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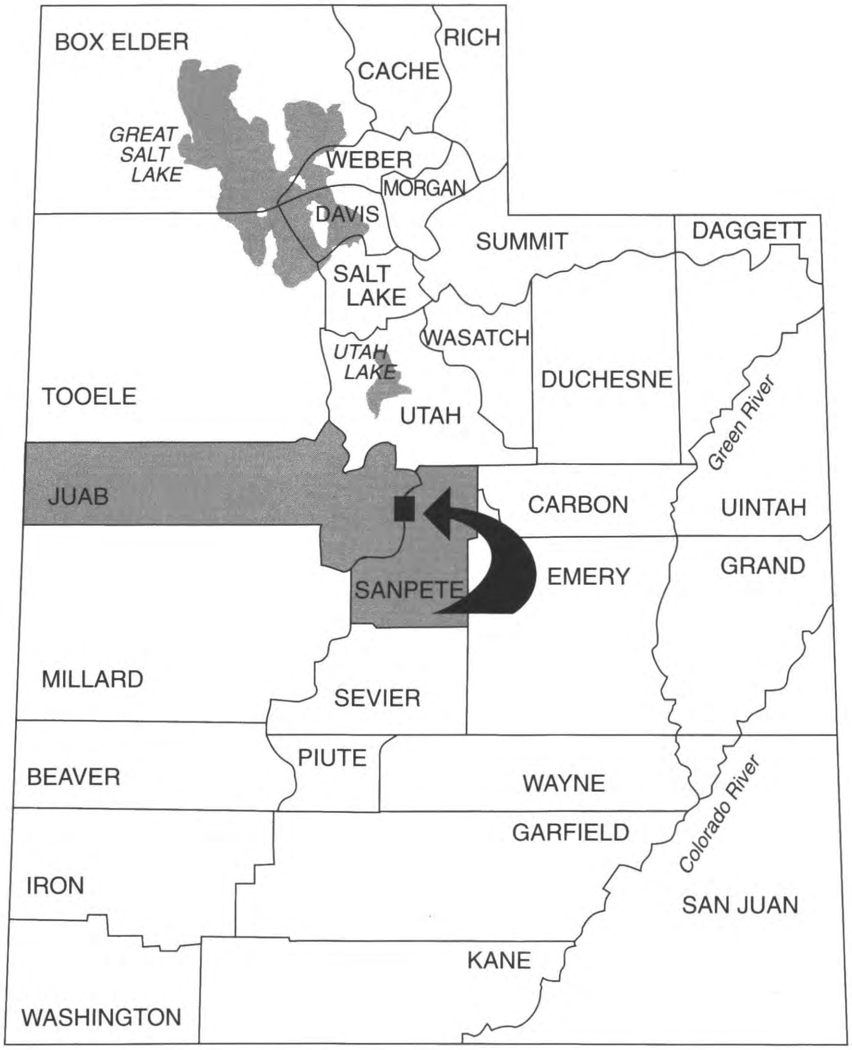
GEOLOGIC MAP OF THE WALES QUADRANGLE, JUAB AND SANPETE COUNTIES, UTAH

by

Timothy F. Lawton and Malcolm P. Weiss



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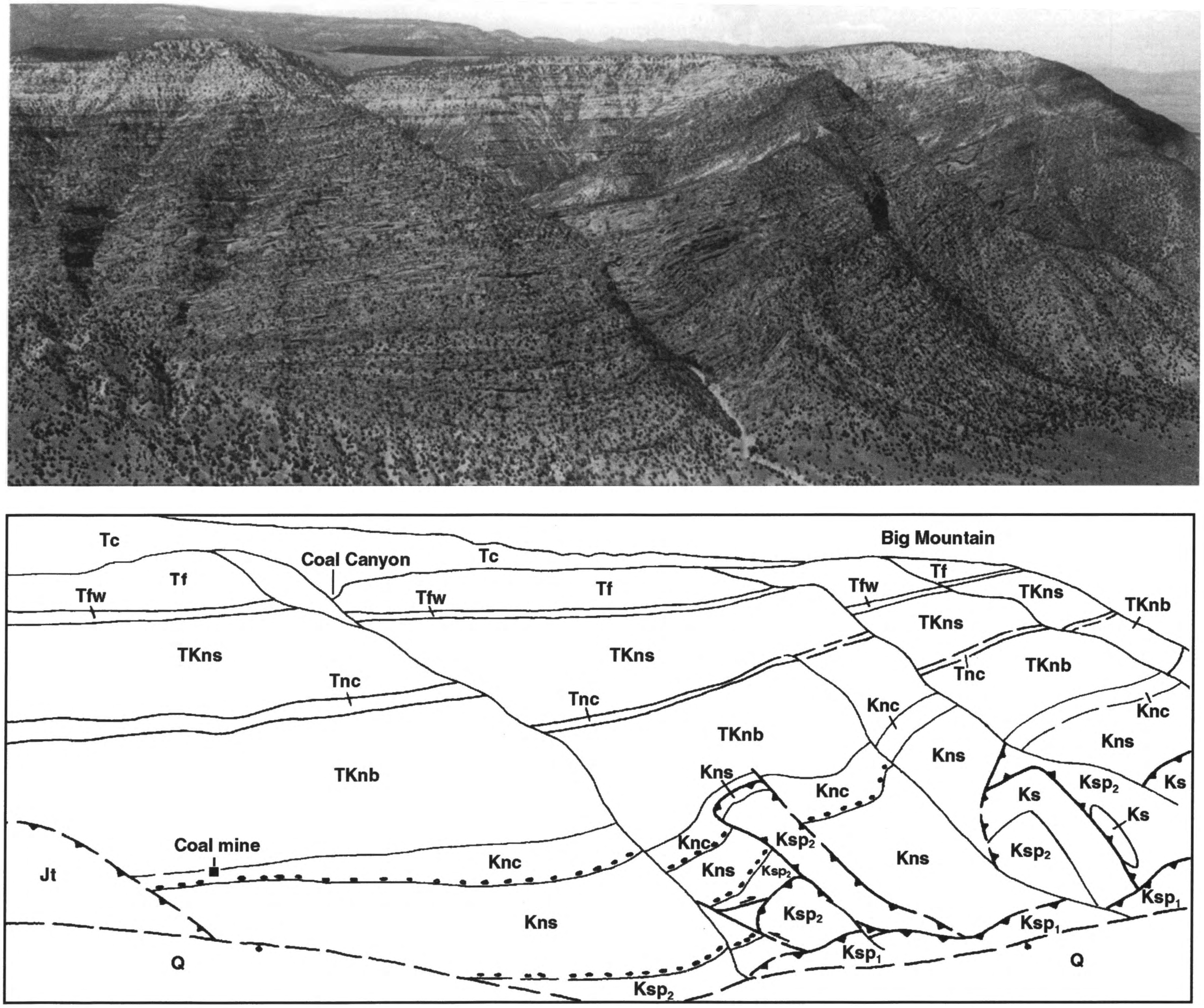

Oblique aerial photograph (above) and geologic interpretation (below) of the eastern escarpment of the San Pitch Mountains. View is to northwest. Explanation: Jt = Twist Gulch Formation; San Pitch Formation - Ksp_1 = lower member; Ksp_2 = upper member; Ks = Sanpete Formation; North Horn Formation - Kns = sheet sandstone member; Knc = coal-bearing member; TKnb = Big Mountain member; TKns = calcareous siltstone member; Tnc = Coal Canyon member; Tfw = Wales Tongue of Flagstaff Limestone; Tf = Flagstaff Limestone; Tc = Colton Formation; Q = undifferentiated Quaternary deposits. Unconformity at base of North Horn indicated by contact with dots; major intraformational unconformity within North Horn indicated by Kns/Knc contact (dotted line). Discordant bedding within Kns was deposited during uplift of older, thrusted strata now exposed discontinuously along foot of mountain. North of the photo, TKns replaces TKnb and Tnc, which pinch out, and rests directly on Knc; the resulting geometry explains the apparent sequencing problems in Mesozoic and Tertiary unit labels. Relief between top of Big Mountain and foot of range is approximately 2,370 feet (723 m).

DEDICATION:

To the hundreds of Ohio State University student geologists who struggled to map the mountain front near Wales in eight weeks with plane table and alidade.

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by
Timothy F. Lawton[1] and Malcolm P. Weiss[2]

ABSTRACT

The Wales quadrangle lies in a region of structural transition between the extended lithosphere of the Basin and Range and the moderately deformed Colorado Plateau. In Late Cretaceous time, this region was the leading edge of the Sevier orogenic belt. Bedrock strata exposed within the quadrangle are from Middle Jurassic (Callovian) through late Eocene in age. Jurassic strata (Twist Gulch Formation) antedate Sevier deformation and are present within a zone of imbricate reverse faults along the eastern foot of the San Pitch Mountains, where the strata have a maximum thickness of 1,400 feet (427 m). Cretaceous strata (Barremian or Aptian to Turonian) deposited in a foreland basin associated with the Sevier orogenic belt are present in outcrop and in the subsurface in the southeastern part of the quadrangle. Although truncated by subsequent erosion, this part of the Cretaceous section is about 3,540 feet (1,080 m) thick. These strata were also deformed by Sevier shortening which created the reverse faults in Jurassic beds.

The synorogenic North Horn Formation was deposited unconformably on older rocks between late Campanian and early Eocene time during intermittent Sevier and Laramide deformation. It represents the fill of a piggyback basin formed on the hanging wall of the Gunnison thrust system which underlies the San Pitch Mountains. The North Horn thickens westward from a pinchout in the subsurface beneath the central Sanpete Valley to at least 3,600 feet (1,100 m) on the east flank of the range. Syndepositional shortening and uplift are recorded by intraformational unconformities and intermittent westward paleocurrent indicators in North Horn beds. The North Horn is divided into eight mappable informal members in the quadrangle.

Eocene strata include the Flagstaff, Colton and Green River Formations, with a total thickness of 3,035 feet (925 m). Although these units postdate most shortening, they were deposited during what we believe to have been the latter part of the Laramide orogeny. Minor, late-stage, west-vergent back-thrusting deformed North Horn, Flagstaff, and locally, Colton strata and is apparently of Laramide origin.

Surficial deposits are largely restricted to Sanpete Valley and to unstable slopes and stream channels in the range. Mass-wasting deposits are conspicuous on slopes of the range, particularly on fine-grained units of the North Horn, Colton, and Green River Formations.

A zone of imbricate, west-verging reverse faults exposed along the foot of the San Pitch Mountains forms the west flank of the Sevier-Sanpete Valley antiform and represents a splay of the Gunnison thrust system. Reverse faults and folds deform Twist Gulch through Colton strata. This fault zone is the surface exposure of the imbricated forelimb, now cut by younger normal faults, of a west-vergent fault-propagation fold that lies beneath Sanpete Valley. This fold is equivalent to the Sevier-Sanpete Valley anticline of earlier literature. West-trending normal faults cut strata at least as young as late Eocene and form the north flank of a graben in the southernmost part of the quadrangle. North- to northeast-trending normal faults cut deposits as young as Holocene along the range front. This range-front fault system has structural relief as great as 4,400 feet (1,340 m) and created the present topography.

Geologic resources of the quadrangle are water, sand, and gravel. Both surface and subsurface water supplies come from watersheds in the San Pitch Mountains. Sand and gravel are abundant in alluvial fans along the range front. Coal has been mined historically in the quadrangle, but oil and gas have proven elusive. Prospects for metallic ores have been disappointing.

Geologic hazards include flooding, mass movements such as landsliding, and earthquakes. Quaternary faults are present in the quadrangle and may present a seismic hazard.

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INTRODUCTION

The Wales quadrangle lies on the east side of the central San Pitch Mountains (also known as the Gunnison Plateau) and the western side of Sanpete Valley, west of U. S. Highway 89 and northwest of the towns of Ephraim and Manti (figure 1). The town of Wales, in the northeastern part of the quadrangle, houses the only permanent inhabitants. The lowest elevation in the quadrangle is approximately 5,430 feet (1,655 m), where the San Pitch River flows across the southeastern corner of the quadrangle. The highest elevation, approximately 8,450 feet (2,577 m), lies in the range crest along the western edge of the quadrangle. The total relief within the Wales quadrangle is about 3,000 feet (915 m). The greatest relief is along the eastern range front, where steep cliffs are cut by ephemeral drainages that open eastward onto Sanpete Valley and provide excellent exposures of the bedrock geology and structure of the mountain range. Canyons in the northwesternmost part of the quadrangle drain westward toward the Juab Valley, west of the San Pitch Mountains (figure 1).

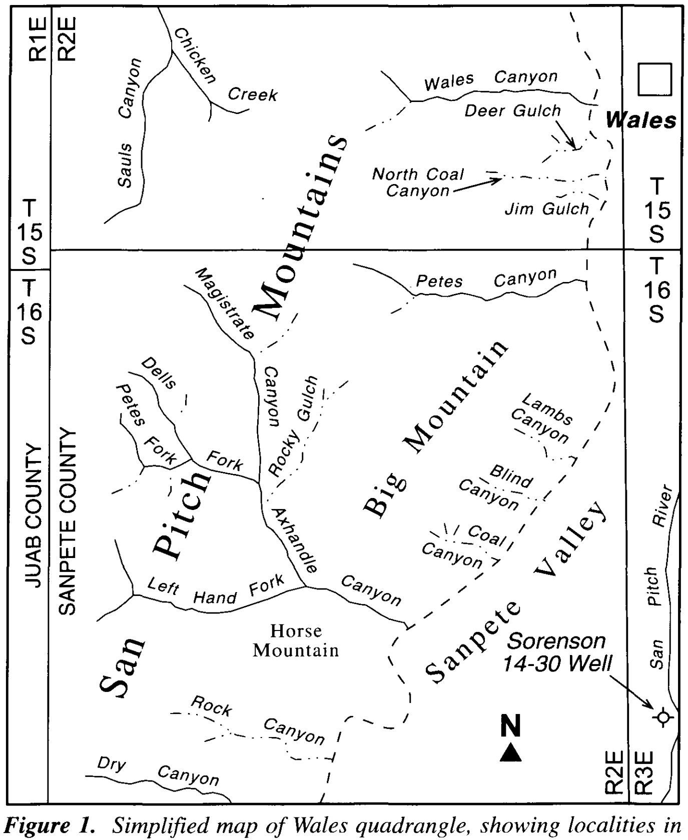

Figure 1. Simplified map of Wales quadrangle, showing localities in quadrangle discussed in text.

Land use within the quadrangle is primarily agricultural, dominated by livestock grazing in the mountain range. Livestock feed is grown on the lower parts of the alluvial fans that fringe Sanpete Valley. The range is an important watershed that provides surface and subsurface water for agricultural and culinary uses.

Parts of the Wales quadrangle have been mapped previously by Spieker (1949a, 1:125,000), Burma and Hardy (1953), Doelling (1972), Birsa (1973) and Lawton and others (1993). Witkind and others (1987) published a 1:100,000-scale map that included the Wales quadrangle. Many topical geologic studies have been conducted within the Wales quadrangle. Spieker (1946), Weiss (1982), Lawton (1985), and Weiss and Roche (1988) have presented structural studies including cross sections within the Wales quadrangle. Gilliland (1963) first described the anticlinal structure of Sanpete Valley and its flanking ranges; he termed the structure the "Sanpete-Sevier Valley anticline." We have modified the term to Sanpete-Sevier Valley antiform. Stratigraphic studies in the quadrangle include those by Spieker (1949b), La Rocque, (1960), Marcantel and Weiss (1968), Birsa (1973), Volkert (1980), Millen (1982), Schwans (1988a, 1988b, 1995), Weiss and Roche (1988), Hobbs (1989), Lawton and others (1993), and Talling and others (1994, 1995).

Late Mesozoic and Paleogene strata exposed in the Wales quadrangle provide important information regarding the tectonic development of this geologic region, which lies at the boundary between the Basin and Range and Colorado Plateau provinces. During the late Mesozoic, the eastern edge of imbricate thrust plates of the Sevier orogenic belt lay along the trend of what is now Sanpete Valley. Sedimentary features and structure of the Cretaceous-Tertiary North Horn Formation demonstrate coeval deformation and deposition that constrain the style and age of thrusting. Therefore, an understanding of the stratigraphy and structural geology within the Wales quadrangle is critical to an improved interpretation of Cordilleran tectonics at the end of the Mesozoic era. Fieldwork for the map of the Wales quadrangle was conducted by Weiss in 1978 and 1979, with revisions in 1991 and 1992, and by Lawton in 1987 through 1991.

STRATIGRAPHY

Formations exposed in the Wales quadrangle are from Middle Jurassic to Eocene in age and fall into three natural structural and stratigraphic categories:

1) Jurassic and pre-Turonian Cretaceous continental and marine strata that predate local contractional deformation are present along the foot of the eastern range front in a zone of west-vergent, reverse-faulted blocks, termed here the zone of imbricate reverse faults;

2) Upper Cretaceous to Eocene synorogenic continental strata (North Horn Formation) of the San Pitch Mountains accumulated in a piggyback basin whose eastern margin roughly coincided with the zone of imbricate reverse faults;
3) younger Eocene strata above the North Horn in the San Pitch Mountains are a largely late-orogenic succession of lacustrine and fluvial strata deposited during waning stages of the Laramide orogeny.

Surficial deposits within the quadrangle are largely restricted to Sanpete Valley and the major drainages of the mountain range. However, significant mass-wasting deposits are present within the San Pitch Mountains.

Jurassic System

Arapien Shale

A thick marine unit of thin-bedded mudstone, calcareous mudstone, muddy limestone and siltstone, and minor calcareous sandstone underlies Sanpete Valley in the axis of the antiform. It is not exposed in the Wales quadrangle, and only its uppermost member is reached by existing wells. The formation is 5,580 feet (1,700 m) thick in a well southwest of the Wales quadrangle (Standlee, 1982). The Arapien is Callovian in age (Imlay, 1980).

Member E (Jae): This unit, shown only in cross section, is the youngest member of the Arapien Shale. Where exposed in southern Sanpete Valley it is a conspicuous unit of brick-red gypsiferous and silty mudstone with streaks and pods of siltstone. It does not have the gray or buff beds so abundant in the older members. Bedding is usually not discernible because of transposition of beds by folding. Halite is more abundant in Member E than in older members of the Arapien, but is present only locally; it has been mined in southern Sanpete Valley in the past, and is still mined farther south in Sevier Valley. The thickness of the member is difficult to determine because of structural distortion; but is about 200-500 feet (60-150 m) where exposed south of the Wales area (Willis, 1986; Weiss, 1994). Member E is regionally concordant with the overlying Twist Gulch Formation.

Twist Gulch Formation (Jt)

The Twist Gulch Formation crops out discontinuously along the foot of the range and is principally light reddish-brown siltstone, dark reddish-brown mudstone, and reddish-brown, very fine grained sandstone in interbeds as much as 12 inches (30 cm) thick. Some very light gray, quartzose sandstone is present in beds 1/2 to 2 inches (1 - 5 cm) thick. The formation typically forms reddish-brown slopes and crops out mainly in arroyo bottoms or on steep hillsides. Sandstone beds commonly contain wave ripples, sometimes with dark brown claystone drapes, horizontal laminae with parting lineation, uncommon fluid-escape structures and uncommon hummocky cross stratification. A single bed of white to tan, fine-grained sandstone 10 to 13 feet (3 - 4 m) thick is present near the middle of the exposed section. It contains horizontal laminae, trough cross-bedding and fluid-escape structures. The thin-bedded, brown sandstone and siltstone facies of the Twist Gulch Formation is interpreted to represent tidal-flat deposits. The thick sandstone unit and thin white sandstone beds with hummocky cross stratification probably represent shoreface deposits, or those formed in the area underlying the breakers and surf and extending offshore to fairweather wave base (for example, Sanders and Kumar, 1975; Balsley, 1982).

Approximately 1,400 feet (427 m) of Twist Gulch Formation is exposed in the Wales quadrangle (cross section C-C′), but no depositional contacts with underlying and overlying formations are exposed. On the western flank of the San Pitch Mountains, northwest of the quadrangle, the complete Twist Gulch is 1,667 feet (508 m) thick and is overlain unconformably by the Cedar Mountain Formation (Auby, 1991). The upper contact there is marked by a change from brown thin-bedded siltstone and sandstone to red thick-bedded siltstone and sandstone, and is commonly difficult to recognize. Sprinkel (1994) interpreted 956 feet (292 m) of Twist Gulch in the Phillips Petroleum Price N well (SE1/4 SE1/4 section 29, T. 15 S., R. 3 E.), located 1.25 miles (2 km) east of the quadrangle boundary, but we believe that the well penetrated as much as 1,837 feet (560 m) of Twist Gulch.

The Twist Gulch is Middle Jurassic (Callovian) in age and correlative with the upper part of the Preuss Sandstone of northern Utah (Imlay, 1980). In Salina Canyon, 32 miles (53 km) south of the quadrangle, the Twist Gulch Formation is correlative with the San Rafael Group and contains strata recognizable as Entrada, Curtis, and Summerville Formations (Imlay, 1980; Willis, 1986; Lawton and Willis, 1987). We believe that the thick shoreface sandstone in the Twist Gulch of the Wales quadrangle is equivalent to the Curtis Formation, but verification of this correlation awaits further study. Continental Early Cretaceous (Aptian-Albian) palynomorphs reported from the Twist Gulch Formation at Chicken Creek on the west side of the San Pitch Mountains (Villien and Kligfield, 1986) likely were sampled from continental beds originally assigned to the uppermost part of the Twist Gulch Formation by Hunt (1950). These beds differ lithologically from the rest of the Twist Gulch Formation, are known to be Early Cretaceous in age on the basis of palynology, and have been reassigned to other formations, including the Pigeon Creek Formation (Schwans, 1988a) or the Cedar Mountain (Standlee, 1982) and San Pitch Formations (Sprinkel and others, 1999).

