95-2	Sevier Lake	Chevron USA Production Company
96-1	Black Rock	Chevron USA Production Company
96-2	Mamba	Equitable Resources

Wells west of the House Range: This area contains a very thick sequence of Paleozoic marine strata in the Confusion Range-Burbank Hills-Mountain Home Range synclinorium, which runs north-south across Millard County. Subsurface geologic relationships inferred from wells drilled in this area are consistent with those shown on maps of the surface geology of the area. All but two wells have drilled a normal upright column of strata that locally was thinned by brittle structural attenuation formed by folding of the strata during downwarping of the synclinorium in the late Mesozoic. Such local attenuation is seen in the Bishop Springs (52-3) and Burbank (52-1) wells. The Horse Heaven (81-8), Pyramid (68-1), and Antelope Valley (81-6) wells penetrated small local thrust faults within the synclinorium that caused repetition of part of the stratigraphy encountered in each well. Because of their locations in valley areas some distance from bedrock, the Baker Creek (56-1), Amerada Hess (79-1), Cobra (95-1), Mamba (96-2), Antelope Valley (81-6), and Bridger (75-1) wells each encountered a considerable thickness of Tertiary sedimentary and volcanic deposits. The former four wells also penetrated rocks like those exposed in the Snake Range (located to the west in Nevada). In short, except for possible Tertiary faulting in the Mamba well and poorly constrained faulting in the Amerada Hess well, wells drilled west of the House Range have revealed no surprises.

Wells in the Sevier Desert: Each well drilled in the Sevier Desert has given new information on the subsurface geology of this flat terrain. The area is on the crest of the Mesozoic Sevier arch from which Cretaceous erosion stripped all older strata down to the Cambrian. The wells are discussed below from north to south.

Argonaut well (78-1): This well penetrated 7,734 feet (2,357 m) of Quaternary-Miocene valley fill, including 3,470 feet (1,058 m) of salt and gypsum at the bottom, before reaching marbleized and sheared graphitic Cambrian limestone and dolomite (3,532 feet [1,077 m] penetrated in well). The well contains the northernmost record of marbleized Cambrian rocks like those exposed in the Mineral Mountains. Other wells (81-7, 80-3, 81-4, and 82-1) document these rocks are at least in a narrow belt that extends 65 miles (104 km) north-northeastward from the Mineral Mountains. When this well was drilled there was some speculation as to whether the salt and gypsum might be Jurassic in age, but Lindsey and others (1981) found it to be Miocene. No other Sevier Desert well has encountered this much Miocene evaporitic material, which probably accumulated in local playa lakes of relatively small areal extent. See Faulds and others (1997) for a report of thick nonmarine Miocene salt in Arizona.

Seismic-reflection data presented by McDonald (1976) show plainly that the triangular-shaped salt body penetrated by the Argonaut well is about 4 miles (6.4 km) wide on his seismic line 8. Flowage of salt from its original flat bed into a triangular salt mass is likely the mechanism that produced the normal faulting of Tertiary beds shown on line 8 by McDonald (1976), as suggested by Anders and Christie-Blick (1994). The original salt layer was probably less than 1,000 feet (300 m) thick and 15 to 20 miles (24-32 km) in east-west width. Its original north-south extent is as yet undefined by seismic or drilling data, although some gypsum and salt were encountered in other deep wells in the Sevier Desert (57-1, 81-7, and 81-4). McDonald's (1976) seismic line 1, less than 4 miles (6.4 km) south of the Argonaut well, does not show salt and therefore constrains the southern extent of the salt body.

The Argonaut well contains the northernmost known record of the Sevier Desert reflector, originally called a "detachment" by McDonald (1976) but thought to be an unconformity between Tertiary and Cambrian rocks by others (Anders and Christie-Blick, 1994; Hamilton, 1994; Anders and others, 2001). Anderson and others (1983) discussed the normal faults in the Tertiary rocks above the Sevier Desert reflector but they ignored the effect that salt mobility played in faulting of the Tertiary strata above the Cambrian basement. Reinterpretation of McDonald's (1976) seismic lines by Dr. James L. Baer (unpublished Intermountain Power Project report, January 1979) shows that some normal faults actually offset the Sevier Desert reflector slightly and also offset reflectors within the Cambrian basement. Smithson and Johnson (1989) also interpreted the COCORP seismic line to the south as showing the Sever Desert reflector is significantly offset by normal faults.

Gronning well (57-1): This is the first deep well drilled in the Sevier Desert basin and it was discussed by McDonald (1976), Lindsey and others (1981), Anderson and others (1983), Planke (1987), and Planke and Smith (1991). The well penetrated 8,064 feet (2,458 m) of Tertiary valley fill, including some Pliocene basalt flows, and it bottomed in Oligocene tuffaceous sediments that include some anhydrite. The well was not deep enough to reach the Sevier Desert reflector (Cambrian basement), which should have been reached at a depth of about 11,000 feet (3,350 m) as predicted on McDonald's (1976) seismic line 1, also shown in figure 7 of Anderson and others (1983). This well served as the impetus for subsequent drilling of deep wells in the Sevier Desert basin.

Sevier Lake well (95-2): This well penetrated 5,160 feet (1,573 m) of Quaternary and Tertiary basin fill before bottoming in Cambrian limestone and dolomite west of the West Cricket fault zone. Similar middle Cambrian carbonate strata are present to the west in the House Range and to the east in the Cricket Mountains.

Pavant Butte well (81-7): This well penetrated 9,770 feet (2,978 m) of Tertiary sediments, including one basalt flow, and nearly 1,200 feet (360 m) of salt and gypsum before reaching the Sevier Desert reflector (Cambrian basement). The basement rocks have undergone phyllitic metamorphism similar to that seen in surface exposures of Cambrian strata at the north end of the Mineral Mountains on the southern border of Millard County.

Black Rock well (96-1): This well is located within the Cricket Mountains horst near outcrops of Pioche Formation and Prospect Mountain Quartzite. The interpretation of this well shown on Hintze and Davis (2002b) differs from that in appendix A, and, with the inferred Mesozoic strata, as well as Mississippian strata, none work with regional reconstructions of Allmendinger (1992) and Royse (1993). The well did penetrate 756 feet (230 m) of Quaternary fill and Tertiary rocks before entering the Cambrian Prospect Mountain Quartzite and Precambrian rocks of the Canyon Range thrust sheet. The exact depth of the Canyon Range thrust fault is uncertain because later normal faults in the Cricket Mountains were likely intersected by the well bore and offset the

Canyon Range thrust. The Pavant thrust, or a splay of the Pavant thrust, was encountered at a depth of 10,610 feet (3,098 m) and, as interpreted for this study, was underlain by overturned Triassic and Jurassic rocks. The well then penetrated one or more faults (possibly including the Sevier Desert reflector) and bottomed in what was interpreted in this study as lower Cambrian quartzite.

Cominco well (80-3): This well is located east of the Cricket Mountains horst, and west of the Clear Lake fault zone. Because it is on the upthrown side of the Clear Lake fault zone, this well penetrated only 2,480 feet (756 m) of Tertiary valley fill before encountering Precambrian quartzite. The drill hole then went through nearly 6,000 feet (2,000 m) of Precambrian metasediments before hitting the Frisco-Canyon Range thrust and passing into an upright section of Cambrian strata more than 4,600 feet (1,400 m) thick. Cambrian strata below a depth of 12,000 feet (4,000 m) in the well are phyllitic, but are not metamorphosed to the extent that Cambrian rocks are metamorphosed in the bottom of wells to the east.

Hole-in-Rock well (81-4): This well is located on the downthrown block just east of the buried Tertiary normal fault called the "Sevier Basin west basin-bounding fault" by Planke (1987) and Planke and Smith (1991). Consequently, it penetrated a great thickness (9,100 feet [2,774 m]) of basin-filling claystone, siltstone, sandstone, and some anhydrite before passing through the Sevier Desert reflector into metamorphosed Cambrian carbonate rocks. Cuttings from this well were microscopically examined by Anders and Christie-Blick (1994; also Anders and others 2001) to determine if quartz grains in rocks near the Sevier Desert reflector have fractures that might be attributed to fault movement on the reflector's surface. No such fractures were found so they concluded that the reflector is not a fault surface as it had been interpreted by some geologists (Allmendinger and Royse, 1995; Coogan and DeCelles, 1996, 1999).

Meadow well (82-1): This well is located about 4 miles (6.4 km) east of the Hole-in-Rock well described above. It passed through only 5,835 feet (1,779 m) of Tertiary valley fill before reaching the Sevier Desert reflector and the metamorphosed Cambrian strata beneath it. Anders and Christie-Blick (1994; also Anders and others, 2001) examined quartz grains from this well with the same result as reported for the Hole-in-Rock well discussed above.

The Tertiary sediments encountered in this well are much coarser than those in the Hole-in-Rock well, probably because the Meadow well is closer to the Pahvant Range which is the principal source for the Tertiary clastics. The well also drilled through a few large slide blocks of Paleozoic rocks within the Tertiary sequence. These are similar to slide blocks seen at the surface in the Pliocene-Miocene Oak City Formation on the west flank of the Canyon Mountains near Oak City (Hintze, 1991a; Hebertson, 1993).

The Meadow well left metamorphosed Cambrian strata at a depth of 13,630 feet (4,154 m) and penetrated quartz monzonite or granitic gneiss for 1,907 feet (581 m) to the bottom of the well. No other well in the Sevier Desert penetrated this much crystalline rock; it may be a subsurface extension of the Tertiary and Precambrian Mineral Mountains complex exposed 20 miles (32 km) southwest of the well. Royse (1993) showed a Precambrian K-Ar age of 1,635 Ma for granitic gneiss in this well, and the small thickness of Prospect Mountain Quartzite in this well suggests that the Cambrian-crystalline rock contact is intrusive and Tertiary. The presence of Tertiary intrusives may help to explain the marbleization of Cambrian rocks seen at the bottom of other wells in the Sevier Desert area (78-1, 81-7, 80-3, and 81-4), as reported above.

Acord well (79-3): This geothermal test well is located south of the Sevier Desert, but is included here because it penetrated Tertiary intrusions and bottomed in Precambrian gneiss about 6 miles (10 km) west of exposures of the Mineral Mountains complex. However, it did not encounter metamorphosed lower Paleozoic carbonate rocks, slide blocks, or a thrust fault. The well did penetrate at least 6,500 feet (1,950 m) of Tertiary valley fill, mostly reworked volcanic rocks, and about 3,000 feet (900 m) of Tertiary volcanic rocks like those exposed to the west in the Beaver Lake Mountains. Smith and others (1989) interpreted a gently (10°) west-dipping reflector on a seismic line through the area as a Basin and Range normal fault. The well log (appendix A) would seem to indicate the reflector is the contact between basin fill and the Mineral Mountains complex.

Wells in eastern Millard and adjacent counties: Petroleum explorationists drilled wells in central Utah to see if the oil-producing potential of the Utah-Wyoming overthrust belt might extend across the Uinta arch. In central Utah, the existence of the Canyon Range thrust and the Pavant thrust at the surface implied that subsurface conditions similar to those in northeastern Utah might be found. This bulletin does not review all wells in central Utah but summarizes what has been learned from six deep wells in eastern Millard County and six wells in adjacent counties (see figure 208 for locations). These well were not productive. Three of the wells, Sunset Canyon (60-1), Barton (79-2), and Howard (80-1), did not encounter any thrust faults. The Sunset Canyon well is on the Paxton thrust sheet. The other two wells may be situated on the Paxton thrust sheet east of the Pavant thrust because two nearby wells, Placid-WXC-State (80-2) and Placid-Monroe (81-3), penetrated thrust faults that repeat Jurassic strata likely on the Paxton thrust sheet. One well, Anschutz-Monroe (76-1), drilled through the Pavant thrust. The Caroline Hunt (78-2), Cove Fort (78-3), Henley (81-1), and Placid-WXC-USA (81-5) wells encountered thrusts within the Pavant thrust sheet that repeat various parts of the stratigraphic section. The Cove Fort-Sulphurdale (78-4) well did not penetrate a thrust despite its proximity to the Cove Fort (78-3) well. The Paxton (82-3) well drilled through the Paxton thrust sheet. The wells are discussed in the order given above.

Sunset Canyon well (60-1): This is the first deep well to be drilled in eastern Millard County. It is actually in Meadow Creek Canyon rather than the canyon 4 miles (6 km) to the south for which it was named. The well started in Upper Triassic Shinarump Conglomerate, passed through the Lower Triassic Moenkopi Formation, and penetrated Permian, Pennsylvanian, Mississippian, Devonian, and Silurian strata, mostly carbonates, before bottoming in the Upper Ordovician Fish Haven Dolomite.

Although the well penetrated no thrust faults, it is on the Paxton allochthon (thrust sheet) and its rocks are believed to have been transported as much as 20 miles (33 km) eastward from their original site of deposition during Cretaceous thrusting (Royse, 1993; DeCelles and others, 1995).

Barton well (79-2): This well passed through 4,450 feet (1,356m) of Tertiary volcanic and sedimentary rocks before encountering Jurassic rocks beneath an unconformity. The well then penetrated a normal sequence of Triassic, Permian, Mississippian, and Devonian strata, bottoming in the Silurian Laketown Dolomite at 21,840 feet (6,657 m). It contains the westernmost complete record of Triassic and Jurassic strata at this latitude in central Utah. Although two nearby wells, Placid-Monroe (81-3) and Placid WXC-State (80-2), encountered small thrusts that repeat the Jurassic sequence, this well apparently is located just east of that zone of thrusting. It is interpreted as being on the Paxton thrust sheet by DeCelles and others (1995).

Howard well (80-1): After drilling through 4,875 feet (1,486 m) of lower Tertiary and Cretaceous conglomerate and sandstone, and the unconformity at their base, this well passed through 4,345 feet (1,324 m) of Jurassic Arapien limestone, anhydrite, shale, and salt before encountering 1,424 feet (434 m) of Twin Creek Limestone and then 1,446 feet (441 m) of Navajo Sandstone. The well bottomed at 12,150 feet (3,703 m) in Chinle shale. The 1:24,000-scale geologic map and cross section by Meibos (1983), that includes this well, shows a normal fault in the zone between 570 and 2,580 feet (174 and 787 m) where the well lost circulation. The well is located between the Nebo thrust, exposed near Nephi, and the Placid-State (80-2) and Placid-Monroe (81-3) wells that encountered small thrusts which repeat the Jurassic section. Like the Barton well (79-2), the Howard well may have penetrated the Paxton thrust sheet rather than the Pavant (Nebo) thrust sheet.

WXC-State well (80-2): After drilling through 4,770 feet (1,454 m) of lower Tertiary and Cretaceous sediments, and the unconformity at their base, this well stayed in Jurassic strata to its total depth of 13,894 feet (4,235 m). The well encountered a thrust fault at 8,070 feet (2,460 m) which repeats the Jurassic section. Thicknesses of the five repeated members of the Twin Creek Limestone differ by less than 10 percent between the upper and lower stacks, suggesting that distance of transport on the thrust was not great. Standlee (1982, figure 14) showed a cross section through this well. However, like the nearby Barton well (79-2) (see DeCelles and others, 1995), the WXC-State well is likely on the Paxton thrust sheet.

Placid-Monroe well (81-3): This well penetrated 3,430 feet (1,045 m) of Tertiary and Cretaceous strata, and the unconformity at their base, and bottomed in Triassic strata at 16,110 feet (4,910 m). It passed through a thrust fault at 7,240 feet (2,207 m) and another thrust at 13,825 feet (4,214 m), both of which repeat the Jurassic-Triassic section. Like nearby wells, this well is likely on the Paxton thrust sheet (see DeCelles and others, 1995).

Anschutz-Monroe well (76-1): In this well, 6,110 feet (1,862 m) of Tertiary and Cretaceous strata, chiefly clastic deposits, lie unconformably over Cambrian carbonate rocks of the Pavant allochthon (thrust plate), which rests on Jurassic strata at 7,200 feet (2,195). Beneath the Jurassic is the normal succession of Triassic, Permian, Mississippian, and Devonian strata to a total depth of 15,369 feet (4,684 m). This well shows that the base of the Pavant thrust has moved (ramped) upsection from the Tintic Quartzite, as exposed in the Pahvant Range near Fillmore, to within the Cambrian carbonate sequence 7 miles (11 km) across strike to the east.

Caroline Hunt well (78-2): This well started in overturned Devonian Sevy Dolomite and drilled through an overturned sequence of Devonian and Mississippian strata, and rocks tentatively identified as Pennsylvanian, Permian, and Triassic, before crossing a thrust fault into Cambrian carbonate rocks. The thrust is probably within the Pavant allochthon (thrust sheet). This unsuccessful geothermal well bottomed at 8,021 feet (2,445 m).

Cove Fort well (78-3): This well, drilled to explore geothermal potential, gives important structural and stratigraphic data on geologic relationships beneath the cover of volcanic rocks on the northwest edge of the Marysvale volcanic field. It confirms that the Tertiary and Cretaceous(?) sandstones and conglomerates (formerly called Price River(?) and North Horn, but interpreted as the Tertiary Flagstaff Formation by Grant Willis, UGS geologist, in this bulletin) are much thinner on the south border of Millard County than they are to the north in central Utah. The Richfield 1:100,000-scale geologic map (Hintze and others, 2003) is the first map to trace these thin strata across the south end of the Pahvant Range in the area north of U.S. Interstate Highway 70.

The Tertiary and Cretaceous(?) conglomerate (in the Flagstaff Formation in this bulletin) unconformably overlies Silurian Laketown Dolomite at a depth of 1,230 feet (375 m) in this well. The Silurian rocks are part of the Pavant or Paxton allochthonous plate that was thrust over Triassic Moenkopi strata at 2,880 feet (878 m) in the well. The well gives the southernmost data point in Millard County for this thrust relationship. The thrust is probably beneath the main Pavant thrust and may be part of the Paxton thrust system of Royse (1993).

Henley well (81-1): This well, located in the Sevier Desert about halfway between Delta and Holden, is included with the eastern group of wells because it is in the Canyon Mountains fault block, which has only a thin cover of surficial deposits over bedrock units similar to those exposed in the Canyon and Pahvant ranges to its east. It is located east of the buried McCormick fault, a Sevier Desert basin-bounding Tertiary normal fault (figure 204). Beneath the surficial deposits the well penetrated 1,610 feet (491 m) of Paleocene-Cretaceous strata that rest unconformably on Paleozoic strata. The Ordovician Fish Haven Dolomite and Eureka Quartzite at the top of the Paleozoic section in this well crop out just east of the well in the Church Hills (Sayre, 1971, 1974; Hintze, 1991g). The thick succession of Ordovician and Cambrian carbonate rocks between 2,010 and 7,470 feet (613 and 2,277 m) were not identifiable in detail, probably because they are a tectonically scrambled melange something like that exposed in the Scipio Pass 7 1/2-minute quadrangle (Michaels and Hintze, 1994). Reappearance of Eureka Quartzite in the well at 7,470 feet (2,277 m) indicates a thrust fault. Coogan (in DeCelles and others, 1995) shows multiple thrust-stacking of Lower Paleozoic strata in his cross section through this well.

WXC-USA well (81-5): This well is located in the Valley Mountains. The geologic relationships encountered in the well are similar to those exposed at the surface in the Pahvant Range, including minor thrusts that cause repetition of part of the Cambrian and Ordovician rocks. An exceptional feature of this well is that it penetrated the Precambrian gneissic basement typical of rocks that underlie Cambrian strata throughout eastern Utah (Hintze, 1988a).

Cove Fort-Sulphurdale well (78-4): This geothermal exploration well also gives important structural and stratigraphic data on geologic relationships beneath the cover of volcanic rocks on the northwest edge of the Marysvale volcanic field. Below the volcanic rocks, the well penetrated an upright sequence of Permian through Mississippian strata. The lower part of the hole penetrated marble, skarn, serpentinite, and quartz monzonite dikes without encountering the thrust fault in the Cove Fort well (78-3), located only about 3 miles (4.8 km) to the northeast.

Paxton well (82-3): This well is located in the southern Pahvant Range a few miles southeast of the Millard-Sevier county line. It passed through Oligocene volcanic rocks, then penetrated Paleocene and Cretaceous(?) strata that unconformably overlie Triassic Moenkopi strata. After going through Triassic, Permian, Pennsylvanian, and Mississippian strata, it encountered small thrust faults that repeat Mississippian and Devonian strata. At a depth of 14,342 feet (4,371 m), it encountered a major thrust that places Paleozoic strata over the Jurassic Arapien Formation. Royce (1993) called this the Paxton thrust, naming it for this well. This thrust is a key feature in structural cross sections of the central Utah thrust belt (Royce, 1993; DeCelles and others, 1995).

Subsurface and Geophysical Information

More than half of Millard County consists of broad, nearly flat basins where Cenozoic valley fill conceals the geologic relationships in the underlying bedrock. Three kinds of geophysical techniques have been used to give some insight into the geology concealed beneath the surficial deposits.

The first technique is seismic reflection surveying. This is a standard petroleum exploration procedure that uses some source of energy to send ground-shaking waves through valley fill and buried rocks. A set of recording devices placed along the survey line records the return of the ground-shaking waves to the Earth's surface after being reflected from reflectors (usually denser rock layers) that are present beneath the area. The Consortium for Continental Reflection Profiling (COCORP) used longer intervals of ground-shaking and recording than those typical for oil-and-gas exploration, to study deeper continental crust reflections. Study of reflection and refraction seismic data from earthquakes provides information about the nature of deeper crustal and mantle rocks.

The second technique involves measuring the strength of Earth's gravity at selected points for which the elevation can be accurately determined. The strength of the gravity field varies with elevation (distance from Earth's central point), surrounding terrain, and latitude. It also varies with the density of the local rocks, and it is this variation that is useful in helping distinguish what kind of rocks may be present in the subsurface.

The third technique is aeromagnetic surveying. This technique measures variations in Earth's magnetic field by means of a magnetometer towed by an airplane. The strength of the Earth's magnetic field may be modified by magnetic rocks, usually igneous in origin. Thus, an aeromagnetic survey helps determine the location of buried igneous bodies.

These geophysical surveys are indirect observations that are subject to various interpretations. The range of interpretations is decreased if the recorded phenomenon can be related to rocks penetrated in a nearby deep well or exposed in nearby outcrops. When this is not possible, the uncertainty of interpretation may be considerable.

Seismic Reflection Surveys

The drilling of a deep exploratory well in an area that has no record of petroleum production is commonly preceded by shallow seismic reflection surveys to determine the best place to locate the proposed well. The seismic information so obtained is usually held by the exploring company as proprietary and confidential, and not publicly released. Only occasionally will a company allow some of its proprietary seismic data to be published. The number of seismic surveys conducted in Millard County has not been documented, but figure 209 shows the location of the few commercial seismic surveys that have been published. They are discussed below.

Northern Sevier Desert: To promote petroleum exploration in the Great Basin, McDonald (1976) published a lengthy paper describing many areas in Nevada and western Utah that he felt held promise for petroleum production. One such area was the Sevier Desert in Millard County north and south of Delta. He published five seismic lines in this area, surveyed in 1974 and 1975 by his employer Pan Canadian Petroleum Company, totaling about 100 miles (160 km) in length (figure 209, Mc 1, 2, 3, 8, and 20). The only deep well drilled prior to McDonald's (1976) study was the Gulf Oil's Gronning No. 1 stratigraphic test well (57-1 on figure 209) northwest of Delta that was drilled in 1957. It penetrated 8,064 feet (2,458 m) of Tertiary valley-filling sedimentary and volcanic rocks. McDonald (1976) speculated that the Eocene Green River Formation exposed in the Uinta Basin might extend into western Utah and be present in the lower third of the Gronning hole. Lindsey and others (1981) corrected McDonald's (1976) misconception by presenting pollen and fission-track dating information showing that the oldest rocks in the Gronning well are about 28 million years old and thus Oligocene. As noted previously, interpretations of the five seismic lines by McDonald (1976) also helped locate some of the faults shown on figure 204.

McDonald (1976) called a prominent westward-dipping reflector that he identified in his seismic lines a "detachment," and speculated that it might represent a glide surface on either a thrust fault or a low-angle normal fault, or both. This idea was adopted by Allmendinger and others (1983) in their interpretation of the COCORP deep reflection seismic survey discussed in later pages of this bulletin. This Sevier Desert reflector is believed by many geologists, including myself, to be at the unconformity between loosely consolidated Tertiary valley fill and the underlying dense Paleozoic bedrock.

Anderson and others (1983), as part of a study of the form and evolution of selected Tertiary basins in western Utah and Nevada, presented cross sections showing their interpretation of McDonald’s (1976) seismic lines 1, 2, 3, and 8. Their cross sections portrayed several grabens and

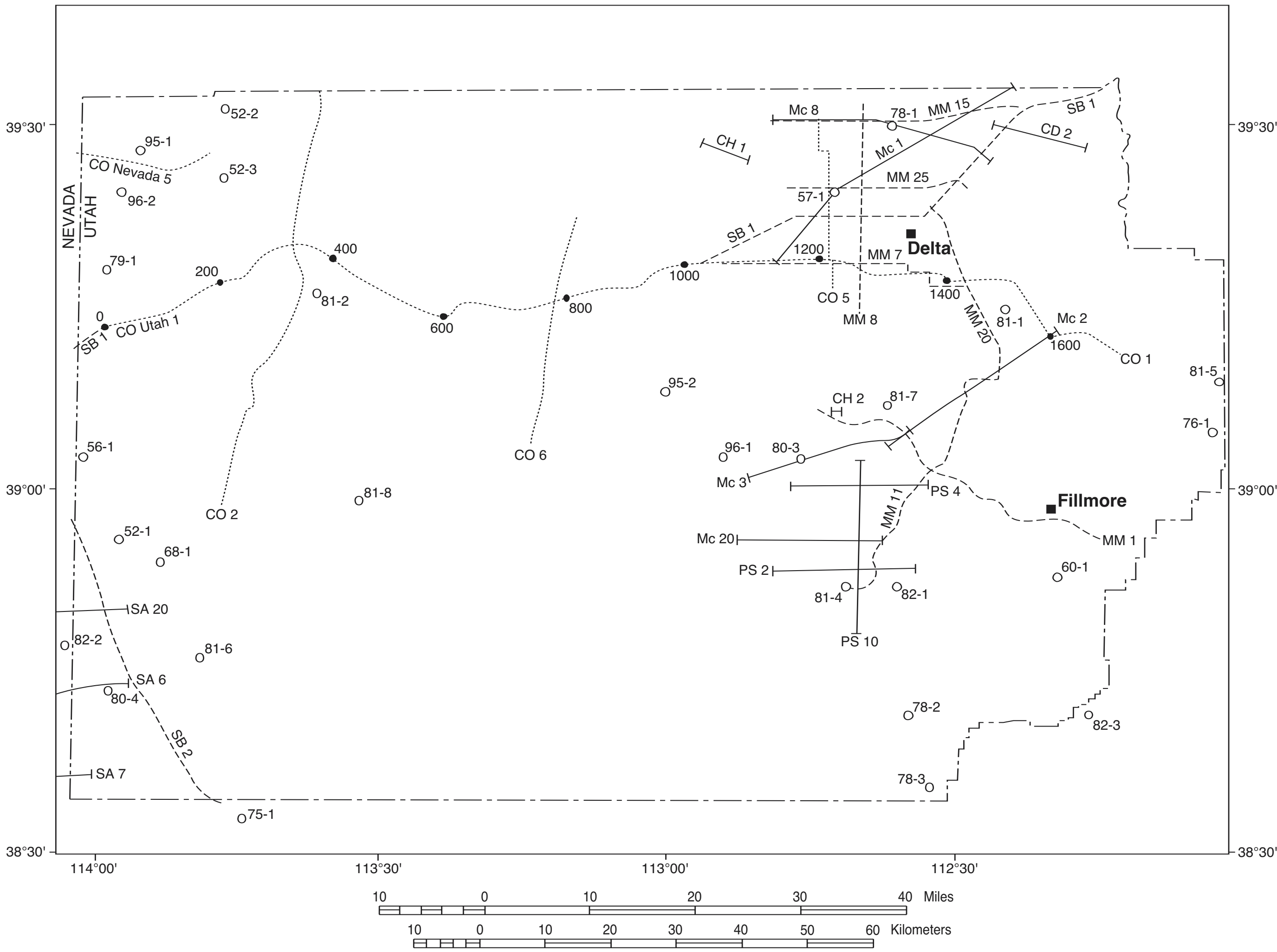


Figure 209. Location of published seismic lines and selected deep exploration wells (appendix A) pertinent to interpretation of the seismic data. Dotted lines are the 1982 COCORP Utah lines (station numbers are shown on line 1) and COCORP Nevada line 5. Other lines are from the following sources: CD=Coogan and DeCelles (1996), CH=Crone and Harding (1984), Mc=McDonald (1976), MM=Mitchell and McDonald (1987), PS=Planke and Smith (1991), SA=Shah Alam (1990), SB=Smith and Bruhn (1984).

they concluded the graben-bounding faults do not offset the Sevier Desert reflector very much. They also concluded that the influence of flowage of Miocene salt on basin tectonism remains in question.

Mitchell and McDonald (1987) published seven seismic lines (figure 209, MM 1, 7, 8, 11, 15, 20, and 25) in the Sevier Desert area, as part of a paper on hydrocarbon exploration potential of that area. These lines were released for publication by Geophysical Service Incorporated (GSI.), who made the surveys in 1980. Mitchell and McDonald (1987) also republished lines Mcl and Mc20 with a reinterpretation of the geology.

Figure 210 shows Coogan and DeCelles' (1996) interpretation of seismic line MM 15 and UHR2 (shown on figure 209 as MM15 and CD2). Line MM15 parallels line Mc 8 to the Argonaut well (78-1) and then tracks eastward to nearly join line CD2 near Lynndyl. Line CD2 proceeds east-southeastward to the west base of the Canyon Mountains. Coogan and DeCelles (1996) presented a synthesis of ideas related to the northern part of the Sevier Desert basin, and concluded that the Sevier Desert reflector is a detachment fault.

The Argonaut well (78-1 on figure 209) penetrated nearly a mile (1.6 km) of Miocene salt and gypsum just above the Sevier Desert reflector (SDR). On seismic lines Mc8 and MM15, the salt shows as an area that lacks reflections ("transparent"), producing a pseudoanticline called a "pull-up" on the diagram. Faulds and others (1997) reported a similar thick, nonmarine Miocene salt deposit in the Haulapai desert basin in northwestern Arizona. The Sevier Desert salt was originally deposited in horizontal layers on the floor of a saline desert lake. During burial it migrated plastically into its present massive lens. Other transparent areas visible on figure 210 may also represent salt bodies.

Coogan and DeCelles (1996) placed more reliance than I do on the identification of a "break away" fault zone along the west side of the Canyon Range, as suggested by Otton (1995, 1996) and Sussman (1995), and geological relationships in critical areas are not exposed. Precambrian Pocatello Formation is faulted against Cambrian Tintic Quartzite north of Oak Creek Canyon; the actual fault plane is not exposed and the fault was interpreted as a thrust by Holladay (1984) and as a Cenozoic normal fault by Sussman (1995) and Mitra and Ismat (2001).

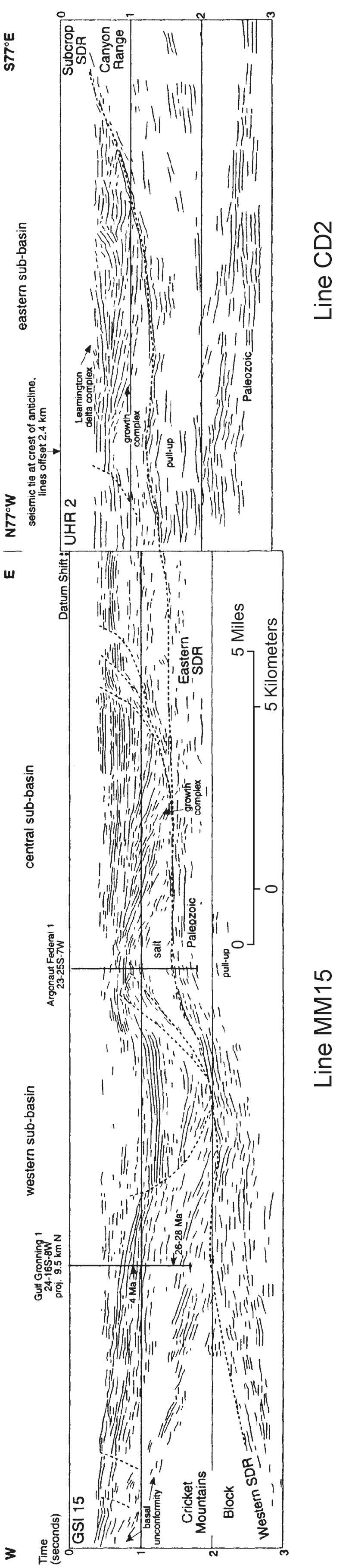


Figure 210. Interpreted seismic lines MM 15 and CD 2 from Coogan and DeCelles (1996); SDR indicates the Sevier Desert reflector. Location of lines is shown on figure 209.

Coogan and DeCelles (1996) identified reflections near the top of the eastern sub-basin as a “Leamington delta complex,” and correlated the underlying “growth complex” with Pliocene-Pleistocene deposits penetrated in wells some distance away (line CD 2, figure 209). These deposits are exposed about 15 and 30 miles (20 and 50 km) south and southwest of the seismic lines west of McCornick (QTln) and near the Cricket Mountains (QTln, QTlf), respectively. When the Sevier River adopted its present course through Leamington Canyon has not yet been determined; no wells deep enough to determine the identity of the reflectors in the Leamington delta area have been reported. These deltaic deposits are likely from the Pleistocene Little Valley or, possibly, some older lake cycle.

Gravity data, discussed below, show that line CD 2 passes north of the Delta gravity low and is on the northeast flank of the East Delta high (figure 215). Although gravity data points are numerous in the eastern sub-basin area, they do not give much indication of Tertiary basinal configuration. Further, no Quaternary faulting has been identified along this side of the Canyon Mountains, although a Quaternary fault is present to the west near Harding (H, figure 204, table 5).

In summary, McDonald's (1976) publication of Pan Canadian's five seismic lines, Mitchell and McDonald’s (1987) publication of seven GSI seismic lines, and Coogan and DeCelles’ (1996) additional UHR2 line contributed significantly to our present understanding of the geology concealed beneath the surface of the Sevier Desert near Delta, but their interpretations remain controversial.

Drum Mountains and Clear Lake faults: As part of the U.S. Geological Survey's earthquake mitigation effort, Crone and Harding (1984) conducted shallow seismic surveys to trace the subsurface pattern of Quaternary faults (DM and CL on figure 204) that offset Holocene valley fill at the surface as shown on maps by Bucknam and Anderson (1979a), Oviatt (1989), Hintze and Oviatt (1993), and Hintze and Davis (2002b). Crone and Harding's (1984) seismic line on the east side of the Drum Mountains (CH-1 on figure 204) is about 3 miles (5 km) long and recorded reflections to an estimated depth of 2,600 feet (790 m). Twenty normal faults of small and mostly down-to-the-east offset were identified on the seismic records, as compared to only seven fault scarps observed at the surface.

The Clear Lake seismic profile (CH-2 on figure 209) is 0.45 miles (0.74 km) long and recorded reflections to a depth of about 4,800 feet (1,450 m). Excellent resolution of seismic reflections at the Clear Lake site enabled Crone and Harding (1984) to trace the surface fault rupture downward and connect it to subsidiary normal-fault offsets at depth. They suggested that the Clear Lake fault zone might be directly related to the regional Sevier Desert reflector ("detachment") but presented no data to support this speculation. The Clear Lake fault zone is discussed by Oviatt (1989).

Sevier Desert and Antelope Valley: CGG-Denver (Compagnie Generale de Geophysique) furnished Smith and Bruhn (1984) with two long lines of seismic reflection data in Millard County. Line SB-1 on figure 209 follows the highway from Leamington to a point west of Delta where it joins the same route followed by the 1982 COCORP Line CO Utah 1, and then continues into Nevada to the Snake Range. Line SB-2 follows the highway from Milford to Garrison, cutting across the southwest corner of Millard County.

Whereas the COCORP data, discussed later in this bulletin, extend to two-way travel-time depths of 12 seconds (approximately 18 miles [30 km]), the CGG-Denver data extend to about half that depth. Data of CGG-Denver line SB-1 show reflections similar to those seen on the upper part of COCORP Utah line 1. The interpretive cross section of Smith and Bruhn (1984) is much like that of Allmendinger and others (1983). This is true even east of Delta where line SB-1 goes around the north end of the Canyon Mountains and CO-1 passes around the south end of the range. Because the interpretations are so similar our discussion of them is presented below under the COCORP heading. As noted before, line SB-1 helps locate some of the faults shown on figure 204.

