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GEOLOGIC MAP OF THE MANTI 7.5-MINUTE QUADRANGLE, SANPETE COUNTY, UTAH

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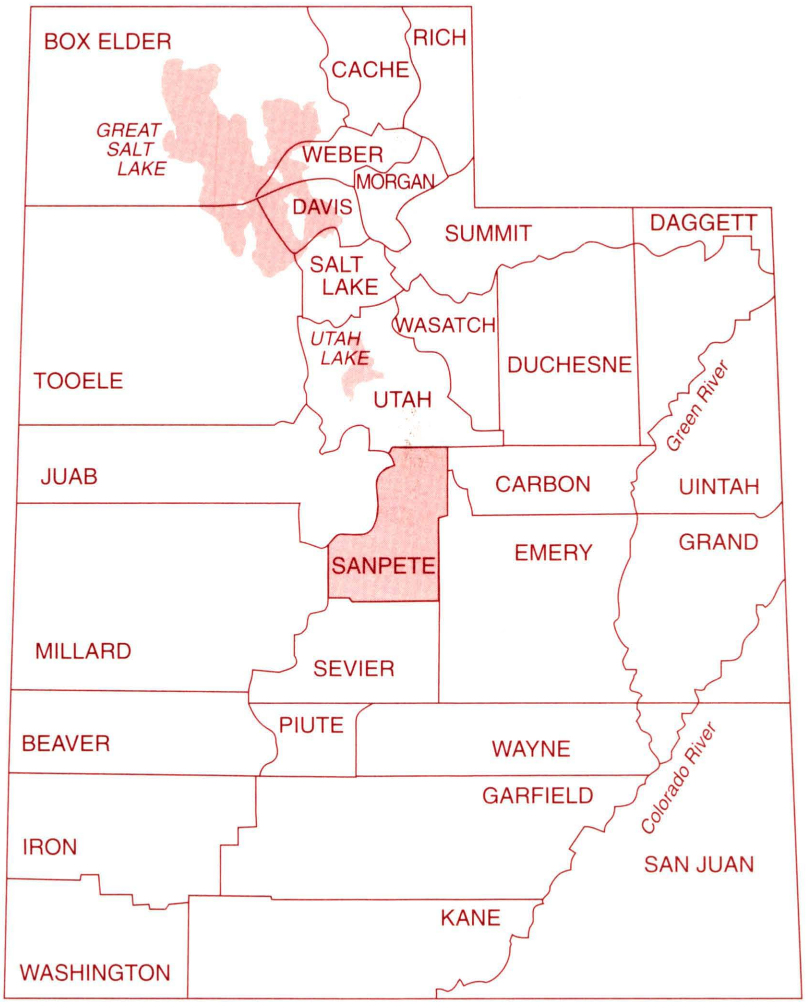

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UTAH GEOLOGICAL SURVEY

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ABSTRACT

The Manti quadrangle lies in a region of structural transition between the extended lithosphere of the Basin and Range Province 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 range in age from Middle Jurassic (Callovian) through late Eocene. Jurassic strata antedate Sevier deformation and are exposed only within a zone of imbricate reverse faults along the eastern foot of the San Pitch Mountains (Gunnison Plateau), where two formations have a maximum exposed thickness of about 1,600 feet (488 m). Cretaceous strata (Aptian to Turonian) deposited in a foreland basin associated with the Sevier orogenic belt are locally present in outcrop and reached by wells in the Sanpete Valley. This part of the section is thinner in this quadrangle than farther north and the maximum exposed thickness of Lower Cretaceous beds is only about 512 feet (156 m). Only about 400 feet (122 m) of Upper Cretaceous strata crop out in the Manti quadrangle. These Mesozoic beds were deformed by Sevier shortening and reverse faults have cut them into steeply dipping slabs along the front of the plateau.

The synorogenic North Horn Formation was deposited unconformably on older rocks between late Campanian and early Eocene time, during intermittent Sevier deformation. It represents the fill of a piggyback basin developed on the hanging wall of the Gunnison thrust system, which underlies the San Pitch Mountains. The North Horn thickens westward from a pinch-out in the subsurface beneath Sanpete Valley to a maximum of 945 feet (288 m) on the east flank of the San Pitch Mountains, but it is even thicker west of the Manti quadrangle in the central part of the mountains. Intraformational unconformities and paleocurrent indicators in the North Horn beds record syndepositional shortening and uplift. The formation is divided into four informal members in the quadrangle; the upper three are Tertiary in age.

Eocene strata include the Flagstaff, Colton, Green River, and Crazy Hollow Formations, with a total maximum thickness of 2,282 feet (696 m). These units postdate most Sevier shortening; however, minor, west-vergent back-thrusting during the later stages of the Sevier orogeny deformed North Horn, Flagstaff, and Colton strata. Although late-stage shortening of the Sevier orogeny in central Utah was coincident with deformation of the Laramide orogeny, we saw little evidence for Laramide deformation in the quadrangle. The mutual development of Sanpete Valley and the Wasatch monocline is generally attributed to basin-and-range extension, but the early development of the monocline may have begun during Laramide time.

Surficial deposits are mostly restricted to Sanpete Valley and to unstable slopes and stream channels on the plateau. Mass-wasting deposits are conspicuous on the slopes of the mountains, particularly on the fine-grained units of the North Horn, Colton, and Green River Formations. Geologic resources are few in the quadrangle; sand and gravel from the Quaternary deposits and water in Sanpete Valley are the most important. Geologic hazards in the area include earthquakes, landslides, and floods and their resultant deposits; flood dangers are the most important because of their greater frequency.

INTRODUCTION

The Manti quadrangle encompasses the southeast-central part of the San Pitch Mountains (Gunnison Plateau) and most of the width of Sanpete Valley, which lies between the Gunnison and the Wasatch Plateaus. Throughout this text "the plateau" refers to the Gunnison Plateau. The city of Manti, the county seat of Sanpete County, lies in the southeast corner of the quadrangle, and houses the majority of permanent inhabitants of the quadrangle. The lowest elevation in the quadrangle is the transient level - about 5,390 feet

(1,643 m) - of the impounded San Pitch River (Gunnison Reservoir) in the south-central part of the quadrangle. The highest elevation, approximately 8,570 feet (2,612 m) at the northwest corner of the quadrangle, is part of the crest of the plateau along the western edge of the quadrangle. The total relief within the Manti quadrangle is thus about 3,180 feet (970 m) and it is concentrated along the mountain front where cliffs and steep slopes face east into Sanpete Valley. Three large drainage systems - Dry, Maple, and Dodge Creeks - cut the eastern flank of the plateau; the largest is Maple Creek, but only Dry Creek is a permanent stream. All surface water, even in Antelope Valley, drains to the San Pitch River and thence out of Sanpete Valley. Each canyon exposes sections of the mostly Tertiary beds of the body of the plateau. Steep gulches draining the edge of the plateau expose the mostly Mesozoic beds contained in the complexly deformed belt at the toe of the plateau.

Agriculture - grazing or the growing of feed for livestock - is the principal use of the land in the quadrangle; forestry is quite subordinate to agriculture. The highlands of the quadrangle, unlike the northern parts of the Gunnison Plateau, are almost entirely privately owned. The plateau is an important source of both surface and subsurface water for the lowlands, although the east side of the valley and the city of Manti are recharged from the Wasatch Plateau on the east.

Parts of the Manti quadrangle have been mapped previously. The geologic map of the Wasatch Plateau and Sanpete Valley area (Spieker, 1949a) included the eastern margin of the Gunnison Plateau. Babisak (1949) mapped the southeastern part of the Gunnison Plateau. Katherman (1949) mapped the Flagstaff Limestone and Birsa (1973) mapped the North Horn Formation along the east front of the plateau. Geologic maps of adjacent quadrangles include those of Wales on the north (Lawton and Weiss, 1999), Sterling on the south (Weiss, 1994), Gunnison on the southwest (Mattox, 1992), Hells Kitchen Canyon Southeast on the west (Mattox, 1987) and Chriss Canyon on the northwest (Weiss and others, in press). Witkind and others (1987) published a 1:100,000-scale map that included the entire Manti quadrangle. A geologic map of the Manti quadrangle was compiled at a scale of 1:24,000 in 1978 and 1979 by Weiss (western third) and Witkind (eastern two-thirds) for publication at 1:100,000 (Witkind and others, 1987). Weiss and Sprinkel revised that work and completed new mapping in 1991, 1992, and 1993.

Numerous topical studies have been carried out within or near the Manti quadrangle. Spieker (1946, 1949b), Weiss (1982a), Lawton (1982, 1985), and Weiss and Roche (1988) presented structural cross sections. Gilliland (1963) first described the anticlinal structure of Sanpete Valley and its flanking plateau; he called that structure the "Sanpete-Sevier Valley anticline." Gundersen and Gilliland (1967) prepared isopach maps of the major rock units involved in the anticline, called an antiform in this report because the core of the antiform consists of the complexly faulted and folded Arapien Shale, whose beds are not simply folded upward. However, the strata above the Arapien Shale are folded upward, which defines the anticlinal form. Numerous stratigraphic studies making reference to Mesozoic and Cenozoic strata exposed in the quadrangle are cited in the stratigraphic section of this report.

Late Mesozoic and Paleogene strata exposed in the Manti quadrangle provide critical tests of the tectonic development of the region, which lies athwart the boundary between the Basin and Range Province and Colorado Plateau. During late Mesozoic time the easternmost edge of the Sevier fold-and-thrust belt lay along the trend of what is now Sanpete Valley. Overturned and reverse-faulted Mesozoic beds in the face of the plateau demonstrate back-thrusting of strata within the upper plate of the Gunnison thrust. Sedimentary features and structure of the North Horn Formation, particularly as revealed in the Wales quadrangle, adjacent on the north, demonstrate coeval deformation and deposition that constrain our interpretation of the style and ages of deformation at the thrust front more precisely than formerly possible (Lawton and Weiss, 1999).

STRATIGRAPHY

Bedrock strata exposed in the Manti quadrangle are from Middle Jurassic to Eocene in age and fall into three structural and stratigraphic categories: (1) Middle Jurassic marine and marginal marine strata and Lower Cretaceous mainly continental strata that predate local contractional deformation are present along the foot of the east front of the Gunnison Plateau in a zone of west-vergent, reverse-faulted blocks that we call the zone of imbricate reverse faults. (2) Upper Cretaceous to Eocene synorogenic continental strata (North Horn Formation) accumulated in a piggyback basin whose eastern margin coincided roughly with the zone of imbricate reverse faults. North Horn rocks make up the body of the plateau and are deformed by the reverse faults in the plateau front. Marine lithofacies of the Cretaceous beds lie to the east and are found in this quadrangle only in the subsurface of Sanpete Valley. (3) Younger Eocene strata capping the plateau above the North Horn are largely late-orogenic lacustrine and fluviatile beds deposited during waning stages of the Sevier orogeny in this region.

Surficial deposits within the quadrangle are largely restricted to Sanpete Valley and the major drainages of the plateau, but mass-wasting deposits are widespread on slopes within the plateau.

Jurassic System

Arapien Shale (Ja)

Only member E of the Arapien Shale, the fifth and youngest of five members defined and described by Hardy (1952), is exposed in the quadrangle. In the Manti quadrangle, the rock is a brick-red gypsiferous mudstone with minor thin layers of siltstone. Although bedding is generally obscure, it can be observed with confidence in an anticline in SE$^{1}/_{4}$ section 4, T. 17 S., R. 2 E. The Arapien is well exposed in the adjacent Sterling quadrangle, where it contains salt (Weiss, 1994). Member E is marine in origin, and was deposited in a restricted basin in which a high rate of evaporation led to the formation of gypsum and halite crystals in the bottom muds. The maximum exposed thickness of the member in the quadrangle is about 200 feet (61 m), whereas its exposed thickness in the vicinity is slightly more than 400 feet (122 m) (Willis, 1986; Weiss, 1994). The Arapien Shale probably had a depositional thickness between 2,000 and

3,000 feet (610-914 m) (Sprinkel, 1994); however, it is 2,700 feet (820 m) to more than 7,000 feet (2,100 m) in wells drilled in and surrounding the Manti quadrangle (Sprinkel, 1994). Even the great thickness of Arapien drilled by wells in the area may not reflect the maximum thickness in the core of the antiform. The enormous thickness variation of the Arapien is caused by structural complications, such as folding, fault-repeated sections, and diapirism.

The contact with the underlying Member D is not exposed in the quadrangle. The upper contact has usually been reported (for example, see Weiss, 1994) to be regionally conformable with the Twist Gulch Formation. At several places in the Manti quadrangle, however, a basal conglomerate - a thin muddy conglomerate composed of angular granules - of the Twist Gulch lies atop member E of the Arapien Shale. The authors have found the same relationship on the west side of the plateau in the Chriss Canyon quadrangle, which adjoins the northwest corner of the Manti quadrangle. Member E is Callovian in age, and the entire Arapien Shale is Middle Jurassic (Bathonian to Callovian) (Imlay, 1980).

Twist Gulch Formation (Jt)

The Twist Gulch Formation crops out widely but discontinuously in the zone of imbricate reverse faults; the most representative exposure is that at the mouth of Dry Canyon. It consists mostly of pale-red and reddish-brown calcareous mudstone and siltstone and has many beds of pinkish-gray to white sandstone 2 to 4 feet (about 1 m) in thickness. The sandstone beds form ribs and the mudstone and siltstone beds make reentrants in the profile of the outcrop. The sandstone is mostly fine or medium grained, with some coarse grains, highly quartzose, and sometimes speckled or variegated with inclusions of red mudstone; some beds have hummocky cross-bedding. Near the middle of the exposure, an interval about 68 feet (21 m) thick of mostly light-gray-weathering sandstone with some mudstone interbeds is present in the wall of Dry Canyon (Roche, 1985) and lies in the Twist Gulch throughout the plateau. The sandstone in this interval is thinly laminated and exhibits trough cross-bedding locally; it is interpreted as a shoreface sand (Lawton and Weiss, 1999), and is considered a western feather edge of the marine Curtis Sandstone.

The rest of the Twist Gulch beds are marginal marine in origin and, although most are highly oxidized, they lack halite and gypsum of the Arapien Shale. The highly colored mudstone and siltstone beds are interpreted as tidal-flat deposits, whereas the thick sandstone unit and the thin pale-pink or white sandstone beds represent either shore-face or surf-zone deposits (Lawton and Weiss, 1999).

The basal contact with the Arapien Shale is exposed at several places in the quadrangle and is remarkable for the basal conglomerate of dark-red grit and coarse sandstone, never more than a few feet thick. These are the first examples of the clearly disconformable contact that we had ever seen, but we have since found the same relation on the west side of the plateau. Although the basal contact with the Arapien Shale is well exposed locally, no depositional upper contact with the Cedar Mountain Formation, which is unconformable regionally, is exposed in this quadrangle. The Twist Gulch is overlain by various younger beds, all in unconformable or fault contact.

The maximum exposed thickness of the Twist Gulch in the quadrangle is 1,150 feet (350 m). A moderately dipping complete section is 1,667 feet (508 m) thick on the northwest flank of the plateau (Auby, 1991). A less disturbed section is present in the Phillips Petroleum Price N well (SE1/4SE1/4 section 29, T. 15 S., R. 3 E.) a few miles northeast of the quadrangle, where the formation has been interpreted as 956 feet (292 m) thick by Sprinkel (1994) and 1,837 feet (566 m) thick by Lawton and Weiss (1999).

The Twist Gulch is Middle Jurassic (Callovian) in age and a correlative of the Preuss Sandstone of northern Utah (Imlay, 1980). The Twist Gulch Formation is also correlative with the San Rafael Group and contains strata recognizable as the Entrada, Curtis, and Summerville Formations (Imlay, 1980; Willis, 1986; Lawton and Willis, 1987). As mentioned earlier, we consider the 68-foot-thick interval of shoreface sandstone within the Twist Gulch Formation in the Gunnison Plateau to be the equivalent of the Curtis Formation, but this has not been demonstrated biostratigraphically. In addition, the beds above and below the shoreface sandstone in the Manti quadrangle are lithologically similar and are not recognizable as typical Entrada or Summerville rocks.