Cretaceous System

In the San Pitch Mountains and Sanpete Valley, Cretaceous continental strata are present above the Twist Gulch Formation and beneath Turonian marine strata of the Indianola Group. In the Wales quadrangle these fluvial rocks (Cedar Mountain and San Pitch formations) are exposed in the zone of imbricate reverse faults; as a result, formation thicknesses are incomplete. These strata are more completely exposed south of the quadrangle in the southeastern part of the San Pitch Mountains (Witkind and others, 1986; Weiss, 1994; Sprinkel and others, 1999), where they lie unconformably on the Twist Gulch Formation. These strata have been penetrated by wells in Sanpete Valley (Sprinkel, 1994), but the formations are difficult to distinguish consistently from well logs. The disparate thicknesses reported below probably result from difficulties in making consistent picks from the well logs, from unconformities and thickness changes within the section, and perhaps from structural complications beneath Sanpete Valley. Our subsurface interpretation indicates that the nonmarine section between the Twist Gulch Formation and Turonian marine strata (Allen Valley Shale) is 1,287 feet (392 m) thick in the Price N well (described above) and 2,190 feet (668 m) thick in the Hanson Oil Moroni #1AX well [NW1/4 SE1/4 NW1/4 section 14, T. 15 S., R. 3 E., located 3.7 miles (5.8 km) east-northeast of the northeastern corner of the quadrangle]. Sprinkel (1994) interpreted thicknesses for this interval of 2,050 feet and 1,634 feet (625 m and 498 m), respectively, in the same wells. The disagreement in interpreted thickness indicates the difficulty of consistently picking this interval of siltstone and sandstone in well logs.

Cedar Mountain Formation (Kc)

The Cedar Mountain Formation consists of purple, gray, reddish-brown and red claystone and mudstone and subordinate yellowish-gray or reddish-gray pebble and cobble conglomerate. Conglomerate beds are poorly sorted, clast-supported, and rich in chert and quartzite clasts. Thick mottled claystone beds contain irregular gray nodules of sandy micrite up to 3 inches (8 cm) in diameter. Beds of brownish-gray, muddy limestone and limy mudstone, and white to pale violet limestone that is speckled red and locally contains oncolites, are present but uncommon. Oncolitic limestone lenses in places grade upsection to conglomerate. Chert-rich, quartzose sandstone locally caps conglomerate beds and forms thin lenticular beds.

Conglomerate and sandstone of the Cedar Mountain Formation (lower member of Pigeon Creek Formation of Schwans, 1988a) represent deposits of ephemeral braided rivers (Schwans, 1988a, 1988b). The thick claystone beds represent floodplain deposits, with horizons of micrite nodules interpreted as paleosols (Schwans, 1988a), probably aridisols. The oncolitic limestones were deposited in small lakes on the floodplain.

The Cedar Mountain Formation is conformably overlain by the San Pitch Formation (Sprinkel and others, 1999), but the contact is not exposed in the Wales quadrangle. An incomplete section of approximately 327 feet (100 m) of Cedar Mountain Formation is exposed in the quadrangle. The complete formation is 305 feet (92 m) thick on the western flank of the San Pitch Mountains (Auby, 1991), and we interpret that approximately 544 feet (166 m) of Cedar Mountain was penetrated in the Price N well, just east of the quadrangle.

The Cedar Mountain Formation is Early Cretaceous (Barremian?-Albian) in age (Sprinkel and others, 1999). Palynomorphs from strata immediately above the Cedar Mountain are middle to late Albian in the southeastern and western San Pitch Mountains (Sprinkel and others, 1999). Late Albian palynomorphs are present near the top of the Cedar Mountain Formation on the Colorado Plateau (Tschudy and others, 1984). Sparse palynological data and lithologic similarity of strata of the thrust belt and Colorado Plateau have been invoked to correlate these strata and to extend use of the Cedar Mountain name to beds in the thrust belt (Standlee, 1982; Witkind and others, 1986). The resulting correlation indicates that the Upper Jurassic Morrison Formation is missing in the thrust belt and likewise indicates an unconformable Twist Gulch-Cedar Mountain contact (Witkind and others, 1986; Schwans, 1988a; Weiss and Roche, 1988; Sprinkel, 1994). The Cedar Mountain Formation is broadly correlative with the Kelvin Formation of northern Utah and the Cloverly Formation of western Wyoming.

Indianola Group

Continental strata conformable above the Cedar Mountain Formation and unconformable beneath the North Horn Formation along the eastern front of the San

Pitch Mountains are included in the Indianola Group. These strata have previously been mapped as undifferentiated Indianola Group where they are present in the Wales quadrangle (Spieker, 1949a). On the eastern side of Sanpete Valley, the Indianola Group is divided into four formations (Spieker, 1946). In ascending order, they are the Sanpete Formation, Allen Valley Shale , Funk Valley Formation, and Sixmile Canyon Formation. In formerly undifferentiated Indianola strata exposed in the Wales quadrangle, we recognized and mapped the San Pitch Formation and overlying Sanpete Formation. Younger formations of the Indianola Group, the Allen Valley Shale, Funk Valley Formation, and uppermost (unnamed) beds, are not exposed in the quadrangle, but are present in the subsurface. The Allen Valley and Funk Valley Formations were penetrated by the Chandler and Associates Inc. Sorenson 14-30 well located in the southeastern part of the quadrangle (SE1/4 SW1/4 section 30, T. 16 S., R. 3 E.)(figure 1, plate 2). They are shown only on cross sections and are also inferred to be present beneath the North Horn Formation in the San Pitch Mountains.

San Pitch Formation (Ksp_1, Ksp_2): A new name, San Pitch Formation, has been proposed by Sprinkel and others (1999) for conglomerate, sandstone, and siltstone conformably overlying the Cedar Mountain Formation and underlying the Sanpete Formation. Sprinkel and others (1999) further proposed that the San Pitch Formation be included in the Indianola Group, thus making the new formation the basal unit of the Indianola Group. The Sanpete Formation previously was considered the basal unit of the Indianola Group and the strata underlying it were named Morrison(?) Formation (Spieker, 1946; Lawton, 1982) or upper member of the Pigeon Creek Formation (Schwans, 1988a, 1988b). At the type locality in the southeastern San Pitch Mountains, the San Pitch Formation is divided into three informal members (Sprinkel and others, 1999). The structural disorder of San Pitch exposures and distance from the type locality make confident recognition of the three members in the Wales quadrangle uncertain.

The San Pitch Formation in the Wales quadrangle consists of interbedded conglomerate, pebbly sandstone, and red siltstone. Conglomerate and sandstone beds overlying the Cedar Mountain Formation are thick (3 to 8 feet; 1 to 2.5 m) and locally are stacked to form successions several tens of feet thick. Clast size in the conglomerate ranges from pebbles to boulders, with maximum dimensions exceeding 14 inches (35 cm). Conglomerate beds are clast supported and normally graded; the amount of coarse-grained sandstone increases upward within individual beds. A distinctive, massive boulder and cobble conglomerate, 66 feet (20 m) thick, is present between Coal and Blind Canyons (figure 1) at the base of Big Mountain (sections 13, 14, and 23, T. 16 S., R. 2 E.). Although quartzite clasts are typically dominant, carbonate clasts range from 10 to 50 percent. A distinctive and diagnostic feature of San Pitch conglomerate, both regionally and in the lower member in the Wales quadrangle, is the presence of light-green to aquamarine quartzite clasts. Subordinate red siltstone is interbedded with the conglomerate and ranges in thickness from 6.5 to 16 feet (2-5 m).

We recognized and mapped two members (Ksp_1, Ksp_2) in the San Pitch Formation. The members are in depositional contact, but the formational base is not exposed in the quadrangle. We tentatively correlate the members with the lower two of three informal members of the San Pitch Formation recognized by Sprinkel and others (1999) in the southern San Pitch Mountains. Our lower member (Ksp_1) comprises beds of chert- and carbonate-pebble conglomerate separated by thick beds of red siltstone; our upper member (Ksp_2) is dominated by quartzite-pebble and quartzite-cobble conglomerate with thin interbeds of red sandy siltstone. The uppermost member of Sprinkel and others (1999), which consists of boulder conglomerate overlain by red siltstone, was not recognized in the Wales quadrangle, either because it is truncated beneath the Sanpete Formation or because of facies changes northward.

The San Pitch Formation probably was deposited on the distal parts of alluvial fans (Schwans, 1988a). The boulder conglomerate within the formation was probably deposited by hyperconcentrated flow events and may represent eastward progradation of proximal alluvial-fan deposits from the Sevier orogenic belt.

A maximum, incomplete thickness of about 327 feet (100 m) of San Pitch Formation is exposed in the Wales quadrangle. The formation is 688 feet (210 m) thick in the southeastern part of the San Pitch Mountains, where palynomorphs indicate a middle to late Albian age for the unit (Sprinkel and others, 1999). This age assignment suggests equivalence with the upper part of the Cedar Mountain Formation of the Colorado Plateau.

Sanpete Formation (Ks): Strata assigned to the Sanpete Formation consist of moderately sorted, cross-bedded quartzose sandstone and pebbly sandstone interbedded with drab, olive-gray siltstone and sandy siltstone. The conformable contact with underlying San Pitch beds is sharp, and is defined as the contact between tan-weathering pebbly sandstone and subjacent thick beds of red siltstone. The contact is best displayed in the hinge region of a chevron fold northeast of south Coal Canyon (SE1/4 SE1/4 section 16, T. 16 S., R. 2 E.). Sanpete sandstone beds are 4 to 10 feet (1.2-3 m) thick, laterally continuous for hundreds of feet (tens to hundreds of meters), and have sharp bases above the siltstone beds, which are of similar thickness. The sandstone beds are moderately well cemented and weather white, yellowish gray, and grayish orange. The sandstone typically contains small (a few millimeters), reddish-gray to yellowish-gray weathering iron-oxide concretions that are most conspicuous on freshly broken surfaces. The Sanpete Formation weathers white beneath the unconformable contact with the North Horn Formation. In the Wales quadrangle the Sanpete Formation is entirely continental, representing deposits of braided rivers.

An incomplete, maximum thickness of about 560 feet (170 m) of Sanpete Formation is exposed in the Wales quadrangle. The formation is present in blocks bounded by reverse faults at the base of Big Mountain and unconformably beneath the North Horn Formation at Wales Canyon and Big Mountain. Schwans (1988b) measured 787 feet (240 m) in Sixmile Canyon, southeast of the Wales quadrangle, although he did not specify the location of the basal contact. At the same locality, Weiss (1994), estimated a thickness of 2,100 feet (640 m).

The Sanpete Formation ranges from late Albian to early Turonian in age. Palynomorphs collected from the unit in the southeastern part of the San Pitch Mountains include *Cicatricosisporites* spp. and *Appendicisporites* spp. (Fouch and others, 1983), which suggest an Albian age (Jacobson and Nichols, 1982). The Sanpete overlies Albian strata of the San Pitch Formation in the southeastern part of the San Pitch Mountains (Sprinkel and others, 1999). At Sixmile Canyon, *Inoceramus labiatus* is present 260 feet (80 m) beneath the top of the formation (Schwans, 1988b) and *Mytiloides mytiloides* is present 15 feet (4.5 m) beneath the top of the formation (W. B. Cobban, written communication, 1982). Both fossils are early Turonian bivalves. The contact with the overlying Turonian Allen Valley Shale is a transgressive unconformity, or flooding surface (Schwans, 1988b, 1995)

Allen Valley Shale (Ka): In outcrops in the region this unit consists of gray siltstone and shale with subordinate thin beds of tan, very fine grained sandstone and bentonitic air-fall tuff (Spieker, 1946; Lawton, 1982; Weiss, 1994). The formation is marine and records the Greenhorn transgression. The Allen Valley Shale contains the ammonite *Collignoniceras woollgari* (Lawton, 1982), which indicates a middle Turonian age (Cobban, 1976). The Sorenson well penetrated 624 feet (190 m) of Allen Valley Shale. An east dip of approximately 30 degrees in the well (Lawton, 1985) yields a stratigraphic thickness of 540 feet (165 m), a value consistent with reported regional thicknesses (Spieker, 1946; Lawton, 1982; Schwans, 1988b).

Funk Valley Formation (Kf, Kfl, Kfu): The lower part (Kfl) consists of interbeds of tan fine- to medium-grained sandstone 10 to 50 feet (3 - 15 m thick) and siltstone up to 25 feet (7.5 m) thick. Gamma-ray logs indicate that the lower two sandstone bodies coarsen upward and have sharp tops; these probably represent shoreface sandstone bodies in the lowest 210 feet (65 m) of the Funk Valley. In contrast, sandstone bodies higher in the section, but also in the lower part of the formation, have bell-shaped or blocky gamma-ray profiles and are interpreted as upward-fining or ungraded fluvial deposits, respectively. The fluvial strata occupy the upper 790 feet (240 m) of the lower Funk Valley interval penetrated by the Sorenson well. The penetrated thickness of the lower part of the Funk Valley Formation is thus 1,000 feet (305 m); when corrected for a 30-degree dip, the stratigraphic thickness is about 870 feet (265 m). Schwans (1988b) reported 1,150 feet (350 m) of lower Funk Valley at Sixmile Canyon. The lower part of the Funk Valley Formation is the lithostratigraphic equivalent of the Ferron Sandstone Member of the Mancos Shale (Lawton, 1982). The Ferron is of middle to late Turonian age in the Castle Valley area east of the Wasatch Plateau (Cobban, 1976).

The upper part of the Funk Valley Formation (Kfu) in the Sorenson well consists of shale and siltstone. In outcrops, the upper Funk Valley is mostly tan, well sorted, very fine grained shoreface sandstone and subordinate gray marine siltstone and shale (Spieker, 1946; Lawton, 1982; Weiss, 1994). The Sorenson well penetrated 822 feet (250 m) of upper Funk Valley below the well casing. Correction for a 30-degree dip yields a minimum stratigraphic thickness of 712 feet (217 m). The Hanson Moroni #1-AX well northeast of the quadrangle (NW1/4 SE1/4 NW1/4 section 14, T. 15 S. R. 3 E.) penetrated 2,400 feet (732 m) of shaly upper Funk Valley beneath shoreface sandstones. In contrast, only about 327 feet (100 m) of dominantly shaly rocks are present in the upper part of the Funk Valley at Sixmile Canyon (Schwans, 1988b). From these observations, we infer that the upper Funk Valley at Sixmile Canyon is reduced in thickness by a thrust fault (see also Lawton, 1982, figure 2).

The upper part of the Funk Valley Formation ranges in age from late Turonian to Coniacian. Shoreface sandstones high in the unit at Sixmile Canyon contain *Inoceramus deformis* (Lawton, 1982), a Coniacian bivalve (Kauffman, 1977). Schwans (1988b) also reported *I. deformis* about 164 feet (50 m) above the base of the upper part of the Funk Valley. The upper part of the Funk Valley is equivalent to part of the Blue Gate Member of the Mancos Shale in the Castle Valley area (Cobban, 1976).

Upper unnamed beds (Ku): This unit, shown only in cross section, is inferred to be present above the Funk Valley Formation in the San Pitch Mountains. It is equivalent to coal, siltstone, sandstone, and conglomerate of Santonian and Campanian age present north of the quadrangle and assigned to the upper part of the Indianola Group and the South Flat Formation (Hunt, 1954; Thomas, 1960; Fong, 1995). Coal-bearing Santonian strata above the upper part of the Funk Valley in the Hanson Moroni #1-AX well are interpreted as equivalent to this unit. These strata are as thick as 3,260 feet (995 m) in the northern part of the San Pitch Mountains, but they are truncated southward beneath conglomerate at the base of the North Horn Formation and are not present in the southwestern part of the range.

We believe that the Sixmile Canyon Formation, the uppermost formation of the Indianola Group on the east side of Sanpete Valley, correlates with the basal part of the North Horn Formation in the Wales quadrangle. This interpretation explains why we do not include the uppermost beds of the Indianola Group in the Sixmile Canyon Formation, but requires explanation at this point. The Sixmile Canyon Formation overlies the Funk Valley Formation unconformably at Sixmile Canyon, the type locality for the Indianola Group (Spieker, 1946; Lawton, 1982). At Sixmile Canyon, it consists of sheetlike beds of white, locally pebbly, quartzose sandstone and interbedded drab siltstone, dark-gray shale and rare coal. Coal-bearing beds near the top of the Sixmile Canyon Formation contain the palynomorph, *Proteacidites retusus* (S. N. Nelson, Chevron USA, written communication, 1990), which ranges from Coniacian through Campanian. In the Hanson Moroni #1-AX well, quartzose sandstone beds that are correlated with the Sixmile Canyon Formation overlie Santonian coal-bearing strata, contain *Acanthotriletes varispinosus, Proteacidites retusus, Nevesisporites semiscalaris, Gleicheniidites senonicus*, and *Trilobosporites humilis*, and have been interpreted as Campanian-Maastrichtian (G.A. Waanders, written communication, 1983). The type Sixmile Canyon Formation is overlain by late Campanian beds of the Price River Formation (Fouch and others, 1983). Therefore, the type Sixmile Canyon Formation is Campanian in age.

The upper contact of the Indianola Group with the Price River Formation at Sixmile Canyon is an angular unconformity at its westernmost exposure (Spieker, 1946), but it becomes concordant eastward in a short distance (Lawton, 1982). Similar discordances are present within strata assigned to the upper member of the Sixmile Canyon Formation. We therefore infer the presence of several unconformities within the Campanian section that become conformable eastward, each formed by progressive rotation of bedding during deposition. Because similar unconformities are present in the basal part of the North Horn Formation, also Campanian, in the Wales quadrangle, we regard the upper part of the Sixmile Canyon Formation at the type locality as equivalent to beds within the lower part of the North Horn Formation in the San Pitch Mountains. These equivalent, but previously miscorrelated, beds formed on opposite sides of the rising Sanpete Valley antiform.

Cretaceous and Tertiary Systems

North Horn Formation

The North Horn Formation, which spans the Cretaceous-Tertiary boundary, rests unconformably on all older formations exposed within the Wales quadrangle. It contains dramatic facies changes in a north-south direction within the quadrangle (figure 2). Intraformational unconformities are also present throughout the North Horn section; these tend to have greater amounts of angularity and stratigraphic omission in easternmost exposures and grade westward into apparently conformable strata where they can be traced an adequate distance into the range. The North Horn is divided into eight informal members (figure 2) in order to better depict the structure of the San Pitch Mountains and to illustrate the synorogenic character of the formation. The eight members are described in greater detail in Lawton and others (1993).

The North Horn Formation varies greatly in thickness in the Wales quadrangle. Its maximum measured thickness is 3,600 feet (1,100 m) at Big Mountain (sections 11, 12, and 13, T.16 S., R. 2 E.; Lawton and others, 1993), where the section is probably thinned somewhat by a reverse fault low in the section. Westward thickening of the individual members of the formation into the range indicates that the North Horn is probably even thicker in the subsurface in the central part of the quadrangle. Immediately south of the quadrangle, the formation is only 138 feet (42 m) thick where it unconformably overlies deformed Twist Gulch beds and the lower six members of the formation are absent (Lawton and others, 1993). Drill holes in Sanpete Valley penetrated thin sections of the North Horn above deformed Indianola strata (Price N and Hanson Moroni wells) and locally the North Horn is absent in the subsurface (Sorenson 14-30 well; plate 2). These relationships doc-

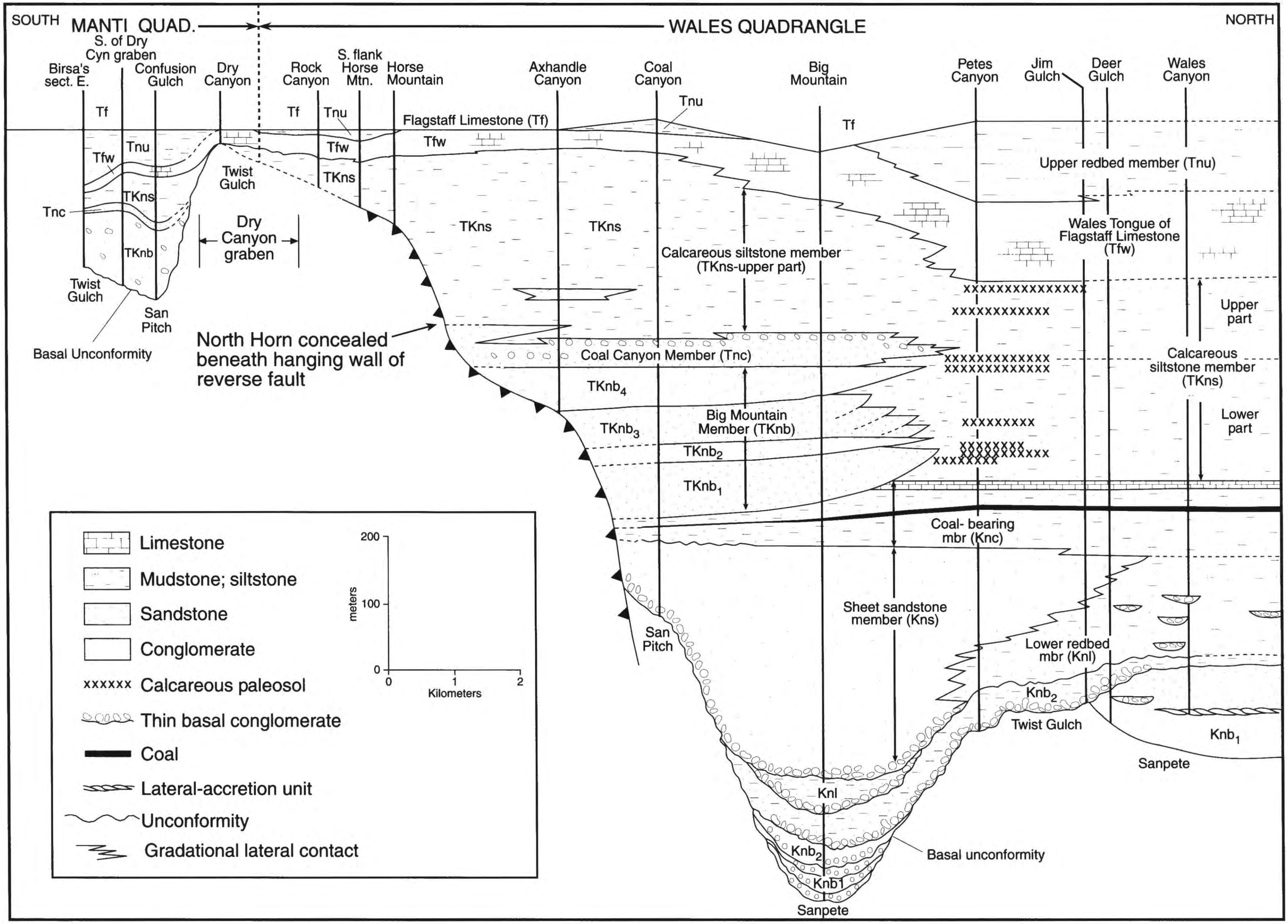

Figure 2. North-south stratigraphic diagram of North Horn Formation and Wales Tongue of Flagstaff Limestone exposed on the eastern range front of the San Pitch Mountains in the Wales and Manti quadrangles. See plate 2 for unit symbols. Westward thickening of the individual members of the North Horn Formation also results in the lateral thickness changes. Modified from Lawton and others (1993). See figure 1 for locations of sections; North Coal Canyon lies between Deer and Jim Gulches. Southernmost section is from Birsa (1973).

ument onlap of the North Horn onto a Cretaceous uplift, the Sevier-Sanpete Valley antiform, that now lies beneath the western part of Sanpete Valley.