Smith and Bruhn's (1984) interpretive cross section of line SB-2, where it crosses Antelope Valley and cuts through Mormon Gap between the Burbank Hills and the Mountain Home Range, shows that the broad synclinorial structure of these ranges can be traced into the subsurface to depths of at least 6 miles (10 km); however, the actual seismic data were not published and hence are not available to help locate faults on figure 204.

Hamlin Valley: Hamlin Valley is located along the Utah-Nevada border west of the Mountain Home and Needle Ranges. Prior to drilling a well in the Nevada portion of the valley, Union Oil Company ran seven seismic lines east-west and north-south across the valley. They later released these lines for publication (Shah Alam, 1990; Shah Alam and Pilger, 1991). The east ends of three of the lines (SA-6, SA-7, and SA-20 on figure 209) extend into Millard County.

Line SA-20 passes from the Needle Point Spring 7 1/2-minute quadrangle into the west half of the Cedar Pass 7 1/2-minute quadrangle (Hintze, 1997c) on the west flank of the Burbank Hills. Shah Alam's (1990) interpretive cross section shows a maximum of 2,200 feet (670 m) of valley fill overlying Paleozoic bedrock in the vicinity of Burbank on the Utah-Nevada line. The valley fill is estimated to be less than 10 million years old. Valley-fill thickness decreases to zero eastward against the bedrock of the Burbank Hills. Bedrock beneath line SA-20 is offset mainly down-to-the-east along several small-displacement normal faults. Shah Alam (1990) tentatively showed the Snake Range decollement extending to a depth of 2 miles (3 km) below sea level into Utah along line SA-20.

Line SA-6 extends from Big Spring, Nevada, across the north end of the Mountain Home Range to Mormon Gap. Permian bedrock is exposed at the surface along much of the Utah portion of this line (Hintze, 1986a). Shah Alam's (1990) interpretive section shows that the bedrock is only thinly covered by alluvial deposits in Utah with no fault on the west flank of the Mountain Home Range.

Line SA-7 extends across Hamlin Valley in Nevada to the west flank of the Mountain Home Range in Utah. Shah Alam's (1990) interpretive section shows progressive westward thickening of Tertiary valley fill off the west flank of the Mountain Home Range, as described by Hintze and Best (1987) from surface exposures, with no fault on the west flank of the range. The basal Tertiary rocks are Oligocene ash-flow tuffs, probably Needles Range Group (ages 30.5 to 32 Ma). These rocks are overlain by shale, limestone, and anhydrite that are probably younger than 17 million years old (Shah Alam and Pilger, 1991). Shah Alam (1990) showed a maximum of about 4,000 feet (1,200 m) of valley fill in the center of Hamlin Valley along line SA-7.

Southern Sevier Desert: Arco Oil and Gas Company released about 160 miles (256 km) of seismic reflection profiles in the Sevier Desert to the Department of Geology and Geophysics at the University of Utah for study by Planke (1987), who integrated this information with other geophysical and well data for his interpretation of the structure and evolution of the Sevier Desert basin. Three of Arco's seismic lines, totaling about 50 miles (80 km), were published by Planke and Smith (1991).

Three main reflectors were correlated across these profiles: (1) the Sevier Desert reflector ("detachment"), which Planke and Smith (1991) correlated with the unconformity between Tertiary basin fill and Paleozoic bedrock; (2) a middle Pliocene basalt reflecting horizon; and (3) a Tertiary-Paleozoic unconformity different than the Sevier Desert reflector.

Planke and Smith (1991) noted apparent termination of most subsurface normal faults, which cut Tertiary basin fill, at the Sevier Desert reflector. Perhaps the most significant feature newly identified by Planke and Smith (1991) was a north-trending, down-to-the-east listric normal fault, that they called the "west basin bounding fault," which offsets the Pliocene basalt reflector as much as 4,750 feet (1,450 m) on line PS-4 (figures 204 and 209). Because of difficulty in locating the lines, as shown in Planke and Smith (1991) and Planke (1987), this “new fault” may be within the Sand Ridge and Clear Lake fault zones.

Planke (1987) and Planke and Smith (1991) followed the speculations of Allmendinger and others (1983) and Von Tish and others (1985) with respect to interpreting the Sevier Desert reflector as a "detachment" as discussed below.

COCORP Deep Reflection Seismic Survey

COCORP (Consortium for Continental Reflection Profiling) was a large research project, based at Cornell University and funded by the National Science Foundation for a decade starting in 1975. Its aim was to increase understanding of the structure of the crust of the conterminous United States by engaging petroleum geophysical companies to run many hundreds of miles of deep (18 miles [30 km]) seismic reflection profiles along selected routes across the United States. In 1982 several COCORP lines were run in central Utah, crossing the state from west to east, with a few short north-south cross lines. COCORP lines in Millard County are shown on figure 209. The Millard County lines were described and interpreted in the following publications: Allmendinger and others (1983, 1985,1986, 1987a-b), Von Tish and others (1985), Klemperer and others (1986), Hauser and others (1987), and Allmendinger (1992).

Allmendinger and others (1983) initially described COCORP's Utah line 1, which stretched 106 miles (170 km) across Millard County (figure 209). Figure 211 is Allmendinger and others' (1983) line drawing, slightly modified for this bulletin, showing seismic reflectors along line 1; letters on this figure refer to features discussed below.

Sevier Desert reflector: Feature A on figure 211, the Sevier Desert reflector, extends from the shallow subsurface at station 1500 to a depth of about 8 miles (12 km) at station 800, with a westward inclination of about 12 degrees. The extent

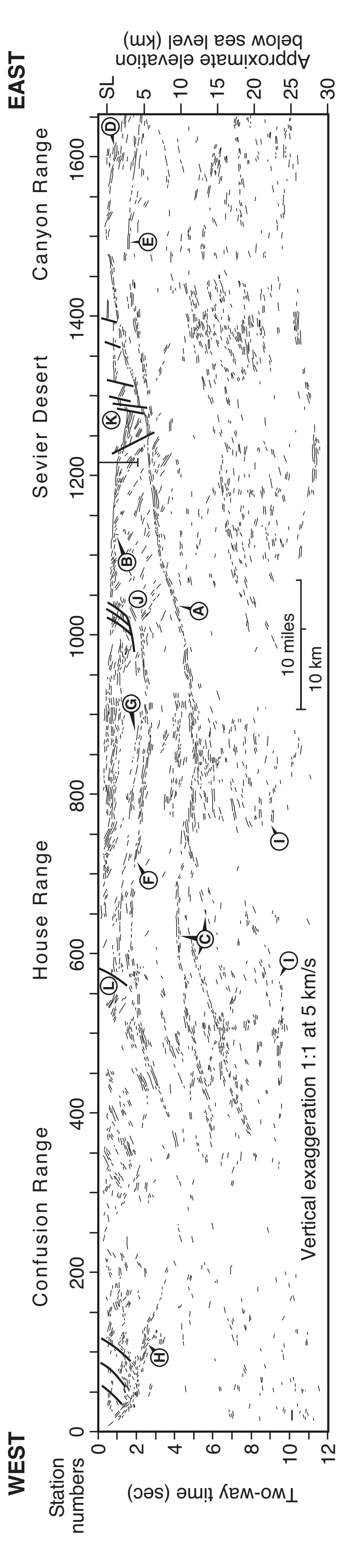


Figure 211. *Line drawing of reflections on COCORP Utah Line 1, modified from Allmendinger and others (1983). Letters refer to features discussed in text. Faults at letters J, K, and L are from Allmendinger and others (1985). Modifications include normal faults east of K and above H. See figure 209 for location.*

of feature A west of station 800 is uncertain because of changes in crustal brittle-ductile transitions in the Great Basin at depths between 6 to 9 miles (10-15 km) (Smith and others, 1989). The Sevier Desert reflector was called a "detachment" by McDonald (1976), and his term was also used by Allmendinger and others (1983), who noted that feature A consists of as many as four stacked reflectors in some places, suggesting some finite thickness to whatever produced feature A. They also noted that the shallow normal faults between stations 1200 and 1400 do not displace feature A very much, suggesting such shallow normal faults might be listric and would be expected to merge with the Sevier Desert reflector in a zone of Tertiary extensional detachment or low-angle normal faulting. Anders and Christie-Blick (1994), Hamilton (1994), and Anders and others (2001) disagreed with Allmendinger and others' (1983) speculation that feature A might represent a low-angle normal fault. They stated that in the four exploration wells that had penetrated the Sevier Desert reflector, the reflector marked the unconformable contact between Tertiary basin fill and Cambrian carbonate rocks. Anders and Christie-Blick (1994), and Anders and others (2001) examined samples from the contact zone in two of the deep wells, Arco Hole-in-Rock (81-4 on figure 209) and Arco Meadow-Federal (82-1 on figure 209), and did not find the rock fracturing that might be expected along a major fault zone. Allmendinger and Royse (1995) vigorously defended the low-angle normal-fault detachment hypothesis and presented new fission-track dates indicating that basement rocks in the Cominco (80-3 on figure 209) and Meadow-Federal wells were substantially uplifted between 8 and 13 million years ago, and suggested that the uplift might have triggered the detachment. Anders and others (1995a-b; 2001) presented additional arguments for their view that the Sevier Desert reflector mainly represents an unconformity upon which no extensional movement has occurred.

Otton (1995) speculated that the Sevier Desert "detachment" might be exposed along the west side of the Canyon Mountains, where he misinterpreted the unconformable contact between the Tertiary Oak City Formation and Cambrian-Precambrian bedrock as a "breakaway" zone. Wills and Anders (1996, 1999) said that their field examination of the contact between bedrock and the Tertiary sediments showed it to be an unconformity, a relationship also noted by Hintze (1991a-i). Sussman (1995) mapped faults in Cambrian quartzite on the west side of the Canyon Mountains and concluded these faults were related to Mesozoic thrusting. But the faults she mapped as separating Precambrian and Cambrian strata are likely Cenozoic normal faults (Mitra and Sussman, 1997; Mitra and Ismat, 2001).

More attention has been given to feature A, the Sevier Desert reflector, than to any other reflections on COCORP's Utah line 1 because all structural interpretations involving significant horizontal transport of large, thick sheets of strata use it as evidence for the position of the most likely surface upon which that transport could occur. Resolution of the differences in opinion on the interpretation of feature A, the Sevier Desert reflector, probably awaits new data from future deep wells and geophysical surveys in the basin, and new mapping and structural analyses along the breakaway zone.

Other reflectors on figure 211: Feature B, the uppermost reflector between stations 1000 and 1400, has been identified as a strong reflection from a 4.2 ± 0.3 Ma basalt flow (K-Ar, whole rock; Lindsey and others, 1981). Von Tish and others (1985) showed normal faults (features near J and K on figure 209) offsetting this reflector. Most of these faults stop at their junction with the Sevier Desert reflector, but some appear to cut feature A, as shown on figure 211 and on McDonald's (1976) shallow seismic lines. The offset of the Sevier Desert reflector (feature A) might be as much as 2,600 feet (500 m) (Smithson and Johnson, 1989). Tertiary salt masses are found above the Sevier Desert reflector as shown on figure 210. The faulting may be related to movement of the salt masses during valley-fill loading and regional extension.

Features near C are a series of westward-steepening reflections that splay off the west end of the Sevier Desert reflector to depths of 12 miles (20 km). Allmendinger and others (1983) speculated that they might be thrust ramps related to late Mesozoic thrusting.

Feature D, near the east end of COCORP line 1, dips eastward. Allmendinger and others (1983) tentatively identified it as the Pavant thrust fault. They also speculated that prominent reflections at E might be from structurally lower Mesozoic thrusts that were inferred in the subsurface by Standlee (1982) and other petroleum geologists from industry data in central Utah, east of Millard County.

Feature F can be traced between stations 400 and 980. Feature G, a slightly less continuous reflector, can be traced from station 560 eastward to station 900 where it pinches out against feature F. Allmendinger and others (1983) speculated that both F and G are thrust faults but noted that they are parallel to bedding of the Cambrian-Precambrian strata over their extent. One of these reflectors was probably identified as a bedding-parallel thrust fault by Allmendinger and others (1983) based on projection of relationships found in the Cominco well (80-3 on figure 209) 20 miles (32 km) south of the COCORP line.

Feature H, a prominent cluster of east-dipping reflections at the west end of line 1, was identified by Allmendinger and others (1983) as the Snake Range decollement, a down-to-the-east middle Cenozoic normal fault related to unroofing of the Snake Range metamorphic core complex. COCORP Nevada line 5 (figure 209), as interpreted by Hauser and others (1987) shows a somewhat similar major down-to-the-east normal fault called the Schell Creek fault beneath the northern Snake Range west of Snake Valley. Allmendinger and others' (1983) identification of feature H as the Snake Range decollement is probably wrong. It is more likely a younger Basin and Range normal fault, as identified beneath Snake Valley north of the COCORP Utah line 1 by Smith and others (1991, figure 2). Note that three west-dipping normal faults on the west side of the Confusion Range, added by Hintze on figure 211, appear to merge into feature H.

Feature L at station 550 was shown by Allmendinger and others (1985) as the major Basin and Range normal fault on the west side of the House Range. The high, steep, west face of the House Range reflects the great displacement on this fault because the same strata exposed on top of Notch Peak are down-dropped to the level of the Tule Valley floor (Hintze and Davis, 2002c). The House Range fault thus appears to merge into reflection F at a depth of only about 3 miles (5 km), rather than extending steeply to greater depths as had been generally supposed prior to interpretation of the COCORP lines.

Feature I consists of two-or-three cycle reflectors between 15-18 miles (25-30 km) deep. Allmendinger and others (1983) identified feature I as the reflection Moho, a widespread geophysical discontinuity that marks the base of the crust. Klemperer and others (1986) compared the Moho as seen on COCORP reflection profiles across Nevada and western Utah with two-way travel-time depths obtained by seismic refraction data and concluded that the reflection and refraction data showed the same features. Allmendinger and others (1987b) traced the Moho from eastern California to eastern Utah.

Summary: COCORP's Utah line 1 deep seismic survey showed that major high-angle normal faults mapped at the surface on the geologic maps of Millard County (Hintze and Davis, 2002b-c) do not extend deep into the crust but merge with low-angle reflectors below depths of about 4 miles (7 km). The low-angle reflectors can be followed considerable distances, but their geologic identity remains mostly speculative. Reflections from greater depths on line 1 are in a zone where crustal rocks are thought to be transitional between the brittle and ductile states. The reflectors are probably related to deep displacement of basement rocks during late Mesozoic compression, or, in my opinion less likely, to late Cenozoic extensional events in the Great Basin. Some geologists argue that they might be both.

Earthquake Seismicity Data

Geophysicists study seismic waves resulting from earthquakes to learn about Earth's structure at levels deeper than can be revealed by the seismic shock recordings as discussed above. Figure 212 shows that the velocity with which earthquake waves travel through the Earth increases with depth somewhat irregularly. Most Utah earthquakes nucleate within a brittle zone in the Earth's crust at depths of less than 7 to 11 miles (11-17 km) (Arabaz and others, 1992). Smith and others (1989) showed that two large (magnitude 7) historical earthquakes in Idaho and Montana nucleated on normal faults at depths of about 9 miles (15 km), in the zone of transition where the brittle upper crust passes below into a quasi-plastic state, and suggested that these larger earthquake events may require greater energy release in order to break apart abruptly in the more ductile part of the crust.

Figure 213 shows historical earthquake epicenters in Utah and adjacent states between 1850 and 1985. The early part of the record only documents earthquakes that were strong enough to merit note in newspapers and journals, and locations are speculative. Utah's first scientific earthquake recording device, a large pendulum seismograph, was not installed at the University of Utah until after the 1906 San Francisco earthquake focused the public's attention on the potential existence of the earthquake hazard in Utah along the then newly recognized Wasatch fault. This primitive seismograph was operated sporadically for several decades, but it was not until 1962 that earthquake records began to be obtained systematically on a modern seismograph network, and earthquakes could be better measured and located (Arabasz, 1979; Smith and Arabasz, 1991).

Since 1850, only one earthquake of greater than magnitude 4.0 had an epicenter within Millard County (figure 214): an estimated magnitude 4.3 earthquake in 1878 near Kanosh (Sue Nava, University of Utah Seismographic Stations, writ-

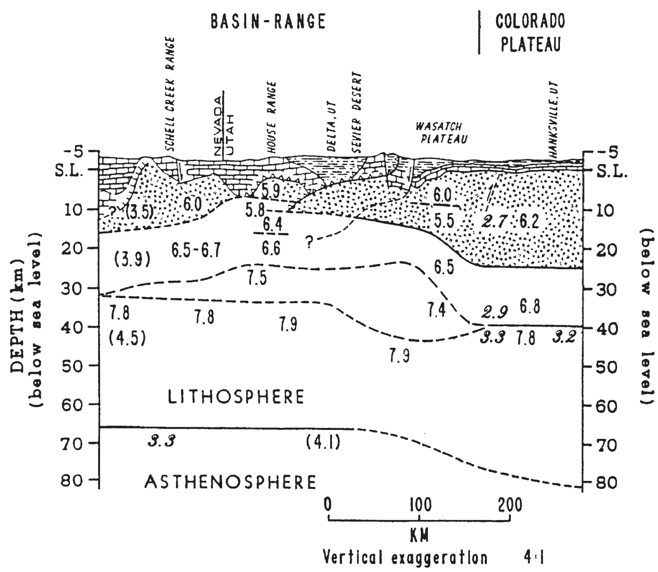


Figure 212. Diagrammatic cross section showing earthquake-wave velocities and rock densities in Nevada and Utah. The cross section is through Millard County. Rock densities (g/cm³) are in italics. S-wave velocities (km/sec) are in parentheses and other numbers are P-wave velocities (km/sec). From Smith and others (1989).

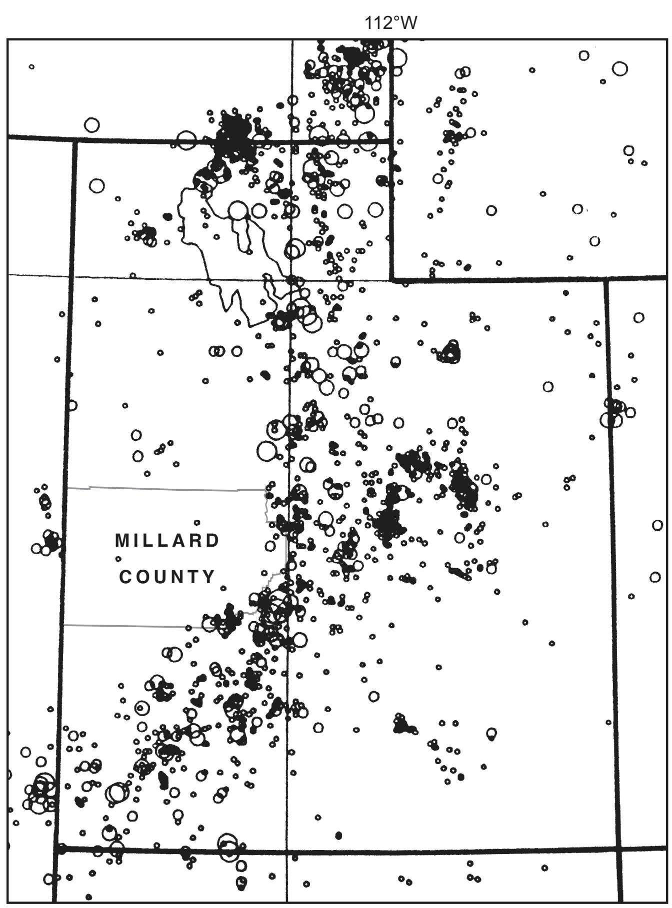


Figure 213. Earthquake epicenter location map of Utah and adjacent states. The larger the circle the greater the earthquake magnitude; the largest circles are magnitude 6 or greater. Minimum magnitude threshold is M 4.0 for the pre-instrumentation period 1850-1961. Minimum threshold for 1962-1985 is M 2.0. From Smith and others (1989).

ten communication, 1998). Figure 214 shows other earthquakes that originated outside the county but were large enough to do damage in the county.

Although figures 213 and 214 show that Millard County has been virtually free of larger earthquakes in historical time, the east edge of the county abuts the Intermountain seismic belt, a zone of seismic activity that extends from central Montana to northern Arizona, along which small earthquakes are recorded frequently (Smith and Sbar, 1974; Smith and Arabasz, 1991). Also, figure 204 shows fault scarps that offset surficial deposits less than 15,000 years old in central and western Millard County, suggesting that large earthquakes may continue to be generated sporadically across the entire county. These and other Quaternary fault scarps are summarized in table 5 and described in earlier pages of this bulletin.

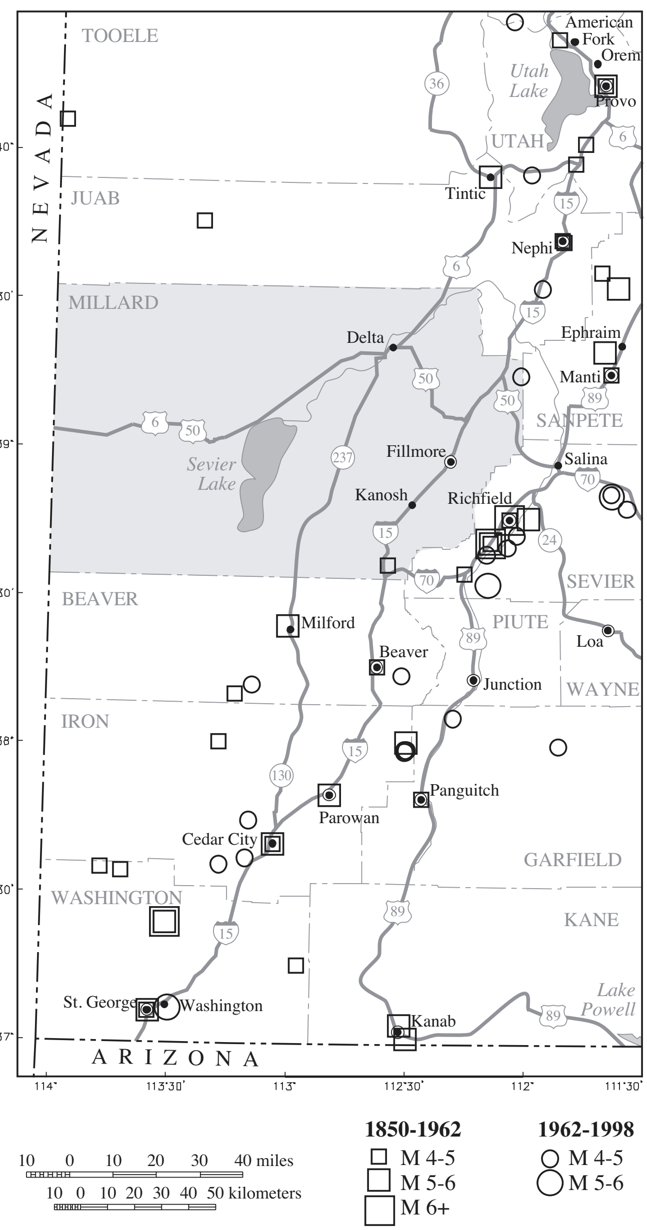


Figure 214. Earthquake epicenter location map of southwest Utah. From Sue Nava, University of Utah Seismograph Stations, (written communication, 1998).

Gravity Data

Gravity maps show density variations that are commonly used to determine the shape of subsurface rock bodies that differ in bulk specific gravity. A gravity map, such as figure 215 for Millard County, shows contrasting highs and lows. Most of the gravity lows shown are beneath flat desert valleys that are underlain by thick late Cenozoic valley fill, the density of which is measurably less than that of the Paleozoic bedrock formations exposed in adjacent ranges. Used in combination with surface geologic, aeromagnetic, and other kinds of maps, gravity data can help predict the types of rocks that may be present in the subsurface.

Kenneth L. Cook and his graduate students at the University of Utah pioneered the gathering of gravity data in Millard County. Johnson and Cook (1957) covered a small part of the Drum Mountains; Mudgett (1963) covered the Wah Wah Mountains, Frisco Peak, and Beaver Lake Mountains 15-minute quadrangles; Sontag (1965) covered the area from Cove Fort to Marysvale; Isherwood (1967) covered eastern Millard County; Crosson (1971) covered the Confusion Range area; Serpa (1979) surveyed the Black Rock Desert; Case (1977) surveyed the Sevier Lake area; Gabbert (1980) studied the southwest corner of the county; Adhidjaja (1981) summarized gravity data across the southern half of Millard County (published in Cook and others, 1981); and Carrier and Chapman (1981) combined gravity with thermal studies in the Twin Peaks volcanic field.

These Millard County gravity data, along with similar data for the other counties, were assembled into a complete Bouguer gravity map of Utah by Cook and others (1989). Supplementary information concerning this map was included in Bankey and Cook (1989) and Cook and others (1991). Figure 215 was prepared for this bulletin in 1991 by Viki Bankey of the U.S. Geological Survey in Denver, using the same database as the state map plus many additional gravity stations.

Gravity contour lines are drawn at more closely spaced intervals on figure 215 than they are on the state map (Cook and others, 1989). This allows certain features to show more clearly on the county map. Throughout the Great Basin, gravity lows are associated with thick valley fill in basins, and the steep gravity gradients that bound these lows are associated with large Basin and Range normal faults. Figure 215, with figure 204, show such features and faults on both sides of the Tule Valley low, the east side of the Wah Wah Valley low, and the east side of the unnamed low (Antelope Valley) between the Mountain Home Range and Tunnel Spring Mountains (and Halfway Hills), as well as on both sides of the Cricket Mountains high and Pine Valley low, the west side of the Snake Valley low, and both sides of the Mineral Mountains. Because of this association, these gradients are interpreted as indicating large down-to-the-low faults in the following discussion, even where surface faulting is absent and seismic data are not available.

Gravity lows in Millard County: Figure 215 identifies closed gravity lows by showing tick marks on contour lines surrounding the low point. There is no fixed negative contour value which forms the "rim" of all low basins because each low is merely low relative to adjacent gravity patterns. Nine lows are named on figure 215 for the surface topographic features where they are located (see figure 8). Additional subsurface data are available for the six selected lows discussed below.

North Snake Valley low: Although Snake Valley extends nearly the entire north-south dimension of western Millard County (figure 8), merging with Hamlin Valley on the south end, the gravity low is present only in the north, between the northern Snake Range in Nevada and the sprawling northern part of the Confusion Range. As noted previously, surface ruptures of the Snake Valley fault zone and seismic data place a large Basin and Range fault along the steep gravity gradient on the west side of the north Snake Valley low. Exploration well 95-1 (Balcron Cobra-State) penetrated 1,080 feet (329 m) of Cenozoic low-density valley fill before reaching dense Paleozoic carbonate rocks on the northeast edge of the north Snake Valley low. The Amerada Hess well (79-1) penetrated 5,600 feet (1,710 m) of valley fill on the southwest flank of the low. In its center, this low must have a greater thickness of Tertiary valley fill than that penetrated in the Amerada Hess well. The deep part of the low may include evaporites that were deposited in a Miocene desert basin, like the anhydrite in Hamlin Valley in Nevada (Shah Alam and Pilger, 1991). The steep gravity gradient between the north Snake Valley low and the northern Confusion Range may indicate a major down-to-the-low normal fault. But because surface rupture is not present and published seismic lines (CO Utah 1, CO Nevada 5, SB-1) do not show offset of near-surface reflectors along the gradient, a concealed fault is not shown on figures 204 and 206. Also, seismic lines in Shah Alam (1990) do not show faults with major offset west of the Mountain Home Range on the east side of Hamlin Valley.

Pine Valley low: Exploration well 75-1 on figure 208 (Bridger's Federal #1) is located near the topographic center of Pine Valley in northern Beaver County. It is located on the west side of the Pine Valley low. The well penetrated 2,810 feet (856 m) of Cenozoic low-density valley fill before reaching Paleozoic bedrock. A well about 2 miles (3 km) to the east in Pine Valley (Husky Oil Company #10-13 Federal, CNW1/4NE1/4 section 13, T. 26 S., R. 17 W.) penetrated about 6,850 feet (2,090 m) of Cenozoic basin fill before bottoming in Middle Cambrian rocks (T.D. 7,048 feet [2,149 m]). The Wah Wah fault (figure 204) has been placed along the Quaternary-bedrock contact and the steep gravity gradient on the east side of the Pine Valley low along the west base of the Wah Wah Mountains. The Pine Valley fault (figure 204) has been placed along the Quaternary-bedrock contact and the steep gravity gradient on the west side of the Pine Valley low at the east base of the Halfway Hills and south end of the Tunnel Spring Mountains.

Sevier Lake low: The steep gravity gradient between the Sevier Lake low and the Cricket Mountains high follows the West Cricket fault (figure 204). Chevron's Sevier Lake stratigraphic test well (95-2 on figure 215) penetrated 5,160 feet (1,573 m) of Cenozoic sedimentary and volcanic valley fill before reaching dense Cambrian carbonate rocks. The well is located between the Sevier Lake low and a smaller low to the north that follows a buried Cenozoic basin developed on a structure called the Chalk Knolls graben by Hintze and Davis (1992a). The south end of the Sevier Lake low was profiled by Case and Cook (1979) who estimated the maximum thickness of Cenozoic valley fill there to be about 4,600 feet (1,400 m). Although no exploratory well has been

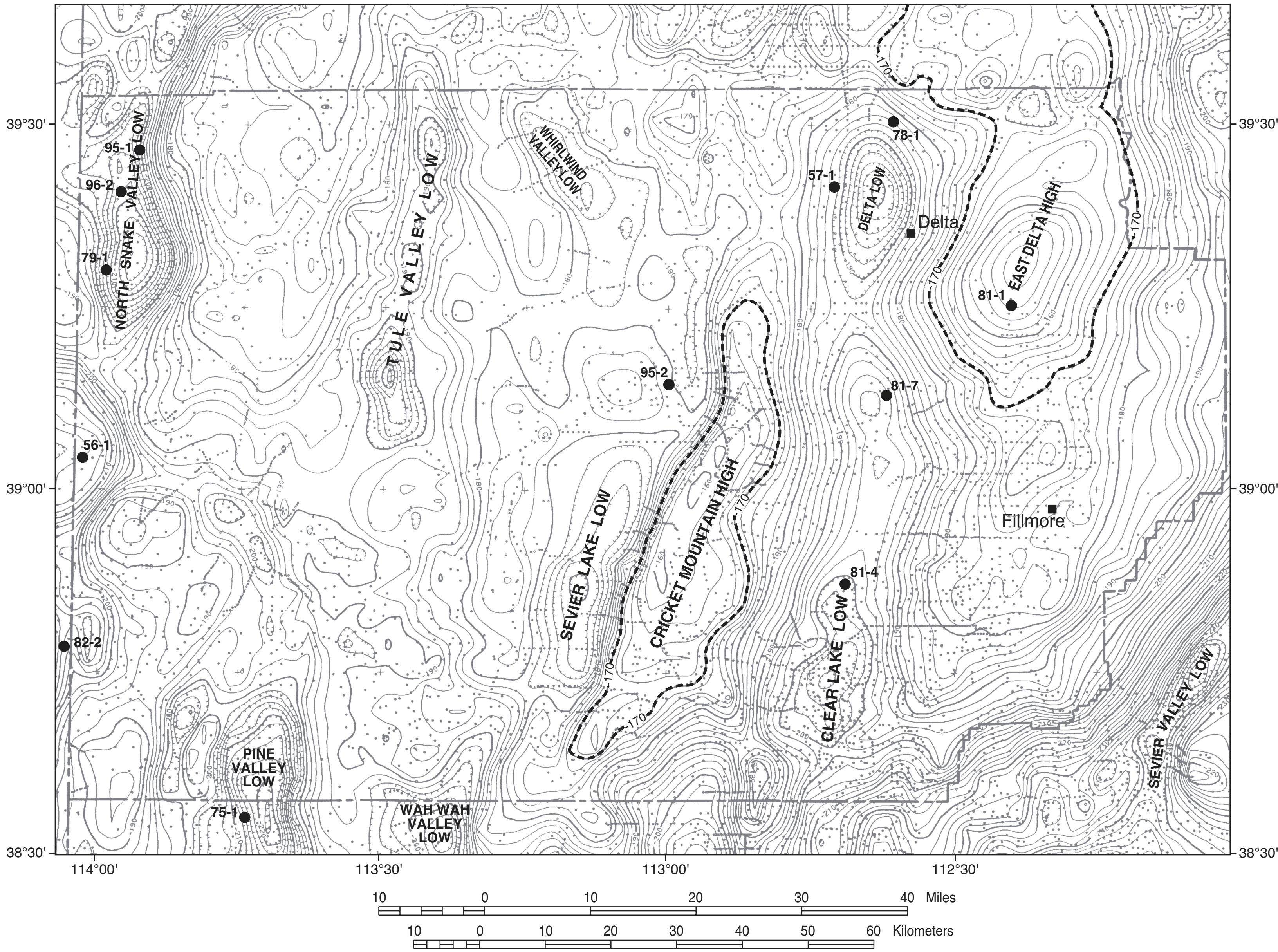


Figure 215. *Bouguer gravity map of Millard County (Bankey, 1991). Small circles show data collection points upon which the contours are based. Gravity lows are enclosed by hachured lines. Two gravity highs are encircled by dashed lines. Contour interval is 2 milligals. Named features and numbered wells are discussed in text. These deep exploration wells are also shown on figures 208 and 209.*

drilled at the deepest part of this low, the south end of Sevier Lake, the log from Chevron's well (well 95-2, appendix A), drilled on a shallower part of the anomaly, suggests either that Case and Cook's (1979) estimate of valley-fill thickness may be much too small, or that there may be a sizeable Miocene salt body, that has an even lower density than other valley fill, beneath the south end of Sevier Lake. The gypsum dikelets, that cut Pleistocene-Pliocene lacustrine deposits west of Sevier Lake (figure 177; Oviatt, 1989), and subsurface brines (Gwynn, 1990) might be indicative of a salt body at depth.

Delta low: The low gravity anomaly shown on figure 215 west of the town of Delta is crossed by several published seismic survey lines (figure 209). McDonald's (1976) line 8 shows the structure best and is interpreted as showing the Delta low is produced by a shallow graben that contains salt, a low-density material. The graben-bounding faults are present where steep gravity gradients bound the low, and unlike most faults in the Great Basin, they are far from any range front. Gulf's Gronning well (57-1), on the west flank of the Delta low, penetrated 8,064 feet (2,458 m) of low-density Cenozoic valley fill. Argonaut Energy's #1 Federal well (78-1), on the north flank of the Delta low, penetrated 7,734 feet (2,357 m) of Cenozoic low-density valley fill, including 3,470 feet (1,058 m) of salt, before reaching denser Cambrian bedrock.

Clear Lake low: This low in the southern part of the Sevier Desert was traversed by several published seismic survey lines (figure 209). McDonald's (1976) lines 2, 3, and 20 are here interpreted as showing a fault along the steep gravity gradient between the East Delta high (including its southern extension) and the Clear Lake low (including its northern extension). Mapping by Fitzhugh Davis for this bulletin (Davis, 1994; Hintze and Davis, 2002b) placed the McCornick fault (figure 215) along this steep gravity gradient on the northeast side of this low where crossed by seismic line Mc2 (figure 209). Mitchell and McDonald's (1987) line GSI 1 doesn't show a fault on the east side of the low. The published seismic lines also show probable faults at the steep gravity gradient on the west side of the Clear Lake low at the Clear Lake and Sand Ridge Quaternary fault zones (figure 204), as discussed previously. Arco's Hole-in-Rock well (81-4), at the north end of the low (figure 215), penetrated 9,100 feet (2,774 m) of Cenozoic basin fill before reaching denser Cambrian carbonate rocks. Planke and Smith's (1991) down-to-the-east "west basin-bounding fault" follows the low-gravity axis from the Clear Lake low northward to the Delta low, but the location of this interpreted fault is questioned by some geologists.

Sevier Valley low: This low, centered along Sevier Valley east of Millard County, differs from the Basin and Range fault-related lows noted and discussed above, because of its great depth. Only a small part of this low shows on the southeast corner of figure 215. The entire low can be viewed on Cook and others' (1989) gravity map of Utah where it extends from the Marysvale volcanic field northeastward along the High Plateaus of Utah to the southern Wasatch Range. The greater depth Sevier Valley low, as identified on figure 215, may be caused by Jurassic salt, having very low specific gravity, that is concentrated beneath the axis of the Sevier Valley low.