Cretaceous System

In the San Pitch Mountains and beneath Sanpete Valley, Lower Cretaceous continental strata lie unconformably on the Twist Gulch Formation and beneath Upper Cretaceous (Cenomanian) marine and terrestrial strata of the upper part of the Indianola Group. In the Manti quadrangle these fluviatile rocks (Cedar Mountain and San Pitch Formations) are exposed only in the zone of imbricate reverse faults and are thus incomplete in thickness. The two formations are better and more completely exposed in the Sterling quadrangle just to the south (Witkind and others, 1986; Weiss, 1994; Sprinkel and others, 1999). Sprinkel (1994) interpreted the thickness of this nonmarine Lower Cretaceous section between the Twist Gulch Formation and Cenomanian marine strata (Sanpete Formation of the Indianola Group) as 1,372 feet (418 m) in the Phillips Petroleum Price N well in the Chester quadrangle (SE1/4SE1/4 section 29, T. 15 S., R. 3 E.) and 1,328 feet (405 m) in the Hanson Oil Moroni #1AX well (NW1/4SE1/4NW1/4 section 14, T. 15 S., R. 3 E.) 16 miles (26 km) north-northeast of the Manti quadrangle. Lawton reported thicknesses of 1,287 feet (392 m) and 2,190 feet (668 m), respectively, from these two wells (Lawton and others, 1993). The different interpreted thicknesses point up the difficulty of selecting consistent contacts from logs in this interval of mudstone, sandstone, and conglomerate.

The Indianola Group in the San Pitch Mountains is entirely nonmarine in origin, but marine beds of the Allen Valley Shale are present in the subsurface of Sanpete Valley. The group is Early to Late Cretaceous in age (Sprinkel and others, 1999).

Cedar Mountain Formation (Kc, Ku)

The Lower Cretaceous Cedar Mountain Formation was named by Stokes (1944, 1952) for beds of variegated mudstone with intercalated sandstone, lacustrine limestone, and a discontinuous basal conglomerate (Buckhorn Conglomerate) exposed at Cedar Mountain in the northwestern part of the San Rafael Swell (section 9, T. 18 S., R. 10 E., Salt Lake Base Line and Meridian, Emery County, Utah). The Cedar

Mountain Formation has since been formally subdivided into four members by Kirkland and others (1997). West of the San Rafael Swell, the Cedar Mountain Formation crops out in a belt of isolated (and undivided) exposures along the margins of the Gunnison Plateau. In the Manti quadrangle the Cedar Mountain exposures are near the base of the east front of the Gunnison Plateau, in the structurally complex zone between Dry and Maple Canyons. It consists of variegated mudstone and intercalated beds of pebbly sandstone and subordinate lacustrine limestone. In addition, the Cedar Mountain contains thick zones of pedogenic carbonate that weather to calcareous nodules. The nodules and the "polished stones" (thought to be gastroliths by Stokes, 1972) in the variegated mudstone are distinctive characteristics of the unit. The Cedar Mountain Formation was deposited in a fluvial-lacustrine environment (Yingling, 1987; Kirkland and others, 1997; Schwans, 1988a, 1988b).

The Cedar Mountain Formation unconformably overlies the marginal marine beds of the Middle Jurassic Twist Gulch Formation west of the San Rafael Swell (Willis, 1986; Willis and Kowallis, 1988; Auby, 1991; Banks, 1991; Biek, 1991; Sprinkel, 1994; Weiss, 1994; Lawton and Weiss, 1999). This contact is not exposed in the Manti quadrangle because of faulting, but the contact with the Twist Gulch was recognized in the exploratory wells drilled within the quadrangle (Sprinkel, 1994; and table 1). Thus, in this region, Upper Jurassic strata were either not deposited or were eroded prior to deposition of Lower Cretaceous beds (Sprinkel, 1994). This implies that a regional topographic high existed or emerged during Late Jurassic time. Near Little Salt Creek, in the adjacent quadrangle northwest of the Manti quadrangle, the unconformable contact between the Cedar Mountain and the Twist Gulch is angular, although this may be a local feature (Weiss and others, in press). A basal Cedar Mountain conglomerate with interbedded sandstone dips about 20° less than the underlying fine-grained, reddish-orange sandstone beds of the Twist Gulch. The upper contact is concordant, sharp, and well exposed, and is placed at the surface where the lowest thick, reddish-brown conglomerate of the San Pitch Formation lies on the massive red and gray mudstone of the Cedar Mountain.

The Cedar Mountain Formation generally thickens northwestward across the San Rafael Swell from 164 to 513 feet (50-160 m) (Craig, 1981; Yingling, 1987). It continues to thicken slightly north and northwestward from about 617 feet (188 m) in Salina Canyon to a maximum thickness of a little more than 650 feet (200 m) under the Sanpete Valley (Sprinkel, 1994), although this represents apparent thicknesses from drill holes in Sanpete Valley. Witkind and others (1986) measured 433 feet (132 m) of Cedar Mountain Formation near Christianburg in the adjacent quadrangle to the south, but that may not be the full thickness, for a fault may cut the formation at that location (Weiss, 1994). An anomalously thick section (1,686 feet [514 m]) of Cedar Mountain beds was drilled in the Mobil Larson #1 (table 1) in the quadrangle (Sprinkel, 1994); that great thickness was probably the result of structural thickening. From Sanpete Valley the Cedar Mountain thins westward rapidly to about 75 feet (23 m) along the western flank of the Gunnison Plateau (Sprinkel and others, 1999), although it is up to 680 feet (207 m) in the northwest face of the plateau (Auby, 1991; Biek, 1991). It pinches out near the West Hills, about 20 miles (32 km) west of the quadrangle (Sprinkel, 1994). The maximum thickness of the incomplete section exposed in the Manti quadrangle is 62 feet (19 m).

The age of the Cedar Mountain Formation in the San Rafael Swell is Barremian to late Albian-early Cenomanian (Katich, 1951, 1956; Craig, 1981; Tschudy and others, 1984; Kirkland and others, 1997, 1999). In Salina Canyon, the Cedar Mountain Formation is likely Aptain to early Albian in age, based on fission-track dates obtained from zircon- and apatite-bearing bentonitic mudstones in the upper half of the formation (Willis and Kowallis, 1988) and the tentative correlation of these beds with beds of the Ruby Ranch Member of the Cedar Mountain Formation to the east (Kirkland and others, 1997, 1999). Samples collected near Christianburg have yielded palynomorphs of non-definitive Early Cretaceous age (Witkind and others, 1986). The Cedar Mountain Formation in the Gunnison Plateau is interpreted as Aptian to middle Albian in age. The Aptian age is based on the Early Cretaceous palynomorphs from Cedar Mountain beds that crop out near Christianburg (south of the Manti quadrangle) and in east-central Utah, and the tentative correlation of these beds with beds of the Ruby Ranch Member of the Cedar Mountain in east-central Utah (Tschudy and others, 1984; Witkind and others, 1986; Kirkland and others 1997, 1999). The middle Albian upper age limit is based on the age of the overlying San Pitch Formation.

Indianola Group (Ki)

Continental and marine strata that concordantly overlie the Cedar Mountain Formation and unconformably underlie the North Horn Formation in the Manti and adjacent quadrangles are included in the Indianola Group. The group includes, in ascending order, the San Pitch and Sanpete Formations, the Allen Valley Shale, and the Funk Valley and Sixmile Canyon Formations (Spieker, 1946, 1949a; Weiss, 1994; Sprinkel and others, 1999). Of these, only the San Pitch and Funk Valley Formations are exposed in the Manti quadrangle, although all underlie Sanpete Valley. The San Pitch beds are in isolated outcrops in the structurally complex zone along the east front of the Gunnison Plateau between Dry and Maple Canyons; steeply dipping Funk Valley sandstone forms a tiny outcrop in the southeast corner of the quadrangle. The upper four formations, lying unconformably between the San Pitch and North Horn Formations, are the classic parts of Spieker's Indianola Group (Spieker, 1946, 1949a) and are described in adjacent and nearby quadrangles (Banks, 1991; Weiss, 1994; Lawton and Weiss, 1999). Not far to the east, beneath Sanpete Valley, the marine facies of the Allen Valley Shale is present. East of Sanpete Valley, in the Wasatch Plateau, the group has been divided traditionally into only the four upper formations (Spieker, 1949a).

San Pitch Formation (Kspa, Kspb, Kspc, Ku)

The name San Pitch Formation is applied to reddish-brown conglomerate and interbedded mudstone and sandstone that overlie the Cedar Mountain Formation concordantly and underlie the Sanpete Formation unconformably. It was defined by Sprinkel and others (1999), and replaces the red conglomerate section of the Morrison(?) Formation (Spieker, 1949a), the upper unit of the "Cedar Mountain" of

Table 1. *Simplified logs of exploratory wells in the Manti quadrangle.*

Operator	Well Name	API Number	Location	Ground Elevation (ft)	Formation Name	Drilled Depth (ft)	Elevation (ft)	Thickness (ft)
Mobil Oil Corporation	Larson #1	43-039-30008	SW1/4SE1/4 section 1, T. 17 S., R. 2 E.	5,434	Alluvium	0	5,434	680
					Flagstaff Limestone	680	4,754	270
					North Horn Formation	950	4,484	810
					Funk Valley Formation	1,760	3,674	912
					Allen Valley Shale	2,672	2,762	202
					Sanpete Formation	2,874	2,560	466
					San Pitch Formation	3,340	2,094	985
					Cedar Mountain Formation	4,325	1,109	1,686
					Twist Gulch Formation	6,011	-577	1,595
					Arapien Shale	7,606	-2,172	6,437
					TD	14,043	-8,609	
Mobil Oil Corporation	Larson #2	43-039-30009	SW1/4SE1/4 section 1, T. 17 S., R. 2 E.	5,424	Alluvium	0	5,424	680
					Flagstaff Limestone	680	4,744	715
					North Horn Formation	1,395	4,029	345
					Funk Valley Formation	1,740	3,684	774
					TD	2,514	2,910	
Chandler & Associates	Madsen 7-25	43-039-30015	SW1/4NE1/4 section 25, T. 17 S., R. 2 E.	5,427	Alluvium	0	5,427	670
					Green River Formation (slide)	670	4,757	460
					Green River Formation (in place)	1,130	4,297	474
					Funk Valley Formation	1,604	3,823	1,958
					Allen Valley Shale	3,562	1,865	1,256
					Sanpete Formation	4,818	609	349
					San Pitch Formation	5,167	260	343
					TD	5,510	-83	
Chandler & Associates	Barton 4-2	43-039-30012	NW1/4NW1/4 section 2, T. 18 S., R. 2 E.	5,447	Alluvium	0	5,447	935
					Green River Formation	935	4,512	475
					Arapien Shale	1,410	4,037	1,250
					TD	2,660	2,787	

Witkind and others (1986), the upper member of the Pigeon Creek Formation (Schwans, 1988a, 1988b), and the unnamed basal unit of the Indianola Group (Weiss and Roche, 1988; Weiss, 1994). It is divisible into three informal members (A, B, and C) that are distinctive in structure, composition, and topography, and that can be recognized and traced regionally. Only members A and B of the San Pitch Formation are exposed in the Manti quadrangle because member C and the higher units of the Indianola Group have been removed by erosion.

Where more fully exposed, the San Pitch is observed to rest concordantly on the Cedar Mountain Formation. Although there is some interfingering of the two units, the contact is placed at the base of the first reddish-brown cobble- and pebble-conglomerate bed (Sprinkel and others, 1999). The lower contact of the San Pitch is generally distinctive because the San Pitch commonly forms the first prominent cliff above the smooth slopes of the Cedar Mountain Formation. It is one of the most obvious and best-described contacts used for mapping in the region (Hunt, 1950; Hardy and Zeller, 1953; Witkind and Page, 1983; Witkind and others, 1986; Weiss and Roche, 1988; Auby, 1991; Biek, 1991; Weiss, 1994; Fong, 1995). The lower contact is also easily recognized in the subsurface on lithologic and petrophysical logs (Sprinkel, 1994).

The San Pitch Formation is a fluvial unit that was deposited in a developing foredeep of the central Utah foreland basin (Sprinkel and others, 1999). It is thickest along the west flank of the Gunnison Plateau and thins to the south and east. On the west flank of the plateau the formation is 3,663 feet (1,116 m) thick. Near Christianburg, in the Sterling quadrangle to the south, the type section of the San Pitch is 646 feet (197 m) thick. It continues to thin southward to 280 feet (85 m) at Salina Canyon, and grades eastward into the Cedar Mountain Formation (Sprinkel and others, 1999). Thicknesses of the members generally vary concordantly with that of the full formation (Sprinkel and others, 1999).

In normal stratigraphic succession the San Pitch Formation underlies the Sanpete Formation unconformably. The upper contact is placed, regionally, at the base of a distinctive, light-gray quartzite-boulder conglomerate (90 to 100 percent quartzite clasts) of the Sanpete Formation (Sprinkel and others, 1999). The San Pitch ranges in age from middle to late Albian (Sprinkel and others, 1999).

The contacts between members A, B, and C of the San Pitch Formation are based on notable grain-size changes, changes in clast composition and matrix color, and changes in general bed geometry (Sprinkel and others, 1999). The contact between members A and B is placed below the first carbonate-pebble conglomerate, which separates the darker reddish-brown channel-form conglomerate beds of member A from the lighter brownish-gray tabular conglomerate, sandstone, and mudstone beds of member B (Sprinkel and others, 1999). Member C is mostly mudstone with cobbles and boulders; it overlies member B in the subsurface of the quadrangle, but has been removed by erosion from the structurally complex area of the eastern front of the plateau between Dry and Maple Canyons. In outcrop, therefore, the upper contact of member B is an unconformity beneath the Big Mountain Member of the North Horn Formation.

Member A (Kspa, Ku): Member A consists of cobble and pebble conglomerate interbedded with calcareous to noncalcareous mudstone. The conglomerate beds are thick- to medium-bedded, with channel-form geometry and subtle, large-scale trough cross-stratification. The conglomerate is clast supported and cemented with a reddish-brown calcareous matrix. Clasts in the conglomerate beds are rounded to subrounded quartzite (about 50 percent) and carbonates (about 45 percent). Member A also contains white and grayish-red sandstone and siltstone clasts (about 5 percent). The quartzite clasts are Late Proterozoic to Cambrian in age and include white to light-gray varieties from the Caddy Canyon Quartzite (Late Proterozoic), purple to banded-purple varieties from the Mutual Formation (Late Proterozoic), very pale orange to pinkish varieties from the Tintic Quartzite (Cambrian), and pale-green quartzite from the Dutch Peak Formation (Late Proterozoic). Grayish-green quartzose sandstone clasts were derived from the Ophir Formation (Cambrian). Siltstone and other sandstone clasts were probably derived from Triassic and Jurassic formations.

The maximum exposed thickness of member A in the Manti quadrangle is 205 feet (62 m), but that may not be a true maximum thickness because of structural attenuation. The member is 495 feet (151 m) thick on Chicken Creek, northwest of the quadrangle, and 186 feet (57 m) at its type section at Christianburg, south of the Manti quadrangle (Sprinkel and others, 1999).

Member B (Kspb, Ku): Member B consists of tabular cobble and boulder conglomerate and sandstone beds interbedded with mudstone. Many of the conglomerate beds in the member contain carbonate cobbles - to nearly 100 percent - which are not common in members A and C. The carbonate clasts are mostly dolomite cemented in a dolomite to dolomitic carbonate matrix, which causes member B to be grayer and lighter in color than the underlying conglomerate beds of member A. Member B also includes conglomerate beds that contain subrounded to subangular clasts of both quartzite and carbonates in about equal amounts. The distinctive pale-green quartzite and grayish-green quartzose sandstone clasts of member A are also present in member B. Sandstone beds are light pinkish orange to light gray, fine to medium grained, and display trough cross-bedding, asymmetrical ripples, flute casts, and tool and groove marks. Sandstone beds also contain burrows and root casts, rare leaf impressions, and a few gastropods. The mudstone beds are reddish orange, silty in part, and calcareous.

The maximum thickness of member B exposed in the quadrangle is 245 feet (75 m). At Chicken Creek the member is 2,200 feet (671 m) thick, and it is 316 feet (96 m) thick at its type section near Christianburg, at the south end of the plateau (Sprinkel and others, 1999).

