Plate 1
Utah Geological Survey Open-File Report 372
Interim Geologic Map of the Manti Quadrangle

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

MANTI QUADRANGLE
UTAH—SANPETE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)

Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography by photogrammetric methods from aerial photographs taken 1963. Field checked 1965

Polyconic projection. 1927 North American Datum
10,000-foot grid based on Utah coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue

Red tint indicates areas in which only landmark buildings are shown

Fine red dashed lines indicate selected fence lines

Area covered by dashed light-blue pattern is subject to controlled inundation

To place on the predicted North American Datum 1983 move the projection lines 8 meters north and 65 meters east as shown by dashed corner ticks

UTM GRID AND 1965 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 10-FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Geology by M.P. Weiss & D.A. Sprinkel Inked 16 Nov. '93

Revised 9/99

Revised again Jan. 2000
Revised again April 2000

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

QUADRANGLE LOCATION

ROAD CLASSIFICATION
Heavy-duty .... Light-duty ....
Unimproved dirt ....
U.S. Route

MANTI, UTAH
39111-C6-TF-024
1965
DMA 3662 I SW-SERIES V897

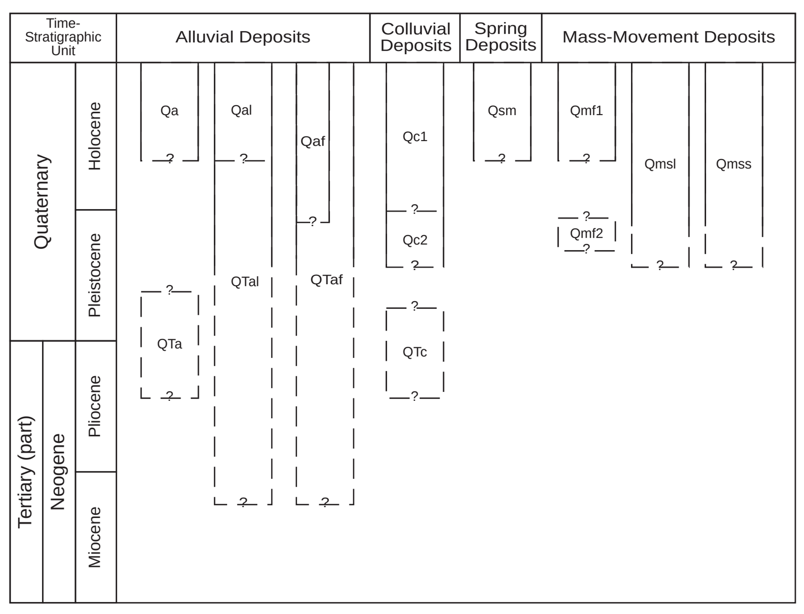
revised 4-11-00

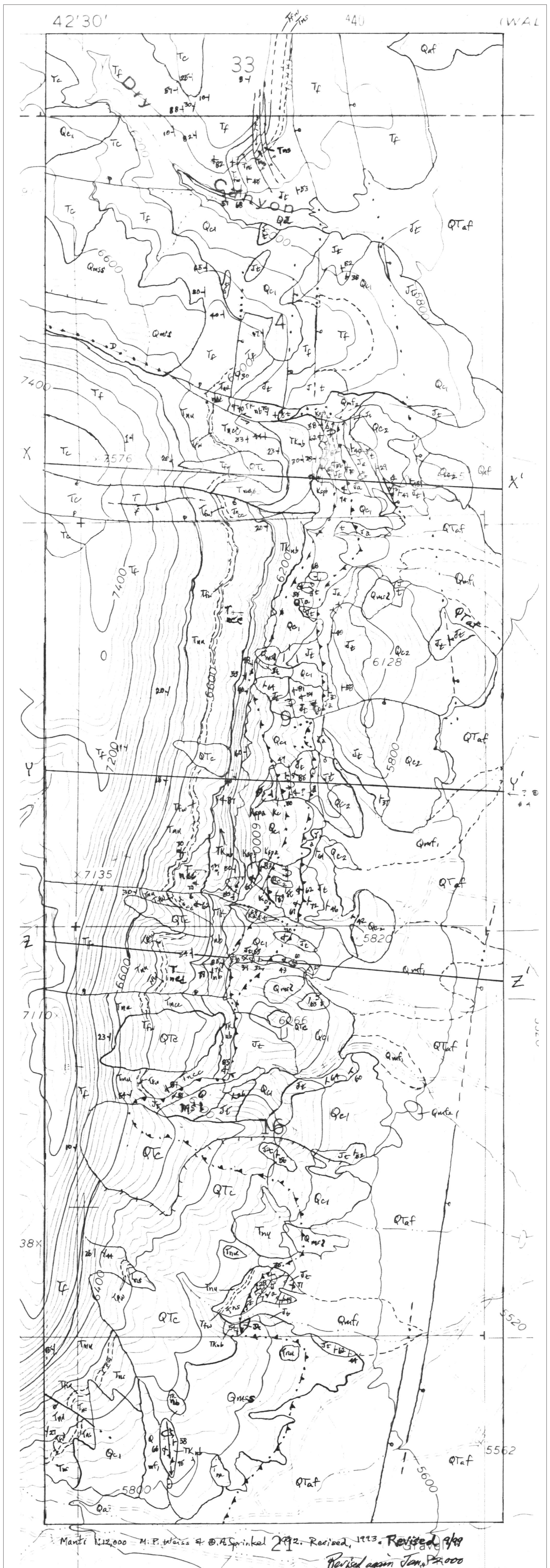
Geologic Column

TIME-STRATIGRAPHIC UNIT			FORMATION			MAP SYMBOL		THICKNESS Feet (meters)	LITHOLOGY
Quaternary		Holocene Pleistocene	Surficial Deposits			see correlation of 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		155-640 (47-197)	
Tertiary		Eocene	North Horn Formation	Upper Redbed mbr.		Tnu	TKn	0-266 (0-81)	