The North Horn Formation ranges in age from Late Cretaceous (late Campanian) to early Eocene (Lawton and others, 1993; Talling and others, 1994, 1995). Dinosaur bones are present within the formation to a point at least 980 feet (300 m) above the base of the section just south of Wales Canyon (SE1/4 section 26, T. 15 S., R. 2 E.). The age of the upper part of the formation is from a paleomagnetic study of composite sections from Axhandle and Petes Canyons (Hobbs, 1989; Lawton and others, 1993; Talling and others, 1994).

Basal conglomerate member (Knb, Knb_1, Knb_2): The basal conglomerate of the North Horn Formation is divided into two submembers separated by an angular unconformity. The lower of these two submembers (Knb1) is exposed discontinuously from the northern edge of the quadrangle to Big Mountain. It is best exposed as the cockscomb between Wales Canyon and Deer Gulch (figure 1), where it is about 328 feet (100 m) thick, and in Lambs Canyon (figure 1) at the foot of Big Mountain (NE1/2 section 13, T. 16 S., R. 2 E.), where it is 180 feet (55 m) thick. At both of these localities, the lower submember rests on overturned, east-dipping Sanpete Formation. It is at least 264 feet (81 m) thick in the central part of the Fountain Green South quadrangle (Hunt, 1950). In its lower part, the lower submember consists of clast-supported boulder and cobble conglomerate in beds 6 to 33 feet (2-10 m) thick interbedded with trough cross-bedded sandstone. The sandstone beds range in thickness from 1 to 33 feet (0.3-10 m). The conglomerate is composed of subequal amounts of rounded quartzite and carbonate (limestone and dolostone) clasts.

The upper submember (Knb_2) onlaps eastward beyond the pinchout of the lower submember onto thrusted Jurassic and Cretaceous strata. In the northern part of the quadrangle, the upper submember consists of reddish-brown weathering, horizontally laminated conglomerate and sandstone in beds 3 to 6 feet (1-2 m) thick and interbedded sandy siltstone that contains scattered, rounded quartzite pebbles and cobbles. Angular blocks of Twist Gulch Formation, some exceeding 5 feet (1.5 m) in diameter, are locally present in the sandy siltstone. At Big Mountain, the upper submember is tan-weathering beds of conglomerate that grade upward into tan, cross-bedded sandstone. Quartzite and carbonate clasts decrease in abundance upsection and are replaced by clasts of tan quartz arenite, gray oncolitic limestone, and conglomerate with pebbles of limestone and quartzite. Clasts increase to boulder size and rounding decreases near the top of the upper submember at Big Mountain. In Lambs Canyon at the foot of Big Mountain, the upper submember is 160 feet (48 m) thick, and it appears to pinch out to the south (figure 2; Lawton and others, 1993).

The lower submember (Knb_1) is absent between Big Mountain and Deer Gulch. The upper submember rests depositionally on overturned Twist Gulch strata between Deer Gulch and Petes Canyon, but the unconformity is commonly hidden beneath faulted panels of Twist Gulch and Cedar Mountain strata. The unconformity is best exposed in (figure 1), a small drainage south of North Coal Canyon.

The observed upsection change in clast types in the basal conglomerate at Big Mountain records a shift from a dominantly western source to an eastern source in the Sanpete-Sevier Valley antiform. In the lower submember, quartzite clasts were derived from Precambrian formations and carbonate clasts were derived from Paleozoic formations exposed west of the Wales quadrangle. Clasts of tan quartz arenite, oncolitic limestone, and polymictic limestone and quartzite-clast conglomerate in the upper submember were derived from Cretaceous formations exposed in the Sanpete-Sevier Valley antiform. Uncommon quartzite clasts are also present, and presumably were recycled from Cretaceous conglomerate beds. Jurassic blocks, described earlier, are present in equivalent strata north of Big Mountain, and were also derived from the Sanpete-Sevier Valley antiform.

At Big Mountain, progressive changes in stratal dips, bounded by angular intraformational unconformities within the basal conglomerate, demonstrate progressive westward structural rotation of the member during its deposition. Unconformity-bounded intervals of sandstone and conglomerate are arranged into upward-fining sequences averaging 66 feet (20 m) thick where they disappear into the subsurface. The bounding unconformities are angular and cause individual sequences to thin eastward and, in some cases, to pinch out. Each successive conglomeratic sequence dips about 20 degrees less to the west than the underlying sequence. Similar geometries in conglomerates that flank the Ebro basin in Spain have been termed "progressive syntectonic unconformities" and are interpreted as representing syndepositional uplift of thrust sheets and offset on basin-bounding faults (Riba, 1976; Anadon and others, 1986).

The lower submember represents braided-fluvial deposits of streams that flowed eastward from the Sevier orogenic belt and transported detritus from Precambrian and Paleozoic formations. The deposits may have filled valleys cut into the Indianola Group. In contrast, the upper submember represents small alluvial fans shed westward from a nearby uplift. Sources for the clasts in the upper submember included the lower submember, which contributed quartzite clasts, and Indianola, Cedar Mountain, and Twist Gulch strata of the Sevier-Sanpete Valley antiform as the stratigraphic section was progressively unroofed by erosion.

The basal conglomerate is late Campanian in age, based on tight stratigraphic brackets. It can be traced northward into the Fountain Green South quadrangle, where it has been mapped as Price River Formation (Fong, 1995) and unconformably overlies coal-bearing strata that contain late Campanian to Maastrichtian palynomorphs (G.A. Waanders, written communication, 1995). It is overlain by strata of the lower redbed member interpreted as late Campanian based on their magnetic reversal stratigraphy (Talling and others, 1994). The basal conglomerate is equivalent to unit 227 of Hunt (1950, p. 191), a quartzite-cobble and -boulder conglomerate exposed in the upper part of Chicken Creek, immediately west of the Wales quadrangle.

Lower redbed member (Knl_1, Knl_2): The lower redbed member overlies the basal conglomerate in angular unconformity. The member consists of thick intervals of poorly exposed reddish-brown siltstone, subordinate clast-supported conglomerate lenses, and some pebbly sandstone. The siltstone is poorly sorted and lacks bedding structure, suggesting bioturbation. Thin (2 - 8 in; 5 - 20 cm) beds of very fine to coarse-grained, very light gray sandstone within the siltstone contain trough crossbeds, mottled tops and vertical rootlet traces. Discrete horizons 5 to 6.6 feet (1.5 - 2 m) thick of sandy micrite nodules are present within the siltstone. These are conspicuous and locally form slopes scattered with nodules, even where the siltstone is not well exposed. Nodules consist of sandy gray micrite and are subspheroidal, warty, and 1/2 to 1 inch (1 - 2 cm) in diameter. Quartz sand grains are present in amounts of a few percent. Vertical micrite tubules with diameters of up to 1.5 in (3 cm) are present in most nodule horizons. Conglomerate lenses are 3.3 to 8 feet (1 - 2.5 m) thick and as little as 33 feet (10 m) wide in outcrop. Clasts within the lenses grade upsection from boulders with a maximum observed diameter of 11 inches (28 cm) at the bases to cobbles and pebbles at the tops.

The lower redbed member thins southward from about 660 feet (200 m) at Wales Canyon to about 260 feet (79 m) at Big Mountain, where it disappears beneath the hanging wall of a reverse fault. Much of the thinning is a result of interfingering with the laterally adjacent and overlying sheet sandstone member. Dinosaur bones, in both siltstone and conglomerate, and magnetostratigraphy indicate that the lower redbed member is late Campanian-early Maastrichtian (Talling and others, 1994). The lower redbed member was deposited by an ephemeral fluvial system, probably in a distal alluvial-fan setting. Conglomerate was deposited in incised narrow channels cut into well-drained interfluves (siltstone) that developed calcareous aridisols, recorded by the micrite nodules and vertical tubules.

Syntectonic, intraformational unconformities marked by angular discordances are present locally, but cannot be mapped for significant distances in the lower redbed member. These are shown schematically on cross sections A-A′ and B-B′ and the submembers thus separated are labeled Knl_1 and Knl_2.

Sheet sandstone member (Kns): The sheet sandstone member gradationally overlies the lower redbed member at Big Mountain and both overlies it and laterally interfingers with it northward from Petes Canyon (figure 2). The sheet sandstone member consists of laterally continuous, tabular, light-brown beds of fine- to coarse-grained sandstone interbedded with carbonaceous siltstone; it weathers to form ribbed or ledgy hillsides. Sandstone beds are typically 10 to 13 feet (3 - 4 m) thick. Sandstone within each bed fines upward and grades into overlying siltstone. Sandstone beds are commonly in stacks of 2 or 3 with little or no intervening siltstone, forming multistory sandstone bodies. The dominant sedimentary structure in the sandstone is large-scale trough cross-bedding. Interbedded siltstone intervals range from less than 3 feet to 50 feet (1 - 16 m) thick. The siltstone is gray to olive gray, mottled, and generally without distinct internal bedding. Siltstone and sandstone are roughly subequal in abundance in the lower part of the member, but siltstone becomes dominant in the upper part. Thin, very fine-grained sandstone beds a few inches thick are present within the siltstone. An uncommon but characteristic rock type is brown-weathering, dark-gray micrite in beds up to 30 inches (80 cm) thick. The micrite beds contain up to 10 percent charophyte fragments, gyrogonites, gastropods, and ostracodes. Like the siltstone, micrite is more common in the upper part of the member and largely absent from the lower part.

The sheet sandstone member represents meanderbelt and floodplain deposits, with some lacustrine or marsh deposits represented by the micrite beds and abundant siltstones of the upper part. It varies dramatically in thickness from north to south within the Wales quadrangle. It is 1,310 feet (400 m) thick in Blind Canyon at Big Mountain (section 14, T. 16 S., R. 2 E.), only 460 feet (140 m) thick at Petes Canyon, and absent at Wales Canyon (figures 1, 2). Between Petes and North Coal Canyons (figures 1, 2), the sheet sandstone member is replaced by the lower redbed member and therefore is not present to the north. Its stratigraphic thickness varies by a factor of two from hanging wall to footwall of a reverse-fault duplex at Coal Canyon (cross section H-H′). This thinning resulted from erosion after faulting but prior to deposition of the overlying coal-bearing member.

The age of the sheet sandstone member is Late Cretaceous, (late Campanian to Maastrichtian; Talling and others, 1994). A Maastrichtian palynomorph assemblage was collected 216 feet (66 m) above the base of the member [705 feet (215 m) above the base of the North Horn Formation] at Petes Canyon (sample 90NH5; appendix 1).

Coal-bearing member (Knc): Olive-gray siltstone with abundant plant fragments is the dominant rock type of the coal-bearing member; abundant coal beds and coal-streaked siltstone are interbedded with the siltstone. Gray to brown micrite beds are abundant near the top of the member and in association with the coal beds. The micrite contains ostracodes, gastropods, and charophyte fragments. Interbedded coal beds are as much as 4 feet (1.3 m) in thickness. Micrite beds are thicker and more abundant northward in the quadrangle, reaching such abundance that they form a hogback in Wales Canyon. The aggregate thickness of coal beds within the member averages 3.7 feet (1.1 m) (Doelling, 1972). A sandstone bed forms the base of the coal-bearing member southward from Coal Canyon; it is 20 feet (6 m) thick at Coal Canyon. It contains large, angular clasts of sandstone that appear to have been derived from the underlying sheet sandstone member. Numerous sandstone beds are present in the member near Coal Canyon. The coal-bearing member is 125 to 375 feet (38-115 m) thick.

The coal-bearing member overlies the sheet sandstone member and locally the lower redbed member (figure 2). The contact is an angular unconformity that becomes increasingly concordant with distance westward from the zone of imbricate reverse faults. It is apparently conformable in Petes Canyon, where the sheet sandstone member grades upward into the coal-bearing member by a loss of sandstone beds and an increase in abundance and thickness of siltstone intervals. Likewise, to the north of North Coal Canyon (figure 1), the lower redbed member grades upward into the coal-bearing member through an alternation of reddish-brown siltstone beds with micrite nodules and mottled olive and gray siltstone that finally gives way to drab gray carbonaceous siltstone and shale. In the vicinity of Coal Canyon and southward to the point where the contact disappears beneath the hanging wall of a reverse fault (figure 2), the coal-bearing member unconformably overlies the sheet sandstone member with about 4 degrees of angular discordance. The angularity of the contact decreases northward. As noted above, angular clasts derived from the sheet sandstone member are present in the basal sandstone of the coal-bearing member above the unconformity. The angular unconformity resulted from active growth, coeval with deposition, of the western forelimb of the Sevier-Sanpete Valley antiform, a fault-propagation fold partially exposed along the flank of the present range. The basal contact of the coal-bearing member records a transition westward (basinward) from angular unconformity on the flank of the piggyback basin to conformable contact with increasing distance from the forelimb of the fold.

The coal-bearing member was deposited in marshy bogs or mires and poorly drained floodplains. The sandstones represent meandering-stream deposits. The member is Maastrichtian in age (Talling and others, 1994). A charophyte assemblage collected near the top of the coal-bearing member, characterized by the presence of *Retusochara* and the absence of *Platychara*, corroborates the age interpretation (R. M. Forester, U. S. Geological Survey, written communication, 1988).

Calcareous siltstone member (TKns): The calcareous siltstone member overlies the coal-bearing member at Petes Canyon and northward (figure 2). The contact is at the base of a nodular calcareous siltstone that sharply overlies a prominent sandstone bed at the top of the coal-bearing member. At Petes Canyon, the calcareous siltstone member is 833 feet (254 m) thick. The principal rocks in the calcareous siltstone member are calcareous siltstone and mudstone in thick beds that weather to blocky or massive ledges. The blocky weathering structure is particularly associated with gray to olive-gray siltstone beds and is believed to be pedogenic in origin. Sand grains compose up to a few percent of the siltstone. Gastropod fragments are locally present. Massive siltstone beds are also sandy and are more brightly colored than the blocky ones. Colors include red, purple and gray. The red and purple horizons are associated with discrete horizons of warty micrite nodules about 1.5 inches (3 cm) in diameter. Vertical micrite tubules 2 inches (5 cm) in diameter are present in some nodular intervals.

Sandstone beds are subordinate in the member. Those associated with blocky siltstone are typically tabular and 8 to 30 inches (20-75 cm) thick; they form upward-thickening and -coarsening sequences that are as much as 6.6 feet (2 m) thick, are very fine to medium grained, bioturbated and sparsely fossiliferous, with gastropods, ostracodes, and algal fragments. Sandstone beds associated with the variegated massive siltstones are broadly lenticular to tabular and as much as 6.6 feet (2 m) thick; they range from fine grained to very coarse grained, with grain size decreasing upward through individual beds. Limestone and quartzite pebbles are locally present in lags at the bases of sandstone beds.

Depositional environments of the calcareous siltstone member alternated between lake-margin settings and well drained floodplains. The drab siltstone was deposited in shallow- or marginal-lacustrine flats; associated upward-coarsening sandstone beds represent sandy lacustrine deltas. The brightly colored massive siltstone beds with micrite nodules represent deposits of floodplains with paleosol; associated lenticular sandstone beds are interpreted as deposits of meandering rivers.

In the southern part of the quadrangle the upper part of the siltstone member, above the Coal Canyon Member, contains abundant lenticular sandstone and conglomerate beds that are uncommon in the northern part of the quadrangle. These interbeds of coarse-grained sandstone and conglomerate pinch out westward into siltstone. The sandstone beds are lenticular and commonly hundreds of meters wide. The beds contain lenses of whole and fragmental oncolites, and cobbles and pebbles with concentrically laminated micrite rims up to 0.4 inch (1 cm) thick. Laminated to stromatolitic micrite caps these lenses and is overlain in turn by blocky calcareous siltstone or sandstone. Conglomerate beds contain large foresets, locally with preserved heights of 13 feet (4 m), extending from the top to the base of the entire bed. Brightly colored siltstones are absent from the southern sections. This coarse-grained lithofacies association of the calcareous siltstone member is interpreted as having been deposited by lacustrine deltas and adjacent fluvial systems.

In the southernmost part of the quadrangle the calcareous siltstone member is the lowest exposed member of the North Horn Formation (figure 2). Sandstone and dolomitic mudstone dominate the member near Dry Canyon immediately south of the quadrangle boundary, where the North Horn thins rapidly eastward from 112 feet (34 m) to a pinchout on a paleohill of Twist Gulch sandstone and mudstone. In the vicinity of the pinchout, the calcareous siltstone member contains clasts and red mud reworked from the underlying Twist Gulch Formation.

The calcareous siltstone member is latest Cretaceous to Paleocene in age. The laterally equivalent Big Mountain member, which is a complex lithosome contained within the calcareous siltstone member (Lawton and others, 1993), contains Late Cretaceous palynomorphs at its base 1.75 miles (2.8 km) south of the Wales quadrangle (sample 92M3; appendix 1). At Axhandle Canyon, the upper part of the calcareous siltstone member, lying above the Big Mountain member, contains *Microcodium*, a microfossil common in Paleocene strata of Europe (Monique Feist, Université de Montpelier II, France, written communication, 1991). A sample of carbonaceous shale collected from the calcareous siltstone member on the flank of Horse Mountain (sample 91W10; appendix 1) yielded the palynomorphs, *Momipites wyomingensis*, found in lower Paleocene to Eocene strata of the Idaho-Wyoming thrust belt (Jacobson and Nichols, 1982), and *Kurtzipites simplex*, with a range of Maastrichtian to early Paleocene (F. E. May, Palynex International, written communication, 1992).

Big Mountain member (TKnb$_{1-4}$): South of Petes Canyon, strata equivalent to the lower part of the calcareous siltstone member consist of interbedded conglomerate and sandstone, with a maximum thickness of 754 feet (230 m) at Big Mountain (figure 2). These members form imposing cliffs at Big Mountain and at the mouth of Axhandle Canyon. In ascending order, the member is divisible into four submembers, or lithosomes: a lower sandstone (TKnb$_1$); a lower conglomerate (TKnb$_2$); an upper sandstone (TKnb$_3$); and an upper conglomerate (TKnb$_4$). The sandstone submembers are medium- to coarse-grained sandstone with trough crossbeds. Pebbles and intraclasts are present as lags at the sharp bases of sandstone beds, which are as much as 10 feet (3 m) thick. Log impressions are present within some lags.

The conglomerate submembers are discrete lithosomes compositionally and texturally different from the sandstones and from each other. They are clast-supported, with imbrication in basal lenses indicating eastward flow. Clasts are a mixture of quartzite and carbonate. The lower conglomerate contains about 50 percent limestone and dolostone clasts, whereas the upper conglomerate contains about 80 percent limestone and dolostone clasts (Lawton and others, 1993). Conglomerate beds are 7 to 10 feet (2-3 m) thick, with sandstone matrix increasing upward within each bed. Crude planar foresets are present, and thin beds of medium- to coarse-grained sandstone are present at the tops of some conglomerate beds. The Big Mountain member was deposited by east-flowing, sandy and gravelly braided rivers. Gravel was deposited as transverse or longitudinal bars capped by sandy bar tops.