Funk Valley Formation (Kfv)

Interbedded fine-grained, yellowish-gray sandstone and gray siltstone and shale of the lower third of the Funk Valley Formation form a small outcrop near the southeast corner of the Manti quadrangle. The strata are dipping steeply, and only about 200 feet (61 m) of the formation is exposed. The whole formation is about 3,000 to 3,100 feet (914-945 m) thick in the adjacent Sterling quadrangle (Weiss, 1994). The lower part of the formation is a deposit of marine shoreface sands (Schwans, 1995; Lawton and Weiss, 1999), although distinctive criteria of its origin are not well displayed in this small outcrop. The Funk Valley Formation is Coniacian to Campanian in age (Fouch and others, 1983; Schwans, 1995).

Tertiary and Cretaceous Systems

North Horn Formation (Knl, TKnb, TKn)

The North Horn Formation, a thick sequence of terrestrial clastic rocks and some limestone, lies unconformably on older Cretaceous and Jurassic formations. It contains many unconformities; many in the mountain front are angular unconformities, but all such unconformities grade westward to disconformities. In the Wales quadrangle, adjacent on the north, the North Horn reaches its maximum thickness of 3,600 feet (1,100 m) in the Gunnison Plateau (Lawton and Weiss, 1999). There, also, is the fullest development of the formation in the region and where it has been divided into eight informal units (Lawton and others, 1993; Lawton and Weiss, 1999). The formation thins markedly southward from the Wales area, however; only the four upper units (Big Mountain, Coal Canyon, calcareous siltstone, and upper red) are exposed in the Manti quadrangle. Their maximum exposed thickness is about 945 feet (288 m), but unit thickness increases westward into the body of the plateau. The four older (lower) units of the North Horn are present in the subsurface in the quadrangle (labeled Knl on cross sections A-A' and B-B'. Within the Dry Canyon graben at the north edge of the quadrangle, only two units having a maximum thickness of 118 feet (36 m) are present because of the complex structural history of the graben area (Lawton and Weiss, 1999). No North Horn beds were identified in wells that were drilled in the southeastern part of the quadrangle (cross section B-B'). The fullest North Horn exposures in the quadrangle are along the mountain front, but the westward-thickening tendency seen in the Wales quadrangle (Lawton and Weiss, 1999) is evident in the Manti quadrangle as well.

The North Horn Formation also thins eastward into the subsurface of Sanpete Valley, where it lies unconformably on progressively older beds in the Sanpete-Sevier Valley antiform (SSVA). Drill holes in Sanpete Valley (table 1) penetrate thin sections of the North Horn above deformed Indianola strata and the North Horn is locally absent in the subsurface. The apparent thickest development of the formation in the subsurface of the Manti quadrangle is 810 feet (247 m) (Sprinkel, 1994).

The North Horn Formation ranges in age from Late Cretaceous (late Campanian) to early Eocene in the Wales quadrangle, where coal-bed palynomorphs and paleomagnetic studies have contributed to dating (Hobbs, 1989; Lawton and others, 1993; Talling and others, 1994, 1995). The formation contains dinosaur bones about 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.) (Lawton and Weiss, 1999). The units of the North Horn Formation exposed in the Manti quadrangle represent beds of Maastrichtian to early Eocene age.

Big Mountain unit (TKnb): In its type area, 5 miles (8 km) north of the Manti quadrangle, the Big Mountain unit is divisible into four subunits, two of conglomerate and two of sandstone. It is not so divisible in the Manti quadrangle, but rather consists of a massive, poorly bedded ledge or "reef" of light-gray sandstone with local lenses of pebble- and cobble-conglomerate that weathers to yellowish gray. The Big Mountain unit is well cemented by calcite, contains minor mud, and forms a conspicuous light-brown wall in the face of the mountain, from the Dry Canyon graben south nearly to Maple Canyon. Small, pebbly outcrops of the unit are present on both sides of the mouth of Maple Canyon, but not farther south; apparently the member pinches out or plunges deeper just south of Maple Canyon.

Fossil logs are abundant at the base of the Big Mountain unit at several sites in section 9, T. 17 S., R. 2 E. The logs are in tangled arrays over tens of square feet at some sites; at others just a few logs are seen. These fossils represent log jams in braided streams which, from evidence in the Wales quadrangle, flowed eastward (Lawton and Weiss, 1999). Here the discharge was less and the substrate was cut less deeply than farther north in the Wales quadrangle. Oncolites to the size of small boulders are abundant in the lower part of the Big Mountain unit locally, particularly in the NW1/4 section 16, T. 17 S., R. 2 E.; many of the specimens were formed on cores of quartzite pebbles and cobbles.

The Big Mountain unit ranges in thickness from 262 feet (80 m) (Birsa, 1973, Section E) to 395 feet (120 m) in the bold reef between Dry and Maple Canyons. It pinches out southward just south of Maple Canyon, and was never deposited in the Dry Canyon graben in the north half of section 4, T. 16 S., R. 2 E.; that area stood above the depositional surface at the time, as will be explained in the chapter on structure. The lower part of the Big Mountain unit is Maastrichtian in age, based on the combination of Late Cretaceous palynomorphs from a claystone lens at its base in NE1/4SW1/4 section 9, T. 17 S., R. 2 E. and Maastrichtian palynomorphs from a claystone in the underlying sheet sandstone unit in SW1/4NW1/4 section 1, T. 16 S., R. 2 E. (Lawton and Weiss, 1999, appendix 1).

Where the Big Mountain unit is fully developed in the Wales quadrangle, it truncates the underlying coal-bearing unit, intertongues to the north with the lower part of the calcareous siltstone unit, and is overlain by the Coal Canyon unit (Lawton and Weiss, 1999). It is absent from the Dry Canyon graben; south of there the Big Mountain unit lies unconformably on or in fault contact with older Cretaceous and Jurassic beds. It underlies the Coal Canyon and calcareous siltstone units.

Tertiary System

North Horn Formation (Tncc, Tns, Tnu)

Coal Canyon and calcareous siltstone units (Tncc, Tns): The Coal Canyon unit is poorly exposed in patches in the Manti quadrangle and is too thin to depict on the map; therefore it is mapped together with the calcareous siltstone unit as Tncc. In the Wales quadrangle to the north, the Coal Canyon member consists of light-gray conglomerate and sandstone arranged in foresets, and is as much as 200 feet (60 m) thick Lawton and Weiss (1999). The foresets indicate transport toward the west and northwest, in marked contrast to the eastward dispersal of the underlying Big Mountain sediments. Foresets preserved in the clastic beds represent small lacustrine deltas built westward into a structural basin developed west of and flanking the SSVA; their occurrence implies a pulse in the uplift of the antiform. The unit is Paleocene in age, based on its gradational overlying and lateral contacts with the upper part of the calcareous siltstone unit (Lawton and Weiss, 1999).

Small outcrops of the Coal Canyon unit are preserved above the great wall of Big Mountain sandstone between the SW1/4 section 4 and the NW1/4 section 16, T. 17 S., R. 2 E. by exposures of the same type of pebbly sandstone beds, with similar west-dipping foresets, as are found farther north in the Wales quadrangle. Thus paleocurrent flow was uniformly to the west of the Sanpete-Sevier Valley antiform during deposition of the Coal Canyon unit. The patches of these west-directed deltaic deposits are 40 to 60 feet (12-18 m) thick and largely covered by debris on the face of the mountain in the Manti quadrangle.

The calcareous siltstone unit (Tns) is made up of calcareous siltstone and sandstone with blocky and massive structure, colored red, purple, olive gray, and gray; it weathers to a reddish- or yellowish-gray soil. The unit is conspicuously red in its upper part on the mountain front and just north of Maple Canyon. The siltstone beds are somewhat sandy, and some sandstone beds are present in the unit. The whole unit is weak and weathers to steep vegetated slopes. Over the wall of Big Mountain sandstone, where patches of the Coal Canyon unit can be seen, it and the calcareous siltstone member are mapped together and labeled Tncc. The combined unit thins southward. At Dry Canyon and within the plateau, the calcareous siltstone member is distinct and is labeled Tns.

The blocky structure of the siltstone is believed to be pedogenic in origin (Lawton and Weiss, 1999). The massive siltstone beds are variegated and more colorful than blocky ones, and contain discrete layers of warty micrite nodules and tubules. Sandstone beds associated with the blocky siltstones are tabular, upward-coarsening beds, bioturbated and sparsely fossiliferous. Those associated with the massive siltstone beds are lenticular to tabular and record upward-fining (Lawton and Weiss, 1999).

The environments of deposition of the calcareous siltstone unit included both shallow- and marginal-lacustrine conditions and alluvial areas of low slope over which streams meandered. The streams formed lenses of sandstone, and overbank deposits developed paleosols (Lawton and Weiss, 1999).

The Coal Canyon and calcareous siltstone units aggregate from 0 to 400 feet (0-122 m) of thickness in the Manti quadrangle. Within the Dry Canyon graben the Coal Canyon unit is absent and the calcareous siltstone unit (Tns) is only 0 to 16 feet (0-5 m) thick where it pinches out over the Jurassic Twist Gulch Formation. Atop the wall of Big Mountain sandstone the mapped interval - Coal Canyon plus the calcareous siltstone units (Tncc) - is 186 feet (57 m) (Birsa, 1973, Section E) to 400 feet (122 m) thick.

Where fully developed, 5 to 6 miles (8-9.7 km) north of the Manti quadrangle, the calcareous siltstone unit is very thick. There it locally lies on the Coal Canyon unit, but elsewhere it intertongues with both the Big Mountain and Coal Canyon units. Thus its age in that area is both Cretaceous and Tertiary (Lawton and Weiss, 1999). In the Manti quadrangle only the upper part of the calcareous siltstone unit is preserved, lying on the patches of the Coal Canyon unit and the much diminished Big Mountain unit. Similar relations persist from this quadrangle to Axhandle Canyon, 2 to 3 miles (3-5 km) north, where the fossils in the calcareous siltstone are Paleocene to Eocene in age (Lawton and Weiss, 1999). However, the calcareous siltstone unit exposed in the Manti quadrangle is believed to be only Paleocene in age.

The patchy Coal Canyon and the calcareous siltstone units (Tncc) lie on the massive ledge of the Big Mountain unit and under the Wales Tongue of the Flagstaff Limestone. Where the calcareous siltstone (Tns) is separately mapped, it is also overlain by the Wales Tongue.

Wales Tongue of the Flagstaff Limestone (Tfw): In the Manti quadrangle the Wales Tongue of the Flagstaff Limestone is a thin sheet of carbonate rock that lies generally between the calcareous siltstone unit (Tns, Tncc) and the upper redbed unit (Tnu) of the North Horn Formation. Near the north edge of the Wales quadrangle the Wales Tongue joins the main body of the Flagstaff Limestone, where the upper redbed unit pinches out (Lawton and Weiss, 1999). Northward thickening of the Wales Tongue is complementary to the northward thinning of the upper redbed unit.

The Wales Tongue is formed of medium and thick beds of light-gray and yellowish-gray dolomite and dolomitic limestone parted by thin and medium beds of somewhat sandy mudstone and shale. The whole weathers whitish to orange gray. The beds in the Manti quadrangle are only the upper part of the unit known farther north in the Wales quadrangle. The belt of square-jointed carbonate ledges is conspicuous between the shaly slopes of the calcareous siltstone and the upper redbed members. Gastropods and oncolites are present locally in the Wales Tongue.

The tongue represents an early development of lacustrine or marshy conditions; it was a harbinger of Lake Flagstaff. Where the upper redbed unit of the North Horn Formation is absent, in the northern part of the Wales quadrangle and in the Dry Canyon graben, lacustrine conditions persisted without interruption to form the main body of the Flagstaff Limestone. In most of both the Manti and Wales quadrangles, however, terrestrial conditions swamped the aqueous environment and formed the upper redbed unit of the North Horn Formation before Lake Flagstaff developed fully and formed the main body of the Flagstaff Limestone.

The Wales Tongue ranges from about 33 feet (10 m) (Birsa, 1973, Section E) to 60 feet (18 m) thick over most of the Manti quadrangle, although it is 102 feet (31 m) thick at the mouth of Dry Canyon (Lawton and Weiss, 1999). Here again the special structural history of the Dry Canyon graben yielded a rock succession that is anomalous compared to the regional succession in the Manti and Wales quadrangles. The tongue is late Paleocene to early Eocene in age, as shown by its fossil content (La Rocque, 1960) and by magnetostratigraphy (Lawton and others, 1993). The tongue is gradational with the calcareous siltstone unit, but is overlain sharply and unconformably by the upper redbed unit outside of the Dry Canyon graben. In the graben, it is overlain conformably by the main body of the Flagstaff Limestone.

Upper redbed unit (Tnu): The upper redbed unit is the uppermost of the mappable lithostratigraphic units of the North Horn Formation. The name is used here to be consistent with the map of the Wales quadrangle, where a lower redbed unit is also present low in the formation (Lawton and Weiss, 1999). The upper redbed unit consists of gray shaly mudstone, reddish-brown and reddish-purple mottled siltstone, yellowish-gray sandy siltstone, and a few thin and medium beds of orange-weathering sandstone. Thin beds of fossiliferous gray micrite are uncommon. The unit weathers to a reddish soil and forms steep slopes between the two cliff-forming elements - the main body and the Wales Tongue - of the Flagstaff Limestone. Its slopes are liberally covered with talus and colluvium from the overlying main body of the Flagstaff Limestone. The red coloration lessens westward in lower Maple Canyon, where the mudstone beds are grayer. Between the northwest and north forks of Maple Creek the unit is grayish below and above and reddish in the middle.

Oncolites are locally abundant, in medium and thick grain-supported beds, as in the NE1/4 section 20, T. 17 S., R. 2 E. The cores of the oncolites there are mostly intraclasts and clam shells; none of the cores are quartzite clasts.

The redbeds represent an intermittent fluvial environment, perhaps a distal fan setting, where alternate wetting and drying oxidized the muds. The sandstone beds are channel and point-bar deposits, and the micrite ledges and oncolite beds indicate marshy or pond conditions. The sediments of the unit are greatly oxidized to red, but may well have been partly red to begin with, as red mud and silt reworked from the Arapien Shale and the Twist Gulch Formation. If so, the presence of such sediment would imply uplift of the SSVA and renewed reverse faulting on its west flank during mid-Flagstaff time.

The upper redbed unit ranges irregularly in thickness from about 160 feet (49 m) to 266 feet (81 m) (Birsa, 1973, Section E) along the mountain front, but it is absent within the Dry Canyon graben. The unit also thins slightly toward the west, for it is only 180 to 200 feet (55-61 m) thick in the interior of Maple Canyon.

The upper redbed unit is Eocene in age (Hobbs, 1989; Lawton and others, 1993; Talling and others, 1994). It pinches out eastward against the SSVA (Lawton and Weiss, 1999); there and in the Dry Canyon graben the main body of the Flagstaff Limestone lies directly on the Wales Tongue.

Flagstaff Limestone (main body) (Tf)

The main body of the Flagstaff Limestone forms a major fraction of the surface of the Gunnison Plateau in the quadrangle and its edges are great cliffs of white- and light-gray-weathering carbonate beds separated by shaly partings and beds of limy mudstone. Both dolomitic limestone and limy dolomite are present, in thin and medium beds. Medium and thick intervals of irregularly bedded limy mudstone weather to slopes covered with angular chips, and separate the cliffy carbonate beds. The limestone, mostly with subordinate dolomite, is light-gray or yellowish-gray micrite and fine sparite, with locally abundant gastropods. Most dolomite beds are limy dolomicrite, with spar-filled cavities and local pseudomorphs of bladed gypsum, as well as fragments of gastropods. Much dolomicrite is mottled, contains micritic intraclasts, and weathers somewhat orange, in contrast to the lighter gray of the weathered limestone. Beds of fine- to medium-grained sandstone are rare in the formation, and grade into calcareous siltstone. Limy mudstone beds are locally somewhat sandy.

Within the quadrangle limy mudstone is about half of the thickness of the formation in the north, but subordinate in the Maple and Dodge Canyon sections. The resistant beds differ in composition from north to south: calcite is equal to or more abundant than dolomite in Dry Canyon, but dolomite exceeds calcite in most of the cliff-forming ledges in the Maple and Dodge Canyon sections.