Tertiary		Paleocene	North Horn Formation	Wales Tongue		Tfw	TKn	33-102 (10-31)	
Tertiary		Paleocene	North Horn Formation	Calcareous Siltstone mbr.		Tns / Tncc	TKn	0-360 (0-110)	
Tertiary		Paleocene	North Horn Formation	Coal Canyon mbr.		Tncc	TKn	40-60 (12-18)	
Tertiary		Paleocene	North Horn Formation	Big Mountain mbr.		TKnb	TKn	262-395 (80-120)	unconformity
Cretaceous	Upper	Maastrichtian / Campanian	North Horn Formation	*Lower four members of North Horn Fm.		Knl	TKn	500-700 (152-213)	
Cretaceous	Upper	Campanian	Indianola Group	*Sixmile Canyon Fm.		Ki	Ksx	~4,000 (~1,219)	
Cretaceous	Upper	Santonian-Conacian	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	245-1,200 (75-366)	
Cretaceous	Lower	Aptian-Albian	Indianola Group	San Pitch Formation	Mbr. A	Ki / Ku	Kspa	205-280 (62-85)	
Cretaceous	Lower	Barremian	Cedar Mountain Formation			Kc	Ku	**62-1,000 (19-305)	unconformity
Jurassic	Middle	Callovian	Twist Gulch Formation			Jt		1,150 (350)	disconformity
Jurassic	Middle	Callovian / Bathonian	Arapien Shale			Ja		***400 (122)	
Jurassic	Middle	Bajocian	*Twin Creek Limestone			Jtc		560-1,056 (171-322)	unconformity
Jurassic	Lower	Toarcian	*Navajo Sandstone			Jn		1,246-1,450 (380-442)	

*Shown on cross sections only.
**Exposed thickness in fault blocks is 62 feet (19 m), but may be as much as 1,000 feet (305 m) thick in the subsurface.
***Exposed thickness. The Arapien Shale may be as much as 5,600 feet (1,707 m) thick in the subsurface.

Correlation of Neogene and Quaternary Units





Scale 1:12,000

DESCRIPTION OF MAP UNITS

Qa Stream alluvium (Holocene) - Unconsolidated silt, sand, and gravel closely associated with existing streams. 0 to 50 feet (0-15 m) thick.