Lithosomes within the Big Mountain member are separated by sharp unconformable contacts. The basal contact of the lower sandstone (TKnb$_1$) cuts downsection through the lower part of the calcareous siltstone member and the coal-bearing member from north to south (figure 2). The sandstone thickens rapidly westward, a relation best exposed in Coal Canyon. The lower conglomerate (TKnb$_2$) is unconformable on the lower sandstone in the vicinity of Coal Canyon. The upper conglomerate (TKnb$_4$) pinches out on the ridge south of

Petes Canyon, where its base rests on the calcareous siltstone member and cuts downward to the south into the upper sandstone submember ($TKnb_3$). These observations indicate that coarse-grained strata of the Big Mountain member occupy a paleovalley or succession of paleovalleys incised into, rather than interfingering with, the calcareous siltstone member (figure 2). Moreover, although dispersal of clastic material was eastward, the eastward thinning of the Big Mountain member indicates that the paleovalley traversed a rising uplift that lay east of present exposures. The lower part of the Big Mountain member is Late Cretaceous, based on palynomorphs collected from a mudstone lens at the base of the member 1.75 miles (2.8 km) south of the Wales quadrangle (sample 92M3; appendix 1).

Coal Canyon member (Tnc): The Coal Canyon member overlies the Big Mountain member and consists of stacked tabular beds of conglomerate, pebbly sandstone, and sandstone arranged in foresets as much as 6.6 feet (2 m) thick. The foresets include both tabular and broadly trough-shaped geometries. Foresets terminate laterally into burrowed sandstone and siltstone of the calcareous siltstone member and are onlapped by sandstone beds of the calcareous siltstone member (figure 2). Foresets indicate sediment transport to the west and northwest, which contrasts with the easterly sediment dispersal of the Big Mountain member and helps to distinguish the two members. The reversal of paleocurrent direction also indicates that, although subtle, an important unconformity separates these members. The Coal Canyon member is about 200 feet (60 m) thick in Coal Canyon and thins westward. Its base is at the top of the uppermost occurrence of east-transported conglomerate. The age of the member is Paleocene, based on its gradational transition upsection into beds of the calcareous siltstone member that contain Paleocene *Microcodium* sp.

The Coal Canyon member was deposited in small lacustrine deltas dispersed westward into a structural basin in which the North Horn Formation accumulated. The west-directed paleocurrents are unambiguous evidence for the existence of positive topographic relief immediately to the east during the Paleocene. The source of sediment for the deltas was probably the subjacent Big Mountain member which stood high in the present area of Sanpete Valley.

Upper redbed member (Tnu): The upper redbed member is the uppermost member of the North Horn Formation. It is best exposed on the ridge north of Petes Canyon (SW1/4 section 35, T. 16 S., R. 2 E.), where it sharply overlies the Wales Tongue of the Flagstaff Limestone. The member consists of red-brown mottled siltstone and sandy siltstone, with a few sandstone beds 1 to 6 feet (1/3 - 2 m) thick. Sandstone beds fine upward and have sharp bases and lenticular shapes; sandstone is fine to medium grained. Thin beds of gray micrite with gastropods and charophytes are uncommon in the member. Maximum thickness of the member is about 400 feet (120 m) in westernmost exposures in Axhandle and Petes Canyons. It thins to 262 feet (80 m) in exposures north of Petes Canyon and to a pinchout in easternmost exposures at Big Mountain. The upper redbed member was deposited on a low-gradient fluvial plain. Lenticular sandstone beds are deposits of fluvial channels cut into well drained, oxidized floodplain deposits represented by the siltstone, although much of the red material is recycled Twist Gulch detritus derived from the western margin of the piggyback basin.

The upper redbed member is early Eocene in age (Hobbs, 1989; Lawton and others, 1993; Talling and others, 1994). It is unconformably overlain by the main body of the Flagstaff Limestone.

Tertiary System

Wales Tongue of Flagstaff Limestone (Tfw)

The Wales Tongue is mostly carbonate rock that is separated from the main body of the Flagstaff Limestone in the northern part of the quadrangle by the upper redbed member of the North Horn Formation (figure 2). It gradationally overlies and intertongues with the calcareous siltstone member throughout the quadrangle. The contact with the upper redbed member is sharp and probably unconformable. South of Axhandle Canyon and along the northern part of Big Mountain, the main body of the Flagstaff lies directly on the Wales Tongue. Where the upper redbed member is absent, the contact is marked by a thin interval of discontinuous red siltstone. The Wales Tongue reaches a maximum thickness of 425 feet (130 m) in exposures in the upper reaches of Petes Canyon. It thins eastward to exposures at Big Mountain, where it is 101 feet (31 m) thick and is composed of distinctive, orange-weathering. sandy carbonate and siltstone beds. It was previously mapped as the calcareous siltstone member at Big Mountain (Talling, 1992; Lawton and others, 1993). It persists southward into the Manti quadrangle, where it is 102 feet (31 m) thick at the mouth of Dry Canyon. In that vicinity, the Wales tongue unconformably overlies the calcareous siltstone member of the North Horn and locally overlies the Twist Gulch; it is in turn overlain by the main body of the Flagstaff Limestone, with apparent unconformity.

The lower part of the Wales Tongue consists of dark gray fossiliferous wackestone and micrite beds as much as 3 feet (1 m) thick, interbedded with intervals of olive-gray and medium-gray claystone several feet thick. Subordinate thick beds of sandstone are present in the claystone. This stratigraphic interval is exposed only locally between Petes and North Coal Canyons (figure 1), for it is extensively covered by landslide deposits. The upper part of the Wales Tongue is ledge-forming dolostone, with some limestone and dolomitic limestone, in thick beds separated by thin mudstone beds. Gastropods are abundant in the limestone beds and oncolites are present locally. The upper part weathers white to orange and forms one of the most conspicuous and readily identifiable markers along the entire upper part of the range front.

The Wales Tongue is late Paleocene in age (La Rocque, 1960; Lawton and others, 1993; Talling and others, 1994). It is equivalent to the lower part of the Flagstaff Limestone of the Wasatch Plateau, as suggested by La Rocque (1960). It was deposited in a variety of open-lacustrine and lake-margin environments (Weiss, 1969; Lawton and others, 1993).

Flagstaff Limestone (main body) (Tf)

The main body of the Flagstaff Limestone weathers to form bold, pale gray to white cliffs along the length of the range front. It consists of light-gray and light-yellowish-gray limestone and light-gray dolostone in thin to thick beds. Limestones of the formation are mostly micrite and fine sparite. Gastropods are locally abundant. Thin interbeds and partings of shaly limestone define bedding in the limestone. Dolostone is typically dolomicrite with common irregular spar-filled cavities and local bladed pseudomorphs of calcite after gypsum. Gastropod shell fragments are common in the dolomicrite. Much of the light-gray dolomicrite is mottled and is intermixed with orange-weathering, tan, calcareous claystone. Rootlet traces are locally present in some mottled beds. Dolomicrite commonly contains very light-gray micritic intraclasts 0.08 to 0.3 inches (2 - 8 mm) in diameter. Sand content in the dolomicrite is as much as 10 percent. Thin beds of bluish-weathering oil shale occur low in the formation above Petes Canyon. Subordinate beds of fine- to medium-grained sandstone are present within the formation. These sandstone beds locally form well defined channels and elsewhere grade laterally into nodular calcareous siltstone, locally with brecciated textures.

The Flagstaff Limestone was deposited in an extensive, shallow, freshwater, carbonate marsh that was alternately subaqueously flooded and subaerially exposed. Intraclastic, sandy, fossiliferous dolomicrite, extensive evidence of bioturbation or rootlet churning, vadose breccias, evaporite pseudomorphs, and pedogenic nodules suggest that carbonate muds and calcareous siltstones were frequently exposed subaerially. Platt and Wright (1992) have used the term *palustrine* for freshwater carbonate successions that bear evidence for subaqueous deposition and subaerial exposure. They suggest that such deposits formed in extensive, very shallow carbonate marshes rather than by pedogenic modification of lake-margin facies.

The main body of the Flagstaff Limestone is 230 to 590 feet (70-180 m) thick in the quadrangle. Its basal contact with the upper redbed member is sharp and probably represents an unconformity near the eastern range front. The same contact appears to be conformable in the upper parts of Axhandle Canyon (section 16 and NE1/2 section 21, T. 16 S., R. 2 E.) and is probably conformable in the subsurface of the western part of the quadrangle.

The main body of the Flagstaff is early Eocene in age. Fouch and others (1983) reported an early Eocene palynomorph (*Platycarya platycaryoides*; Jacobson and Nichols, 1982) from a sample 256 feet (78 m) above the Flagstaff-North Horn contact at South Maple Canyon, 4 miles (7 km) south of the quadrangle. A Wasatchian carnivore was reported from float believed to be from the main body of the Flagstaff, also in South Maple Canyon (Rich and Collinson, 1973). Previous workers have correlated the main body of the Flagstaff in the San Pitch Mountains with the upper part of the Flagstaff on the Wasatch Plateau (La Rocque, 1960; Stanley and Collinson, 1979); unfortunately, the biostratigraphy remains ambiguous on this point. Alternatively, we suggest that the main body of the Flagstaff Limestone in the San Pitch Mountains is correlative, at least in part, with the middle part of the Flagstaff on the Wasatch Plateau (Cove Mountain Member of Stanley and Collinson, 1979). This correlation is suggested by comparable features of desiccation, such as dolostone and evaporite pseudomorphs that are common to both stratigraphic units. The Cove Mountain Member was interpreted by Stanley and Collinson (1979) to represent a major lowstand of Lake Flagstaff in the Wasatch Plateau on the basis of abundant features of desiccation and pedogenesis, as well as extensive gypsum beds in the member. We infer that those lowstand conditions simultaneously affected basins of the San Pitch Mountains and Wasatch Plateau, although the basins were separated intermittently by the Sanpete Valley antiform. The basin of the San Pitch Mountains, either because it lay nearer the relict, rainy highlands of the Sevier orogenic belt or because it had an outlet to the east, did not develop voluminous bedded gypsum.

Colton Formation (Tc)

The Colton Formation is present only in the western half of the quadrangle. It is dominantly mudstone and claystone of numerous colors, including reddish brown, light gray, violet, olive green, and red. Subordinate beds of yellowish-gray to yellowish-brown siltstone and silty sandstone are present in the mudstone. Sandstone is poorly cemented, fine to medium grained, and contains trough crossbeds. Sandstone beds have both sheet and channelform shapes.

Limestone beds are present locally in the mudstone successions of the Colton Formation. Limestone forms thin beds of dense, glassy micrite and finely crystalline sparite. The limestone layers are varied in color, including light-gray, white, olive, red, and violet shades. Some limestone beds contain mollusks and ostracodes. Intraclastic limestones, about half of which are micritic, make up 76 percent of the limestone beds (Volkert, 1980); the others are intrasparites and intrarudites, in about equal parts.

In strong contrast to older units, feldspar is an abundant mineral in Colton sandstones. Most grains are so weathered that identification is difficult, but plagioclase and potassium feldspar appear to be present in about equal amounts (Volkert, 1980). The feldspar is normally 7 to 12 percent of the grain population, but reaches as much as 27 percent in some samples. The feldspar content supports the hypothesis that the Colton had a basement source to the southeast (Stanley and Collinson, 1979; Dickinson and others, 1986).

Depositional environments of the Colton were mainly floodplains, represented by the claystone and mudstone beds, with subordinate sinuous channels, represented by the sandstone beds, and overbank ponds or marshes, represented by the limestone beds. The Colton is 560 to 647 feet (170 - 213 m) thick (Marcantel and Weiss, 1968; Volkert, 1980); it thickens westward in the quadrangle, but is thinner here than on the Wasatch Plateau.

In the Wales quadrangle, Volkert (1980) distinguished tongues up to 50 feet (15 m) thick at the top of the Colton Formation that consist of colored mudstone speckled with white patches having abundant analcime and dolostone. The speckles are surrounded by ferruginous mudstone. He suggested that the tongues may have formed in saline lakes high in soda.

The Colton Formation is early Eocene in age based on stratigraphic position between the early Eocene Flagstaff Limestone and middle to late Eocene Green River Formation.

Green River Formation (Tgl, Tgu)

In the San Pitch Mountains the Green River Formation consists of two unnamed members, a lower shale member (Tgl) and an upper limestone member (Tgu). The Green River Formation is a lacustrine deposit with a maximum thickness of 1,100 feet (335 m) in the central San Pitch Mountains (Millen, 1982). In the Wales quadrangle, the lower member thins from nearly 910 feet (277 m) to a feather edge in the northwest corner of the quadrangle. The upper member is present only in the southwestern part of the quadrangle, where 175 feet (53 m) of the member cap Big Baldy (NE1/4 section 25, T. 16 S., R. 1 E.).

The lower shale member is light-gray and grayish-green calcareous, thin-bedded, fissile shale. Numerous thin beds of gray to white micritic, glassy, or silty limestone, are present in the shale. The upper member (Tgu) is pale-yellowish-gray to pale-yellowish-brown, micritic dolostone and finely crystalline sparite in thin to thick beds. Some carbonate beds contain abundant, well-rounded coarse quartz sand grains. Thin shale and shaly limestone interbeds and biotitic tuff beds are present in the limestone. Tuff beds in the upper part of the Green River Formation at the northern end of the Wasatch Plateau, northeast of the Wales quadrangle, have yielded zircon fission-track ages ranging from 44.9 ± 2.1 to 42.3 ± 2.0 Ma (Bryant and others, 1989). The Green River Formation is middle to late Eocene in age in the Uinta basin to the north (Bryant and others, 1989).

Surficial Deposits

Consolidated alluvial-fan deposits (QTaf)

Consolidated alluvial-fan deposits consist of coalesced alluvial-fan complexes of large length and width. They are composed of silt, sand, and gravel up to boulder size. They grade away from the San Pitch Mountains to floodplain and channel deposits, with which they interfinger. Younger fan deposits locally overlie these consolidated alluvial fans. The deposits are comparable in thickness to the valley-fill deposits of Sanpete Valley; a well 0.5 mi southeast of Wales encountered 250 feet (75 m) of bouldery sand and silt above Jurassic(?) beds (Robinson, 1971), but elsewhere the deposits are thicker, perhaps as much as 820 feet (250 m).

Floodplain and channel deposits (Qal, QTal)

Floodplain and channel deposits consist of mud, silt, and sand of alluvial and minor debris-flow origin that occupy the axial region of Sanpete Valley. The detritus was derived from both the San Pitch Mountains and

Wasatch Plateau to the east. Thickness of the younger floodplain deposits (Qal) is not well constrained, but is estimated to be about 165 feet (50 m). The younger floodplain deposits (Qal) overlie similar older deposits (QTal). Older floodplain deposits are present only in the subsurface of the Wales Quadrangle. The thickness of valley fill is generally thicker on the west side of Sanpete Valley near the San Pitch Mountains, where it is 300-500 feet (92-153 m) thick, than on the east side of the valley (Robinson, 1971). Well logs and cuttings descriptions from Sanpete Valley indicate local valley-fill thicknesses (Qal and QTal) of perhaps as much as 820 feet (250 m). The deeper, older parts are Tertiary, probably Pliocene, in age.

Pediment-mantle deposits (Qap_1, Qap_2, Qap_3)

Pediment-mantle deposits consist of poorly sorted silt, sand, and gravel of pebbles and cobbles locally exposed on surfaces elevated above modern drainages. They were deposited on flat, planar bedrock surfaces which slope downstream parallel to modern stream profiles. Deposits are 0 to 33 feet (0 - 10 m) thick. Older deposits (Qap_2 and Qap_3) are exposed on successively higher surfaces, as much as 170 feet (52 m) above the streams, and give evidence of intermittent uplift of the plateau. They are most conspicuous in the lower part of North Coal Canyon (figure 1).

Alluvial-fan deposits (Qaf_1, Qaf_2, Qaf_3)

Alluvial-fan deposits consist of poorly sorted, variably consolidated mud, silt, sand, and gravel ranging in size up to large boulders. The deposits are exposed at the mouths of canyons and arroyos draining the San Pitch Mountains and form large, lobate, depositional features with slopes as much as 10 degrees. The deposits are as much as 50 feet (15 m) thick. Youngest alluvial-fan deposits (Qaf_1) are unconsolidated, of small size and active construction; they overlie older fan or floodplain deposits. The youngest alluvial-fan deposits are cut by a normal fault at only one location in the quadrangle (NE1/4 section 23, T. 16 S., R. 2 E). Older alluvial-fan deposits (Qaf_2) are more consolidated, are commonly offset by range-front normal faults, and are conspicuously dissected by modern drainage courses. Oldest alluvial-fan deposits (Qaf_3) are more dissected and are also offset by normal faults at the range front. The bottoms of clasts in fresh exposures of the oldest deposits have thin coatings of stage I calcium carbonate (for example, Gile and others, 1970) in the upper few feet (meter) of the deposit.

Slide and slump deposits (Qmsu, Qmst)

Slide and slump deposits mapped in the Wales quadrangle are mass-wasting deposits that consist of unsorted masses of soil and broken rock, up to very large boulders, some of which are crudely rounded. There are two types of slump deposits in the quadrangle. The first (Qmsu) consists of elongate deposits with high length-width ratios on steep slopes; they form extensive linear tracts that probably formed by accumulation of many failure episodes, both slumping and sliding, and incorporation with older slide masses during renewed sliding. In some instances, their upper ends are marked by a depression at the foot of a failure scarp; the downhill terminus of many deposits is lobate and steep, indicating recent movement. The slump deposits have irregular surfaces; many have ridges parallel to the length of the mass and some have wavy ridges across the width of the mass at its toe. Dead trees, particularly junipers, are common on their surfaces, indicating disruption of root systems during movement. Thicknesses range from 0 to 50 feet (0-15 m).

The second type of deposit (Qmst) consists of disorderly masses of broken rock formed on steep, shaded slopes in mudstone-rich formations. Movement of these deposits is rotational above inferred listric or curviplanar failure planes, causing bedding of formations within the deposit to dip into the hillside. If bedding is not extensively disrupted, these may be called toreva blocks. Angular clasts of many sizes are present, but the deposits are dominated by fine-grained sediment derived from the parent formations. Headwall scarps are typical. Surfaces are hummocky with many small closed depressions. Thicknesses range from 0 to 330 feet (0-100 m).

An excellent example of this second type of deposit (Qmst) is a great tumbled mass of broken Flagstaff Limestone on the east slope of Horse Mountain. It straddles the valley-bounding fault system and is arranged in a step-like fashion. Small exposures of the Twist Gulch and North Horn Formations show through the mass. Witkind and others (1987) mapped this deposit as a series of stepped faults. This deposit can also be interpreted as a set of multiple toreva blocks. For this report, we have mapped most of it as a slump mass because the stratigraphy is so disrupted that faults cannot be distinguished on the ground; they are suggested only by the morphology of the surface (see also cross-section J-J´). Some slump deposits, mostly those of the second type (Qmst), are deeply dissected, suggesting that they are older than the less-dissected deposits.

Debris-flow deposits (Qmf_1, Qmf_2)

Debris-flow deposits consist of poorly sorted silt, sand, and gravel with very coarse, angular boulders up to 8 feet (2.5 m) in diameter that project from the surface of the deposits. These deposits are exposed at the mouths of major canyons and constitute large parts of some alluvial fans. Estimated thicknesses are 0 - 26 feet (0 - 8) m. These deposits consist of natural boulder levees which flank a topographically low fanhead trench formed by large-discharge floods. Older debris-flow deposits (Qmf_2) have a rounded topography and more soil development than younger debris-flow deposits (Qmf_1) and are dissected by modern arroyos.

Colluvial deposits (Qc_1, Qc_2)

Colluvial deposits are unconsolidated mud, sand, and angular pebble- to large boulder-sized clasts that mantle bedrock on unstable slopes. Some deposits grade to alluvium at their lower edges. Colluvial deposits are mapped only if they are extensive or if they obscure unit contacts. Many unmapped small, thin exposures are present in the quadrangle. Colluvial surfaces are smoother than slumps and the deposits are thinner, being only 0 to 40 feet (0 - 12 m). Some colluvial deposits are dissected, not connected to an up-slope source of material, and no longer active. These older colluvial deposits are mapped as Qc_2.

Tufa deposit (Qst)

A single tufa deposit is present in the northeastern corner of the Wales quadrangle. It is a deposit of porous, dark yellowish-gray calcium carbonate. The deposit is mound-like, with an irregular, rough surface. It probably represents calcium carbonate deposited by a spring located on the trace of a reverse fault. Similar tufa deposits were mapped by Fong (1995) immediately north of the Wales quadrangle, but they are located on the range-front normal fault.

Stream alluvium (Qa_1, Qa_2)

These units consist of unconsolidated silt, sand, and gravel. No bedrock is exposed beneath these deposits. Estimated thicknesses range from 0 to 28 feet (0 - 8.5 m). The younger deposits (Qa_1) lie in and along modern steams and are not dissected; the older deposits (Qa_2) are dissected to depths of 10-28 feet (3 - 8.5 m) by modern streams.

STRUCTURAL GEOLOGY

The Wales quadrangle contains structures that originated by crustal shortening during the Sevier and Laramide orogenies, and younger structures that formed during Basin-and-Range extension. A large synform is present in the western two-thirds of the quadrangle in the upper plate of the Gunnison thrust system (figure 3). The fold contains Jurassic and Cretaceous strata deposited both before and during folding. The synform has an overturned east limb and an east-dipping axial surface near the eastern range front (figure 3). The zone of imbricate reverse faults at the range front cuts the overturned limb and contains the most prominent contractional structures in the quadrangle. Growth strata of the North Horn Formation, deposited during folding, occupy much of the central part of the range. The North Horn Formation was deposited in a piggyback basin that lay between a west-vergent fault-propagation fold (Sevier-Sanpete Valley antiform) at the eastern range front and a fault-bend fold or ramp anticline along the western side of the San Pitch Mountains (figure 3).