The Flagstaff Limestone was deposited in a large lake and marsh that extended over most of central Utah (Stanley and Collinson, 1979). Usually called Lake Flagstaff (La Rocque, 1960; Weiss, 1969), the basin fluctuated between a shallow lake and a broad calcareous marsh. Sedimentary features, fossils, and the abundance of dolomite attest to the shallowness of the lake and to the intermittent exposure of large areas of lacustrine or marsh (paludal) muds (Lawton and Weiss, 1999). Platt and Wright (1992) suggested the term palustrine for freshwater carbonate deposits formed under alternating subaqueous and subaerial conditions. They also suggested that shallow carbonate marshes produced most such sediment, rather than lake-margin facies that were later modified by pedogenic processes.

The Flagstaff Limestone ranges from 155 to 640 feet (47-197 m) in thickness where exposed in the Manti quadrangle, but it thickens westward under the plateau and is thinnest in the area of the S-fold in the Dry Canyon graben, at the mouth of Dry Canyon (SE1/4 section 33, T. 16 S., R. 2 E.). No Flagstaff beds were identified in wells that were drilled in the southeastern part of the quadrangle (cross section B-B'). The main body of the Flagstaff is early Eocene in age (Rich and Collinson, 1973; Jacobson and Nichols, 1982; Fouch and others, 1983).

The main body of the Flagstaff Limestone in the Gunnison Plateau has previously been correlated with the upper part of the Flagstaff of the Wasatch Plateau (La Rocque, 1960; the Musinia Member of Stanley and Collinson, 1979), but the biostratigraphy is ambiguous and a magnetostratigraphic comparison has not yet been attempted. Lawton and Weiss (1999) suggested that the Flagstaff main body in the Gunnison Plateau correlates with the middle part of the Flagstaff of the Wasatch Plateau, the Cove Mountain Member of Stanley and Collinson (1979). Their reasons are the presence of similar evidences of desiccation and emergence in these two units, in contrast to the more lacustrine nature of the lower and upper members of the Flagstaff Limestone in the Wasatch Plateau (Stanley and Collinson, 1979).

Colton Formation (Tc)

The Colton Formation is widespread on the plateau top, but is well vegetated in most places and also obscured by its readiness to slump and to form a deep soil. It consists mostly of mudstone and claystone of many colors, including reddish brown, red, purple or violet, light gray, greenish gray, and very light gray. Many thin beds of vitreous micritic limestone and fine sparite are interspersed among the fine clastics, and these also exhibit a similar variety of colors. However, most limestone beds are shades of gray, which suggests a lower state of oxidation than that in the colorful mudstones. Mollusks and ostracodes are present in some beds. Intraclasts are conspicuous in 76 percent of the limestone beds (Volkert, 1980); about half the beds are micritic and the rest are about equally intrasparites and intrarudites (Marcantel and Weiss, 1968). The carbonate sheets and lenses are the products of ponds and carbonate marshes.

Yellowish-gray to yellow-brown siltstone and silty sandstone beds are also present, and are typically weakly cemented. Sandstone beds are either sheet-like or channel-form in shape. Weathered feldspar (subequal plagioclase and K-feldspar) is the most abundant mineral grain after quartz in Colton sandstone beds; in most samples feldspar comprises 7 to 12 percent of the grains, but may reach 27 percent in some (Volkert, 1980). The feldspathic sandstone contrasts sharply with the highly quartzose and lithic sandstone of the Cretaceous units and those younger than the Colton. The Colton sandstone supports the hypothesis that the fluviatile clastics that overlie the lacustrine and palustrine Flagstaff carbonates came from the southeast (Stanley and Collinson, 1979; Dickinson and others, 1986).

The formation is less colorful and has less limestone close to the east margin of the plateau, particularly in the Dry Canyon graben. This is believed to have resulted from the coarser and more abundant clastics close to the SSVA.

The Colton formed under a variety of fluviatile environments: wide areas of floodplain, local overbank splays of sand or silt, and ponds and marshes in which the limestone formed (Marcantel and Weiss, 1968; Volkert, 1980). Local channel-sand deposits formed lenses of weakly cross-bedded sandstone. The Colton Formation ranges from 550 to 860 feet (167-262 m) in thickness within the quadrangle; it is thinnest in the west-central district and of intermediate thickness in the Dry Canyon graben. In addition, no Colton beds were identified in wells that were drilled in the southeastern part of the quadrangle (cross section B-B').

The Colton Formation contains a fauna similar to that of the Flagstaff Limestone and is thereby also Eocene in age (Weiss, 2001). As a great thickness of mostly fluviatile clastics, it blotted out Lake Flagstaff and its marshes, but the transition was gradual (Weiss, 2001).

Green River Formation (Tg, Tgl, Tgu)

The Green River Formation occupies the crest of the Gunnison Plateau regionally; in the Manti quadrangle it is present only in the western part of the Dry Canyon graben and in the southwestern quadrant of the quadrangle. It is made up of two major unnamed rock units, a lower shale member and an upper limestone member, that reach a maximum combined thickness of 1,311 feet (400 m) in the quadrangle. The lower shale member of the Green River Formation and the Colton Formation together form a very thick interval of soft, weak rock that is poorly protected by the relatively thin, resistant upper part of the Green River. The Green River beds that form the narrow crest of the plateau at this latitude are thus anomalous in that setting. They are preserved atop the plateau only because they lie within a graben (the "divide graben" of Mattox, 1987) that greatly reduces the exposed thickness of mudrocks between the main body of the Flagstaff Limestone and the upper limestone member of the Green River. The divide graben trends north-northwest and lies mostly to the west of the Manti quadrangle, but it does enter the southwest quadrant of this quadrangle and continues into Antelope Valley. Both members of the Green River Formation are also present along the foot of the Wasatch Plateau along the east side of Sanpete Valley, but only a small outcrop is preserved in this quadrangle in Temple Hill at the north edge of the city of Manti.

Lower shale member (Tgl): This member consists of light-gray and greenish-gray mudstone and shale with many thin and medium beds of very light gray, white-weathering limestone. It forms steep slopes of greenish-gray mud and soil. The limestone beds are micritic, brittle, poorly fossiliferous with few mollusks, and some have a vitreous appearance. Some beds are dolomitic limestone or dolomite, and those also have a higher content of siliciclastics than the limestone (Millen, 1982). The lower shale member is generally ascribed to sedimentation in Lake Uinta (see Stanley and Collinson, 1979). The transition from the terrestrial deposits of the Colton to the lacustrine regime of Lake Uinta in which the lower shale member of the Green River Formation was deposited was also a gradual change of conditions, and the abundance of siliceous mud suggests that the prevailing environment may have been palustrine (Platt and Wright, 1992). Thus, the lower Green River beds, like those of the Flagstaff Limestone, include both lacustrine and palustrine sediments.

The lower shale member ranges from about 500 to 911 feet (152-278 m) thick in the quadrangle; it is thickest in the northwest corner and thinnest in the southwest. It also thins to between 220 and 270 feet (67-82 m) not far west of this quadrangle (Mattox, 1987). A very small thickness of this member crops out in Temple Hill.

The transition from the lower shale member to the overlying upper limestone member occupies only a short interval of thickness. The lower shale member is persistent in central Utah and present also on the flank of the Wasatch Plateau; from there it is exposed around the northern end of that plateau and into the Uinta Basin. The age of the whole formation is middle Eocene (Bryant and others, 1989).

Upper limestone member (Tgu): The upper limestone member consists of finely crystalline, yellowish- or gray-weathering sparite in thin to thick beds, very light gray micritic limestone, pale-yellowish-gray micritic dolomite, and tuff. The member forms a resistant cap and cliffs that are especially conspicuous above the soft lower shale member at the head of Antelope Valley. Some sparite beds contain abundant, well-rounded, fine and medium quartz sand grains, and are weakly cross-bedded. Thin shale and shaly limestone interbeds and biotitic tuff beds separate the limestone beds. In Temple Hill some limestone beds are oolitic and others are made of innumerable ostracode valves and appear superficially oolitic. These rocks have been used abundantly for dimension stone in the city of Manti, most notably in the Manti Temple. Tuff beds in the upper limestone member at the northern end of the Wasatch Plateau have been dated by zircon fission-track ages ranging from 44.9 ± 2.1 to 42.3 ± 2.0 Ma (Bryant and others, 1989). Tuffs in the uppermost part of the limestone member near Ephraim, just east of this quadrangle, have ages of 43.1 to 46.4 Ma by $^{40}Ar/^{39}Ar$ (Sheliga, 1980).

A lacustrine interpretation for the upper limestone member is traditional, and probably correct, because features that point to a palustrine origin are not prevalent (Platt and Wright, 1992).

The upper limestone member is reduced in thickness over much of the quadrangle where there is no covering formation because of erosion. However, where the member is capped by the Crazy Hollow Formation in the southwestern quadrant of the quadrangle and at nearby sites just to the west, it ranges from about 220 to 400 feet (67-122 m) in thickness. However, like the lower shale member below it, the upper limestone member is persistent widely over the region; it rims the west flank of the Wasatch Plateau and continues across its northern end into the Uinta Basin, where the

Green River Formation is divided differently and its members have different names.

Crazy Hollow Formation (Tch)

The Crazy Hollow Formation is the youngest bedrock unit in the quadrangle. In the Sanpete Valley area, the Crazy Hollow Formation contains red mudstone; thin, gray lacustrine limestone; light-gray sandstone; and the lithologic "signature" of the formation, "salt-and-pepper sandstone," which contains abundant grains (including pebbles) of black chert and light-gray chert (Norton, 1986).

The Crazy Hollow Formation overlies the upper limestone member of the Green River along the crest of the plateau for nearly the whole length of the Manti quadrangle, but enters the quadrangle only in the southwest quadrant where the divide graben and the plateau crest turn southeast toward Antelope Valley. In addition, numerous pebbles of black chert lie on the slumped mudstones of the lower Green River and Colton Formations near the headwaters of the northwest fork of Maple Canyon; they come from pebbly salt-and-pepper sandstone lenses on the plateau crest to the west. The exposures of Crazy Hollow lying in the southwest quadrant are of weakly cemented light-gray quartzose sandstone with local cross-bedding; these beds contain only a little of the signature black chert of the Crazy Hollow, but such "clean" sandstone is also present elsewhere in the region.

The Crazy Hollow Formation also lies on the backs of the Green River cuestas that rim the toe of the Wasatch Plateau; Temple Hill is an example. The Crazy Hollow lithofacies on Temple Hill are dominantly sandstone and pebbly sandstone beds. The Crazy Hollow there also includes salt-and-pepper sandstone beds, both with and without pebbles of black chert.

The Crazy Hollow Formation was deposited in a highly varied fluviatile environment with local pond or paludal carbonate lenses (Weiss, 1982b, 2001). Because of discontinuous outcrops and no superjacent deposits to protect the Crazy Hollow, all thicknesses are variable and incomplete. The thickest remnant in the quadrangle, in the southwest quadrant, is 70 feet (21 m) thick.

As the Flagstaff lacustrine/palustrine environment was swamped by the mostly fluviatile lithofacies of the Colton Formation, the basin of the diminishing Lake Uinta was partly covered by the fluviatile deposits of the Crazy Hollow Formation. The Colton, in contrast to the Crazy Hollow, is very widespread in central and northeastern Utah and consists of broadly persistent lithofacies. The Crazy Hollow is found only in central Utah and, although widespread there, it is discontinuously exposed and its lithofacies differ markedly over even short distances.

Fossils in the limestone beds of the Crazy Hollow Formation are not sensitive to details of its age, for they are the same species seen in the Green River Formation. The Crazy Hollow appears to be unconformable on the upper Green River in the Manti quadrangle, but the intimate, gradational relations of the two elsewhere show that the Crazy Hollow is also Eocene in age (Weiss, 1982b, 1994, 2001; Norton, 1986; Mattox and Weiss, 1989). No correlatives of the Crazy Hollow have been identified in other regions, although the Green River Formation in the Uinta Basin is succeeded by extensive thick clastic deposits having different names.

Surficial Deposits

Older Stream Alluvium (QTa)

A well-consolidated but weakly cemented deposit of yellowish-gray and grayish-red silt and sand with some pebbles (evenly bedded floodplain and cross-bedded channel deposits, like modern stream alluvium) is preserved beneath an isolated giant boulder from the Big Mountain unit of the North Horn Formation that is 30 feet (10 m) in diameter. This small but significant deposit lies in a steep gulch in the SW1/4NW1/4NE1/4 of section 9, T. 17 S., R. 2 E. The setting suggests that the boulder has protected the deposit for an exceedingly long time. Erosion subsequent to the placement of the boulder has washed out all of the old alluvial material except that compressed under the boulder. The deposit is 30 feet (10 m) wide and 12 feet (4 m) thick.

This is a most unusual occurrence and we believe that the alluvial sediment is probably Pliocene in age. Having no proof of such great age, we consider it Pliocene-Pleistocene in age.

Consolidated Alluvial-Fan Deposits (QTaf)

Large areas of well-compacted but weakly cemented alluvial-fan deposits (QTaf) are coalesced along the plateau front and the foot of the Wasatch monocline. Like younger fans (Qaf), they are composed of gray and yellowish-gray mud, sand, and gravel up to boulder size; they differ in their large size, greater thickness, and much greater age. They grade headward into stream alluvium (Qa) and downslope into floodplain and channel deposits of the valley fill (QTal, Qal); this is possible because the surfaces of these old coalesced fans are modern and still growing locally.

Younger fan deposits (Qaf) locally overlie the upper edges of the older alluvial fans; debris-flow deposits (Qmf_1, Qmf_2) lie across them at lower elevations. The older fan deposits are comparable in thickness to the older valley-fill deposits (QTal) in Sanpete Valley, with which they intertongue at depth. Older alluvial-fan deposits thin upstream to zero thickness, and downstream at the lower edge may be as thick as the valley-fill deposits (QTal plus Qal), which are estimated from well logs to be as much as 935 feet (285 m). A thickness of 250 feet (75 m) was recorded for QTaf near the village of Wales, 8 miles (13 km) north of the quadrangle (Robinson, 1971).

The great age of the consolidated fans pertains only to the depths of such deposits, which grade downslope into the floodplain and channel deposits (Qal and QTal) in Sanpete Valley. They are Holocene at the surface and may be as old as Miocene at the base.

Alluvial-Fan Deposits (Qaf)

Unconsolidated deposits of light-brown to gray mud, silt, sand, and poorly sorted gravel with clasts to boulder size lie like hemicones at the mouths of small drainages. A larger deposit of the same type is forming at the mouth of Dodge Canyon, where the valley floor was depressed structurally. These younger fan deposits grade laterally into or overlie alluvium (Qa), colluvium (Qc_1), older fans (QTaf), or valley fill (QTal or Qal). Alluvial-fan deposits range from 0 to 50 feet (0-15 m) thick, but in most areas are 30 to 50 feet (9-15 m) thick. They are Pleistocene and Holocene in age.

Floodplain and Channel Deposits (QTal, Qal)

Floodplain and channel deposits consist of poorly consolidated to unconsolidated brown and brownish-gray mud, silt, sand, and gravel of pebbles and cobbles. The valley-filling sediment is of alluvial, mudflow, and debris-flow origin. Cumulatively, these deposits may be thickest along the west side of Sanpete Valley. The deposits were derived from both the Gunnison and Wasatch Plateaus and the older deposits (QTal) likely grade laterally at depth into the older fan deposits (QTaf).

The distinction between deposits shown as QTal or Qal in the subsurface is an arbitrary one, for the chronological boundary cannot be known accurately. Older material likely fills the major volume of the half-graben system beneath Sanpete Valley, and has been subsequently elevated and tilted locally (most likely, in our opinion, by diapirism of the subjacent Arapien evaporitic mudstone) to form low hills grouped in the southern part of the valley. These hills, including Twin Knolls and River Knoll, are known locally as the "river knolls." We believe that the older part of the floodplain and channel deposits filling the valley (QTal) may be as old as Miocene at their base.

The younger part of the floodplain and channel deposits (Qal) is of the same sort of material that comprises QTal, is modern at the surface, and is still accumulating over most of the valley. It abuts the older valley fill (QTal) where it laps onto the flanks of the river knolls. It also grades laterally to the spring deposits (Qsm) that form the valley floor at the southeast edge of the quadrangle. The younger part of the floodplain and channel deposits (Qal) is considered Holocene in age.