QTa Older stream alluvium (Pliocene? - Pleistocene?) - Like Qa, but weakly cemented 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) - Compacted but uncemented deposits of mud, silt, sand, and gravel, mostly of alluvial, debris-flow, and mudflow origin, that occupy central Sanpete Valley. They grade laterally or interfinger with older fan deposits (QTaf). The younger valley fill (Qal) forms the gentle floor of Sanpete Valley, grades laterally to spring deposits (Qsm), and laps onto bedrock and older valley fill in the river knolls. The older deposits (QTal) have been elevated and tilted 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 feet (9-15m) 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 700 to 800 feet (213-244 m).

Qc1 / Qc2 / 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 (Qc1) are still forming today; the older colluvium (Qc2) 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 Qc2. 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 (QTaf) and older valley- fill (QTal) deposits; its thickness, like theirs, is the order of 800 to 900 feet (244-274 m).

Qmf1 / Qmf2 Debris-flow deposits (Pleistocene? - Holocene) - Unconsolidated, elongated deposits of poorly sorted mud, silt, sand, and gravel with angular blocks of Flagstaff Limestone to 6 feet (1.8 m) long exposed on top and as levees. Formed below steep gulches or at mouths of larger canyons, and lying on fan deposits (QTaf); 0 to 15 feet (0-5 m) thick. The younger deposits (Qmf1) continue development today and contribute to the fans (QTaf) and valley fill (Qal). The older deposits (Qmf2) have subdued relief, some soil development, are being dissected, are partly buried by younger deposits (Qaf, Qc1), and are at least 50 feet (15 m) thick.

Qmsl / Qmss Mass-wasting 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) of 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 dolostone 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, glassy, or silty limestone; the latter are dolomite or dolomitic limestone. Ranges from 500 to 911 feet (152-278 m) thick.

Tc Colton Formation (Eocene) - Mostly mudstone and claystone, reddish brown, light gray, violet, greenish gray, and red. Local beds of feldspathic yellowish-gray to yellowish-brown siltstone and silty sandstone; some sandstone beds are sheetlike, 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) - Limestone, light gray to light yellowish gray, mostly micrite and fine sparite, and dolostone, 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 528 to 640 feet (161-197 m) thick, but is only 155 feet (47 m) thick at the mouth of Dry Canyon.

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 (31 m) thick in the Dry Canyon graben.

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 members; only the four younger members, diminished in thickness, are exposed in the Manti quadrangle. The four older members are represented on cross sections as Knl. The whole, undivided formation is locally labeled TKn on cross sections. The North Horn Formation, including the Wales Tongue, is estimated to be 835 to 1,883 feet (254-573 m) thick in the Manti quadrangle.

Tnu Upper redbed member 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.

Tncc / Tns Calcareous siltstone (Paleocene to Eocene) and Coal Canyon (Paleocene) of the North Horn Formation - These members are mapped as a unit (Tncc) in this quadrangle because the latter is thin and intermittent. The combined units are 0 to 400 feet (122 m) thick. The calcareous siltstone member-mapped locally as Tns in Dry Canyon graben and in the interior of the plateau-consists of calcareous siltstone and sandstone with a blocky or 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 member. It is 0 to about 360 feet (0-110 m) thick. The Coal Canyon member 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. Patches of these west-directed deltaic deposits are 40 to 60 feet (12-18 m) thick and largely covered by debris.

Tknb Big Mountain member 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 to small boulder size locally in the conglomerates. Is 262 to 395 feet (80-120 m) thick in the mountain front.

Knl Lower North Horn Formation, undivided (Late Cretaceous [Campanian - Maastrichtian]) - The four older members are represented 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 with numerous intraformational angular unconformities. Is estimated to be 500 to 700 feet (152-213 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 sections.

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 beds of the lowest part of the formation are 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 sections.

Ks Sanpete Formation - shown only on cross sections.

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. The thickness of the two members exposed in the quadrangle is 205 feet (62 m) of member A and 245 feet (75 m) of member B for a total of 445 feet (137 m) thick; 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 origin. 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 about 1,000 feet (305 m) thick in the subsurface of the Manti quadrangle.