Structures formed during later crustal extension include three systems of normal faults: 1) northeast-southwest trending faults that offset strata as young as the Colton Formation in the northwestern part of the quadrangle; 2) east-west trending faults that offset strata as young as the Green River Formation and form the north side of the Dry Canyon graben near the southernmost edge of the quadrangle; 3) generally north-trending faults that lie along the western edge of Sanpete Valley, offset deposits of Quaternary age (Qaf_1, Qaf_2, Qaf_3), and create the modern structural and topographic relief between the San Pitch Mountains and Sanpete Valley.

The structural features of the quadrangle are described in detail and the timing and origin of structural deformation are interpreted in the sections that follow.

Zone of Imbricate Reverse Faults

Faults

These imbricate reverse faults on the west flank of the Sevier-Sanpete Valley antiform dip consistently eastward at angles of between 50 and 70 degrees and separate panels of Twist Gulch, Cedar Mountain, and Indianola strata (Plate 1; sections A-A´ to G-G´). Strata are overturned with moderate to steep east dips, except for some thick panels of upright Twist Gulch beds. One upright panel at the eastern exposure of bedrock extends from just south of Petes Canyon to the north edge of the quadrangle (cross sections A-A´ to E-E´). Twist Gulch beds faulted against the North Horn and Flagstaff at Horse Mountain and southward are also upright (cross sections J-J´; K-K´). The westernmost exposed faults emplace either Jurassic or Cretaceous rocks over strata as young as the Big Mountain member of the North Horn Formation. Fault planes, where visible, are characterized by extensive shearing of mudstone, inclusion of lozenge-shaped sandstone blocks in the mudstone, and spaced fracture cleavage parallel to the fault plane.

The zone of imbricate reverse faults has two distinct trends within the quadrangle. From the northern bound-

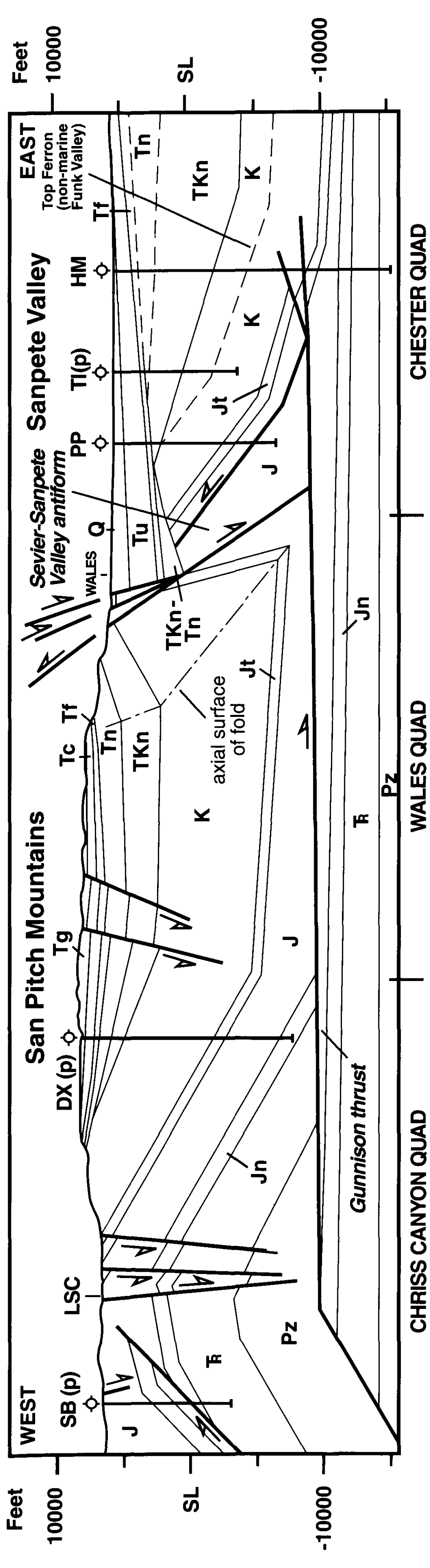

Figure 3. Structure section of San Pitch Mountains and Sanpete Valley. Data from this report, our unpublished surface mapping, and oil tests in adjacent quadrangles. ***Oil Wells (p, projected onto line of section):*** *DX=Dixel Gunnison State #1, NE¼NE¼ section 15, T. 16 S., R. 1 E; HM=Hanson Oil Moroni #1-AX, SE¼NW¼ section 14, T. 15 S., R. 3E.; PP=Phillips Price N #1, SE¼SE¼ section 29, T. 15 S., R. 3E.; SB=Amoco Sevier Bridge Unit #1, SW¼SE¼ section 11, T. 16 S., R. 1 W.; Tl=Tennessee Gas Irons #1, SE¼NE¼ section 16, T. 15 S., R. 3 E..* ***Rock units:*** *Pz=undifferentiated Paleozoic strata; ₮=undifferentiated Triassic strata; Jn=Navajo Sandstone; J=undifferentiated Middle Jurassic strata; Jt=Twist Gulch Formation; K=Cedar Mountain Formation and Indianola Group; TKn=North Horn Formation (basal conglomerate through Big Mountain memebers); Tn=North Horn Formation (Coal Canyon through upper redbed members); Tf=main body of Flagstaff Limestone; Tc=Colton Formation; Tg=Green River Formation; Tu=undifferentiated Colton and Green River Formations; Q=Quaternary deposits. LSC is Little Salt Creek in Chriss Canyon quadrangle. Formations TKn through Tg form younger syncline described in text; Jt and K form older syncline. Unlabelled panels of fault-bounded rock on east flank of range contain undifferentiated Jurassic and Cretaceous strata.*

ary of the quadrangle to Big Mountain, and south of Axhandle Canyon, continuing into the next quadrangle, the trend is north-south. In the northern area most of the faulted strata are Twist Gulch and Cedar Mountain Formations, but the San Pitch Formation is present in a fault-bounded block at the mouth of Wales Canyon (plate 1; cross sections A-A′ to F-F′). In the southern area, hanging-wall rocks of the fault zone are dominated by upright Twist Gulch strata; in the footwall, beds of the Big Mountain member are vertical and overturned with steeply east-dipping attitudes (cross sections J-J′; K-K′). Between the northern and southern areas, fault trends are northeast, but still parallel to the range front.

In this central area, faulted strata are dominantly Cedar Mountain, San Pitch, and Sanpete beds; Twist Gulch beds are present mainly in the southernmost exposures (cross sections G-G′ to I-I′). Unlike the areas to the north and south, these strata occupy horses of limited lateral extent, as exemplified by a small allochthon of San Pitch Formation on the north side of Coal Canyon. Slickenlines on fault surfaces in this area demonstrate oblique slip. At least one reverse fault (SW¼ section 13 and SE¼ section 14, T. 16 S., R. 2 E.) is folded concordantly with Indianola strata. Basal North Horn conglomerate (Knb) rests unconformably on Sanpete strata in a hanging wall position in SW¼, section 14, T. 16 S., R. 2 E.

Folds

Folds on the west flank of the Sevier-Sanpete Valley antiform are present in both hanging-wall blocks of the imbricate zone of reverse faults and in footwall North Horn strata. Hanging-wall folds are tight, small structures adjacent to the faults. Footwall strata occupy a west-vergent syncline with a shallowly east-dipping west limb and an east limb that is upright with moderate west dips to overturned with steep east dips (figure 3; cross sections A-A′ to K-K′). Because most of the hanging-wall strata in the fault zone are overturned, most hanging-wall folds are antiformal synclines. These synclines formed by the propagation of reverse faults through already overturned beds. These features and the folded reverse fault described above suggest protracted and repeated faulting of the western forelimb of the Sevier-Sanpete Valley antiform.

Fold pair near Dry Canyon graben: A west-vergent fold pair with an overturned common limb is exposed in Rock Canyon (NE½, section 33, T. 16 S.,R. 2 E.) and continues southward into the adjacent quadrangle. The fold is in North Horn and Flagstaff beds that lie unconformably on the Twist Gulch Formation. The unconformity is folded into an erect "S" if viewed from the south. The anticline that forms the eastern half of the fold pair lies above the termination of an east-dipping reverse fault and is interpreted as a fault-propagation fold. The fault is subparallel to bedding in the Twist Gulch Formation and emplaces Twist Gulch over the calcareous siltstone member of the North Horn Formation (TKns). The tip of the reverse fault is near the top of the calcareous siltstone member; beds of the Wales Tongue of the Flagstaff are unbroken and fold around the tip of the fault. Along the east flank of Horse Mountain (sections 27 and 28, T. 16 S.,R. 2 E.), only the overturned common limb and Twist Gulch within the core of the fold are exposed, because the synclinal footwall limb occurs in the subsurface and the anticlinal hanging-wall limb has been eroded or dismembered by slump and landslide deposits southeast of Horse Mountain (plate 1; cross sections J-J´; K-K´). Between Rock and Dry Canyons (figure 1), the fault-propagation fold affects beds as young as the lower part of the Colton Formation. The deformation recorded by the fold appears to represent late reactivation of the zone of imbricate reverse faults.

Normal Faults

Northeast-southwest-trending normal faults

Several small normal faults trend northeast-southwest in the northwestern part of the quadrangle. North Horn, Flagstaff, and Colton beds have stratigraphic separations of 40 to 50 feet (12-15 m), and nowhere greater than about 100 feet (30 m). These faults probably developed from bedding-plane faults in the subjacent, northeast-striking, moderately dipping, rocks of the Indianola Group.

East-west-trending normal faults

Major west-trending normal faults are confined to the region of the Dry Canyon graben. The faults of the Dry Canyon graben are truncated by north-trending faults of the mountain front. The northeastern quarter of the graben is in the southwestern part of the Wales quadrangle, and the southeastern quarter is in the Manti quadrangle. The graben is 1.3 to 1.5 miles (2-2.4 km) wide and extends westward, with decreasing displacement, 3.2 miles (5 km) from the mountain front into the neighboring Chriss Canyon and Hells Kitchen Canyon Southeast quadrangles. Major scarps are in the Flagstaff Limestone, but graben faults cut beds as old as the Twist Gulch Formation, and as young as the upper member of the Green River Formation at the west end of the graben. Several subsidiary faults within the graben cut the Flagstaff Limestone and lower part of the Colton near the mountain front; west of the mountain front, the upper Colton and lower Green River beds are so extensively slumped that such faults cannot be detected. The main fault on the north side of the graben has a stratigraphic separation of about 200 feet (61 m) in the Wales quadrangle. A subsidiary fault lying north of the main graben fault (sections 28 and 29, T. 16 S., R. 2 E.) has a separation of about 130 feet (40 m) near the fold pair at Rock Canyon and about 200 feet (61 m) farther west.

The North Horn Formation is anomalously thin in the Dry Canyon graben (figure 2). At the mouth of Dry Canyon, just south of the quadrangle boundary, the North Horn rests unconformably on Twist Gulch beds and is only 138 feet (42 m) thick (Lawton and others, 1993). It thickens southward in the Manti quadrangle, where the Big Mountain member is present above Jurassic and Cretaceous units.

North-trending normal faults

Normal faults along the western edge of Sanpete Valley parallel the range front, trending north in the northern and southern parts of the quadrangle, and northeast in the central part (plate 1). The range-front fault system was referred to as the "valley fault" by Fong (1995) and the "Gunnison fault" by Weiss (1982). A splay of the northern leg continues southward into Sanpete Valley, and in sections 24 and 25, T. 16 S., R. 2 E. it cuts consolidated alluvial-fan deposits (QTaf) east of the mouth of Axhandle Canyon. East-dipping faults of the system are inferred to be steep, on the order of 70 degrees. Scarps ranging from 3 to 20 feet (1-6 m) high are visible in Quaternary deposits. The most prominent fault scarps are developed in older alluvial-fan deposits (Qaf_2, Qaf_3). A conspicuous scarp is present immediately north of the Wales Canyon road, where a scarp 20 feet (6 m) high is present in older alluvial-fan deposits (Qaf_2) and consolidated alluvial-fan deposits (QTaf) in land-grid blocks 53 and 54. Springs present at the foot of a scarp in oldest alluvial-fan deposits (Qaf_3) in section 12, T. 16 S., R. 2 E. locally result in concentrations of vegetation along traces of the fault system. A normal fault cuts young Quaternary alluvial-fan and debris-flow deposits (Qaf_1 and Qmf_1) at a single location southeast of the mouth of Coal Canyon (NE1/4 section 23, T. 16 S., R. 2 E). At some places in the fault system, two or more fault strands are present, marked either by multiple scarps or offset bedrock blocks (exemplified by the exposures of Flagstaff Limestone in NE1/4 section 12, T. 16 S., R. 2 E.).

Minimum stratigraphic separation of the Flagstaff

Limestone by the fault system is about 2,100 feet (640 m)(cross sections E-E´; F-F´). In the Price N well, the base of the Flagstaff is at 2,800 feet elevation (Sprinkel, 1994), indicating that total structural relief on the fault zone is at least 4,400 feet (1,340 m) (figure 3). Locally the fault zone is not exposed, as at the mouth of Axhandle Canyon and in section 26, T. 16 S., R. 2 E.

Timing and Origin of Structural Deformation

Reverse faulting and folding

The folded and faulted strata of the eastern range front are part of the imbricated forelimb of a west-directed fault-propagation fold that was cut by subsequent normal faulting (figure 3). The fold is equivalent to the Sanpete-Sevier Valley anticline of Gilliland (1963). An implication of our correlation of the lower part of the North Horn Formation in the San Pitch Mountains with the upper Sixmile Canyon Formation of the Wasatch Plateau is that unconformities within both formations record growth of the Sanpete-Sevier Valley antiform. We regard the unconformity beneath the Sixmile Canyon Formation (Lawton, 1982) as recording Campanian onset of growth; likewise, unconformities within Campanian strata (Sixmile Canyon and Price River Formations) in Sixmile Canyon (Spieker, 1946; Fouch and others, 1982; Lawton, 1982; Weiss, 1994) resulted from contemporary uplift and deposition along the backlimb of the fault-propagation fold. Santonian to early Campanian strata that predate deformation are present beneath Sanpete Valley (Lawton and Trexler, 1991).

The fold and fault zone of the eastern range front, and therefore the Sevier-Sanpete Valley antiform, underwent a protracted history of deformation. Progressive steepening of the western forelimb and resultant growth of the fault-propagation fold resulted in the rotation of dips in syntectonic strata of the lower part of the North Horn Formation (basal conglomerate, lower redbed, sheet sandstone, and coal-bearing members) along the flank of the San Pitch Mountains. Most structural relief was probably developed during late Campanian time. Progressive rotation of bedding demonstrates that the fold did not acquire its forelimb angle instantaneously by kink-band migration as predicted by the models of Suppe and others (1992); instead, the forelimb angle steepened incrementally during shortening. Moreover, syntectonic strata of the North Horn Formation onlapped the forelimb to form a time-transgressive angular unconformity. Continued shortening resulted in fault imbrication of the overturned forelimb and attendant development of antiformal synclines. The antiformal synclines common along the range front are broken fault-propagation folds that formed within already overturned strata. The geometry of late forelimb faulting is complex, consisting of duplex structures in North Horn and older strata, rotated and folded thrusts (e.g., cross section H-H´), and thrust horses with restricted strike-parallel extent, such as those exposed from Coal Canyon to Big Mountain. Early folding associated with uplift of the Sevier-Sanpete Valley antiform also created the tighter of two nested synclines in the San Pitch Mountains (figure 3).

Deformation also occurred during deposition of the Big Mountain and Coal Canyon members of the North Horn Formation, as indicated by multiple intraformational unconformities and eastward thinning of the Big Mountain member and west-directed sediment dispersal of the Coal Canyon member. A lull in deformation or decrease in deformational rate began late in the Paleocene, when the Wales Tongue of the Flagstaff Limestone was deposited on deformed Twist Gulch through North Horn strata. Deformation may have continued at a reduced pace, as indicated by eastward thinning of the overlying early Eocene upper redbed member of the North Horn Formation. Also in the early Eocene, the main body of the Flagstaff was deposited across older deformed strata to create the unconformity between Flagstaff and Indianola beds in the subsurface of Sanpete Valley (Lawton, 1985; Sprinkel, 1994) and at Sixmile Canyon (Spieker, 1946; Lawton, 1982).

The fold pair near Dry Canyon graben records post-early Eocene deformation along the east flank of the San Pitch Mountains, because it affects beds as young as the lower part of the Colton Formation. We regard this as a late Laramide structure of probable late Eocene or early Oligocene age, roughly coeval with uplift of the Uinta Mountains (Anderson and Picard, 1974; Bryant and others, 1989). In conclusion, reverse faulting and folding in the eastern San Pitch Mountains began in middle to late Campanian time and ended late in the Eocene or early in the Oligocene. Deformation therefore spanned Maastrichtian to Eocene time, a time interval normally considered as Laramide (Dickinson and others, 1988).

An alternative hypothesis to the contractional deformation history outlined above is that the unconformities and folds of the Sanpete Valley region are primarily the result of diapirism of evaporites and shales of the Jurassic Arapien Shale (Witkind, 1982, 1983, 1992, 1994; Witkind and Page, 1984). Three lines of evidence indicate the diapir model can not explain the deformation in the Wales quadrangle. 1) Overturning of fault-repeated strata and consistent west vergence of faults and folds requires shortening not predicted by the diapiric model. 2) The Arapien Shale does not breach the crest of the antiform in Sanpete Valley by vertical penetration above its normal stratigraphic level (i.e., does not extrude through younger units), as shown by the Sorenson well, nor is it out of place stratigraphically in any other well in the region (Sprinkel, 1994). Fault-bounded Arapien is exposed in the core of the deformed zone on the east flank of the San Pitch Mountains 2 miles (3.2 km) south of the quadrangle, where it is present with the Twist Gulch Formation in fault-bounded panels. 3) Major deformation took place during the Sevier and Laramide orogenies, and has not been continuous since deposition of the Arapien, as might be expected in the case of diapirism.

Diapirism may modify large-scale structures locally (for examples see Willis, 1986; Weiss, 1994); however, we believe its importance in the tectonic evolution of this part of central Utah has been overestimated.

Northeast-southwest-trending normal faults

The normal faults in the northwestern corner of the quadrangle are post-Eocene because they offset beds of the Colton Formation.

East-west-trending normal faults

The east-west-trending normal faults probably resulted from early (Miocene) Basin-and-Range extension. They are clearly post-Eocene because they affect Green River strata. However, the fault system is truncated by north-trending normal faults that form the mountain front and cut both Tertiary and Quaternary deposits.

The east-west-trending faults of the Dry Canyon graben are probably the result of reactivation of an older contractional structure. We interpret an older structure beneath the Dry Canyon graben as a lateral ramp in the Gunnison thrust (figure 4). Evidence for this interpretation is the thin North Horn section within the graben flanked by thicker North Horn sections north and south of the graben. We infer that transport of hanging-wall rocks oblique to the trend of the ramp in the thrust footwall created an east-west anticline during deposition of the North Horn. Coarse-grained fluvial deposits of the North Horn at Big Mountain were deposited immediately north of the anticline. During younger extension, normal faulting occurred along the trend of the footwall ramp (figure 4).

North-trending normal faults

North-trending normal faults that define the present topography of the Wales quadrangle have been active in the Quaternary and possibly the late Tertiary. The faults cut the youngest alluvial-fan deposits (Qaf_1), which lack extensive carbonate coatings on their constituent clasts, suggesting an age of well under the Holocene limit of 10,000 years (for example, Gile and others, 1970).

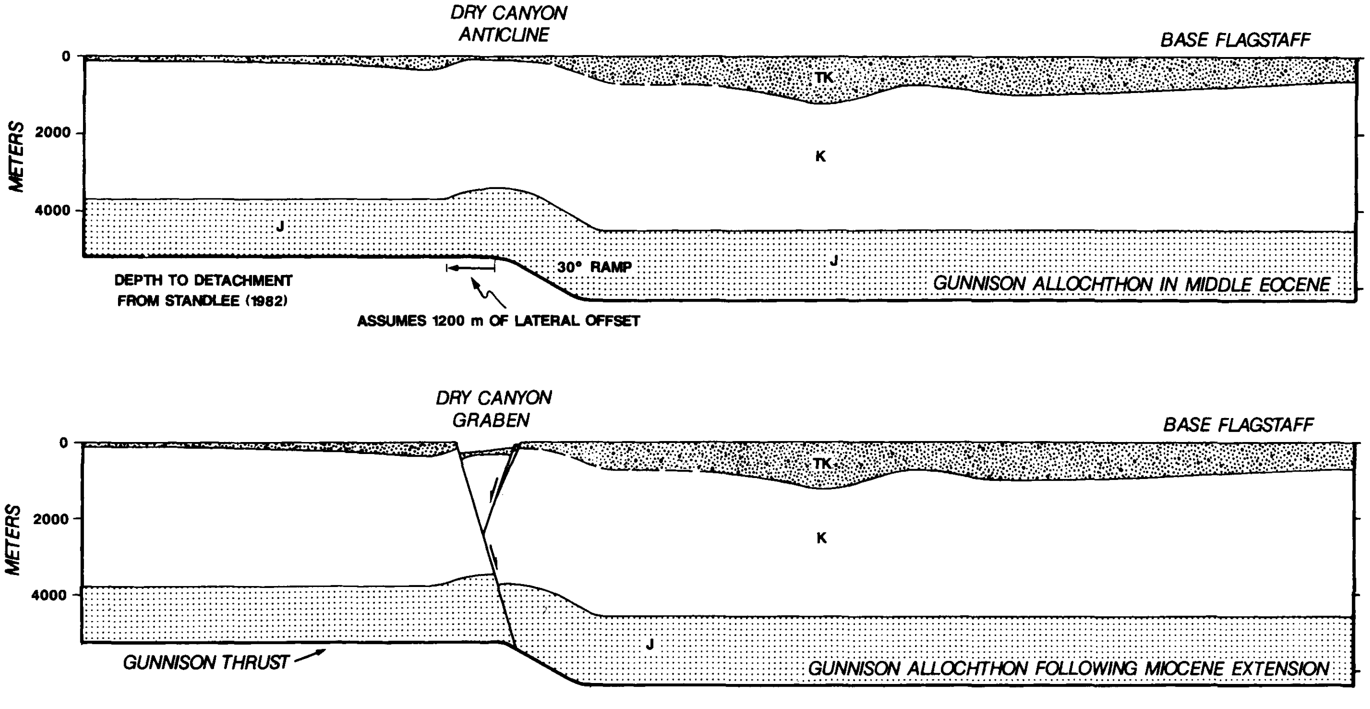

Figure 4. *Model, looking west, for origin of Dry Canyon graben by negative inversion (reactivation of shortening structures during subsequent extension) of lateral ramp in footwall of Gunnison thrust. Anticline formed above lateral ramp of the Gunnison allochthon; lateral offset is indicated in the figure. During extension, normal faulting occurred along the trend of the footwall ramp, which served as a locus for the deformation. rock units: J=undifferentiated Jurassic strata; K=Cedar Mountain Formation and Indianola Group; TK=North Horn Formation.*

ECONOMIC GEOLOGY

The primary mineral and energy resources that have been extracted or sought within the Wales quadrangle include sand and gravel, coal, petroleum, and metallic ores.