The older valley fill (QTal) is exposed in River Knoll and appears in cross sections below about 165 feet (50 m) under the valley floor. Most of the valley floor is mapped as younger floodplain and channel deposits (Qal), and cross sections display Qal above a maximum depth of about 165 feet (50 m) below the valley floor. Robinson (1971) estimates the thickness of the entire valley fill ranges from zero to a maximum of about 500 feet (0-153 m). Locally, however, the valley fill (QTal plus Qal) is estimated to be as much as 935 feet (285 m) thick, the drilled thickness in the Chandler and Associates Barton 4-2 well (NW1/4NW1/4 section 2, T. 18 S., R. 2 E.). The thickness decreases from north to south, for it is as much as 820 feet (250 m) thick locally in the Wales quadrangle (Lawton and Weiss, 1999), and a culmination of bedrock rises to the surface at the south edge of the Manti quadrangle and continues for some distance to the south (Weiss, 1994).

Spring Deposits (Qsm)

Spring deposits consist of very light yellowish-gray marshy soil and mud at the surface of the east branch of Sanpete Valley near the south edge of the quadrangle. This is part of a much larger area in the adjacent Sterling quadrangle, where it was mapped as "salt-marsh deposits on valley fill" (Weiss, 1994). The mineralized water that wets this area, and brings salts that cement the deposit when it dries, comes from springs in the Sanpete and Funk Valley Formations in the Sterling quadrangle. The surface of the deposit is coextensive with younger valley-fill materials (Qal) and the body is continuous into fan (QTaf) and older valley-fill material (QTal); the "spring deposits" are mapped separately because the smooth, clayey, salty crust on the soil is quite different from those of the well-drained fan and valley-fill deposits, and also highly reflective on aerial photographs. The spring deposits lap over the older valley fill (QTal) in section 15, T. 18 S., R. 2 E.; the older valley fill there has been tilted eastward by the rise of a local diapir of Arapien Shale near the river.

The thickness and age of the spring deposits are like those of the younger valley fill (Qal), and are assigned an arbitrary thickness of 0 to 165 feet (0-50 m) and an age of Holocene.

Stream and Fan Alluvium (Qa)

Stream and fan alluvium consists of brown and yellowish-gray mud, silt, sand, gravel, and boulders that lie in the major canyons of the Gunnison Plateau. The deposits are unconsolidated and uncemented, locally cross-bedded, and closely associated with stream courses that flow into Sanpete Valley. They grade laterally into fan deposits (QTaf) and intertongue with colluvial deposits (Qc_1) on the lower walls of canyons. The deposits have surfaces of low relief, range from 0 to 50 feet (0-15 m) thick, and are Holocene in age.

Debris-Flow Deposits (Qmf_1, Qmf_2)

Debris-flow deposits consist of unconsolidated deposits of mud, silt, sand, and angular blocks (cobble to boulder size) of bedrock units - mostly the Flagstaff Limestone. The steeper the drainage profile, the larger and more angular are the boulders within the deposits. These deposits have rough surfaces because of the large boulders; they might also be called mudflows, except for the abundance of very large clasts in this quadrangle. They lie on the consolidated alluvial-fan deposits (QTaf), and have thicknesses of 0 to 50 feet (0-15 m). These were likely deposited rapidly - probably triggered by rapid snowmelt or localized high-intensity thunderstorm events - and are generally confined to steep gulches and the major streams.

The younger debris-flow deposits (Qmf_1) continue to form today, contributing to the alluvial fans (QTaf) and ultimately to the valley fill (Qal). These deposits are Holocene in age. The older ones (Qmf_2) have a more subdued relief and some soil development, are being dissected, and are probably late Pleistocene in age.

Colluvial Deposits (Qc_1, Qc_2, QTc)

Colluvial deposits consist of unconsolidated mud, sand, and angular pieces of granule- to boulder-size sediment that mantle steep, unstable slopes. They are deposited by gravity from weathered bedrock above and may grade downslope into alluvial or fan deposits. Thicknesses of each type are generally 0 to 20 feet (0-6 m), but reach 50 feet (15 m) locally. Slopes composed of soft bedrock units are typically covered by some debris from higher outcrops, but colluvium is mapped only where the deposit is extensive or obscures bedrock unit contacts. Colluvial slopes have smooth, almost geometric, curves in profile.

The youngest deposits (Qc_1) are still accumulating today and are considered Holocene in age. Older colluvial deposits (Qc_2) are dissected and detached from any upslope source of new material, and are believed to be Pleistocene in age. The oldest deposits (QTc) are detached from a source of material too, but are also dissected, have a well-developed soil profile, are slumped locally, and have a different, much higher topographic profile than that of Qc_2. The material of QTc is probably Pliocene in age in part.

Mass-Movement Deposits (Qmsl, Qmss)

Mass-movement deposits are masses of soil (including vegetation), mud, sand, and boulders, some of which are crudely rounded. They moved by gravity on steep slopes, typically when saturated with water during wet periods. Trees and other vegetation likely were churned into the mass of mobile rock material. The deposits are generally brown or gray, except where material is derived from the varicolored Colton Formation. Two types of mass-movement deposits, debris slides (Qmsl) and slumps (Qmss), are mapped in the quadrangle. Some of each type have undergone repeated movement over numerous wet seasons, and the two types are not entirely mutually exclusive. Repeated movement or reactivation of a slide typically involves only part of a slide or slump mass. Generally, smaller slumps form locally on the deposit. Both types of deposits range in age from Pleistocene to Holocene.

Debris slide deposits (Qmsl) are elongate with a high length-width ratio and lie in gulches or depressions on steep slopes. A failure scarp and depression at the head of a slide and lobe of crumpled mud and rock at the toe typically define the extent of the deposit. Debris slides generally move rapidly downslope and can mobilize into debris flows. Debris slide deposits are 0 to 50 feet (15 m) thick.

Slump deposits (Qmss) are broader and irregular in shape, with a width along a hillside that exceeds downslope length. A failure scarp or "headwall" in undisturbed bedrock may be preserved at the top of a slump. Slump masses are locally furrowed or ridged parallel to the slope and have an elevated bulge at the toe where the mass shoves against lower material; their surfaces are typically hummocky. Slumps generally move slowly. Slump deposits in the quadrangle may reach thicknesses of 200 feet (61 m).

STRUCTURAL GEOLOGY

The Manti quadrangle contains structures that resulted from crustal shortening during the Sevier orogeny, younger structures of relaxation and sagging that formed during basin-and-range extension, and local diapirism in the Arapien Shale. The body of the Gunnison Plateau (San Pitch Mountains) contains a growth synform of which the east limb is exposed in the quadrangle. Along the east flank of the plateau is a complex zone of imbricate reverse faults and younger extensional normal faults along which the valley block dropped down to form a half graben. The Sanpete-Sevier Valley antiform (SSVA) is a large fault-propagation fold that underlies the down-dropped Sanpete Valley block.

The growth synform records progressive fold tightening during deposition of Upper Cretaceous and lower Tertiary strata in the body of the plateau. Jurassic and Cretaceous strata were deposited before folding. These beds are tightly folded and form the deepest part of the synform. Growth strata of the North Horn Formation were deposited during folding and lie in the transition zone from tightly folded to less tightly folded beds. Gently folded Flagstaff through Green River beds complete the shallow, upper part of the synform (Mattox, 1987; Lawton and Weiss, 1999). The east limb of the lower part of the synform is overturned and intimately related to a zone of imbricate reverse faults in the steep, west-verging west limb of the SSVA; its axis lies along the eastern front of the plateau. The axis of the upper part of the synform is subparallel to and near the west edge of the quadrangle. The synform is part of the upper plate of the Gunnison thrust system (Villien and Kligfield, 1986; Lawton and Trexler, 1991).

Five structural elements are preserved in the rocks of the quadrangle and are listed below in order of decreasing age, although elements 2 and 3 are coeval: (1) a zone of imbricate reverse faults in folded Jurassic through Eocene rocks, which forms the western limb of the SSVA along the eastern foot of the Gunnison Plateau; (2) west-trending normal faults that offset strata as young as the Green River Formation, and form the Dry Canyon graben, which is shared by the Manti and Wales quadrangles; (3) generally north-trending normal faults that separate the Gunnison Plateau from Sanpete Valley, and that form the divide graben in the interior of the plateau; (4) diapirism of the mobile mudstone and evaporate beds in the Arapien Shale that has raised local blocks of Arapien and overlying formations, including Quaternary valley-fill deposits near the south edge of the quadrangle; and (5) a large slide block that has moved off the Wasatch Plateau at Temple Hill.

Zone of Imbricate Reverse Faults

Faults

The imbricate reverse (or thrust) faults that are exposed in the east flank of the plateau dip eastward at angles from 45 to 85 degrees and separate panels of the Arapien, Twist Gulch, Cedar Mountain, and San Pitch Formations. Most strata are overturned, but panels of upright, steeply east-dipping Arapien and Twist Gulch beds form the lower slopes of the plateau, close to the valley. The westernmost exposed thrust fault emplaced Twist Gulch beds over beds of the Cedar Mountain and San Pitch Formations; the Big Mountain, Coal Canyon, calcareous siltstone, and upper red units of the North Horn Formation; and the Wales Tongue of the Flagstaff Limestone (section 9 and NW1/4 section 16, T. 17. S., R. 2 E.).

Two subparallel reverse faults are exposed in sections 9 and part of 16. These faults are mapped as joining in the NE1/4NW1/4 of section 16. To the south, two fault segments are exposed for a very short distance south of Maple Canyon, in the NW1/4NE1/4NW1/4 of section 28 and again in the NW1/4SE1/4NW1/4 of section 28. We have therefore mapped a single hidden fault over most of the distance south of the junction of the two faults in the NW1/4 of section 16 (plate 1); that fault is also illustrated in cross section B-B'. As the zone of imbricate reverse faults lies low on the face of the plateau, we believe that the structural plunge carries this fault beneath Sanpete Valley south of township T. 17 S., R. 2 E.

We believe there is also a blind reverse fault buried by the Big Mountain member of the North Horn Formation west of the exposed reverse faults (see cross sections A-A' and B-B'). This sort of relationship is exposed at the south end of the plateau, in the Christianburg area (Sprinkel and others, 1999). The propagation of faults in this zone also bent younger beds of the North Horn Formation and the Flagstaff Limestone that are exposed above the zone of imbricate faults, some of which cut the North Horn Formation. The zone once extended much higher and a little farther west, but that upper part has been eroded away. The dynamics that created this zone also created the S-fold in the Dry Canyon graben, which is described below.

Folds

Folds on the west flank of the SSVA are present in both the hanging-wall blocks of the zone of imbricate reverse faults and in North Horn, Flagstaff, and Colton strata in the footwall. These footwall strata form the east limb of a west-vergent synform that makes up the main body of the plateau; dips range from moderate toward the west to vertical or overturned and dipping steeply to the east. The east-dipping faults and the upturned edges of the footwall formations suggest that the west-vergent stress was long continued and intermittent. Tight isoclinal folds in the softer beds - Arapien and Twist Gulch - are contained within some of the hanging-wall panels (figure 1). Few of these smaller folds extend very far in the strike direction. Because most of the beds in the hanging wall of the zone of imbricate reverse faults are overturned, some of the folds are synformal anticlines (figure 1). A fold pair (figure 2) in the soft Twist Gulch beds (N$^{1}/_{2}$ section 28, T. 17 S., R. 2 E.) resembles the one described below from Dry Canyon, and shows clearly the intensity of deformation in the zone.

A west-vergent fold pair with an overturned common limb is exposed in Dry Canyon (N$^{1}/_{2}$ section 4, T. 17 S., R. 2 E.) and continues north to Rock Canyon in the Wales quadrangle (Lawton and Weiss, 1999). It is much larger than the one shown in figure 2, and is formed in rocks much stronger than the Twist Gulch Formation. The fold pair affects North Horn, Flagstaff, and Colton beds that lie unconformably on the Twist Gulch Formation. The unconformity and the overlying beds are bent into an erect "S," as viewed from the south. The unconformity is of Cretaceous age and the fold is Eocene in age, for most of the Cretaceous North Horn beds are absent from the area and the Colton Formation is included in the folding. The unconformity and S-fold were formed in concert with the episodes of reverse- and thrust-faulting of the late Mesozoic beds seen along the entire east front of the Gunnison Plateau. The anticline that forms the upper half of the fold pair is interpreted as a fault-propagation fold that resulted from motion on a blind east-dipping reverse fault. The evidence for this conclusion is better displayed at and just north of Rock Canyon, which lies in the north part of the Dry Canyon graben and in the Wales quadrangle (Lawton and Weiss, 1999).

Figure 1. Synformal (overturned) anticline in red siltstone and mudstone beds of the Twist Gulch Formation pressed against member B of the San Pitch Formation, near the entrance to the mine slope (SE$^{1}/_{4}$NW$^{1}/_{4}$NE$^{1}/_{4}$ section 9, T. 17 S., R. 2 E.). The mine tunnel was cut about 50 feet (15 m) into the hard San Pitch conglomerate (Kspb) and close to the fault with the Twist Gulch rocks. A compressed air tank about 24 inches (0.6 m) in diameter serves as a scale. The photo was taken about 1965 with view to the southeast; the adit is now filled with talus and the anticline is covered.

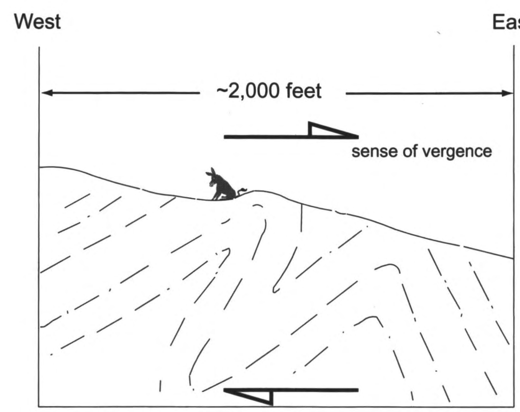

Figure 2. Sketch of a complete Z-fold in the Twist Gulch Formation on the plateau front 1 mile (1.6 km) south of the mouth of Maple Canyon (SW$^{1}/_{4}$NE$^{1}/_{4}$ section 28, T. 17 S., R. 2 E.). The z-fold geometry indicates deformation in an east-vergence sense. Sketch is not drawn to scale.

Dry Canyon Graben and Other West-Trending Normal Faults

A family of west-trending high-angle normal faults is present at and south of the Dry Canyon graben. Those of greatest stratigraphic separation form the south margin of the Dry Canyon graben, and are mirrored in the north margin of the graben, in the Wales quadrangle. Others break the graben block itself into long east-west slices. The long, nearly straight slump scarps within the graben and parallel to the south graben fault (in the N$^{1}/_{2}$ section 5, T. 17 S., R. 2 E. for example) are probably related to normal faults of this series that are now buried beneath mass-wasting deposits. The graben faults have their greatest displacements at the east, near the mountain front. Buried faults within the graben die out westward within this quadrangle, and the bounding faults of the graben die out within a mile or two (<3 km) west of the Manti and Wales quadrangles. The major scarps of the graben are in the Flagstaff Limestone, but those faults juxtapose Green River beds against Colton beds and cut everything down through the Twist Gulch Formation. The stratigraphic separation on the south graben fault near the mouth of Dry Canyon is about 530 feet (162 m).

Several faults of the same orientation lie as far as 3 miles (5 km) south of the graben, and are considered to be related to the same north-south extension that produced the graben. Several fracture zones in the plateau top lie parallel to the graben faults within this same distance south of the graben. The fracture zones are marked by lines of more abundant vegetation, faint lineations seen on aerial photographs, and some springs. No displacement of strata can be observed at these zones, but the fractures are expressed in the Colton Formation, which contains few thick, brittle beds that might record displacement.

The Dry Canyon graben is unique on the Gunnison Plateau, for it is a large structure at right angles to the length of the plateau and the major bounding fault that separates the plateau from Sanpete Valley. This peculiar condition is not easily accounted for, and several unpublished hypotheses of its origin have been proposed and abandoned. Furthermore, the North Horn, Flagstaff, and Colton Formations are anomalously thin in the part of the Dry Canyon graben close to the mountain front, in the area of the S-fold. Stratigraphic thinning and structural orientation have been attributed to a lateral ramp of the Gunnison thrust plate that extended east-west about here, at right angles to the sedimentary strike of the later Cretaceous and Paleocene formations, and that, during Neogene extension, moved downward to form the Dry Canyon graben (Lawton and Weiss, 1999, figure 4). The marked north-south differences in the thickness and lithofacies of the latest Cretaceous deposits (members of the North Horn Formation), the Flagstaff Limestone, and the Colton Formation are concentrated at the latitude of the Dry Canyon graben, a fact that accords with the postulated lateral ramp anticline.

