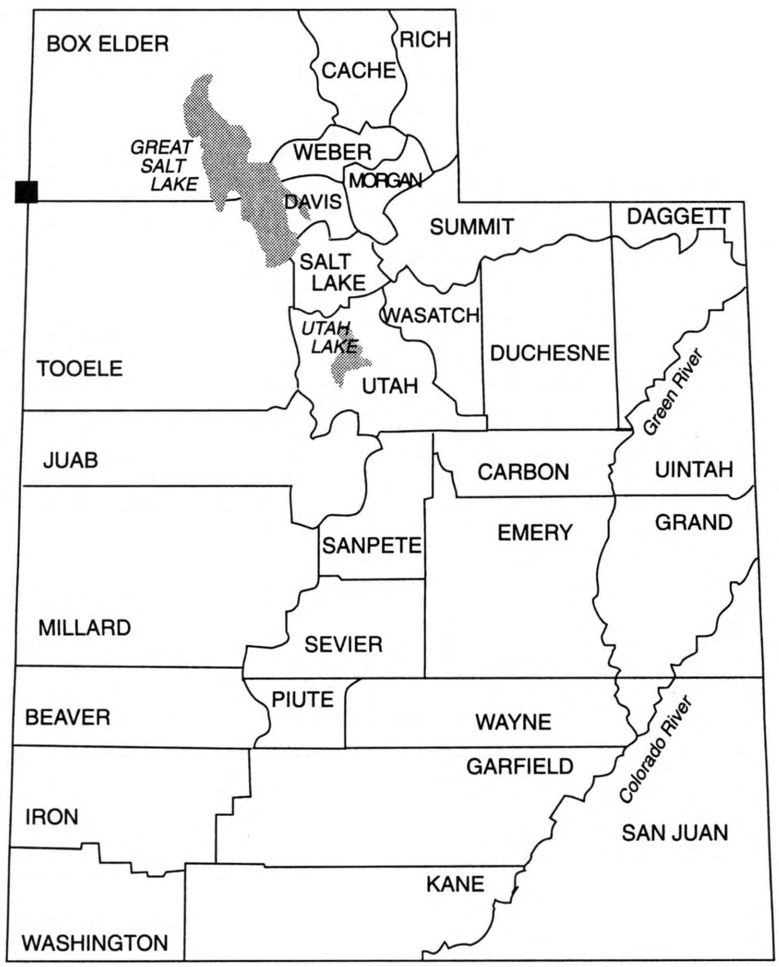
GEOLOGIC MAP OF THE PILOT PEAK QUADRANGLE, BOX ELDER COUNTY, UTAH, AND ELKO COUNTY, NEVADA

by
David M. Miller and Andrew P. Lush
U. S. Geological Survey



Map 160 **1994**
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with
U.S. GEOLOGICAL SURVEY

UTAH CENTENNIAL 1896-1996

UTAH GEOLOGICAL SURVEY
2363 South Foothill Drive
Salt Lake City, Utah 84109-1491
Phone: (801) 467-7970 Fax: (801) 467-4070

THE UTAH GEOLOGICAL SURVEY is organized into three geologic programs with Administration, Editorial, and Computer Resources providing necessary support to the programs. THE ECONOMIC GEOLOGY PROGRAM undertakes studies to identify coal, geothermal, uranium, hydrocarbon, and industrial and metallic mineral resources; to initiate detailed studies of the above resources including mining district and field studies; to develop computerized resource data bases, to answer state, federal, and industry requests for information; and to encourage the prudent development of Utah's geologic resources. THE APPLIED GEOLOGY PROGRAM responds to requests from local and state governmental entities for engineering geologic investigations; and identifies, documents, and interprets Utah's geologic hazards. THE GEOLOGIC MAPPING PROGRAM maps the bedrock and surficial geology of the state at a regional scale by county and at a more detailed scale by quadrangle. The Geologic Extension Service answers inquiries from the public and provides information about Utah's geology in a non-technical format.

The UGS manages a library which is open to the public and contains many reference works on Utah geology and many unpublished documents on aspects of Utah geology by UGS staff and others. The UGS has begun several computer data bases with information on mineral and energy resources, geologic hazards, stratigraphic sections, and bibliographic references. Most files may be viewed by using the UGS Library. The UGS also manages a sample library which contains core, cuttings, and soil samples from mineral and petroleum drill holes and engineering geology investigations. Samples may be viewed at the Sample Library or requested as a loan for outside study.

The UGS publishes the results of its investigations in the form of maps, reports, and compilations of data that are accessible to the public. For information on UGS publications, contact the Sales Office, 2363 South Foothill Drive, Salt Lake City, Utah 84109-1491, (801) 467-0401.

GEOLOGIC MAP OF THE PILOT PEAK QUADRANGLE, BOX ELDER COUNTY, UTAH, AND ELKO COUNTY, NEVADA

by
David M. Miller [1] *and Andrew P. Lush* [2]
U.S. Geological Survey

ABSTRACT

The Pilot Peak quadrangle straddles the Utah-Nevada border in northwestern Utah and northeastern Nevada, and includes much of the highest part of the central Pilot Range. Flanking the range are piedmonts; on the west side is part of a broad, west-sloping piedmont, whereas that on the east side is steeper and narrower. The north-trending fault block forming the Pilot Range contains structures and rock units typical of the northern Basin and Range Province. Bedrock in this fault block constitutes two lithotectonic domains that are separated by the Pilot Peak detachment fault at the south end of the quadrangle. Most rock units in the quadrangle lie below the fault. These rocks are mostly Late Proterozoic and Cambrian siliciclastic strata that typically have well-developed tectonite fabrics caused by Mesozoic ductile deformation and metamorphism. Generally unmetamorphosed Ordovician to Permian carbonate strata lie above the fault. Flanking the Pilot Range are young sedimentary basins formed during tectonic extension. The presumably middle Cenozoic deposits of these basins are concealed by Pliocene(?) to Quaternary alluvial deposits and Pleistocene lacustrine deposits of Lake Bonneville.

INTRODUCTION

The Pilot Peak quadrangle straddles the Utah-Nevada border in northwestern Utah and northeastern Nevada and includes much of the south-central Pilot Range (figure 1). The Pilot Range crest passes from southwest to northeast in the quadrangle. This crest includes Pilot Peak (3,266 meters; 10,716 ft) and two slightly lower peaks (3,202 and 3,172 meters; 10,504 and 10,406 ft) that together form a triple-humped high ridge used as a landmark from a great distance by early travelers; hence the name of the mountain range. Parts of broad piedmonts lying on both sides of the Pilot Range are exposed in the quadrangle, where they range in altitude from about 1,890 meters (6,200 ft) to 1,448 meters (4,750 ft). Few physiographic features are named in the Pilot Peak quadrangle, making it difficult to describe locations of geologic features. In addition to named features such as Pilot Peak, Bettridge Creek, Debbs Canyon, and Cove Spring, we refer informally to "Marble Canyon" on the east side of the range in the northeastern corner of the quadrangle (along the north side of sections 9 and 10, T. 4 N., R. 19 W.) and "the pinnacle" about 1.5 kilometers (1 mi) northeast of peak "Pilot Peak Az" in the center of the quadrangle (NW¼ section 33, T. 37 N., R. 70 E.).

The Pilot Range and nearby mountains are north-trending fault blocks (figure 1), typical of the Basin and Range Province in western Utah. This part of the Basin and Range Province was part of the subsiding continental margin during Late Proterozoic and Paleozoic time, when great thicknesses of miogeoclinal sedimentary strata accumulated (Miller, 1984; Hintze, 1988). During the Mesozoic, the Pilot Range region was the site of Jurassic igneous intrusion, metamorphism, folding, and low-angle faulting that possibly continued into the Cretaceous (Miller and others, 1987). During the Late Cretaceous and earliest Tertiary, rocks exposed in the Pilot Range region probably were passively carried eastward above deep thrust faults of the Cor-

[1] *U.S. Geological Survey, 345 Middlefield Road, Menlo Park CA 94025*
[2] *Currently with Applied Geosystems, 4191-E Power Inn Road, Sacramento CA 95826*

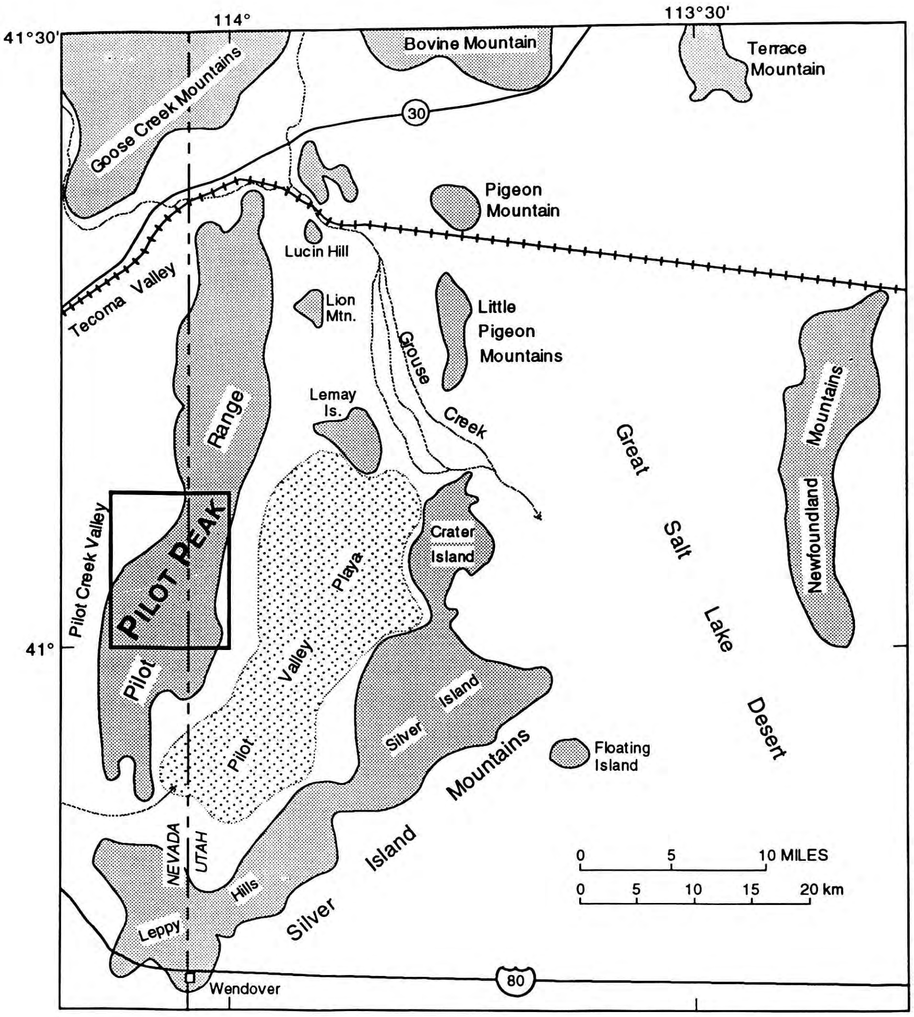


Figure 1. Location of physiographic features in the vicinity of the Pilot Peak quadrangle, northwestern Utah and northeastern Nevada.

dilleran fold and thrust belt (Miller, 1990a). During the Cenozoic, the region was tectonically extended. High- and low-angle normal faults, plutons and volcanic rocks, and deep sedimentary basins are characteristic features. During the Pleistocene, Lake Bonneville and its precursors inundated the northwestern Utah area. Lacustrine deposits and shorelines cut into older alluvial aprons in the Pilot Peak quadrangle indicate that the surface of Lake Bonneville reached an altitude of about 1,591 meters (5,220 ft) at its maximum height along the east side of the Pilot Range.

Two lithotectonic domains in the Pilot Range are separated by a low-angle fault, referred to as the Pilot Peak detachment. This fault is exposed in the southern extreme of the Pilot Peak quadrangle, where it separates deformed and metamorphosed Late Proterozoic and Cambrian rocks below the fault from generally unmetamorphosed Paleozoic carbonate strata, ranging in age from Cambrian to Permian, above the fault. The fault was intruded by latest Eocene granitoid dikes. Late Cenozoic normal faults define the range fronts and cut rocks both above and below the detachment fault. These faults are overlapped by, and in places cut, Pliocene(?) to Holocene surficial deposits.

The Pilot Range was mapped as part of a larger project to understand the Mesozoic and Cenozoic tectonics of northwestern Utah. The project has yielded a number of geologic maps (figure 2). Detailed mapping of the Pilot Range showed structural, stratigraphic, and metamorphic relations that were not apparent in earlier studies by Woodward (1967) and O'Neill (1968). O'Neill, nevertheless, accurately outlined the stratigraphy and structure of much of the Pilot Peak quadrangle and adjacent areas. This report provides new information and interpretations that supersede a preliminary map of the Pilot Peak quadrangle (Miller and Lush, 1981).

DESCRIPTION OF MAP UNITS

Map units within the Pilot Peak quadrangle consist of Late Proterozoic and Paleozoic strata of the Cordilleran miogeocline, Mesozoic and Cenozoic intrusive igneous rocks, and upper Cenozoic(?) and Quaternary surficial deposits. Detailed descriptions of these units, discussions of their ages, and interrelations between units are included in this section. Most Paleozoic rock units in the quadrangle were geographically extended to the Pilot Range by Miller and Schneyer (1985), many igneous rocks were named and described by Miller and others (1987), and Late Proterozoic and Cambrian strata were extended to the Pilot Range (and in some cases named) by Woodward (1967), Miller (1983), and McCollum and Miller (1991).

Late Proterozoic and Cambrian strata within the quadrangle are metamorphosed to greenschist and lower amphibolite facies, whereas Upper Cambrian and younger strata show minimal dynamothermal metamorphism. We describe most metamorphic rocks by their protolith compositions, except for micaceous rocks, which we term phyllitic argillite or metasiltstone at low grade and phyllite or schist at higher grade. These higher grade rocks generally lack sedimentary structures and textures, but they probably represent argillite and siltstone protoliths. The metamorphosed rock units vary laterally in thickness; we calculated thicknesses from outcrop widths of representative sections.

Late Proterozoic

McCoy Creek Group

The McCoy Creek Group of Misch and Hazzard (1962) was defined for a thick sequence of alternating phyllite and quartzite units underlying the Late Proterozoic and Cambrian (restricted)

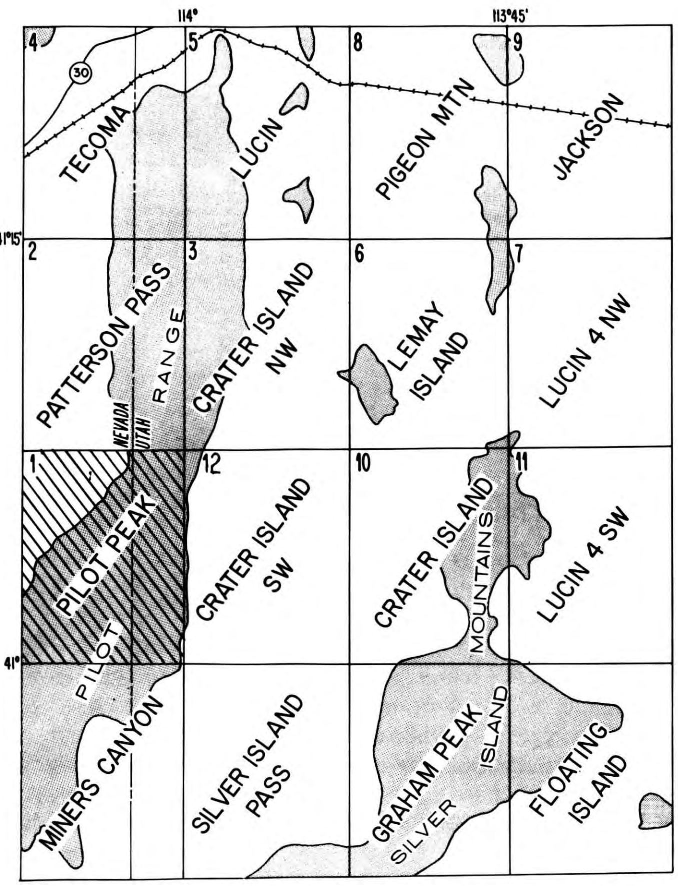


Figure 2. *Index map of Pilot Peak and nearby quadrangles. Numbers indicate 1:24,000-scale geologic maps published by the Utah Geological Survey: 1, this report; 2, Miller and others, 1993; 3, Miller, 1993; 4, Miller and Schneyer, 1985; 5, Miller, 1985; 6, Miller and Glick, 1986; 7, Glick and Miller, 1986; 8, Glick and Miller, 1987; 9, Miller and Glick, 1987; 10, Miller, Jordan and Allmendinger, 1990; 11, Miller, 1990b; 12, Miller, 1990c.*

Prospect Mountain Quartzite in the Schell Creek Range, east-central Nevada. This nomenclature was extended to the Pilot Range by Woodward (1967), O'Neill (1968), Miller and Lush (1981), and Miller (1983). Miller (1983) followed Stewart (1974) and included rocks assigned to the uppermost unit of Misch and Hazzard's (1962) McCoy Creek Group, unit H, within the lower part of the Prospect Mountain Quartzite because the two units are indistinguishable in most places. This modified sequence of the McCoy Creek Group extends from unit G at the top to unit A at the base. The McCoy Creek Group is Late Proterozoic in age.

In the Pilot Peak quadrangle, units G to C of the McCoy Creek Group crop out northwest of Pilot Peak in a nearly unbroken section. The lower units, tentatively assigned to units B and A (following O'Neill, 1968), are structurally isolated from upper units and lie north of Marble Canyon in the northeastern part of the quadrangle. Unit G in this quadrangle changes character from south to north by the addition of thick conglomerate within its lower part (Miller, 1983). Detailed descriptions of units G and F are given by Miller (1983).

Unit A(?) (Zma, Zmas)

Unit A(?) is primarily a heterogeneous clastic unit of impure quartzite and schist. The unit is divided into a lower subunit of quartzite and schist and an upper schist subunit, which contains distinctive green actinolite schist and brown mica schist that pinch out along strike. The base of unit A(?) is not exposed.

The lower subunit (Zma) consists of flaggy quartzite, schist, and conglomerate. The main rock type is schistose, tan, bedded quartzite. No major lithologic variations were noted, although distinctive steel gray, graphitic schist is exposed in the lower part of the sequence. In addition to graphite, this schist contains a biotite-white mica-fibrolite-quartz-plagioclase metamorphic assemblage (Miller and Hoisch, 1992). Aggregates of felted white mica have replaced andalusite.

The schist subunit (Zmas) consists mainly of green, crenulated actinolite schist; brown, quartzose schist; and steel-gray graphitic schist. The actinolite schist is up to 95 percent coarse actinolite with interstitial feldspar. A minor rock type is biotite-white mica schist, locally containing minor fibrolite. Near the southernmost outcrops of the schist subunit, metadiorite(?) amphibole gneiss crops out at the top of unit A. This rock suggests metamorphosed igneous sills or lava flows, whereas the actinolite schist may be derived from mafic igneous rock such as tuff.

The heterogeneous quartzite and schist of unit A(?) are lithologically similar to unit A in the type area of Misch and Hazzard's (1962) McCoy Creek Group in the Schell Creek Range, although the unit in the Schell Creek Range contains two intervals of marble. O'Neill (1968) included part of the marble that we assign to unit B in his unit A(?), but we consider that all marble in the Pilot Range constitutes a single, complexly folded unit. Because basal unit B of the type McCoy Creek Group contains the greatest thickness of marble, we assign the marble unit in the Pilot Range to unit B(?). Type unit A is overlain by schist and marble in both ranges, and amphibolite in lower unit B in the Schell Creek Range possibly corresponds to meta-igneous rocks at the top of unit A(?) in the Pilot Range. We therefore follow O'Neill (1968) in assigning the quartzite and schist to unit A(?) of the McCoy Creek Group, but exclude marble from the unit. Unit A(?) is more than 450 meters (1,480 ft) thick.

Unit B(?) (Zmb)

Marble of unit B(?) is white and gray, commonly with bluish tinges, and is generally laminated and medium to coarsely crystalline. Massive, white, coarsely crystalline marble crops out in a few places. The marble is fairly pure, containing at most 10 percent white mica, fine quartz, tremolite, and iron oxide minerals. The unit forms steep slopes in the northeastern part of the quadrangle. The upper part of the unit is truncated by the Pinnacle fault, adjacent to which the marble is highly deformed and extremely fine grained. At its base, the marble grades to schistose tremolite-calcite marble and calcareous quartzite near the schist subunit of unit A(?). The unit is at least 155 meters (510 ft) thick, but its top is truncated.