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

Jt Twist Gulch Formation (Middle Jurassic [Callovian]) - Mostly well sorted, thinly bedded, fine-grained clastic rocks-pale-red and dark reddish brown mudstone 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 [Bajocian - 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. Thick gypsum (anhydrite in the subsurface) beds and some thin salt beds are also part of the Arapien. The bulk of the Arapien Shale not exposed in the quadrangle but is represented in cross section only. The lower contact with the Twin Creek Limestone is not exposed, but the top is overlain disconformably 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 5,600 feet (1,706 m), based on regional thickness.

Jtc Twin Creek Limestone - shown only on cross sections.

Jn Navajo Sandstone - shown only on cross sections

Map Symbols

Contacts - dashed where approximate:

Wales Tongue - where thin on plate 1: W

FAULTS

Normal fault - Dashed where inferred; dotted where concealed; bar and ball on downthrown side:

Hidden fault - known from indirect evidence; D on downthrown side: D

Thrust or reverse fault - teeth on hanging wall; dash-dot where concealed:

FRACTURE ZONES - Crust broken, but with no discerned displacement; more vegetation because of concentration of ground water: F F

MASS MOVEMENT

Headwall scarps of large slumps - Ticks are on downdropped side:

Small mass movement - Arrow indicates direction of movement:

TRACES OF AXIAL SURFACE OF FOLDS

Anticline | Overturned Anticline | Syncline | Overturned Syncline

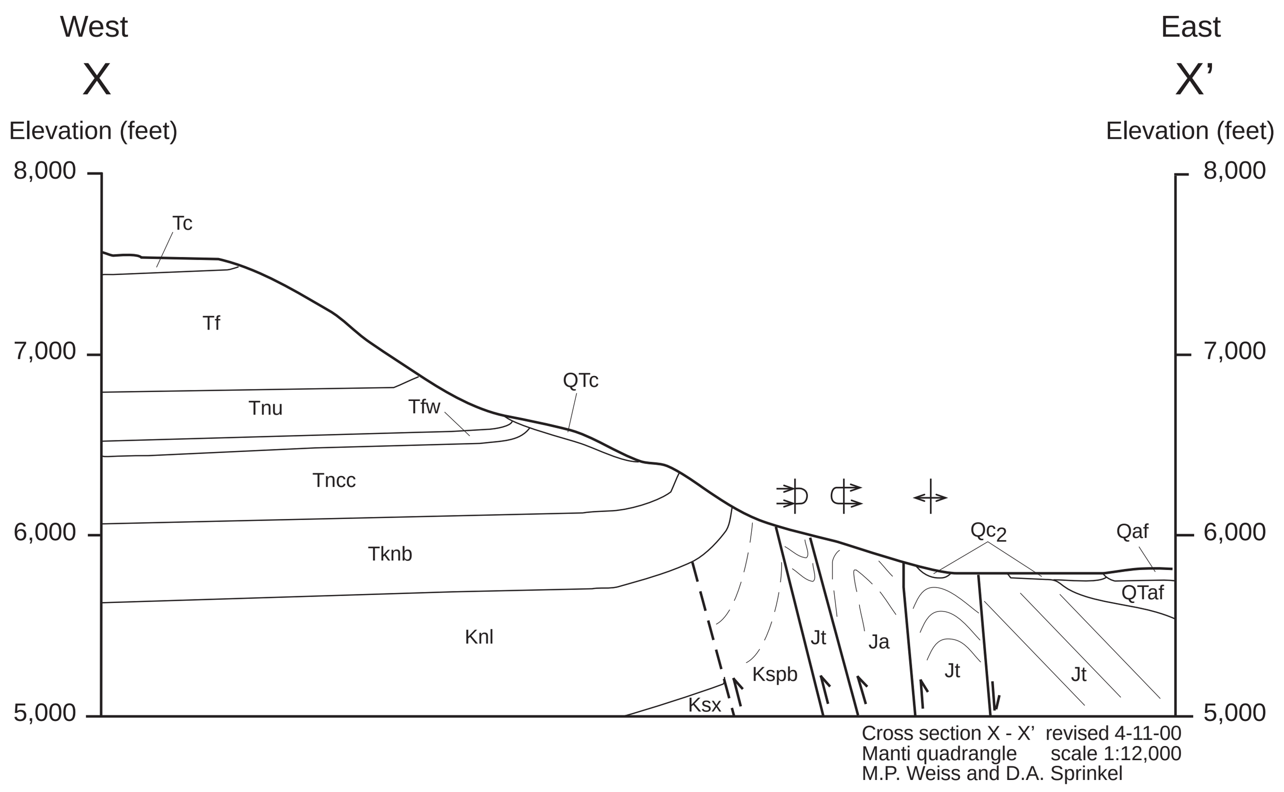
STRIKE AND DIP OF BEDDING

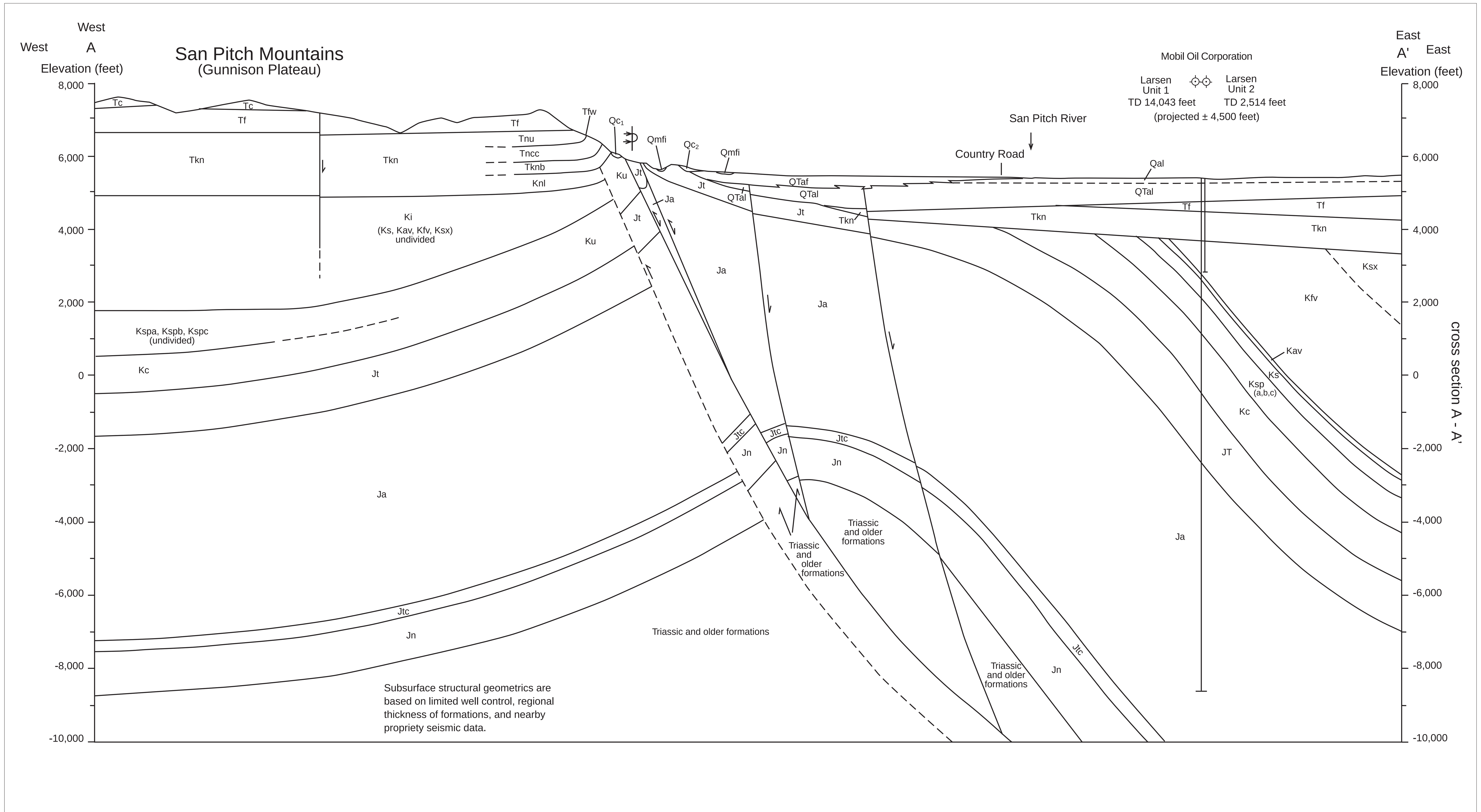
Inclined (25, 70) | Horizontal | Vertical | Overturned (65)