North-Trending Normal Faults

Range-Front Faults

The Gunnison Plateau is separated from Sanpete Valley, along its entire eastern front, by a normal fault zone that creates the topographic differential between the plateau and the valley. The range-front fault zone was called the "valley fault" by Fong (1995) and the "Gunnison fault" by Weiss (1982a). The height of the fault scarp (and probable amount of displacement) is greatest near the north end of the plateau. The fault scarp height decreases to zero at the south end of the plateau, in the Sterling quadrangle, where the rocks of the plateau plunge beneath the Quaternary deposits of Sevier Valley (Mattox, 1992; Weiss, 1994). The structural relief on the range-bounding fault(s) is at least 4,400 feet (1,350 m) in the Price N well (SE1/4SE1/4 section 29, T. 15 S., R. 3 E.), near Wales, about 7 miles (11 km) north of the Manti quadrangle (Sprinkel, 1994). Five miles (8 km) south of the Manti quadrangle the displacement is only about 300 feet (91 m) (Weiss, 1994).

The range-front fault zone is not as well exposed in the Manti quadrangle as it is north and south of the quadrangle, but faults do cut Quaternary deposits (QTaf) in sections 2, 15, 16, and 21, T. 17 S., R. 2 E. Low scarps of 2 to 6 feet (0.6-2 m) are present locally, are conspicuous on aerial photographs, and tend to have lines of more abundant vegetation along them. Most of the length of the fault(s) in the Manti quadrangle is hidden by Holocene deposits and agricultural disturbance. Even Holocene surfaces are cut in the Wales quadrangle, where displacement of deposits of Quaternary age on this fault system is six to eight times greater (Lawton and Weiss, 1999); this suggests that the plateau block is still tilting toward the south.

This range-front fault zone is subparallel to and just east of the zone of imbricate reverse faults, and is believed to have resulted from Neogene extension affecting that weak zone of older faults. The zone of normal faults may have reactivated on thrust surface(s), and probably merges at depth into the thrust decollement that underlies the Sanpete Valley (Standlee, 1982). The dropping of the Flagstaff, Colton, and Green River beds into the subsurface along the west side of Sanpete Valley formed the Sanpete Valley half-graben and was an integral part of the formation of the Wasatch monocline, across Sanpete Valley to the east. Withjack and others (1995) modeled features very similar to those beneath Sanpete Valley and low on the Wasatch monocline, except that there was no antiform in their down-faulted block (see Withjack and others, 1995, figures 2, 8, and the colored cover of number 1 of that volume).

The Divide Graben

The Green River Formation is preserved along the crest of the plateau partly because it lies within a graben, as described above. Mattox (1987) named this graben the divide graben, and it is conspicuously developed in the Hells Kitchen Canyon Southeast quadrangle, west of the Manti quadrangle. The divide graben extends south-southeastward from the western end of the Dry Canyon graben and crosses into the Manti quadrangle just north of Antelope Valley. The stratigraphic displacement on the main bounding faults is about 600 feet (183 m) where it enters the Manti quadrangle (Mattox, 1987), but decreases rapidly in Antelope Valley; the graben dies out southward in the Sterling quadrangle, midway down Antelope Valley (Weiss, 1994). The divide graben is believed to have developed during Neogene extension.

Diapirism

Much has been written about the role of diapirism in the regional structural development of central Utah (Witkind, 1982, 1983, 1992, 1994; Witkind and Page, 1984). The diapiric hypothesis argues that the unconformities, faults, and folds rimming the Sanpete and Sevier Valleys, as well as the formation of these valleys, were not the result of contractional deformation by the Sevier orogeny and basin-and-range extension. Instead, this hypothesis proposes that they were caused by the vertical action of salt diapirism within the Arapien Shale, followed by solution collapse (Witkind, 1982, 1983, 1992, 1994; Witkind and Page, 1984). We do not subscribe to the hypothesis that regional salt diapirism is the sole cause of the tectonic development of the area since the Cretaceous. We believe that crustal shortening during the Sevier orogeny, followed by regional extension, created nearly all of the stratigraphic and structural relations in central Utah, particularly in pre-Pliocene strata. Several reasons make it clear to us that tectonic forces rather than only regional diapirism and salt dissolution are responsible for the major tectonic and sedimentary history of the Sanpete-Sevier Valley region: (1) surface and subsurface examples of major regional deformational features caused by the Sevier orogeny and basin-and-range extension are well documented in central Utah; (2) sedimentation and deformation of growth strata are consistent with the style and timing of the Sevier orogeny; (3) overturning of fault-repeated strata and consistent west-vergence of faults and folds along the east flank of the Gunnison Plateau requires crustal shortening not predicted by the diapirism model; and (4) the Arapien Shale does not pierce the crest of the antiform in Sanpete Valley as expected in a salt diapir, but instead crops out along the western margin of the antiform in the zone of imbricate reverse faults.

However, we do believe that diapirism of the Arapien mudstone and evaporate beds as a whole contributed to local deformation of bedrock units and poorly consolidated deposits during late Tertiary and Quaternary time. Local diapirism of the Arapien Shale has modified structures at several places in both Sanpete and Sevier Valleys (Willis, 1986; Weiss, 1994). In the Manti quadrangle, we believe local diapirism is expressed by the Arapien Shale exposed near the south edge (NW1/4 section 15, T. 18 S., R. 2 E.) and by the uplifted and tilted (as much as 50° west) old valley-fill deposits (QTal) that form the river knolls. Effects of local diapirism are also described along this trend of uplifted Arapien Shale to the south into the Sterling quadrangle, where it is more conspicuous (Weiss, 1994). Significantly, these manifestations of local diapirism are preserved (here and in the Sterling quadrangle) where Sanpete Valley is narrowest, where the masses of the Gunnison and Wasatch Plateaus appear to be jammed together.

Temple Hill Toreva Block

Temple Hill is at the north edge of the city of Manti, in the southeastern quadrant of the quadrangle; most of Temple Hill lies in the adjacent Ephraim quadrangle. On Temple Hill stands the lovely Victorian Manti Temple, built of oolitic and ostracodal limestone from the upper member of the Green River Formation, which crops out in, and was quarried from, the hill on which the temple stands. The western part of Temple Hill is a northwest-dipping cuesta of upper Green River limestone and salt-and-pepper sandstone of the overlying Crazy Hollow Formation. The cuesta is one of a series that extends northward, intermittently, for about 40 miles (64 km) along the east side of Sanpete Valley, at the toe of the Wasatch Plateau.

The structure in the whole hill is more complicated than a simple cuesta. The higher and eastern part of the hill is formed by a synclinal mass of lower Green River, upper Green River, and Crazy Hollow beds that lie above the northwest-dipping cuestiform Green River and Crazy Hollow beds in the western part of the hill. The section from the upper part of the lower Green River mudstones through the Crazy Hollow beds is thus repeated in the hill. The synclinal upper block lies above a slide surface between the repeated sections. That surface is not a tectonic thrust surface, but rather a surface along which a large block of Green River and Crazy Hollow beds slid off the Wasatch monocline (a west-dipping flexure along the west flank of the Wasatch Plateau that is east of the Manti quadrangle), bent into a synclinal mass, and came to rest on a cuesta of Green River and Crazy Hollow rocks. The slide block is unusual in that it remained coherent during the movement, and its strata are not much disturbed - it is a toreva block in the classic sense. We noticed that a normal fault does cut the synclinal mass on the northeast, outside this quadrangle.

We believe the slide block extends northwestward from Temple Hill into the subsurface, for it is present in the Madsen 7-25 well (table 1; section B-B'). Dip meter and other petrophysical log interpretations suggest that a slab of displaced Green River beds, 474 feet (145 m) thick, rests on northwest-dipping Green River beds in the well. The slide surface probably has the shape of a shallow spoon plunging northwestward from Temple Hill. The aspect shown in section B-B' is somewhat artificial because the well record has been projected into the line of section from its site northwest of Temple Hill.

Other slides, both smaller and larger, where soft Colton and Green River beds have slid or slumped off the Wasatch monocline, lie along the east side of Sanpete Valley. Only the synclinal block on Temple Hill is a coherent toreva block; the others are all churned up. Temple Hill and the other slides outside of the Manti quadrangle are considered to have formed during wetter intervals in the Pleistocene, when the Colton and Green River mudstone beds on the flank of the monocline were so weak and heavy that they could not support themselves on the monoclinal slope (Weiss, 1994). Thus, the Temple Hill toreva block is a rather late feature, of Pleistocene (probably Wisconsinan) age.

Origin and Timing of Structural Deformation

Reverse Faulting and Folding

The folded and faulted strata of the east front of the Gunnison Plateau are part of the imbricated forelimb of a large, west-directed fault-propagation fold that was cut by subsequent normal faulting. The fold is the Sanpete-Sevier Valley antiform (SSVA) (Sanpete-Sevier Valley anticline of Gilliland, 1963). The fold arose as a back-thrusted fold on the upper plate of the Gunnison thrust (Standlee, 1982; Lawton, 1985; Lawton and Weiss, 1999). The evidence for the initial growth of the fold in Campanian time is found in the Wales quadrangle (Lawton and Weiss, 1999), where the North Horn Formation is much thicker and offers numerous members from which to diagnose the sedimentary story. By contrast, elements of the formation exposed in the Manti quadrangle are fewer and much reduced in thickness.

The antiform rose and pressed westward episodically over a long interval of time - into the Eocene. For example, the great lens of redbeds (Tnu) between the Wales Tongue and the main body of the Flagstaff Limestone suggests a renewal of elevation of the west limb of the SSVA and the concomitant release of a new flood of red sediment from the Jurassic beds in the zone of imbricate reverse faults. Most of the structural relief was probably developed during Campanian time (Lawton, 1985; Lawton and Weiss, 1999). During deposition of the Coal Canyon member of the North Horn

Formation the prevailing regional eastward transport of sediment was reversed; for a time the SSVA was itself a source that yielded earlier-deposited sediment back westward into a piggyback basin (Lawton and Weiss, 1999). The final bending of the S-fold in the Dry Canyon graben records post-early Eocene deformation in the same belt, for it affects beds as young as the lower part of the Colton Formation.

Rocks of Mesozoic age (Arapien through North Horn Formations) in and under the Gunnison Plateau and underlying the Sanpete Valley are part of the upper plate of the Gunnison thrust, which moved eastward during the Sevier orogeny (Standlee, 1982; Lawton, 1985; Lawton and Weiss, 1999). The leading edge of the upper plate lies under eastern Sanpete Valley, and the SSVA resulted from a back thrust that developed near the edge of the plate and raised the younger Mesozoic rocks into the SSVA (Lawton and Weiss, 1999, figure 3). As the antiform rose and tightened east-west, its west limb was overturned westward, so that beds of the west limb sheared upward and westward in what is recognized today as the zone of imbricate reverse faults. Subsidiary folds in that west limb tightened and sheared, such that some of the beds exposed in the zone today are overturned and others are upright. The structural and stratigraphic relationships are shown in cross-sections A-A' and B-B'. The vertical displacement of Jurassic beds, which are now at the surface, exceeds 10,000 feet (3,050 m) (Lawton and Weiss, 1999).

East-Trending Normal Faults

East-trending normal faults, including those flanking the Dry Canyon graben, resulted from early basin-and-range extension, probably in the Miocene epoch. They are post-Eocene, for they cut the Colton and Green River Formations everywhere. They may have resulted from relaxation of an older contractional structure; a lateral ramp in the hanging wall of the Gunnison thrust plate (Lawton and Weiss, 1999, figure 4). Evidence for this scheme is the thin North Horn-Colton section in the graben, contrasted with thicker sections north and south of the graben. Transport of hanging-wall rocks oblique to the trend of the ramp in the footwall of the Gunnison thrust created an east-west anticline during deposition of the North Horn. Subsequent extension permitted normal faulting along the trend of that footwall ramp. The graben is cut on the east by the range-bounding fault system, of course. That was subsequent to the development of the graben, but may have been very soon after the formation of the graben, for the range-bounding fault system is owed to the same basin-and-range extension episode.

North-Trending Normal Faults

North-trending normal faults define the plateau/valley boundary and also the divide graben. When they began is not evident from the rocks of the quadrangle, but basin-and-range extension in the Miocene probably initiated these faults. They have moved repeatedly since then and continue to do so, as shown by the scarps in the consolidated alluvial fans (QTaf). In the Wales quadrangle the range-bounding fault(s) cut the youngest Holocene fan deposits (Lawton and Weiss, 1999). The possible influence of the range-front fault zone on the formation of the Wasatch monocline is not known; the two may have been integral parts of the same dynamic couple.

ECONOMIC GEOLOGY

The main earth resources sought or produced within the Manti quadrangle are sand and gravel, limestone, and petroleum. Prospecting for metallic minerals has also been attempted.

Sand and Gravel

The younger alluvial-fan deposits and, locally, the older valley-fill materials have been quarried for road metal and construction fill. The principal sources have been the Maple Canyon fan and the River Knoll on the county road west of Manti. The gravels are very poorly sorted and contain much sand; boulders from the debris-flow deposits on the Maple Canyon fan are also conspicuous. The pebbles and larger clasts are mostly of carbonates from the Flagstaff Limestone and the finer particles are mostly quartz sand from the North Horn and Colton Formations. See also Pratt and Callaghan (1970) and Utah Department of Highways (1966) for information on the sand and gravel deposits in the Manti quadrangle.

Limestone

Dimension stone from the smooth, even ledges of the upper member of the Green River Formation was formerly produced in large quantities from the part of Temple Hill lying in the Ephraim quadrangle. The rock was used first for the Manti Temple and later for many residential and other buildings in Manti. The quarries have lain unused since the depression of the 1930s. Temple Hill is a part of the monumental architecture that stands on it and cannot again support a major quarry industry. However, some rock was removed in the late 1990s for repair of the east face of the Manti Temple.

A lime kiln for the production of lime mortar was built and operated in pioneer days in Dodge Canyon, in the SW1/4NE1/4 section 5, T. 18 S., R. 2 E. Lumps of fused rock, firebrick, and remnants of the kiln walls are still present. A small prospect pit, perhaps for the same purpose, was dug low on the plateau face in the SE1/4NW1/4 of section 4. Abundant limestone suitable for aggregate lies in the Flagstaff and Green River Formations on the Gunnison Plateau, but difficult access hinders development of these deposits.

Petroleum

Although no petroleum or natural gas has been economically produced in Sanpete County, exploration for these resources has been intermittently vigorous. Sanpete Valley has experienced two intervals of petroleum exploration: in the late 1950s, and again in the 1970s and early 1980s. During the 1950s cycle, companies drilled the SSVA. From that effort, gas was reportedly recovered on a drill stem test from the Cretaceous Funk Valley Formation (Ferron Sandstone equivalent) in the Tennessee Oil & Gas Transmission Irons #1 (NE1/4SE1/4 section 16, T. 15 S., R. 3 E., Wales quadrangle), but no commercial production resulted. Exploration intensified in the 1970s when companies, inspired by better seismic reflection data and shows of oil in wells, again drilled the SSVA. During this period the Hanson Oil Company drilled the Moroni 1AX (SE1/4NE1/4 section 14, T. 14 S., R. 3 E., Wales quadrangle), and recovered oil from the Cretaceous Allen Valley Shale (Tununk Shale equivalent). Hanson attempted for several months to establish commercial production, but the well was eventually abandoned.

Four wells, two Mobil wells and two Chandler wells, were drilled in the Manti quadrangle (table 1) during the later cycle. All four wells were drilled near the crest of the SSVA or along its steeply dipping east limb. The Mobil Larson #1 well (table 1) was drilled to test the deeper parts of the SSVA structure. Surprisingly, the well drilled through significant oil shows in the Cretaceous Funk Valley Formation in the shallow part of the hole. To test those shows while continuing to drill to the primary objective, Mobil brought in a second rig and drilled the Larson #2 through the stratigraphic interval that contained the oil shows. Mobil performed completion tests on the interval for several weeks and eventually abandoned the well. The Larson #1 was also abandoned after drilling more than 6,000 feet (1,829 m) of Jurassic Arapien Shale.