Unit B(?) is questionably correlated with type unit B of the McCoy Creek Group in the Schell Creek Range, as defined by Misch and Hazzard (1962), on the basis of rock type and stratigraphic position. Unit B contains the thickest marble sequence in the McCoy Creek Group, although Misch and Hazzard (1962) de-emphasized it in their description of unit B. Marble in unit A at the type section is present in two intervals, as defined by Misch and Hazzard. The lower interval lies within quartzite of unit A, is 15 meters (50 ft) thick, and is yellow to buff in color. The upper interval is about 35 meters (115 ft) thick and forms the top of unit A; it is also yellow in color. Unit B marble is interbedded with phyllite over the basal interval about 150 meters (500 ft) thick; it is gray to white in color and laminated. We therefore correlate the thickest interval of marble (unit B) in the Schell Creek Range with the marble in the Pilot Range. This correlation is supported by similar lithology and thickness of the units.

Unit C (Zmc)

Unit C consists of yellowish-green and silvery-brown phyllite, metasiltstone, and slate; rocks are commonly laminated. The slope-forming unit crops out poorly in two areas along the western base of the range. A minimum thickness of 35 meters (115 ft) is indicated by exposures south of Debbs Canyon, but the unit is probably much thicker: It may be 250 to 400 meters (820 to 1,315 ft) thick on the basis of scattered exposures to the north, or thicker on the basis of the great thickness of the type section (670 m; 2,200 ft). The base is not exposed in the Pilot Range. The unit is correlated with type unit C of the McCoy Creek Group in the Schell Creek Range, Nevada as defined by Misch and Hazzard (1962), on the basis of rock type and stratigraphic position (O'Neill, 1968).

Unit D (Zmd)

Unit D consists of cliff-forming, massive quartzite. The base of the unit is poorly bedded, medium-grained, light-gray quartzite with as much as 20 percent detrital feldspar. Quartzite grades upward, through an interval of intercalated quartzite and thin conglomerate beds, into massive, light-colored, clast-supported conglomerate. Clasts are composed of white and blue quartz, and white and gray quartzite, and typically are smaller than 1 centimeter (0.4 in). Rip-up clasts of phyllite are increasingly common toward the top of the massive conglomerate, where interbeds of metasiltstone and phyllite crop out. Sedimentary structures such as flute casts, graded beds, and soft-sediment folds are present near the top of unit D. The contact with unit E is drawn at the top of the highest quartzite bed thicker than 1 meter (3 ft). The unit ranges in thickness from about 220 meters (720 ft) near Debbs Canyon to nearly twice that thickness in the northernmost exposures. Unit D in the Pilot Range is correlated with type unit D of the McCoy Creek Group in the Schell Creek Range as defined by Misch and Hazzard (1962), on the basis of rock type and stratigraphic position (O'Neill, 1968).

Unit E (Zme)

Slope-forming, brown metasiltstone and phyllite are assigned to unit E. Rocks in the unit are laminated or thin-bedded and consist of metasiltstone; phyllite; micaceous, fine-grained quartzite; and sparse conglomerate near the base. The phyllite contains primary white mica, biotite, epidote, chlorite, and quartz; secondary chlorite partly to completely replaces biotite. Although superficially similar to unit G, unit E is thinner, more micaceous, and contains no marble. Unit E ranges from about 70 meters to 250 meters (230 to 820 ft) thick. The unit is correlated with type unit E of the McCoy Creek Group in the Schell Creek Range as defined by Misch and Hazzard (1962), on the basis of rock type and stratigraphic position (O'Neill, 1968).

Unit F (Zmf)

Unit F is composed of gray, well-bedded, cross-laminated quartzite that forms steep slopes and cliffs. Most quartzite is thick bedded and typically displays tabular, wedge, and trough cross laminations. Bed surfaces bounding the cross sets locally carry scattered white vein quartz pebbles. Most of the unit is monotonous quartzite, but minor rock-types serve to distinguish its lower and upper parts. Approximately the basal 40 meters (130 ft) of the unit is composed of faintly bedded, gray quartzite containing feldspar fragments (10 to 20 percent) and sparse beds of conglomerate with pebbles as large as 2 centimeters (0.8 in). The uppermost part of the unit, as much as 30 meters (100 ft) thick, consists of lenticular channels and beds of massive conglomerate separated by quartzite and rare mica schist beds. Rip-up wedges of phyllite (originally shale), boulders and cobbles of quartzite, feldspar grains, and sparse jasperoid clasts are common throughout this conglomeratic upper part of the unit.

A thick, structurally complex sequence of quartzite south of Marble Canyon is assigned to unit F despite several unusual features. The quartzite appears to be thicker than typical unit F rocks, it contains several interbedded zones of pelitic schist, and minor parts are conglomeratic. However, the quartzite structurally underlies unit G, as does unit F in the Bettridge Canyon area, and much of the quartzite is pure and cross-bedded unlike unit D.

Unit F is about 425 meters (1,400 ft) thick (Miller, 1983), and on the basis of rock type and stratigraphic position (O'Neill, 1968) is correlated with type unit F of the McCoy Creek Group in the Schell Creek Range as defined by Misch and Hazzard (1962).

Unit G (Zmg)

Metasiltstone and marble of unit G concordantly overlie unit F and underlie the Prospect Mountain Quartzite. Unit G as a whole is slope-forming, in marked contrast with the cliffs and steep talus slopes characteristic of the quartzite units above and below. A basal zone of interbedded conglomerate and phyllite and a distinctive thinly interbedded zone of marble and schist near the middle part of unit G provide convenient markers for mapping.

Miller (1983) distinguished a lower conglomerate subunit of alternating coarse conglomerate and phyllite or schist, and an upper subunit of metasiltstone, phyllitic argillite, and calcareous phyllite. The conglomerate subunit is well developed in the northern part of the quadrangle but consists only of several discontinuous conglomeratic zones in the southern part. Despite these facies variations, the unit is correlated with type unit G of the McCoy Creek Group in the Schell Creek Range as defined by Misch and Hazzard (1962), on the basis of rock type and stratigraphic position (O'Neill, 1968; Miller, 1983). The unit is about 480 meters (1,575 ft) thick.

Conglomerate subunit (Zmgc): In the southern part of the quadrangle, the (lower) conglomerate subunit consists of an interval of two or three conglomerate beds 10 to 20 meters (30 to 65 ft) thick. This interval crops out about 80 meters (269 ft) above the base of unit G (cross section BB′, plate 2). North of Debbs Canyon the subunit encompasses the entire basal 120 meters (400 ft) of unit G, where it consists mostly of interbedded pebble conglomerate, fine-grained micaceous quartzite, and phyllitic argillite. The conglomerate is poorly sorted and its matrix is arkose to graywacke. Rip-up clasts of phyllitic argillite are common. Intervening brown phyllitic argillite and micaceous quartzite are thin-bedded to laminated and contain ripples and flute casts. Dark-brown, rhythmically bedded, phyllitic argillite and metasiltstone form gentle slopes. Somewhat impure, black to gray quartzite is distinctive in being darker than most quartzite in the McCoy Creek Group. It is generally poorly size sorted, contains feldspar and mica, and forms conspicuous cliffs. Both the phyllitic argillite and quartzite typically contain quartz-white mica-biotite-feldspar-epidote-chlorite metamorphic assemblages except in the vicinity of Bettridge Creek where metamorphic assemblages of higher rank are present.

Upper subunit: The upper subunit can be roughly divided into four parts with gradational boundaries. Gray and green metasiltstone and flaggy quartzite containing rare lenses of coarse quartzite make up the lowermost part, which grades upward to a thick sequence of dark phyllitic argillite comprising the second part. Above the dark phyllitic argillite is a distinctive interval of interbedded light-colored marble, metasiltstone, and dark, fine-grained quartzite. The marble is white, tan, dark gray, or blue-gray weathering and slightly micaceous; in places it contains metamorphic epidote and garnet. Intervening beds are dark-gray, green, or brown, micaceous, commonly calcareous quartzite. The uppermost part of the subunit is dark colored, thin- to medium-bedded and cross-laminated, fine-grained metasiltstone and quartzite. Near Bettridge Creek, the upper subunit contains diagnostic metamorphic minerals such as staurolite-garnet-biotite-white mica and andalusite-garnet-biotite-white mica in two common rock compositions (Miller and Hoisch, 1992).

Late Proterozoic and Cambrian

Prospect Mountain Quartzite (€Zpm)

The Prospect Mountain Quartzite is recognized by its great thickness, cliff-forming outcrop style, lithology, and sedimentary structures. The formation is chiefly thick-bedded and prominently cross-laminated gray quartzite. Scattered pebbles of white quartz less than 1 centimeter (0.4 in) in diameter are common, particularly at the base of amalgamated sets of cross-strata. Darker quartzite beds and schistose beds are present near the top and base of the Prospect Mountain, close to overlying and underlying, fine-grained argillaceous rock units. Quartz is partly to completely recrystallized. Detrital plagioclase and microcline compose as much as 20 percent of the rock, and white mica and biotite are common minor components. Detailed descriptions of the Prospect Mountain are given by Miller (1983). The unit is about 955 meters (3,100 ft) thick in the Pilot Range. As restricted by Misch and Hazzard (1962), the Prospect Mountain Quartzite (€Zpm) comprises the topmost thick quartzite in a sequence of interlayered argillaceous rock and quartzite, the lower part of which they named the McCoy Creek Group.

Where exposures permit, such as south of Bettridge Creek, the Prospect Mountain is divisible into three parts that are not distinguished on the map: a lower white, vitreous, pure quartzite; a middle blue-gray quartzite containing as much as 30 percent feldspar fragments; and an upper gray, thick-bedded, distinctly cross-laminated quartzite. The lower part of the Prospect Mountain is about 100 meters (330 ft) thick, the middle part is about 15 meters (50 ft) thick, and the upper part makes up most of the formation. The upper part ranges in grain size from medium sand to pebble, but for the most part is coarse sand. The quartzite generally consists of quartz with small amounts of metamorphic mica and detrital feldspar. Cross sets are commonly tabular or wedge shaped although festoons were noted at several locations. Beds typically have gravel layers at their base, perhaps representing lag deposits. Distinctive color and grain size mark the uppermost 70 meters (230 ft) of the formation, where many beds are dark gray due to the presence of iron oxide minerals, and conglomerate beds as much as 4 meters (13 ft) thick locally are present. Thick conglomerate sections contain phyllite beds and rip-up wedges of phyllite (originally shale).

The Prospect Mountain Quartzite is herein used as defined by Misch and Hazzard (1962) and further modified by Woodward (1967), Stewart (1974), and Miller (1983). Following Stewart (1974), the Prospect Mountain Quartzite is considered to be mainly Late Proterozoic in age but also contains Lower Cambrian beds in its upper part.

Cambrian

Killian Springs Formation (€ks)

The Killian Springs Formation is a dark-colored unit forming topographic benches covered by dark soils, in striking contrast to the light-colored cliffs of the underlying Prospect Mountain Quartzite. Two rather different sequences of the Killian Springs are present in the Pilot Peak quadrangle. West of the Pinnacle fault and along the south edge of the quadrangle near the Pilot Peak detachment fault, the unit is undivided and consists mostly of dark-gray and black phyllitic argillite that reflects lower greenschist facies metamorphism. East of Pilot Peak it is metamorphosed to amphibolite facies and is composed of two members: a lower member of black schist and an upper quartzose member.

West of the Pinnacle fault and along the south edge of the quadrangle near the Pilot Peak detachment fault, the lower part of the Killian Springs is mostly homogeneous dark-gray to black, graphitic, phyllitic argillite and metasiltstone; sparse fine-grained metasandstone layers outline bedding. The upper part of the formation consists of slightly calcareous phyllite and siltstone interbedded with laminated, dark-gray limestone in the uppermost 10 to 15 meters (33 to 45 ft). Limestone beds typically are 2 to 10 centimeters (1 to 4 in) thick and interbedded phyllite is 10 to 30 centimeters (4 to 12 in) thick. Disseminated cubes of pyrite are ubiquitous. Metamorphic minerals include fine-grained biotite, muscovite, clinozoisite, and chlorite; coarse-grained muscovite is probably detrital. The base of the Killian Springs is in sharp contact with thick-bedded quartzite of the Prospect Mountain Quartzite, and the top grades into clastic limestone of the lower part of the Toano Limestone.

East of Pilot Peak the Killian Springs Formation is divided into two members. The lower member (€ksl)consists of black, graphitic andalusite schist, compositionally corresponding to the graphite phyllite of the undivided Killian Springs elsewhere in the quadrangle. This member is of uncertain thickness due to faulted contacts, but is roughly 80 meters (260 ft) thick at its thickest exposure.

The quartzose member (€ksq) is a heterogeneous assemblage mainly consisting of interlayered quartzite, impure marble, and calcareous schist. Two marker zones – tan, pelitic schist and black, graphite marble, each about 20 meters (64 ft) thick – help with identifying low-angle faults and large folds. The tan schist contains retrograded porphyroblasts of staurolite, garnet, and andalusite in a matrix of quartz, biotite, white mica, fibrolite, sphene, and plagioclase. The retrograde assemblage of the schist is epidote-chlorite-white mica±biotite. The black marble contains graphite, calcite, and white mica with a trace to abundant tremolite and quartz. The remainder of the quartzose member is thin to medium bedded and consists of interlayered calcareous quartzite, quartzose and/or schistose marble, calcareous schist, and greenschist (metamorphosed siltstone). Tremolite, diopside, hornblende, biotite, andalusite, fibrolite, sillimanite, and white mica are common metamorphic minerals in various composition rocks (Miller and Hoisch, 1992). Only rarely do detrital calcite or feldspar (microcline) grains remain, because the rocks are highly foliated and recrystallized. The upper part of the quartzose member is typically green or brown schist interlayered with schistose marble. Quartz- and calcite-rich beds rapidly decrease in abundance at the base of the quartzose member, where it locally grades(?) into underlying schist of the lower member of the Killian Springs. Where the contact is well exposed, however, beds of the upper member are truncated at the boundary between the members and the lower member pinches out southward. As a result, the contact is interpreted as a fault with little or no disruption locally. The quartzose member is of uncertain thickness due to repetition by folding and faulting, but is roughly 220 meters (720 ft) thick as mapped. The upper quartzose member is lithologically unlike the undivided graphitic phyllite and probably represents a depositional facies change.

The basal contact of the Killian Springs Formation in many places is a fault nearly parallel to bedding planes and of probable small horizontal and vertical separation, because underlying quartzite beds are truncated at low angles and little or no strata are missing. The contact is mapped as a fault only in those locations where significant truncation of section is demonstrable. The Killian Springs is about 300 meters (985 ft) thick at its type section in the northern Pilot Range (McCollum and Miller, 1991), but is structurally thinned to about 125 meters (410 ft) thick at the most intact sections in the southwestern corner of the Pilot Peak quadrangle.

The Killian Springs Formation was formally named by McCollum and Miller (1991), revising the informal term "phyllite of Killian Springs" as used by Miller (1983). The new formation was established to emphasize the contrast between graphitic black phyllite in the Pilot Range and the green siltstone, quartzite, and limestone of the broadly correlative Pioche Formation (Hintze and Robison, 1975), which overlies the Prospect Mountain Quartzite in much of eastern Nevada and western Utah. McCollum and Miller (1991) provisionally regarded the Killian Springs to be Early and Middle Cambrian in age and suggested that the quartzose member correlates with a quartzite in the upper part of the Killian Springs in the Silver Island Mountains, Utah.

Toano Limestone (€t)

The Toano Limestone is impure limestone that varies considerably in appearance within the quadrangle, chiefly due to degree of metamorphism. Near the Pilot Peak detachment, it is slightly metamorphosed silty limestone, whereas on the lower flank of the range east of Pilot Peak, it is schistose marble.

Near the Pilot Peak detachment, where the formation is only slightly metamorphosed, it is characteristically thin bedded to laminated. The lower part of the section is mainly medium-gray, laminated limestone with tan dolomitic laminations and interbeds. Sparse calcareous quartzite beds also are present. Rocks of the lower part grade upward into very thinly bedded, tan, silty limestone and fissile, gray calcareous and graphitic phyllite. Both upper and lower parts of the unit contain disseminated cubes of pyrite. In this area, metamorphic minerals are muscovite and chlorite. The base of the unit is drawn at the top of the uppermost dark, calcareous phyllite bed of the underlying Killian Springs Formation. Due to tight folding and strong cleavage, as well as faulting of the upper part of the unit, no estimate of its thickness can be made. The Toano is 850 meters (2,790 ft) thick in the type section in the Toano Range 15 kilometers (9 mi) to the west (McCollum and Miller, 1991).

East of Pilot Peak, the Toano consists of white to tan or gray, slightly micaceous marble, schistose marble, calcareous schist, and minor calcareous quartzite. It forms white, tree-covered slopes. Metamorphic minerals include white mica, biotite, hornblende, sphene, and tremolite. The unit is strongly foliated at low angles to bedding, and is tightly folded in places. In this area, the marble appears to gradationally overlie schist assigned to the Killian Springs Formation, and therefore we assign the marble to the Toano Limestone. The partial section east of Pilot Peak is estimated to be about 330 meters (1,080 ft) thick where least affected by large folds. The top of the unit is in fault contact with sedimentary rocks.

Middle Cambrian trilobites were recovered from the Toano Limestone elsewhere in the Pilot Range area; the type Toano Limestone in the Toano Range is considered to be Middle Cambrian in age (McCollum and Miller, 1991).

Cambrian(?)

Limestone (€l)

Two isolated exposures of ooidal limestone and dolomite lie near the foot of the range east of Pilot Peak. Limestone is dark blue gray to medium gray and fine to medium grained, with silt and shale partings. Zones of echinoderm and brachiopod remains are common, but no diagnostic forms were identified that permit a more precise age assignment than Paleozoic (table 1, no. 1). The limestone is faulted against marble and schist of the Toano Limestone to the west and probably underlies, or is faulted against, Ordovician rocks that crop out to the east on the pediment. The unit is about 20 meters (65 ft) in minimum thickness. Based on general similarity with Middle and Upper Cambrian rocks south of the Pilot Peak quadrangle, we consider the limestone unit to be Cambrian(?) in age.

Cambrian and Ordovician

Notch Peak Formation (O€np)

The Notch Peak Formation consists mainly of massive gray limestone and less common brown, silty limestone, and is similar to massively bedded parts of the upper Garden City Formation (exposed south of the Pilot Peak quadrangle). The unit is locally pisolithic and in places contains chert nodules irregularly positioned along bedding planes. Pisoliths and vertical algal buildups serve to distinguish the unit from the Garden City Formation. It is exposed above the Pilot Peak detachment fault near the southern border of the quadrangle. About 180 meters (520 ft) of the Notch Peak is present in the Pilot Peak quadrangle.

Only the upper part of the Notch Peak is present in the quadrangle; most of the formation is truncated by the detachment fault. We follow McCollum and Miller (1991) in assigning the upper part of the Notch Peak a Late Cambrian and earliest Ordovician age.

Ordovician

Garden City Formation (Ogc)

The Garden City Formation consists mainly of cleaved, thinly bedded, gray limestone with interbedded zones of brown, silty limestone. Rare beds of calcareous quartz sand and beds containing abundant brown chert nodules also are present. The Garden City is medium gray to bluish gray, thick to thin bedded, and contains shaly laminae or mottled texture. It is fossiliferous, and contains rare beds with abundant white, light- to dark-gray, and tan chert lenses. It is exposed in fault-bounded blocks above the detachment fault and along both sides of the Pilot Range in the southern part of the quadrangle. Partial thickness of the Garden City in the Pilot Peak quadrangle is about 200 meters (655 ft), but the top of the section is faulted.

Conodonts from the Garden City in a fault block west of the main range are middle to late Early Ordovician age (table 1, no. 2). Rocks in this fault block are lithologically similar to other rocks assigned to the Garden City. The rocks are correlated with the type Garden City of the Bear River Range on the basis of lithology and fauna.

Kanosh Shale (Ok)

Isolated exposures of the Kanosh Shale east of Pilot Peak consist of bench-forming, green and brown, calcareous siltstone with thin interbeds of gray-brown limestone. The Kanosh lies between the Garden City Formation and the Lehman Formation, and is about 92 meters (302 ft) thick, but its base is not exposed and its top is covered by a narrow talus zone. Another exposure of possible Kanosh, a short distance to the north, could not be verified by fossils. These rocks are correlated with the type Kanosh of central Utah on the basis of lithology and stratigraphic position.