Gravity highs in Millard County: Figure 215 shows two prominent gravity highs in Millard County. They differ from one another in their relationship to exposed bedrock, as shown on figure 8 and discussed below.

Cricket Mountains high: This gravity high roughly conforms to the shape of Cambrian bedrock outcrops in the Cricket Mountains horst. The West Cricket Basin and Range normal fault bounds the horst on its west side, and the East Cricket fault bounds it on the east (figure 204). The density of exposed Cambrian and buried Precambrian rocks of the horst contrast markedly with that of the relatively porous and unconsolidated valley fill on the flanking basins. The gravity map clearly shows the northward extension of strata of the Cricket Mountains horst beyond its surface outcrops.

East Delta high: Comparison of the outline of the East Delta high with the bedrock outcrop of the Canyon Mountains (figures 8 and 215) shows that the gravity high extends west of the bedrock outcrops, showing no influence from the western limit of bedrock outcrop. The Canyon Range is a tilted Basin and Range fault block, bounded on its east side by the Canyon Range normal fault, active still in Quaternary time (figure 204, table 5). But the existence of the prominent East Delta gravity high west of the Canyon Mountains suggests the probability that late Cenozoic valley fill only thinly covers denser bedrock in the area between the Canyon Mountains and the town of Delta, and that a range-bounding fault is not present on the west side of the range.

The extent of the East Delta high may continue south of the -170 milligal contour line on figure 215, with less intensity to the south of Fillmore. Surface geology along the eastern alluviated slopes of the Pahvant Range shows a belt of Tertiary Oak City Formation thinly covering complexly deformed Paleozoic strata, such as are exposed in the Church Hills and east of Kanosh (George, 1985). If there is a large normal fault between the Pahvant-Canyon mountain front and the Clear Lake-Delta lows, it would appear from the gravity map to be located many miles west of the mountain front underneath the Black Rock-Sevier Desert. However, the steepness of this gravity gradient is not as great as that along the fault west of the Cricket Mountains, so the location of this fault, if it exists, is not as well constrained.

Aeromagnetic Data

Regional aeromagnetic patterns in Utah are shown in color on a 1:1,000,000-scale map by Zietz and others (1976) and Bankey and others (1998), but no written discussion accompanied these maps. Mabey and others (1978) presented an interpretation of the anomalies shown on this map and the following is summarized from their paper.

Magnetic anomalies in Utah mostly reflect the interaction between magnetic properties of Precambrian basement rocks and the superimposed effects of later (chiefly Cenozoic) igneous bodies. East of the heavy line that cuts northward through Utah on figure 216, the magnetic anomalies are governed largely by variations in rock types in the Precambrian metamorphic and igneous basement complex; local magnetic highs are produced by mid-Cenozoic laccoliths in the Henry (HM), La Sal (LS), and Abajo (AB) mountains. West of the heavy line, in the Great Basin in western Utah and eastern Nevada, magnetic anomalies from basement rock

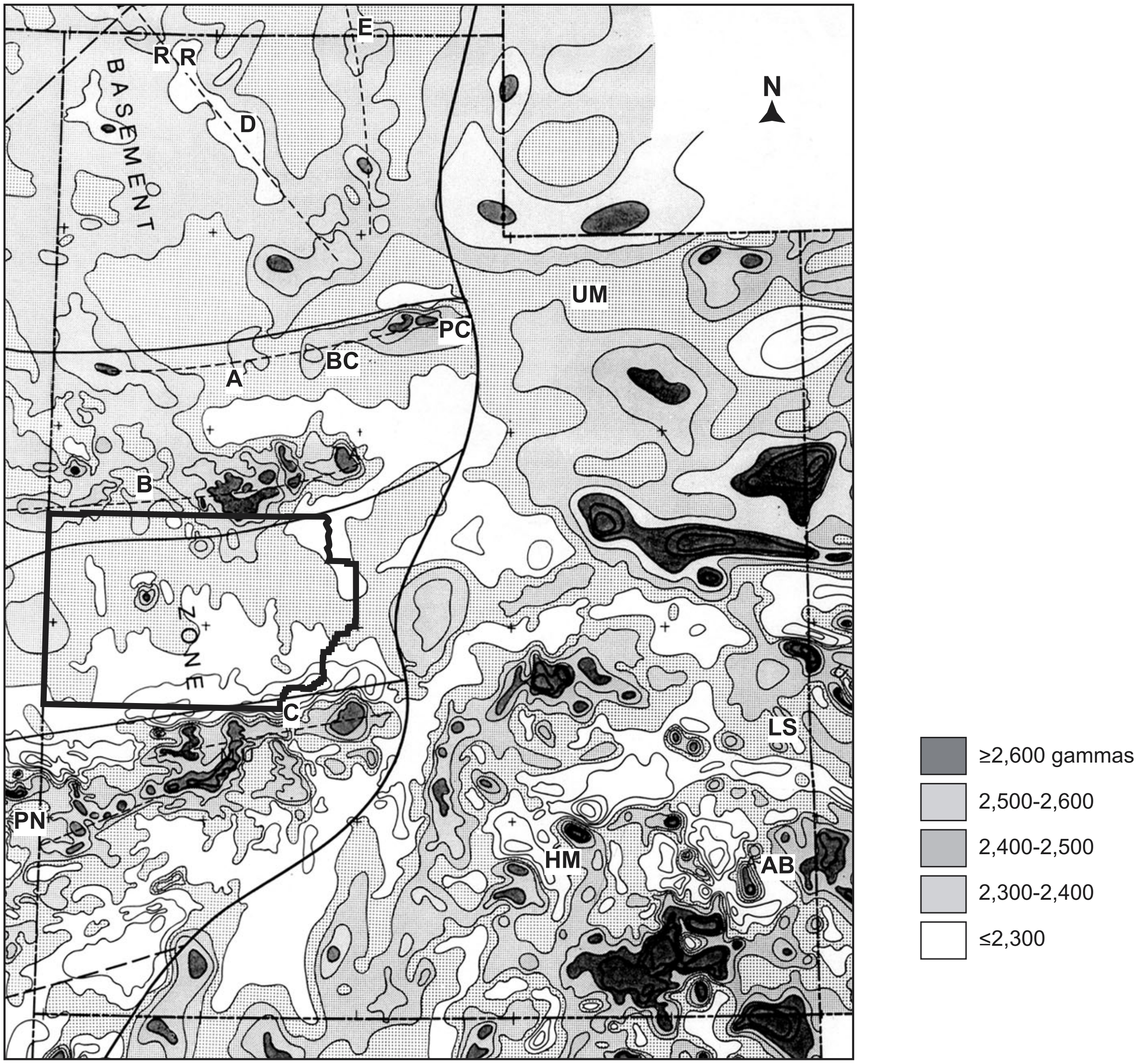


Figure 216. *Aeromagnetic map of Utah, showing Millard County border (modified from Mabey and others, 1978). Contour interval 200 gammas. Darkest shading indicates 2,600 gammas and above; white areas are 2,300 gammas and below. Heavier line separates Utah into an eastern part dominated by readings from the Precambrian basement, and a western part showing belts of highs that correspond to Cenozoic volcanic areas. Refer to Mabey and others (1978) for more detailed explanation.*

are inconspicuous in what has been called the "basement quiet zone." The crust is thin in western Utah and the Precambrian basement may have been heated enough to modify its original magnetic characteristics in contrast to the more normal Precambrian basement pattern in eastern Utah.

Figure 216 shows belts of high magnetic value both north and south of Millard County. Belt A trends from Gold Hill through Bingham Canyon (BC) to Park City (PC). Belt B, just north of Millard County, shows highs from the Drum Mountains to the Tintic mining district. Belt C extends from the Needle Range, through the Mineral Mountains, to the Marysvale volcanic field just south of the county. These belts correspond to late Eocene, Oligocene, and early Miocene igneous belts that are superimposed on the basement quiet zone.

Mabey and Virgin's (1980) and Kucks' (1991) 1:250,000-scale aeromagnetic maps of Millard County show greater detail than Zietz and others' (1976) 1:1,000,000 map. Kuck's (1991) map covers the north half of the county and shows that minor magnetic anomalies associated with silicic volcanic rocks in the Little Drum Mountains extend westward beneath Whirlwind Valley nearly to the House Range. It also shows minor anomalies associated with volcanic rocks in the Sevier Desert from Pahvant Butte to Smelter Knolls. Millard County's most prominent magnetic high is caused by the Jurassic granitic intrusion at Notch Peak. Kuck's (1991) map shows that the anomaly is centered beneath the south edge of the surface outcrop of the granitic stock. Mabey and Virgin's (1980) map, which covers the south half of Millard County, shows high anomalies from Cove Fort southward into Beaver

County, but most of southern Millard County is aeromagnetically monotonous, consistent with the absence of silicic intrusions. Widely spaced flight lines also contribute to the monotonous pattern on Mabey and Virgin's (1980) map. It should be noted that the basaltic lava flows that are prominent on the floor of the southern part of the Sevier Desert do not show up on this aeromagnetic anomaly map (Mabey and Virgin, 1980) with widely spaced flight lines.

Geothermal Heat-Flow Studies

Heat is generated in the mantle and crust of the earth from disseminated radioactive elements. This radiogenic heat powers the convective movement in the mantle and the motion of lithospheric plates, and rises to earth's surface where it dissipates. Near-surface heat flow is measured in boreholes; heat-flow measurements did not become common until the 1970s when interest in plate tectonics and geo-thermal power sources provided the incentive. A heat-flow map may be complex because it shows the combined effects of crust and mantle radioactivity, magmatic heat sources, regional hydrology, and structurally related heat conductivity contrasts, in addition to reflecting uneven coverage of heat-flow data points.

On the basis of heat-flow measurements made at more than 500 drilling sites in the western United States, Lachenbruch and Sass (1978) showed that heat flow measured at the surface, minus heat production from assumed crustal radioactivity, is characteristically 50 to 100 percent greater in the Great Basin than in stable regions in the United States. However, they neglected regional hydrology in this conclusion and most of their data are from around hot springs. They suggested that this extra heat is being transferred from the asthenosphere by convection to the lithosphere and by magmatic intrusion, thereby stretching the crust. They presented a model showing that as anomalous heat flow increases, so do rates of crustal extension in the Great Basin. Blackwell (1978) showed a belt of unusually high heat flow along the eastern margin of the Great Basin, following the trend of major fault zones (Hurricane, Wasatch) along Utah's hingeline.

The regional studies mentioned above do not include any heat-flow measurements made in Millard County. The only deep wells in the county from which heat-flow information has been published are two geothermal exploration wells drilled near Cove Fort by Union Oil company. Ross and Moore (1985) reported that Union's well 42-7 (well 78-4 on figure 208) reached a maximum temperature of 352°F (178°C) at a depth of 7,318 feet (2,237 m) 13 hours after fluid circulation stopped. Well 31-33 (78-3 on figure 208) reached 295°F (146°C) at a depth of 4,700 feet (1,433 m) 7 hours after circulation stopped.

Maps of hot springs in Utah (Mundorff, 1970; Blackett, 1994) show that most of Utah's thermal springs are in the Great Basin portion of the state. Millard County's hottest spring waters are at Hatton Hot Spring with its temperature of 145°F (63°C). Blackett (1994) showed other warm springs in Millard County at the following locations listed from east to west: Meadow, Twin Peaks, Tule Valley, and Gandy.

Geothermal areas hot enough to qualify as "Known Geothermal Resource Areas" (KGRA) are located just outside the Millard County boundary in the Cove Fort-Sulphurdale area, the Roosevelt Hot Springs area near Milford, and in Juab County north of Delta at an area variously known as Abraham, Baker, or Crater Hot Springs. Mabey and Budding (1987) described the high-temperature geothermal resources of Utah; Budding and Bugden (1986) presented an annotated geothermal bibliography of the state.

Carrier and Chapman (1981) conducted a detailed gravity and heat-flow study of the Twin Peaks silicic volcanic center to determine if the area had retained enough residual heat from its volcanism, which ceased 2.3 million years ago, to be exploitable now as a geothermal resource. They published a terrain-corrected Bouguer gravity anomaly map of the area, and made heat-flow determinations at six sites. They concluded that negligible residual heat flow remained in the area and that it had no potential as a geothermal resource.

Paleotemperature Indicators

Several techniques have been devised to estimate temperature conditions that existed at some time during a rock's history. Two such techniques, conodont color alteration and fission-track analysis, have provided useful information on paleotemperatures in Millard County. Paleotemperatures are of interest because sedimentary rocks must be heated to about 140°F (60°C) to convert their organic detritus into gas and/or oil. But if they are heated above 320°F (140°C) the petroleum is destroyed.

Conodont color alteration index (CAI)

Conodonts are microscopic tooth-like fossils that are abundant in Paleozoic marine strata (figures 67, 91, 92, 93, 130, 138, 148, 153, and 157). Conodonts are made of a phosphatic mineral, essentially carbonate apatite, and in their unaltered state they are pale-yellow and translucent. When heated they pass through a succession of color changes as the temperature rises, from translucent to dark-brown, black, gray, and, finally, to nearly crystal clear when heated to 1,742°F (950°C). Conodonts retain their color change upon cooling. Epstein and others (1977) published a color chart that divides the temperature-induced changes into stages called color alteration indexes 1 to 8 (CAI 1 to CAI 8). The CAI technique has been widely applied by the oil industry to determine if rocks have been heated too much (over about 320°F [140°C]) to retain oil-producing potential or not enough (140°F [60°C]) to generate gas and oil.

Harris and others (1980) compiled maps of western Utah and Nevada giving CAI numbers for Ordovician through Triassic strata. In Millard County, their maps show the CAI ranges between 2 and 4 in Ordovician strata, equivalent to a maximum paleotemperature of 608°F (300°C). Conodonts from Triassic rock in Millard County show CAI of 1-1.5, equivalent to a maximum temperature of 194°F (90°C). The Ordovician rocks attained the higher temperatures during burial beneath 4 miles (6.4 km) of Silurian through Triassic marine strata.

Gans and others (1987) used conodont geothermometry to constrain timing of structural events in eastern Nevada and western Millard County. They noted that the very low CAI (1-1.5) of the uppermost Paleozoic and Triassic units preclude this area west of the Sevier arch from ever having been buried beneath a significant Mesozoic or early Cenozoic structural or sedimentary cover.

Fission-track analysis

Fission tracks are microscopic damage trails produced within mineral grains by the fissioning mode of decay of uranium-238. When an atom of ^{238}U undergoes fission, its nucleus breaks into two lighter nuclei that "recoil" with great energy, producing a damaged zone in a mineral called a fission track. Because the fissioning of uranium proceeds in earth's crustal rocks at a constant rate, fission tracks form a kind of clock that records the cumulative time since the host mineral last cooled below its annealing temperature. The annealing t*f*emperature is different for each mineral, but it is that temperature above which ions in the damage zone return to their normal positions in the crystal structure and the fission track is erased.

Uranium occurs in trace amounts as an impurity in a number of common minerals. If a mineral has never been reheated above its annealing temperature since its original crystallization, then a fission-track count can be used to calculate the original age of crystallization of the mineral in an igneous rock. If the mineral has later been reheated past its annealing temperature and then cooled, the fission-track age will reflect the age of the last cooling. Because each mineral has its own annealing temperature, a comparison of fission-tracks ages in different minerals contained in the same rock can tell something about the thermal history of the rock.

The two minerals most commonly used in thermal history studies are apatite and zircon (Naeser and others, 1990). This is because these minerals have annealing temperatures that nearly coincide with petroleum generation temperatures (greater than about 140°F [60°C] to less than 320°F [140°C]). The annealing process in apatite is both temperature and time controlled. Naeser's (1981) drill-hole data indicate that apatite is totally annealed at 221°F (105°C) under long-term heating (100 million years), and at 302°F (150°C) under shorter term heating (100,000 years or less). Chemical composition variations in apatite also affect the annealing temperature. Temperatures at which fission tracks in zircon are totally annealed are not as well known, but are in the range of 320°F to 482°F (160-250°C) for heating periods greater than one million years (Naeser and others, 1990).

At present, fission-track studies are increasingly used for reconstructing time-temperature paths of rocks at temperatures below 572°F (300°C). Below this temperature, tectonic uplift is the most important geological process that causes rocks to cool. As a rock column is lifted it cools continuously, provided the overlying rocks are removed by erosion and the geothermal gradient of the region stays the same. Allmendinger and Royse (1995) presented fission-track ages to show that Cambrian and Precambrian rocks encountered in wells in the Sevier Desert were raised to their present elevation in late Miocene time. They reported that the apatite fission-track age of Prospect Mountain Quartzite, now at a depth of 6,000 feet (1,818 m) in the Cominco well (80-3 on figure 208), is 8.5 ± 2.2 Ma. Zircon fission-track ages from Precambrian granitic gneiss in the interval between 13,610 and 15,537 feet (4,124 and 4,708 m) in the Arco Meadow well (82-1 on figure 208) are between 10.8 ± 0.9 and 13.0 ± 1.0 Ma. Allmendinger and Royse (1995) ascribed these ages to late Miocene domal uplift of the Sevier Desert area rather than earlier Cretaceous and Paleocene (Sevier-age) uplift with later reset due to volcanic activity. Therfore, the fission-track data place important time constraints on the structural development of the Sevier Desert basin.

Regional Structural Interpretations

Although McDonald's (1976) publication revealed parts of the subsurface structural conditions in Millard County, the COCORP deep seismic reflection data (figure 211) were needed to enable Allmendinger and others (1983) to draw a cross section that postulated the extension of rocks exposed in the county's mountain ranges into the depths beneath the county's desert floors. Figure 217D is Allmendinger and Sharp's (in Allmendinger, 1992) revised version of the original Allmendinger and others (1983) interpretive cross section.

The 1983 COCORP cross section was much copied, with some modifications, by later authors: for example Smith and Bruhn (1984), using shallow seismic reflection data, presented a cross section very similar to the COCORP model. Von Tish and others (1985) refined the interpretation of the COCORP data in the vicinity of Delta, showing subsurface Tertiary normal faults in greater detail than the 1983 version. Saleeby (1986) incorporated the 1983 Millard County COCORP section in his California-to-eastern-Utah transect and added Smith and others' (1975) velocity layers beneath the bedrock. He also merged the west end of the Utah line, with its west-directed Sevier Desert detachment, with the Nevada COCORP line, showing its east-directed North Snake Range decollement running head-on into the Sevier Desert detachment, an improbable collision. Allmendinger and others (1986) presented a preliminary version of the palinspastic restoration shown on figure 217E on the basis of a study by Sharp (1984). Smith and others (1989) integrated a generalized regional cross section across Millard County with hypothetical shear-stress curves and velocity-depth data (figure 212). At the request of the American Association of Petroleum Geologists, Hintze and others (1990) prepared an east-west cross section through central Utah that included the 1983 COCORP subsurface model beneath Millard County. Hintze and Davis (1992a-b) incorporated some of Von Tish and others' (1985) COCORP structural interpretations in their cross sections through the Sutherland Basin-Red Knolls-House Range-Tule Valley area.

Allmendinger (1992), in a summary discussion of fold-and-thrust tectonics of the western United States, presented a reinterpretation of the Millard County COCORP line and extended it into Sevier County to show the eastward extent of thrusting (figure 217D). He estimated the total Mesozoic-early Tertiary shortening in west-central Utah, based on a balanced restored cross section (figure 217E) constrained by deep-well data, to be between 60 and 75 miles (100 and 120 km). He estimated subsequent late Tertiary extension on the Sevier Desert detachment to be 18 to 24 miles (30 to 40 km).

In a combination stratigraphic and structural analysis, Royse (1993) presented a new cross section through Millard County (figure 217A) that is similar to Allmendinger's (1992) west of the Cricket Mountains (figure 217D), but crosses southeastward into Sevier County using different deep wells and unpublished seismic data to constrain its con-

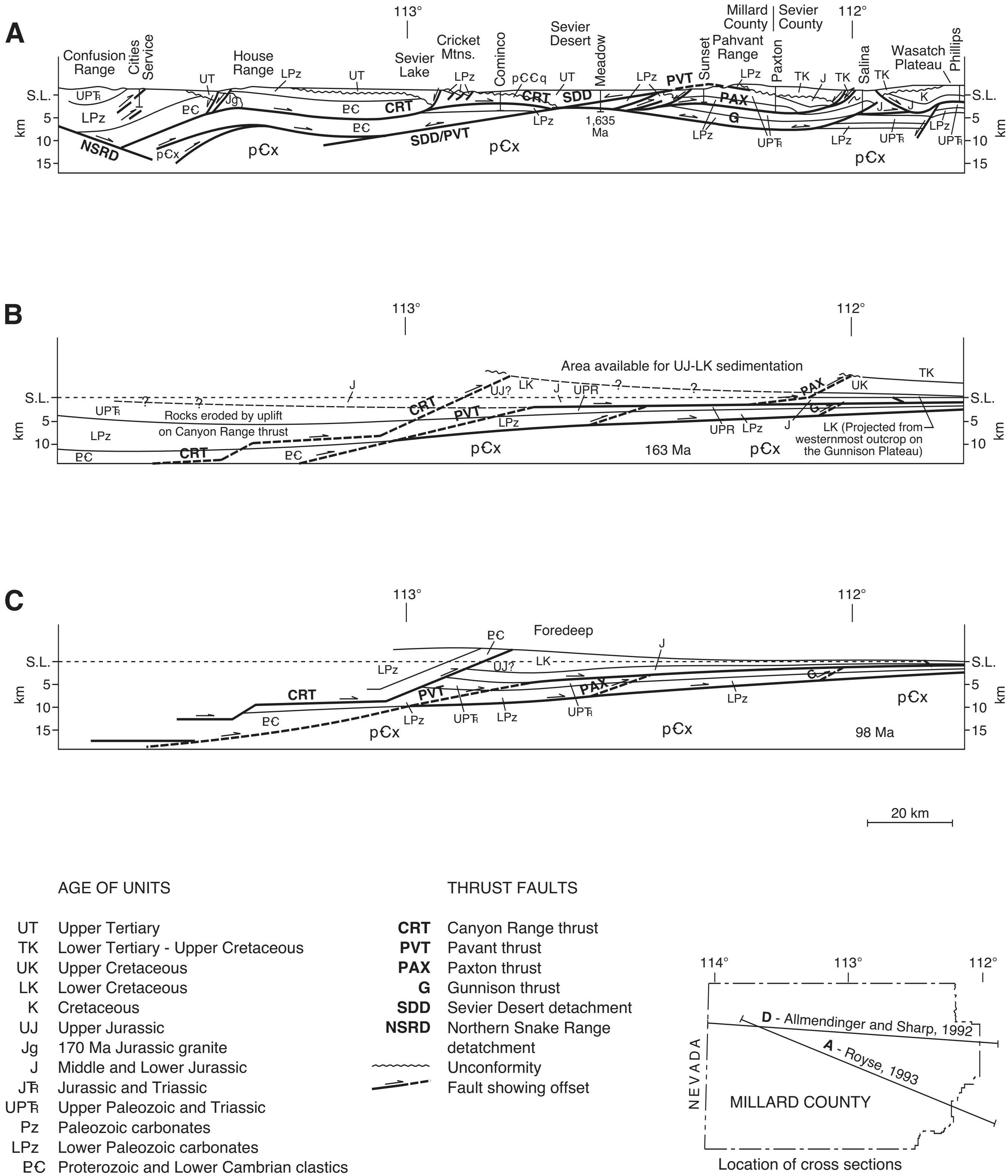
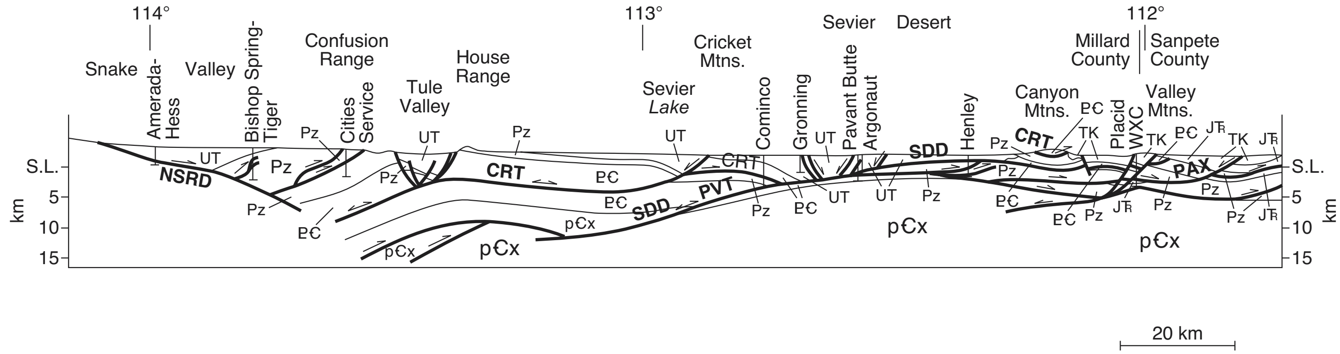


Figure 217. (caption on next page)

Figure 217. (continued)

D



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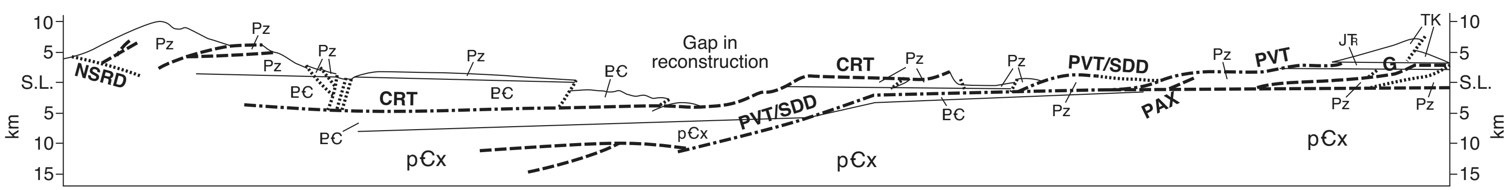

Figure 217. Cross sections through Millard County showing two interpretations of geologic structure to a depth of 15 km (9.3 miles). Sections have been redrawn using common scales and symbols for ease of comparison, but the interpretations have not been altered. Vertical labels identify the deep exploratoration wells used for control: A, Royse's (1993) interpretation of present-day structure; B, Royse's (1993) restoration of pre-faulting stratigraphic thicknesses near the end of Early Cretaceous time. Position of future thrust faults shown by heavy dashed lines. Position of post-thrusting deposits is postulated in area above sea level. The large volume of strata available for erosion after thrusting is shown above the Canyon Range thrust on the left side of the section; C, Royse's (1993) interpretation of relationships after movement on the Canyon Range thrust had created a highland that was eroded to produce thick Upper Jurassic(?) and Lower Cretaceous deposits in a foredeep area that was later cannibalized to produce the extensive Upper Cretaceous and lower Tertiary deposits now found in eastern Utah; D, Allmendinger and Sharp's (in Allmendinger, 1992) interpretation of present-day structure; E, Allmendinger and Sharp's (in Allmendinger, 1992) palinspastic restoration of geologic units to their postulated prefaulting position. Dotted and dashed faults are restored normal and thrust fault traces, respectively. Dot-and-dash lines are east-directed thrust faults that were reactivated to accommodate normal fault extensional movement.

struction. Cretaceous conglomerate deposits in Sevier and Sanpete Counties, which had previously been regarded as late Cretaceous, were reassigned by several geologists (Standlee, 1982; Witkind and others, 1986; Schwans, 1988; Weiss and Roche, 1988; Lawton and others, 1997) to the Early Cretaceous, and possibly late Jurassic, on the basis of new palynological identifications. Royse (1993) postulated that the earliest thrusting in Millard County (movement on the Canyon Range thrust) created a highland in western Millard County from which erosion spread gravel and sand eastward into a foredeep basin in eastern Millard County. Royse (1993) called it a "phantom" foredeep because its deposits were largely destroyed by erosion that resulted from uplift and eastward movement on later underlying thrusts: in sequence, the Pavant, Paxton, and Gunnison thrusts (figure 217B and C). Most geologists consider the Canyon Range thrust to be correlative with thrusts exposed in the southern Wah Wah, San Francisco, Mineral, Canyon, and Sheeprock ranges, and covering perhaps 150,000 square miles (400,00 km^2) (Welsh, 1983). Royse (1993) considered the Canyon Range thrust to be of the same age as the Willard-Paris thrusts in northern Utah and eastern Idaho. Royse's structural restoration of the west-central Utah thrust belt shows that much of the early synorogenic stratigraphic record is missing because of erosion, and that its reconstruction clarifies our understanding of the source and distribution of the strata that remain today. Royse's (1993) key observation is that Early Cretaceous conglomerate contains Precambrian quartzite clasts that came from the upper plate of the Canyon Range thrust.

Timing of Thrusting

DeCelles and others (1995) included the interpretive cross section by Coogan and others (1995) and dated thrusting in central Utah by dating the sedimentary deposits derived from each major thrust episode. DeCelles and others (1995) conclusions as to timing are summarized on figure 53. Most of the sedimentary deposits that date the thrusting in Millard County are exposed in the San Pitch Mountains (also called the Gunnison Plateau) in Sanpete County. These units are not described herein; the interested reader is referred to Lawton and others (1997) and DeCelles and others (1995) for a summary of lithologic content of the Cedar Mountain, San Pitch, Indianola, and North Horn Formations shown on figure 218. DeCelles and others (1995) also discussed some of the structural relationships in the Canyon Mountains which were produced by elevation and minor reactivation of movement on the Canyon Range and Pavant thrusts during late Cretaceous time. They describe “growth” anticlines and a “growth” syncline on the east side of the Canyon Range where the Canyon Range Conglomerate was deformed by later thrusting. Gardner (1995) ascribed variations in Upper Cretaceous stratigraphy in east-central Utah to movements on the Pavant thrust in Millard County.

Thrusting in central Utah is usually referred to by geologists as "Sevier" thrusting, or sometimes as "Sevier-age" thrusting. Armstrong (1968a) defined the Sevier orogeny as occurring between the start of the Cretaceous and extending into the Campanian. Prior to Armstrong's definition, an older term, the Laramide orogeny, had been used broadly for all Cretaceous and early Tertiary compressive deformation in the Rocky Mountains, but Armstrong restricted the term

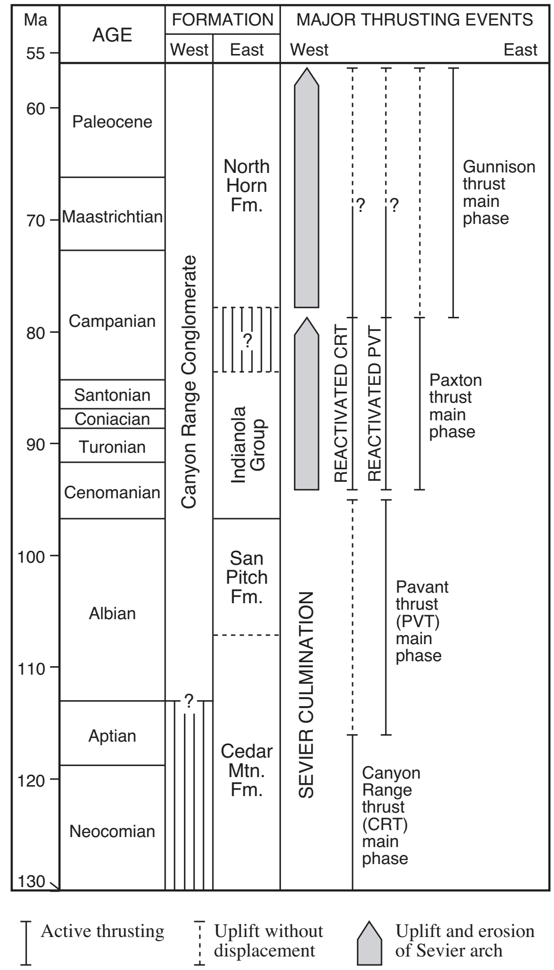

Figure 218. Diagram showing formations generated from thrust uplifts. West signifies the Canyon Mountains area; east includes the San Pitch Mountains and Wasatch Plateau east of Millard County. Early Cretaceous sandstone and conglomerate deposits (Cedar Mountain and San Pitch Formations) were laid down just east of Millard County. Later Cretaceous clastics (Canyon Range Conglomerate and North Horn Formation) were deposited in the Canyon and Pahvant ranges, where, locally, they were penecontemporaneously deformed by reactivated movement on the Canyon Range and Pavant thrusts (from Lawton and others, 1997, figures 4 and 6).

Laramide to formation of the late Cretaceous-early Tertiary anticlinal structures, such as the Uinta Mountains in northeastern Utah, that are clearly of that age. As figure 218 shows, the Canyon Range, Pavant, and Paxton thrusts fall within Armstrong's Sevier orogeny time frame, but the same style of thrust, the Gunnison thrust, extends into the Laramide age bracket, contemporaneous with the folding of the Uinta Mountains, the San Rafael Swell in central Utah, and other Laramide-age structures in the Rocky Mountains. Armstrong's (1968a) definitions helped geologists to focus on differences in structural style as contractional forces moved the thick Proterozoic and Paleozoic rocks of eastern Nevada and western Utah across the Wasatch hingeline and reacted with the much thinner cover of rocks in eastern Utah, where contraction formed the typical Laramide-style elongate anticlinal uplifts involving Precambrian basement rocks. Where the term "Sevier" thrusting is used in central Utah, it is used to describe a style of deformation rather than to limit its age.

Structural Relationships Between the Snake Range, Nevada, and the Confusion Range, Utah

Although this topic was discussed earlier under the section "Exposed Structures," it is reiterated here as it applies to the interpretive cross sections. Bedrock geology exposed in these two large ranges contrasts greatly. The Snake Range, one of the highest ranges in Nevada, is made up mostly of Proterozoic and lower Paleozoic strata that were locally intruded and metamorphosed during Mesozoic and early Tertiary events; its middle and late Paleozoic cover rocks became separated from these older strata and slid off the "roof" of the range on a spectacularly exposed surface called the North Snake Range decollement (or detachment) (Miller and others, 1988). This range, with the Kern Mountains and Deep Creek Range, is what is called a metamorphic core complex, a geologic feature characteristic of the Basin and Range. The Confusion Range, so-called because it is a group of low, scattered, look-alike hills with few prominent landmarks, is made up mostly of middle and upper Paleozoic strata folded into a broad sinuous synclinorium; it contains no intrusive or metamorphic rocks and the thrust and normal faults within the range are of relatively small displacement.

Regional cross sections between Nevada and Utah face the problem of reconciling the stark difference between the geology of those two adjacent ranges. Allmendinger and others (1983) identified an east-dipping reflector on the COCORP Utah line 1 as the Snake Range decollement. But to the north this reflector is missing on COCORP Nevada line 5 (Hauser and others, 1987), and offset of near-surface reflectors can be seen on the west side of Snake Valley. Because scarps in Quaternary surficial deposits are present on the west side of Snake Valley in Utah (Hintze and Davis, 2002c) and Nevada (Dohrenwend and others, 1991a-b), the surface projection of a steeply dipping fault can be constrained. To the west in Nevada, Gans and others (1985) clearly showed that the Snake Range decollement is offset by younger, more steeply dipping down-to-the-east normal faults within the Snake Range. Thus, the cross section of Smith and others (1991) shows the Snake Range decollement as having been truncated by a steeper, east-dipping, unnamed Basin and Range normal fault under Snake Valley. Further, using shallow seismic and surface data, Gans and others (1985) portrayed a major late-Cenozoic, east-dipping normal fault, the Schell Creek fault, that Hauser and others (1987) traced to a depth of about 12 miles (20 km) beneath the northern Snake Range on the COCORP Nevada line 5. Finally, the reflector that Allmendinger and others (1983, 1985) showed at the Utah-Nevada border, called the Northern Snake Range decollement, is similar in dip and magnitude to the better documented Schell Creek fault (Smith and others, 1991), the next major Basin and Range fault to the west of it. So, instead of calling the reflector a decollement, it might be more appropriately a late-Cenozoic normal fault, called the Snake Valley fault.

Bedrock encountered at depth in the five exploratory wells drilled to date in Snake Valley can be categorized as belonging to either the Snake Range block or the Confusion Range synclinorium. The Mamba (96-2), Cobra (95-1), Amerada-Hess (79-1), and Baker Creek (56-1) wells (see figures 209 and 215, and appendix A) penetrated rocks like those exposed nearby to the west in the foothills of the Snake Range block. The Outlaw (82-2) well spudded in Permian rocks of the Confusion Range synclinorium.