Interest in discovering petroleum in the Cretaceous strata along the east limb of the SSVA continued in the 1990s. This activity is within the Wales quadrangle, and was an attempt to evaluate the oil shows in the Hanson Moroni 1AX well. To date, the efforts have produced sub-economic quantities of oil. The source of the oil that was recovered from the Cretaceous reservoirs in Sanpete Valley is probably the Allen Valley Shale (Tununk equivalent). Geochemical analysis indicates that the oil and gas produced from Cretaceous reservoirs under the Wasatch Plateau fields, about 15 miles (24 km) northeast of the Sanpete Valley, is from organic-rich beds in the Cretaceous (Sprinkel and others, 1997). In addition, unpublished geochemical analyses indicate that the oil recovered from the Hanson Moroni 1AX well is geochemically similar to the Cretaceous oil and gas from the Wasatch Plateau fields. The study by Sprinkel and others (1997) also analyzed outcrop samples of the Allen Valley Shale, the Tununk Shale, the Blue Gate Shale, and the Blackhawk Formation for organic richness and other source-rock characteristics. They found that the Allen Valley and Tununk Shales were lean compared to the Blue Gate Shale and the Blackhawk Formation (Sprinkel and others, 1997). Unfortunately, the Allen Valley Shale is the only organic-rich mudstone of Cretaceous age drilled in the Moroni 1AX well; the Funk Valley Formation there contains few mudstone beds and the overlying Sixmile Canyon Formation (Blue Gate Shale equivalent) contains none. The organic-rich facies of the Ferron, Blue Gate, and Blackhawk are east of the Sanpete Valley and under the Wasatch Plateau, which is structurally higher than their equivalent beds in Sanpete Valley. The poor production performance from the Cretaceous in Sanpete Valley may be in part due to the poor source quality of the Allen Valley Shale (Tununk Shale equivalent). Both these factors probably limit the petroleum potential for Cretaceous targets in the Manti quadrangle.

Other targets that may have petroleum potential in the Manti quadrangle are likely restricted to Permian or Mississippian reservoirs associated with the SSVA, at depths generally greater than 18,000 feet (5,486 m) (Sprinkel and others, 1995). The source of oil and gas for those reservoirs is thought to be the organic-rich mudstone beds in the Permian Toroweap Formation (Sprinkel and others, 1997), but no wells have been drilled through the Toroweap in the Sanpete Valley to confirm that potential source beds are present in the area.

Metals

No metals have been produced from the Manti area, but some valiant attempts have been made to obtain them. Adits and short tunnels were dug in several places. Such workings are found along the thrust-fault surface in the SE1/4NW1/4 section 16, T. 17 S., R. 2 E., north of Maple Canyon, but the metal sought is not known. Two tunnels were dug into the lowest Twist Gulch beds in SE1/4NW1/4NE1/4 section 9, T. 17 S., R. 2 E., for copper, during World War I. A sloping tunnel about 50 feet (15 m) long was cut into the cemented conglomerate of member B of the San Pitch Formation, just beneath the Twist Gulch beds (figure 1), in the northwest corner of the SW1/4SE1/4 section 4, T. 17 S., R. 2 E. It is not known when it was started, but the tunnel was lengthened intermittently during the late 1950s and early 1960s. The objective was silver according to local residents of Sanpete Valley.

WATER RESOURCES

The most valuable natural resource in the Manti quadrangle is water, both surface and subsurface. Dry Creek, ironically, is one of only three perennial streams on the entire east face of the Gunnison Plateau. Manti Creek discharges abundant surface water from high on the Wasatch Plateau and supplies the city of Manti with irrigation and drinking water. The course of the San Pitch River is mostly channelized above the choke point at the River Knoll, and the river forms a vast shallow lake in the valley during wet years. Dry, Maple, and Dodge Canyons discharge large volumes of water and sediment during storms and snowmelt. All of these sources combine to recharge the valley-marginal fans and the central-valley fill with subsurface water.

The water table in the valley center is generally less than 30 feet (9 m) below the surface and the interbedding of permeable with impermeable layers produces both confined and unconfined aquifers (Robinson, 1971). The water table is greater than 30 feet (9 m) below the surface along the valley margins, especially along the base of the Wasatch Plateau (Robinson, 1971). A number of flowing wells provide water for stock and irrigation for Sanpete Valley.

GEOLOGIC HAZARDS

Three types of hazards are enduring threats to people, livestock, and cultural installations in the Manti quadrangle. In decreasing order of frequency, they are floods, landslides, and earthquakes. Floods and the accompanying debris flows from the larger canyons are an almost annual threat. Fortunately, the area of the quadrangle is given over almost entirely to forestry and agricultural uses that are less sensitive to flood damage. A debris flow on the Maple Canyon fan (Qmf_1) occurred in August of 1965, during a particularly wet year, but the road was restored across it within days. The city of Manti suffered a severe scare and some damage during the record wet years of 1983-84, but the stream has incised enough into the fan on which Manti is built to contain most flood debris. The periodic flooding of the central and northern portions of Sanpete Valley is an inconvenience to owners who own grazing rights, but is an important replenishment of the ground-water supply.

Landsliding and slumping are constant threats on the steep slopes of the plateau escarpment and on canyon walls. Slope failures are hastened during snowmelt and in wet years, and affect particularly the soft mudstone units of the North Horn and Colton Formations, and the lower shale member of the Green River Formation. The Arapien and Twist Gulch Formations are also susceptible to slope failures, but the hazard is less significant than in other failure-prone units because these areas are generally small and form more gentle slopes. Mountain roads are the most commonly impacted cultural features by landslides and slumps in the Manti quadrangle.

Seismic activity along the range-front fault zone and other active faults in the area is a potential source of earthquakes in the Manti quadrangle. Subdued scarps in Quaternary deposits in the quadrangle show that geologically recent movement has occurred and therefore surface-rupturing earthquakes are likely to recur. The most recent event, with probable displacement of less than 3 feet (1 m) in the Wales quadrangle, may have taken place in late Holocene time (Hecker, 1993). Paleoseismic data are needed to more accurately date the most recent surface-rupturing earthquake event and evaluate the recurrence interval for future surface-rupturing earthquakes. Generally, citizens of central Utah have only felt a few earthquakes. Of the historic earthquakes, most are small-to-moderate in strength and generally have occurred in Sevier Valley, south than Manti. Impacts from earthquakes include ground shaking, and possibly liquefaction of saturated alluvial deposits along the San Pitch River that could disrupt irrigation ditches and weirs. The features at most risk are masonry buildings in the city of Manti, which is built on an alluvial fan made of uncemented sediments.

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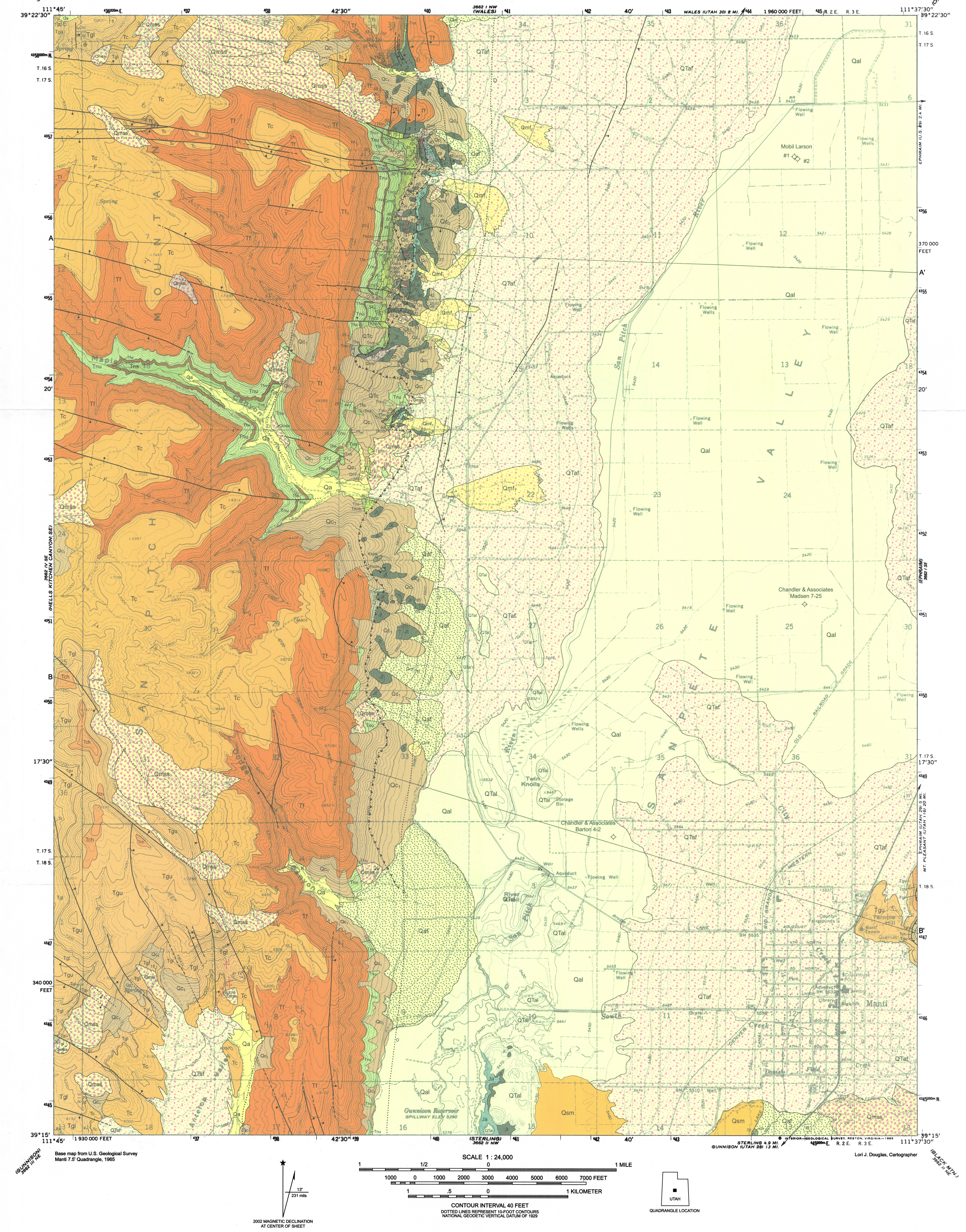

GEOLOGIC MAP OF THE MANTI QUADRANGLE, SANPETE COUNTY, UTAH

by
Malcolm P. Weiss
and
Douglas A. Sprinkel

2002

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Description of Map Units

Qa Stream and fan allluvium (Holocene) - *Unconsolidated mud, silt, sand, gravel, and boulders closely associated with existing streams that flow into Sanpete Valley from the Gunnison Plateau. 0 to 50 feet (0 - 15 m) thick.*

QTa Older stream alluvium (Pliocene? - Pleistocene?) - *Like Qa, but poorly consolidated and preserved under a large boulder in gulch in SW1/4 NW1/4NE1/4 section 9, T. 17 S., R. 2 E., south of Dry Canyon. Deposit is 30 feet (10 m) wide and 12 feet (4 m) thick.*

Qal / QTal Floodplain and channel deposits (Miocene? - Holocene) - *Poorly consolidated to unconsolidated valley-filling deposits of mud, silt, sand, and gravel, mostly of alluvial, debris-flow, and mudflow origin, that occupy central Sanpete Valley. They grade latterally into interfinger with older fan deposits (QTaf). The younger valley fill (Qal) forms the gently sloping floor of the Sanpete Valley, grades laterally to spring deposits (Qsm), and laps onto bedrock and older valley fill (QTal) in the river knolls. The older deposits (QTal) have been tilted and elevated locally from a former valley-floor position; elsewhere they underlie the younger deposits (Qal). The younger valley fill (Qal) is considered to be Holocene in age and is diagrammed as 100 to 200 feet (30-61 m) thick in cross sections only. The entire mass (QTal + Qal) ranges from 0 to 935 feet (285 m) in thickness.*

Qaf Alluvial-fan deposits (Pleistocene - Holocene) - *Unconsolidated deposits of mud, silt, sand, and poorly sorted gravel (to boulder size) at the mouths of smaller drainages and at Dodge Canyon. Grade into or overlie alluvium (Qa), older fans (QTaf), or valley fill (Qal); 0 to 50 feet thick but mostly 30 to 50 (9-15 m) thick.*

QTaf Consolidated alluvial-fan deposits (Miocene? - Holocene) - *Material like that in the younger fan deposits, but better compacted; still accumulating at the surface and locally dissected. Forms coalesced alluvial-fan complexes of great area and thickness, and grades to valley fill (QTal and Qal) and spring deposits (Qsm). Thickness estimated to be as great as 0 to 935 feet (0-285 m).*

Qc_1 / Qc_2 / QTc Colluvial deposits (Pliocene? - Holocene) - *Unconsolidated mud, sand and angular pieces of rock (to boulder size) lying on steep, unstable slopes. May grade downslope to alluvial or fan deposits. Youngest colluvial deposits (Qc_1) are still forming today; the older colluvium (Qc_2) is both dissected and detached from any upslope source of material; the oldest colluvium (QTc) is dissected, has a well developed soil, is slumped locally, and has a different, higher profile than deposits of Qc_2. Thickness of each type ranges from 0 to 20 feet (0-6 m) at most sites, but locally reaches 50 feet (15 m).*

Qsm Spring deposits (Holocene) - *Marshy and salty soil and mud at the surface of the east branch of Sanpete Valley near the south edge of the quadrangle; kept moist by saline springs east of that area. The surface of the deposit is coextensive with younger valley fill (Qal). The body of the deposit is continuous into fan (QTal) deposits; its thickness is on the order of 0 to 165 feet (0-51 m).*

Qmf_1 / Qmf_2 Debris-flow deposits (Pleistocene? - Holocene) - *Unconsolidated, elongate deposits of poorly sorted mud, silt, sand, and gravel with angular blocks of Flagstaff Limestone to 6 feet (1.8 m) long. Formed below steep gulches or at mouths of larger canyons, and lies on fan deposits (QTaf); 0 to 15 feet (0-5 m) thick. The younger deposits (Qmf_1) continue development today and contribute to the fans (QTaf) and valley fill (Qal). The older deposits (Qmf_2) have subdued relief and some soil development, are being dissected, are partly buried by younger deposits (Qaf, Qc_1), and are at least 50 feet (15 m) thick.*

Qmsl / Qmss Mass-movement deposits (Pleistocene - Holocene) - *Masses of poorly sorted mud, sand, angular broken rock, and vegetation that have moved down steep slopes, either rapidly as slides (Qmsl) or slowly as slumps (Qmss), in response to gravity. Both types may have depressions at the heads, hummocky surfaces and steep, lobate toes. The two varieties are distinguished by form: large irregular areas believed to have slumped slowly and repeatedly (Qmss) and narrow, linear deposits believed to have been rapid, catastrophic landslides (Qmsl) in depressions on steep slopes. The slump masses may reach 200 feet (61 m) in thickness; the landslide masses are less than 50 feet (15 m) thick.*

Tch Crazy Hollow Formation (Eocene) - *Weakly cemented light-gray quartzose sandstone in the southwest quadrant is locally cross-bedded and contains a few pebbles of black chert, the "signature" feature of the formation regionally. In the southeast quadrant the unit is pebbly salt-and-pepper sandstone. Unit is locally disconformable on the upper Green River (Tgu) and has no bedrock cover. Maximum thickness here is 70 feet (21 m).*

Tgu / Tgl / Tg Green River Formation (Eocene) - *Consists of two unnamed members: a lower shale member and an upper limestone member. Upper limestone member (Tgu): Yellowish- or gray-weathering micritic dolomite and sparry limestone, thin to thick bedded; abundant well-rounded, fine- to medium-grained quartz sand; some limestone beds are locally cross-bedded. Thin shale and shaly limestone interbeds and some biotitic tuff locally; oolitic and ostracodal limestone in the southeast quadrant. Ranges from 220 to 400 feet (67-122 m) thick. Lower shale member (Tgl): Light-gray and greenish-gray mudstone and shale, numerous thin and medium beds of very light gray, white-weathering, micritic, vitreous, or silty limestone; the latter are dolomite or dolomitic limestone. Ranges form 500 to 911 feet (152-278 m) thick.*