Lehman Formation (Ol)

The Lehman Formation consists of medium-gray, silty to pure, thin-bedded limestone. The partial section exposed is approximately 61 meters (200 ft) thick. It lies between the Eureka Quartzite and the Kanosh Shale in a single exposure east of Pilot Peak. The upper part of the unit contains dark dolomite and sandy, silty, and pure limestone, which apparently led O'Neill (1968) to assign it to the Crystal Peak Dolomite; alternatively, this lithologic association has been assigned to part of the Swan Peak Formation in the Silver Island Mountains (Miller, 1990b). We did not distinguish the unit from the Lehman because of its minimal outcrop in the Pilot Peak quadrangle. We correlate the rocks to the type Lehman in the Snake Range, Nevada, on the basis of lithology and stratigraphic position.

Eureka Quartzite (Oe)

The Eureka Quartzite forms prominent, white, resistant outcrops where present in a fault slice in the southwest corner of the quadrangle and in faulted exposures near the Bonneville shoreline east of Pilot Peak. It consists of white, vitreous orthoquartzite and lesser bluish-gray or charcoal-gray orthoquartzite. It is exceptionally well-sorted, consisting of well-rounded, medium sand-sized grains in a silica cement. Recrystallization and stress solution have altered the size and shape of grains locally. In the quadrangle, it typically is highly fractured. Thickness of the incomplete Eureka section is 150 meters (490 ft). It is correlated with the type Eureka Quartzite near Eureka, Nevada, by lithology and stratigraphic position.

Ely Springs Dolomite (Oes)

The Ely Springs Dolomite consists of black to dark-gray, calcareous dolomite. It lies on the Eureka Quartzite in the southeastern and southwestern corners of the quadrangle. Rocks

Table 1.
Paleontologic data for the Pilot Peak quadrangle

Map no.	Field (USGS) no.	Rock unit	Fossil age	Date of report	Paleontologist	Faunal description	Latitude	Longitude
1	P80PR-10	Limestone	Early Paleozoic	1/29/81	J.E. Repetski, A.K. Armstrong	600 g processed for conodonts; no fossils were recovered. However, large calcite crystals in the lime-mud matrix are probably echinoderm remains. Outlines of brachiopod shells and long hollow spines are common. There is nothing age-diagnostic in the sections, except the sample is Paleozoic and probably early Paleozoic.	41°01'08"	114°01'45"
2	M79PR-51 (9141-CO)	Garden City Formation	Early Ordovician	3/4/80	J.E. Repetski	230 g sample processed; hundreds of conodont elements were recovered, of which the following are most significant: *Acodus deltatus* (Lindstrom) acodontiform, drepanodontiform, distacondontiform, trichonodelliform, oistodontiform elements *Drepanodus arcuatus* Pander pipaform, sculponeaform elements *D.* spp. s.f. *Oistodus* n. sp. *Paroistodus proteus* (Lindstrom) drepanodoniform elements *Protopanderodus*? sp. *Scandodus* spp. s.f. "*Scolopodus*" *gracilis* Ethington and Clark triangulariform elements *S. pseudoquadratus* Branson and Mehl s.f. *Triangulodus*? sp. triangulodontiform, erect scandodontiform elements *Walliserodus*? cf. *W. ethingtoni* (Fahraeus) Age is middle to late Early Ordovician; the assemblage most likely represents the lower Arenigian (British Series) *Paroistodus proteus* or *Prioniodus elegans* Zone, or the Ibexian Series (North American Midcontinent province conodont fauna D or possibly E). CAI=5.	41°00'11"	114°06'45"
3	L79PR-61 (10163-SD)	Simonson Dolomite	Early to Late Devonian	2/4/80	A.G. Harris	1.4 kg was processed and yielded the following conodonts: *Pandorinellina insita* (Stauffer) or *P. exigua* (Philip) 5 Pa and 3 Sa elements 32 indet. bar, blade, and platform fragments Age range is late Early Devonian through much of the Late Devonian. CAI=5	41°00'34"	114°07'12"
4	M79PR-53 (10162-SD)	Guilmette Formation	Middle to Late Devonian	2/4/80	A.G. Harris	1.6 kg of sample processed and yielded the following conodonts: 2 Pb element fragments of Frasnian morphotype 4 Pa elements of *Polygnathus decorosus* s.l. (Ziegler, 1965) 2 Pb and 1 Sc unassigned elements 28 indet. bar, blade, and platform fragments Age range is latest Middle Devonian through most of the Frasnian; age is probably Frasnian. CAI=5.	41°00'05"	114°07'08"
5	L79PR-63 (10057-SD)	Guilmette Formation	Middle or Late Devonian	1/29/80	W.A. Oliver, Jr.	This sample contains a part of a colony of a colonial rugose coral. The coral is a disphylloid but may have some peneckielloid dissepiments, and is probably *Disphyllum*? sp. It is Middle or early Late Devonian in age, and more likely Frasnian than Middle Devonian because of its morphology.	41°00'17"	114°07'22"
6	M84PR-39 (29555-PC)	Joana Limestone	Early Mississippian (Kinderhookian)	2/19/85	K.S. Schindler, A.G. Harris	5.2 kg of limestone yielded the following conodonts: 7 Pa elements of *Gnathodus delicatus* Branson & Mehl. 1 Pa element of *Hindeodus crassidentatus* (Branson & Mehl) 1 Pa element of "*Ozarkodina*" sp. (long-bladed morphotype) 13 Pa elements of *Polygnathus communis communis* Branson & Mehl 1 Pa element of *Siphonodella crenulata* (Cooper) *Siphonodella isosticha-S. Obsoleta* Hass 3 Pa, 4 Pb, and 1 Sc elements 1 M, 2 Sa, and 6 Sc unassigned elements 58 indet. bar, blade, and platform fragments Age is late Kinderhookian; lower part of *isosticha*-Upper *crenulata* Zone. CAI=4.5 to 5.	41°00'03"	114°07'17"

Table 1 (continued)

Map no.	Field (USGS) no.	Rock unit	Fossil age	Date of report	Paleontologist	Faunal description	Latitude	Longitude
7	M84PR-126	Joana Limestone	Latest Devonian or Early Mississippian	2/19/85	K.S. Schindler, A.G. Harris	3.9 kg of limestone yielded the following conodonts: 2 Pa elements of *Patrognathus* sp. 1 unassigned Sc element 15 indet. bar and blade fragments Age is middle Famennian to Kinderhookian. CAI=5 to 5.5.	41°00'08"	114°07'23"
8	M84PR-127 (29390-PC)	Joana Limestone	Early Mississippian (Kinderhookian)	12/20/84	O.L. Karklins, A.G. Harris	2.5 kg of cherty limestone yielded the following conodonts: 5 Pa, 4 S elements *Hindeodus crassidentatus* (Branson & Mehl) 1 Pa element "*Ozarkodina*" sp. (long-bladed morphotype) 11 Pa elements *Polygnathus communis communis* Branson & Mehl 26 Pa elements *Polygnathus inornatus* E.R. Branson 1 Pa element *P. symmetricus* E.R. Branson 47 Pa, 6 Pb, 1 M, 4 S elements *Siphonodella isosticha* (Cooper) 110 indet. bar, blade, and platform fragments Age is upper part of Lower *crenulata* through Upper *crenulata-isosticha* Zones, which is late Kinderhookian. CAI=4.5.	41°00'04"	114°07'21"
9	M84PR-128 (29391-PC)	Joana Limestone	Early Mississippian (Kinderhookian)	12/20/84	O.L. Karklins, A.G. Harris	2.8 kg of limestone yielded the following conodonts: 2 Pa elements *Polygnathus communis* Branson & Mehl 1 Pa element *Polygnathus* sp. 10 Pa (adult), 18 Pa (juvenile), 6 Pb, 1 M elements *Siphonodella isosticha* (Cooper) 38 indet. bar and blade fragments, and abundant platform fragments Age is upper part of Lower *crenulata* through upper *crenulata-isosticha* Zones, which is late Kinderhookian. CAI=4.5 to 5.	41°00'04"	114°07'21"
10	L79PR-04 (27626-PC)	Ely Limestone	Pennsylvanian	9/4/80 & 6/2/80	J.E. Repetski, O.L. Karklins	Bryozoans in this sample include *Ascopora* sp., and fenestelloids. The known stratigraphic range of *Ascopora* is from Early Mississippian to Early Permian. 181 g were processed and yielded the following conodonts: 2 *Idiognathodus delicatus* Gunnell 2 juvenile Pa elements of ?*Neognathodus* sp. common ramiform fragments Age is Pennsylvanian, probably limited to Morrowan through Desmoinesian. CAI=6 to 7.	41°00'00"	114°02'07"
11	L79PR-06 (27627-PC, 27628-PC)	Ely Limestone	Pennsylvanian	9/4/80 & 6/2/80	J.E. Repetski, O.L. Karklins	Bryozoans in this sample include *Ascopora* sp., *Rhombotrypella* sp., rhabdomesids, fistuliporoids, and fenestelloids. The known stratigraphic range of *Rhombotrypella* is from Early Mississippian to the Permian, and it is abundant in Pennsylvanian and Permian rocks. 308 g from 2 samples were processed for conodonts and yielded: 1 Pa element *Idiognathodus delicatus* Gunnell 4 indet. bar, blade, and platform fragments Age is Pennsylvanian. CAI=7.	41°00'00"	114°02'07"
12	M88PR-19 (12058-SD)	Guilmette Formation	Middle to Late Devonian	11/07/90	A.G. Harris	2.3 kg of rock was processed for conodonts and yielded: 2 S elements of *Pelekysgnathus* sp. indet. 1 robust Pa element of *Polygnathus* sp. of Givetian-Famennian morphotype 1 Pa element fragment of *Polygnathus* sp. indet. 2 unassigned Sc elements (2 morphotypes) 4 indet. bar and blade fragments BIOFACIES: warm, relatively shallow water AGE: Givetian-Famennian, but probably late Givetian-Frasnian. CAI=5	41°00'10"	114°07'23"

of this unit are poorly bedded and highly fractured; the unit is poorly exposed. The Ely Springs in the southeastern corner of the quadrangle is overlain by a low-angle(?) fault block of Mississippian rocks. Due to complex structure, the partial thickness of the unit was estimated as 50 meters (160 ft). The unit is correlated with the type Ely Springs Dolomite in Nevada by lithology and stratigraphic position.

Devonian

Simonson Dolomite (Ds)

The Simonson Dolomite is generally dark-colored, finely laminated, recrystallized dolomite that forms steep slopes. Alternating light- and dark-colored intervals are a hallmark of the Simonson. Most beds are strikingly laminated and cross-laminated, but rare beds are nearly homogeneous due to extensive bioturbation. The uppermost 20 meters (65 ft) of the unit consists of bioclastic beds containing abundant brachiopods, typically in an alternating limestone/dolomite sequence or in shaly limestone. Approximately 185 meters (605 ft) of the Simonson are exposed in an incomplete section.

The Simonson is latest Early and Middle Devonian in age in the northern Pilot Range (Miller and others, 1993). Conodonts low in the exposed sequence in the Pilot Peak quadrangle are late Early Devonian to Late Devonian in age (table 1, no. 3) and compatible with the age of the Simonson in the northern Pilot Range. The unit is correlated with the type Simonson Dolomite of the Deep Creek Mountains, Utah, on the basis of age, lithology, and stratigraphic position.

Guilmette Formation (Dg)

The Guilmette Formation is a thick, cliff-forming limestone unit exposed in the southwest corner of the quadrangle. Interbedded limestone and laminated, light-gray primary dolomite mark the upper part of the unit. Irregular zones of quartzose sand are also present at the top of the Guilmette. It is well-bedded and fossiliferous throughout. The base of the unit is placed above the thin, shaly, fossiliferous limestone beds in the uppermost part of the Simonson Dolomite and at the base of the first thick, cliff-forming bed of limestone of the Guilmette. The top is drawn at the top of the highest laminated dolomite, above which is massive, light-colored limestone of the lower part of the Joana Limestone. About 350 meters (1,130 ft) of the Guilmette is preserved in the quadrangle, but its base is faulted.

The Guilmette is late Middle and Late Devonian in age in the northern Pilot Range (Miller and others, 1993). We recovered a Middle to early Late Devonian coral from the lower part of the unit (table 1, no. 5) and late Middle to early Late Devonian conodonts from the upper part of the unit (table 1, no. 4). Conodonts from the top of the unit are no younger than Frasnian (table 1, no. 12). The unit is correlated with the type Guilmette Formation of the Deep Creek Mountains, Utah, on the basis of age, lithology, and stratigraphic position.

Mississippian

Joana Limestone (Mj)

The Joana Limestone typically forms cliffs above the Guilmette Formation and its lower part is difficult to distinguish from underlying Guilmette. Light-colored, nearly structureless to thick-bedded, non-fossiliferous limestone characterizes the lower part of the Joana. Quartzose sand and primary dolomite in the lithologically similar upper part of the Guilmette are used to distinguish the two. The base of the Joana is drawn above the highest laminated dolomite bed. The upper part of the Joana is more distinctive than its lower part, consisting of fossiliferous, black, coarse-grained limestone that contains black, irregular-shaped chert nodules as long as 30 centimeters (12 in). This coarse limestone locally contains abundant crinoid fragments in its upper part. Maximum thickness of the Joana Limestone is 125 meters (415 ft) in the Pilot Peak quadrangle, but its top is faulted.

In the southern Silver Island Mountains (figure 1), the Pilot Shale lies between the Guilmette Formation and the Joana Limestone (Schaeffer, 1960; Schneyer, 1990), but the Pilot is missing farther north in that range (Schaeffer, 1960). The same unconformity marked by the absence of the Pilot Shale is present in the Pilot Peak quadrangle. Absence of strata representing the uppermost Devonian (see below) requires non-deposition or subsequent erosion.

Conodonts collected from the Joana Limestone in the Pilot Peak quadrangle are mostly or entirely Early Mississippian (Kinderhookian) in age (table 1, no. 6-9). Possible exceptions are conodonts from the basal part of the Joana (no. 7), which are less definitive and permit ages from latest Devonian to Kinderhookian. However, conodonts from the uppermost part of the lower part of the Joana are Kinderhookian (table 1, no. 8). Because no prominent lithic break is present within the lower part of the formation, we consider the entire lower unit to be dated by the precise determinations (Kinderhookian), and therefore the entire Joana is late Kinderhookian in age in this area. The unit is correlated with the type Joana Limestone near Ely, Nevada, on the basis of age and stratigraphic position.

Mississippian and Pennsylvanian

Chainman Shale and Diamond Peak Formation, undivided (IPMcd)

This unit is mainly composed of quartzite; gray, fissile shale; siltstone; fossiliferous limestone; and conglomerate. Clasts in the conglomerate are mostly dark chert and quartzite. Graded arkosic sandstone and fossiliferous, sandy to silty, dark limestone are distinctive. The unit is exposed only in the southeastern part of the quadrangle, where it is in low-angle(?) fault contact with the underlying Ordovician Ely Springs Dolomite. The unit is structurally complex; but its thickness is probably greater than the exposed outcrop width of about 375 meters (1,230 ft). Undivided Chainman Shale and Diamond Peak Formation is correlated with Chainman and Diamond Peak rocks exposed in the Silver Island Mountains (figure 1) on the basis of lithology. The unit is Pennsylvanian and Mississippian in age in the Silver Island Mountains (Schaeffer, 1960; Schneyer, 1984).

Pennsylvanian

Ely Limestone (IPe)

The Ely Limestone consists of highly fossiliferous, argillaceous, dolomitic, and cherty limestone. The unit is a heterogeneous assemblage of (a) medium-gray to brownish-gray, medium- to thick-bedded, fine-grained limestone, (b) brown, thin-bedded, shaly limestone, (c) blue-gray to medium-gray dolomite and dolomitic limestone, and (d) bioclastic limestone. Red-brown chert nodules are common in zones parallel to bedding. The Ely is exposed in the pediment east of Pilot Peak. Immediately south of the Pilot Peak quadrangle, this exposure of Ely is overlain by limestone-chert sedimentary breccia of the Pennsylvanian and Permian Strathearn Formation. In the Pilot Peak quadrangle the base of the Ely is truncated by a north-striking normal fault. Total thickness of the partial section is about 250 meters (820 ft).

Bryozoans from samples collected at the southern border of the quadrangle, about 50 meters (165 ft) stratigraphically below the top of the unit, yielded a Mississippian to Permian age in one case and a Carboniferous age in the other (table 1, nos. 10, 11). Conodonts from the same samples are Pennsylvanian, probably Morrowan to Desmoinesian, in age. The Ely Limestone in the Pilot Range is therefore considered to be Early and Middle Pennsylvanian in age. We correlate the rocks in the Pilot Range with the type Ely Limestone near Ely, Nevada, on the basis of age, lithology, and stratigraphic position.

Jurassic

Miners Spring Granite (Jms)

The Miners Spring Granite forms white, leucocratic, muscovite-biotite granite and pegmatite dikes and small bodies. The dikes crop out widely east of Pilot Peak, and in most cases are nearly concordant with bedding and schistosity in the enclosing metamorphic rocks. The granite, ranging from syenogranite to monzogranite, in many cases is distinguished by the presence of muscovite±garnet and by its foliation. Some dikes are pegmatitic and aplitic with rare mafic minerals. Aplites carry abundant garnet. Muscovite and biotite are probably recrystallized from their primary igneous counterparts. Quartz is completely recrystallized, and margins of feldspar crystals are commonly recrystallized to smaller grains. Minor phases are apatite, zircon, sphene, garnet, and opaque iron oxide. In one thin section, clinozoisite was abundant, but it was not observed elsewhere in the granite. Quartz veins appear to be associated with the pegmatites. Many dikes show tectonic foliations and lineations defined by preferred orientation of micas and partly recrystallized minerals, whereas others appear to cut foliated wallrocks. These relations suggest that some dikes intruded late in a period of ductile deformation.

Most outcrops of the granite are in the metamorphosed Cambrian schist and marble east of Pilot Peak. In most cases, the granite intruded as dikes and small elongate bodies, including some net-veined outcrops south of the Pilot Peak quadrangle. From the broad expanse permeated with dikes we infer an intrusive setting at the top of a mesozonal pluton, from which highly evolved dikes injected the roof rocks. Two dikes east of Cove Springs are pegmatitic, mafic-poor rocks that lack muscovite and are unfoliated; they are questionably included in this map unit.

The age of the Miners Spring Granite is 155 to 165 Ma (table 2, no. 5) on the basis of U-Pb study of zircon (Miller and others, 1987). The K-Ar age on muscovite of 56 Ma (table 2, no. 4) probably represents closure of argon diffusion during early Cenozoic cooling, although post-emplacement heating events and subsequent cooling cannot be ruled out. The Miners Spring Granite in the Pilot Range is Jurassic in age.

Tertiary

Granodiorite dikes (Tg)

Dikes ranging considerably in composition and texture, and distributed over nearly the entire map area, are grouped in this unit. They are approximately granodiorite in composition, and contain biotite, plagioclase, potassium feldspar, and quartz as major phases, and many also contain abundant hornblende and sphene. Minor phases are zircon and apatite. The dikes typically are fine to medium grained, subequigranular, and not foliated. Smaller dikes typically have a medium-gray, aphanitic matrix, a product of rapid cooling. A mafic body about 1.5 kilometers (1 mi) south of Cove Springs contains abundant phenocrysts of plagioclase and oikocrysts of hornblende set in, and enclosing, a finer grained matrix of biotite, hornblende, potassium feldspar, and quartz. Another small mafic body, the easternmost of several on the north side of Bettridge Creek, is biotite-hornblende quartz monzonite and displays chilled margins. The granodiorite dikes generally are slightly to moderately fractured and generally intrude low- and high-angle fault zones. Many dikes strike between north-northeast and east-northeast.

Lithologic similarity with the Eocene Bettridge Creek Granodiorite suggests an Eocene age for many of the granodiorite dikes. The 30 Ma (table 2, no. 8) K-Ar age for biotite from one dike in the Pilot Peak quadrangle supports the inference based on composition, although conventional K-Ar ages on biotite are variable and in some cases show complex Ar loss (Miller and others, 1987). A lithologically similar granodiorite dike that crops out south of the Pilot Peak quadrangle yielded a K-Ar age of 37.5 Ma on biotite (Miller and others, 1987).

Table 2.
*Geochronologic data for the Pilot Peak quadrangle**

Map no.	Sample no.	Sample site Lat.	Sample site Long.	Rock unit	Mineral dated	Age (Ma) K-Ar	Age (Ma) $^{40}Ar/^{39}Ar$	Age (Ma) U-Pb
1	M80PR-43	41°03'38"	114°01'16"	McCoy Creek Group (unit G)	Hornblende	179.7±9.0		
2	M80PR-26	41°02'03"	114°01'33"	Killian Springs Formation	Hornblende Biotite	170.3±5.1 63.9±1.9	149.9±0.9	
3	P80PR-14	41°02'02"	114°02'10"	Killian Springs Formation	Muscovite	83.4±2.5		
4	M79PR-171	41°01'17"	114°01'52"	Miners Spring Granite	Muscovite	56.2±0.8		
5	M80PR-19	41°01'13"	114°01'53"	Miners Spring Granite	Zircon			155 to 165
6	M79PR-85	41°03'57"	114°01'33"	Bettridge Creek Granodiorite	Biotite Hornblende	27.1±0.5 91.2±1.5		
7	M81PR-82	41°03'57"	114°01'31"	Bettridge Creek Granodiorite	Hornblende Zircon	96.4±2.9	[no plateau]	 38.9±0.9
8	M79PR-21	41°01'27"	114°02'24"	Granodiorite dike	Biotite	30.1±0.5		

* All data reported by Hoggatt and Miller (1981) and Miller and others (1987).