E.L. Miller and others (1999) presented fission-track data from 67 samples from the Snake Range-Kern Mountains-Deep Creek ranges. These data suggest that the fault system that extends along the east flank of these ranges for 90 miles (150 km) accommodated at least 7 to 9 miles (12-15 km) of rapid slip and uplift at about 17 million years ago, in the Miocene, younger by 15 to 20 million years than the earlier extensional movement in these ranges related to the Snake Range decollement, which occurred in late Eocene to early Oligocene time (E.L. Miller and others, 1999). Despite showing the down-dropping of the decollement by the steeper dipping normal faults noted above (their figure 4), E.L. Miller and others (1999) suggested that the two styles of faulting (low-angle detachment and high-angle rotational) occurred simultaneously along the length of a single normal fault system. They concluded that data from the northern Snake Range underscored the importance of vertical uplift of the range in Miocene time.

The Sevier Desert Reflector Problem

As explained in earlier pages of this bulletin under the "COCORP Deep Seismic Survey" heading, not all geologists agree with the designation of this prominent reflector as a "detachment." The four deep wells that have penetrated the reflecting surface encountered it where valley fill overlies denser bedrock. The interpretive cross sections on figure 217 are based on the notion that the west-dipping reflector represents not only a surface of Mesozoic eastward thrust displacement on the Pavant thrust, but also a late Cenozoic reactivation on the surface that allowed westward displacement during Basin and Range uplift and extension. Most geologists agree that there must be a west-dipping surface, configured like the Sevier Desert reflector, upon which Mesozoic thrusting took place. Anders and Christie-Blick (1994) and DeCelles and others (1995) regard the western portion of the reflector as representing ramps associated with Mesozoic thrusting. However, specific identification of the Sevier Desert reflector as the Pavant thrust as shown in figure 217A and D remains to be proven. Even more tentative is the identification of the Sevier Desert reflector as a glide plane for Cenozoic extensional movement extending to a depth of more than 6 miles (10 km). Nonetheless, although Anders and Christie-Blick (1994), Hamilton (1994), and Anders and others (2001) have questioned the interpretation of the Sevier Desert reflector as a "detachment," Allmendinger and Royse (1995) responded that extensional movement on the Sevier Desert reflector is the simplest explanation for the relationships seen. They argued that the arching of the Precambrian crystalline basement beneath the Sevier Desert is related in both time and space to accumulation of the late Cenozoic deposits that underlie the Sevier Desert. They showed that the age of basement uplift is given by young fission-track ages obtained from crystalline basement rocks in wells, and may also be reflected in the eastward dip of early Cenozoic strata on the southeast flank of the Pahvant Range. In addition, proprietary seismic information shows no high-angle normal faults that offset the basement.

Royse (written communication, March 11, 1996) noted that near-surface subsidence and basement uplift cannot occur in the same location unless dense rocks (Paleozoic and Precambrian strata) are moved laterally away from the area and replaced by less-dense late Cenozoic sedimentary and volcanic deposits. He suggested that this process would be somewhat similar to deroofing of metamorphic core complexes in Arizona (see for example, Crittenden and others, 1980), and that the Sevier Desert, in fact, might be the site of an aborted core complex. John E. Welsh, in logging the bottom-hole rocks in the Hole-in-Rock and Pavant Butte wells (81-4 and 81-7 in appendix A), noted that they are similar to the metamorphosed and attenuated Cambrian rocks exposed at the north end of the Mineral Mountains, likely a metamorphic core complex (see column 4, appendix C), and stated that they might represent the roof of a core complex beneath the Sevier Desert.

Late Cenozoic high heat flow beneath the Sevier Desert is supported by the numerous geothermal studies (see section "Geothermal Heat-Flow Studies") and eruptions of ash and lava. Most of the volcanic rocks exposed at the surface of the Sevier Desert are younger than 3 million years (column 4, appendix C), but older late Cenozoic lava flows and welded ash-flow tuffs are interbedded with Miocene-Pliocene sediments and form many of the reflectors seen on seismic lines that cross the area. In the Antelope Valley 7 1/2-minute quadrangle, 12 miles (19 km) east of Black Rock, Pliocene volcanic rocks were folded to form the Cove Creek anticline, which extends more than 6 miles (10 km) south from South Twin Peak. This anticline might be a hanging-wall structure above the Sevier Desert detachment or be a local phenomenon related to magmatic doming. Either way, it demonstrates continuing late Cenozoic tectonic disturbance at the south end of the Sevier Desert.

Cambrian Stratigraphic Constraints on Structural Interpretations

Cambrian strata are the most widespread rocks in Millard County, and their stratigraphy and thickness can be used to assess major relative horizontal displacement of structural blocks. In general, Cambrian deposits are thin in eastern Utah and thicken westward across the state (Hintze, 1988a). In eastern Millard County the Cambrian rocks are subdivided using nomenclature from the Tintic mining district in Juab County as shown on columns 2 and 3 (appendix C). In central Millard County the Cambrian nomenclature of the House Range is used (column 7). House Range formations are also mapped in the Cricket Mountains (column 5), the Drum Mountains (column 6), the Mineral Mountains (column 4), and the Canyon Mountains. In the latter range, House Range terminology applies only to Cambrian strata above the Canyon Range thrust (column 1). Cambrian rocks below that thrust in the central Canyon Mountains are part of the parautochthonous Pavant thrust sheet that is best exposed southeast of Scipio Pass in the Pahvant Range (column 2).

The basal Cambrian quartzite, called "Prospect Mountain" in western and central Millard County and "Tintic" in eastern Millard County (correlation chart 1, appendix C), is not useful for judging major tectonic displacement because it looks pretty similar across large distances. The complete Middle and Upper Cambrian section above the quartzite would be useful if it were preserved in its entirety in more places, but its top is present only in the House and Pahvant Ranges. In the House Range, the sequence from the base of the Pioche Formation to the top of the Notch Peak Formation is about 8,700 feet (2,650 m) thick. The comparative interval in the northern Pahvant Range is about 4,300 feet (1,300 m), or half as thick.

Because the mostly Middle Cambrian interval overlying the basal quartzite can be certainly identified by its trilobite succession in several ranges, it is the most suitable interval for tectonic-transport estimates. Above the Prospect Mountain Quartzite, the interval is the Pioche, Howell, Chisholm, Dome, and Whirlwind Formations, and to the east its temporal equivalent, overlying the Tintic Quartzite, is the Ophir Formation (correlation chart 1, appendix C). Comparative thicknesses of these two intervals are shown in table 9.

Table 9, taken from columns 1 through 3 and 5 through 7 (appendix C) shows general west-to-east thinning of this mostly Middle Cambrian interval in the Canyon Range plate, as might be expected from original Cambrian depositional distribution on the miogeosynclinal shelf. The most prominent thickness contrast occurs in the Canyon Mountains where Cambrian strata above the Canyon Range thrust are substantially thicker than those in the underlying Pavant plate. This thickness difference is accompanied by the inability, caused by minor facies changes, to recognize the widespread Cambrian formations of the House Range within the Ophir Formation of the same age in the Pavant thrust plate. Rocks in the Pavant plate were originally deposited east of those of the Canyon Range plate, and any tectonic reconstruction must reflect this original depositional relationship. How much farther west both sequences were originally deposited cannot be quantitatively determined from the stratigraphy. But, given the gently sloping nature of the shallow shelf on which both sequences accumulated, the distance between the depositional location of the House Range sequence and its nearest Ophir Formation counterpart could have been tens of miles.

Table 9. *Comparative thicknesses of selected Lower and Middle Cambrian strata in Canyon Range and Pavant thrust plates.*

Thrust Plate	Location	Thickness Feet	Thickness Meters	Cambrian Interval
Canyon Range	House Range	1,930	590	Pioche-Whirlwind
Canyon Range	Cricket Mts.	1,890	580	Pioche-Whirlwind
Canyon Range	Drum Mts.	1,420	430	Pioche-Whirlwind
Canyon Range	N. Canyon Mts.	1,630	500	Pioche-Whirlwind
Pavant	Canyon Mts.-N. Pahvant	1,080	330	Ophir
Pavant	Southern Pahvant	850	260	Ophir

Age and Amount of Crustal Extension in Millard County

Some geologists working in the eastern Great Basin have suggested that tectonic extension and volcanism are so closely linked in time and space that volcanism might be regarded as an evidence of extension (for example, see Axen and others, 1993). Best and Christiansen (1991) studied the relationship between volcanism and extension and showed that, during the most voluminous volcanic activity (between 31 and 20 million years ago), angular unconformities, epiclastic deposits, and other evidences of extension were of limited occurrence. They concluded that, in the Great Basin as a whole, major extension (post-17 million years ago) and peak volcanism (31-20 million years ago) correlate poorly in time and space. Field relationships in Millard County, as mapped by the author on many quadrangle maps and summarized on the geologic maps of the County (Hintze and Davis, 2002a-c; Hintze and others, 2003), support Best and Christiansen's (1991) conclusion. Gans and others (1989) cited the Oligocene deposits of interbedded ash-flow tuffs, conglomerates, and lake beds in the Confusion Range and Burbank Hills as evidence of extension. But, whereas the ash-flow tuffs are a blanket deposit blown out of a distant caldera, and thus are widely distributed and easily dated, the conglomerates and lake beds are likely of local origin and distribution, and are too poorly dated (younger than 30 or 17 million years old [columns 7-11, appendix C]) and discontinuously exposed to be regarded as evidence for a major fault-block basin. Instead, these probably represent deposits in local valleys in the folded rocks of the Confusion Range synclinorium.

Major development of fault-block basins in Millard County began about 17 million years ago, in Miocene time, and continues today as part of the process commonly called "Basin and Range extension." The magnitude of this extension is shown by the thickness and volume of valley fill, mostly sedimentary but partly volcanic, that has accumulated in the major fault-block basins (gravity lows) in Millard County, namely North Snake Valley, Pine Valley, Tule Valley, and Sevier Lake, and in the Clear Lake and Delta gravity lows of the Sevier Desert basin (figure 215). Compared with the thousands of feet of post-17 million-year-old valley fill in these basins, pre-17 million-year-old sedimentary deposits in western Millard County are likely insignificant in volume and cannot be regarded as an evidence of pre-17 million-year-old extension.

Eddington and others (1987) estimated the rate of Quaternary widening of the northern Great Basin as 0.3 to 0.4 inches (8-10 mm) per year, based on strain-rate studies. But it is more difficult to tell how much total Great Basin extension has occurred from the beginning of the Basin and Range extensional process in Miocene time to the present because so many assumptions are involved in the assessment.

In the cross sections in Millard County, Von Tish and others (1985) and Coogan and DeCelles (1996) estimated that 17.5 to 24 miles (28-38 km) and at least 11 to 24 miles (18-39 km), respectively, of extension must have occurred to produce the relationships portrayed on the sections. Royse (1993) and Allmendinger and others (1986) estimated 21 and 22 miles (33 and 35 km), respectively. Because extension is not evenly distributed across any extended terrane, it is important to identify the locus of any particular extension estimate. In these cases, the extension relates to the area of the Sevier Desert between the Canyon Mountains and the House Range, and, according to these authors, began in the Oligocene (~30 million years ago).

A rough estimate of the amount of Basin and Range extension between two unextended mountain blocks can be made by measuring the volume of valley fill between the blocks. By this scheme the Basin and Range extension in Millard County is greatest in the Sevier Desert between the Cricket Mountains, including their northern subsurface extension, and the Pahvant Range-Canyon Mountains unextended block.

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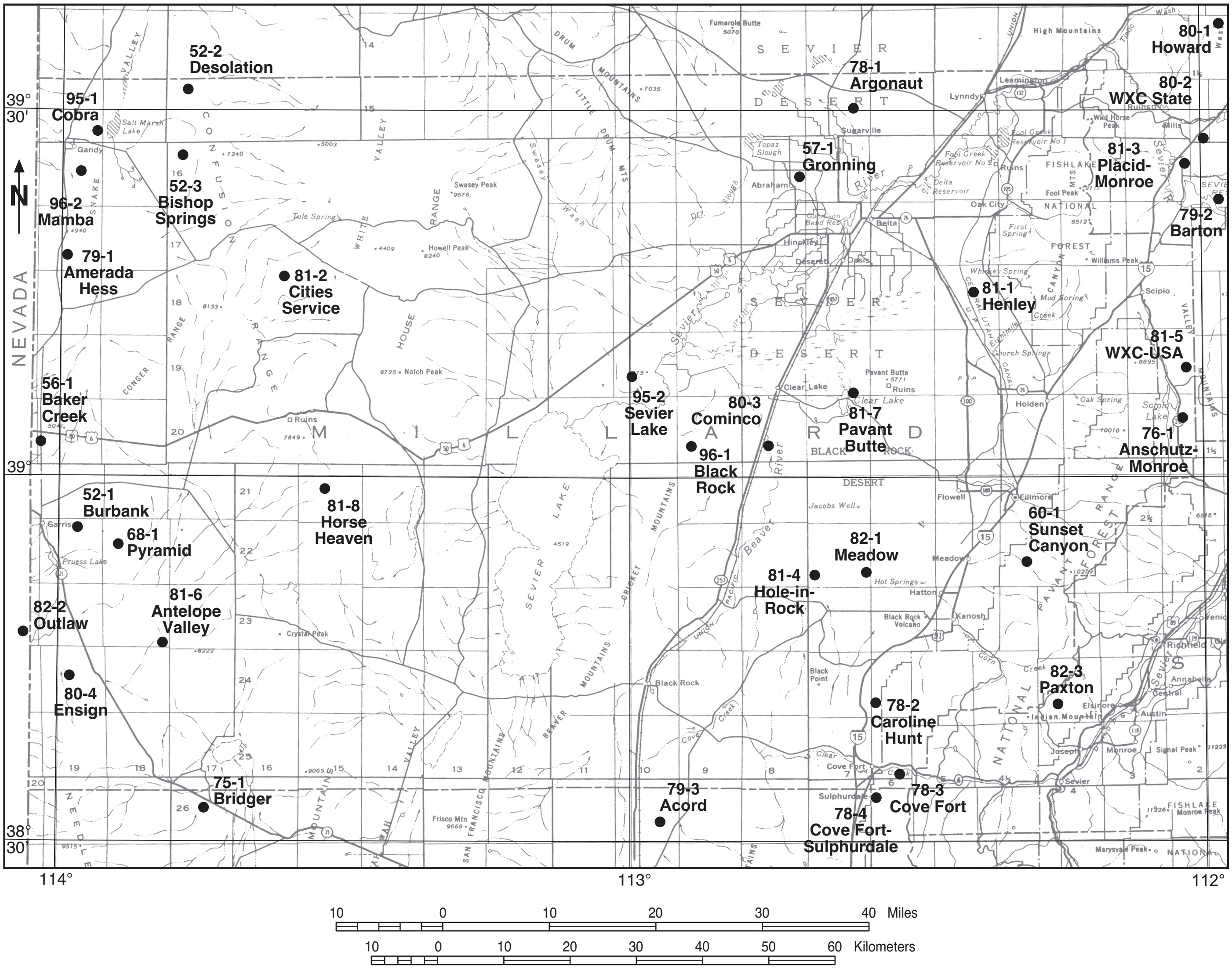
APPENDIX A

DATA FOR SELECTED DEEP WELLS IN AND NEAR MILLARD COUNTY



Index map of selected deep exploration wells in and adjacent to Millard County. Numbers indicate the year in which each well was completed (for example 1979 = 79-). Also shown are the names by which the wells are commonly known; several names differ from the more precise names listed in the appendix.

Abbreviations

USGS=United States Geological Survey

UGS=Utah Geological Survey well files in Department of Natural Resources Library

For names and lithologies; those in { } are the names used in this bulletin.

Names:

Gp=Group

Fm=Formation

Mbr=Member, formal

mbr=member, informal

Lithologies, capitalized where part of formal name:

ls=limestone

dolo=dolomite

sh=shale

ss=sandstone

sltst=siltstone

qtzt=quartzite

cg=conglomerate

Wells (names are those on index map), listed by age beginning with the oldest well in 1952:

Well No.	**Well Name**	**Operator**
52-1	Burbank	Standard Oil of California
52-2	Desolation	Standard Oil of California
52-3	Bishop Springs	Gulf Oil; Tiger Oil in 1980
56-1	Baker Creek	Shell Oil Company
57-1	Gronning	Gulf Oil Company
60-1	Sunset Canyon	Shell Oil Company
68-1	Pyramid	Pyramid Oil & Gas
75-1	Bridger	Bridger Petroleum Company
76-1	Monroe	Anschutz-Williams Energy
78-1	Argonaut	Argonaut Energy
78-2	Caroline Hunt	Hunt Energy Corporation
78-3	Cove Fort	Union Oil Company
78-4	Cove Fort-Sulphurdale	Union Oil Company
79-1	Amerada Hess	Amerada Hess Corporation
79-2	Barton	Placid Oil Company
79-3	Acord	Phillips Petroleum - Geothermal Division
80-1	Howard	Placid Oil Company
80-2	WXC State	Placid Oil Company
80-3	Cominco	Cominco American Inc.
80-4	Ensign	Commodore Resources Corp.
81-1	Henley	Placid Oil Company
81-2	Cities Service	Cities Service Oil Company
81-3	Placid Monroe	Placid Oil Company
81-4	Hole-in-Rock	Arco Oil and Gas Company
81-5	WXC-USA	Placid Oil Company
81-6	Antelope Valley	American Quasar Petroleum
81-7	Pavant Butte	Arco Oil and Gas Company
81-8	Horse Heaven	American Quasar Petroleum
82-1	Meadow	Arco Oil and Gas Company
82-2	Outlaw	Commodore Resources Corporation
82-3	Paxton	Placid Oil Company
95-1	Cobra	Balcron Division-Equitable Energy
95-2	Sevier Lake	Chevron USA Production Company
96-1	Black Rock	Chevron USA Production Company
96-2	Mamba	Equitable Resources

Number on index map: 52-1

Operator: Standard Oil of California

Well name: Burbank Anticline

USGS 1:24,000 (7 1/2-minute) quadrangle: Burbank Pass

Location: NE1/4 SE1/4 section 3, T. 22 S., R. 19 W.

Total depth: 6,955 feet Completion date: 3-19-52

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, July 1978 log, using samples and gamma-ray--neutron records (UGS).

Formation tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	100
100	Pilot Shale (Mississippian-Devonian)	350
450	Guilmette Fm, including West Range Ls Mbr	2,570
3,020	Simonson Dolomite	550
3,570	Sevy Dolomite	1,160
4,730	Laketown Dolomite (Silurian)	1,140
5,870	Ely Springs Dolomite (Ordovician)	240
6,110	Eureka Quartzite	340
6,450	Crystal Peak Dolo and Watson Ranch Qtzt	40
6,490	Lehman Formation	210
6,700	Kanosh Shale	255
6,955	T.D.	

Comments: Ordovician units (Ely Springs through Lehman) have been structurally thinned to about half their normal thickness; see geologic map by Hintze (1997a).

Number on index map: 52-2

Operator: Standard Oil of California

Well name: Desolation Anticline

USGS 1:24,000 (7 1/2-minute) quadrangle: Cockscomb Ridge

Location: NE1/4 NW1/4 section 8, T. 15 S., R. 17 W.

Total depth: 6,200 feet   Completion date: 5-18-52

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher; partial log at UGS.

Formation/Member tops (feet)		**Thicknesses drilled (feet)**
0	Surficial deposits	140
140	Arcturus Formation - ss, dolo	740
880	Riepe Spring Limestone	110
990	"Pakoon" Dolomite	170
1,160	Ely Limestone	1,550
2,710	Chainman Fm, Jensen Mbr - sh, ls, ss	570
3,280	Chainman Fm, Willow Gap Ls Mbr - ls, sh	130
3,410	Chainman Fm, Camp Canyon Mbr - sh, ls	700
4,110	Chainman Fm, Needle Siltstone Member	470
4,580	Joana Limestone	40
4,620	Pilot Fm {Shale} - limy sh, ls	1,040
5,660	Guilmette Formation - ls, dolo, ss	540
6,200	T.D.	

Comments: Comparable to surface rocks in the Confusion Range as exposed at Skunk Spring. The Riepe Spring Limestone is a Permian-age member of the Ely Limestone and here refers to a limestone at the top of the Ely Limestone. The interval identified as "Pakoon," a name typically used in eastern Millard County and to the south, is dolomite strata in the upper Ely Limestone.

Number on index map: 52-3

Operator: Gulf Oil to 9,058 in 1952
Tiger Oil to 16,058 in 1980

Well Name: Bishop Springs Anticline

USGS 1:24,000 (7 1/2-minute) quadrangle: Foote Range

Location: NW 1/4 SW 1/4 section 8, T. 16 S., R. 17 W.

Total depth: 16,058 feet Completion date: 6-10-52; 6-19-80

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Hansen and Scoville (1955); Kerns (1987); modified by Hintze from geologic map of Hose (1963b).

Formation tops (feet)		**Thicknesses drilled (feet)**
0	Surficial deposits and Pilot Shale	940
940	Guilmette Fm - dolo, ls, ss	1,060
	THRUST OR REVERSE FAULT	
2,000	Pilot Shale (faulted) - limy shale	300
2,300	Guilmette Fm	1,375
3,675	fault - more Guilmette Fm	1,593
5,268	Simonson Dolomite	732
6,000	Sevy Dolomite	770
6,770	Laketown Dolomite (faulted)	680
7,450	THRUST FAULT ZONE	120
	Silurian Laketown over Devonian Guilmette	
7,570	Simonson Dolomite	540
8,110	Sevy Dolomite	843
8,953	Laketown Dolomite (faulted) - thin	359
9,312	Ely Springs Dolomite	784
10,096	Eureka Qtzite (faulted) - thin	229
10,325	Crystal Peak Dolomite	367
10,692	Lehman Formation - ls, sltst, shale	362
11,054	Kanosh Shale - sh, ls	370
11,424	Juab Limestone	250
11,674	Wah Wah Limestone	314
11,988	Fillmore Formation - ls, sh	1,706
13,694	House Limestone	1,082
14,776	Notch Peak Formation - dolo, ls	1,282
16,058	T.D.	

Comments: Several units are thinner than expected, probably cut by attenuation or thrust faults. Watson Ranch Quartzite, between the Crystal Peak and Lehman strata, was apparently included in Crystal Peak interval.

Number on index map: 56-1

Operator: Shell Oil Company

Well name: Baker Creek

USGS 1:24,000 (7 1/2-minute) quadrangle: Baker

Location: SW 1/4 SE 1/4 section 19, T. 20 S., R. 19 W.

Total depth: 4,218 feet   Completion date: 6-20-56

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Heylmun and others (1965); see also Peters Formation Logging Co. lithologic log at UGS.

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Surficial deposits - likely Quaternary	730
730	Tertiary basin-fill deposits, including gypsum and limestone	3,450
	UNCONFORMITY	
4,180	Prospect Mountain Quartzite	38
4,218	T.D.	

Comments: Prospect Mountain Quartzite is widely exposed in the Snake Range, Nevada a few miles west of the well site.

Number on index map: 57-1

Operator: Gulf Oil Company

Well name: Gronning

USGS 1:24,000 (7 1/2-minute) quadrangle: Sutherland

Location: NE1/4 NE1/4 section 24, T. 16 S., R. 8 W.

Total depth: 8,064 feet   Completion date: 3-20-57

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: McDonald (1976); Lindsey and others (1981); Anderson and others (1983); Planke (1987); see also John E., Welsh, stratigrapher, May 1978 log, using Schlumberger electric log and samples (UGS).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits - likely Quaternary	30
30	Pleistocene-Pliocene alluvial and lacustrine deposits	2,090
2,120	Pliocene claystone and marl	400
2,520	Basalt, K-Ar date 4.2 ± 0.3 Ma (Pliocene) (Lindsey and others, 1981)	80
2,600	Miocene sandstone and claystone	130
2,630	Basalt	80
2,710	Miocene sandstone and claystone	110
2,820	Basalt	100
2,920	Miocene claystone, limestone and sandstone	130
3,050	Basaltic andesite	20
3,070	Miocene sandstone and claystone	230
3,300	Basaltic andesite	50
3,350	Miocene sandstone and lacustrine deposits	150
3,500	Oligocene volcanic agglomerate	750
4,250	Oligocene claystone and fine tuffaceous sandstone	610
4,860	Claystone, tuffaceous sandstone, some lacustrine limestone, green tuff, and anhydrite	1,390
6,250	Red shale, gray and green siltstone, tuffaceous sandstone, minor anhydrite and gypsum. Core 6,905-6,920 yielded Oligocene/Miocene pollen, and zircon and apatite crystals which gave a fission-track age of about 28 Ma (Lindsey and others, 1981)	705
6,955	Tuffaceous sandstone, calcareous siltstone, and claystone with nodular anhydrite, conglomeratic sandstone with grains of Tertiary rhyodacite and Paleozoic quartzite and limestone.	1,109
8,064	T.D.	

Comments: Volcanic agglomerates like those between 3,500 and 4,250 feet are exposed in the volcanic sequence of Dennison Canyon (~37 Ma) and the Little Drum Formation (~38 Ma) in the Little Drum Mountains 15 miles west of the well (Hintze and Oviatt, 1993; this bulletin). The isotopic ages of these agglomerates indicate that the fission-track age of 28 Ma is too young. John Welsh's log placed the Miocene-Oligocene boundary at 3,750 feet based on the appearance of crystal tuffs at that level. No mafic rocks correlative with the 4.2 Ma basalt are exposed in the area.

Number on index map: 60-1

Operator: Shell Oil Company

Well name: Sunset Canyon

USGS 1:24,000 (7 1/2-minute) quadrangle: Fillmore

Location: SW1/4 SE1/4 section 21, T. 22 S., R. 4 W.

Total depth: 8,962 feet   Completion date: 11-4-60

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, 1978 log, using samples and radioactive log (UGS).

Formation/Member tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	30
30	Chinle Fm, Shinarump Cg Mbr - cg, ss	170
100	Moenkopi Fm, upper red mbr - ss, sltst, sh	1,150
1,650	Moenkopi Fm, Shnabkaib Member	330
1,980	Moenkopi Fm, middle red member	390
2,370	Moenkopi Fm, Virgin Limestone Member	360
2,730	Moenkopi Fm, lower red member	350
3,080	Moenkopi Fm, Sinbad Limestone Member	50
3,130	Moenkopi Fm, Black Dragon Member	280
3,410	Kaibab Fm {Ls} (Permian)	110
3,520	Toroweap Fm, evaporitic member	180
3,700	Toroweap Fm, sandy dolomite member	140
3,840	Toroweap Fm, cherty dolomite member	160
4,000	Queantoweap Sandstone	290
4,290	Pakoon Dolomite	220
4,510	Callville Limestone (Pennsylvanian)	270
4,780	Humbug-Deseret Fms - ls, ss (Mississippian)	820
5,600	Gardison Fm - ls, dolo	440
6,040	Fitchville Formation	160
6,200	Pinyon Peak Fm (Devonian) - sltst	110
6,310	Crystal Pass Limestone (Devonian)	140
6,450	Simonson Dolomite	650
7,100	Sevy Dolomite	650
7,750	Laketown Dolomite (Silurian)	695
8,445	Fish Haven Dolomite (Ordovician)	517
8,962	T.D.	

Comments: The thicknesses of the upper red and Shnabkaib members of the Moenkopi Formation shown above are three times thicker than found in surface exposures in the Dog Valley area 15 miles south of the well. These Triassic beds may be steeply tilted or complexly folded in the well, giving an abnormally high thickness. The Moenkopi members listed are a mixture of southwestern and eastern (Colorado Plateau) Utah terminology. The Toroweap strata are part of Davis' (1983) Kaibab map unit. The Mississippian names are north-central Utah terminology for strata called Redwall Limestone in this bulletin. The Pinyon Peak interval may be the Delle Phosphatic Member. The Crystal Pass Limestone is southwestern Utah terminology for what here may be the Pinyon Peak Limestone. Cove Fort Quartzite is apparently missing. The Simonson interval may contain Guilmette strata.

Number on index map: 68-1

Operator: Pyramid Oil & Gas

Well name: Cedar Pass

USGS 1:24,000 (7 1/2-minute) quadrangle: Burbank Pass

Location: NE1/4 NE1/4 NW1/4 section 17, T. 22 S., R. 18 W.

Total depth: 7,510 feet   Completion date: 3-24-68

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Kerns (1987).

Formation/Member tops (feet)		Thicknesses drilled (feet)
0	no record	1,197
1,197	Ely Limestone (Pennsylvanian-Mississippian)	683
2,880	Chainman Formation, Jensen Member	620
3,500	Chainman Formation	1,600
5,100	Joana Limestone (Mississippian)	710
5,810	Pilot Shale - limy shale (Devonian)	985
6,795	Guilmette Formation - ls, dolo, ss	715
7,510	T.D.	

Comments: A geologic map of the Burbank Pass 1:24,000-scale quadrangle shows that this well spudded in the upper (Permian) part of the Ely Limestone (Hintze, 1997d). A minor thrust fault places east-dipping Ely over the Ely and Arcturus Formations about 0.3 miles west of the well site. The upper 1,197 feet of the drill hole should have penetrated Ely Limestone beds above and below the thrust.

Number on index map: 75-1

Operator: Bridger Petroleum Co.

Well name: Federal #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Pine Valley Hardpan South

Location: C SE1/4 section 15, T. 26 S., R. 17 W., Beaver County

Total depth: 8,555 feet Completion date: 3-19-75

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: John E. Welsh, stratigrapher, in 1982, using samples and gamma-ray log.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial fanglomerate	90
90	Needles Range Group tuff	420
510	Slide block of Cambrian limestone	340
850	no samples	620
1,470	Welded tuff	280
1,750	Latite flow	170
1,920	Rhyolitic dome/flow	890
	UNCONFORMITY	
2,810	Notch Peak Fm - dolo	1,300
4,110	Orr Fm, Sneakover Ls Mbr - ls	70
4,180	Orr Fm, Steamboat Pass Mbr - shale	200
4,380	Orr Fm, Big Horse Ls Member - ls	510
4,890	Wah Wah Summit Fm, white marker mbr - dolo	250
5,140	Wah Wah Summit Fm, ledgy mbr - dolo, ls	640
5,780	Pierson Cove Fm- dolo, ls	510
6,290	Wheeler Shale tongue	110
6,400	Eye of Needle Limestone	405
6,805	Swasey Limestone	175
6,980	Whirlwind Fm	70
7,050	Dome Limestone	260
7,310	Chisholm Shale	40
7,350	Howell Limestone	250
7,600	Pioche Fm, Tatow Mbr	210
7,810	Pioche Fm, lower mbr - qtzt, argillite	700
8,510	Prospect Mountain Quartzite	45
8,555	T.D.	

Comments: Lower Paleozoic section similar to nearby surface rocks (Hintze, 1974e). A well about 2 miles to the east in Pine Valley (Husky Oil Company #10-13 Federal, CNW1/4 NE1/4 section 13, T. 26 S., R. 17 W.) penetrated about 6,850 feet of Cenozoic basin fill, including slide blocks and a rhyolite “dome,” before bottoming in Middle Cambrian rocks (T.D. 7,048 feet) (John E. Welsh, March 1981 log at UGS). Cuttings from this well are in the Utah Geological Survey Core Research Center.

Number of index map: 76-1

Operator: Anschutz-Williams Energy

Well name: Monroe Fee #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Scipio Lake

Location: SE1/4 SE1/4 section 14, T. 20 S., R. 2 W.

Total depth: 15,369 feet   Completion date: 3-11-76

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: John E. Welsh, stratigrapher, in 1978, using samples and gamma-ray logs (UGS).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	700
700	Green River Formation	240
940	Colton Formation	340
1,280	Flagstaff Ls {Formation}	510
1,790	North Horn Formation	1,500
3,290	Mesaverde Sandstone {Canyon Range Cg?}	1,210
4,500	Indianola {Canyon Range} Conglomerate	1,610
	UNCONFORMITY	
6,110	Opex {Formation} (Cambrian) - dolo	100
6,210	Cole Canyon {Dolomite} Fm	280
6,490	Bluebird {Dolomite} - ls	150
6,640	Herkimer {Limestone} - dolo	240
6,880	Dagmar Dolomite	70
6,950	Teutonic {Limestone} - dolo	250
7,200	PAVANT THRUST	
7,200	Jurassic Arapien {Shale} Fm	1,700
8,900	Carmel {Twin Creek} Ls	350
9,250	Navajo Sandstone	840
10,090	Kayenta Formation	40
10,130	Wingate Sandstone	380
10,510	Chinle Formation, upper	410
10,920	Chinle Formation, Petrified Forest Mbr	80
11,000	Chinle Formation, Mossback Mbr	80
11,080	Chinle Formation, lower	50
11,130	Moenkopi Formation, upper red mbr	660
11,790	Moenkopi Formation, Shnabkaib Member	290
12,080	Moenkopi Formation, middle red mbr	540
12,620	Moenkopi Formation, Sinbad Ls Mbr	675
13,295	Moenkopi Formation, Black Dragon Member	220
13,515	Kaibab Fm - dolo	245
13,760	Deseret Limestone - dolo	570
14,330	Gardison Limestone - dolo	270
14,600	Fitchville Formation - dolo	120
14,720	Pinyon Peak Limestone - sltst	50
14,770	Crystal Pass Limestone	150
14,920	Elbert equivalent {Victoria? Fm} - sltst	30
14,950	Simonson Dolomite	419
15,369	T.D.	

Comments: See Standlee (1982, figure 6) for regional structural position of this well. The Moenkopi members listed are a mixture of southwestern and eastern (Colorado Plateau) Utah terminology. The Mississippian terminology of north-central Utah is used here. The Pinyon Peak interval may be the Delle Phosphatic Member. The Crystal Pass is terminology from southwestern Utah and here may be the Pinyon Peak Limestone. Elbert terminology is from Colorado.

Number of index map: 78-1

Operator: Argonaut Energy

Well name: #1 Federal

USGS 1:24,000 (7 1/2-minute) quadrangle: Rain Lake

Location: C NW1/4 NW1/4 section 23, T. 15 S., R. 7 W.

Total depth: 11,266 feet   Completion date: 6-22-78

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Lindsey and others (1981); Planke (1987); John E. Welsh, stratigrapher, in February 1979, logged the interval below 7,300 feet.

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Quaternary-Pliocene sand, silt with minor clay and gravel	600
600	Pliocene-Miocene shale, with minor calcareous sandstone and siltstone	1,950
2,550	Miocene SALT, gypsum, anhydrite, and minor clay and volcanic material	1,690
4,240	Clay with volcanic particles	24
4,264	Miocene salt and gypsum	3,470
7,734	SEVIER DESERT REFLECTOR (UNCONFORMITY)	
7,734	Marbleized Cambrian limestone and dolomite, sheared, graphitic, with fractured quartzite vein at 8,600	3,532
11,266	T.D.	

Comments: Welsh interpreted the Cambrian rocks below 7,734 feet as having been metamorphosed, and regarded this metamorphism as an extension of that seen in Cambrian strata in the Mineral Mountains 60 miles to the south. In the Mineral Mountains, these metamorphic rocks are related to what Welsh (1983) interpreted as the Frisco-Canyon Range thrust.

Number on index map: 78-2

Operator: Caroline Hunt Trust, Hunt Energy Corp

Well name: CHTE 15-30 Geothermal test

USGS 1:24,000 (7 1/2-minute) quadrangle: Dog Valley Peak

Location: NW 1/4 SW 1/4 section 30, T. 24 S., R. 6 W.

Total depth: 8,021 feet   Completion date: 7-4-78

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Dr. James L. Baer, Brigham Young University, in 1978 for upper part of hole; John E. Welsh, stratigrapher, May 1980 partial log (UGS). For geologic map see Davis (1983).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Sevy Dolomite (Devonian)	470
470	Guilmette Formation - ls, dolo, ss	160
630	Cove Fort Quartzite	50
680	Crystal Pass/Pinyon Peak Fm	150
830	Mississippian ls	390
1,220	Mississippian phosphatic shale [FAULT ZONE?]	47
1,267	Deseret {Redwall} Ls (Mississippian)	1,283
2,550	Callville Ls and Pakoon Dolo (Pennsylvanian)	370
2,920	Queantoweap Ss, and possibly Toroweap and Kaibab Fms	1,080
4,000	lower Triassic	500
4,500	Moenkopi Formation	1,124
5,624	THRUST FAULT	
5,624	Teutonic Limestone	~371
5,630	Latite porphyry intrusion	20
5,895	Dagmar and Herkimer Fms	435
6,330	Bluebird Dolomite	590
6,920	Cole Canyon Fm [and likely Opex Fm]	1,101
8,021	T.D.	