Tc Colton Formation (Eocene) - *Mostly reddish-brown, light-gray, violet, greenish-gray, and red mudstone and claystone. Local beds of feldspathic yellowish-gray to yellowish-brown siltstone and silty sandstone; some sandstone beds are sheet-like, others are channel form, poorly cemented, and cross-bedded. Many thin beds of glassy micritic and fine sparry limestone show the same colors as the mudstones, and contain mollusks and ostracodes locally. Ranges from 550 to 860 feet (167-262 m) thick.*

Tf Main body of the Flagstaff Limestone (Eocene) - *Light-gray to light-yellowish-gray, micritic and sparry limestone and dolomite; light-gray, mostly mottled dolomicrite; thin to thick bedded; thin shaly limestone partings and interbeds. Gastropod fossils are locally abundant. Weathers to bold, pale-gray to white cliffs. Ranges from 155 to 640 feet (47-197 m) thick where exposed, but is 0 feet thick in the subsurface in the southern part of Sanpete Valley.*

Tfw Wales Tongue of Flagstaff Limestone (Paleocene) - *A tongue of light-gray and yellowish-gray dolomite and dolomitic limestone parted by thin and medium beds of sandy mudstone and shale. The Wales Tongue is separated, except in the Dry Canyon graben, from the base of the Flagstaff Limestone (Tf) by the upper redbed member (Tnu) of the North Horn Formation. Unit weathers whitish to orange gray. Gastropods and oncolites are present locally. From 33 to 50 feet (10-15 m) thick at most sites, but 102 feet (31m) thick in the Dry Canyon graben and 0 feet thick in the subsurface along the east side of Sanpete Valley.*

TKn North Horn Formation (Late Cretaceous to early Tertiary [Campanian - early Eocene]) - *A complex unit of mostly clastic beds with minor limestone and dolomite; many lithofacies characterized by complex intertonguing regionally. Unconformable on older Cretaceous and Jurassic rocks, and with numerous intraformational angular unconformities. The North Horn is 3,600 feet (1,100 m) thick in the Wales quadrangle, where it is divided into eight informal units; only the four younger units, diminished in thickness, are exposed in the Manti quadrangle. The four older units are represented on cross sections as Knl. The whole, undivided formation is labeled TKn on cross sections. The North Horn Formation, including the Wales Tongue of the Flagstaff Limestone, is estimated to be 0 to 1,889 feet (0-573 m) thick in the Manti quadrangle.*

Tnu Upper redbed unit of the North Horn Formation (Eocene) - *Gray shaly mudstone and reddish-brown and reddish-purple mottled siltstone and yellowish-gray sandy siltstone, with a few thin and medium orange-weathering sandstone beds. Sparse thin beds of micrite contain gastropods and charophytes, and oncolites are locally common in grain-supported clastic beds. Is 160 to 266 feet (49-81 m) thick in the mountain front, 180 to 200 feet (55-61 m) in the interior, and absent from the Dry Canyon graben and in the subsurface along the east side of Sanpete Valley.*

Tns / Tncc Calcareous siltstone (Paleocene to Eocene) and Coal Canyon (Paleocene) units of the North Horn Formation - *These units are mapped together (Tncc) in most parts of this quadrangle because the latter is thin and discontinous. The combined units are 0 to 400 feet (122 m) thick. The calcareous siltstone unit, mapped locally as Tns in Dry Canyon graben and in the interior of the plateau, consists of calcareous siltstone and sandstone with a blocky massive structure; red, gray, and purple fine clastics weather to reddish- or yellowish-gray soil; commonly poorly exposed. Warty micritic nodules are present in the unit. It is 0 to about 360 feet (0-110 m) thick. The Coal Canyon unit is of sandstone and pebbly sandstone in stacked tabular beds to 7 feet (2 m) thick. Some contain foresets that extend from top to base of bed. Sediment dispersal was to west and northwest during Coal Canyon deposition. Patches of these west-directed deltaic deposits are 40 to 60 feet (12-18 m) thick and largely covered.*

TKnb Big Mountain unit of the North Horn Formation (Late Cretaceous to early Tertiary [Maastrichtian-Paleocene]) - *Light-gray, yellowish-gray-weathering sandstone, pebbly sandstone, and some clast-supported pebble and cobble conglomerate, all well cemented by calcite. Forms bold wall halfway up face of the mountain, but is absent from Dry Canyon graben and pinches out south of Maple Canyon. Contains abundant oncolites locally in the conglomerates. Is 262 to 395 feet (80-120 m) thick in the mountain front and 0 feet thick in the subsurface along the east side of Sanpete Valley.*

Knl Lower North Horn Formation, undivided (Late Cretaceous [Campanian - Maastrichtian]) - *Consists of the four older units as mapped in the Wales quadrangle (Lawton and Weiss, 1999). Shown only on cross sections. These beds, where exposed in the Wales quadrangle, are mostly clastic beds with minor limestone and dolomite; many lithofacies characterized by complex intertonguing regionally. They lie unconformably on older Cretaceous and Jurassic rocks, and have numerous intraformational angular unconformities. Estimated to be 0 to 700 feet (0-213 m) thick in the Manti quadrangle.*

Ki Indianola Group (Early to Late Cretaceous [middle Albian - Campanian]) - *A thick unit of mostly clastic rocks divided into five formations: from top down, the Sixmile Canyon Formation, the Funk Valley Formation, the Allen Valley Shale, the Sanpete Formation, and the San Pitch Formation. The San Pitch is exposed in small patches in the mountain front and the Funk Valley crops out in a small patch south of Manti. The Sanpete Formation, Allen Valley Shale, and Sixmile Canyon Formation are present only in the subsurface and are shown only in the cross section.*

Ksx Sixmile Canyon Formation - *Shown only on cross sections.*

Kfv Funk Valley Formation (Late Cretaceous [Coniacian-Campanian]) - *Tan, well sorted, fine-grained sandstone and gray siltstone and shale in upper part. Only about 200 feet (61 m) of the lowest part of the formation is exposed in the quadrangle; the whole formation nearby in the Sterling quadrangle is 3,000 to 3,100 feet (914-945 m) thick.*

Kav Allen Valley Shale - *shown only on cross section.*

Ks Sanpete Formation - *shown only on cross seciton.*

Kspc / Kspb / Kspa San Pitch Formation (late Early Cretaceous [middle to late Albian]) - *Conglomerate, pebbly sandstone, and red mudstone. Divided into three informal members: the older member A (Kspa) consists of conglomerate beds with quartzite and carbonate pebbles and cobbles interbedded with thick beds of red mudstone; the younger member B (Kspb) consists of mostly carbonate pebble and cobble conglomerate with thin beds of red sandstone and mudstone. Green quartzite pebbles are present in both older members. Member C (Kspc) does not crop out in the quadrangle but is likely present in the subsurface and is represented in the cross sections. Member A is 205 feet (62 m) thick and member B is 245 feet (75 m) thick for a total of 450 feet (137 m) exposed thickness; however, the San Pitch Formation thickens westward and is estimated to be as much as 2,000 feet (610 m) thick in the subsurface near the western margin of the quadrangle.*

Kc Cedar Mountain Formation (Early Cretaceous [Barremian? - middle Albian]) - *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 orgin. Polished pebbles (gastroliths?) of quartz and quartzite are present locally. 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. A very incomplete section only 62 feet (19 m) thick is exposed in the quadrangle. The Cedar Mountain Formation may be as much as 1,100 feet (335 m) thick in the subsurface of the Manti quadrangle.*

Ku Cretaceous undivided (Early Cretaceous [Barremian to late Aptian]) - *Consists of undivided Cedar Mountain and San Pitch Formations.*

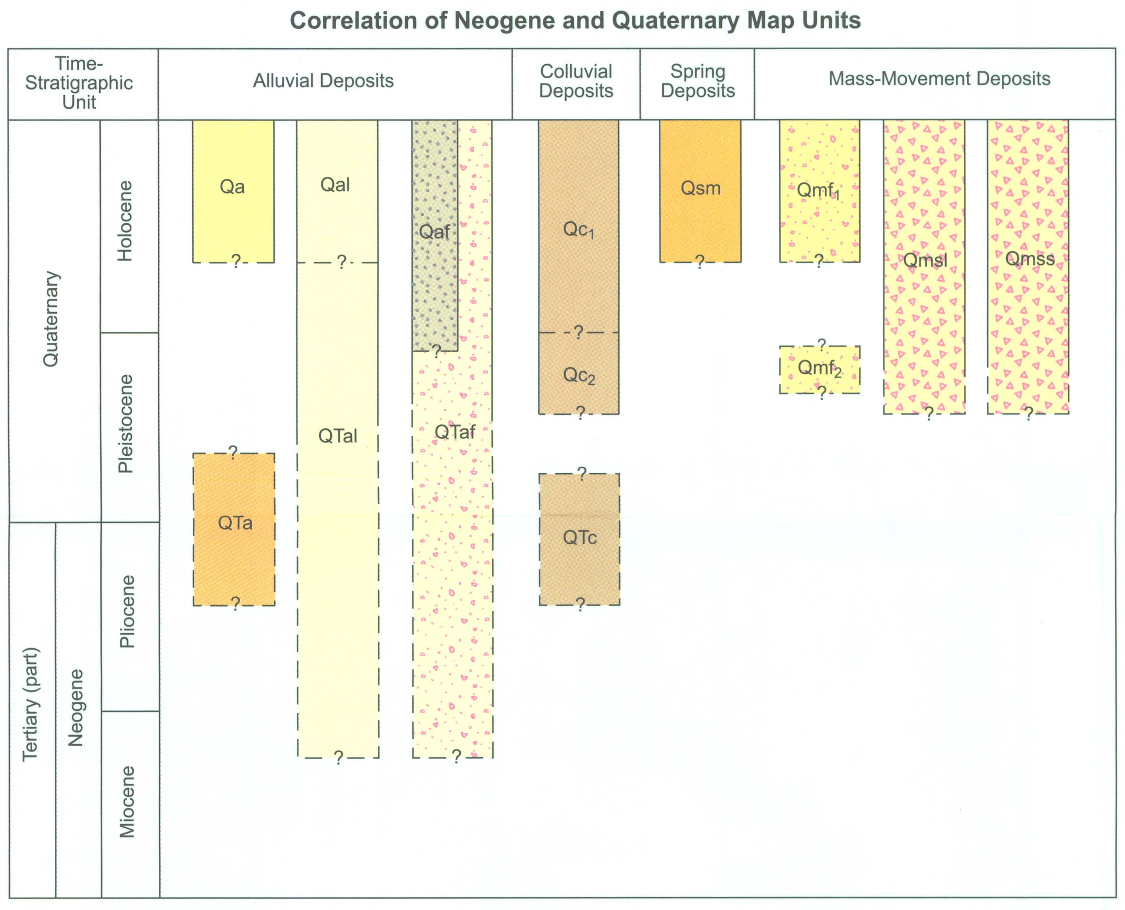
Jt Twist Gulch Formation (Middle Jurassic [Callovian]) - *Mostly well-sorted, thinly bedded, pale-red and dark-reddish-brown mudstone and siltstone that weathers to a chocolate brown. Thin interbeds of light-reddish-brown or pinkish-gray sandstone are scattered in the mudstone. An interval about 68 feet (21 m) thick of light-gray or pinkish-gray quartzose sandstone is concentrated near the middle of the outcrop belt. Basal conglomerate of grit lies on the Arapien Shale. The maximum exposed thickness in the quadrangle is 1,150 feet (350 m), about two-thirds of the regional thickness.*

Ja Arapien Shale (Middle Jurassic [Bathonian - Callovian]) - *Brick-red gypsiferous mudstone with some siltstone beds of similar color are exposed in the Manti quadrangle. This is likely member E. The older members (A-D) of the Arapien Shale consist of gray-green and reddish-brown mudstone, gray-green limestone, and some sandstone; are exposed in nearby quadrangles; and are preserved in the subsurface of the Manti quadrangle. Thick gypsum (anhydrite in the subsurface) beds and some thin salt beds are also part of the Arapien. The lower contact with the Twin Creek Limestone is not exposed, but the upper contact is exposed. The Arapien is disconformably overlain by the Twist Gulch Formation. Maximum exposed thickness is about 200 feet (61 m); however, the entire Arapien Shale in the Manti quadrangle is estimated to be about 7,000 feet (2,100 m), which likely represents structural thickening of the formation.*

Map Symbols

- Contacts - *includes approximately located*
- Wales Tongue- *marker bed where thin on plate 1*
- Faults
  - Normal fault - *dashed where approximately located; dotted where concealed; bar and ball on downthrown side*
  - Hidden fault - *concealed; inferred from regional mapping; D on downthrown side*
  - Thrust or reverse fault - *teeth on hanging wall; dotted where concealed*
- Fracture zones - *Crust broken, but with no discerned displacement; more vegetation because of concentration of ground water*
- Mass movement - *Scarps of large slumps, some of which may be related to buried normal faults*
- Trace of axial surface of folds (arrow on axis shows direction of plunge)
  - Anticline
  - Overturned anticline
  - Syncline
  - Overturned syncline
- Strike and dip of bedding
  - 23 Inclined
  - Horizontal
  - Vertical
  - 40 Overturned
- Adit
- K Limestone kiln
- Gravel pit
- Dry hole - oil and gas exploration well

Correlation of Neogene and Quaternary Map Units



Lithologic Column

TIME-STRATIGRAPHIC UNIT			FORMATION		MAP SYMBOL		THICKNESS Feet (meters)	LITHOLOGY
Quaternary		Holocene Pleistocene	surficial deposits		see correlation of Neogene and Quaternary units for symbols		0-935 (0-285)	
Tertiary		Miocene-Pliocene						unconformity
Tertiary		Eocene	Crazy Hollow Formation		Tch		70 (21)	unconformity
Tertiary		Eocene	Green River Formation	limestone member	Tgu	Tg	220-400 (67-122)	
Tertiary		Eocene	Green River Formation	shale member	Tgl	Tg	500-911 (152-278)	
Tertiary		Eocene	Colton Formation		Tc		550-860 (167-262)	
Tertiary		Eocene	Flagstaff Limestone		Tf		0-640 (0-197)	
Tertiary		Eocene	North Horn Formation	upper redbed unit	Tnu	TKn	0-266 (0-81)	
Tertiary		Paleocene	North Horn Formation	Wales Tongue of the Flagstaff Limestone	Tfw	TKn	0-102 (0-31)	
Tertiary		Paleocene	North Horn Formation	calcareous siltstone unit	Tns / Tncc	TKn	0-360 (0-110)	
Tertiary		Paleocene	North Horn Formation	Coal Canyon unit	Tncc	TKn	0-60 (0-18)	
Tertiary		Paleocene	North Horn Formation	Big Mountain unit	TKnb	TKn	0-395 (0-120)	unconformity
Cretaceous	Upper	Maastrichtian	North Horn Formation	*lower four units	Knl	TKn	0-700 (0-213)	
Cretaceous	Upper	Campanian	North Horn Formation	*lower four units	Knl	TKn	0-700 (0-213)	unconformity
Cretaceous	Upper	Campanian	Indianola Group	*Sixmile Canyon Fm.	Ki	Ksx	~4,000 (~1,219)	
Cretaceous	Upper	Santonian-Coniacian	Indianola Group	Funk Valley Fm.	Ki	Kfv	3,000-3,100 (914-945)	
Cretaceous	Upper	Turonian	Indianola Group	*Allen Valley Shale	Ki	Kav	150-600 (46-83)	
Cretaceous	Upper	Cenomanian	Indianola Group	*Sanpete Fm.	Ki	Ks	200-300 (61-91)	unconformity
Cretaceous	Lower	Aptian-Albian	Indianola Group: San Pitch Formation	*mbr. C	Ki	Kspc	144-520 (44-158)	
Cretaceous	Lower	Aptian-Albian	Indianola Group: San Pitch Formation	mbr. B	Ki	Kspb (Ku)	245-1,200 (75-366)	
Cretaceous	Lower	Aptian-Albian	Indianola Group: San Pitch Formation	mbr. A	Ki	Kspa (Ku)	205-280 (62-85)	
Cretaceous	Lower	Barremian	Cedar Mountain Formation		Kc	Ku	**62 (19)	unconformity
Jurassic	Middle	Callovian	Twist Gulch Formation		Jt		1,150 (350)	disconformity
Jurassic	Middle	Bathonian	Arapien Shale		Ja		***200 (61)	

*Shown on cross sections only.
**Represents the exposed thickness of the formation in fault blocks within the quadrangle.
***Represents the exposed thickness in the quadrangle.