Bettridge Creek Granodiorite (Tbc)

The Bettridge Creek Granodiorite is a small pluton of hornblende-biotite granodiorite approximately 1.5 kilometers (1 mi) in length and 0.6 kilometers (0.5 mi) in width. It contains biotite, quartz, plagioclase, potassium feldspar, and hornblende as major phases, and minor amounts of apatite, zircon, and opaque iron oxides. Biotite and quartz grains are deformed. Weakly to moderately developed foliations are inconsistently oriented, which suggests a magmatic origin. Abundant small inclusions of mafic igneous rocks are scattered throughout the pluton and ragged edges on the inclusions suggest partial "digestion" by the granodiorite magma. The pluton is less resistant than adjacent metamorphic rocks and therefore is poorly exposed. The relatively easily eroded rock accounts for the wide, flat-floored canyon north of Bettridge Creek, which contrasts with the steep-walled, V-shaped canyons typical of the range. Satellitic pods and dikes occur within several kilometers of the pluton.

Although conventional K-Ar on hornblende gives ages of 91 to 96 Ma for the Bettridge Creek, suggesting an Early Cretaceous age of intrusion (Hoggatt and Miller, 1981), U-Pb study of zircons and $^{40}Ar/^{39}Ar$ study of hornblende showed that the pluton is 38.9 ± 0.9 Ma (table 2, no. 7) and that hornblende contains excess argon (Miller and others, 1987). The pluton is therefore late Eocene in age.

Felsite (Tf)

Dikes of light-gray felsite crop out in the northern part of the quadrangle. The felsite contains abundant rounded, embayed quartz phenocrysts, and lesser amounts of anhedral plagioclase and alkali feldspar phenocrysts, all set in an aphanitic, pale-gray groundmass. Feldspars in many dikes are altered to clay or sericite. One large dike at the mouth of Marble Canyon contains biotite in addition to quartz and feldspars. The dikes generally strike northward.

Felsite dikes are concentrated in and around the latest Eocene McGinty Monzogranite north of the quadrangle and do not intrude nearby Miocene strata (Miller and others, 1993). Although the felsite may be a late magmatic phase of the McGinty intrusion, the dikes crop out much farther south than the McGinty, suggesting that they are not related spatially or genetically to the pluton. We follow Miller and others (1993) and regard the felsite to be of Oligocene(?) age.

TERTIARY(?) AND QUATERNARY

Oldest Alluvial-Fan Deposits ($QTaf_3$)

Partly consolidated to unconsolidated coarse gravel, sand, and silt underlying extensive, incised geomorphic surfaces along both sides of the Pilot Range are assigned to the oldest alluvial-fan deposits unit. The alluvial-fan morphology and clast composition indicates that the deposits were derived from the Pilot Range in approximately its current physiographic configuration. The deposits throughout most of the map area are characterized by large, white-weathered boulders of quartzite. Thickly laminated pedogenic calcrete is common in the gravel and the unit is overlapped by an alluvial-fan unit (Qaf_2) that is older than upper

Pleistocene deposits of Lake Bonneville. Thick laminae in pedogenic calcrete suggests a middle Pleistocene or older age (Machette, 1985). The geomorphic relations are characteristic of the old alluvial-fan deposits of Christenson and Purcell (1985), which they consider to be generally older than 500,000 years. We consider the oldest alluvial-fan deposits to be Pliocene(?) to middle Pleistocene in age.

The most extensive exposures of the oldest alluvial-fan deposits are east of the Pilot Range. These deposits are more incised southward, progressing from broad, thick deposits with undulating upper surfaces near Bettridge Creek, through smaller, highly incised remnants of once-broad deposits, to remnants overlying a pediment of faulted Paleozoic strata.

Quaternary

Most Quaternary deposits in the Pilot Peak quadrangle are alluvial in origin, primarily representing alluvial-fan complexes built west and east from the Pilot Range. The alluvial deposits are divided on the basis of age and geomorphology into a sequence older than latest Pleistocene Lake Bonneville and one younger than Lake Bonneville. Mass-movement deposits, mostly talus, are widespread in the mountains. Quaternary lacustrine and eolian deposits are also present in the quadrangle but are less widespread.

Older alluvial-fan deposits (Qaf_2)

Poorly sorted gravel and sand underlying the piedmonts flanking the Pilot Range are overlain by deposits of Lake Bonneville and underlain by the Pliocene(?) and Pleistocene oldest alluvium, and so the deposits are early to late Pleistocene in age. The older alluvial-fan deposits are distinguished from oldest fan deposits by less incision, few boulders on flat surfaces, and diminished calcrete development. As presently exposed, the most extensive older alluvial-fan deposits underlie the piedmont west of the Pilot Range, but fans on the east side of the range were probably as large before inundation by Lake Bonneville. The older alluvial-fan deposits unconformably lie on an incised surface cut into the oldest alluvial fan deposits. These relations may indicate an episode of erosion between the deposition of the two alluvial-fan sequences.

Lacustrine and alluvial deposits, undivided (Qla)

At altitudes below the Bonneville shoreline, complexly interlayered deposits of lacustrine and alluvial origins are mapped as undivided lacustrine and alluvial deposits. In most places, this unit consists of thin sheets of lacustrine sand and gravel lying on the older alluvial-fan deposits. In many places, thin alluvium also lies on the lacustrine deposits. The rough topography in alluvium above the Bonneville shoreline contrasts sharply with the smoothly beveled topography below the shoreline where the undivided lacustrine and alluvial deposits lie. Lacustrine and alluvial deposits east of the Pilot Range, which formed on a steep piedmont facing the main body of Lake Bonneville, are marked by numerous small shorelines imparting a striped appearance to aerial photographs of the landscape. Lacustrine and alluvial deposits west of the range formed on gentle piedmont topography in a restricted embayment of Lake Bonneville. The deposits consist of broad, thin patches of sand and silt and represent reworked alluvium deposited in lower energy environments than those east of the Pilot Range. This unit encompasses deposits of Holocene and Pleistocene age.

Lacustrine gravel (Qlg)

Lacustrine gravel was deposited along shorelines of Lake Bonneville along the east margin of the quadrangle. Gravel accumulations mainly represent the high stand of Lake Bonneville about 1,591 meters (5,220 ft) altitude (the Bonneville shoreline [-B-]), but, in the southeast corner of the quadrangle, gravel deposits at 1,480 meters (4,855 ft) represent the Provo shoreline [-P-] and deposits at 1,573, 1,562, 1,548, and 1,518 meters (5,160, 5,125, 5,080, and 4,980 ft) represent intermediate shorelines. West of the Pilot Range the Bonneville shoreline is about 1,585 meters (5,200 ft). Different altitudes on different sides of the range are due to differential isostatic uplift. The lake was at its maximum depth at roughly 16,000 years ago and lowered to levels outside of the quadrangle before the end of the Pleistocene (Scott and others, 1983; Currey and others, 1984). Gravel supply from alluvial and fluvial detritus derived from Pilot Peak appears to control the site of greatest lacustrine gravel accumulation.

Lacustrine fines (Qlf)

The lacustrine fines unit is composed of clay, silt, and sand that form slightly vegetated, light-colored patches in the northwestern Pilot Peak quadrangle. The unit probably was deposited by low-energy lake currents near the shorezone in the shallow lake on the west side of the Pilot Range.

Lacustrine sand (Qls)

Well size-sorted sand deposits lie near the Bonneville shoreline north of Bettridge Creek. The sand deposits are as much as 3 meters (10 ft) thick and form part of a fining-upward transgressive sequence of gravel to sand and locally to unmapped fines. This sequence is typically capped by thin regressive gravel.

Lacustrine marl (Qlm)

Lacustrine marl, although composed of relatively pure marl in many places in the Pilot Range area, is impure at the lone outcrop in the southeastern Pilot Peak quadrangle. There the unit contains much clay, silt, and sand because it was deposited in the shorezone.

Talus and colluvium (Qmt)

Talus and colluvium deposits are common along many steep slopes in the Pilot Range. Particularly abundant and blocky talus deposits lie on slopes underlain by the Prospect Mountain Quartzite. One unusually large talus slope that heads just south of "Pilot Pk Az" is 1,160 meters (3,800 ft) in vertical extent. It contains lobate features and closed depressions in its lower reaches, possibly indicating ice-aided transport. Along the lower parts of talus slopes the talus deposits are gradational with colluvium consisting of conglomerate, gravel, and sand. Colluvium generally supports vegetation, whereas talus contains little fine material between talus blocks and supports little vegetation.

Landslide deposits (Qms)

Disaggregated talus and colluvium forms hummocky small landslides in several places in the northern Pilot Peak quadrangle. Ages of these landslides are limited only as Quaternary, since they formed on current topographic surfaces and are partly overlapped by Holocene colluvium. Many of the landslides on the west side of the Pilot Range are spatially associated with springs, some of which form lines, suggesting control by youthful faults. The more obvious lineaments are shown on the map, but others may be present.

Huge detached masses of coherent bedrock and of jumbled bedrock are mapped as gravity-slide blocks. Several gravity-slide blocks of jumbled bedrock are present along the west side of the Pilot Range and two crop out along the crest of the range. Two gravity slides near and south of Debbs Canyon are overlapped by middle Pliocene(?) to Pleistocene alluvial deposits ($QTaf_3$), suggesting that the gravity slides are Pliocene or older in age. The gravity slide masses appear to overlie range-front faults.

Younger alluvial-fan deposits (Qaf_1)

Stream and fan deposits of poorly sorted gravel, sand, and silt are mapped as younger alluvial-fan deposits. They are cut across lacustrine deposits at the Bonneville shoreline, and are therefore mostly or entirely Holocene in age. These stream and fan deposits are found as alluvial fans at mouths of canyons and gullies, as alluvial floodplains bordering streams, and as sediments in stream channels. Channels containing these youngest alluvial deposits have been cut into the older (Qaf_2) and oldest ($QTaf_3$) alluvial-fan deposits. Likewise, fans consisting of younger fan deposits overlap the older and oldest fan deposits.

Alluvial and eolian deposits (Qae)

Unconsolidated alluvial and eolian deposits of moderately sorted fine sand, silt, and clay lie along the axis of Pilot Creek Valley (mostly west of the Pilot Peak quadrangle). These deposits are restricted to altitudes above the Provo shoreline. They represent interbedded fine-grained alluvium deposited in the distal parts of alluvial-fan systems, eolian material reworked from lacustrine marl and sand, and alluvial floodplain material from Pilot Creek. The alluvial and eolian deposits overlie lacustrine marl, as well as the undivided lacustrine and alluvial deposits (Qla), and interfinger with the youngest alluvial-fan deposits (Qaf_1).

Alluvial mud (Qam)

Unconsolidated alluvial mud and silt with subordinate fine sand were deposited by a combination of alluvial and lacustrine processes due to ponding behind an unbreached barrier beach of Lake Bonneville located 1 kilometer (0.6 mi) north of Bettridge Creek. This area contains standing water during periodic rainfall.

GEOLOGIC OVERVIEW OF THE PILOT RANGE

Many of the key relations for interpreting the geologic history of the Pilot Range lie in the Pilot Peak quadrangle, and the history of the Pilot Range in turn is key for understanding the tectonic evolution of northwestern Utah. Indeed, many regional events are directly dated only in the Pilot Range, where igneous and metamorphic minerals are present and amenable to radiometric dating techniques. For these reasons, we provide in this section a synopsis of the geologic evolution of northwestern Utah by focussing on the Pilot Range.

In general, the geologic evolution of the Pilot Range can be conveniently described within the framework of several major geologic time intervals: Precambrian, Paleozoic, Mesozoic, Tertiary, and Quaternary. Of these intervals, the events recorded in the Pilot Range are particularly informative for the Mesozoic Era and Tertiary Period; these events will be emphasized. Recent regional geologic descriptions of the northeastern Great Basin (Miller, 1990a), Nevada (Stewart, 1980), and Utah (Hintze, 1988) provide additional information.

Precambrian

Archean and Early Proterozoic metamorphic, sedimentary, and igneous rocks underlie northwestern Utah and form the basement upon which Late Proterozoic to Triassic sedimentary sequences were deposited. A poorly constrained east-trending boundary between Archean crust to the north and Early Proterozoic crust to the south lies near latitude 40°N. This boundary is identified on the basis of isotopic signatures in Phanerozoic granitoids (Stacey and Zartman, 1978; Lush and others, 1988; Wright and Wooden, 1991). Archean crystalline rocks crop out in the Albion, Raft River, and Grouse Creek Mountains of northern Utah and adjacent Idaho (Armstrong and Hills, 1967; Armstrong, 1976; Compton and others, 1977), farther west in the East Humboldt Range of north-central Nevada (Lush and others, 1988), and in the Farmington Canyon Complex in the Wasatch

Range and on Antelope Island (Hedge and others, 1983; Bryant, 1988). The boundary between Archean and Early Proterozoic crust lies near, and probably south of, the Pilot Range. Miller and others (1987) found inherited zircons in a Tertiary granite in the Pilot Range that are between 1,800 and 3,470 million years old. The Pilot Range data are not precise enough to determine whether Archean or Proterozoic crust underlies the rocks exposed in the range.

The Archean and Early Proterozoic craton was rifted during the Late Proterozoic – and perhaps during the early Middle Proterozoic – (Stewart, 1972; Stewart and Poole, 1974), forming a westward-facing continental margin in western Utah that received voluminous sediments until the Triassic. The Late Proterozoic siliciclastic rocks in the vicinity of the Pilot Range, assigned to the McCoy Creek Group and the Prospect Mountain Quartzite, are greater than 3,975 meters (13,040 ft) thick, and record fluvial and shallow marine deposition. Rapid lateral thickness and facies changes in some stratigraphic units support a rift-basin interpretation for their depositional sites.

Paleozoic

Paleozoic strata were deposited conformably on Late Proterozoic strata in the Pilot Range area, but they represent a nearly permanent shift to shallow marine carbonate (miogeoclinal) deposition. Three episodes of siliciclastic sedimentation (some with erosion) that were caused by tectonic disturbances interrupted the carbonate sedimentation that prevailed during most of the Paleozoic. (1) The latest Devonian-Mississippian Antler orogeny produced a thick wedge of siliciclastic rocks in eastern Nevada and western Utah that was derived from highlands to the west (Poole, 1974). (2) A widespread Middle to Late Pennsylvanian unconformity in northwestern Utah (Steele, 1960; Marcantel, 1975) may reflect orogenic disturbances to the west (Ketner, 1977). Alternatively, it may represent uplift west of the Oquirrh basin, one of several basins formed during the ancestral Rockies orogeny (Miller and others, 1991). (3) The Early Triassic Sonoma orogeny resulted in a widespread unconformity between mid-Permian and Lower Triassic rocks (Collinson and others, 1976).

Mesozoic

Mesozoic marine sedimentation ended by the Late Triassic, after which the sedimentary record in the miogeocline is sparse. Isolated exposures of Triassic to Lower Jurassic nonmarine sedimentary rocks in the Currie Hills, Nevada, may be remnants of a widespread sequence coextensive with the lower Mesozoic continental sequence of the Colorado Plateau (Stewart, 1980), indicating that pronounced tectonism in the northeastern Great Basin did not begin until the mid-Jurassic. The major regional unconformity on early Mesozoic strata records profound Mesozoic and Cenozoic tectonism.

Late Jurassic plutons provide the best markers for assessing the ages of middle Mesozoic structures and provide clues to lower crustal and mantle processes that generated the magmas. Jurassic plutons and dikes across the northeastern Great Basin indicate a widespread magmatic event (Miller, 1990a). Most plutons are dated at 155 to 165 Ma by U-Pb on zircon and K-Ar (Miller and others, 1987; Miller and others, 1990). Most plutons were emplaced at depths of about 6 to 8 kilometers (3.7-5 mi) on the basis of reconstructed stratigraphy above the wallrocks and aluminum-in-hornblende geobarometry. Deeper plutons in the Pilot and Toano Ranges (12-13 kilometers; 7-8 mi) are also at depths consistent with the reconstructed stratigraphy of wallrocks (Miller and Hoisch, 1992).

Most Jurassic plutons are composed of alkali-enriched hornblende-biotite granodiorite, but compositions vary, with felsic granite in the Pilot Range and mafic diorite, monzodiorite, and quartz monzonite in several mountain ranges. Initial Sr ratios (mostly 0.705 to 0.707) and $^{\epsilon}$Nd values (-4.5 to -8.6) for Jurassic plutons (Stacey and Zartman, 1978; Farmer and DePaolo, 1983; Miller and others, 1989; Wright and Wooden, 1991), whether felsic or mafic, are only slightly more evolved than bulk earth, which is more typical of granitoids melted from primitive crust or mantle than of granite and granodiorite that was derived from Precambrian crust. Miller and others (1989) suggested that these isotopic and geochemical signatures, coupled with the alkalic compositions and common association with normal faults, indicate a rift-related environment for emplacement much like a back-arc but without basinal sediments.

In the southern Pilot Range, low-angle normal faults subparallel to bedding, large-scale folds overturned to the southeast, thrust faults, and upper greenschist to amphibolite facies metamorphism all are of Jurassic (150 million years) age. The low-angle normal faults thin the stratigraphic section but are synmetamorphic and associated with overturned folds and thrust faults, a relation that Snoke and Miller (1988) interpreted as thrusting associated with regional shortening. Metamorphism was approximately coeval with pluton emplacement (Miller and Hoisch, 1992) and probably caused by heat derived from the magma. Although thrust faults and folds indicate Jurassic shortening, the total shortening apparently was small. Indeed, in nearby ranges in Utah, tectonic extension took place at the same time (Miller and Allmendinger, 1991).

The fold and thrust belt that crops out in central to northern Utah is probably Early Cretaceous to Eocene in age, and major thrusts from that belt must pass west at depth. However, few thrust faults are observed west of the belt. Instead, low-angle faults that are nearly parallel to bedding and that place younger rocks over older or do not disrupt the stratigraphic sequence are widespread. These low-angle faults are undated in most places, but in a few cases are Mesozoic in age and in some cases are associated with overall shortening parallel to bedding (Allmendinger and Platt, 1983). The distinction between Mesozoic low-angle faults and Cenozoic extensional faults, which have the same younger-over-older geometric relations, is problematic (Armstrong, 1972; Allmendinger and Platt, 1983).

Probable Early Cretaceous tectonism in the hinterland is widely described in the literature but is rarely proven. Several low-angle faults, many of which place younger rocks over older, are assumed to be Mesozoic in age but are not accurately dated (Allmendinger and others, 1984). Widespread greenschist and amphibolite facies metamorphism in the Albion Mountains, and probably also the Grouse Creek and Raft River Mountains, may be Early Cretaceous in age (Armstrong, 1968b, 1982) on the basis of Late Cretaceous K-Ar cooling ages on metamorphic minerals.

The best established Late Cretaceous structures from the hinterland are in the Black Pine Mountains and eastern Raft River Mountains, where Wells (1988, 1992; Wells and others, 1990) documented metamorphism, recumbent folds, and low-angle faults that are late Early Cretaceous. Some of these structures indicate extension and explain the consequent cooling in the Late Cretaceous. Moderately dipping ductile normal faults in the Pilot Range may also be mid-Cretaceous.

Although few documented structures of Late Cretaceous age are known in northwestern Utah, many metamorphic rocks record Cretaceous cooling by K-Ar ages on micas. Miller and others (1987, 1990) showed that K-Ar mica systems were set between 88 and 62 million years ago in many ranges. Late Cretaceous granitoids are widespread in the Great Basin but only one is documented in the northeastern Great Basin (Toano Range; Miller and others, 1990), making heating by magmas an unlikely cause for the widespread Late Cretaceous K-Ar ages.