Comments: This well began in overturned Devonian and Mississippian strata and then had serious problems with lost circulation and was drilled without returns from 1,294 to 5,624 feet and at other intervals representing 60% of the entire depth. The strata in the 1,267 to 5,624 foot interval were tentatively identified, using gamma logs and a few feet of cores, as mostly limestone and dolomite with some shale and siltstone. These strata are attenuated. In this case, the thrust itself may be overturned and underlying Cambrian limestone and dolomite are overturned and dip 40-60°. The Simonson Dolomite, which should be between the Sevy and Guilmette, is apparently missing. Crystal Pass is terminology from southwestern Utah.

Number on index map: 78-3

Operator: Union Oil Company

Well name: Cove Fort-Sulphurdale Unit 31-33

USGS 1:24,000 (7 1/2-minute) quadrangle: Cove Fort

Location: NE 1/4 NW 1/4 section 33, T. 25 S., R. 6 W.

Total depth: 5,207 feet Completion date: 1978?

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, in December 1978, using samples and gamma ray-neutron log. This was a geothermal test well; see Ross and Moore (1985).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	50
50	Miocene-Oligocene volcanic rocks (Bullion Canyon Volcanics)	950
	UNCONFORMITY	
1,000	North Horn {Aurora} Formation	140
1,140	Price River(?) Cg	90
	UNCONFORMITY	
1,230	Laketown Dolomite	1,540
2,770	brecciated dolomite	110
2,880	THRUST FAULT	
2,880	Moenkopi Fm, upper red siltst member	500
3,380	Moenkopi Fm, Shnabkaib Member	300
3,680	Moenkopi Fm, middle red siltst member	340
4,020	Moenkopi Fm, Virgin Ls Member	260
4,280	Moenkopi Fm, lower red siltst member	180
4,460	Moenkopi Fm, Sinbad Ls Member	110
4,570	Moenkopi Fm, Black Dragon Member	210
4,780	fractured zone, no log	427
5,207	T.D.	

Comments: Thicknesses of some Moenkopi members in this drill hole are much less than those reported from the 1960 Shell Oil Sunset Canyon well 15 miles to the north. The Moenkopi members listed are a mixture of southwestern and eastern (Colorado Plateau) Utah terminology. The thrust fault in this hole is beneath the main Pavant thrust. Ash and others (1979) reported Kaibab Limestone from minor core recovery between 5,015 and 5,021 feet. From well logs in Ash and others (1979) and Moore and Samberg (1979), J.K. King thinks the Bullion Canyon Volcanics include lava flows and intermediate intrusions (Tbci) and, probably, the Three Creeks Tuff (Tbct). The correct names for the intervals labeled North Horn and Price River(?) are uncertain. As noted in the bulletin they may be the Aurora Formation, or the Aurora Formation and Flagstaff Formation, respectively.

Number on index map: 78-4

Operator: Union Oil Company

Well name: Cove Fort-Sulphurdale Unit 42-7

USGS 1:24,000 (7 1/2-minute) quadrangle: Cove Fort

Location: SE1/4NE1/4NW1/4 section 7, T. 26 S., R. 6, W., Beaver County

Total depth: 7,735 feet   Completion date: 1978

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Moore and Samberg (1979) and Ash and others (1979) modified by J.K. King, UGS geologist. This was a geothermal test well.

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Surficial deposits	60
60	Bullion Canyon Volcanics, other volcanic rocks, and welded ash-flow tuffs	1,980
	UNCONFORMITY OR FAULT	
2,040	Queantoweap Sandstone	810
2,850	Pakoon Dolomite, metamorphosed	550?
3,400?	Callville Limestone(?) and Delle Phosphatic Member(?)	580?
3,980	finely crystalline light-colored marble; likely metamorphosed Mississippian and Devonian strata	2,200?
6,180	Tertiary quartz monzonite dike	40
6,220	marble	270
6,490	Tertiary quartz monzonite dike	50
6,540	marble	150
6,960	Tertiary quartz monzonite dike	20?
6,980?	skarn	120?
7,100	mostly serpentinite	430
7,530	Tertiary quartz monzonite dike	10
7,540	mostly serpentinite	190
7,735	T.D.	

Comments: The lack of a thrust fault in this hole and presence in the nearby geothermal well (78-3) indicates a major structural change.

Number on index map: 79-1

Operator: Amerada Hess Corporation

Well name: Federal 1-28

USGS 1:24,000 (7 1/2-minute) quadrangle: Gandy SW

Location: SW 1/4 NE 1/4 NE 1/4 section 28, T. 17 S., R. 19 W.

Total depth: 7,782 feet Completion date: 7-3-79

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Notes by Dr. J.L. Baer, Brigham Young University, on January 21, 1996, from neutron density and borehole compensated sonic logs.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Valley fill; well cased to 1,035 feet	5,608
5,608	Limestone with minor shale	145
5,753	Shale with some limestone beds	42
5,795	Limestone	90
5,885	Shale with thin limestone beds	27
5,912	Limestone with thin shale breaks in lower 30 feet	88
6,000	Shale with thin limestone beds	27
6,027	Dolomite with a few thin shale beds	185
6,212	Mostly shale with some dolomite beds	28
6,240	Dolomite	360
6,600	Shale	14
6,614	Dolomite	708
7,322	Shale with thin dolomite beds	38
7,360	Dolomite with a few shale beds	100
7,460	Quartzite with a few shale beds	179
7,639	Shale or phyllite with thin quartzite beds	83
7,722	Quartzite; probably Cambrian Prospect Mountain Quartzite	60
7,782	T.D.	

Comments: Well is on the west flank of the North Snake Valley gravity low (figure 215). The Paleozoic rocks encountered below 5,608 feet are probably related to those exposed in the northern Snake Range, Nevada. The well bottomed in a dense quartzite which is probably the top beds of the Cambrian Prospect Mountain Quartzite. The interval 7,322 to 7,722 is probably the Cambrian Pioche Formation. The interval 6,027 to 7,322 feet is probably Middle and Late Cambrian in age. The limestone and shale interval 5,608 to 6,027 feet is probably Lower Ordovician Pogonip Group. All of these units are exposed in the hills west of Gandy, about 10 miles north of the Amerada-Hess well site. Allmendinger and others (1985) identified the Snake Range decollement at 7,350 feet.

Number on index map: 79-2

Operator: Placid Oil Company

Well name: WXC Barton #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Skinner Peaks

Location: NW1/4 SE1/4 section 32, T. 16 S., R. 1 W., Juab County

Total depth: 21,840 feet Completion date: 11-27-79

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, in 1979, using samples and gamma-ray log.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial and volcanic rocks	300
300	Copperopolis volcanic rock	720
1,020	Packard tuff	170
1,190	Tuffaceous deposits	525
	UNCONFORMITY	
1,715	Green River Formation	1,215
2,930	Flagstaff Formation	1,520
	UNCONFORMITY	
4,450	Arapien Shale/Twist Gulch Fm	1,885
6,335	upper Twin Creek Limestone/Carmel Fm	1,217
7,552	Twin Creek Limestone, Watton Canyon Mbr	143
7,695	Twin Creek Limestone, Boundary Ridge Mbr	159
7,854	Twin Creek Limestone, Rich Mbr	164
8,018	Twin Creek Limestone, Sliderock Mbr	104
8,122	Twin Creek Limestone, Gypsum Spring Mbr	150
8,272	Navajo Sandstone	1,243
9,515	Ankareh Fm/Chinle Fm - sh, sltst, ss	2,185
11,700	"Shinarump" {Cg Mbr of Chinle} - ss	60
11,760	Moenkopi Fm, upper red siltstone mbr	1,260
13,020	Moenkopi Fm, Shnabkaib Mbr - marine strata	1,185
14,205	Moenkopi Fm, middle red siltstone mbr	355
14,560	Moenkopi Fm, Virgin Limestone Mbr	1,150
15,710	Moenkopi Fm, lower red siltstone mbr	355
16,065	Moenkopi Fm, limestone tongue	115
16,180	Moenkopi Fm, lower red siltstone mbr	970
17,150	Moenkopi Fm, Sinbad Dol {Ls} Mbr	60
17,210	Moenkopi Fm, Black Dragon Mbr	470
17,680	Moenkopi Fm, Timpoweap Dolo {Mbr}	80
17,760	Black Box Dolomite (Permian)	130
17,890	Queantoweap Sandstone	430
18,320	Pakoon Dolomite	740
19,060	Gardison Dolo {Ls} (Mississippian)	340
19,400	Fitchville Dolomite {Fm}	200
19,600	Pinyon Peak Fm {Ls} (Devonian)	385
19,985	Crystal Pass Limestone {Guilmette}	465
20,450	Simonson Dolomite	400
20,850	Sevy Dolomite	450
21,300	Laketown Dolomite (Silurian)	540
21,840	T.D.	

Comments: This thick unfaulted sequence lies east of the Sevier-age Pavant thrust fault on the Paxton thrust sheet (DeCelles and others, 1995). It contains the westernmost complete record of Triassic and Jurassic strata at this latitude in central Utah. The Moenkopi members listed are a mixture of southwestern and eastern (Colorado Plateau) Utah terminology. Black Box is terminology for Permian carbonates on the Emery high in central Utah (Welsh and others, 1979). The Mississippian terminology of north-central Utah is used here. Crystal Pass is terminology from southwestern Utah. Permian terminology is from southern Utah and may not be appropriate.

Number on index map: 79-3

Operator: Phillips Petroleum - Geothermal Division Company

Well name: McCulloch Acord #1-26

USGS 1:24,000 (7 1/2-minute) quadrangle: Read

Location: SE1/4 SW1/4 section 26, T. 26 S., R. 10 W., Beaver County

Total depth: 12,650? feet   Completion date: 2-29-79?

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: John E. Welsh, stratigrapher, December 1979 partial log (UGS).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial and Pleistocene valley fill	500
500	Pliocene-Miocene claystone	1,410
1,910	Tuffaceous valley fill	1,640
3,550	Ash-fall tuff, rhyolitic(?)	70
3,620	Volcaniclastic or volcanic-clast sedimentary rocks; distal Mount Dutton Fm(?)	1,090
4,710	Harmony Hills(?) Tuff	570
5,280	Ash-fall tuffs	1,500
6,780	Quartz-rich, crystal tuff over plagioclase-quartz tuff	150
6,930	Reworked tuff	140
7,070	Sweet Tuff(?) Mbr, Condor Canyon Fm - too thick	530
7,600	Leach Canyon Formation	230
7,830	Isom Fm, Bald Hills Tuff	280
8,110	Needle Range Group tuff(s)	210
8,320	Horn Silver Andesite	1,850
10,170	INTRUSIVE CONTACT Mineral Mountains batholith or Beaver Lake Mountains intrusions	1,940
12,110	Precambrian gneiss septa intruded by hornblende-biotite granite	550
12,650	T.D.	

Comments: This was a geothermal test well. The intrusive contact is a fault contact in Smith and others (1989, figures 14 and 15).

Number on index map: 80-1

Operator: Placid Oil Company

Well name: 1-A WXC Howard

USGS 1:24,000 (7$^{1}/_{2}$-minute) quadrangle: Juab

Location: NE$^{1}/_{4}$ NW$^{1}/_{4}$ section 5, T.14 S., R. 1 W., Juab County

Total depth: 12,150 feet   Completion date: 4-25-80

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, in September, 1981, using samples and gamma log. For geologic map see Meibos (1983).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	150
150	Paleocene(?) cg {North Horn Fm?}	420
570	no samples, fault zone	2,010
2,580	Paleocene-Cretaceous cg {Canyon Range?}	2,295
	UNCONFORMITY	
4,875	Arapien Shale - ls, anhydrite, sh, salt	4,345
9,220	Twin Creek Limestone, Watton Canyon Mbr	440
9,660	Twin Creek Limestone, Boundary Ridge Mbr	125
9,785	Twin Creek Limestone, Rich Member	365
10,150	Twin Creek Limestone, Sliderock Member	230
10,380	Twin Creek Limestone, Gypsum Spring Mbr	264
10,644	Navajo Sandstone	1,446
12,090	Chinle Shale {Formation}	60
12,150	T.D.	

Comments: Meibos' (1983) map and cross section through this well show a normal fault in the zone between 570 and 2,580 feet where the well lost circulation. Formation tops given in Kerns (1987) differ from those shown above. The term Indianola, used by Kerns, is probably not appropriate here.

Number of index map: 80-2

Operator: Placid Oil Co

Well name: WXC State #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Skinner Peaks

Location: NE1/4 NW1/4 section 36, T. 15 S., R. 1 1/2 W., Juab County

Total depth: 13,894 feet   Completion date: 6-1-80

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, in June 1979. Also see Kerns (1987) and Standlee (1982).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	310
310	Goldens Ranch Formation (Oligocene)	670
980	Green River Formation	210
1,190	Flagstaff Formation - ls, marl, silt	960
2,150	North Horn Formation - ss, cg, ls	950
3,100	Cretaceous cg	1,670
	UNCONFORMITY	
4,770	Arapien Shale/Twist Gulch Fm	2,090
6,860	Twin Creek Limestone, Watton Canyon Mbr	224
7,084	Twin Creek Limestone, Boundary Ridge Mbr	168
7,252	Twin Creek Limestone, Rich Member	248
7,490	Twin Creek Limestone, Sliderock Mbr	266
7,756	Twin Creek Limestone, Gypsum Spring Mbr	314
8,070	THRUST FAULT	
8,070	Arapien Shale/Twist Gulch Fm	1,230
9,300	not logged, (Arapien Shale)	2,150
11,450	basal Arapien Shale	174
11,624	Twin Creek Limestone, Watton Canyon Mbr	235
11,859	Twin Creek Limestone, Boundary Ridge Mbr	161
12,020	Twin Creek Limestone, Rich Member	246
12,266	Twin Creek Limestone, Sliderock Mbr	308
12,574	Twin Creek Limestone, Gypsum Spring Mbr	364
12,938	Navajo Sandstone	956
13,894	T.D.	

Comments: Thrust repeats Jurassic section.

Number on index map: 80-3

Operator: Cominco American Inc.

Well name: Federal Number 2

USGS 1:24,000 (7 1/2-minute) quadrangle: Neels

Location: SW1/4 NW1/4 section 28, T. 20 S., R. 8 W.

Total depth: 13,193 feet Completion date: 7-31-80

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: John E. Welsh, stratigrapher, in May 1980, using samples and gamma-ray log. See also Planke (1987).

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Quaternary(?) lake deposits	400
400	Calcareous claystone [likely Pleistocene]	600
1,000	Pleistocene(?)-Pliocene sediments	480
1,480	Pliocene-Miocene marlstone	1,000
	UNCONFORMITY	
2,480	Mutual Qtzt {Fm} (Precambrian)	780
3,260	Inkom Formation - phyllite	370
3,630	Caddy Canyon Quartzite	440
4,070	Black Rock Canyon Limestone	110
4,180	Pocatello Formation - qtzt, phyllite	4,210
	FRISCO-CANYON RANGE THRUST FAULT	
	(Precambrian over Upper Cambrian)	
8,390	Notch Peak Formation (Cambrian)	580
8,970	Orr Formation, Sneakover Ls Mbr	80
9,050	Orr Formation, Steamboat Pass Shale Mbr	40
9,090	Orr Formation, Big Horse Ls Member	560
9,650	Lamb Dolomite {Wah Wah Summit Fm(?)}	540
10,190	Trippe Limestone	420
10,610	Limestone of Cricket Mountains	1,430
12,040	Whirlwind Formation - phyllitic shale	110
12,150	Dome Limestone	210
12,360	Chisholm Formation - phyllitic shale	140
12,500	Howell Limestone	90
12,590	Pioche Formation - phyllitic qtzt	430
13,020	Prospect Mountain Quartzite	173
13,193	T.D.	

Comments: Well documents regional extent of Frisco-Canyon Range thrust plate. The Quaternary(?) lake deposits and calcareous claystone reported by Welsh are probably lake sediments described and mapped by Oviatt (1991a) as late Pleistocene and Pliocene-Pleistocene lacustrine and deltaic deposits. This well lies west of the Clear Lake fault zone and is on the upthrown Cricket Mountains block of Cambrian and Precambrian strata. This well does not penetrate the Sevier Desert reflector, nor does it encounter marbleized Cambrian carbonate rocks as do the wells that lie in the down-dropped Sevier Desert basin east of the basin-bounding fault. Allmendinger and others (1985) placed the Precambrian over Upper Cambrian thrust at 8,364 feet.

Number on index map: 80-4

Operator: Commodore Resources Corporation

Well name: Ensign #1-16

USGS 1:24,000 (7 1/2-minute) quadrangle: Mormon Gap

Location: S 1/2 SW 1/4 section 16, T. 24 S., R. 19 W.

Total depth: 12,238 feet   Completion date: 12-29-80

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Kerns (1987). For geologic map see Hintze (1986a).

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	not logged, valley fill in nearby wells	714
714	Ely Limestone	1,156
1,870	Illipah Formation (upper Chainman Fm)	260
2,130	Chainman Formation	2,012
4,142	Joana Limestone	1,278
5,420	Devonian, and older strata?, undivided	6,818
12,238	T.D.	

Comments: This is the deepest of several promotional wells drilled in this area. Although the above log is sketchily documented, it gives more information than other nearby wells, most of which were promoted by Wilburn J. Gould in 1968-1974.

Number on index map: 81-1

Operator: Placid Oil Company

Well name: Henley #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Harding

Location: NW 1/4 NW 1/4 section 15, T. 18 S., R. 5 W.

Total depth: 13,106 feet   Completion date: 3-17-81

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Davis (1994); see also Kerns (1987).

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	150
150	Flagstaff(?) Formation - ls, sh, ss	11
161	North Horn(?) Formation - ss	1,599
	UNCONFORMITY, SEVIER DESERT REFLECTOR	
1,760	Fish Haven Dolomite	190
1,950	Eureka Quartzite	60
2,010	Pogonip Group	1,490
3,500	Cambrian dolomite	3,970
7,470	THRUST FAULT	
7,470	Eureka Quartzite melange	480
7,950	Ordovician-Cambrian carbonate	5,130
13,080	Pioche(?) {Ophir} Fm, Lower Cambrian	26
13,106	T.D.	

Comments: The Canyon Range thrust plate is not represented here, apparently eroded away before deposition of the North Horn Formation. Coogan (in DeCelles and others, 1995) shows multiple thrust-stacking of lower Paleozoic strata in his cross section through this well. Davis (1994) discussed regional aspects of this well. Allmendinger and others (1985) placed the Cambrian over Ordovician thrust at 7,467 feet.

Number on index map: 81-2

Operator: Cities Service Oil Company

Well name: State AB #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Chalk Knolls

Location: SW 1/4 NW 1/4 section 2, T. 18, S., R. 16 W.

Total depth: 11, 822 feet Completion date: 4-11-81

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Kerns (1987); supplemented by L.F. Hintze examination of lithologic log by Exploration Services (UGS), and sonic log loaned by John E. Welsh. For geologic map see R.K. Hose (1963b).

Formation tops (feet)		**Thicknesses drilled (feet)**
0	Simonson Dolomite	1,000±
1,000	Sevy Dolomite - dolo, ls, ss	3,000±
4,000	Laketown and Ely Springs Dolomites	1,800±
5,800	Eureka Quartzite	414
6,214	Crystal Peak Dolomite	99
6,313	Watson Ranch Quartzite	220
6,533	Lehman Formation	357
6,890	Kanosh Shale	330
7,220	Juab and Wah Wah Limestones	605
7,825	Fillmore Formation - ls, sh	1,960
9,785	House Limestone	505
10,290	Notch Peak Formation - dolo, ls	532
11,822	T.D.	

Comments: Occurrence of faulted Ordovician strata and a fault above the Eureka Quartzite as reported by Kerns (1987) was not supported by examination of lithologic and sonic logs by Hintze whose estimates (shown with ±) are shown above. Well appears to have penetrated a normal unbroken sequence. Allmendinger and others (1985) noted a “Lower Ordovician over Upper Ordovician thrust” at 5,802 feet, but this is unlikely.

Number on index map: 81-3

Operator: Placid Oil Company

Well name: Monroe 13-7

USGS 1:24,000 (7 1/2-minute) quadrangle: Mills

Location: SW1/4 NE1/4 section 13, T. 16 S., R. 2 W., Juab County

Total depth: 16,110 feet Completion date: 4-17-81

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: John E. Welsh, stratigrapher, in 1983, using samples and gamma-ray and lateral logs.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Quaternary lake deposits	600
600	Pliocene(?) claystone	250
850	Tertiary conglomeratic ss	1,180
2,030	Flagstaff Formation - ls, ss	610
2,640	North Horn Formation - ss	450
3,090	Cretaceous cg [likely Canyon Range Cg]	340
	UNCONFORMITY	
3,430	Arapien Shale/Twist Gulch Fm	1,230
4,660	Twin Creek Limestone, Watton Canyon Mbr	190
4,850	Twin Creek Limestone, Boundary Ridge Mbr	110
4,960	Twin Creek Limestone, Rich Member	350
5,310	Twin Creek Limestone, Sliderock Mbr	210
5,520	Twin Creek Limestone, Gypsum Spring Mbr	350
5,870	Navajo Sandstone	1,370
7,240	THRUST FAULT	
7,240	Arapien Shale/Twist Gulch Fm	620
7,860	Twin Creek Limestone, Watton Canyon Mbr	170
8,030	Twin Creek Limestone, Boundary Ridge Mbr	120
8,150	Twin Creek Limestone, Rich Member	320
8,470	Twin Creek Limestone, Gypsum Spring Mbr	382
9,032	Navajo Sandstone	1,523
10,555	Ankareh Fm/Chinle Fm - sltst, ss, sh	2,895
13,450	Thaynes Fm/Moenkopi Fm - ls, sltst	375
13,825	THRUST FAULT	
13,825	Navajo Sandstone	570
14,395	NORMAL FAULT	
14,395	Thaynes Fm/Moenkopi Fm - ls	1,415
15,810	no samples	300
16,110	T.D.	

Comments: Structure similar to Placid WXC State #1 (well number 80-2 in this bulletin). See also Standlee (1982).

Number on index map: 81-4

Operator: Arco Oil and Gas Company

Well name: #1 Hole-in-Rock

USGS 1:24,000 (7 1/2-minute) quadrangle: Black Point

Location: SE1/4 SW1/4 section 30, T. 22 S., R. 7 W.

Total depth: 10,990 feet   Completion date: 5-14-81

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Planke (1987); Anders and Christie-Blick (1994).

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	no record	600
600	Pliocene claystone and siltstone	1,130
1,730	Miocene claystone and siltstone	1,300
3,030	Anhydrite with calcite and clay	120
3,150	Claystone, fine-grained sandstone	550
3,700	Claystone and siltstone	440
4,140	Anhydrite, claystone, and siltstone	450
4,590	Claystone and siltstone	410
5,000	Siltstone and claystone with traces of dolomite, anhydrite	400
5,400	Red and brown micaceous siltstone, claystone, sandstone, and conglomerate	1,800
7,200	Oligocene sediments with traces of volcanic rocks	1,900
9,100	SEVIER DESERT REFLECTOR (UNCONFORMITY)	
9,100	Dolomitic limestone	120
9,220	Dolomite with traces of oolites and fossil fragments	770
10,990	T.D.	

Comments: John E. Welsh (verbal communication, early 1980s) said that the Paleozoic rocks at the bottom of the hole are metamorphosed Cambrian carbonates similar to those exposed at the north end of the Mineral Mountains. In the Mineral Mountains, these metamorphic rocks are related to what Welsh (1983) interpreted as the Frisco-Canyon Range thrust. Anders and Christie-Blick (1994) measured microfractures in quartz grains from samples spaced between 7,300 and 9,300 feet in depth and found no indication of grain deformation that could be attributed to fault movement on the Sevier Desert reflector at 9,100 feet, and concluded that the seismic reflection was caused by the density differences between the Tertiary sediments and the Cambrian carbonates, and that the reflecting surface represents an unconformity between the two rock types. Anders and others (2001) noted Cretaceous Ar/Ar ages on volcanic chips from Tertiary samples from the borehole. Cretaceous igneous activity is reported to the west in Nevada (Lee and others, 1980), but is not documented in Millard County.

Number on index map: 81-5

Operator: Placid Oil Company

Well name: WXC-USA #1-2

USGS 1:24,000 (7 1/2-minute) quadrangle: Scipio South

Location: NW1/4 SW1/4 section 25, T. 19 S., R. 2 W.

Total depth: 18,266 feet   Completion date: 5-29-81?

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Kerns (1987); John E. Welsh, stratigrapher, partial log in July 1995.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	North Horn Formation - ss	2,054
2,054	Cretaceous cg [Canyon Range Cg?]	4,704
	UNCONFORMITY	
6,758	Fish Haven Dolomite (Ordovician)	562
7,320	Eureka Quartzite	110
7,430	Kanosh Shale {top of Pogonip Group}	354
7,784	THRUST FAULT	
7,784	Fish Haven Dolomite	210
7,994	Eureka Quartzite	35
8,029	Kanosh Shale {top of Pogonip Group}	211
8,240	lower Pogonip Group limestones	1,715
9,955	Ajax Dolomite (Cambrian)	625
10,580	Opex Formation - ls	378
10,958	Cole Canyon [and Bluebird] Dolomite - dolo	599
11,557	Herkimer Ls [and Dagmar Dolo] - dolo, ls	374
11,931	Teutonic Ls - dolo	639
12,570	THRUST FAULT	
12,570	Cambrian carbonate rocks	4,545
17,115	Ophir Formation - phyllite, ls	295
17,410	Tintic Quartzite	750
18,160	Precambrian gneiss (K-Ar biotite age 1,154 Ma)	106
18,266	T.D.	

Comments: Standlee (1982) showed Jurassic Arapien in this well, but this must be an error. Strata above 12,570 feet show dips of 10 to 20 degrees. Strata below 12,570 feet dip 60 to 70 degrees and are very dense. J.L. Baer (verbal communication, 1995) thinks that strata below 12,570 feet may be Precambrian sedimentary rocks instead of those reported above. The Precambrian gneiss is considered to be older (~1,750 Ma) and "reset" by the thermal event noted by Lee and others (1980) in eastern Nevada. The lack of Mesozoic strata in this well compared to the Anschutz Monroe well (76-1) about 5 miles to the south implies a major subsurface structure is present between the wells.

Number on index map: 81-6

Operator: American Quasar Petroleum Company

Well name: Antelope Valley-State 36-22

USGS 1:24,000 (7 1/2-minute) quadrangle: Big Jensen Pass

Location: SE1/4 NW1/4 section 36, T. 23 S., R. 18 W.

Total depth: 9,633 feet   Completion date: 5-29-81

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Bill Covey, well site geologist, May 1981 log (UGS); partly reinterpreted by L.F. Hintze.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	230
230	Tertiary slide block of Devonian rock	340
570	Needles Range Gp tuffs and sedimentary rocks	490
1,060	Slide block of Paleozoic rocks	40
1,100	Tunnel Spring Tuff, 35 Ma	30
	UNCONFORMITY	
1,130	Laketown Dolomite (Silurian)	670
1,800	Ely Springs Dolomite (Ordovician)	620
2,420	Eureka Qtzite-Crystal Peak Dolo-Watson Ranch Qtzite	290
2,710	Lehman Formation - ls, sh, ss	120
2,830	Kanosh Shale - sh, ls, ss	330
3,160	Juab and Wah Wah Limestones - ls	260
3,420	Fillmore Formation - ls, sh	1,240
4,660	House Limestone	710
5,370	FAULT, repeat House Limestone	482
5,852	Notch Peak Formation (Cambrian) - dolo, ls	1,900
7,752	Orr Fm, Corset Spring Shale Mbr	123
7,875	Orr Fm, Big Horse Limestone Mbr	750
8,625	Wah Wah Summit Fm - dolo, ls	1,008
9,633	T.D.	

Comments: Most Ordovician strata are thinner than surface exposures nearby. They have been brittley structurally attenuated.

Number on index map: 81-7

Operator: Arco Oil and Gas Company

Well name: #1 Pavant Butte

USGS 1:24,000 (7 1/2-minute) quadrangle: Pavant Butte South

Location: NW 1/4 NE 1/4 section 35, T. 19 S., R. 7 W.

Total depth: 11,133 feet   Completion date: 8-29-81

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: John E. Welsh, stratigrapher, June 1982, using samples and limited gamma-ray log information. See Planke (1987) for additional notes.

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Quaternary, no samples	600
600	Pliocene-Miocene Sevier Desert valley fill, calcareous claystone	3,300
3,900	Basalt flow	120
4,020	Miocene claystone valley fill	1,970
5,990	Salt with gypsum stringers	190
6,180	Shale, siltstone, sandstone	280
6,460	Salt, some shale, one limestone bed	990
7,450	Shaly limestone, siltstone, shaly anhydrite, trace of dolomite and sandstone near bottom	1,480
8,930	Miocene sandstone with volcanic rock fragments	480
9,410	Oligocene claystone with volcanic rock fragments	290
9,700	Oligocene quartz crystal tuff, Tunnel Spring Tuff(?)	70
9,770	SEVIER DESERT REFLECTOR (UNCONFORMITY)	
9,770	Cambrian phyllite and marble similar to northern Mineral Mts.	730
10,500	Cambrian phyllite, Pioche Formation(?)	170
10,670	Prospect Mountain Quartzite	463
11,133	T.D.	

Comments: Drill stem test at 7,020 feet yielded some black dead oil. Metamorphosed rocks below 9,770 feet are similar to those exposed at the north end of the Mineral Mountains and at depth in other wells in the Sevier Desert area. In the Mineral Mountains, these metamorphic rocks are related to what Welsh (1983) interpreted as the Frisco-Canyon Range thrust. The Sevier Desert seismic reflector is caused by density differences between the relatively unconsolidated Tertiary sediments and the metamorphosed Cambrian strata. Allmendinger and others (1985) placed the Sevier Desert reflector at 9,800 feet.

Number on index map: 81-8

Operator: American Quasar Petroleum Company

USGS 1:24,000 (7 1/2-minute) quadrangle: King Top

Well name: Horse Heaven-State #16-21A

Location: SE 1/4 NW 1/4 section 16, T. 21 S., R. 15 W.

Total depth: 12,131 feet Completion date: 11-2-81

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: From 3,100 feet down, John E. Welsh, stratigrapher, 1980 log, using samples and neutron-density log (UGS). Upper 3,100 feet reconstructed by L.F. Hintze from surface geology by Hintze (1974c).

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Alluvium	50
50±	Simonson Dolomite (Devonian)	600
650±	Sevy Dolomite	1300
1,950±	KINGS CANYON THRUST FAULT	
1,950±	Simonson Dolomite	600
2,550±	Sevy Dolomite	1,310
3,860	Laketown Dolomite (Silurian)	995
4,855	Ely Springs Dolomite (Ordovician)	435
5,290	Eureka Quartzite	540
5,830	Crystal Peak Dolomite	100
5,930	Watson Ranch Quartzite	102
6,032	Lehman Formation - ls, ss, sh	380
6,412	Kanosh Shale - ls, sh, ss	358
6,770	Juab Limestone	200
6,970	Wah Wah Limestone	368
7,338	Fillmore Formation - ls, sh	1,249
8,587	House Limestone	513
9,100	Notch Peak Fm, Lava Dam Mbr (Cambrian)	370
9,470	Notch Peak Fm, Red Tops Mbr	98
9,568	Notch Peak Fm, Hellnmaria Mbr	1,425
10,993	Orr Fm, Corset Spring Shale Mbr	127
11,120	Orr Fm, Johns Wash Ls Mbr	304
11,424	Orr Fm, Candland Sh Mbr	190
11,614	Orr Fm, Big Horse Ls Mbr	517
12,131	T.D.	

Comments: Except for minor thrust fault at 1,950 feet the well penetrated the usual Devonian-Cambrian sequence for this area, although some of the Cambrian and Ordovician units are thinner than normal.

Number on index map: 82-1

Operator: Arco Oil and Gas Company

Well name: #1 Meadow-Federal

USGS 1:24,000 (7 1/2-minute) quadrangle: Sixmile Point

Location: SW 1/4 NE 1/4 section 25, T. 22 S., R. 7 W.

Total depth: 15,537 feet   Completion date: 12-4-82

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: John E. Welsh, stratigrapher, in March 1983. See also Planke (1987); Anders and Christie-Blick (1994).

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Surficial deposits	15
15	Pleistocene-Pliocene fanglomerate	3,688
3,703	Miocene(?) silt and sandstone, with three slide blocks of Paleozoic rocks, one more than 100 feet thick	2,132
5,835	SEVIER DESERT REFLECTOR (UNCONFORMITY)	
5,835	Cambrian limestone and dolomite. Trilobite fragments in lowest 100 feet suggest lower Late Cambrian Orr Formation	455
6,290	Dolomite and limestone	1,250
7,540	Dolomite	1,490
9,030	Limestone, dolomitic	430
9,460	Dolomite, some oolitic	1,790
11,250	Dolomarble, recrystallized	750
12,000	Phyllitic dolomarble, possibly Dome-Chisholm-Howell Fms	400
12,400	Phyllitic quartzite, Pioche Fm(?)	500
12,900	Prospect Mountain Quartzite	730
	INTRUSIVE CONTACT(?)	
13,630	Quartz monzonite or granite gneiss; Mineral Mountains batholith(?)	1,907
15,537	T.D.	

Comments: Cambrian carbonate section is 20% thicker than similar interval exposed in the Cricket Mountains. The granitic gneiss at 13,630 feet is similar to rocks exposed near the Mineral Mountains batholithic complex. Royse (1993) showed a K-Ar age of 1,635 Ma for the granitic gneiss in this well. Royse (written communication, September 9, 1995) noted that K-Ar age determinations indicated that the Precambrian gneiss was affected by a thermal event at 70 Ma. Zircon fission-track ages for these rocks are 10 to 13 Ma.

Anders and Christie-Blick (1994) measured microfractures in quartz grains from samples collected between 5,500 and 6,000 feet in depth and found no grain deformation that could be attributed to fault movement on the Sevier Desert reflector at 5,835 feet. They concluded that the seismic reflector comes from an unconformity between dense Cambrian carbonate rocks and less dense Tertiary deposits.

Number on index map: 82-2

Operator: Commodore Resources Corporation

Well name: Outlaw #1 Federal

USGS 1:24,000 (7 1/2-minute) quadrangle: Needle Point Spring

Location: NE1/4 NE1/4 section 1, T. 10 N., R. 70 E., White Pine County, Nevada

Total depth: 13,000 feet Completion date: 9-18-82

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Shah Alam (1990).

Formation tops (feet)		Thicknesses drilled (feet)
0	Surficial deposits	11
11	Arcturus Fm (Permian) - ss, dolo	1,243
1,254	Ely Ls - ls, some sh, dolo	1,176
2,430	Chainman Fm (Mississippian) - sh, ls, ss	1,980
4,410	Joana Limestone	490
4,900	Pilot Shale - limy shale	900
5,800	Guilmette Fm, West Range Ls Mbr - silty ls	530
6,330	Guilmette Fm - dolo, ls, ss	1,722
8,052	Simonson Dolomite	538
8,590	Sevy Dolomite	1,380
9,970	Laketown and Ely Springs Dolomites	1,672
11,642	Eureka Quartzite (Ordovician)	436
12,078	Pogonip Group	922
13,000	T.D.	

Comments: Well penetrated a Mississippian to Ordovician section that is comparable in thickness to strata exposed in the Mountain Home Range and Burbank Hills. The Crystal Peak Dolomite and Watson Ranch Quartzite were not recognized in the well. The well lies southeast of the Snake Range, Nevada metamorphic core complex.

Number on index map: 82-3

Operator: Placid Oil Company

Well name: Paxton #1

USGS 1:24,000 (7 1/2-minute) quadrangle: Joseph Peak

Location: SW1/4 NW1/4 section 28, T. 24 S., R.4 W., Sevier County

Total depth: 14,826 feet   Completion date: 3-7-82

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: Douglas A. Sprinkel, Placid Oil Company, in 1982. Sprinkel now with Utah Geological Survey.

Formation/unit tops (feet)		Thicknesses drilled (feet)
0	Three Creeks Tuff, volcanic rocks of Dog Valley (Oligocene) [and Aurora Fm]	1,674
1,674	Paleocene and Cretaceous ss, cg, ls {includes Eocene Flagstaff Formation}	2,130
	UNCONFORMITY	
3,804	Moenkopi Fm, upper member(s)	1,882
5,686	Moenkopi Fm, Sinbad Ls and lower members	959
6,645	Kaibab Limestone	1,275
7,920	Permian and Pennsylvanian dolomite	1,330
9,230	Mississippian limestone with foraminifera	1,355
10,605	THRUST FAULT	
10,605	Mississippian limestone with foraminifera	945
11,550	Devonian dolomite	779
12,329	THRUST FAULT	
12,329	Mississippian-Devonian rocks	2,013
14,342	PAXTON THRUST FAULT	
14,342	Arapien Shale (Jurassic) - sltst, ss, several salt and gypsum zones	484
14,826	T.D.	