Sand and gravel

Alluvial-fan deposits have been exploited extensively for road metal. Pits exist at the mouths of Wales, Petes, Coal, and Axhandle Canyons. The gravel is mixed siliciclastic and carbonate clasts from Cretaceous sandstones and conglomerates and Flagstaff Limestone. See also Pratt and Callaghan (1970) and Utah Department of Highways (1966).

Coal

Coal was mined in the Wales quadrangle prior to 1914 (Doelling, 1972); no mining took place after the discovery of the Wasatch Plateau coal fields. Coal beds are restricted to the coal-bearing member of the North Horn Formation (Knc). Nearly every accessible coal exposure was mined in the quadrangle, including beds in Wales Canyon (NE 1/4 section 26, T. 15 S., R. 2 E.), North Coal Canyon (NE 1/4 section 35, T. 15 S., R. 2 E.), Petes Canyon (SE 1/4 section 2, T. 16 S., R. 2 E.), Blind Canyon (NE 1/4 section 14), Coal Canyon (SW 1/4 section 14, T. 16 S., R. 2 E.), and the southernmost exposure of the coal-bearing member (NW 1/4 section 23, T. 16 S., R. 2 E.). The coal beds do not exceed 4 feet (1.3 m) thick, and are more typically 1 foot (0.3 m) thick (Doelling, 1972). Impediments to coal exploitation include bed thinness, poor coal quality, and westward dip of the beds, which results in a rapid attendant increase in overburden.

Petroleum

No oil or gas has been produced from the Wales quadrangle or from the central Utah part of the Sevier orogenic belt, although numerous exploration wells have been drilled in and near the quadrangle. The Sorenson 14-30 well was drilled into the crest of the Sanpete Valley antiform (figure 1), as were other wells shown in figure 3. Potential source rocks, the Cretaceous marine mudstones of the Allen Valley Shale (Ka) and upper part of the Funk Valley Formation (Kfu), are present beneath Sanpete Valley in the core of the fold and are truncated beneath the North Horn Formation in the San Pitch Mountains (figure 3; plate 2; cross section H-H′). Potential reservoirs above the deformed Cretaceous source rocks are coarse-grained sandstones and conglomerates of the North Horn Formation or fractured limestones of the Flagstaff. Seals might exist where shaly units overlie the pre-North Horn unconformity, such as where the calcareous siltstone member overlies the unconformity in Rock Canyon. Another possible seal may be formed on structure where marine siltstones and mudstones of the upper part of the Funk Valley Formation overlie the nonmarine lower part of the Funk Valley Formation. The main obstacles to accumulation of oil and gas in the Wales quadrangle are probably lack of maturity of the source rocks and lack of a seal. See also Pratt and Callaghan (1970).

Metallic Minerals

Although no metals have been produced from the Wales quadrangle, considerable prospecting occurred in the late 1950s and early 1960s on the face of Horse Mountain. A stope was excavated into the base of the Big Mountain member of the North Horn Formation (TKnb) immediately above the fault contact with the Twist Gulch Formation (NE1/4SE1/4SE1/4 section 28, T. 16 S.,R. 2 E.). Many truckloads of broken rock were removed and reportedly taken to a smelter. The objective was silver, and it was further reported that values of lead and zinc were sufficient to pay the overhead, with the silver providing a profit. Samples of the rock removed contained trivial amounts of sphalerite and galena; Weiss believes that the "silver ore" was illusory. Ramps and a loading device were built, but after a man was crushed on the loader, in 1961, the enterprise was abandoned. An attempt was made to duplicate the prospect higher in the thrust plate (center of NE1/4SE1/4 of section 28), but aside from the access road nothing was done. See also Pratt and Callaghan (1970) and Perry and McCarthy (1977).

WATER RESOURCES

Perhaps the most valuable commodity of the Wales quadrangle is its ground water. The main ground-water aquifer is in the alluvial-fan and floodplain deposits (Qaf$_2$, Qaf$_3$, QTaf, QTal) in Sanpete Valley (Robinson, 1971). The water table within surficial deposits in the valley is everywhere less than 60 feet (18 m) below the surface, and in the southeastern part of the quadrangle, the water table intersects the surface near the San Pitch River (Robinson, 1971). Aquifers in the alluvial fan deposits are both unconfined and confined; artesian aquifers are the result of interbedded claystone and permeable layers in the floodplain and channel deposits of the valley (Robinson, 1971). Groundwater flow in the quadrangle is mostly eastward away from the mountain front, but flow is to the west-southwest, following the

San Pitch River, in the southeast corner of the quadrangle. Total dissolved solids in the ground water range from about 500 to greater than 1000 mg/l in the Wales quadrangle (Robinson, 1971). The alluvial-fan deposits (Qaf_2, Qaf_3, QTaf) of the western Sanpete valley are excellent aquifers, and numerous wells are situated on the fans, particularly the Axhandle Canyon fan. Natural springs along the range-front fault system are collected for irrigation at the foot of Big Mountain (eastern part of section 12, T. 16 S., R. 2 E.). A spring in the coal-bearing member of the North Horn Formation in Wales Canyon provides water for the town of Wales.

Perennial streams in Wales, Petes, and Axhandle Canyons contain fresh water (Robinson, 1971). Surface water in Petes Canyon is dammed and used for irrigation and watering livestock. Surface runoff in Axhandle Canyon was used for irrigation prior to destruction of the collection system by a flood in 1983. Surface flow of the San Pitch River is highly variable and dependent on ground-water discharge from adjoining alluvial-fan deposits; the water quality deteriorates somewhat downstream due to evapotranspiration and waste water from irrigation, becoming slightly saline in the southeast corner of the Wales quadrangle (Robinson, 1971).

The surface and subsurface water resources of the Wales quadrangle result mainly from precipitation within the drainage area and recharge of Mesozoic and Cenozoic formations in the higher parts of the San Pitch Mountains, as well as from influent flow from channels on the upper parts of the alluvial fans at the mountain front (Robinson, 1971). See also Wilberg and Heilwell (1995).

GEOLOGIC HAZARDS

Major geologic hazards in the Wales quadrangle include high-discharge flood events and associated debris flows. Current land use is compatible with this potential threat. Most damage would be restricted to dirt roads and irrigation collection systems in the canyons and to flooding of roads, water impoundments, and livestock corrals on the alluvial fans. A potential exception is the town of Wales, which is situated on consolidated alluvial-fan deposits at the mouth of Wales Canyon. Younger alluvial-fan deposits have formed southwest of the town as a result of southeast-trending entrenchment of the modern drainage into older fan deposits. This suggests most flooding will take place south of town.

Slope failures also pose a hazard in lower elevations of the San Pitch Mountains, and are particularly prevalent in areas underlain by the Twist Gulch Formation (Jt), the calcareous siltstone member of the North Horn Formation (TKn), and the Colton Formation (Tc). Rock falls pose a hazard near steep cliffs formed by the Big Mountain member of the North Horn Formation (TKnb). Given present land use, slope-failure damage would likely be restricted to the road in Wales Canyon.

Seismic activity on the range-front fault system is a potential hazard in the Wales quadrangle. The most recent event, with a probable displacement of less than 3 feet (1 m), may have taken place in late Holocene time (Hecker, 1993). Demonstrable offset of as much as 20 feet (6 m) of Quaternary fan deposits (Qaf_2, Qaf_3) and offset Holocene fan and debris-flow deposits (Qaf_1, Qmf_2) indicates that earthquakes of large magnitude may be expected on this fault system. The lack of fresh, steep fault scarps suggests a long recurrence interval. Liquefaction of saturated alluvial deposits near the San Pitch River may pose an additional seismic hazard in the southeastern corner of the quadrangle.

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REFERENCES

Anadon, Pere, Cabrera, Luis, Colombo, Ferran, Marzo, Mariano and Riba, Oriol, 1986, Syntectonic intraformational unconformities in alluvial fan deposits, eastern Ebro basin margins (NE Spain), *in* Allen, P.A., and Homewood, Peter, editors, Foreland basins: International Association of Sedimentologists Special Publication 8, p. 259-271.

Anderson, D.W., and Picard, M.D., 1974, Evolution of synorogenic clastic deposits in the intermontane Uinta basin of Utah, *in* Dickinson, W.R., editor, Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 167-189.

Auby, W.L., 1991, Provisional geologic map of the Levan quadrangle, Juab County, Utah: Utah Geological Survey Map 135, 13 p., scale 1:24,000.

Balsley, J.K., 1982, Cretaceous wave-dominated delta systems, Book Cliffs, east-central Utah: American Association of Petroleum Geologists Guidebook, 219 p.

Birsa, D.S., 1973, The North Horn Formation, central Utah: Sedimentary facies and petrography: Columbus, Ohio State University, M.S. thesis, 189 p., scale 1:24,000.

Bryant, Bruce, Naeser, C.W., Marvin, R.F., and Mehnert, H.H., 1989, Upper Cretaceous and Paleogene sedimentary rocks and isotopic ages of Paleogene tuffs, Uinta basin, Utah: U.S. Geological Survey Bulletin 1787J, 22 p.

Burma, B.H., and Hardy, C.T., 1953, Pre-North Horn orogeny in Gunnison Plateau, Utah: American Association of Petroleum Geologists Bulletin, v. 37, p. 549-569, scale 1:37,500.

Cobban, W.A., 1976, Ammonite record from the Mancos Shale of the Castle Valley-Price-Woodside area, east-central Utah: Brigham Young University Geology Studies, v. 22, p. 117-126.

Dickinson, W.R., Lawton, T.F., and Inman, K.F., 1986, Sandstone detrital modes, central Utah foreland: Stratigraphic record of Cretaceous-Paleogene tectonic evolution: Journal of Sedimentary Petrology, v. 56, p. 276-293.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023-1034.

Doelling, H.H., 1972, Central Utah coal fields: Sevier-Sanpete, Wasatch Plateau, Book cliffs, and Emery: Utah Geological and Mineralogical Survey Monograph Series, no. 3, 570 p.

Fong, A.W., 1995, Geologic map of the Fountain Green South quadrangle, Sanpete and Juab Counties, Utah: Utah Geological Survey Miscellaneous Publication Map MP 95-1, 18 p., scale 1:24,000.

Fouch, T.D., Lawton, T.F., Nichols, D.J., Cashion, W.B. and Cobban, W.A., 1983, Patterns and timing of synorogenic sedimentation in Upper Cretaceous rocks of central and northeast Utah, *in* Reynolds, M.W. and Dolly, E.D., editors, Mesozoic paleogeography of west-central United States, Symposium 2: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 305-336.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1970, Distribution and genesis of soils and geomorphic surfaces in a desert region of southern New Mexico: Soil Science Society of America, Geomorphology Field Conference Guidebook, 156 p.

Gilliland, W.N., 1963, Sanpete-Sevier Valley anticline of central Utah: Geological Society of America Bulletin, v. 74, p. 115-124.

Hecker, Suzanne, 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, 157 p., 2 pl., scale 1:500,000.

Hobbs, R.S., 1989, The physical and magnetic polarity stratigraphy of the Upper Cretaceous-lower Tertiary North Horn and Flagstaff Formations, Gunnison Plateau, central Utah: Los Angeles, University of Southern California, M.S. thesis, 162 p.

Hunt, R.E., 1950, The geology of the northern part of the Gunnison Plateau, Utah: Columbus, Ohio State University, Ph.D. dissertation, 267 p.

Hunt, R.E., 1954, South Flat Formation, new Upper Cretaceous formation of central Utah: American Association of Petroleum Geologists Bulletin, v. 38, p. 118-128.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U. S. Geological Survey Professional Paper 1062, 134 p.

Jacobson, S.R., and Nichols, D.J. 1982, Palynological dating of syntectonic units in the Utah-Wyoming thrust belt - The Evanston Formation, Echo Canyon Conglomerate and Little Muddy Creek Conglomerate, *in* Powers, R.B., editor, Geologic studies of the Cordilleran thrust belt - Denver, Rocky Mountain Association of Geologists, p. 735-750.

Kauffman, E.G., 1977, Geological and biological overview - Western Interior Cretaceous basin: The Mountain Geologist, v. 14, p. 75-99.

La Rocque, Aurèle, 1960, Molluscan faunas of the Flagstaff Formation of central Utah: Geological Society of America Memoir 78, 100 p.

Lawton, T.F., 1982, Lithofacies correlations within the Upper Cretaceous Indianola Group, central Utah, *in* Nielson, D.L., editor, Overthrust belt of Utah: Utah Geological Association Publication 10, p. 199-213.

Lawton, T.F., 1985, Style and timing of frontal structures, thrust belt, central Utah: American Association of Petroleum Geologists Bulletin, v. 69, p. 1145-1159.

Lawton, T.F., and Trexler, J.H., Jr., 1991, Piggyback basin in the Sevier orogenic belt, Utah - Implications for development of the thrust wedge: Geology, v. 19, p. 827-830.

Lawton, T.F., and Willis, G.C., 1987, The geology of Salina Canyon, Utah: Geological Society of America Centennial Field Guide - Rocky Mountain Section, p. 265-268.

Lawton, T.F., Talling, P.A., Hobbs, R.S., Trexler, J.H., Jr., Weiss, M.P., and Burbank, D.W., 1993, Structure and stratigraphy of Upper Cretaceous and Paleogene strata (North Horn Formation), eastern San Pitch Mountains, Utah: Sedimentation at the front of the Sevier orogenic belt: U.S. Geological Survey Bulletin 1787-II, 33 p.

Marcantel, E.L., and Weiss, M.P., 1968, Colton Formation (Eocene: fluviatile) and associated lacustrine beds, Gunnison Plateau, central Utah: Ohio Journal of Science, v. 68, p. 40-49.

Millen, T.M., 1982, Stratigraphy and petrology of the Green River Formation (Eocene), Gunnison Plateau, central Utah: DeKalb, Northern Illinois University, M.S. thesis, 220 p.

Perry, L.I., and McCarthy, B.M., 1977, Lead and zinc in Utah, 1976: Utah Geological and Mineral Survey Open-File Report 22, 525 p.

Platt, N.H., and Wright, V.P., 1992, Palustrine carbonates and the Florida Everglades - Towards an exposure index for the fresh-water environment?: Journal of Sedimentary Petrology, v. 62, p. 1058-1071.

Pratt, A.R., and Callaghan, Eugene, 1970, Land and mineral resources of Sanpete County, Utah: Utah Geological and Mineral Survey Bulletin 85, 69 p.

Riba, Oriol, 1976, Syntectonic unconformities of the Alto Cardener, Spanish Pyrenees - a genetic interpretation: Sedimentary Geology, v. 15, p. 213-233.

Rich, T.H.V., and Collinson, J.W., 1973, First mammalian fossil from the Flagstaff Limestone, central Utah - *Vulpavis australis* (Carnivora: Miacidae): Journal of Paleontology, v. 47, p. 854-860.

Robinson, G.B., Jr., 1971, Ground-water hydrology of the San Pitch River drainage basin, Sanpete County, Utah: U.S. Geological Survey Water-Supply Paper 1896, 80 p.

Sanders, J.E., and Kumar, Naresh, 1975, Evidence of shoreface retreat and in-place "drowning" during Holocene submergence of barriers, shelf off Fire Island, New York: Geological Society of America Bulletin, v. 86, p. 65-76.

Schwans, Peter, 1988a, Depositional response of Pigeon Creek Formation, Utah, to initial fold-thrust deformation in a differentially subsiding foreland basin, *in* Schmidt C.J. and Perry, W.J., editors, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 531-556.

Schwans, Peter, 1988b, Stratal packages at the subsiding margin of the Cretaceous foreland basin: Columbus, Ohio State University, Ph.D dissertation, 2 volumes, 447 p.

Schwans, Peter, 1995, Controls on sequence stacking and fluvial to shallow-marine architecture in a foreland basin, *in* Van Wagoner, J.C., and Bertram, G.T., editors, Sequence stratigraphy of foreland basin deposits; outcrop and subsurface examples from the Cretaceous of North America: American Association of Petroleum Geologists Memoir 64, p 55-102.

Spieker, E.M., 1946, Late Mesozoic and early Cenozoic history of central Utah: U.S. Geological Survey Professional Paper 205-D, p. 117-161.

Spieker, E.M., 1949a, The transition between the Colorado Plateaus and the Great Basin in central Utah: Utah Geological Society, Guidebook to the Geology of Utah, No. 4, 106 p., scale 1:125,000.

Spieker, E.M., 1949b, Sedimentary facies and associated diastrophism in the Upper Cretaceous of central and eastern Utah: Geological Society of America Memoir 39, p. 55-81.

Sprinkel, D.A., 1994, Stratigraphic and time-stratigraphic cross sections - A north-south transect from near the Uinta Mountain axis across the Basin and Range transition zone to the western margin of the San Rafael Swell, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2184-D, 31 p.

Sprinkel, D.A., Weiss, M.P., and Fleming, R.W., 1992, Stratigraphic reinterpretation of a synorogenic unit of late Early Cretaceous age, Sevier orogenic belt, central Utah (abstract): Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 63.

Sprinkel, D.A., Weiss, M.P., Fleming, R.W., and Waanders, G.L., 1999, Redefining the Lower Cretaceous stratigraphy within the central Utah foreland basin: Utah Geological Survey Special Study 97, p.

Standlee, L.A., 1982, Structure and stratigraphy of Jurassic rocks in central Utah - their influence on tectonic development of the Cordilleran foreland thrust belt, *in* Powers, R.B., editor, Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, p. 357-382.

Stanley, K.O., and Collinson, J.W., 1979, Depositional history of Paleocene-lower Eocene Flagstaff Limestone and coeval rocks, central Utah: American Association of Petroleum Geologists Bulletin, v. 63, p. 311-323.

Suppe, John, Chou, G.T., and Hook, S.C., 1992, Rates of folding and faulting determined from growth strata, *in* McClay, K.R., editor, Thrust tectonics: London, Chapman and Hall, p. 105-121.

Talling, P.J., 1992, Magnetostratigraphically constrained evolution of the 75 to 51 m.y. Axhandle thrust-top basin, central Utah: Los Angeles, University of Southern California, M.S. thesis, 214 p.

Talling, P.J., Burbank, D.W., Lawton, T.F., Hobbs, R.S., and Lund, S.P., 1994, Magnetostratigraphic chronology of Cretaceous-to-Eocene thrust belt evolution, central Utah, USA: Journal of Geology, v. 102, p. 181-196.

Talling, P.J., Lawton, T.F., Burbank, D.W., and Hobbs, R.S., 1995, Evolution of latest Cretaceous-Eocene nonmarine deposystems in the Axhandle piggyback basin of central Utah: Geological Society of America Bulletin, v. 107, p. 297- 315.

Thomas, G.E. 1960, The South Flat and related formations in the northern part of the Gunnison Plateau, Utah: Columbus, Ohio State University, M.S. thesis, 137 p.

Tschudy, R.H., Tschudy, B.D., and Craig, L.C., 1984, Palynological evaluation of Cedar Mountain and Burro Canyon Formations, Colorado Plateau: U.S. Geological Survey Professional Paper 1281, 24 p.

Utah Department of Highways, 1966, Material inventory, Sanpete and Sevier Counties: Utah Department of Highways Materials and Research Division, Materials Inventory Section, 22 p.

Villien, Alain, and Kligfield, R.M., 1986, Thrusting and synorogenic sedimentation in central Utah, *in* Peterson, J.A., editor, Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 281-308.

Volkert, D.G., 1980, Stratigraphy and petrology of the Colton Formation (Eocene), Gunnison Plateau, central Utah: DeKalb, Northern Illinois University, M.S. thesis, 132 p.

Weiss, M.P. 1969, Oncolites, paleoecology, and Laramide tectonics, central Utah: American Association of Petroleum Geologists Bulletin, v. 52, p. 1,105-1,120.