One interpretation of the coincident cooling across the belt and the juxtaposition of deep and shallow metamorphic facies roughly along the Nevada-Utah border is that a major thrust fault rooted in the lower crust beneath the metamorphic belt emplaced the metamorphic rocks eastward over cold rocks (Armstrong, 1982). The Late Cretaceous timing for this cooling and postulated thrusting coincides with major thrusting to the east in the frontal thrust belt, suggesting a possible link between the hinterland and thrust belt structures (Miller and others, 1987). An alternative interpretation is that upper-crustal tectonic and erosional denudation may have rapidly cooled a thickened crust. The Cretaceous cooling by extensional denudation described by Wells and others (1990) supports this model. A critical constraint for all models is the lack of major angular unconformities beneath early Tertiary rocks across the eastern Great Basin, limiting deformation near the surface to broad folding and minor faulting and limiting the amount of Paleozoic and Triassic rocks eroded to less than 2 or 3 kilometers (1.2-1.8 mi) over much of the northeastern Great Basin (Armstrong, 1968a).

Tertiary

During Tertiary time, extensional tectonics affected virtually all of northern Utah, producing a number of distinctive structural, magmatic, and sedimentary characteristics that largely control the surface of the Earth at present. The extensional tectonics can be broadly divided into two events with differing attributes.

Hallmarks of an Eocene and Oligocene extensional event are low- and high-angle normal faults, broad sedimentary basins, andesitic and rhyolitic volcanism, and widespread epizonal plutons. Sedimentary basins, many of which contain only a few hundred meters (less than a thousand feet) of sedimentary and volcanic rocks, apparently were many tens of kilometers (tens of miles) wide. Many volcanic and intrusive rocks across northern Utah range in age from 41 to 33 million years and define a southward-transgressive sweep of volcanism noted by many studies (for example, Lipman and others, 1972; Best and others, 1989). A later plutonic pulse, spatially restricted to granitoids in the exhumed, but originally deep-seated, footwall rocks of the metamorphic core complexes, is late Oligocene in age.

In the Pilot Range, the Pilot Peak detachment fault places highly faulted and generally unmetamorphosed Paleozoic rocks on metamorphosed Late Proterozoic and Cambrian rocks (Miller and others, 1987). The detachment is intruded by sills of latest Eocene (~40 million year old) granodiorite, limiting its age to Eocene or older. By analogy with detachment models for the Egan Range in Nevada (Gans and Miller, 1983), the detachment fault was probably active during the time of latest Eocene magmatism and the several sets of normal faults in its hanging wall that accomplish eastward tilting of strata were coeval with the detachment. The pattern of hanging-wall faults indicates down-to-the-west normal faulting and strata juxtaposition across the detachment, corroborating the westward movement of the hanging wall. Despite the evidence for large extensional strain in the Pilot Range area, uppermost Eocene sedimentary rocks only locally show lithofacies indicating faulted basin margins and topographic relief (Miller and others, 1993).

The Eocene and Oligocene event is distinguishable from late Miocene to present extension by several features: basins were broader and their margins probably did not have high relief, few thick basin-fill sequences formed, magmatism was mainly intermediate to felsic, and extension apparently was strongly localized. A hiatus between the last magmatism and extension of the Eocene and Oligocene event about 25 million years ago and the initiation of the basin-and-range event in the late Miocene (~17 million years ago) is suggested by the sparse rock record for that interval.

The Basin and Range Province is characterized by north-trending mountain ranges separated by narrow basins, widespread volcanic rocks, high heat flow, high average elevation, low Bouguer gravity, active faulting, and thin lithosphere (Stewart, 1978; Eaton and others, 1978; Smith, 1978; Zoback and others, 1981). Davis (1979) and Zoback and others (1981) considered 15 to 17 million years to be the approximate time that basin-and-range faulting was initiated. During about the same 17 million year interval, the formation of the eastern Snake River Plain was initiated by downsagging of the crust and a tremendous outpouring of rhyolite, followed by basalt (Armstrong and others, 1975). Although many volcanic rock ages are not known, some data point to a time-transgressive eastward progression of volcanism across northern Utah (Smith and Nash, 1976), much like that documented for the Snake River Plain. Wide basins in northern Utah are internally segmented by many faults (Cook and others, 1964; Mikulitch and Smith, 1974; Zoback, 1983); these and many narrow basins contain thick Quaternary sedimentary prisms that indicate neotectonic activity. In general, Miocene sequences in northern Utah contain abundant volcanic and volcaniclastic rocks, whereas Pliocene and Quaternary sequences contain less volcanic material.

Many lithologic types and sequences of diverse ages have been lumped together in the Tertiary Salt Lake Formation in northern Utah and southern Idaho, leading to much confusion in the application of that name. The Salt Lake Formation in many places consists of lower conglomerate; middle tuff, sandstone, mudstone, and limestone; and upper conglomerate or volcanic rocks (Heylmun, 1965). The most recent work in the northeastern Great Basin suggests that most sequences consist of reworked volcanic sediments and interlayered rhyolite ash, shale, and limestone that were deposited in many long, narrow, internally segmented basins that were 10 to 20 kilometers (6-12 mi) wide. Most of these sequences are strictly Miocene in age because they are unconformably overlain by lava flows 8 to 12 million years old, such as in the Pilot Range area (Armstrong, 1970; Miller, 1984). Other basins received continuous detritus into the Pliocene and Quaternary. Thicknesses of the basin fill, estimated from surface exposures of tilted Miocene strata and from drill holes in basins, are as much as 4 to 5 kilometers (2.5 to 3.5 mi) (Sacks and Platt, 1985) and commonly 2 to 3 kilometers (1.5 to 2 mi) (Zoback, 1983; Bortz and others, 1985).

The little information available on depositional environments for Miocene and Pliocene strata suggests tectonically active settings. In many places lacustrine deposits interfinger with alluvial and fluvial conglomerate, suggesting rapidly subsiding, closed depressions with high-relief margins. The common presence of huge surficial gravity-slide blocks also suggests tectonically active settings.

Quaternary

The Pilot Range area has remained tectonically active throughout the Quaternary. It is near the Intermountain seismic belt, a concentration of seismicity comprising a broad zone from Yellowstone southward along the Wasatch Front and on to the south (Smith and Sbar, 1974) that coincides with the locus of many Holocene fault scarps. The entire Basin and Range Province has scattered seismicity and probable Quaternary faults are known throughout most of the northwestern Utah including near the Pilot Range.

The valleys around the Pilot Range have experienced several episodes of lacustrine deposition. Glacial lakes in the Bonneville and nearby basins are known mainly from upper Pleistocene lacustrine deposits, although Pliocene and early and middle Pleistocene lakes existed (Oviatt and Currey, 1987). These lakes outline several neotectonic basins.

METAMORPHISM

All bedrock in the Pilot Peak quadrangle shows evidence for elevated temperatures. Paleozoic strata above the Pilot Peak detachment locally carry metamorphic sericite, and conodonts from carbonate rocks yielded color alteration indexes of 5 to 7, indicating minimum temperatures of 300 to 450°C (table 1). However, none of these rocks displays tectonite fabrics or other features typical of regional metamorphism as do rocks in the footwall of the Pilot Peak detachment. Metamorphism in the footwall rocks ranges from lower greenschist to upper amphibolite facies. The age of footwall metamorphism is Mesozoic, on the basis of intrusive relations and K-Ar ages of metamorphic minerals.

Assemblages

Metamorphic assemblages in rocks below the detachment indicate generally lower greenschist facies on the west side of the Pilot Range and upper greenschist to upper amphibolite facies on the east side (Miller and Hoisch, 1992). The differently metamorphosed rocks of the two sides of the range are separated approximately by the Prospect Mountain Quartzite in the south and the Pinnacle fault in the north. The Prospect Mountain Quartzite does not contain suitable mineral assemblages for identifying metamorphic conditions. Because about 60 percent of the rock below the detachment is too calcareous or quartzose to provide suitable mineral assemblages, we were unable to map isograds; however, general trends in metamorphic grade were evident.

Along the west side of the Pilot Range, semi-pelitic rocks, now slate and phyllite, contain assemblages (white mica-epidote-chlorite-biotite) indicating lower greenschist facies metamorphism; micaceous carbonate rocks contain tremolite or garnet; and quartzite and strongly quartz-rich rocks are recrystallized but contain less diagnostic mineral assemblages such as white mica±biotite. Chlorite porphyroblasts in the presence of quartz were noted in most pelitic rocks, indicating that metamorphism was not in the amphibolite facies. The texturally coarsest rocks on the west side of the range crop out between Cove Springs and Debbs Canyon. These phyllites are fine grained and speckled, containing 1-2 mm (0.04-0.08 in) biotite, chlorite, and muscovite porphyroblasts. Farther north and south the rocks are slate or phyllite and contain less biotite.

Typical greenschist facies assemblages in slate and phyllite are: quartz-white mica-chlorite ± epidote ± biotite ± albite(?). In some thin sections, biotite is pale and may be phlogopite. Plagioclase composition is ambiguous; determinations of plagioclase composition by the Michel-Levy method indicate compositions of albite or oligoclase. Albite is consistent with assemblages containing epidote and chlorite in the presence of quartz. White mica may be either muscovite or pyrophyllite. Mafic schist from unit G of the McCoy Creek Group yielded the assemblage: biotite-plagioclase-hornblende-white mica. Micaceous carbonate rocks contain: calcite-quartz-white mica ± chlorite ± biotite/phlogopite ± epidote ± tremolite ± garnet. Tremolite is colorless in thin section and therefore probably has little actinolite (Fe-rich) component. Coexistence of tremolite and calcite, and the presence of chlorite and epidote, indicates greenschist facies metamorphism. The temperatures required for the mineral assemblages are about 400°C, but pressures are not constrained by the mineral assemblages (Winkler, 1967). The wide extent of these assemblages and their uniformity indicates that the metamorphism is regional (Miller and Hoisch, 1992).

Amphibolite facies metamorphism along the east side of the range is typified by garnet, staurolite, fibrolite, sillimanite, andalusite, hornblende, and cummingtonite(?) in various rock types, indicating low-pressure amphibolite facies metamorphism (Winkler, 1967). Virtually all of the thin sections examined contain evidence of retrograde metamorphism, most commonly manifested as chlorite after biotite and white mica after alumino-silicate minerals.

Prograde assemblages of minerals in the amphibolite facies rocks are difficult to determine due to retrograde metamorphism, but relics of prograde porphyroblasts generally are present. Semipelitic rocks contain mineral assemblages of: quartz-white mica-biotite ± staurolite ± garnet ± andalusite ± sillimanite ± fibrolite. Staurolite, garnet, and biotite coexist in schist in the Bettridge Creek area. Schist of slightly different composition in the same area contains andalusite-biotite-garnet, but andalusite is typically retrograded. Staurolite commonly is replaced by white mica and chlorite; garnet is replaced by biotite, white mica, and chlorite; and andalusite is replaced by white mica. Graphite schist east of Pilot Peak contains andalusite-graphite-white mica assemblages. Impure calcareous rocks in the same area contain: calcite-white mica ± sphene ± biotite ± tremolite ± epidote ± hornblende(?) ± microcline. Where present, plagioclase is oligoclase or andesine, as determined by the Michel-Levy method. Hornblende(?) is black or dark brown in hand sample, but white/pale brown pleochroic in thin section, perhaps indicating a solid solution composition low in Na, Al, and Fe. Tremolite is colorless or pale green, indicating little actinolite component in the solid solution series.

Staurolite and sillimanite/fibrolite in the semipelites, and hornblende in the calcareous rocks, indicate amphibolite facies metamorphism, as does the An content of plagioclase. Coexisting sillimanite and andalusite, in conjunction with stable muscovite, quartz, and staurolite, indicate temperatures of about 575 to 625°C and pressures of about 3.5 kb (Miller and Hoisch, 1992). Unoriented hornblende grows poikilitically from flattened and elongated spots of uncertain origin in the tremolite-calcite rocks, appearing to support a polymetamorphic history. If these are relict porphyroblasts, a post-deformation event caused growth of minerals in amphibolite facies. Alternatively, the spots could represent sedimentary features (mud balls?) of different composition than the rest of the rock. In either case, some mineral growth took place under static stress conditions.

Amphibolite-facies mineral assemblages in the Killian Springs Formation are most evident in northern exposures of outcrops east of Pilot Peak, where sillimanite is present. Southward along outcrops of that unit and marble of the Toano Limestone, diagnostic minerals are not present and textural grade lessens. At the southern border of the quadrangle the rocks are made up of biotite-muscovite and tremolite-muscovite-calcite assemblages, probably indicating a decrease in metamorphic grade compared to the northern exposures. In the Bettridge Creek area, unit G of the McCoy Creek Group contains staurolite-garnet-biotite-andalusite-tourmaline assemblages over a wide area. Grade possibly decreases westward toward the Pinnacle fault, but does not seem to change northward, where the schist subunit of unit A(?) of the McCoy Creek Group contains fibrolite, andalusite, and sillimanite. Metamorphic assemblages of garnet-staurolite-andalusite-muscovite-biotite are present in quartzite of unit A(?) and are present at least locally in unit G to the northwest across the Pinnacle fault in the Patterson Pass quadrangle.

Physical conditions

Peak temperature for prograde regional greenschist-facies metamorphism was about 400 ± 50°C and pressures are uncertain. Higher grade metamorphism along the east side of the range was at temperatures of about 575 to 625°C and pressures of about 3.5 kb (Miller and Hoisch, 1992), or about 13.5 kilometers (8.1 mi) depth. Miller and Hoisch (1992) reasoned that the minimum stratigraphic thickness of rocks overlying the McCoy Creek Group in and near the Pilot Range was 11.1 kilometers (6.7 mi) and the thickness overlying the Toano Limestone was 8.9 kilometers (5.3 mi) (data compiled from Schaeffer, 1960; Miller and Glick, 1986; Glick and Miller, 1987; McCollum and Miller, 1991). These thickness figures do not include 1 to 3 kilometers (0.6 to 1.8 mi) of probable Triassic and Jurassic strata since removed by erosion. No tectonic thickening is required to explain the pressures for regional metamorphism, and a reasonable thermal gradient of 30°C/km is required for the greenschist metamorphism. Amphibolite facies metamorphism was probably caused by locally increased temperatures of 150 to 200°C near the Jurassic pluton. Amphibolite facies metamorphism extends the entire length of the Pilot Peak quadrangle, suggesting that in the subsurface the pluton is much larger in extent than surface exposures indicate.

Age

Metamorphism occurred during the Middle to Late Jurassic. Fabrics formed during regional metamorphism affected the Miners Spring Granite of Middle Jurassic age (155 to 165 million years ago), and are cross-cut by the 39-million-year-old Bettridge Creek Granodiorite. K-Ar ages on metamorphic minerals along the east side of the Pilot Range record cooling to about 500°C by 150 million years ago (table 2, no. 2) and to 280 to 350°C by 83 to 56 million years ago (table 2, nos. 2, 3, 4). These data suggest that amphibolite facies metamorphism took place in the Jurassic and that metamorphic rocks returned to ambient conditions of about 400°C at ~13 kilometers (8 mi) depth until cooling in the Cretaceous (Miller and others, 1987; Miller and Hoisch, 1992).

STRUCTURE

Diverse structures including low- and high-angle faults, penetrative folds and cleavage, and major folds control the distribution of rock units in the Pilot Peak quadrangle. Many of these structures are known or inferred to be post-Middle Jurassic to pre-latest Eocene in age on the basis of relations with dated igneous rocks and metamorphic minerals, but some low-angle and high-angle faults are Neogene to Holocene in age.

Pre-Cenozoic rocks in the quadrangle fall into two lithotectonic domains on the basis of age, metamorphism, and structural history. Metamorphosed Late Proterozoic and Cambrian strata, as well as Jurassic granite, have undergone ductile deformation on all scales; these widespread rocks comprise the structurally lower lithotectonic domain. These rocks contrast sharply with little-metamorphosed Paleozoic strata near the south border of the Pilot Peak quadrangle, which form a structurally overlying lithotectonic domain consisting of Cambrian(?) to Pennsylvanian rocks that are cut by high- and low-angle brittle faults. The Pilot Peak detachment fault separates the two domains. Metamorphic rocks of the lower lithotectonic domain are continuous northward with metamorphic rocks in the adjacent Patterson Pass quadrangle (figure 2), where they are intruded by the Eocene McGinty Monzogranite (Miller and others, 1993). Unmetamorphosed rocks of the upper domain are continuous southward with extensive exposures of Cambrian to Permian strata in the Miners Canyon quadrangle (Miller and Schneyer, 1981, unpublished mapping).

Normal faults flanking the Pilot Range are mapped where they cut bedrock, and locally where they cut upper Cenozoic deposits. These faults apparently are part of a system of late Cenozoic range-margin faults associated with uplift of the Pilot Range block.

Structures are here described in order of decreasing age within the lithotectonic domains as follows: (1) structures below the Pilot Peak detachment, (2) Pilot Peak detachment fault, (3) structures above the Pilot Peak detachment, and (4) structures along the range margins.

Structures Below the Pilot Peak Detachment

Below the Pilot Peak detachment, metamorphosed strata exhibit a wide variety of structures. Most rocks contain one or more foliations (cleavages or schistosities), and many exhibit minor folds. Shear zones, or ductile faults, that lie nearly parallel to bedding both duplicate and truncate strata, and ductile-brittle normal faults also cut strata at moderate angles. The oldest structures are bedding-subparallel foliation and bedding-parallel shear zones. These are cut by northeast-striking foliation that is related to the development of northeast- to east-trending folds and some bedding-plane shear zones. Both of these foliation sets were accompanied by metamorphic mineral growth. Ductile-brittle normal faults formed after peak metamorphism and appear to be related to north-northeast-trending kink folds. All of these structures are truncated by the brittle Pilot Peak detachment.

The oldest penetrative foliation (S_1) is developed in phyllite, schist, and marble. It is oriented nearly parallel with bedding and contains rare, roughly east-trending, mineral-elongation lineations. Sparse isoclinal folds (F_1) with axes oriented parallel to the lineation probably are associated with S_1. This oldest foliation is deformed by steeply northwest-dipping penetrative foliation (S_2) that is axial planar to small folds (F_2) with shallowly northeast-plunging axes. East-trending F_1 penetrative lineations are folded about northeast-trending F_2 folds in unit B(?) of the McCoy Creek Group east of China Springs. Metamorphic minerals aligned with S_1 and S_2 foliations indicate similar metamorphic conditions during the formation of both cleavages. The F_2 folds are generally open to tight, and are similar in geometry and orientation to major southeast-vergent folds to the north (Miller and others, 1993). The broad syncline exhibited by the embayed map pattern of the Killian Springs Formation east of Pilot Peak is probably also a major northeast-trending fold, deformed to a nearly east trend by subsequent folding. Farther north, south of Bettridge Creek, the Prospect Mountain Quartzite is vertical to overturned, strikes east-northeast, and represents the overturned limb of the syncline displayed by the Killian Springs Formation.

In Cambrian marble east of Pilot Peak, folds are highly variable in shape and orientation. As a result, the two phases (F_1 and F_2) of small-scale folding are difficult to systematically separate and they cannot be correlated with the development of larger folds or low-angle faults. Axial plane foliations, penetrative lineations, and folds are widely developed in the marble but appear to represent complex deformation gradients.

Bedding-plane shear zones east of Pilot Peak are primarily ductile and formed early in the metamorphic cycle, as indicated by: (1) absence of breccia, (2) similar metamorphic assemblages across the faults, and (3) abundant ductile minor structures near the faults. Most shear zones probably are normal because they truncate small amounts of stratigraphic section. Zones with greater stratigraphic consequences lie east of Pilot Peak. A thrust-sense shear zone duplicates the upper part of the Prospect Mountain Quartzite and much of the Killian Springs Formation, and other structurally higher and smaller thrust zones duplicate parts of the Killian Springs. In contrast, a bedding-plane normal-sense shear zone south of these thrusts truncates the uppermost part of the Prospect Mountain Quartzite and much of the Killian Springs Formation, omitting several hundred meters of section. Both thrust- and normal-sense shear zones east of Pilot Peak are pre- to syn-metamorphic and they are folded by the map-scale F_2 syncline.

Bedding-plane shear zones just north of Bettridge Creek separate units F and G of the McCoy Creek Group, and omit the conglomerate subunit of unit G. The shear zones are ductile, normal in sense of stratigraphic separation, and appear to be younger than the bedding-plane shear zones east of Pilot Peak because they appear to postdate minor F_2 folds. However, they are folded by map-scale folds that we assign to F_3, and are cut by moderate-angle faults. Quartzite near the bedding-plane faults is mylonitic with prominent southeast-trending stretching lineations, probably younger than L_2. The presence of mylonite suggests declining temperatures and (or) water content following peak metamorphism.

Moderate-angle faults that cut bedding at moderate to steep angles are common north of the main outcrop of the Prospect Mountain Quartzite in the Pilot Peak area. These faults are normal, strike north-northeast, and appear to have behaved in a brittle-ductile manner. The largest, the Pinnacle fault, displays brecciated quartzite and grain-size-reduced marble and schist in a zone as much as 50 meters (165 ft) wide. Muscovite is stable in the deformed rocks, suggesting some fault movement at metamorphic temperatures. The Pinnacle fault and parallel faults to the east dip west, whereas faults with north strikes lying west of the Pinnacle fault dip east.