Comments: Royse (1993) showed this well as projected to a regional geologic cross section. He named the thrust at 14,342 feet the Paxton thrust and stated that Cambrian rocks are above the Jurassic on this thrust plate.

Number on index map: 95-1

Operator: Balcron Oil Division, Equitable Resources Energy Co.

Well Name: 12-36 Cobra-State

USGS 1:24,000 (7 1/2-minute) quadrangle: Gandy

Location: SW1/4 NW1/4 section 36, T.15 S., R. 19 W.

Total Depth: 3,765 feet Completion Date: 7-25-95

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: L.F. Hintze examination of well cuttings on September 12, 1995. See also Donna M. Herring, petroleum geologist, 1995 lithologic log (UGS) for different interpretation.

Formation/unit tops (feet)		**Thicknesses drilled (feet)**
0	Surficial alluvial and playa deposits - marl, sand, gravel	60
60	Marly silt and sand	580
640	White limestone (Tertiary)	60
700	Marly debris from weathered granite and other terranes	300
1,000	White igneous rock with 2% biotite in small flakes, probably eroded from Kern Mts.	80
1,080	Dolomite; upper third may be Devonian Sevy Dolo, remainder Silurian Laketown Dolo	2,020
3,100	Ely Springs Dolomite - dark gray	460
3,560	Eureka Quartzite	205
3,765	T.D.	

Comments: Paleozoic rocks below 1,080 feet are like those exposed in low hills west of Gandy, but lack the structural complications. They probably represent the strata above the north Snake Range, Nevada detachment.

Herrings' interpretation showed: older, more indurated, valley fill - cg, ss, claystone (Tertiary top) - at 910 feet; Simonson Dolomite (Devonian) slide block between 1,317 and 1,625 feet; more Tertiary valley fill; Tertiary limestone top at 1,740 feet; the first bedrock, Laketown Dolomite (Silurian), at 2,672 feet; and slightly different Ely Springs and Eureka tops.

Number on index map: 95-2

Operator: Chevron USA Production Co

Well Name: 1-29 Sevier Lake - Federal Stratigraphic Test

USGS 1:24,000 (7 1/2-minute) quadrangle: Rocky Knoll

Location: SE1/4 NE1/4 section 29, T. 19 S., R. 10 W.

Total depth: 6,014 feet Completion date: 7-30-95

Well samples on file at Utah Geological Survey Core Research Center: Yes

Log reference: L.F. Hintze examination of well cutting samples in September, 1995

Formation/Unit tops (feet)		**Thicknesses drilled (feet)**
0	Pleistocene-Pliocene lacustrine clayey silt	590
590	Pliocene sandy siltstone containing quartz crystals, biotite flakes, and latitic rock fragments	810
1,400	Sand with clear quartz crystals and pink volcanic rock fragments, Pliocene(?)	240
1,640	Sand and grit with 10-60% clear quartz sand and gray biotite-rich rhyolitic tuff fragments perhaps from Twin Peaks rhyolitic dome area. Dolomitic limestone fragments between 2,030 and 2,090	1,560
3,200	Lacustrine limestone 20-80%, gray biotite-rich rhyolite tuff 10-50%, pink tuff 5-80%	1,100
4,300	Pink and gray latitic tuff with small biotite and 1% quartz crystals	860
5,160	Cambrian dolomite and limestone	854
6,014	T.D.	

Comments: Cambrian carbonates in this well are probably on the east edge of the House Range east-tilted fault block, which in the southern House Range is overlain by Needles Range Group tuffs. The Sevier Lake bed has 740,000-year-old lacustrine beds below thin surface and Lake Bonneville deposits (Oviatt, 1989, 1991a).

Number on index map: 96-1

Operator: Chevron USA Production Co

Well name: 1-29 Black Rock Federal

USGS 1:24,000 (7 1/2-minute) quadrangle: Red Pass

Location: NW1/4 NW1/4 section 29, T. 20 S., R. 9 W.

Total depth: 17,477 feet   Completion date: 6-10-96

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Jon K. King, UGS geologist, interpretation of Chevron well file and logs held by Utah Division of Oil, Gas and Mining.

Formation/Unit tops (feet)		**Thicknesses drilled (feet)**
0	Gravelly valley fill (Quaternary), may include Flagstaff Fm	756
756	Tannish qtzt; Prospect Mtn Qtzt (no Pioche Fm, despite nearby outcrops)	1,524-1,824
2,280-2,580	Reddish qtzt; Mutual Fm, transitional contact	2,155-2,455
4,735	Gray-green “siltstone”; Inkom Fm [too thick]	685
5,040	Reddish qtzt; Inkom Fm	
~5,180	Gray-green “siltstone”; Inkom Fm	
~5,330	Gray “shale”; Inkom Fm	
~5,420	“White” qtzt; Caddy Canyon Qtzt, thickness intermediate between those exposed in Canyon and San Francisco Mts.	1,110
6,530	FAULT?; dark phyllitic sh, ls & qtzt; Black Rock Canyon Ls if no fault (Pioche Fm if normal fault or Ophir Fm if fault is Canyon Range thrust)	485
6,820	Gray qtzt and dark sh; Black Rock Cyn Ls (Pioche Fm or Ophir Fm if as noted above)	
7,015	Mostly gray qtzt; Pocatello Fm (Prospect Mtn Qtzt or Tintic Qtzt if as noted above)	1,525
~7,920	Light-colored qtzt	
8,540	CANYON RANGE THRUST? ls; Ophir Fm (Pioche Fm or Black Rock Canyon Ls if normal fault)	210
~8,600	Mostly gray qtzt & “shale”; Ophir Fm-Tintic Qtzt if near vertical (Pioche Fm-Prospect Mtn Qtzt or, since noisy, Black Rock Canyon Ls-Pocatello Fm if normal fault)	
~9,150	Mostly sltst	
9,760	Gray qtzt & “shale,” most “shale” at bottom; fault repeated section like above? (lower Pocatello Fm if normal fault)	850
10,610	PAVANT THRUST FAULT	
10,610	variegated sltst, sh, ss and lesser ls; Moenkopi Fm(?) (Triassic), near vertical or strata too thick	3,260
13,870	FAULT, dolo; Carmel Fm(?), thickness not as expected	1,000
~13,910	Gray sltst; but flat low gamma and density	
~14,180	Light-gray qtzt(?); geophysical logs imply ss not qtzt	
~14,760	Ss; Temple Cap Fm(?)	
14,850	Pink and white “quartzite”; Navajo Sandstone	1,490
16,360	FAULT, gray (meta?) sh and qtzt; Ophir or Pioche Fm	960
17,020-17,050;	Brecciation; no sign of conglomerate	(30+200)
17,120-17,320	SEVIER DESERT REFLECTOR, UNCONFORMITY?	
17,320	Gray qtzt (Cambrian)	157

Number on index map: 96-2

Operator: Equitable Resources Energy

Well name: Mamba Federal 31-22

USGS 1:24,000 (7 1/2-minute) quadrangle: Gandy

Location: NW1/4 NE1/4 section 22, T. 16 S., R. 19 W.

Total depth: 3,256 feet Completion date: 10-25-96

Well samples on file at Utah Geological Survey Core Research Center: No

Log reference: Modified by Jon K. King, UGS, geologist, from Donna Herring, well-site geologist, report held by Utah Division of Oil, Gas and Mining.

Formation/Unit tops (feet)		**Thicknesses drilled (feet)**
0	Clay/claystone, some ls and ss; valley fill	~1,400
~1,400	Clay-rich sedimentary rocks, with volcanic and sedimentary (ls & ss) rock fragments; more indurated valley fill	~1,050
2,450	Cg of mostly volcanic clasts (also 2,350-2,390)	351
2,821	Dark shale; middle(?) Chainman Fm	269
3,090	Orange, crystalline to oolitic limestone; Chainman Fm or Joana Ls	10
3,100	Olive-gray, medium-dark gray, brownish black, argillaceous ls with brachiopod fragments; lowermost Chainman Fm, Joana Ls, or upper Pilot Sh	90 or 128
3,190	Lost samples; same as above	
3,228	Drill break; fault	
3,240-3,245	Core, argillaceous dolo rubble & breccia; core barrel “dropped to 3,258 after coring; dolomitized fault zone?	

Comments: The bottom of the borehole may have encountered the north Snake Range, Nevada detachment. Strata exposed northwest of Gandy are Devonian and older, and likely are above the detachment. If the Chainman pick is correct, the Paleozoic strata in this area dip to the west from the Balcron Cobra well (95-1) and east from the strata exposed northwest of Gandy.

APPENDIX B

LIST OF PUBLICATIONS ON GEOLOGY OF MILLARD COUNTY AFTER 1959

Publications on Geology of Millard County, 1960-1969

Publications on the geology of Millard County are grouped below in four categories: (1) stratigraphy and paleontology, (2) geologic maps, (3) ground water resources, and (4) structure, geophysics, and miscellaneous other topics.

There were 31 publications on stratigraphy and paleontology: Armstrong (1968b), Baer and others (1968), Bissell (1962, 1964), Budge (1966), Flower (1968a-b), Hintze (1960c, 1963a), Hintze and others (1967, 1969), Hose (1966), Jensen (1967), Miller (1969), Osmond (1962), Palmer (1965), Rigby (1962, 1965, 1966, 1969), Robison (1960a-b, 1962, 1964a-c, 1965, 1967), Rowell (1966), Sadlick (1965), and Yochelson and Jones (1968).

There were 18 geologic maps published: Hanks (1962), Hintze (1960a-b, 1961, 1963b), Hose (1963a-b, 1965a-b), Hose and Repenning (1963, 1964), Hose and Ziony (1963, 1964), Nelson (1966), Ridd (1963), Schneider (1964), Whitebread (1969), and Zimmerman (1961).

There were 16 publications related to water resources: Bjorklund and Robinson (1968), Carpenter and others (1967), Hahl and Mundorff (1968), Handy and others (1969), Hood and Rush (1965), Milligan and others (1966), Mower (1961, 1963a-b, 1965, 1967), Mower and Feltis (1964, 1968), Snyder (1963), Whitaker (1969), and Young (1960).

Thirteen publications were related to structural, subsurface, and economic geology: Armstrong (1968a), Crittenden (1963), Crittenden and others (1961), Crosson (1964), Heylmun and others (1965), Hilpert (1964), Hintze (1967), Isherwood (1969), McCarthy and others (1969), Mudgett (1963), Sontag (1965), Utah State Department of Highways (1966), and Whelan (1969).

Publications on Geology of Millard County, 1970-1979

There were 66 publications on stratigraphy and paleontology: Berdan (1976), Biller (1976), Brady and Koepnik (1979), Brady and Rowell (1976), Braithwaite (1976), Campbell (1978, 1979), Chamberlain (1975), Church (1974), Collinson and others (1976), Collinson and Hassenmueller (1978), Demeter (1973), Dutro and others (1979), Ethington (1978, 1979), Ethington and Clark (1971), Flower (1971), Gutschick and Rodriguez (1979), Hinds (1970), Hintze (1973a, 1974f, 1979), Hintze and others (1972), Hintze and Palmer (1976), Hintze and Robison (1975), Hook and Flower (1977), Johnson and Sandberg (1977), Kelly and Ausich (1978, 1979), Kepper (1972), Koepnick (1976), Lane (1970), Lilley (1976), Lohmann (1976, 1977), McClure (1978), McGee (1978), Miller (1978), Oldroyd (1973), Palmer (1971), Paul (1972), Randolph (1973), Rees and others (1976), Rigby (1976, 1978), Rigby and Hintze (1977), Robison (1971, 1976), Robison and Hintze (1972), Sheehan (1971), Spinosa and others (1977), Stevens (1977, 1979), Stewart and Suczek (1977), Sweet and Bergstrom (1976), Taylor (1971), Taylor and Glanzman (1979), Taylor and Robison (1976), Terrell (1973), Welsh (1972), Welsh and Bissell (1979), White (1973), Woodward (1972), Wyatt (1979), Young (1973), and Zabriskie (1970).

There were 17 geologic maps published: Evans (1977), Hickox (1971), Hintze (1974a-e), Hoover (1974), Hose (1974a-b), Leedom (1974), Pierce (1974), Sayre (1971, 1974), Steven (1979a-b), and Whelan and Bowdler (1979).

Six publications were related to water resources: Bolke and Sumison (1978), Mower and Cordova (1974), Mundorff (1970), and Stephens (1974, 1976, 1977).

There were 46 publications on structural geology, volcanism, geophysics and other topics: Anderson and Bucknam (1979), Anderson and Miller (1979), Arabasz (1979), Armstrong (1970, 1972), Armstrong and Suppe (1973), Ash and others (1979), Bailey (1974), Best and Hamblin (1978), Bucknam and Anderson (1979a-b), Bullock (1970), Bushman (1973), Butler and Marsell (1972), Case (1977), Case and Cook (1979), Chidsey (1978a-b), Clark (1977), Condie and Barsky (1972), Hampton (1978), Hintze (1972, 1973b, 1978), Hogg (1972), Hose (1977), Howard (1976), Lemmon and others (1973), Luedke and Smith (1978), Mabey and others (1978), McDonald (1976), Mehnert and others (1978), Mitchell (1979), Moore and Samberg (1979), Mueller and Mueller (1979), Nash and Smith (1978), O'Neil and Bailey (1979), Peterson (1976), Serpa (1979), Stewart and others (1977), Stott and Olsen (1976), Stott and others (1977), Valastro and others (1977), Welsh (1976, 1979), and Zietz and others (1976).

Publications on Geology of Millard County, 1980-1989

There were 72 publications on stratigraphy and paleontology: Babcock and Robison (1988), Berdan (1988), Briggs and Robison (1984), Budge and Sheehan (1980a-b), Caldwell (1980), Carr and Paull (1983), Carr and others (1984), Christie-Blick and others (1988), Conway Morris and Robison (1982, 1986, 1988), Currey and others (1983a-b), Dattilo (1988), Ethington and Clark (1981), Gil (1988), Gordon (1984), Gordon and Yochelson (1987), Grannis (1982), Gunther and Gunther (1981), Hintze (1982, 1985, 1987, 1988b), Hintze and Robison (1987), Hintze and others (1988), Karklins (1986), Kopaska-Merkel (1983, 1988), Larsen and others (1988), Lawton (1986), Lewis (1981), Miller (1980), Miller and others (1982), Miller and Taylor (1989), Nelson and Madsen (1987), Newman (1980), Oviatt (1988, 1989), Oviatt and Nash (1989), Rees (1984, 1986), Rigby (1981, 1983), Robison (1982, 1984a-b, 1985), Robison and Richards (1981), Rogers (1984), Ross and Naeser (1984), Ross and others (1988, 1989), Rowell and Rees (1981), St. Aubin-Hietpas (1983), Sandberg and Gutschick (1984), Sandberg and others (1980, 1988, 1989), Sando and Bamber (1985), Scott and others (1983), Sprinkle (1985), Stitt and Miller (1987), Taylor and Miller (1981), Tynan (1980), Ubaghs and Robison (1985, 1988), Vorwald (1982, 1983), Webster and others (1984), and Yochelson (1988).

There were 28 geologic maps published: Best and Hintze (1980a), Cunningham and others (1983), Davis (1983), Dommer (1980), Galyardt and Rush (1981), George (1985), Higgins (1982), Hintze (1980a, c; 1981a-e; 1984, 1986a), Hintze and Best (1987), Hintze and others (1984), Holladay (1984), Lemmon and Morris (1984), Millard (1983), Morris (1987, 1989), Nutt and Yambrick (1989), Pampeyan (1989), Peterson and Nash (1980), Steven (1989), and Steven and Morris (1983).

Eighteen publications were related to water resources: Bedinger and others (1984), Bunch and Harrill (1984), Enright (1987), Enright and Holmes (1982), Gates (1987), Gates and Kruer (1981), Harrill and others (1988), Herbert and others (1982), Holmes (1984), Holmes and Wilberg (1982), Mason and others (1985), McHugh and others (1981), Price and Arnow (1986), Price and others (1989), Thiros (1988), Thomas and others (1986), Thompson and Nuter (1984), and Wilberg and Stolp (1985).

There were 87 publications on structural geology, volcanism, geophysics, and other topics: Adhidjaja (1981), Adrian and others (1988a-b), Allmendinger and others (1983, 1985, 1986, 1987a-b), Anderson (1980, 1983), Anderson and others (1983), Arabasz and Julander (1986), Arbogast and others (1988), Armin and Mayer (1983), Bankey and Cook (1989), Best and Grant (1987), Best and others (1980, 1989b), Brown (1987), Budding and Bugden (1986), Cadigan and Robinson (1982), Campbell and Labson (1989), Campbell and Visnyei (1989), Carrier and Chapman (1981), Christiansen and others (1986), Cook and others (1981, 1989), Cox and others (1989), Crecraft and others (1981), Crone (1983), Crone and Harding (1984), Currey (1982), Eddington and others (1987), Ertec Western (1981), Evans and others (1980), Gabbert (1980), Gillett and others (1982), Harris and others (1980), Heller and others (1986), Heller and Paola (1989), Hintze (1986b, 1988a), Hover-Granath and others (1983), Izett (1981), Izett and Wilcox (1982), Kerns (1987), Labotka and others (1988a-b), Lawton (1983, 1985), Lee and others (1980), Lindsey and others (1981, 1989), Lundby (1987), Lynch (1980), Mabey and Budding (1987), Mabey and Virgin (1980), McCarthy (1986), Miller and Gans (1989), Mitchell and McDonald (1986, 1987), Morris (1983), Nabelek (1986), Nabelek and others (1983, 1984, 1986), Nash (1986), Nelson and Fuchs (1987), Picha (1986), Piekarski (1980), Planke (1987), Ren and others (1989), Ross and Moore (1985), Rush (1983), Sharp (1984), Smith and Bruhn (1984), Sprinkel and Baer (1982), Steven (1981), Stewart (1980), Stover and others (1986), Tuftin (1987), Turley and Nash (1980), Villien and Kliigfield (1986), Von Tish and others (1985), Welsh (1983), Zimbelman and others (1989), and Zoback and Anderson (1983).

Publications on Geology of Millard County, 1990-2001

There were 54 publications on stratigraphy and paleontology: Adrain and others (2001), Beebe (1990), Benner and Ekdale (1999), Blake and Guensburg (1993), Bond and Kominz (1991), Bond and others (1991), Church (1991), Dattilo (1993), Drummond and Wilkinson (1993), Fortey and Droser (1996), Gardner (1995), Giles (1994), Goebel (1991), Gregory-Wodzicki (1997), Guensburg and Sprinkle (1990, 1994), Gunther and others (1993), Hebertson (1993), Kelsey (1995), Lawton and others (1997), Levy and Christie-Blick (1991), McCormick (1999), McDowell (1995), Miller, J.F., and others (1993, 1999, 2001), Morris and Hebertson (1996), Nichols and Silberling (1990), Osleger (1991a-b), Osleger and Read (1991), Oviatt (1991a-b; 1992, 1994), Oviatt and others (1992, 1994a, c), Pisera and others (1996), Rigby and Church (1990), Robison (1991), Rodriguez and Gutschick (2000), Ross and Ethington (1992), Ross and others (1997), Royse (1993), Saltzman and others (1998), Sandberg and others (1997), Sheehan and Harris (1997), Sprinkle and Guensburg (1997), Sundberg (1990, 1994), Thompson and others (1995), Wilson and others (1992), and Zahner and others (1990).

There were 26 geological maps released: Davis (1994), Gans and others (1999), Hintze (1991a-j, 1997a-d), Hintze and Davis (1992a-b), Hintze and Oviatt (1993), Michaels and Hintze (1994), Oviatt and others (1994b), Sack (1990, 1994a-b), Steven and others (1990), and Varnes and Van Horn (1991).

Six ground water reports were published: Bedinger and others (1990), Burbey and Prudic (1991), Harrill and Prudic (1998), Holmes and Thiros (1990), Mason (1998), and Wilberg (1991).

There were 62 publications on structural geology, geophysics, volcanism, and other topics: Allmendinger (1992), Allmendinger and Miller (1991), Allmendinger and Royse (1995), Anders and Christie-Blick (1994), Anders and others (1995a-b, 1999, 2001), Arbogast and other (1990a-b), Best and Christiansen (1991), Best and others (1993), Blackett (1994), Coleman and others (1997), Coogan and DeCelles (1996, 1999), Coogan and others (1995), DeCelles and others (1995), Diggles and others (1990), Dohrenwend and others (1991a-b), Ferry and Dipple (1992), Goter (1990), Gwynn (1990), Hamilton (1994), Hecker (1993), Hintze and others (1990), Kowallis and Best (1990), Kucks (1991), Lawton (1994), Lawton and others (1993), Linn (1998), Luedke (1993), Miller, E.L., and others (1999), Mitra and Sussman (1997), Nabelek and Labotka (1993), Nabelek and others (1992), Novick and Labotka (1990), Nutt and others (1991, 1996), Nutt and Thorman (1992), Otton (1995, 1996), Planke and Smith (1991), Ross and others (1993), Rowley and others (1994), Shah Alam (1990), Shah Alam and Pilger (1991), Smith and Arabasz (1991), Smith and others (1991), Stoeser and others (1990), Sussman (1995), Sussman and Mitra (1993), Todd (1990), White (1996), Wills and Anders (1996, 1999), Zimbelman (1994a-b), and Zimbelman and others (1990, 1991a-b).

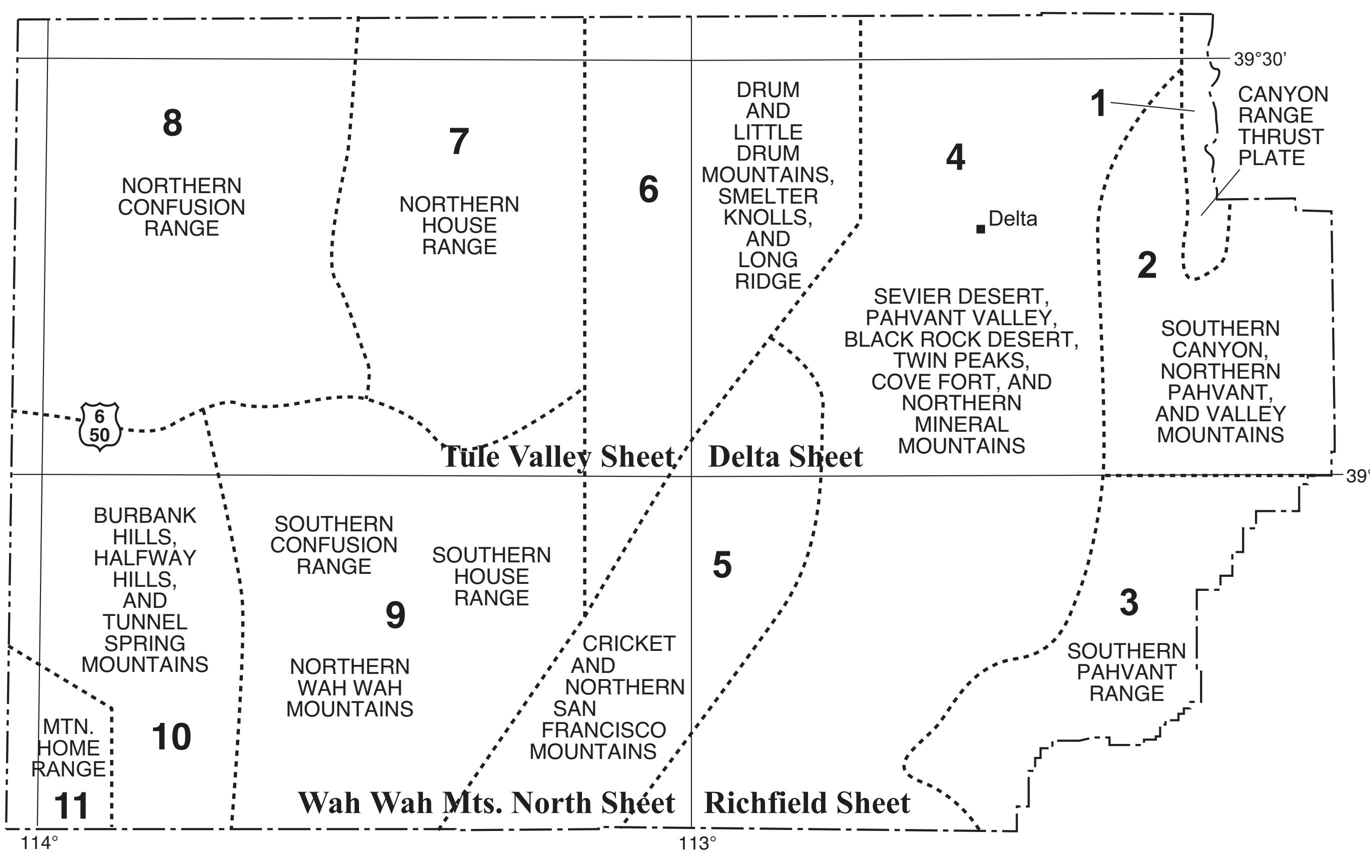
APPENDIX C

STRATIGRAPHIC COLUMNS AND CORRELATION CHARTS

Column 1. Stratigraphic column for Canyon Range thrust plate and nearby post-thrust rocks.
Column 2. Stratigraphic column for Canyon, northern Pahvant, and Valley mountains.
Column 3. Stratigraphic column for central and southern Pahvant Range.
Column 4. Stratigraphic column for Sevier Desert, Pahvant Valley, Black Rock Desert, Twin Peaks, Cove Fort, and northern Mineral Mountains.
Column 5. Stratigraphic column for Cricket and northern San Francisco Mountains.
Column 6. Stratigraphic column for Drum and Little Drum Mountains, Smelter Knolls, and Long Ridge.
Column 7. Stratigraphic column for northern House Range.
Column 8. Stratigraphic column for northern Confusion Range.
Column 9. Stratigraphic column for southern Confusion Range, southern House Range, and northern Wah Wah Mountains.
Column 10. Stratigraphic column for Burbank Hills, Tunnel Spring Mountains, and Halfway Hills.
Column 11. Stratigraphic column for Mountain Home Range.

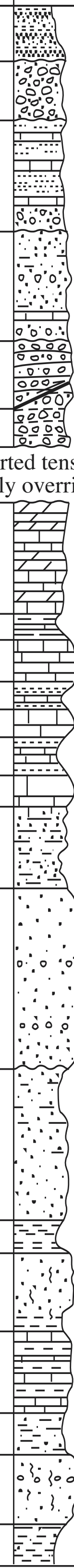
Chart 1. Cambrian correlation chart
Chart 2. Cambrian-Ordovician boundary correlation chart
Chart 3. Ordovician and Silurian correlation chart
Chart 4. Devonian correlation chart
Chart 5. Mississippian correlation chart
Chart 6. Pennsylvanian - Permian correlation chart
Chart 7. Triassic-Jurassic-Cretaceous correlation chart
Chart 8. Cenozoic correlation chart

Location map for stratigraphic columns 1-11



STRATIGRAPHIC COLUMN 1

CANYON RANGE THRUST PLATE AND NEARBY POST-THRUST ROCKS

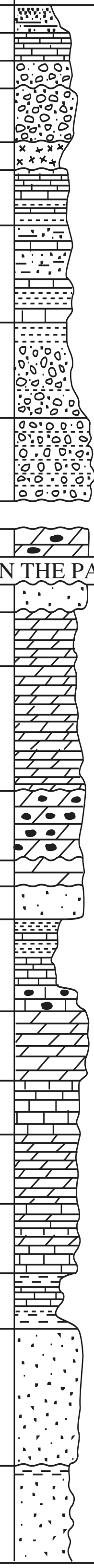


AGE	MAP SYMBOL	ROCK UNIT		THICKNESS FEET	THICKNESS METERS	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, lacustrine, and eolian deposits		0-600±	0-180±	Includes Lake Bonneville deposits	Oviatt, 1992; Varnes and Van Horn, 1991
MIO?	Tfc	Fool Creek Conglomerate		0-530	0-160	Age uncertain	Lawton and others, 1997; this bulletin
PALEOCENE	Tf	Flagstaff Formation		1,600-2,470	500-750	Holladay mapped Tf in Juab County on east side Canyon Mts. as "Red beds of Wide Canyon" Freshwater limestone beds	Holladay, 1984, modified by formational reassignments in this bulletin; Stolle, 1978; Lawton and others, 2003
PALEOCENE / CRET.	TKn	North Horn Formation		3,900+	1,200+	Holladay (1984) mapped TKn on east side of Canyon Mts. as "upper member of the Canyon Range Formation"	
CRET.	Kc	Canyon Range Conglomerate	"Hanging wall assemblage"	2,770	844		Lawton and others, 1997, 2003; Holladay, 1984; Stolle, 1978
			"Footwall assemblage"	1,700	520	Burrows, marine tongue? Cow Canyon	
MAJOR UNCONFORMITY: Strata listed below were transported tens of miles (kilometers) from the west. The Canyon Range Conglomerate is synorogenic and was locally overridden by late movement on the thrust.							
U.C. / MIDDLE CAMBRIAN	Ꞓum	Upper and middle Cambrian strata, undivided		353-1,300 exposed	107-360 exposed	*Crepicephalus* zone	Higgins, 1982; Holladay, 1984; this bulletin
MIDDLE CAMBRIAN	Ꞓww	Wheeler Shale		100	30	*Elrathia* (trilobite)	Higgins, 1982
		Swasey Limestone		614	186	1990 cement rock quarry	
		Whirlwind Formation		145	44	*Ehmaniella* (trilobite)	
	Ꞓdh	Dome Limestone		181	55	Abandoned rock quarry	Higgins, 1982
		Chisholm Formation		247	75	*Glossopleura* (trilobite)	
		Howell Limestone		303	92	Abandoned rock quarry	
MIDDLE CAMBRIAN / EARLY CAMBRIAN	Ꞓp	Pioche Formation		750	228	Phyllitic quartzite with trace fossils	Higgins, 1982
EARLY CAMBRIAN	Ꞓpm	Prospect Mountain Quartzite		2,760	835	Pale orange, weathers brown	Higgins, 1982 published measured sections
LATE PRECAMBRIAN	pꞒm	Mutual Formation		1,600-2,470	500-750	Siltstone and quartzite Reddish purple quartzite	Higgins, 1982; Millard, 1983; Holladay, 1984; this bulletin
	pꞒi	Inkom Formation		275-308	84-93	Phyllitic olive shale	Higgins, 1982; Millard, 1983; this bulletin
	pꞒc	Caddy Canyon Quartzite		1,930	585	Pale orange to pinkish gray	
	pꞒb	Blackrock Canyon Limestone		150-610	45-186	Oolitic pelloids	Millard, 1983; Holladay, 1984; this bulletin
	pꞒp	Pocatello Formation	Upper shale and siltstone member	700-1,040	210-317	Phyllite, thin-bedded quartzite	Holladay, 1984; Millard, 1983; Woodward, 1972
			Middle quartzite member	1,320	400	White, weathers orange brown	
			Lower shale member	600	180	Forms olive-gray soil	

Diagram is schematic- no fixed scale

STRATIGRAPHIC COLUMN 2

CANYON, NORTHERN PAHVANT, AND VALLEY MOUNTAINS

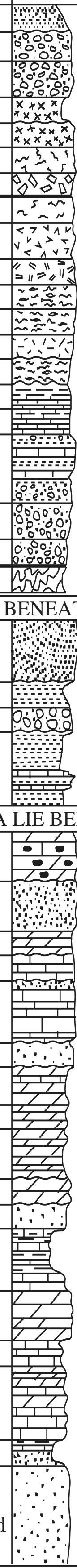


AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, lacustrine, and eolian deposits	0-600±	0-200±	Includes Lake Bonneville deposits	Oviatt, 1992
TERTIARY	QTt	Travertine in Canyon Mountains	0-140	0-43		This bulletin
TERTIARY	QTaf	Alluvial-fan deposits	0-50+	0-15+		Oviatt, 1992
TERTIARY	Toc	Oak City Formation (includes breccia, Tqb and Tcb)	0-2,000	0-600	Unsorted, poorly bedded debris-flow deposits	Campbell, 1979; Hintze, 1991i; this bulletin
TERTIARY	Tht	Tuff of Holden	0-200?	0-60?	**10.5-10.8 Ma?**	
TERTIARY	Tg	Green River Formation	0-800+	0-245+	Shaly lacustrine deposits	This bulletin
TERTIARY	Tf	Flagstaff Formation	1,300±	395±	As exposed in Valley Mountains Commonly pink Fresh-water limestone beds	
TERTIARY	TKn	North Horn Formation	3,000±	910±	Conglomeratic in Pahvant Range; mostly yellow sandstone in the Valley Mountains	Tucker, 1954; this bulletin
K.	Kc	Canyon Range Conglomerate	3,100	950	As exposed in Pahvant Range	Lawton & others, 1997, 2003; Michaels & Hintze, 1994
MAJOR UNCONFORMITY						
P.	Pc	Cherty dolomite near Holden	100+	30+	Thrust relationship uncertain	This bulletin
STRATA BELOW HAVE BEEN TRANSPORTED EASTWARD ON THE PAVANT THRUST PLATE						
DEVONIAN	Dc	Cove Fort Quartzite	250	77	Brown-weathering	Millard, 1983
DEVONIAN	Dgu	Upper Guilmette Dolomite	774	236	Dark gray	
DEVONIAN	Dss	Lower Guilmette, Simonson, and Sevy equivalents, undivided	2,720	830	Light gray Chertless	
SIL.	Sl	Laketown Dolomite	832-1,092	254-333	Cherty, dark gray	Millard, 1983; Michaels and Hintze, 1994
ORDOVICIAN	Ofh	Fish Haven Dolomite	138-261	42-79	Chertless, dark gray	
ORDOVICIAN	Oe	Eureka Quartzite	180-394	54-120		Millard, 1983; Tucker, 1954
ORDOVICIAN	Op	Pogonip Group	1,684	513	Orthid brachiopods common Trilobite fragments common Intraformational conglomerate Cherty limestone	Hintze, 1951; Tucker, 1954
CAMBRIAN	Ꞓum: Ꞓa	Ajax Dolomite	966	295	Algal stromatolites	Hintze, 1991i; Michaels and Hintze, 1994; this bulletin
CAMBRIAN	Ꞓum: Ꞓox	Opex Formation	670	204	Bioclastic limestone *Tricrepicephalus* (trilobite)	
CAMBRIAN	Ꞓum: Ꞓcb	Cole Canyon and Bluebird Dolomites, undivided	536	164		
CAMBRIAN	Ꞓum: Ꞓht	Herkimer, Dagmar, and Teutonic Formations, undivided	1,000+	300+	Few algal stromatolites Thin beds of white laminated dolomite are common	
CAMBRIAN	Ꞓop	Ophir Formation	1,080	329	*Ehmaniella* (trilobite) *Glossopleura* (trilobite)	This bulletin
CAMBRIAN	Ꞓt	Tintic Quartzite	3,000±	950±		Holladay, 1984; this bulletin
pꞒ	pꞒm	Mutual Formation	1,500±	450±	Siltstone and quartzite Reddish purple quartzite Structurally complex Incompletely exposed	

Diagram is schematic-- no fixed scale

STRATIGRAPHIC COLUMN 3

CENTRAL AND SOUTHERN PAHVANT RANGE



AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	SCHEMATIC COLUMN	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, lacustrine, and eolian deposits	0-200±	0-60±		Lake Bonneville deposits below 5200'	Oviatt, 1991a
	QTaf	Quaternary-Tertiary alluvial-fan deposits	0-300	0-90			This bulletin
TERTIARY	Toc	Oak City Formation	0-2,000	0-600		**2.6 Ma** ash bed near top; mostly debris-flow deposits	This bulletin
	Tht	Tuff of Holden	0-200?	0-60?		**10.5-10.8 Ma?**	
	Tmj	Joe Lott Tuff Mbr, Mt. Belknap Volcanics	0-200	0-60		**19 Ma**	Steven, 1979a, 1979b; Steven and Morris, 1983; Cunningham and others, 1983; Steven and others, 1990; Rowley and others, 1994, 2002
	To	Osiris Tuff	0-200	0-60		**23 Ma**	
	Tbci	Intrusions in Bullion Canyon Volcanics	small			**23-27 Ma;** monzonitic	
	Tzt	Zeolitic tuff	400±	120±		**24.6 Ma?**	
	Tac	Tuff of Albinus Canyon	0-650	0-200		**25.3 Ma K-Ar**	
	Tbct	Three Creeks Tuff Mbr, Bullion Canyon Volcanics	0-720	0-220		**27 Ma**	
	Tw	Volcanic rocks of Wales Canyon	440	135			
	Tdv	Volcanic rocks of Dog Valley	0-1,200	0-370		**33 Ma fission track**	
	Tdt	Tuff of Dog Valley	400±	120±		**33.6 Ma**	This bulletin
	Tdvt	Dipping Vat Formation	<300	<90		**Age uncertain**	Lautenslager, 1952; Willis, 1994; this bulletin
	Tau	Aurora Formation	0-1,200	0-360		**38-40 Ma**	
	Tg	Green River Formation	0-200	0-60			
	Tf	Flagstaff Formation	0-3,500	0-1,070		Includes freshwater limestone beds	
	TKn	North Horn Formation	0-2,500	0-760		Thins rapidly to south	Lautenslager, 1952; this bulletin
K.	Kc	Canyon Range Conglomerate	0-866	0-264		Includes rocks formerly called Price River Conglomerate	
	Ktm	Tectonic melange beneath Pavant thrust	0-200	0-60			Hickox, 1971; this bulletin
JURASSIC AND TRIASSIC STRATA ARE FOLDED IN-PLACE ROCKS BENEATH THE PAVANT THRUST							
JUR.	Jn	Navajo Sandstone	2,000±	600±		Eolian cross-bedded	Crosby, 1959; Davis, 1983; Hickox, 1971
TRIASSIC	ŦRcu	Chinle Formation: Upper member	69-274	21-83			Crosby, 1959; Davis, 1983; George, 1985; this bulletin
	ŦRcs	Chinle Formation: Shinarump Conglomerate Mbr	177-428	54-130		Petrified wood	
	ŦRm	Moenkopi Formation	1,876	572		*Meekoceras* (cephalopod)	
OVERTURNED AND LOCALLY THRUSTED POST-CAMBRIAN STRATA LIE BENEATH THE MAIN PAVANT							
PERMIAN	Pk	Kaibab Limestone	1,160	353		Includes Toroweap equivalents	Davis, 1983; this bulletin
	Pq	Queantoweap Sandstone	817	249		290 ft (88 m) thick in Sunset Canyon well near Meadow	
	Pp	Pakoon Dolomite	445	136			
IP.	IPc	Callville Limestone	538	164			
MISS.	Mr	Redwall Limestone	1,545	471		Delle Phosphatic Member near top; Marine fossils common	Davis, 1983; Sandberg and Gutshick, 1984
DEVONIAN	Dc	Cove Fort Quartzite	82-160	25-49		Pinyon Peak Ls equivalent	Biller, 1976
	Dg	Guilmette Formation	575	175		Stromatoporoids	Crosby, 1959; Davis, 1983
	Ds	Simonson Dolomite	185	56			
	Dsy	Sevy Dolomite	710	217		Fragments of fossil fishes	
S.	SOu	Laketown and Fish Haven Dolomites, undivided	566-1,000	173-300			
ORD.	Oe	Eureka Quartzite	150-180	45-55			Hickox, 1971; George, 1985; Davis, 1983; this bulletin
	Op	Pogonip Group	1,125-1,200	343-350		Orthid brachiopods common; Intraformational conglomerate	
CAMBRIAN	Ꞓa	Ajax Dolomite	700	210		Exposed Cambrian strata below upper Ajax are on Pavant thrust plate	
	Ꞓox	Opex Formation	390	120		*Tricrepicephalus* (trilobite)	
	Ꞓum	Upper and middle Cambrian carbonate rocks	2,400±	735±		Laminated white dolomite beds common in the middle	
	Ꞓop	Ophir Formation	850±	260±		*Glossopleura* (trilobite); *Scolithus* (vertical worm tubes)	This bulletin
	Ꞓt	Tintic Quartzite	3,300 estimated	1,000 estimated		*NOTE: Structural attenuation has greatly reduced the thickness of Paleozoic strata in parts of this range. Maximum measured thicknesses shown are likely depositional.*	George, 1985

Diagram is schematic-- no fixed scale

STRATIGRAPHIC COLUMN 4

SEVIER DESERT, PAHVANT VALLEY, BLACK ROCK, TWIN PEAKS, COVE FORT, NORTHERN MINERAL MTNS.

AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	SCHEMATIC COLUMN	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
QUATERNARY	various	Alluvial, eolian, and lacustrine deposits	0-300±	0-100±		Includes Lake Bonneville deposits	Oviatt, 1989, 1991a
	Qvb_1	Basalt of Ice Springs	0-200	0-60		**660 to 4,000± yrs**	Hoover, 1974
	Qvb_2	Basalt of Tabernacle Hill	0-200	0-60		**14,320 yrs**	Oviatt and Nash, 1989
	Qva	Basaltic ash and tuff (Qvt) of Pahvant Butte	0-600	0-180		**15,300 to 16,000 yrs**	
	Qvc	Basaltic cinders	<30	<9		Near Pahvant Butte	Oviatt, 1989
	Qvb_3	Basalt of Pahvant Butte	0-1,000	0-300		**Est. 128,000 yrs**	Hoover, 1974; Oviatt, 1989, 1991a
		Basalt of Deseret, Pot Mtn., Sunstone Knoll	0-300	0-90		**0.4? Ma** local vents	
	Qvr_4	Rhyolite dome of White Mountain	0-120	0-40		**0.4 Ma**	
	Qcg	Basaltic andesite of Cedar Grove	0-200	0-60		**0.3 Ma**	Steven & Morris, 1983
	Qcf	Basaltic andesite of Cove Fort	0-800	0-250		**0.5 Ma**	
	Qvb_4	Basalt of Kanosh	0-300	0-90		**0.7 Ma**	Hoover, 1974; Oviatt, 1991a; Condie & Barsky, 1972
		Basalt of Beaver Ridge	0-200	0-60		**0.5 and 0.9 Ma**	
		Basalt of Mineral Mountains	0-200	0-60		**0.9 Ma**	Sibbet & Nielson, 1980
	Qvb_5	Basalt of Black Rock	0-200	0-60		**1.0-1.3 Ma**	Hoover, 1974; Oviatt, 1991a; Condie & Barsky, 1972
	Qva_5	Andesite of Beaver Ridge	0-200	0-60		**1.5 Ma**	
		(Basalt of Deseret through Andesite of Beaver Ridge: Fine-grained lacustrine deposits of Sevier Desert)					
	QTln	Near-shore limestone	0-90	0-27		Bishop ash **760,000 yr B.P.**	Oviatt, 1989, 1991a; Davis, this bulletin
TERTIARY	QTlf	Fine-grained lacustrine deposits of Sevier Desert	0-1,000 estimated	0-300 estimated		Huckleberry Ridge ash **2.02 Ma**	
	Tbm	Basaltic andesite of Burnt Mountain	0-500	0-150		**2.1 Ma**	Steven & Morris, 1983
	Trt	Rhyolite of South Twin Peak	0-1,000	0-300		**2.35 Ma**	Crecraft and others, 1981; Whelan and Bowdler, 1979; Steven & Morris, 1983
		Rhyolite of North Twin Peak	0-600	0-180		**2.4 Ma**	
		Rhyolite of Mid-Dome	0-300	0-100		**2.5 Ma**	
	Tcc	Basalt of Cove Creek	0-400	0-120		**2.55 Ma**	
	Ttl	Limestone of Twin Peaks	0-262	0-80			
	Tlr	Basalt of Lava Ridge	0-200	0-60		**2.5 Ma**	
	Tcr	Rhyolite of Cudahy Mine	0-500	0-150		**2.6 Ma**	
		Rhyodacite of Coyote Hills	0-650	0-200		**2.7 Ma**	
	Toc	Oak City Formation	0-1,500±	0-450±		**2-11? Ma**	This bulletin
	Tht	Tuff of Holden	0-200?	0-60?		**10.5-10.8 Ma?**	
	Trd	Mineral Mts. intrusive rocks: Rhyolite porphyry	Dikes			**11-12 Ma**	Sibbet & Nielson, 1980; Nielson & others, 1986; Coleman & Walker, 1994
	Tqm	Mineral Mts. intrusive rocks: Quartz monzonite	Stock			**18 Ma**	
	Tgm	Mineral Mts. intrusive rocks: Hornblende granodiorite	Stock			**25 Ma**	
CRET.	Kcg	Conglomerate of Mineral Mountains	0-100±	0-30±		May be partly Tertiary	Liese, 1957; Coleman and others, 1997
		MAJOR UNCONFORMITY					
CAMBRIAN	Ꞓwt	Wah Wah Summit(?) and Trippe Formations, undivided	Several hundred			Metamorphosed and attenuated carbonate rocks at the north end of the Mineral Mountains	
	Ꞓdh	Dome, Peasley, and Howell Formations, undivided	Several hundred			Thinned Chisholm?	
	Ꞓp	Pioche Formation	Several tens			MINERAL MTS. THRUST	
	Ꞓpm	Prospect Mountain Quartzite	Several hundred; base cut by thrust			Earlier Cambrian rocks are overthrust on later Cambrian carbonate rocks	
pꞒ	pꞒg	Banded gneiss	----------			MAJOR UNCONFORMITY **1,750 Ma**	Aleinkoff & others, 1986

NOTE 1: Ma ages are from K-Ar data and may contain substantial error, thus the stacking on this column may be more apparent than real. Because each unit is only local in distribution, relative age by superposition is known between only a few units.

NOTE 2: Thicknesses for all volcanic units shown on this chart were estimated from 1:24,000 geologic and topographic map relationships.

Diagram is schematic-- no fixed scale

STRATIGRAPHIC COLUMN 5

CRICKET AND NORTHERN SAN FRANCISCO MOUNTAINS

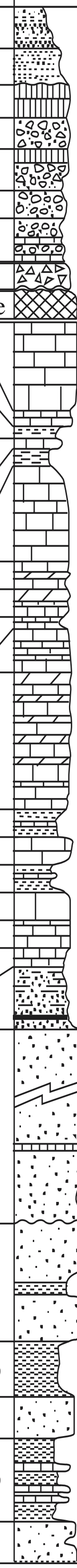
AGE	MAP SYMBOL	ROCK UNIT		THICKNESS FEET	THICKNESS METERS	SCHEMATIC COLUMN	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q	various	Alluvial, lacustrine, and eolian deposits		0-600±	0-200±			Oviatt, 1989, 1991a
	QTlf,QTln	Lacustrine deposits of Sevier Desert		1,000 est.	300 est.		Bishop ash **760,000 yr B.P.** Huckleberry Ridge ash **2.02 Ma**	Oviatt, 1989, 1991a
TERTIARY	Thb	Basalt of High Rock		0-150	0-50			Lemmon and Morris, 1984; this bulletin
	Tsr	Skull Rock Pass Conglomerate		--	--		Correlation uncertain	
	Ths	Horn Silver Andesite		0-1,600+	0-500+		Flows and pyroclastic rocks **31.6 & 35.0 Ma K-Ar**	
	Thr	Conglomerate of High Rock Pass		0-300	0-90		Oligocene	
	Tf	Flagstaff Formation		300-585	90-190		Paleocene? Cg of Red Pass and Ls of Fillmore Canyon	Hintze, 1984; this bulletin
	Tbr	Breccia of Cat Canyon		0-165	0-50		MAJOR UNCONFORMITY	Hintze, 1984; Hintze & others, 1984; this bulletin
CRET.	TKbr	Tectonic breccia in San Francisco Mtns.		1,600 wide	500 wide		Age uncertain	
CAMBRIAN	OꞒn	Notch Peak Formation		100+	30+		Top not preserved; regional thickness about 1,600 ft (500 m)	
	Ꞓou	Orr Fm	Sneakover Limestone Mbr	100	30			Hintze, 1984; this bulletin
			Corset Spring Shale Mbr	40	12			
			Johns Wash Limestone Mbr	100	30		*Dunderbergia**	
			Candland Shale Mbr	165	50		Bioclastic limestone	
	Ꞓob		Big Horse Limestone Mbr	656	200		*Crepicephalus**	
	Ꞓwt	Wah Wah Summit Fm	White Marker Mbr	165-230	50-70			
			Ledgy member	410	125			
		Trippe Limestone	Fish Springs Mbr	100	30		*Eldoradia**	
			Lower member	660-760	200-230		White algal boundstone	
	Ꞓcm	Limestone of Cricket Mountains		1,970	600		Unfossiliferous; Bioturbated limestone, dolomite and light gray laminated boundstone	
	Ꞓw	Whirlwind Formation		200-265	60-80		*Ehmaniella**	
	Ꞓdh	Dome Limestone		230-330	70-100		Cement quarry rock	
		Chisholm Formation		165-265	50-80		*Glossopleura**	
		Howell Limestone	Upper member	100-165	30-50		Light gray	
			Millard Member	200-250	60-75		Dark gray	
	Ꞓp	Pioche Formation	Tatow Member	82-115	25-35		*Paraalbertella**	
			Lower member	660-760	200-230		*Olenellus** Hematite bed	
	Ꞓpm	Prospect Mountain Quartzite		4,000+	1,200+		Pink vitreous quartzite; Basalt flow 15 to 50 ft (5-15 m) thick, 1,650 ft (500 m) above bottom	Lemmon and Morris, 1984
LATE PRECAMBRIAN	pꞒm	Mutual Formation		2,100	635		Purple conglomerate quartzite; Maroon slate; Reddish-purple pebbly quartzite	Woodward, 1968, 1972; Christie-Blick, 1982; Lemmon and Morris, 1984
	pꞒi	Inkom Formation		460-530	140-160		Red and green phyllitic argillite	
	pꞒc	Caddy Canyon Quartzite		265-330	80-100		Light-colored quartzite	
	pꞒb	Black Rock Canyon Limestone		600-990	180-300		Argillite, metasiltstone, quartzite and marble	
	pꞒp	Pocatello Formation		970	300		Light gray quartzite	

Diagram is schematic-- no fixed scale

*Trilobites

STRATIGRAPHIC COLUMN 6

DRUM AND LITTLE DRUM MOUNTAINS, SMELTER KNOLLS, LONG RIDGE

AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	SCHEMATIC COLUMN	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
QUAT.	various	Alluvial, lacustrine, and eolian deposits	0-600±	0-200±			Oviatt, 1989
QUAT.	Qvb_3	Tholeiitic basalt of Smelter Knolls	0-60±	0-20±		**0.3 Ma K-Ar**	Turley & Nash, 1980
QUAT.	Qvb_5	Basalt of Crater Bench	0-20±	0-6±		**~1.0 Ma**	Galyardt & Rush, 1981
P.	Tr	Rhyolite of Smelter Knolls	flow dome			**3.4 Ma K-Ar**	Turley & Nash, 1980
OLIGO.-MIOCENE	Tbsk	Basaltic andesite north of Smelter Knolls	0-30+	0-10+		**6.1 Ma K-Ar**	
OLIGO.-MIOCENE	Tr	Rhyolite of Whirlwind Valley	intrusive?				This bulletin
OLIGO.-MIOCENE	Tsr	Skull Rock Pass Conglomerate	320	98			Hintze & Davis, 1992a,b; this bulletin
OLIGO.-MIOCENE	Trk	Red Knolls Tuff	210	64		**36.5 Ma Ar/Ar**	
OLIGO.-MIOCENE	Tdc	Volcanic sequence of Dennison Canyon	2,000-2,500	600-760		**35.1 Ma Ar/Ar** **36.7 Ma Ar/Ar** Debris and lava flows Pink tuff **37.1 Ma Ar/Ar**	Hintze and Oviatt, 1993; Hintze, 2003
OLIGO.-MIOCENE	Ta	Altered strata	--	--		Drum mine area	Nutt & others, 1996; Hintze, 2003
EOCENE	Timl,Tdi	Mt. Laird intrusive rocks, Drum Mtns. intrusion	plugs and dikes			**36.0-37.2 Ma Ar/Ar**	
EOCENE	Tdr	Drum Mountains Rhyodacite	2,000	600		**36.7 to 37.6 Ma Ar/Ar**	Lindsey, 1979, 1982; Hintze, 2003
EOCENE	Tld	Little Drum Formation	1,500-2,325	450-708		White tuff? **37.6 Ma Ar/Ar** Pink tuff Orange tuff? **38.6 Ma Ar/Ar**	Hintze and Oviatt, 1993; Hintze, 2003
EOCENE	Tdr	Pyroxene latite of Black Point	1,000+	300+		Fault? **38.8 Ma K-Ar**	Hintze, 2003
		MAJOR ANGULAR UNCONFORMITY					
CAMBRIAN	Ꞓou	Orr Formation: Sneakover Limestone Member	224	68			
CAMBRIAN	Ꞓou	Orr Formation: Corset Spring Shale Member	30	9			
CAMBRIAN	Ꞓou	Orr Formation: Light purple member	275	84			
CAMBRIAN	Ꞓob	Orr Formation: Big Horse Limestone Member	1,000±	300±		*Crepicephalus** Silty and bioclastic	Dommer, 1980
CAMBRIAN	Ꞓlw	Lamb Dolomite	625	190			
CAMBRIAN	Ꞓlw	Trippe Limestone: Fish Springs Member	70	21		*Eldoradia**	
CAMBRIAN	Ꞓlw	Trippe Limestone: Lower member	384	108		White laminated dolomite beds	
CAMBRIAN	Ꞓmp	Pierson Cove Formation	800	243		Dark gray	
CAMBRIAN	Ꞓww	Wheeler Shale	910	277		*Elrathia**	Hintze and Oviatt, 1993; Vorwald, 1983
CAMBRIAN	Ꞓww	Swasey Limestone	180	55			
CAMBRIAN	Ꞓww	Whirlwind Formation	137	42		*Ehmaniella**	Kopaska-Merkel, 1983
CAMBRIAN	Ꞓdh	Dome Limestone	300-365	90-111			Dommer, 1980
CAMBRIAN	Ꞓdh	Chisholm Formation	205	62.5		*Glossopleura**	Hintze and Oviatt, 1993
CAMBRIAN	Ꞓdh	Howell Limestone	330	101			
CAMBRIAN	Ꞓp	Pioche Formation: Tatow Member	55	17		Dark olive-green quartzite and phyllite	Nutt and Thorman, 1992
CAMBRIAN	Ꞓp	Pioche Formation: Lower member	360	110			
CAMBRIAN	Ꞓpm	Prospect Mountain Quartzite	4,000+	1,200+		Pink and orange quartzite	Dommer, 1980
PRECAMB.	pꞒm	Mutual Formation	3,000±	915±		Dark red quartzite	

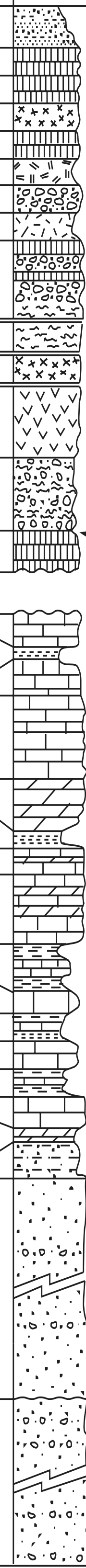


Diagram is schematic-- no fixed scale

*Trilobites

STRATIGRAPHIC COLUMN 7

NORTHERN HOUSE RANGE

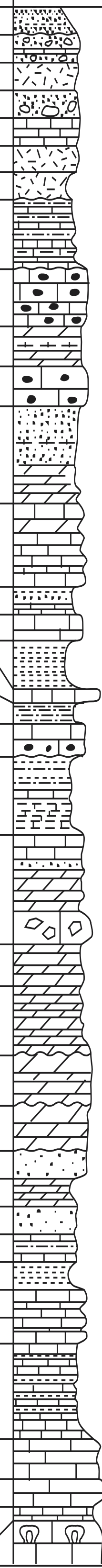
AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	SCHEMATIC COLUMN	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, lacustrine, and eolian deposits	0-600±	0-200±			Sack, 1990
TERTIARY	Tcs	Conglomerate and tuffaceous sandstone	0-1,000	0-300		Tilted	Hintze, 1981b
TERTIARY	Tnu	Wah Wah Springs Fm, Needles Range Group	0-60	0-20		**30.5± Ma** crystal-rich tuff	Best and Grant, 1987
TERTIARY	Tsr	Skull Rock Pass Conglomerate	0-200	0-60			Hintze and Davis, 1992a
TERTIARY	Tl	Lacustrine limestone and breccia	0-225	0-70		Fossil leaves	Hintze, 1981a; this bulletin
TERTIARY	Twb	Windous Butte Tuff	<20	<6		**31.4 Ma Ar/Ar**	
TERTIARY	Tt	Tunnel Spring Tuff	0-50	0-15		**35.4 Ma** quartz crystals	Bushman, 1973
—?—	Tid	Diorite dikes	dike				This bulletin
K.	Kbm	Breccia along tear faults in House Range	0-30	0-9		Width	
J.	Jg	Notch Peak quartz monzonite	intrusive stock			**170 Ma**	Hover Granath and others, 1983
ORDOVICIAN	Of	Pogonip Group: Fillmore Formation	1,800	550		*Paranileus** *Trigonocerca** *Protopliomerella** *Hintzeia** *Rossaspis** Intraformational conglomerate *Leiostegium**	Hintze, 1973a; Ross and others, 1997
ORDOVICIAN	Oh	Pogonip Group: House Limestone	515	153		*Hystricurus* *Symphysurina**	
LATE CAMBRIAN	OꞒn	Notch Peak Fm: Lava Dam Member	364	111		*Missisquoia** *Eurekia**	Hintze and others, 1988
LATE CAMBRIAN	OꞒn	Notch Peak Fm: Red Tops Member	140	43		*Saukiella*	
LATE CAMBRIAN	OꞒn	Notch Peak Fm: Hellnmaria Member	1,203	367		Stromatolites *Idahoia**	
LATE CAMBRIAN	Ꞓou	Orr Fm: Sneakover Limestone Member	185	56			Hintze and Palmer, 1976; Brady and Rowell, 1976; Lilley, 1976; Koepnick, 1976; Lohman, 1976
LATE CAMBRIAN	Ꞓou	Orr Fm: Corset Spring Shale Member	130-170	40-52		*Elvinia**	
LATE CAMBRIAN	Ꞓou	Orr Fm: Johns Wash Limestone Member	140-330	43-100		*Dunderbergia*	
LATE CAMBRIAN	Ꞓou	Orr Fm: Candland Shale Member	412	126		*Aphelaspis**	
LATE CAMBRIAN	Ꞓob	Orr Fm: Big Horse Limestone Member	715	218		*Crepicephalus** Bioclastic limestone	
MIDDLE CAMBRIAN	Ꞓlw	Weeks Ls 1,200 ft (366m): Lamb Dolomite	452	138		*Cedaria** *Lejopyge**	Weeks Ls Hintze, 1974d; Beebe, 1990; Hintze and Robison, 1975
MIDDLE CAMBRIAN	Ꞓlw	Trippe Ls: Fish Springs Member	320	98		*Eldoradia**	
MIDDLE CAMBRIAN	Ꞓmp	Trippe Ls: Lower member	520	158		White boundstone	
MIDDLE CAMBRIAN	Ꞓmp	Marjum Formation (Marjum Pass area--many fossils) / Pierson Cove Formation (east flank of House Range-few fossils)	531-1,410; 1,200	162-430; 370		*Bolaspidella** *Ptychagnostus** Dark gray limestone *Marjumia**	Marjum Fm- Brady and Koepnick, 1979
MIDDLE CAMBRIAN	Ꞓww	Wheeler Shale	420-487	128-148		*Elrathia kingii** *Peronopsis**	Randolph, 1973; Caldwell, 1980; Kopaska-Merkel, 1983, 1988
MIDDLE CAMBRIAN	Ꞓww	Swasey Limestone	250	76			
MIDDLE CAMBRIAN	Ꞓww	Whirlwind Formation	147	45		*Ehmaniella**	
MIDDLE CAMBRIAN	Ꞓdh	Dome Limestone	320	98			
MIDDLE CAMBRIAN	Ꞓdh	Chisholm Formation	220	67		*Glossopleura**	Oldroyd, 1973
MIDDLE CAMBRIAN	Ꞓdh	Howell Limestone: Upper member	335	102		Light gray	This bulletin
MIDDLE CAMBRIAN	Ꞓdh	Howell Limestone: Millard Member	310	94		Dark gray	
MIDDLE CAMBRIAN	Ꞓp	Pioche Formation: Tatow Member	178	54		*Albertella**	
EARLY CAMB.	Ꞓp	Pioche Formation: Lower member	420	128		*Olenellus** Phyllitic quartzite	Robison and Hintze, 1972; this bulletin
EARLY CAMB.	Ꞓpm	Prospect Mountain Quartzite	2,200+ exposed; regional thickness 4,000+	670+ exposed; regional thickness 1,200+		Pink, vitreous, with minor cross-bedding	Hintze, 1974d; this bulletin

Diagram is schematic-- no fixed scale

*Trilobites

STRATIGRAPHIC COLUMN 8

NORTHERN CONFUSION RANGE

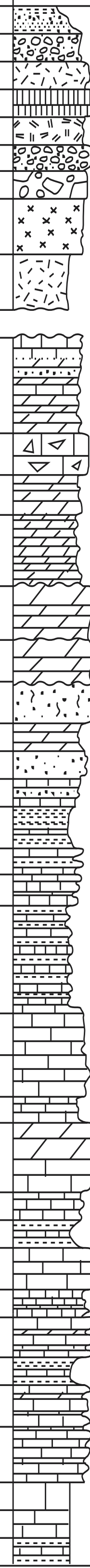


AGE	MAP SYMBOL	ROCK UNIT		THICKNESS FEET	THICKNESS METERS	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, eolian, and lacustrine deposits		0-200±	0-60±	Lake Bonneville deposits	Sack, 1990
TERTIARY	Tct	Conglomerate and tuff		0-2,000+	0-600+	Tilted	Hose, 1965b; Hose and Repenning, 1963; Anderson, 1983; this bulletin
TERTIARY	Tnu	Wah Wah Springs Tuff, Needles Range Group		100-400	30-120	**30.5± Ma** crystal-rich tuff	
TERTIARY	Tsr	Skull Rock Pass Conglomerate		0-120	0-40	Eureka Quartzite boulders	
TERTIARY	Tl	Lacustrine limestone		200	60	Mile-and-A-Half Canyon	
TERTIARY	Twb	Windous Butte Tuff		<20	<6	**31.4 Ma Ar/Ar**	
TERTIARY	Tt	Tunnel Spring Tuff		0-20	0-6	**35.4 Ma** quartz crystals; ANGULAR UNCONFORMITY	
TRI.	TRt	Thaynes Formation		1,935	590	Platy claystone, thin limestone; Conodonts; *Meekoceras* (cephalopod)	Hose and Repenning, 1959; Hose, 1965b
PERMIAN	Pg	Gerster Limestone		1,100	335	Siliceous nodules; *Punctospirifer* (brachiopod)	
PERMIAN	Pp	Plympton Formation		690	210	Gypsiferous	
PERMIAN	Pk	Kaibab Limestone		480-600	146-180	Chert nodules abundant	
PERMIAN	Pa	Arcturus Formation		2,700+	820+	Yellow sandstone; Gypsum; Limy dolomite	
IP.	PIPMe	Ely Limestone		1,850-2,000	560-610	Fusulinids common; Chert & silicified fossils common; Basal beds chertless	
MISSISSIPPIAN	Mc	Chainman Formation	Jensen Member	100-190	30-58	Marine fossils abundant; Thins to north	Sadlick, 1965; Webster and others, 1984; Sandberg and others, 1980
MISSISSIPPIAN	Mc	Chainman Formation	Willow Gap Ls Member	352	107		
MISSISSIPPIAN	Mc	Chainman Formation	Camp Canyon Member	1,050±	320±	Thins to north	
MISSISSIPPIAN	Mc	Chainman Formation	Skunk Spring Ls Member	5-16	2-5	*Goniatiles* (cephalopod)	
MISSISSIPPIAN	Mc	Chainman Formation	Needle Siltstone Member	167	51	Phosphatic beds at base	
MISSISSIPPIAN	Mj	Joana Limestone		200-390	60-118	Thins to north	Goebel, 1991
DEVONIAN	MDp	Pilot Shale		830	250	Conodonts common	Sandberg and others, 1980, 1988
DEVONIAN	Dg	Guilmette Formation		2,600	793	Brachiopods and conodonts at top; "Spaghetti" and "cauliflower" stromatoporoids common; Basal massive solution breccia	Hose, 1966; Hintze, 1974b
DEVONIAN	Ds	Simonson Dolomite		660±	200±	Dark gray with relic fossils	
DEVONIAN	Dsy	Sevy Dolomite		1,300-1,600	400-488	Barren light-gray dolomite with floating brown quartz sand grains in upper part	
SIL.	SOu: Sl	Laketown Dolomite		920-1,100	280-335	*Pentamerus* (brachiopod)	Budge and Sheehan, 1980a-b; this bulletin
ORDOVICIAN	SOu: Oes	Ely Springs Dolomite		552-620	168-189	*Streptelasma* (coral)	
ORDOVICIAN	Oew	Eureka Quartzite		450	137		Hintze, 1973a, 1974b, d; Hintze and others, 1988; Ross and others, 1997; Fortey and Droser, 1996
ORDOVICIAN	Oew	Crystal Peak Dolomite		90	27	*Eofletcheria* (coral)	
ORDOVICIAN	Oew	Watson Ranch Quartzite		200	60		
ORDOVICIAN	Opu	Pogonip Group	Lehman Formation	200	60	Ostracodes	
ORDOVICIAN	Opu	Pogonip Group	Kanosh Shale	550	167	*Orthambonites* (brachiopod)	
ORDOVICIAN	Opu	Pogonip Group	Juab Limestone	160	49		
ORDOVICIAN	Opu	Pogonip Group	Wah Wah Limestone	250	76	*Pseudocybele* (trilobite)	
ORDOVICIAN	Of	Pogonip Group	Fillmore Formation	1,800	550	*Trigonocerca* (trilobite); *Histricurus* (trilobite); Intraformational conglomerate; *Leiostegium* (trilobite)	
ORDOVICIAN	Oh	Pogonip Group	House Limestone	500	152	*Symphysurina* (trilobite)	
CAMB.	O-Cn	Notch Peak Fm	Lava Dam Member	350	107	*Mississquoia* (trilobite)	
CAMB.	O-Cn	Notch Peak Fm	Red Tops Member	120	37	Stromatolites	
CAMB.	O-Cn	Notch Peak Fm	Hellnmaria Member	1,200	366	*Mattheria* (gastropod)	

Diagram is schematic-- no fixed scale

STRATIGRAPHIC COLUMN 9

SOUTHERN CONFUSION / SOUTHERN HOUSE RANGES, AND NORTHERN WAH WAH MTNS.

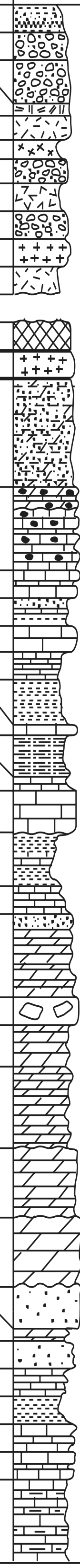


AGE	MAP SYMBOL	ROCK UNIT		THICKNESS FEET	THICKNESS METERS	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, eolian, and lacustrine deposits		0-200	0-60		Oviatt, 1989
—?—	Ts	Valley-fill sediments (partly exposed near Crystal Peak)		0-100	0-30		Hintze, 1974c; Hintze & others, 1984
TERTIARY	Tnu	Needles Range Group	Wah Wah Springs Tuff	0-200	0-65	**30.5± Ma**	Hintze, 1974a, c, d; Hintze and others, 1984
			Basalt of Brown Knoll (Tnb)	0-250	0-80		
			Cottonwood Wash Tuff	0-220	0-70	**31± Ma** Large biotite crystals	
	Tnc		Conglomerate and large slide blocks	0-500	0-150		Hintze, 1974a, c
	Tsr	Skull Rock Pass Conglomerate		0-300	0-90		Hintze, 1974c
	Twc	Dacite of Wah Wah Cove		0-1,500	0-450	**34 & 34.5 Ma** Basal tuff	Hintze & others, 1984
	Tt	Tunnel Spring Tuff		0-1,000	0-300	**35.4 Ma** Abundant quartz crystals	Bushman, 1973
MAJOR ANGULAR UNCONFORMITY							Hintze, 1974a, d
DEVONIAN	Dg	Guilmette Formation	"Upper" member	1,950	595	Brachiopods Thin brown sandstone beds "Spaghetti" and spherical stromatoporoids	Hose, 1966; Osmond, 1962; Hintze, 1974a, c
			Breccia member	500-650	152-200	Solution breccia	
	Ds	Simonson Dolomite		540-700	165-213	Dark dolomite with poorly preserved fossil relicts	
	Dsy	Sevy Dolomite		1,300	400	Barren light gray dolomite with floating quartz sand grains in upper part	
SIL.	Sl	Laketown Dolomite		1,000	300	Silicified corals and brachiopods near top	Budge and Sheehan, 1980a-b; Hintze, 1974a, c
ORDOVICIAN	Oes	Ely Springs Dolomite		630	192	Dark gray, cherty dolomite *Streptelasma* (coral)	
	Oew	Eureka Quartzite		470-560	143-170		Webb, 1956, 1958; Hintze, 1974a, c; Rigby and Hintze, 1977
		Crystal Peak Dolomite		90	27	*Eofletcheria* (coral)	
		Watson Ranch Quartzite		175-250	53-76		
	Opu	Pogonip Group	Lehman Formation	170-210	52-64		Hintze, 1951, 1952, 1973a, 1974a, c; Ross and others, 1997
			Kanosh Shale	560	170	Orthid brachiopods abundant	
			Juab Limestone	160	49		
			Wah Wah Limestone	258	79	*Pseudocybele* (trilobite)	
	Of		Fillmore Formation	1,800	550	*Presbyrelius* (trilobite) *Trigonocerca* (trilobite) *Leiostegium* (trilobite)	
	Oh		House Limestone	420-500	128-150	*Symphysurina* (trilobite)	
CAMBRIAN	OꞒn	Notch Peak Fm	Lava Dam Member	254-437	77-133	*Missisquoia* (trilobite) *Euptychaspis* (trilobite)	Hintze and others, 1988
			Red Tops Member	50-130	15-40	*Saukiella* (trilobite)	
			Hellnmaria Member	1,000-1,340	305-408	Large algal stromatolites common near top	
	Ꞓou	Orr Fm	Sneakover Limestone Member	150-170	46-52		Hintze and Palmer, 1976
			Steamboat Pass Member	175-265	53-81	Abundant trilobite fragments	
	Ꞓob		Big Horse Limestone Member	660-700	201-213	Bioclastic limestone *Tricrepicephalus* (trilobite)	
	Ꞓwt	Wah Wah Summit Fm	White marker member	157-170	48-52	White laminated dolomite	Hintze, 1974a, c; Hintze and Robison, 1975; Hintze and others, 1984
			Ledgy member	550-825	167-252		
		Trippe Limestone	Fish Springs Member	115-135	35-41	*Eldoradia* (trilobite)	
			Lower member	506	154	Much white laminated dolomite	
	Ꞓmp	Pierson Cove Formation		1,441	439	Dark gray	
	Ꞓew	Eye of Needle Limestone		240	80	Subsurface in Millard county; exposed west of Wah Wah Summit along Highway 21	
		Swasey Limestone		440	140		
		Whirlwind Formation		99	30	*Ehmaniella* (trilobite)	Kopaska-Merkel, 1983