Weiss, M.P., 1982, Structural variety on the east front of the Gunnison Plateau, central Utah, *in* Nielson, D.L., editor, Overthrust belt of Utah: Utah Geological Association Publication 10, p. 49-63.

Weiss, M.P., 1994, Geologic map of the Sterling quadrangle, Sanpete County, Utah: Utah Geological Survey Map 159, 26 p. scale 1:24,000.

Weiss, M.P. and Roche, M.G., 1988, The Cedar Mountain Formation (Lower Cretaceous) in the Gunnison Plateau, central Utah, *in* Schmidt C.J. and Perry, W.J., editors, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 557-569.

Wilberg, D.E., and Heilweil, V.M., 1995, Hydrology of Sanpete Valley, Sanpete and Juab Counties, Utah, and simulation of ground-water flow in the valley-fill aquifer: Utah Department of Natural Resources, Division of Water Rights, Technical Publication 113, 121 p.

Willis, G.C., 1986, Geologic map of the Salina quadrangle, Sevier County, Utah: Utah Geological Survey Map 83, 20 p., scale 1:24,000.

Witkind, I.J., 1982, Salt diapirism in central Utah, *in* Nielson, D.L., editor, Overthrust Belt of Utah: Utah Geological Association Publication 10, p. 13-30.

Witkind, I.J., 1983, Overthrusts and salt diapirs, central Utah, *in* Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the east-central Great Basin region: Geological Society of America Memoir 157, p. 45-59.

Witkind, I.J., 1992, Paired, facing monoclines in the Sanpete-Sevier Valley area, central Utah: The Mountain Geologist, v. 29, p. 5-17.

Witkind, I. J., 1994, The role of salt in the structural development of central Utah: U.S. Geological Survey Professional Paper 1528, 145 p.

Witkind, I.J., and Page, W.R., 1984, Origin and significance of the Wasatch and Valley Mountains monoclines, Sanpete-Sevier Valley area, central Utah: The Mountain Geologist, v. 21, p. 143-156.

Witkind, I.J., Standlee, L.A., and Maley, K.F., 1986, Age and correlation of Cretaceous rocks previously assigned to the Morrison(?) Formation, Sanpete-Sevier Valley area, central Utah: U.S. Geological Survey Bulletin 1584, 9 p.

Witkind, I.J., Weiss, M.P. and Brown, T.L., 1987, Geologic map of the Manti 30´ x 60´ quadrangle, Carbon, Emery, Juab, Sanpete, and Sevier counties, Utah: U.S. Geological Survey Map I-1631, scale 1:100,000.

APPENDIX 1

Species lists for palynomorph samples collected from North Horn Formation. Processing, species identifications, and age interpretations of samples 1 and 2 by Dr. Gerald Waanders, Waanders Palynology Consulting, Inc.; sample 3 was processed and analyzed by Dr. Fred E. May, Palynex International. Species marked with asterisks are key indicators of age of sample.

1. 90NH5. Medium olive-gray, silty claystone overlying micrite with charophyte gyrogonites and gastropod fragments, sheet sandstone member, 705 feet (215 m) above base of North Horn Formation, Petes Canyon. Elevation 5,940 feet, SW1/4 NW1/4 section 1, T. 16 S., R. 2 E.

   Spores and pollen:
   - *Balmeisporites canadensis**
   - *B. longiramosus**
   - *B. rarus**
   - *B. rigidus**
   - *Deltoidospora* spp.
   - *Liburnisporis* sp.
   - *Lycopodiumsporites* sp.
   - *Sphagnum* sp.
   - Taxodiaceae
   - Undifferentiated bisaccates
   - *Zlivisporis novomexicanum*

Age: Maastrichtian

2. 92M3. Dark-gray, slightly calcareous claystone from abandoned channel above mixed-clast conglomerate at base of Big Mountain member, North Horn Formation. Elevation 6,180 feet, NE1/4 SW1/4 section 9, T. 17 S., R. 2 E. Manti quadrangle.

   Spores and pollen:
   - *Araucariacites australis*
   - *Cingulatisporites* sp.
   - *Classopollis classoides**
   - *Deltoidospora* spp.
   - *Heliosporites* sp.
   - *Leptolepidites bullatus*
   - *Momipites tenuipolis*
   - *Pachysandra* sp.
   - *Polypodiidites inhangahuensis**
   - *?Proteacidites retusus**
   - *Triporopollenites* sp.
   - Undifferentiated bisaccates

Age: Late Cretaceous (undifferentiated)

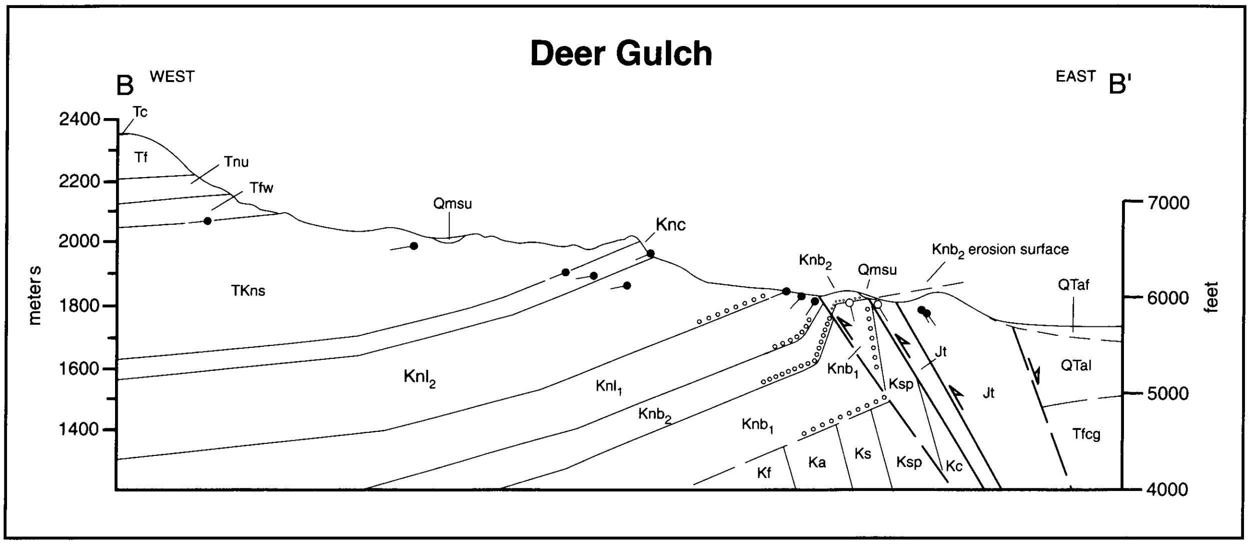
3. 91W10. Dark brownish-gray, carbonaceous shale from lowermost exposed part of calcareous siltstone member (upper part), North Horn Formation, uphill from thrust fault at mine, southeast flank of Horse Mountain. Elevation 6,400 feet, NW1/4 SE1/4 section 28, T. 16 S., R. 2 E. Wales quadrangle.

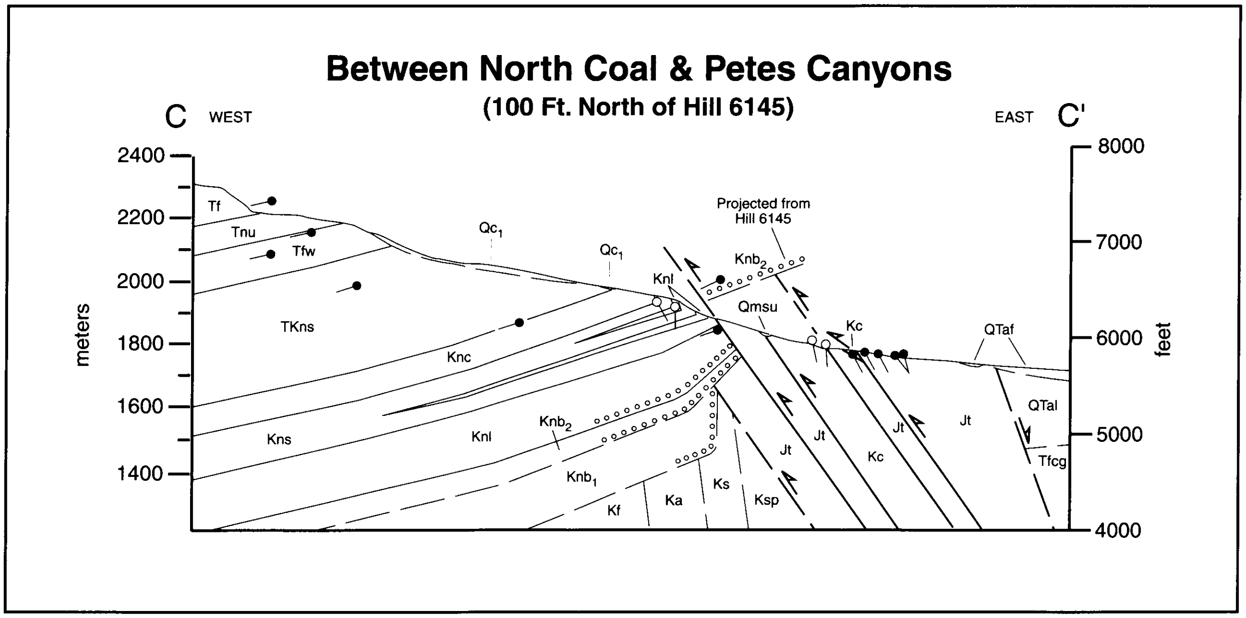
   Spores and pollen:
   - *Kurtizipites simplex*
   - *Momipites wyomingensis*

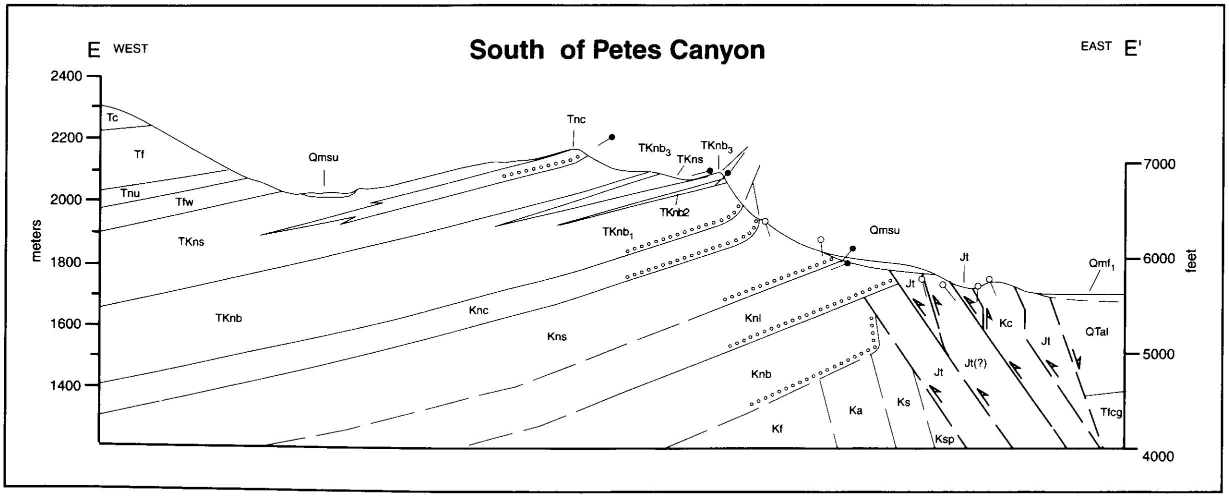
Age: Early Paleocene

APPENDIX 2

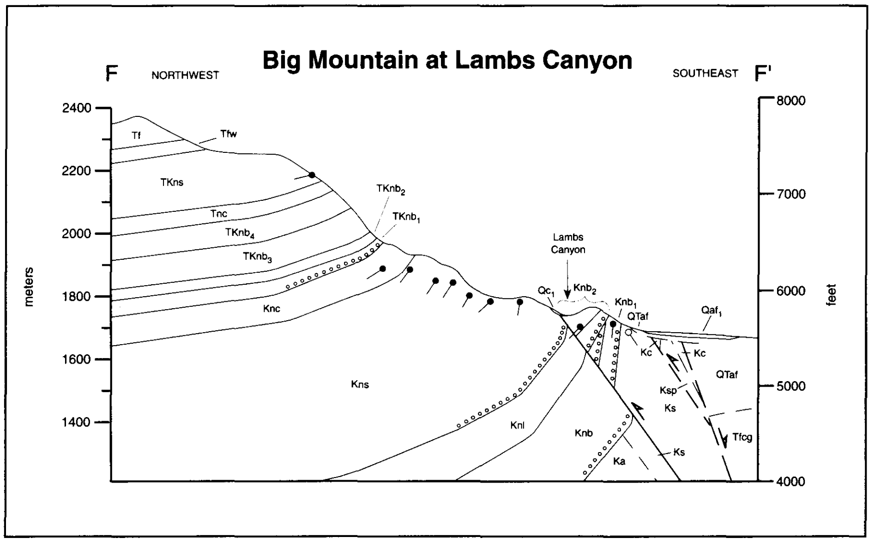
Diagrammatic cross sections showing structural variation along the east flank of the San Pitch Mountains. Cross section locations shown on plate 1 and figure 1. Scale 1:24,000. No vertical exaggeration. See plate 2 for explanation of symbols. (Cross sections A-A', D-D', G-G', H-H' shown on plate 2).

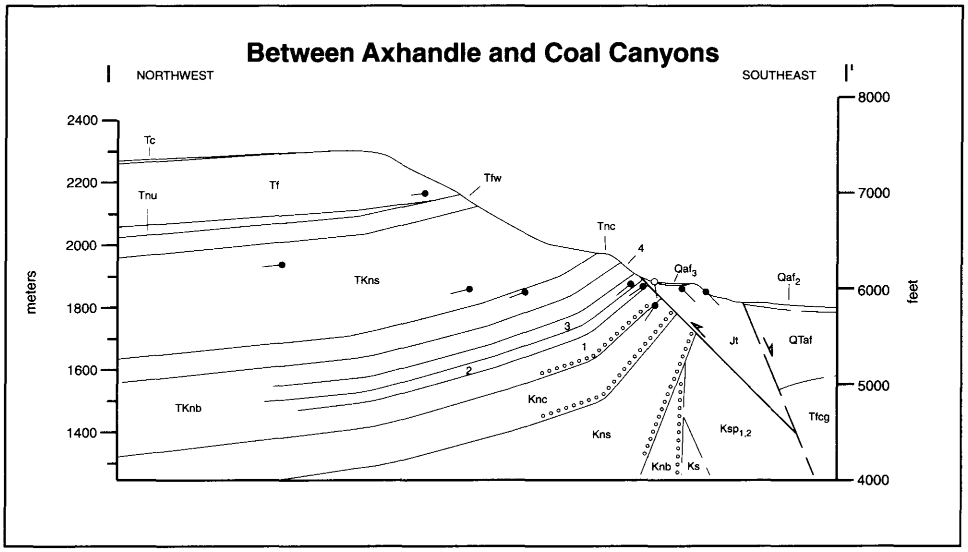


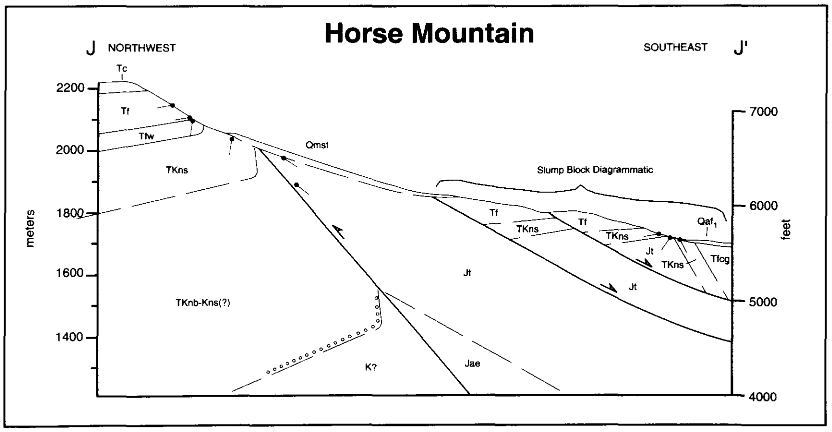




Appendix 2 (continued)







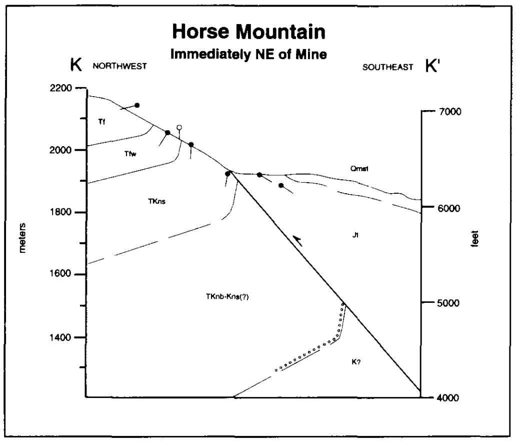


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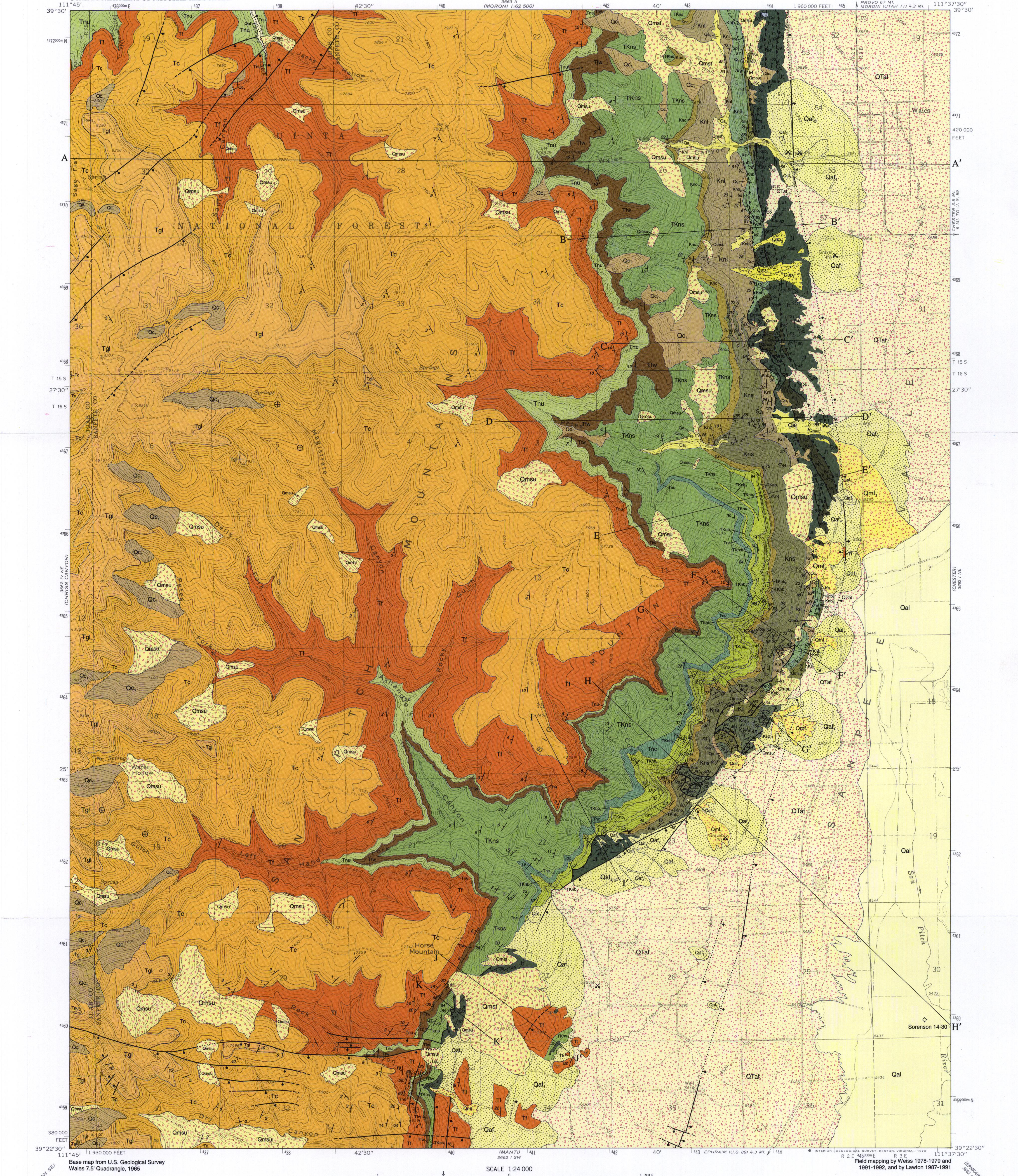
Plate 1
Utah Geological Survey Miscellaneous Publication 99-2
Geologic Map of the Wales Quadrangle



Base map from U.S. Geological Survey
Wales 7.5' Quadrangle, 1965

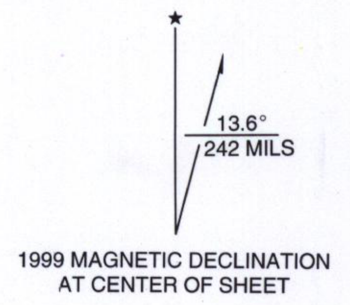
Field mapping by Weiss 1978-1979 and
1991-1992, and by Lawton 1987-1991

(WELLS KITCHEN CANYON SE) 3662 IV SE

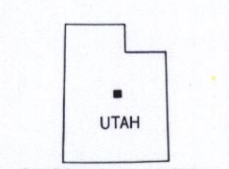
(EPHRAIM) 3662 I SE

SCALE 1:24 000
1 ½ 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 20-FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929