Open, kink-style folds (F_3) and small faults that break nearly parallel to axial planes of the kink folds appear to be related to the Pinnacle fault. The F_3 folds trend north to north-northeast, have nearly planar limbs and tight hinges, and verge eastward on the east side of the Pinnacle fault and westward west of the fault (plate 2, section C-C′). Small-scale F_3 folds related to the kink folds are rare; the small folds have no axial plane foliation and minerals such as biotite and quartz in the hinge zones are deformed but not recrystallized. Low- and moderate-angle faults that break near the hinges of the kink folds have normal separations and apparently were developed as the asymmetric folds broke along surfaces nearly parallel to axial planes in the tight hinge zones.

The Pinnacle fault, a moderate-angle (dip 30° to 50° west) normal fault whose trace nearly follows the present crest of the range, separates regions of opposing vergence in the kink folds. Thick quartzite units are truncated by the fault, but schist and marble wrap into parallelism with the fault as thin, highly deformed wedges. Deformation in marble resulted in extreme flattening of the calcite grains and a reduction in grain size by nearly two orders of magnitude. East-dipping faults west of, and intersecting, the Pinnacle fault are interpreted as antithetic faults. The Pinnacle fault and related faults, along with related (parasitic) F_3 kink folds, all deform F_2 structures and yet represent modest ductile deformation, so we interpret these structures as late-metamorphic.

The Pinnacle fault dies out southward and upward in the section of thick, competent Prospect Mountain Quartzite, which is arched in a large, complex, north-trending fold that refolds earlier folds (plate 2, section BB′). The maximum stratigraphic separation on the Pinnacle fault, near the northernmost exposures, is about 1.5 kilometers (0.9 mi). The termination of the Pinnacle fault southward is partly caused by merging with the antithetic fault to the west and also is apparently compensated by complex kink folding within the Prospect Mountain Quartzite. This faulting and folding apparently resulted in net thinning of the stratigraphic section and complex rotation of strata in individual fault blocks.

The fault, with an apparent east-trending trace in Marble Canyon, is interpreted as a low-angle normal fault. The fault is not exposed, but it is required to account for omission of part of the McCoy Creek Group. Regardless of the assignment of the thick mass of quartzite south of Marble Canyon, as unusually thick unit F or as unit D, the fault is required to account for truncated strata north of the canyon and for missing section between unit F (or D) and unit B. The inferred Marble Canyon fault does not cut the Pinnacle fault and is not expressed in the block west of the Pinnacle fault. These relations are best explained by a low-angle fault active during movement on the Pinnacle fault. Since such a low-angle fault is most likely normal, like the Pinnacle fault, it is inferred to dip southward (plate 2, section AA′).

Folds and pre- to syn-metamorphic bedding-plane shear zones below the Pilot Peak detachment are Jurassic to latest Eocene in age, as bracketed by dated granite bodies. The Jurassic Miners Spring Granite intruded thrust-sense and other low-angle shear zones, and is variably deformed. It predates at least part of the strain that produced F_2 folds. Metamorphic hornblende in the Killian Springs Formation east of Pilot Peak cooled 150 million years ago following peak metamorphism, indicating that much ductile deformation and peak amphibolite facies metamorphism was Middle and Late Jurassic in age. Metamorphic temperatures declined to ~300°C by the Late Cretaceous (Miller and others, 1987). This cooling might have been triggered by Late Cretaceous extension, perhaps as exemplified by the Pinnacle and Marble Canyon normal faults and related structures.

Several structures that are mapped within units underlying the detachment fault probably formed during, or after, development of the detachment. These structures are briefly described here, even though they belong genetically with structures described in following sections. The group of moderately east-dipping normal faults in the southwest corner of the quadrangle is probably related to the development of the Pilot Peak detachment. Other high-angle faults, mostly striking north to north-northwest, below the detachment show separations of a few tens of meters in most cases and are characterized by narrow breccia zones. These faults cut faults of the Pinnacle fault system, but are of uncertain age and significance. Some are oriented parallel to Neogene faults along the west margin of the range, and therefore are probably Neogene in age. The faults close to the Pilot Peak detachment and those probably Neogene in age are described in greater detail in sections below.

Pilot Peak detachment fault

The Pilot Peak detachment fault, which places texturally unmetamorphosed Ordovician and Cambrian limestone and dolomite on Cambrian schist and marble in the southern Pilot Peak quadrangle, postdates metamorphism and predates latest Eocene to Oligocene granodiorite dikes (Miller and Lush, 1981; Miller and others, 1987; Miller and others, 1992). The Pilot Peak detachment is marked by highly sheared and locally shattered slivers of the metamorphosed Killian Springs Formation and Toano Limestone. Above the detachment is brecciated and dolomitized limestone. Granodiorite bodies intruded the sheared and broken rocks, and yet are undeformed or at most locally fractured and chloritized. The detachment eliminates a thick section of Cambrian strata, and therefore is a normal-sense fault zone. We have not located kinematic markers within or near the detachment in the Pilot Peak quadrangle, but in the Miners Canyon quadrangle syntaxial calcite veins and fractures indicate generally top-to-west shear followed by top-to-east shear (Camilleri and others, 1992).

North-striking normal- or oblique-slip faults in the southwest corner of the quadrangle closely underlie but do not cut the Pilot Peak detachment. These faults dip 35° to 45° east, are cut by Eocene granodiorite bodies, and displace distinctive Cambrian strata by less than 200 meters (660 ft) on individual faults. Lineations developed in locally mylonitized rocks of the Prospect Mountain Quartzite adjacent to the faults trend S. 50° E., and probably indicate the movement direction during faulting. The faults have identical strike, but opposite dip, to normal faults in the hanging wall of the Pilot Peak detachment (exposed widely in the Miners Canyon quadrangle).

We consider that the north-striking faults, both in the hanging wall and the footwall of the Pilot Peak detachment, probably formed during movement on the detachment. The north strike of these faults indicates extension in roughly an east-west direction, and mylonitic lineations on the footwall faults suggest movement was oriented in a southeast direction. The widespread down-to-the-west normal faults in the hanging wall suggest that the hanging wall moved generally relatively westward during extension, an inference supported by contrasting sedimentary environments for Cambrian strata above and below the detachment (McCollum and Miller, 1991) and by minor structures (Camilleri and others, 1992). Timing of detachment is constrained by crosscutting late Eocene granodiorite and Late Cretaceous cooling of metamorphic micas. We conclude that the detachment underwent top-to-the-northwest movement sometime between about 80 and 40 million years ago. The common association of magmatism with detachment in Cordilleran extensional fault systems we take as evidence favoring Eocene detachment, roughly coeval with granodiorite emplacement.

Structures Above the Pilot Peak Detachment

Generally unmetamorphosed Paleozoic strata above the Pilot Peak detachment are exposed in fragments in the pediments flanking the Pilot Range and in one small area near the southern border of the quadrangle. In the Miners Canyon quadrangle to the south, the same rocks are complexly faulted. Most of the hanging-wall rocks in the Pilot Peak quadrangle dip moderately eastward, and are cut by high- and low-angle faults. Faults in Ordovician strata on both sides of the range fall into two groups: (1) faults nearly parallel to bedding, cutting out stratigraphic section, and (2) west-dipping, north-striking moderate-angle faults oblique to bedding. A small segment of a low-angle fault, marked by dark brecciated jasperoid, is parallel to bedding in the Joana Limestone near the southern border of the quadrangle. It places dolomitized limestone, probably the Joana Limestone, but possibly the Ely Limestone, above rock that is unquestioned Joana. Some of the hanging wall faults may predate the Pilot Peak detachment, others may be related to development of the detachment, and yet others may be related to late Cenozoic faults flanking the range.

Structures Along the Range Margins

Two or more buried faults are inferred along the east margin of the Pilot Range on the basis of gravity data (Cook and others, 1964), and some faults cut upper Cenozoic deposits in places on both sides of the range. Several faults are inferred from physiographic expression and spring lines along both sides of the range (shown by dotted and queried lines on plate 1).

On the west side of the range near Cove Springs, fault traces extending south from the Patterson Pass quadrangle are mapped by vegetation stripes and poorly defined (highly rounded) linear steps in topography that we consider to be scarps on the surfaces of oldest alluvial-fan deposits ($QTaf_3$). These faults lose expression southward. The easternmost fault displays two scarps developed in probable Holocene alluvium where it crosses a flat-floored wash. These scarps are rounded, with downthrown sides to the west; one is about 3 meters (10 ft) high, and the other is about 2 meters (6 ft) high.

Similar faults may localize the spring lines along the east side of the Pilot Range. Spring lines and topographic lineaments in the oldest alluvial-fan deposits ($QTaf_3$) near Marble Canyon and east of Pilot Peak are interpreted as marking early Pleistocene or older faults. The faults near the mouth of Marble Canyon may link across the low pass in the range crest to those west of the range. A steep, down-to-the-west fault crossing that pass is possibly such a link. The fault east of Pilot Peak that separates metamorphosed Cambrian from unmetamorphosed Ordovician rocks is moderately east dipping and carries slices of the brecciated Killian Springs Formation and granodiorite in the zone. We interpret this fault as a normal fault bounding the Pilot Range that in part has reactivated the Pilot Peak detachment and in part has displaced it along a subparallel structure (plate 2, section B-B′). Part of this fault aligns with fault traces in the oldest alluvium, but elsewhere the fault traces in the oldest alluvium are straighter, suggesting some realignment of the fault with time.

Structural Summary

Structural data from the Pilot Peak quadrangle form a key part of an interpretive structural history of the Pilot Range. The earliest events were low-angle faulting, metamorphism, plutonism, folding, and cleavage-formation in rocks underneath the Pilot Peak detachment (Miller and others, 1987). East- or southeast-directed shear accompanied at least part of this deformation, as expressed in the main set of folds that are overturned to the southeast. On the basis of deformed Jurassic granite and K-Ar data for metamorphic minerals, peak metamorphism was Late Jurassic in age, but metamorphic rocks last cooled to lower greenschist temperatures during the Late Cretaceous (Miller and others, 1987). The last cooling in the Late Cretaceous possibly resulted in part from unroofing associated with regional extension, of which the development of the extensional Pinnacle fault system and related folds and faults may be a part. The Pilot Peak detachment probably formed during large-scale regional extension in the Eocene (Miller, 1990a), and was a northwest-dipping fault zone whose hanging wall moved northwest with respect to the metamorphic rocks in the footwall. The detachment probably was arched as part of the Eocene extension.

During the Miocene and probably the Pliocene, deep basins and wide tilt-blocks formed, blocking out the current basins and ranges (Miller, 1990a). Some blocks apparently behaved plastically, forming anticlines or domes such as the Pilot Range. Moderately dipping normal faults bounded the basins and ranges, and movement along these produced moderate to steep tilting of Cenozoic basin sediments. The Pilot Peak detachment probably was folded during uplift of the range. Some of the basin-and-range faults continued to be active into the Quaternary, since faults bounding both sides of the range have youthful surface expressions.

ECONOMIC GEOLOGY

Considerable mining activity in the Pilot Range took place north and south of the Pilot Peak quadrangle during the late 1800s and early 1900s, but virtually no prospects were developed in the quadrangle. Lead and silver mines were developed in and just above the detachment fault in Miners Canyon just south of the Pilot Peak quadrangle, raising the possibility that similar mineralization might exist in the quadrangle. However, the only prospect observed during geologic mapping is located on the ridge crest in SW1/4 NW1/4 section 28, T. 4 N., R. 19 W. There, specular hematite is present in brecciated quartz veins cutting the quartzose member of the Killian Springs Formation.

Jurassic and Eocene igneous rocks in the Pilot Peak quadrangle crop out mainly as scattered dikes and pods although one pluton is present north of Bettridge Canyon. For both ages of intrusion, a magmatic setting above a large mass of granitoid is suggested. Such a setting at the roof of plutons indicates the possibility of metal enrichment, especially for tungsten and molybdenum.

Several other features in the quadrangle may have potential economic interest. (1) Jasperoid breccia in the fault cutting the Joana Limestone in the southwestern corner of the quadrangle could be mineralized. (2) Small outcrops of the Eureka Quartzite in the southern part of the quadrangle are a potential source for pure silica. (3) Sorted gravel deposits along the shores of ancient Lake Bonneville may be suitable for construction aggregate. (4) Felsite dikes are locally altered with sericite and clays, are brecciated, and, in some cases, contain casts after pyrite; they may have served as conduits for mineralizing fluids. (5) The upper part of the Guilmette Formation may serve as a source for pure limestone. (6) Epidote-lined fractures are common in many Eocene granodiorite bodies, including the Bettridge Creek Granodiorite, and other forms of mineralization may also be present in these igneous rocks. (7) Marble and schist are probably not appropriate for building materials but may have uses as decorative stone.

GEOLOGIC HAZARDS

Pleistocene and probable Holocene faulting is indicated by rounded scarps, linear terraces, and well-developed linear arrays of springs in the Pilot Peak quadrangle. Periodic activity on these youthful faults could give rise to moderate or large earthquakes. Earthquakes may trigger liquefaction in sand-size sediments, such as small patches of lacustrine materials. Landslides, gravity-slide blocks, and talus slopes in the Pilot Range potentially could be activated by earthquakes or excessive precipitation. Talus slopes are especially common near outcrops of the Prospect Mountain Quartzite, probably as a result of prominent jointing in that unit.

Alluvial fans bordering the Pilot Range and alluvial deposits in canyons were emplaced primarily by destructive debris flows and sheet wash. At many sites, alluvium is currently being deposited or erosion is taking place. There is considerable potential for localized destructive floods and debris flows, particularly close to the range front and within canyons underlain by younger alluvial-fan deposits.

The Miners Spring Granite is uranium-rich and may produce radioactive daughter products such as radon that can be concentrated to harmful levels. Uranium concentrations in the granite are 3 to 14 ppm, which are higher than in most rocks. Radon produced by decay of uranium may be harmful if concentrated in structures such as dwellings; harmful levels could result if structures were built on the granite or on sediment, such as alluvium or lacustrine sand, derived from the granite. Future development of the area east of Pilot Peak should consider this potential hazard.

ACKNOWLEDGMENTS

Our studies have benefitted from discussions and (or) field visits with M.D. Carr, M.D. Crittenden, Jr., A.G. Harris, L.F. Hintze, T.D. Hoisch, L.B. McCollum, M.B. McCollum, J.E. Repetski, and L.W. Snee. Capable assistance by Martha A. Pernokas during field mapping in 1980 is greatly appreciated. Many paleontologists, identified in table 1, aided greatly by identifying fossils; the aid provided by Anita Harris and John Repetski was especially valuable. Geochronology studies by Wendy Hillhouse (K-Ar), and Robert Zartman (U-Pb) were critical. R.W. Gloyn, D. S. Harwood, F. K. Miller, B. Solomon, and W. A. Yonkee provided constructive reviews. To all these persons we are grateful for their contributions.

REFERENCES CITED

Allmendinger, R.W., and Platt, L.B., 1983, Stratigraphic variation and low-angle faulting in the North Hansel Mountains and Samaria Mountain, southern Idaho, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 149-163.

Allmendinger, R.W., Miller, D.M., and Jordan, T.E., 1984, Known and inferred Mesozoic deformation in the hinterland of the Sevier belt, northwest Utah, *in* Kerns, G.J. and Kerns, R.L., Jr., editors, Geology of northwest Utah, southern Idaho and northeast Nevada: Utah Geological Association Publication 13, p. 21-34.

Armstrong, R.L., 1968a, Sevier orogenic belt in Nevada and Utah: Geological Society America Bulletin, v. 79, p. 429-458.

—1968b, Mantled gneiss domes in the Albion Range, southern Idaho: Geological Society America Bulletin, v. 79, p. 1295-1314.

—1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range Province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochimica et Cosmochimica Acta, v. 34, p. 203-232.

—1972, Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah: Geological Society of America Bulletin, v. 83, p. 1729-1754.

—1976, The geochronometry of Idaho, Pt. 2: Isochron/West, v. 15, p. 1-33.

—1982, Cordilleran metamorphic core complexes--From Arizona to southern Canada: Annual Reviews of Earth and Planetary Sciences, v. 10, p. 129-154.

Armstrong, R.L., and Hills, F.A., 1967, Rubidium-strontium and potassium-argon geochronologic studies of mantled gneiss domes, Albion Range, southern Idaho, U.S.A.: Earth and Planetary Science Letters, v. 3, p. 114-124.

Armstrong, R.L., Leeman, W.P., and Malde, J.E., 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225-251.

Best, M.G., Christiansen, E.H., Deino, A.L., Gromme, C.S., McKee, E.H., and Noble, D.C., 1989, Eocene through Miocene volcanism in the Great Basin of the western United States: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 91-133.

Bortz, L.C., Cook, S.A., and Morrison, O.J., 1985, Great Salt Lake area, Utah, *in* Gries, R.R., and Duer, R.C., editors, Seismic exploration of the Rocky Mountain region: Rocky Mountain Association of Geologists and Denver Geophysical Society, [Denver, CO], p. 275-281.

Bryant, Bruce, 1988, Evolution and Early Proterozoic history of the margin of the Archean continent in Utah, *in* Ernst, W.G., editor, Metamorphic and crustal evolution of the western United States: Prentice-Hall, Englewood Cliffs, New Jersey, p. 432-445.

Camilleri, P.A., Miller, D.M., Snoke, A.W., and Wells, M.L., 1992, Structure and fabric of metamorphic terrains in the northeastern Great Basin: Implications for Mesozoic crustal shortening and extension, *in* Wilson, J.R., editor, Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 92-3, p. 19-58.

Christenson, G.E., and Purcell, C.R., 1985, Correlation and age of Quaternary alluvial-fan sequences, Basin and Range Province, southwestern United States, *in* Weide, D.L., editor, Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 115-122.

Collinson, J.W., Kendall, C.G.St.C., and Marcantel, J.B., 1976, Permian-Triassic boundary in eastern Nevada and west-central Utah: Geological Society of America Bulletin, v. 87, p. 821-824.

Compton, R.R., Todd, V.R., Zartman, R.E., and Naeser, C.W., 1977, Oligocene and Miocene metamorphism, folding, and low-angle faulting in northwestern Utah: Geological Society of America Bulletin, v. 88, p. 1237-1250.

Cook, K.L., Haverson, M.O., Stepp, J.C., and Berg, J.W., 1964, Regional gravity survey of the northern Great Salt Lake Desert and adjacent areas in Utah, Nevada, and Idaho: Geological Society of America Bulletin, v. 75, p. 715-740.

Currey, D.R., Atwood, Genevieve, and Mabey, D.R., 1984, Major levels of Great Salt Lake and Lake Bonneville: Utah Geological and Mineral Survey Map 73, scale 1:500,000.

Davis, G.A., 1979, Problems of intraplate extensional tectonics, western United States, with special emphasis on the Great Basin, *in* Newman, G.W., and Goode, H.D., editors, Basin and Range Symposium: Denver, Rocky Mountain Association of Geologists, p. 41-54.

Eaton, G.P., Wahl, R.R., Protska, H.J., Mabey, E.R., and Kleinkopf, M.D., 1978, Regional gravity and tectonic patterns: Their relation to late Cenozoic epeirogeny and lateral spreading in the western Cordillera, *in* Smith, R.B., and Eaton, G.P., editors, Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 51-91.

Farmer, G.L., and DePaolo, D.J., 1983, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure -- 1. Nd and Sr isotopic studies in the geocline of the northern Great Basin: Journal of Geophysical Research, v. 88, p. 3379-3401.

Gans, P.B., and Miller, E.L., 1983, Style of mid-Tertiary extension in east-central Nevada, *in* Gurgel, K.D., editor, Geologic excursions in the overthrust belt and metamorphic core complexes of the Intermountain Region: Utah Geological and Mineral Survey Special Studies 59, p. 107-160.

Glick, L.L., and Miller, D.M., 1986, Geologic map of the Lucin 4 NW quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 93, 4 p., 2 pl., scale 1:24,000.

Glick, L.L., and Miller, D.M., 1987, Geologic map of the Pigeon Mountain quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 94, 9 p., 2 sheets, scale 1:24,000.

Hedge, C.E., Stacey, J.S., and Bryant, Bruce, 1983, Geochronology of the Farmington Canyon Complex, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 33-44.

Heylmun, E.B., 1965, Reconnaissance of the Tertiary sedimentary rocks in western Utah: Utah Geological and Mineral Survey Bulletin 75, 38 p.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Geology Studies Special Publication 7, 202 p.