Diagram is schematic-- no fixed scale

STRATIGRAPHIC COLUMN 10

BURBANK HILLS, TUNNEL SPRING MOUNTAINS, AND HALFWAY HILLS

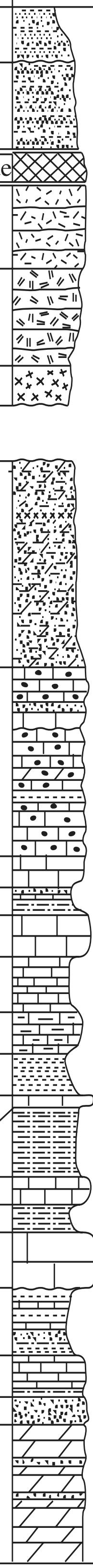


AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvial, eolian, and lacustrine deposits	0-200±	0-60±		This bulletin
TERTIARY	Tc	Post-Needles Range conglomerate	0-1,000	0-300		Hintze, 1974c, 1981d, 1997b, d; this bulletin
	Tcs	Conglomerate and sandstone	0-1,000	0-300	Limestone locally Poorly exposed	
	Ti	Isom Tuff	20	6	**27 Ma**	
	Tnu	Needles Range Group: Lund, Wah Wah Sps & Cottonwood Wash	0-600	0-200	**28, 30.5 & 31 Ma** crystal-rich tuffs	Best and Hintze, 1980a; Hintze, 1981d, 1997b; Hintze and Best, 1987; this bulltein
	Tnl	Needles Range Group: Escalante Desert Formation	0-120	0-40	**32(?) Ma K-Ar** crystal-poor tuff	
	Tnc	Needles Range Group: Conglomerate and large slide masses	0-200	0-60		
	Twb	Windous Butte Tuff	0-95	0-29	**31.4 Ma Ar/Ar**	
	Tsr/Tsv	Skull Rock Pass Cg / Sed. & volcanic rocks	0-350	0-107		
	Tir	Rhyolitic intrusions of Tunnel Spring Mtns.	small domes or plugs			Hintze, 1981d, 1997d
	Tt	Tunnel Spring Tuff	0-1,000	0-300	**35.4 Ma** quartz crystals	
		MAJOR ANGULAR UNCONFORMITY				
K.	TKbr	Tectonic breccia	0-1,850	0-560	Width	Best & Hintze, 1980a
J.	Jd	Diabase plug in Burbank Hills	small intrusion		**141 Ma**	This bulletin
PERMIAN	Pa	Arcturus Formation	2,500±	760±	Orange dolomitic sandstone	Hintze, 1988b
PENN.	PIPMe	Ely Limestone: Cherty member	2,500±	760±	*Pseudoschwagerma, Triticites* (fusulinids) Corals, brachiopods, and bryozoans abundant	St. Aubin-Hietpas, 1983; Hintze, 1997d
		Ely Limestone: Chertless member	200	60		
MISSISSIPPIAN	Mc	Chainman Fm: Jensen Member	430-600	131-180	Many brachiopods	Sadlick, 1965; Sandberg and others, 1980; Tynan, 1980; Karklins, 1986; Gordon, 1984; Hintze, 1997d; this bulletin
		Chainman Fm: Willow Gap Limestone Member	0-300	0-90		
		Chainman Fm: Camp Canyon Member: Upper unit	670	203		
		Chainman Fm: Camp Canyon Member: Black shale unit	320	98		
		Chainman Fm: Skunk Spring Limestone Member	0-6	0-2		
		Chainman Fm: Needle Siltstone Member	315	96		
		Chainman Fm: Delle Phosphatic Member	0-80	0-24		
	Mj	Joana Limestone	520-560	160-170		
DEVONIAN	MDp	Pilot Shale	511-600	156-180	Leatham Member	Biller, 1976; Sandberg and Poole, 1977; Hintze, 1988b, 1997d
	Dg: Dgw	Guilmette Formation: West Range Ls Member	633-860	193-260	Conodonts common	
	Dg: Dgm	Guilmette Formation: Middle member	2,958	902	Brown-weathering sandstone Spaghetti-type stromatoporoids	
	Dg: Dgb	Guilmette Formation: Lower breccia member	330-660	100-200	Paleokarst cave collapse?	
	Ds	Simonson Dolomite	660±	200±	Dark brownish-gray	Budge and Sheehan, 1980b; Hintze, 1981d, 1997d
	Dsy	Sevy Dolomite	1,300±	400±	Unfossiliferous Light-gray laminated	
SIL.	Sl	Laketown Dolomite	1,560	474	Silicified brachiopods near top Banded light and dark brownish-gray	
ORDOVICIAN	Oes	Ely Springs Dolomite	345	105	Dark gray	
	Oew	Eureka Quartzite	467-600	142-180	Yellowish-gray, vitreous	Webb, 1956, 1958; Hintze, 1981d, 1997d
		Crystal Peak Dolomite	92-164	28-50	*Eofletcheria* (coral)	
		Watson Ranch Quartzite	174-190	53-58	Orange, thin-bedded	
	Opu	Pogonip Group: Lehman Formation	277	85	Ostracodes abundant	Hintze, 1951, 1981d, 1997d
		Pogonip Group: Kanosh Shale	420±	128±	Brachiopods abundant	
		Pogonip Group: Juab Limestone	152	46		
		Pogonip Group: Wah Wah Limestone	230	70	Trilobite fragments common	
	Of	Pogonip Group: Fillmore Formation	1,530±	465±	Intraformational conglomerate	

Diagram is schematic-- no fixed scale

STRATIGRAPHIC COLUMN 11

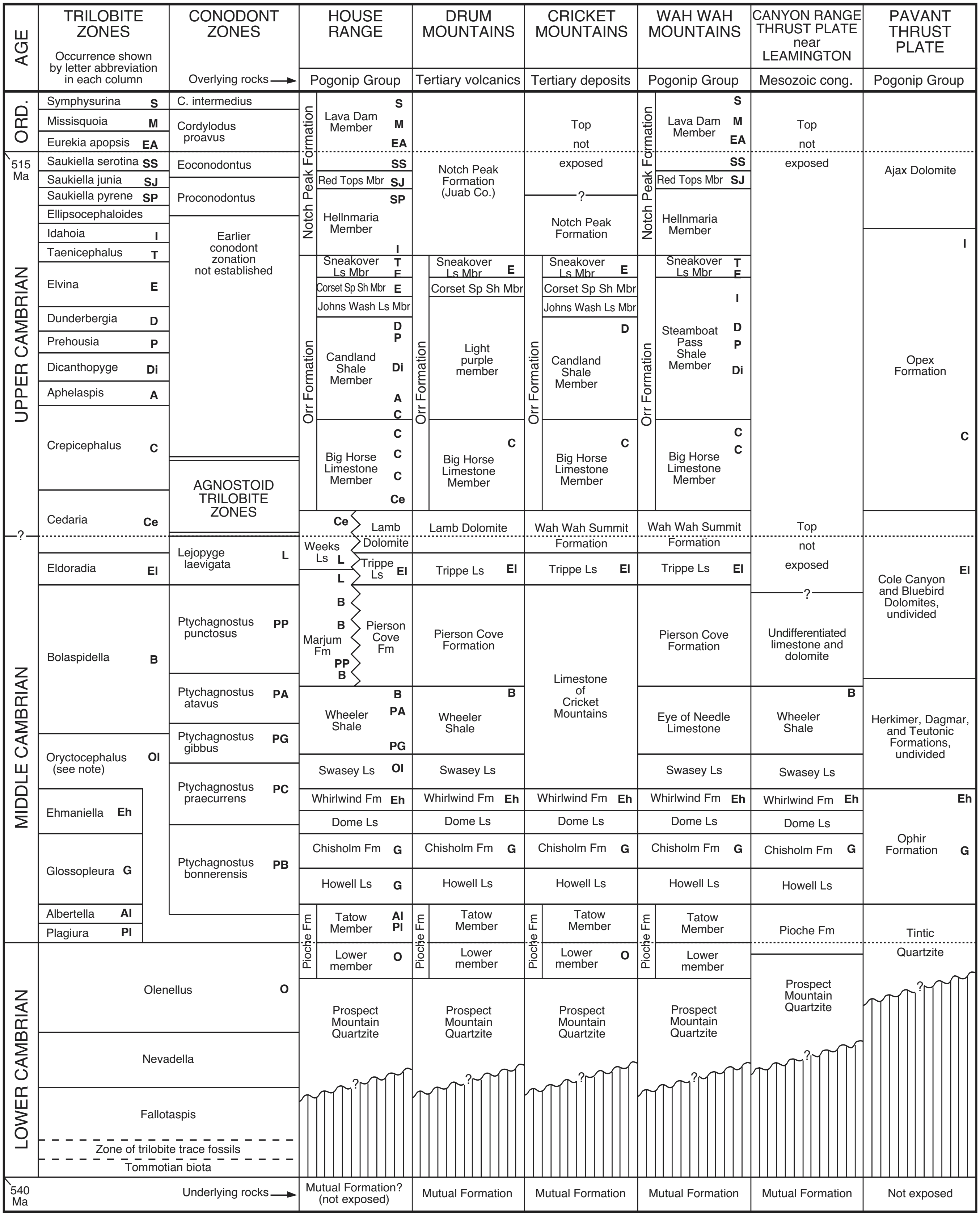
MOUNTAIN HOME RANGE



AGE	MAP SYMBOL	ROCK UNIT	THICKNESS FEET	THICKNESS METERS	FOSSILS, ISOTOPIC AGES, AND OTHER INFORMATION	REFERENCES
Q.	various	Alluvium and colluvium	0-200±	0-60±		Stephens, 1976
MIOCENE	Tcs	Conglomerate and sandstone	2,000	600	Tilted valley-fill deposits on west flank of range	Hintze and Best, 1987
MIOCENE	TKbr	Tectonic breccia	500+ wide	150+ wide	Age uncertain	Hintze and Best, 1987
OLIGOCENE	Tnu	Needles Range Group: Wah Wah Springs Formation, outflow tuff member	1,000±	300±	**30.5± Ma** Crystal-rich	Hintze and Best, 1987; Best and Grant, 1987
OLIGOCENE	Tnu	Needles Range Group: Cottonwood Wash Tuff	900-1,300	275-400	**31± Ma** Large biotite phenocrysts	Hintze and Best, 1987; Best and Grant, 1987
OLIGOCENE	Tnl	Needles Range Group: Escalante Desert Formation	0-80	0-25	**32± Ma** crystal-poor	Hintze and Best, 1987; Best and Grant, 1987
		MAJOR ANGULAR UNCONFORMITY				
PERMIAN	Pa	Arcturus Formation	2,300+	700+	Gypsum; Orange dolomitic sandstone	Hintze, 1986a
PERMIAN / PENN.	PIPMe	Ely Limestone: Cherty member	2,540	775	*Pseudofusulina,* (fusulinid); *Pseudoschwagerina* (fusulinid); Permian fossils in upper 150 m (500 ft); *Chaetetes* (hair coral); *Profusulinella* (fusulinid); *Endothyra* (fusulinid)	St. Aubin-Hietpas, 1983
PENN. / MISSISSIPPIAN	PIPMe	Ely Limestone: Chertless member	200	60		St. Aubin-Hietpas, 1983
MISSISSIPPIAN	Mc	Chainman Fm: Jensen Member	260-400	80-120	Abundant marine fossils	Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Willow Gap Limestone Member	260-360	80-110		Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Camp Canyon Member: Rusty limestone unit	650	200		Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Camp Canyon Member: Clayey limestone unit	300	90		Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Camp Canyon Member: Black shale unit	400	120	*Cravenoceras* (cephalopod)	Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Skunk Spring Limestone Member	6	2		Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Needle Siltstone Member	600	180		Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN	Mc	Chainman Fm: Delle Phosphatic Mbr: Limestone unit	80-110	25-35		Sandberg and Gutschick, 1984
MISSISSIPPIAN	Mc	Chainman Fm: Delle Phosphatic Mbr: Siltstone unit	40-65	13-20		Sandberg and Gutschick, 1984
MISSISSIPPIAN	Mj	Joana Limestone	460	140	Horn corals	Hintze, 1986a; Hintze and Best, 1987
MISSISSIPPIAN / DEVONIAN	MDp	Pilot Shale	360	110		Hintze, 1986a; Hintze and Best, 1987
DEVONIAN	Dg: Dgw	Guilmette Formation: West Range Ls Member	260-400	80-120	Conodonts	Hintze, 1986a; Hintze and Best, 1987
DEVONIAN	Dg: Dgm	Guilmette Formation: Sandstone member	130	40		Hintze, 1986a; Hintze and Best, 1987
DEVONIAN	Dg: Dgm	Guilmette Formation: Lower (dolomite and sandstone) member	1,300+	400+	Spaghetti-like stromatoporoids very common	Hintze, 1986a; Hintze and Best, 1987

Diagram is schematic-- no fixed scale

CORRELATION CHART 1 - CAMBRIAN



Note: In Middle Cambrian, agnostoid trilobite zones are shown at right side of zone list; Oryctocephalus is a long-ranging open-shelf group that extends from the base of the Middle Cambrian to the base of the Bolaspidella Zone. REFERENCES: Robison (1976, 1984a); Palmer (1979); Hintze (1988a); Ross and others (1997).

CORRELATION CHART 2 - CAMBRIAN-ORDOVICIAN BOUNDARY

System	Series	Stage	Litho-stratigraphy		Trilobite zone	Trilobite subzone	Conodont subzone	Conodont zone
ORDOVICIAN	Ibexian	Skullrockian	House Limestone		Symphysurina	*Symphysurina bulbosa	Conodont fauna B	
						?		
						Symphysurina brevispicata	Clavohamulus hintzei	Cordylodus proavus
							Hirsutodontus simplex	
			Notch Peak Formation	Lava Dam Member	Missisquoia	Missisquoia typicalis	Clavohamulus elongatus	
							Fryxellodontus inornatus	
						Missisquoia depressa	Hirsutodontus hirsutus	
CAMBRIAN	Upper	Trempealeauan			Saukia	Eurekia apopsis		
						Saukiella serotina	Cambrooistodus minutus	Proconodontus
				Red Tops Member		?	Eoconodontus notchpeakensis	
						Saukiella junia	Proconodontus muelleri	

References: Hintze and others (1988); Ross and others (1997).

CORRELATION CHART 3 - ORDOVICIAN-SILURIAN

ORDOVICIAN-SILURIAN CORRELATION TABLE FOR MILLARD COUNTY

Note: North American Silurian series and stage names are not used here because European series terms are applicable (Berry and Boucot, 1970). Brachiopods and corals are the only fossils commonly found in the Silurian Laketown Dolomite from which Sheehan (1971) identified brachiopod communities of Wenlock and Llandovery age listed below on right.

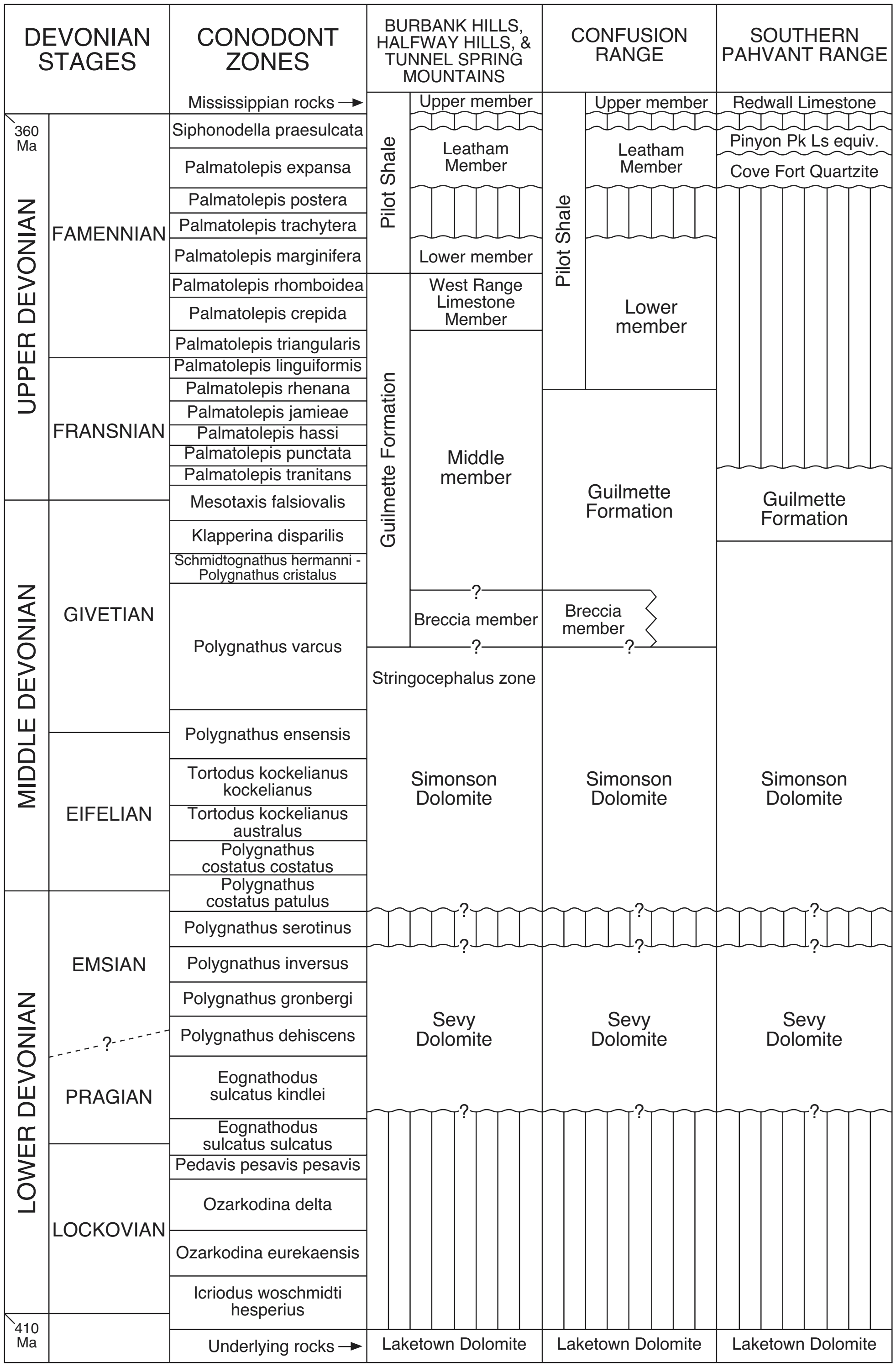
Conodont zones and occurrences in the Ibex area: Silurian-- not documented; Cincinnatian and Mohawkian from Sweet and Bergstorm (1976); Whiterockian and Ibexian from Ethington and Clark (1981), and Ross and others (1997).

System Names	English-Welsh Series Names	North American Series Names	North American Ordovician Stage Names	Zone	Conodont zones	Graptolite Occurrences in the Ibex Area (Braithwaite, 1976)	Shelly Fossil Zones in the Ibex Area (Hintze, 1973a; Ross and others, 1997)	Zone	IBEX AREA WESTERN MILLARD CO.	PAHVANT RANGE AND CANYON MOUNTAINS
							Overlying rocks →		Sevy Dolomite	Sevy Dolomite
SILURIAN (410 Ma at top)	PRIDOLI								(hiatus)	(hiatus)
SILURIAN	LUDLOW								(hiatus)	(hiatus)
SILURIAN	WENLOCK						Spirinella; Verticillopora		Laketown Dolomite	Laketown Dolomite
SILURIAN	LLANDOVERY						Pentamerus; Virgiana		Laketown Dolomite / (hiatus)	Laketown Dolomite / (hiatus)
ORDOVICIAN (440 Ma at top)	ASHGILL	CINCINNATIAN	Gamachian						(hiatus)	(hiatus)
ORDOVICIAN	ASHGILL	CINCINNATIAN	Richmondian		Fauna 12				Ely Springs Dolomite	Fish Haven Dolomite
ORDOVICIAN	ASHGILL	CINCINNATIAN	Maysvillian		Fauna 11				Ely Springs Dolomite	Fish Haven Dolomite
ORDOVICIAN	ASHGILL	CINCINNATIAN	Edenian		Fauna 10				(hiatus)	(hiatus)
ORDOVICIAN	CARADOC	MOHAWKIAN	Shermanian		Fauna 10				(hiatus)	(hiatus)
ORDOVICIAN	CARADOC	MOHAWKIAN	Kirkfieldian		Fauna 9				(hiatus)	(hiatus)
ORDOVICIAN	CARADOC	MOHAWKIAN	Rocklandian		Fauna 8				Eureka Quartzite	Eureka Quartzite
ORDOVICIAN	CARADOC	MOHAWKIAN	Black Riveran		Fauna 7				Eureka Quartzite	Eureka Quartzite
ORDOVICIAN	LL'D'O	WHITEROCKIAN	Chazyan	O	? Phragmodus; Paraprioniodus Chosonodina		Eofletcheria Oepikina	O	Crystal Peak Dolomite; Watson Ranch Quartzite	Pogonip Group
ORDOVICIAN	LLAN-	WHITEROCKIAN	Kanoshian	N	Paraprioniodus Chosonodina; Histiodella sinuosa	Didymograptus bifidus	Pseudoolenoides acicaudus	N	Lehman Formation	Pogonip Group
ORDOVICIAN	LLAN-	WHITEROCKIAN	Kanoshian	M	Histiodella sinuosa	Didymograptus bifidus	Pseudoolenoides dilectus	M	Kanosh Shale	Pogonip Group
ORDOVICIAN	ARENIG	WHITEROCKIAN	Rangerian	L	Tripodus laevis - Histiodella altifrons	Didymograptus nitidus	Paralenorthis sublata - Orthidiella - Ectenonotus	L	Juab Limestone	Pogonip Group
ORDOVICIAN	ARENIG	IBEXIAN	Blackhillsian	K	Reutterodus andinus		Hesperonomiella	K	Wah Wah Limestone	Pogonip Group
ORDOVICIAN	ARENIG	IBEXIAN	Blackhillsian	J	Reutterodus andinus	Tetragraptus	Pseudocybele nasuta	J	Wah Wah Limestone	Pogonip Group
ORDOVICIAN	ARENIG	IBEXIAN	Blackhillsian	I	Reutterodus andinus	Didymograptus fillmorensis	Presbynileus ibesensis	I	Fillmore Formation 6	Pogonip Group
ORDOVICIAN	ARENIG	IBEXIAN	Blackhillsian	H	Oepikodus communis	Didymograptus fillmorensis	Trigonocerca typica	H	Fillmore Formation 5	Pogonip Group
ORDOVICIAN	ARENIG / TREMADOC	IBEXIAN	Tulean	G2	Oepikodus communis; Acadus deltatus - Oneotodus costsatus	Clonograptus flexilis - Phyllograptus archaios	Protopliomerella contracta	G2	Fillmore Formation 4, 3	Pogonip Group
ORDOVICIAN	TREMADOC	IBEXIAN	Tulean	G1	Acadus deltatus - Oneotodus costsatus	Adelograptus	Hintzeia celsora	G1	Fillmore Formation 2	Pogonip Group
ORDOVICIAN	TREMADOC	IBEXIAN	Stairsian	F	Macerodus dianae		Rossaspis	F	Fillmore Formation 1	Pogonip Group
ORDOVICIAN	TREMADOC	IBEXIAN	Stairsian	E	Low diversity	dendrograptids	Tesselacauda	E	Fillmore Formation 1	Pogonip Group
ORDOVICIAN	TREMADOC	IBEXIAN	Stairsian	D	Low diversity; Rossodus manitovensis		Leiostegium - Kainella	D	Fillmore Formation 1	Pogonip Group
ORDOVICIAN	TREMADOC	IBEXIAN	Skullrockian	C	Rossodus manitovensis		Paraplethopeltis	C	House Limestone	Pogonip Group
ORDOVICIAN	TREMADOC / MERIONETH	IBEXIAN	Skullrockian	B	C. angulatus; Iapetognathus; C. lindstromi; C. intermedius		Symphysurina	B	House Limestone	Pogonip Group
ORDOVICIAN	MERIONETH	IBEXIAN	Skullrockian	Mi	Corylodus proavus		Missisquoia	Mi	Notch Peak Fm; Lava Dam Member	? Ajax Dolomite
ORDOVICIAN	MERIONETH	IBEXIAN	Skullrockian	EA	Corylodus proavus		Eurekia apopsis	EA	Notch Peak Fm; Lava Dam Member	Ajax Dolomite
515 Ma			Underlying Cambrian units →		Eoconodontus		Saukiella serotina	SS	Notch Peak Fm; Lava Dam Member	Ajax Dolomite

Numbers show informal members of Hintze (1973a)

Isotopic ages (Ma) after Harland and others (1990); Ross and Ethington (1992).

CORRELATION CHART 4 - DEVONIAN

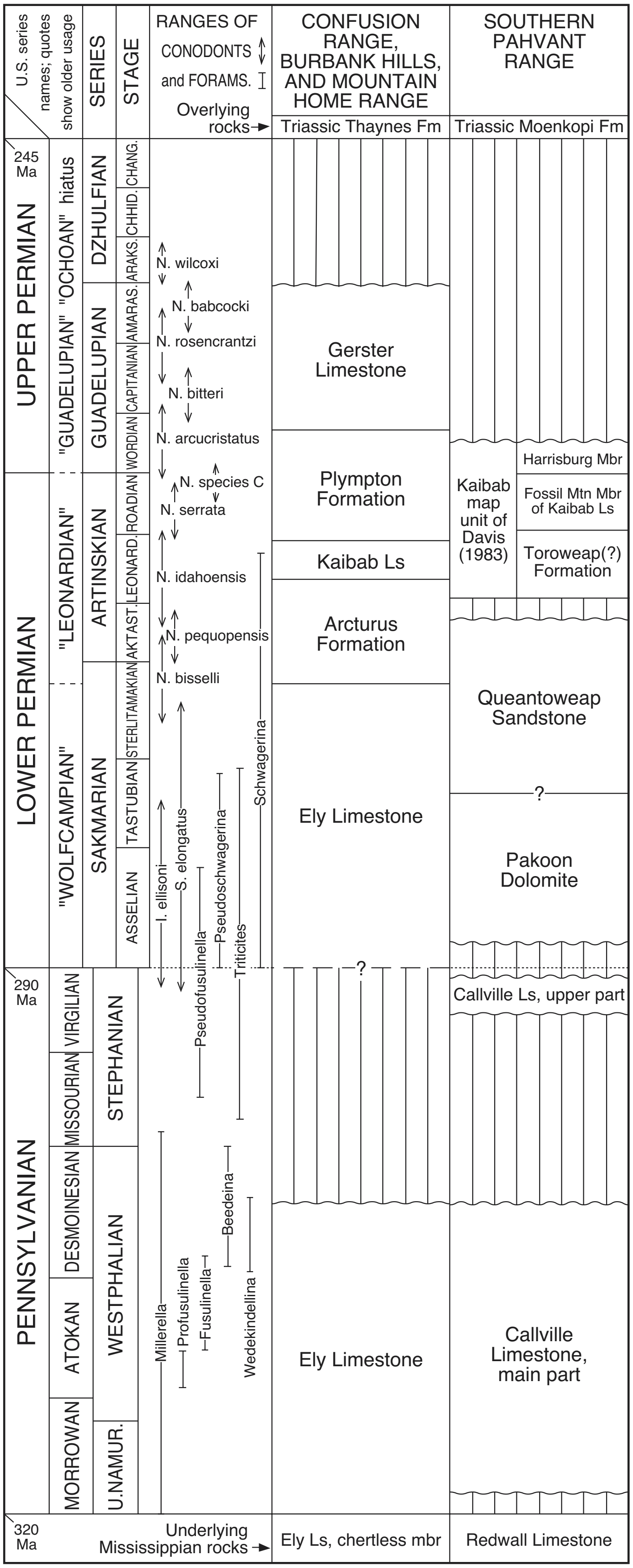


References: Sandberg and others (1980, 1989); Sandberg (personal communication, 1994).

CORRELATION CHART 5 - MISSISSIPPIAN

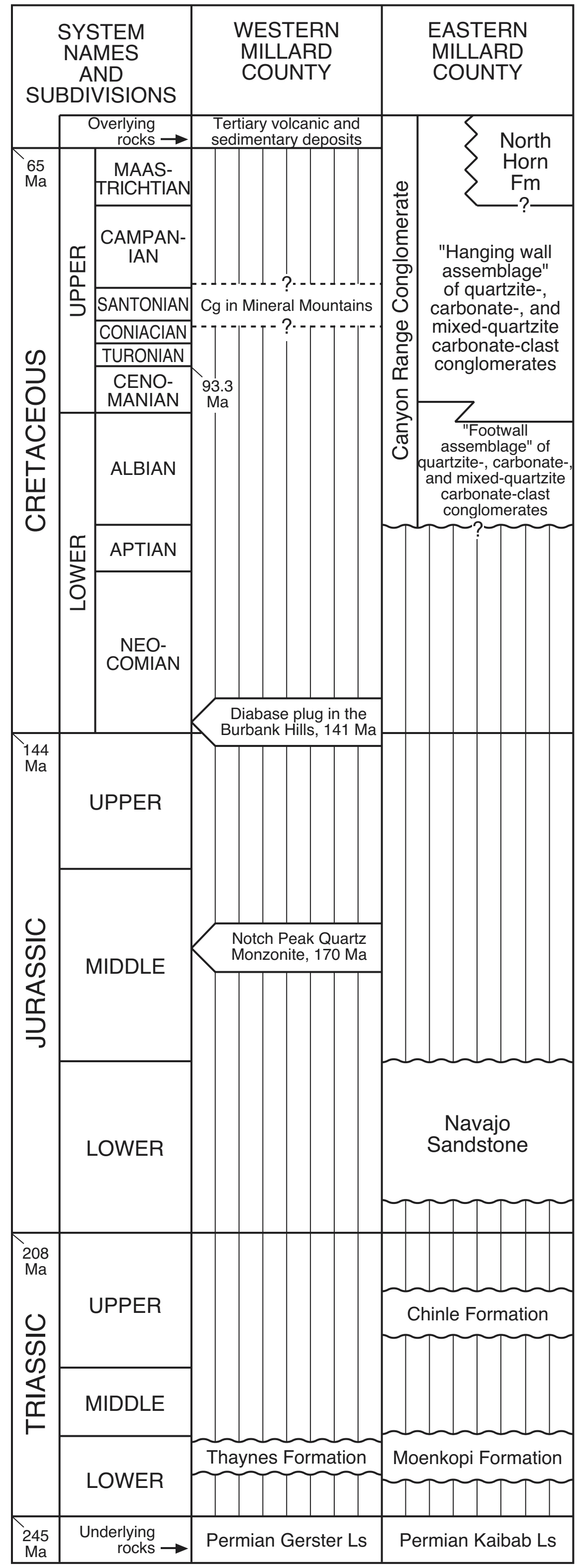
System	N. AMER. SERIES	EUROPEAN	FORAM.-ZONES (Mamet and Skipp, 1970)	WESTERN U.S. CONODONT ZONES (Poole and Sandberg, 1991) *Zone identified in western Utah	CORAL ZONES (Sando and Bamber, 1985)		STRATIGRAPHIC UNITS Mountain Home Range, Burbank Hills, and Confusion Range			Upper Mississippian key ammonoids and a guide brachiopod in the Chainman Formation (Webster and others, 1984; Gordon, 1984)
PENN.										
MISSISSIPPIAN (320 Ma)	CHESTERIAN	LOWER NAMURIAN	19	* Rhachistognathus primus	VI		Chertless lower part of Ely Limestone			Rhipidomella nevadensis (brachiopod guide fossil)
				* Rhachistognathus muricalus			Chainman Formation	Jensen Member		Eumorphoceras bisulcatum, Richarsonites merriami
				* Adelognathus unicornis						
			18	* Cavusgnathus naviculus				Willow Gap Limestone Member		↑ Cravenoceras hesperium ↓
			17		V	B		Camp Canyon Member	Rusty ls unit	
		VISEAN	16s	* Gnathodus bilineatus UPPER Cavusgnathus		A			Clayey limestone unit	Syngastrioceras barnettense; Goniatites granosus
			16i	*					Black shale unit	Goniatites multiliratus
	MERAMECIAN		15	* LOWER Cavusgnathus	IV					↑ Goniatites americanus ↓
			14					Skunk Spring Ls Member		
			13	Paragnathodus homopunctatus UPPER Gnathodus texanus	III	D		Needle Siltstone Member		
						C				
			12			B				
	OSAGEAN		? 11 ?	Polygnathus mehli LOWER Gnathodus texanus		A		Delle Phosphatic Member	Limestone unit	
			10							
		TOURNAISIAN	9	Scaliognathus anchoralis - Doliognathus latus	II	B			Siltstone unit	
			8	* UPPER Gnathodus typicus						Corals from the Joana Limestone listed by Sando and Bamber (1985):
			7	* LOWER Gnathodus typicus			Joana Limestone			Amplexizaphrentis, Stelechophyllum, Syringgopora, Vesiculophyllum?
	KINDERHOOKIAN		Pre-7	Siphonodella isosticha - UPPER Siphonodella crenulata		A				Other Joana fossils noted by Rush (1951):
				* LOWER Siphonodella crenulata	I	C				Crinoid stem fragments, Spiriferid brachiopods, Fenestellate bryozoans, Gastropod traces
						B				
			Unzoned	Siphonodella sandbergi		A	Pilot Shale	Upper member		
				* Siphonodella duplicata						
(360 Ma)				Siphonodella sulcata						
DEV.	Underlying Devonian strata →							Leatham Member		

CORRELATION CHART 6
PENNSYLVANIAN - PERMIAN



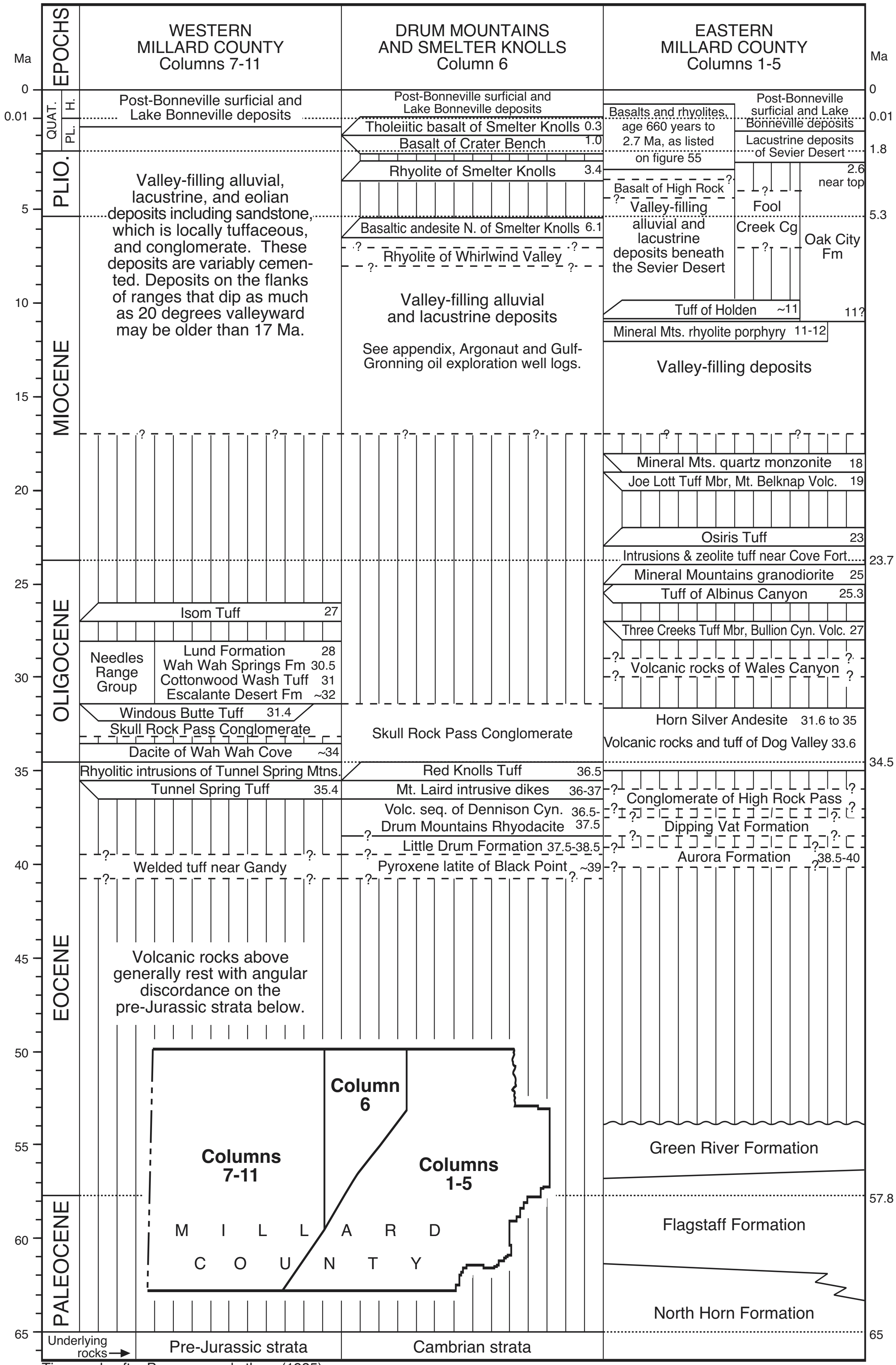
References: Clark and others (1979), conodont ranges; Welsh, John E. (written communication, 1994), Pennsylvanian foram. ranges; Ross and Ross (1979), Permian foram. ranges.

CORRELATION CHART 7
TRIASSIC - JURASSIC - CRETACEOUS



References: Hintze (1988a and 2nd edition, 1993); Lawton and others (2003).

CORRELATION CHART 8



Time scale after Berggren and others (1985).