1999 MAGNETIC DECLINATION
AT CENTER OF SHEET



QUADRANGLE LOCATION

GEOLOGIC MAP OF THE WALES QUADRANGLE, SANPETE COUNTY, UTAH

by

T.F. Lawton and M.P. Weiss

1999

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Plate 2
Utah Geological Survey Miscellaneous Publication 99-2
Geologic Map of the Wales Quadrangle

DESCRIPTION OF MAP UNITS

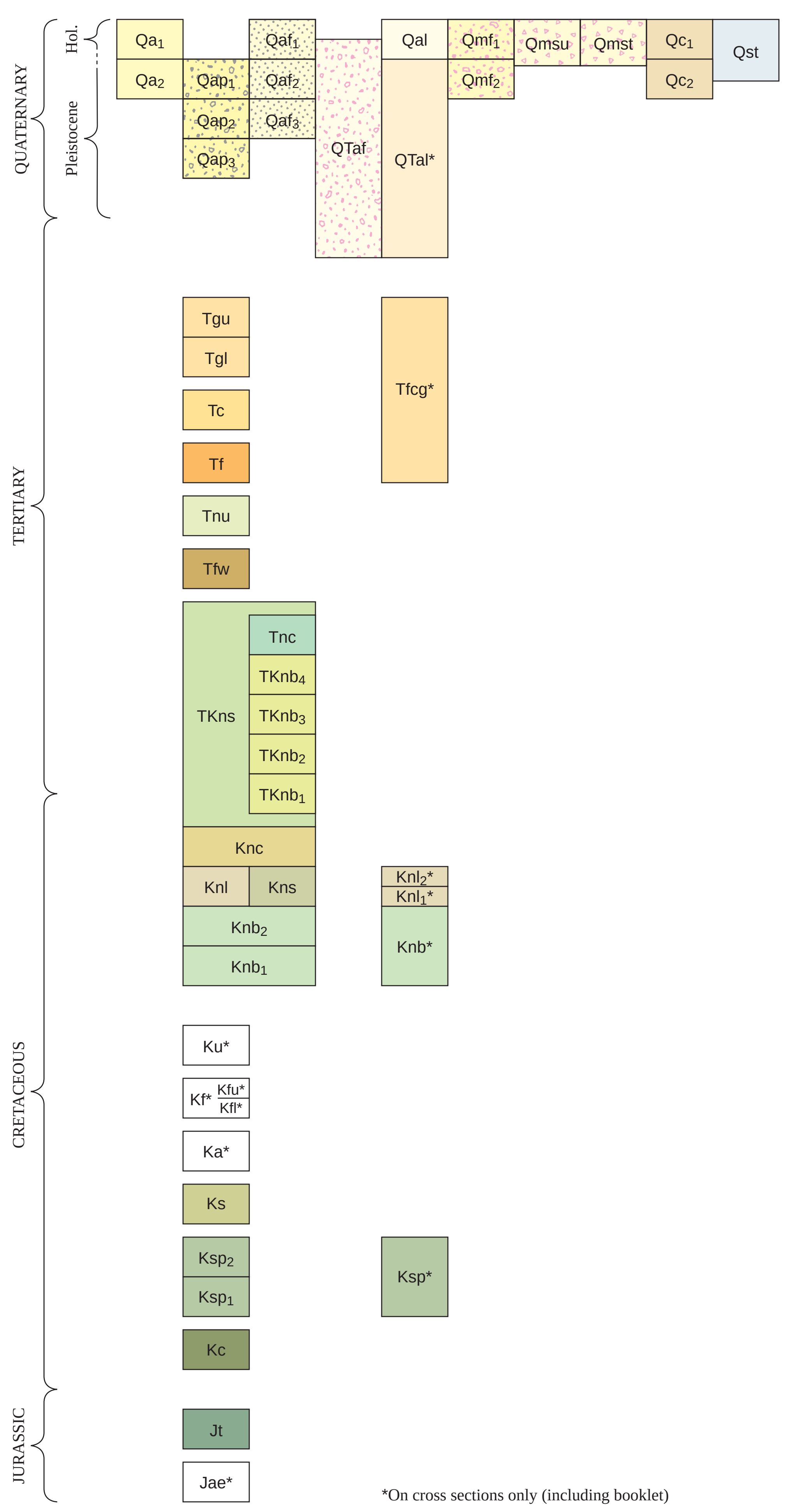
$\mathrm{Qa}_{1,2}$	Stream alluvium (Late Pleistocene-Holocene)- Unconsolidated silt, sand, and gravel, in and close to existing streams; older alluvium (Qa_2) is dissected with surface elevations 10-28 feet (3-8.5 m) above current stream courses; 0-28 feet (0-8.5 m) thick.
Qst	Tufa deposit (Late Pleistocene-Holocene)- Light yellowish-gray, porous calcium carbonate that forms irregular mounded outcrop.
$\mathrm{Qc}_{1,2}$	Colluvial deposits (Late Pleistocene-Holocene)- Unconsolidated mud, sand, and angular gravel of pebbles to large boulders on unstable slopes. Some grade downslope to alluvium or fan deposits. Older colluvium (Qc_2) is dissected and separated from source of material; 0-40 feet (0-12 m) thick.
$\mathrm{Qmf}_{1,2}$	Debris-flow deposits (Late Pleistocene-Holocene)- Very coarse, poorly sorted silt, sand, and gravel with boulders to 8 feet (2.5 m) in diameter that form levees on the flanks of arroyos of alluvial fans. Older debris-flow deposits (Qmf_2) have rounded topography, more soil development, and are dissected by modern drainages; 0-26 feet (0-8 m) thick.
Qmsu, Qmst	Slide and slump deposits (Pleistocene-Holocene)- Two types of deposits of similar age are in quadrangle: 1) Unsorted mass-flow deposits with hummocky surfaces, commonly with topographic depressions at upper ends and lobate, steep toes (Qmsu); 0-50 feet (0-15 m) thick. 2) Unsorted mass-flow deposits cut by and underlain by discrete, curviplanar failure surfaces (Qmst). Characterized by hummocky surfaces, significant continuity of original stratigraphic units within deposit, and headwall scarps; 0-330 feet (0-100 m) thick. Some of each type are dissected.
$\mathrm{Qaf}_{1,2,3}$	Alluvial-fan deposits (Pleistocene-Holocene)- Variably consolidated mud, silt, sand, and gravel as large as boulders that form lobate depositional features at the mouths of canyons. Youngest alluvial-fan deposits (Qaf_1) are unconsolidated and of small size and active construction. Older alluvial-fan deposits (Qaf_2) are better consolidated, dissected by modern drainage and commonly cut by range-front normal faults. Oldest alluvial-fan deposits (Qaf_3) are dissected, cut by range-bounding normal faults, and have thin coatings of calcium carbonate on the lower surfaces of clasts; 0-50 feet (0-15 m) thick.
$\mathrm{Qap}_{1,2,3}$	Pediment-mantle deposits (Pleistocene)- Poorly sorted silt, sand, and gravel of pebbles and cobbles that lie on planar bedrock surfaces elevated above modern drainages, but slope downstream essentially parallel to modern stream profiles; older deposits (Qap_2 and Qap_3) are elevated at successively higher elevations as much as 170 feet (52 m) above the stream course; 0-33 feet (0-10 m) thick.
Qal	Younger floodplain and channel deposits (Holocene)- Mud, silt, and sand of alluvial and minor debris-flow origin occupying the central Sanpete Valley and derived from both the San Pitch Mountains and Wasatch Plateau to the east. Estimated thickness about 165 feet (50 m).
QTal	Older floodplain and channel deposits (Pliocene?-Pleistocene; cross sections only)- Older deposits beneath Qal. Estimated thickness from oil wells in Sanpete Valley about 655 feet (200 m).
QTaf	Consolidated alluvial-fan deposits (Pliocene?-Holocene)- Consolidated silt, sand, and gravel as large as boulders in coalesced alluvial-fan complexes of large length and width. At mouths of major drainage basins. Estimated thickness to 820 feet (250 m).
Tfcg	Flagstaff, Colton, and Green River formations, undivided- on cross sections only
Tgu Tgl	Green River Formation (Eocene)- Consists of two unnamed members, a lower shale member and upper limestone member, of which the upper has been stripped from most of the area except near Big Baldy Peak, near the southwest corner of the quadrangle. Upper limestone member (Tgu): Pale yellowish-gray to pale yellowish-brown micritic dolostone and sparry limestone, thin- to thick-bedded; abundant well-rounded, coarse-grained quartz sand in some limestone beds. Thin shale and shaly limestone interbeds and some biotitic tuff locally; 175 feet (53 m) thick. Lower shale member (Tgl): Light-gray and grayish-green calcareous shale, thin-bedded and fissile; numerous thin beds of gray to white micritic, glassy, or silty limestone; up to 910 feet (277 m) thick. Total exposed thickness of formation is 1,100 feet (335 m).
Tc	Colton Formation (Eocene)- Mostly mudstone and claystone, reddish-brown, light gray, violet, olive-green, and red. Local beds of yellowish-gray to yellowish-brown siltstone and silty sandstone. Some sandstone beds are sheetlike; others are channelform, poorly cemented, with cross beds. Dense, micritic, glassy limestone beds are also present; all are thin and local in extent, some are fossiliferous, containing mollusks and ostracodes; 560-647 feet (170-213 m) thick.
Tf	Flagstaff Limestone (Eocene)- Limestone, light gray to light-yellowish-gray, mostly micrite and fine sparite, and dolostone, light-gray, mostly dolomicrite; thin- to thick-bedded; thin shaly limestone partings and interbeds. Weathers to bold, pale gray to white cliffs; 230-590 feet (70-180 m) thick.
Tfw	Wales Tongue of Flagstaff Limestone (Paleocene)- A tongue of mostly carbonate rock that thins southward that is separated from the base of the Flagstaff Limestone by the upper redbed member of the North Horn Formation. The lower Wales Tongue is dark gray, fossiliferous wackestone and micrite beds as much as 3 feet (1 m) thick that alternate with olive-gray and medium-gray claystone several feet thick, and a few thick beds of sandstone. The upper part is ledge-forming limestone, dolostone, and some mudstone; it weathers white to orange, and is a conspicuous marker throughout the area. Oncolites are present locally; gastropods are numerous in limestone beds; 101-425 feet (31-130 m) thick.
	North Horn Formation (Late Campanian, Maastrichtian, Paleocene, and Eocene)- Complex unit, dominantly clastic with subordinate limestone and dolostone, with many lithofacies characterized by complex intertonguing. Unconformable on older Cretaceous and Jurassic rocks, and with numerous intraformational angular unconformities (refer to figure 2); as much as 3,600 feet (1,100 m) thick.
Tnu	Upper redbed member- Reddish-brown mottled siltstone and sandy siltstone, with a few sandstone beds to 6 feet (2 m) thick, upward-fining and lenticular. Thin beds of micrite contain gastropods and charophytes; 0-400 feet (0-120 m) thick.
TKns	Calcareous siltstone member- Calcareous siltstone and mudstone with blocky or massive structure, red, gray, and purple, and commonly poorly exposed; sandy siltstone beds are common, and contain some sandstone. Quartzite and limestone pebbles are present at bases of some sandstone beds. Some sandstone and conglomerate beds have oncolites and micritic limestone caps; 120-833 feet (37-254 m) thick in the quadrangle. Both overlies and is laterally equivalent to TKnb_1 through TKnb_4, grades laterally into and overlies Tnc.
Tnc	Coal Canyon member- Sandstone, pebbly sandstone, and conglomerate in stacked tabular beds to 7 feet (2 m) thick. Some beds contain foresets that extend from top to base of bed. Sediment dispersal was to west and northwest; 0-200 feet (0-60 m) thick. Grades laterally into TKns and also underlies upper part of TKns.
$\mathrm{TKnb}_{1\text{-}4}$	Big Mountain member- Medium- to coarse-grained sandstone and pebbly sandstone with crossbeds, and clast-supported pebble conglomerate; forms succession of sandstone and conglomerate submembers separated by erosional bases and deposited within a paleovalley by eastward-flowing rivers; laterally equivalent to, but erosive into, calcareous siltstone member (TKns), which also overlies it. Present only south of Petes Canyon. In ascending order, the member is divided into a lower sandstone (TKnb_1), a lower conglomerate (TKnb_2), an upper sandstone (TKnb_3), and an upper conglomerate (TKnb_4); 0-754 feet (0-230 m) thick.
Knc	Coal-bearing member- Olive-gray, carbonaceous siltstone with abundant plant fragments, interbedded with conspicuous thin beds of fossiliferous gray to brown micrite, coal, and lignitic siltstone in upper part. Micrite beds contain charophytes, gastropods, and ostracodes and form a hogback in the vicinity of Wales Canyon. Abundant sandstone beds present southward from Coal Canyon. Continuous from northern edge of quadrangle to disappearance into subsurface near Axhandle Canyon; 125-375 feet (38-115 m) thick.
Kns	Sheet sandstone member- Tabular beds of fine- to medium-grained, light brown sandstone with cross beds, upward-fining, interbedded with gray to olive-gray siltstone. Sandstone beds arranged singly or amalgamated to form multistory sandstone bodies. Forms ledgy outcrops; 0-1,310 feet (0-400 m) thick. Grades laterally into Knl.
Knl	Lower redbed member- Red sandy siltstone and subordinate quartzite-clast conglomerate and pebbly sandstone. Conglomerate beds are lenticular, commonly with boulders at bases. Calcareous paleosols, marked by sandy micrite nodules, are common in the siltstone. Dinosaur bones present locally in both siltstone and conglomerate. Angular unconformities are present within the member and are shown schematically on the cross sections only, dividing the member into submembers Knl_1 and Knl_2; 260-660 feet (79-200 m) thick. Grades laterally into Kns.
$\mathrm{Knb}_{1,2}$	Basal conglomerate member- Upward-fining conglomerate and sandstone containing numerous angular unconformities that cause individual submembers to thin eastward toward Sanpete Valley. Unconformity-bounded sequences are on the order of 66 feet (20 m) thick. Conglomerate is clast-supported, with well rounded clasts in a matrix of fine-grained to coarse-grained sandstone. Clast types and ratios change upsection at Big Mountain: Precambrian quartzite clasts are most common near base, Paleozoic carbonate clasts increase in abundance upsection, and Cretaceous sandstone and limestone clasts dominate in the upper part. A mappable unconformity locally separates older (Knb_1) and younger (Knb_2) subunits; 0-488 feet (0-148 m) thick.
	Indianola Group (Early-Late Cretaceous, Aptian to Campanian)- Dominantly clastic rocks, mostly conglomerate and sandstone with subordinate mudstone and siltstone.
Ku	Upper unnamed beds (cross sections only)- Equivalent to coal, siltstone, sandstone, and conglomerate beds exposed north of the quadrangle and probably of Santonian to Campanian age based on correlation with beds in Hanson Moroni 1-AX well (NW1/4 SE1/4 NW1/4 section 14, T. 15S., R. 3E.); inferred to lie above the Funk Valley Formation in the hinge region of a syncline beneath the range. Thickness uncertain and variable; truncated beneath North Horn Formation.
Kf $\frac{\mathrm{Kfu}}{\mathrm{Kfl}}$	Funk Valley Formation (cross sections only)- Tan, well sorted, very fine grained sandstone and gray siltstone and shale in upper part (Kfu of cross section H-H'); interbedded tan, fine- to medium-grained sandstone and siltstone in lower part (Kfl of cross section H-H'). Approximately 1,580 feet (482 m) thick.
Ka	Allen Valley Shale (cross sections only)- Gray siltstone and mudstone with subordinate thin, very fine grained sandstones and bentonitic air-fall tuff beds. Approximately 540 feet (165 m) thick.
Ks	Sanpete Formation- Moderately sorted, mostly fine- to medium-grained, cross-bedded sandstone and pebbly sandstone, quartzose, moderately well cemented, interbedded with drab, olive-gray siltstone and sandy siltstone. Sandstone contains abundant small iron-oxide concretions. Sandstone beds weather yellowish gray and grayish orange, except where white beneath the unconformity with the North Horn Formation. Top not exposed in quadrangle; apparently conformable on Ksp. Approximately 560 feet (170 m) exposed in quadrangle.
$\mathrm{Ksp}_{1,2}$	San Pitch Formation- Conglomerate, pebbly sandstone, and red siltstone. Divided into two informal members: The older member (Ksp_1) consists of conglomerate beds with chert and carbonate pebbles interbedded with thick beds of red siltstone; the younger member (Ksp_2) consists of quartzite-pebble and -cobble conglomerate with thin beds of red sandy siltstone. Green quartzite pebbles are present in older member. Base not exposed in quadrangle. Exposed thickness is 327 feet (100 m).
Kc	Cedar Mountain Formation (Early Cretaceous, Barremian?-Aptian)- Claystone, mudstone, subordinate pebble and cobble conglomerate, uncommon chert-rich quartzose sandstone and uncommon limestone. Claystone and mudstone are red, reddish-brown, purple, and gray and contain micritic nodules of pedogenic origin. Muddy limestone and associated limy mudstone are brownish-gray. Limestone ranges from white to pale violet, speckled with red, and locally contains uncommon oncolites. Conglomerate beds are light yellow and gray or reddish gray, poorly sorted, clast supported, and contain mostly chert and quartzite clasts. Conglomerate beds are irregular and lenticular; oncolitic limestone grades to conglomerate in places. An incomplete section about 327 feet (100 m) is exposed in quadrangle, but thickness is 544 feet (166 m) in nearby wells.
Jt	Twist Gulch Formation (Middle Jurassic, Callovian)- Mostly well sorted, thinly bedded, fine-grained clastic rocks, including light reddish-brown and very light gray quartzose sandstone, light reddish-brown siltstone and dark reddish-brown mudstone, with siltstone and mudstone predominating. Complete section is 1,667 feet (508 m) thick on west side of San Pitch Mountains, and 1,837 feet (560 m) in a nearby well, but an incomplete thickness of approximately 1,400 feet (427 m) is present in fault-bounded exposures of the quandrangle.
Jae	Arapien Shale, member E (Middle Jurassic, Callovian; cross section J-J' only)- Brick-red silty mudstone, with gypsum and locally with halite. About 500 feet (150 m) thick in Hanson-Moroni #1-AX well in Sanpete Valley.

NOTE: Cross sections B-B', C-C', E-E', F-F', I-I', J-J', and K-K'are shown in black and white in booklet.

STRATIGRAPHIC COLUMN

SYSTEM	SERIES or STAGE	FORMATION			SYMBOL	THICKNESS Feet (Meters)	LITHOLOGY
QUAT.	Holocene Pleist.	surficial deposits			Q, QT	0-820 (0-250)	
TERTIARY	Pliocene	Green River Formation	limestone member		Tgu	175 (53)	
	Eocene		shale member		Tgl	~910 (~277)	
		Colton Formation			Tc	560-647 (170-213)	
		Flagstaff Limestone			Tf	230-590 (70-180)	
		upper redbed member of North Horn Fm.			Tnu	0-400 (0-120)	
	Paleocene	Wales Tongue of Flagstaff Limestone			Tfw	101-425 (31-130)	
CRETACEOUS	Maastrichtian	North Horn Formation	Coal Canyon member		Tnc	0-200 (0-60)	
			Big Mountain member	4	$\mathrm{TKnb}_{1\text{-}4}$	0-754 (0-230)	
				3			
				2			
				1			
			calcareous siltstone mbr.		TKns	120-833 (37-254)	
			coal-bearing member		Knc	125-375 (38-115)	
			sheet sandstone member		Kns	0-1,310 (0-400)	
	Campanian		lower redbed member		Knl	260-660 (79-200)	
			basal conglomerate member	upper part	Knb_2	0-160 (0-48)	
				lower part	Knb_1	0-328 (0-100)	
	Campanian Santonian	Indianola Group	unnamed beds		Ku	0-3,260 (0-995)	*Subsurface only*
	Coniacian Turonian		Funk Valley Formation	upper part	Kf Kfu	712 minimum (217 minimum)	
				lower part	Kfl	870 (265)	
			Allen Valley Shale		Ka	540 (165)	
	Cenomanian		Sanpete Formation		Ks	560 (170)	
	Albian		San Pitch Formation	upper mbr.	Ksp_2	327 (100)	
				lower mbr.	Ksp_1		
	Aptian Barremian	Cedar Mountain Formation			Kc	544 (166)	
JURASSIC	Callovian	Twist Gulch Formation			Jt	1,400+ (427+)	

CORRELATION OF MAP UNITS



*On cross sections only (including booklet)

MAP AND CROSS SECTION SYMBOLS

Contact: Dashed where approximate

Normal fault: Bar and ball on downthrown side; dashed where located approximately or inferred; dotted where concealed

55 Reverse or thrust fault: Teeth on hanging wall; dashed where located approximately or inferred; measured dip azimuth and value indicated

Overturned anticline: Showing trace of axial surface and plunge direction

Antiformal syncline: Showing trace of axial surface and plunge direction

⊥⊥⊥⊥⊥⊥⊥⊥⊥⊥ Scarp formed by slumping

45 Strike and dip of bedding

63 Strike and dip of overturned bedding

Strike and dip of vertical bedding

⊕ Horizontal bedding

Adit

◪ Shaft

⚒ Gravel pit

SYMBOLS USED ONLY ON CROSS SECTIONS

Angular unconformity due to growth of the west limb of the fault-propagation fold, or Sevier-Sanpete Valley antiform. Dashed where inferred.

Apparent dip, upright strata

Apparent dip, overturned strata

Arrow showing relative fault movement