Hintze, L.F., and Robison, R.A., 1975, Middle Cambrian stratigraphy of the House, Wah Wah, and adjacent ranges in western Utah: Geological Society of America Bulletin, v. 86, p. 881-891.

Hoggatt, W.C., and Miller, D.M., 1981, K-Ar ages of intrusive rocks of the Pilot Range, Nevada and Utah: Isochron/West, no. 30, p. 21-22.

Ketner, K.B., 1977, Late Paleozoic orogeny and sedimentation, southern California, Nevada, Idaho, and Montana, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., editors, Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 363-369.

Lipman, P.W., Protska, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States, I, early and middle Cenozoic: Royal Society of London, Philosophical Transactions (A), v. 271, p. 217-248.

Lush, A.P., McGrew, A.J., Snoke, A.W., and Wright, J.E., 1988, Allochthonous Archean basement in the northern East Humboldt Range, Nevada: Geology, v. 16, p. 349-353.

Machette, M.N., 1985, Calcic soils of the southwestern United States, *in* Weide, D.L., editor, Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

McCollum, L.B., and Miller, D.M., 1991, Cambrian stratigraphy of the Wendover area, Utah and Nevada: U.S. Geological Survey Bulletin 1948, 45 p.

Marcantel, J.B., 1975, Late Pennsylvanian and Early Permian sedimentation in northeast Nevada: American Association of Petroleum Geologists Bulletin, v. 59, p. 2079-2098.

Mikulitch, M.J., and Smith, R.B., 1974, Seismic reflection and aeromagnetic surveys of the Great Salt Lake, Utah: Geological Society of America Bulletin, v. 85, p. 991-1002.

Miller, D.M., 1983, Allochthonous quartzite sequence in the Albion Mountains, Idaho, and its proposed Proterozoic Z and Cambrian correlatives in the Pilot Range, Utah and Nevada, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 191-213.

— 1984, Sedimentary and igneous rocks of the Pilot Range and vicinity, Utah and Nevada, *in* Kerns, G.J., and Kerns, R.L., Jr., editors, Geology of northwest Utah, southern Idaho and northeast Nevada: Utah Geological Association Publication 13, p. 45-63.

— 1985, Geologic map of the Lucin quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 78, 10 p., 2 pl., scale 1:24,000.

— 1990a, Mesozoic and Cenozoic tectonic history of the northeastern Great Basin, *in* Shaddrick, D.R., Kizis, J.A., Jr., and Hunsaker, E.L., III, editors, Geology and ore deposits of the northeastern Great Basin: Geological Society of Nevada, p. 43-73.

— 1990b, Geologic map of the Lucin 4 SW quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 130, 13 p. 2 sheets, scale 1:24,000.

— 1990c, Geologic map of the Crater Island SW quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 129, 8 p., 2 pl., scale 1:24,000.

— 1993, Geologic map of the Crater Island NW quadrangle, Box Elder County, Utah: Utah Geological Survey Map 145, 13 p., 2 sheets, scale 1:24,000.

Miller, D.M., and Allmendinger, R.W., 1991, Jurassic normal and strike-slip faults at Crater Island, northwestern Utah: Geological Society of America Bulletin, v. 103, p. 1239-1251.

Miller, D.M., and Glick, L.L., 1986, Geologic map of the Lemay Island quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 96, 9 p., 2 sheets, scale 1:24,000.

Miller, D.M., and Glick, L.L., 1987, Geologic map of the Jackson quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 95, 7 p., 2 pl., scale 1:24,000.

Miller, D.M., Hillhouse, W.C., Zartman, R.E., and Lanphere, M.A., 1987, Geochronology of intrusive and metamorphic rocks in the Pilot Range, Utah and Nevada, and comparison with regional patterns: Geological Society of America Bulletin, v. 99, p. 866-879.

Miller, D.M., and Hoisch, T.D., 1992, Mesozoic structure, metamorphism, and magmatism in the Pilot and Toano Ranges, *in* Wilson, J.R., editor, Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publications 92-3, p. 79-92.

Miller, D.M., Jordan, T.E., and Allmendinger, R.W., 1990, Geologic map of the Crater Island quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Map 128, 16 p., 2 pl., scale 1:24,000.

Miller, D.M., and Lush, A.P., 1981, Preliminary geologic map of the Pilot Peak and adjacent quadrangles, Elko County, Nevada and Box Elder County, Utah: U.S. Geological Survey Open-File Report 81-658, 21 p., 2 sheets, scale 1:24,000.

Miller, D.M., Lush, A.P., and Schneyer, J.D., 1993, Geologic map of the Patterson Pass quadrangle, Box Elder County, Utah and Elko County, Nevada: Utah Geological Survey Map 144, 2 sheets, scale 1:24,000.

Miller, D.M., Nakata, J.K., and Glick, L.L., 1990, K-Ar ages of Jurassic to Tertiary plutonic and metamorphic rocks, northwestern Utah and northeastern Nevada: U.S. Geological Survey Bulletin 1906, 18 p.

Miller, D.M., Repetski, J.E., and Harris, A.G., 1991, East-trending Paleozoic continental margin near Wendover, Utah, *in* Cooper, J.D., and Stevens, C.H., editors, Paleozoic paleogeography of the western United States-II: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 67, p. 439-461.

Miller, D.M., and Schneyer, J.D., 1985, Geologic map of the Tecoma quadrangle, Box Elder County, Utah, and Elko County, Nevada: Utah Geological and Mineral Survey Map 77, 8 p., 2 sheets, scale 1:24,000.

Miller, D.M., Wooden, J.L., and Wright, J.E., 1989, Mantle-derived Late Jurassic plutons emplaced during possible regional extension of the crust, northwest Utah and northeast Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 21, p. 117.

Misch, Peter, and Hazzard, J.C., 1962, Stratigraphy and metamorphism of late Precambrian rocks in central northwestern Nevada and adjacent Utah: American Association of Petroleum Geologists Bulletin, v. 46, p. 289-343.

O'Neill, J.M., 1968, Geology of the southern Pilot Range, Elko County, Nevada, and Box Elder County, Utah: Unpublished M.S. thesis, University of New Mexico, 112 p.

Oviatt, C.G., and Currey, D.R., 1987, Pre-Bonneville Quaternary lakes in the Bonneville basin, Utah, *in* Kopp, R.S., and Cohenour, R.E., editors, Cenozoic geology of western Utah: Utah Geological Association Publication 16, p. 257-263.

Poole, F.G., 1974, Flysch deposits of the Antler foreland basin, western United States, *in* Dickinson, W.R., editor, Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 58-82.

Sacks, P.E., and Platt, L.B., 1985, Depth and timing of decollement extension, southern Portneuf Range, southeastern Idaho, *in* Kerns, G.J. and Kerns, R.L., Jr., editors, Orogenic patterns and stratigraphy of north-central Utah and southeastern Idaho: Utah Geological Association Publication 14, p. 119-127.

Schaeffer, F.E., 1960, Stratigraphy of the Silver Island Mountains, *in* Schaeffer, F.E., editor, Geology of the Silver Island Mountains, Box Elder and Tooele Counties, Utah, and Elko County, Nevada: Utah Geological Society Guidebook to the Geology of Utah no. 15, p. 15-113.

Schneyer, J.D., 1984, Structural and stratigraphic complexities within an extensional terrain: Examples from the Leppy Hills area, southern Silver Island Mountains, near Wendover, Utah, *in* Kerns, G.J., and Kerns, R.L., Jr., editors, Geology of northwest Utah, southern Idaho, and northeast Nevada: Utah Geological Association Publication 13, p. 93-116.

— 1990, Geologic map of the Leppy Peak quadrangle and adjacent area, Elko County, Nevada and Tooele County, Utah: U.S. Geological Survey Miscellaneous Investigations Map 1938, scale 1:24,000.

Scott, W.R., McCoy, W.D., Shroba, R.R., and Rubin, Meyer, 1983, Reinterpretation of the exposed record of the last two cycles of Lake Bonneville, western United States: Quaternary Research, v. 20, p. 261-285.

Smith, R.B., 1978, Seismicity, crustal structure, and intraplate tectonics of the western Cordillera, *in* Smith, R.B., and Eaton, G.P., editors, Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 111-144.

Smith R.B., and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the Intermountain seismic belt: Geological Society of American Bulletin, v. 85, p. 1205-1218.

Smith, R.P., and Nash, W.P., 1976, Chemical correlation of volcanic ash deposits in the Salt Lake Group, Utah, Idaho, and Nevada: Journal of Sedimentary Petrology, v. 46, p. 930-939.

Snoke, A.W., and Miller, D.M., 1988, Metamorphic and tectonic history of the northeastern Great Basin, *in* Ernst, W.G., editor, Metamorphic and crustal evolution of the western United States: Prentice-Hall, Englewood Cliffs, New Jersey, p. 606-648.

Stacey, J.S., and Zartman, R.E., 1978, A lead and strontium isotopic study of igneous rocks and ores from the Gold Hill mining district, Utah: Utah Geology, v. 5, p. 1-15.

Steele, Grant, 1960, Pennsylvanian-Permian stratigraphy of east-central Nevada and adjacent Utah, *in* Geology of east-central Nevada: Intermountain Association of Petroleum Geologists Guidebook 11, p. 91-113.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline: Evidence of a late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345-1360.

— 1974, Correlation of uppermost Precambrian and Lower Cambrian strata from southern to east-central Nevada: U.S.Geological Survey Journal of Research, v. 2, p. 609-618.

— 1978, Basin-range structure in western North America: A review, *in* Smith, R.B., and Eaton, G.P., editors, Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 1-31.

— 1980, Geology of Nevada, a discussion to accompany the geologic map of Nevada: Nevada Bureau of Mines and Geology Special Publication 4, 136 p.

Stewart, J.H., and Poole, F.G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran miogeocline, Great Basin, western United States, *in* Dickinson, W.R., editor, Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 28-57.

Wells, M.L., 1988, Structural geometry, sequence, and kinematics of the Black Pine Mountains, southern Idaho: Implications from the cover rocks to metamorphic core complexes: Ithaca, New York, Cornell University, [Unpublished] M.S. Thesis, 95 p.

—1992, Kinematics and timing of sequential deformations in the eastern Raft River Mountains, *in* Wilson, J.R., editor, Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publications 92-3, p. 59-78.

Wells, M.L., Dallmeyer, R.D., and Allmendinger, R.W., 1990, Late Cretaceous extension in the hinterland of the Sevier thrust belt, northwestern Utah and southern Idaho: Geology, v. 18, p. 929-933.

Wright, J.E., and Wooden, J.L., 1991, New Sr, Nd, and Pb isotopic data from plutons in the northern Great Basin: Implications for crustal structure, and granite petrogenesis in the hinterland of the Sevier thrust belt: Geology, v. 19, p. 457-460.

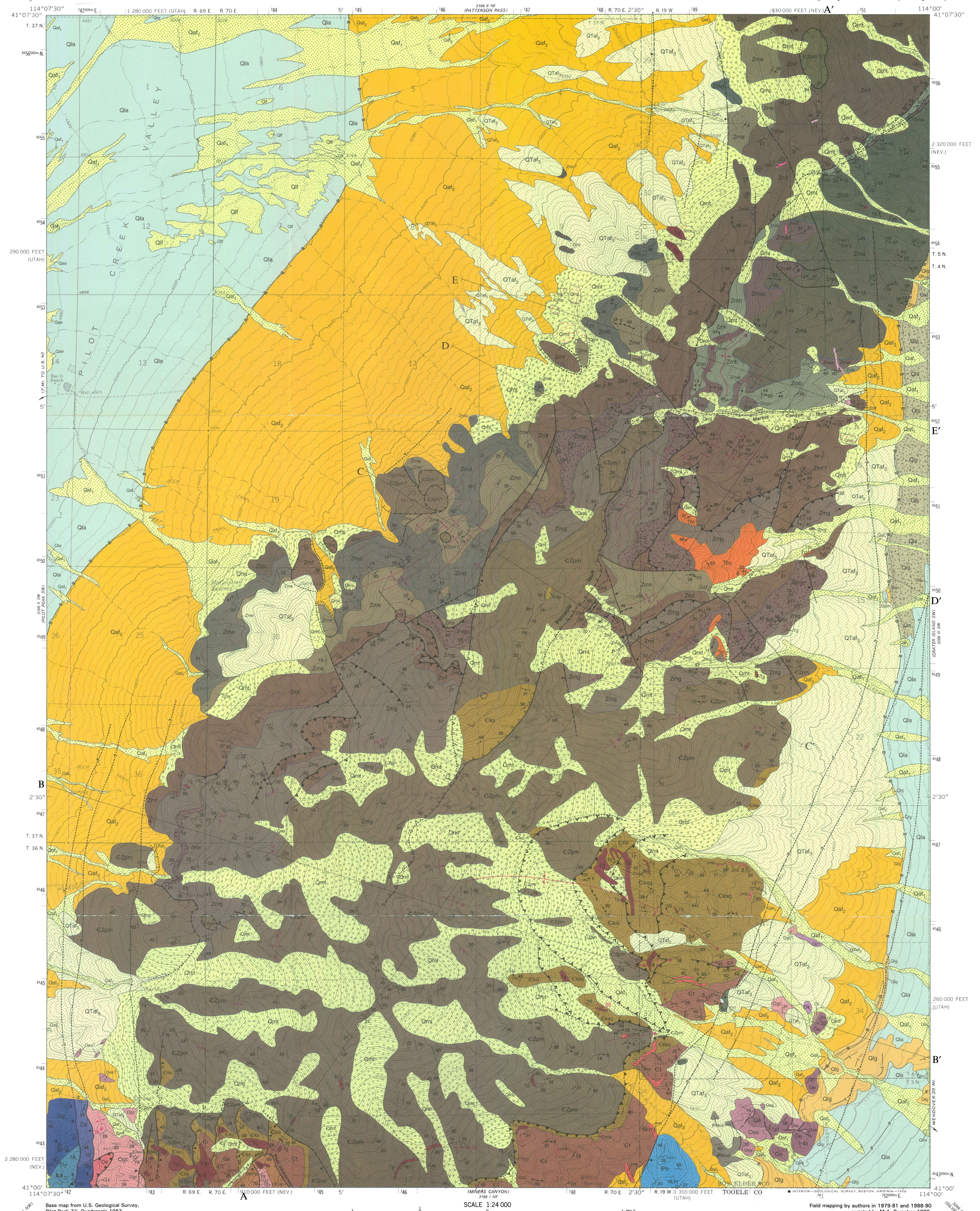
Winkler, H. G. F., 1967, Petrogenesis of metamorphic rocks (revised second edition): New York, Springer-Verlag.

Woodward, L.A., 1967, Stratigraphy and correlation of Late Precambrian rocks of Pilot Range, Elko County, Nevada, and Box Elder County, Utah: American Association of Petroleum Geologists Bulletin, v. 51, p. 235-243.

Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 3-27.

Zoback, M.L., Anderson, R.E., and Thompson, G.B., 1981, Cenozoic evolution of the state of stress and style of tectonism of the Basin

UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with
THE UNITED STATES GEOLOGICAL SURVEY

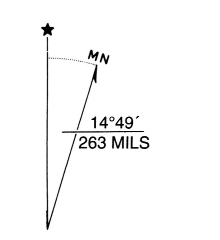


Base map from U.S. Geological Survey, Pilot Peak 7½ Quadrangle,1967.

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Field mapping by authors in 1979-81 and 1988-90 assisted by M.A. Pernokas 1980.
Cartography by Patricia H. Speranza.



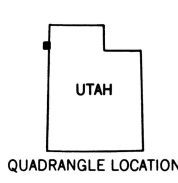
1994 MAGNETIC DECLINATION AT CENTER OF MAP

GEOLOGIC MAP OF THE PILOT PEAK QUADRANGLE, ELKO COUNTY, NEVADA AND BOX ELDER COUNTY, UTAH

by

David M. Miller and Andrew P. Lush
U.S. Geological Survey

1994



QUADRANGLE LOCATION

UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with
THE UNITED STATES GEOLOGICAL SURVEY

MAP SYMBOLS

CONTACT - *Dotted where covered*

HIGH-ANGLE FAULT - *Dashed where inferred, dotted where concealed; dip indicated; bar and ball on downthrown side; queried where uncertain*

LOW- TO MODERATE-ANGLE FAULT DISCORDANT TO BEDDING - *Dashed where inferred, dotted where concealed; barbs on hanging wall; dip indicated*

BEDDING-PLANE FAULT - *Dashed where inferred, dotted where concealed; barbs on hanging wall*

LOW-ANGLE NORMAL FAULT - *Dashed where inferred, dotted where concealed; barbs on hanging wall; dip indicated*

GRAVITY-SLIDE BLOCK - *Dashed where inferred, dotted where concealed*

HEADSCARP OF SLUMP OR SLIDE

ORIENTATION OF BEDDING
- Inclined
- Overturned
- Vertical
- Horizontal

APPROXIMATE ORIENTATION OF BEDDING
- Inclined
- Overturned
- Vertical

ORIENTATION OF FOLIATION AND BEDDING AT SAME OUTCROP

LINEATION
- Strike and dip of beds and plunge of lineation
- Strike and dip of beds showing horizontal lineation
- Vertical beds, showing plunge of lineation
- Vertical foliation, showing plunge of lineation
- Strike and dip of foliation showing plunge of lineation
- Lineation on trend with bedding dip

MINOR FOLD - *Showing trend and plunge*

TRACE OF AXIAL SURFACE OF ANTICLINE - *Showing plunge*

TRACE OF AXIAL SURFACE OF SYNCLINE - *Showing plunge*

TRACE OF AXIAL SURFACE OF MONOCLINE - *Showing plunge*

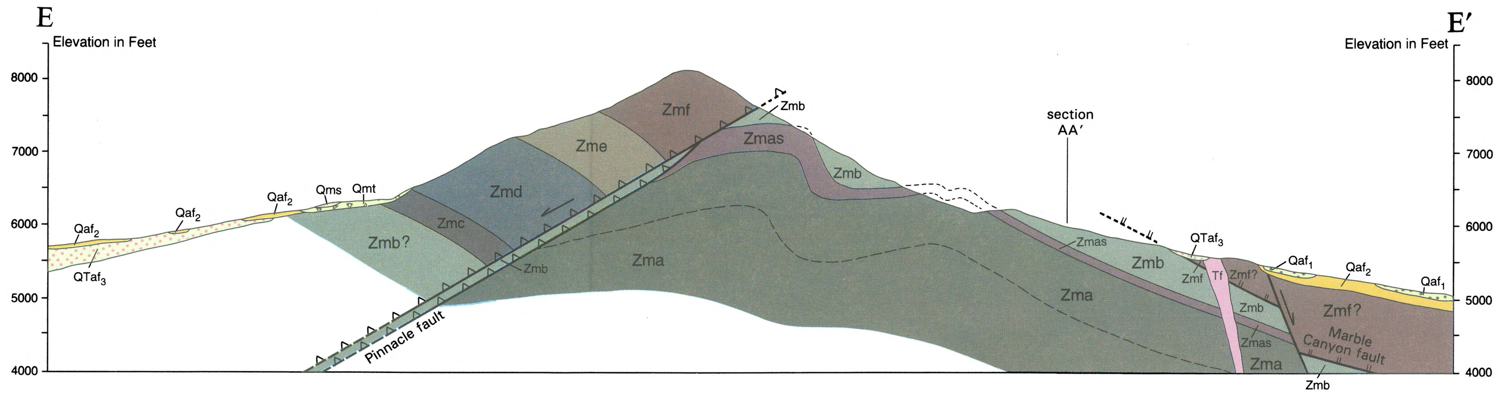
BONNEVILLE SHORELINE

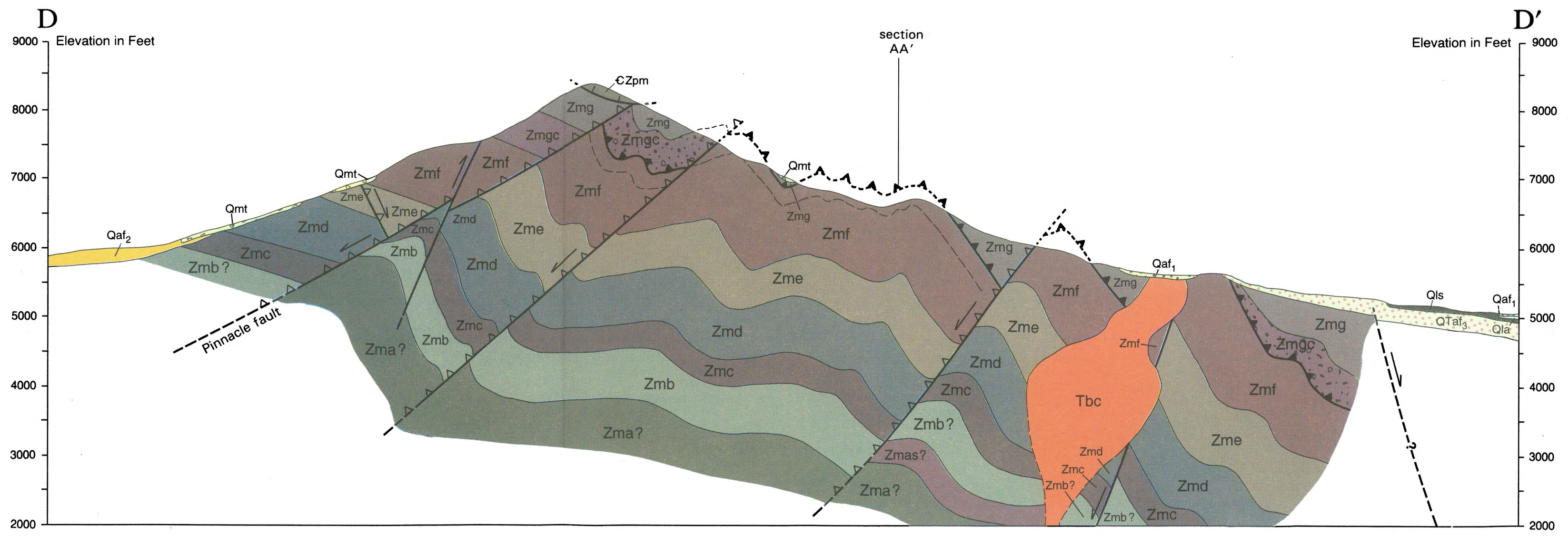
INTERMEDIATE SHORELINE

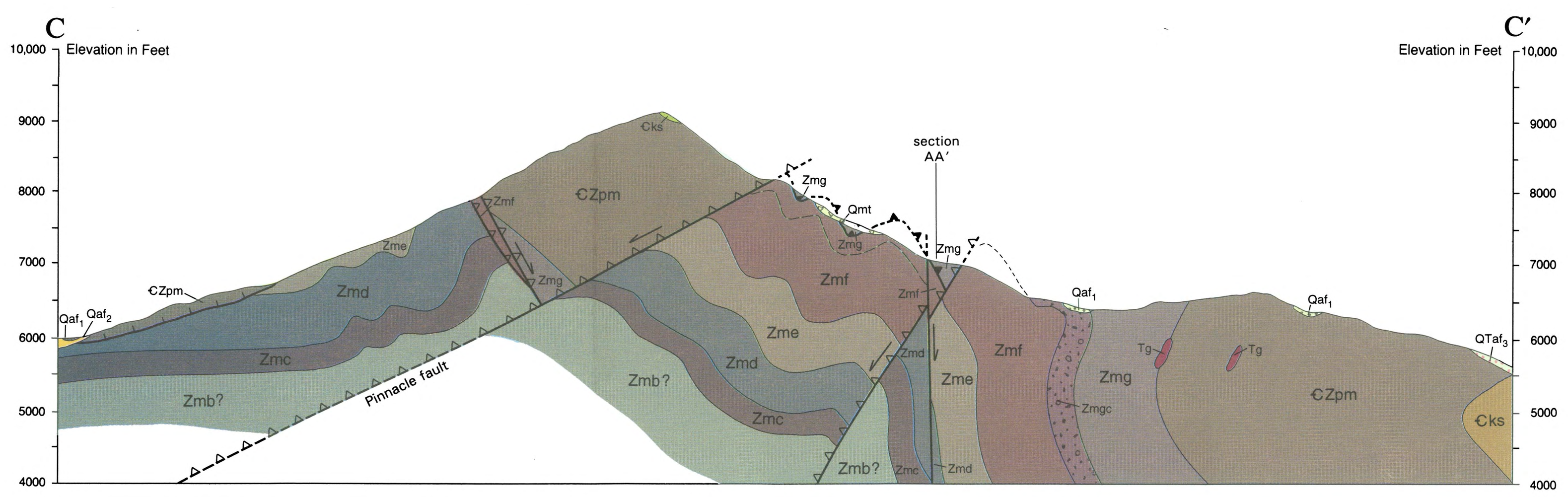
PROVO SHORELINE

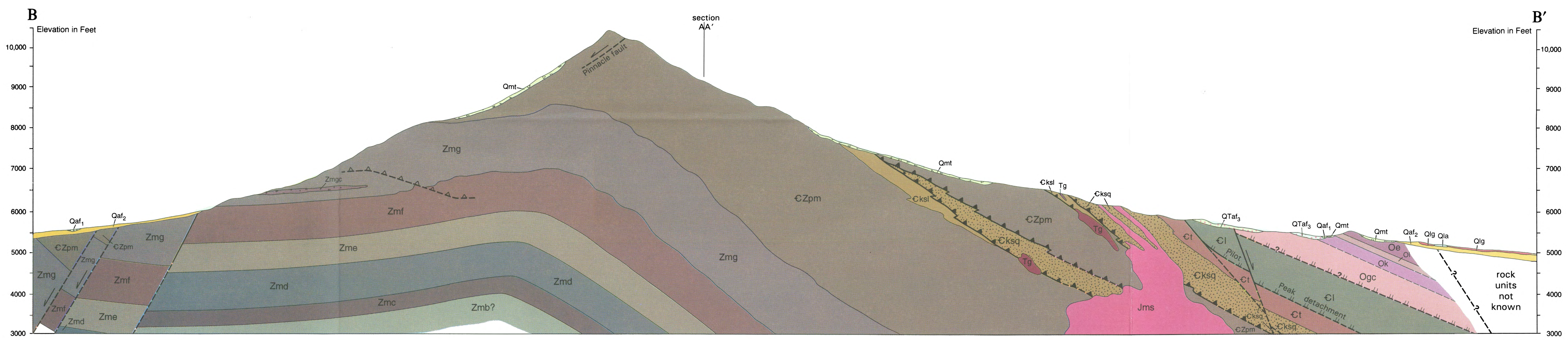
LOCATION OF PALEONTOLOGY SAMPLE

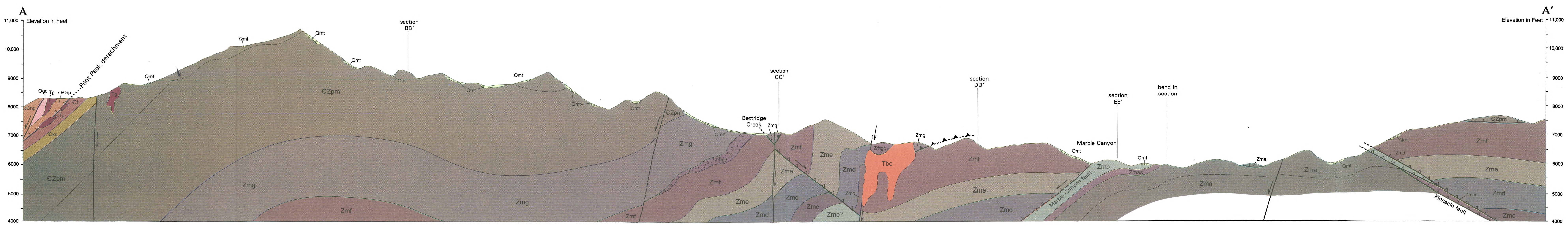
LOCATION OF GEOCHRONOLOGY SAMPLE



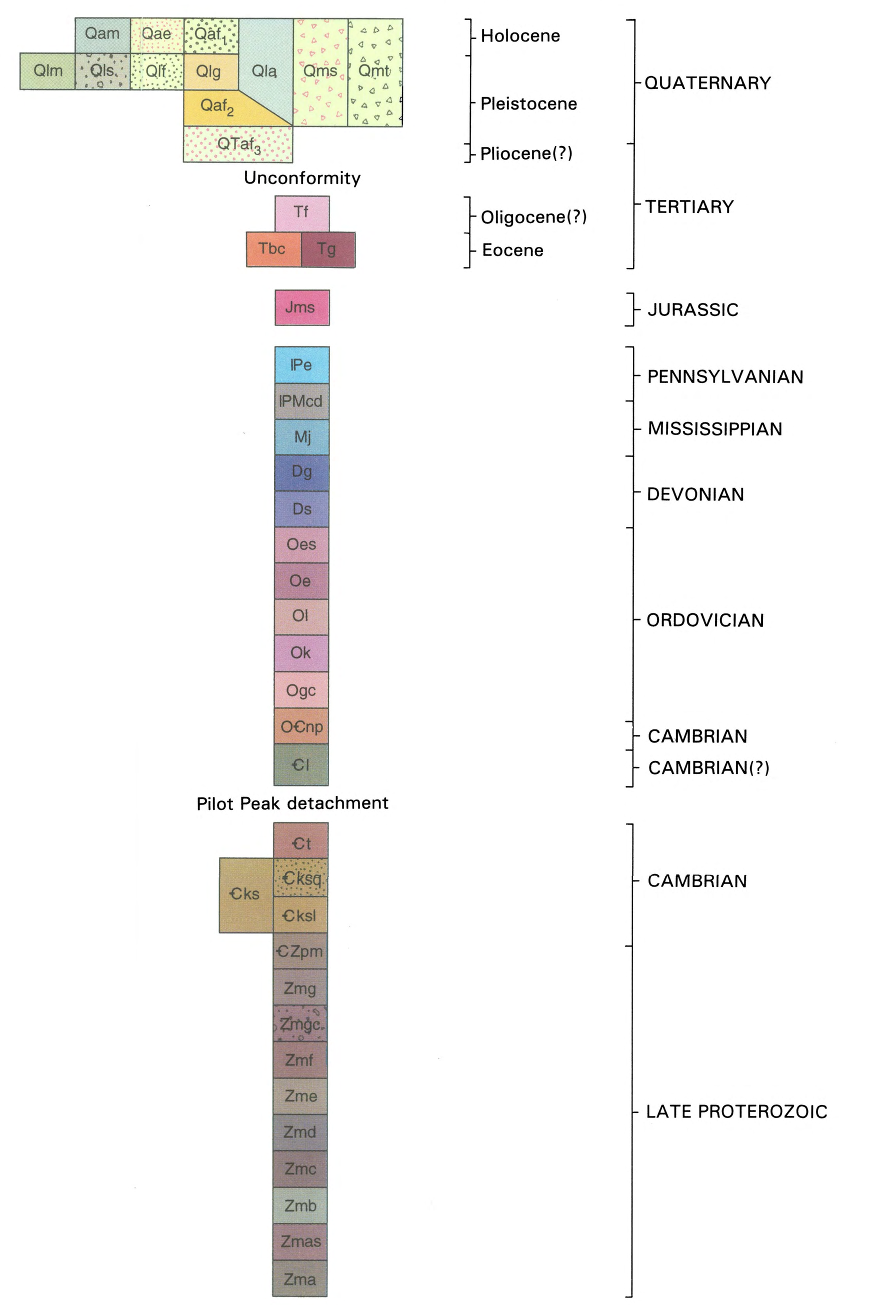








CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Qam Alluvial mud (Holocene)--*Mud and silt deposited by ponding behind unbreached parts of Lake Bonneville barrier beach.*

Qae Alluvial and eolian deposits (Holocene)--*Mixed fine-grained deposits of alluvial and eolian origin. Mostly silt and fine sand, red and brown in color. Deposited within low-gradient alluvial systems along floodplains, and by eolian reworking of fine-grained materials deposited by Lake Bonneville.*

Qaf_1 Younger alluvial-fan deposits (Holocene)--*Stream and fan deposits of poorly sorted gravel, sand, and silt. Deposited within and at mouths of canyons and gullies, along alluvial floodplains bordering streams, and as sediments in stream channels. Colluvium included locally.*

Qla Lacustrine and alluvial deposits, undivided (Holocene and Pleistocene)--*Varied, complexly interlayered deposits of lacustrine and alluvial origins.*

Qms Landslide deposits (Holocene and Pleistocene)--*Displaced deposits of disaggregated rock and colluvium that form hummocky terrain. Larger detached masses of bedrock are not distinguished as landslide deposits, but are mapped as gravity-slide blocks, identified by bedrock unit symbols.*

Qmt Talus and colluvium (Holocene and Pleistocene)--*Blocky deposits on talus slopes; unsorted colluvium along lower part of mountain.*

Qlm Lacustrine marl (Pleistocene)--*White and pale tan, laminated marl containing clay, silt, and sand.*

Qls Lacustrine sand (Pleistocene)--*Brown sand in sheets as much as 3 meters (10 ft) thick. Most deposits are just below the Bonneville shoreline.*

Qlf Lacustrine fines (Pleistocene)--*Silt, fine sand, and clay forming light-colored, irregularly shaped patches below the Bonneville shoreline west of the Pilot Range.*

Qlg Lacustrine gravel (Pleistocene)--*Moderate- to well-sorted, rounded pebbles and cobbles, with sand and silt matrix.*

Qaf_2 Older alluvial-fan deposits (Pleistocene)--*Poorly sorted gravel and sand forming piedmonts flanking the Pilot Range. Mostly stream and fan deposits; colluvium included locally. Overlain by deposits of Lake Bonneville.*

$QTaf_3$ Oldest alluvial-fan deposits (Pleistocene and Pliocene?)--*Unconsolidated to partly consolidated, poorly sorted boulder, cobble, gravel, sand, and silt alluvial deposits forming raised surfaces. Surfaces typically littered with large boulders (2-6 meters; 7-20 ft) of white quartzite. In places contains extensive pedogenic calcite.*

Tf Felsite (Oligocene?)--*Light-gray felsite containing sparse phenocrysts of subhedral quartz, plagioclase, and alkali feldspar in an aphanitic, pale-gray groundmass; rarely contains biotite. Largest outcrop is at mouth of Marble Canyon.*

Tbc Bettridge Creek Granodiorite (Eocene)--*Light-gray, medium-grained, subequigranular, biotite-hornblende granodiorite. Weak magmatic foliation. U-Pb age of zircon is 38.9 ± 0.9 Ma (Miller and others, 1987).*

Tg Granodiorite dikes (Eocene)--*Biotite-hornblende granodiorite and biotite granodiorite porphyry typically with medium-gray, aphanitic groundmass. More mafic rocks present locally. Forms dikes and small bodies.*

Jms Miners Spring Granite (Jurassic)--*Light-gray to white, medium-grained, felsic granite and pegmatite with small amounts of biotite and muscovite. Forms dikes and small bodies, all fully crystalline. Composition ranges from syenogranite to monzogranite. U-Pb age of zircon is 155 to 165 Ma (Miller and others, 1987). Tectonic foliation in granite is concordant with that in metamorphosed country rock.*

IPe Ely Limestone (Pennsylvanian)--*Gray and brown, medium- to thick-bedded limestone and argillaceous and cherty limestone; fossiliferous.*

IPMcd Chainman Shale (Mississippian) and Diamond Peak Formation (Pennsylvanian and Mississippian), undivided--*Dark-gray and black shale, and dark-gray, dark-brown, and black arkosic sandstone and conglomerate with quartz, chert, and feldspar clasts.*

Mj Joana Limestone (Mississippian)--*Massive to thick-bedded, unusually pure limestone. Dark-gray to black, coarse-grained limestone with abundant black chert and crinoid fragments in upper part. Light gray and fine grained in lower part.*

Dg Guilmette Formation (Devonian)--*Light-gray weathering, dark-gray, blue-gray, and black, thick-bedded limestone. Throughout unit, rock displays prominent bedding planes or laminations and is fossiliferous. Sedimentary breccia and soft-sediment slump features common.*

Ds Simonson Dolomite (Devonian)-- *Interlayered dark- to medium-gray and light-gray, calcareous dolomite forming steep slopes with distinctive banding. Most beds finely laminated.*

Oes Ely Springs Dolomite (Ordovician)--*Dark-gray to black, faintly bedded, fractured, calcareous dolomite.*

Oe Eureka Quartzite (Ordovician)--*White and light-gray orthoquartzite. Well size-sorted and well-rounded medium quartz sand grains are indented by pressure solution, and in places are partly recrystallized. Highly fractured in most exposures.*

Ol Lehman Formation (Ordovician)--*Thin-bedded, gray, fossiliferous limestone. Contains sandy and silty beds and dark dolomite in uppermost part.*

Ok Kanosh Shale (Ordovician)--*Green and brown, calcareous siltstone and gray-brown, silty limestone.*

Ogc Garden City Formation (Ordovician)--*Massive, gray limestone and thinly interbedded blue-gray limestone, gray and brown silty limestone, and brown calcareous siltstone. Locally bioclastic or cherty.*

O€np Notch Peak Formation (Ordovician and Cambrian)--*Massive, gray limestone and less common brown, silty limestone. Locally pisolithic or cherty.*

€l Limestone (Cambrian?)--*Dark-blue-gray and medium-gray limestone with silt partings and zones of ooids; much is dolomitized and highly fractured.*

€t Toano Limestone (Cambrian)--*Dark-gray to black, platy, laminated and thin-bedded, silty limestone; phyllitic where slightly metamorphosed. White to light-gray and tan, micaceous, coarsely crystalline marble where more highly metamorphosed east of Pilot Peak.*

€ks Killian Springs Formation, undivided (Cambrian)--*Dark-colored, graphitic and calcareous phyllite; forms gentle to moderate slopes. Where highly metamorphosed east of Pilot Peak, divided into:*

€ksq Quartzose member--*Quartzose and calcareous phyllitic argillite, pelitic schist, and calcareous quartzite. Unit is typically brown, tan, or green in color and thin bedded.*

€ksl Lower member--*Black, graphite-andalusite schist.*

€Zpm Prospect Mountain Quartzite (Cambrian and Late Proterozoic)--*Light-colored, prominently bedded and cross-laminated quartzite forming massive cliffs. Contains minor feldspar and mica in most places.*

McCoy Creek Group of Misch and Hazzard (1962) (Late Proterozoic)--*Alternating phyllitic argillite and quartzite units. In this area, consists of:*

Zmg Unit G--*Dark-gray and green phyllitic argillite and metasiltstone with interbedded marble and quartzite.*

Zmgc Conglomerate subunit--*Dark- to light-gray conglomerate and coarse-grained arkosic quartzite alternating with dark-brown, rhythmically bedded phyllitic argillite and metasiltstone. Subdivided in north part of quadrangle.*

Zmf Unit F--*Gray, well-bedded and cross-laminated, cliff-forming quartzite. Lenticular conglomerate at top contains rip-up clasts of phyllite, boulders and cobbles of quartzite, and rare jasperoid clasts.*

Zme Unit E--*Brown, laminated phyllitic argillite and metasiltstone.*

Zmd Unit D--*Poorly bedded to massive, cliff-forming quartzite and conglomerate. Generally gray, poorly sorted, and feldspathic.*

Zmc Unit C--*Laminated, yellow-green and silvery-brown phyllitic argillite, slate, and metasiltstone.*

Zmb Unit B(?)--*White or gray, laminated, crystalline calcite marble; contains sparse, minor white mica, tremolite, or quartz.*

Unit A(?)--*Divided into:*

Zmas Schist subunit--*Pale green, crenulated, coarsely crystalline actinolite schist; brown, quartzose schist; and mafic metaigneous gneiss.*

Zma Lower subunit--*Interbedded flaggy metaquartzite, conglomerate, schistose quartzite, and schist.*

FORMATION			SYMBOL	THICKNESS feet(meters)	LITHOLOGY
Ely Limestone			IPe	820+ (250+)	
Chainman Shale and Diamond Peak Formation, undivided			IPMcd	1230+ (375+)	
Joana Limestone			Mj	415 (125)	
Guilmette Formation			Dg	1130+ (350+)	
Simonson Dolomite			Ds	605 (185)	
Ely Springs Dolomite			Oes	160 (50)	
Eureka Quartzite			Oe	490 (150)	
Lehman Formation			Ol	200 (61)	
Kanosh Shale			Ok	302 (92)	
Garden City Formation			Ogc	655 (200)	
Notch Peak Formation			O€np	520 (180)	
limestone			€l	uncertain	Pilot Peak detachment
Toano Limestone			€t	1080+ (330+)	
Killian Springs Formation			€ks	985 (300)	
Prospect Mountain Quartzite			€Zpm	3100 (955)	
McCoy Creek Group	Unit G	upper subunit	Zmg	1175 (360)	
		conglomerate subunit	Zmgc	400 (120)	
	Unit F		Zmf	1400 (425)	
	Unit E		Zme	820 (250)	
	Unit D		Zmd	720 (220)	
	Unit C		Zmc	820+ (250+) ?	
	Unit B?		Zmb	510+ (155+)	
	Unit A?	schist subunit	Zmas	260 (80)	
		lower subunit	Zma	1480+ (450+)	