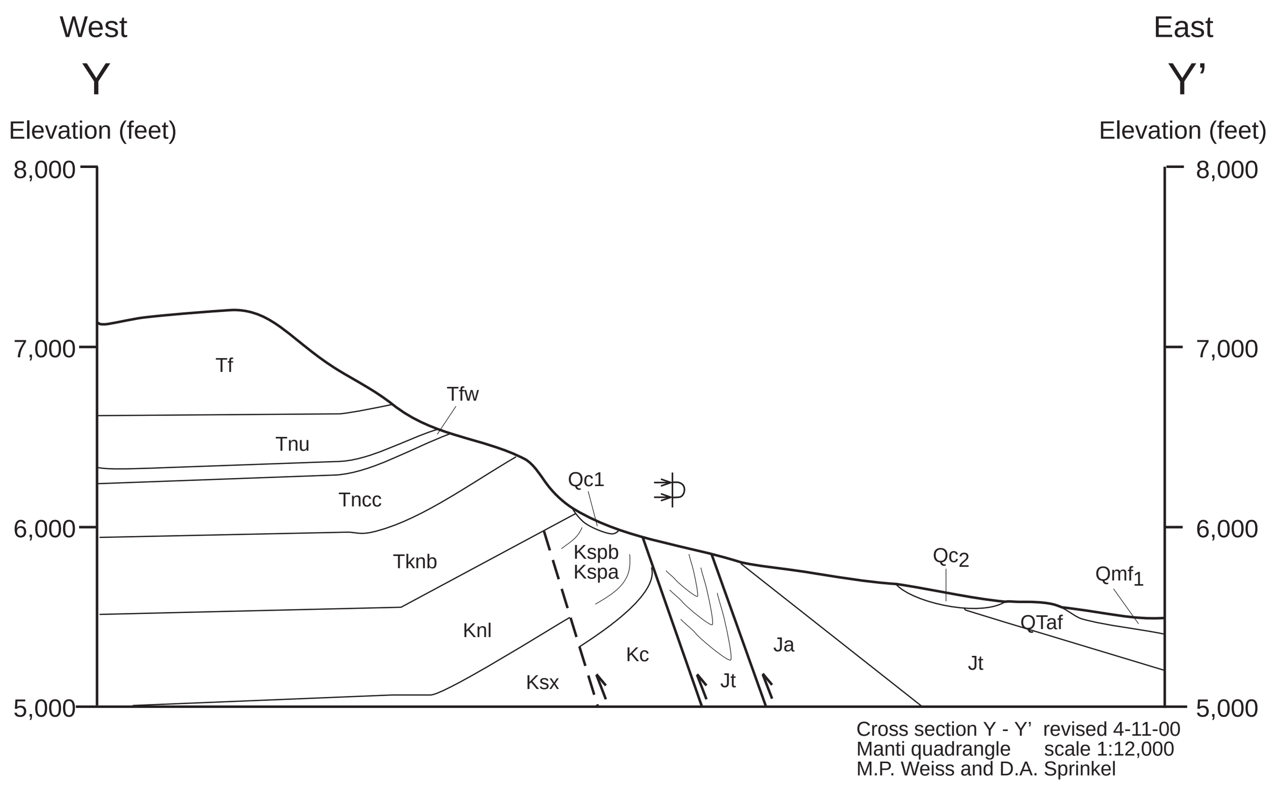
Miscellaneous

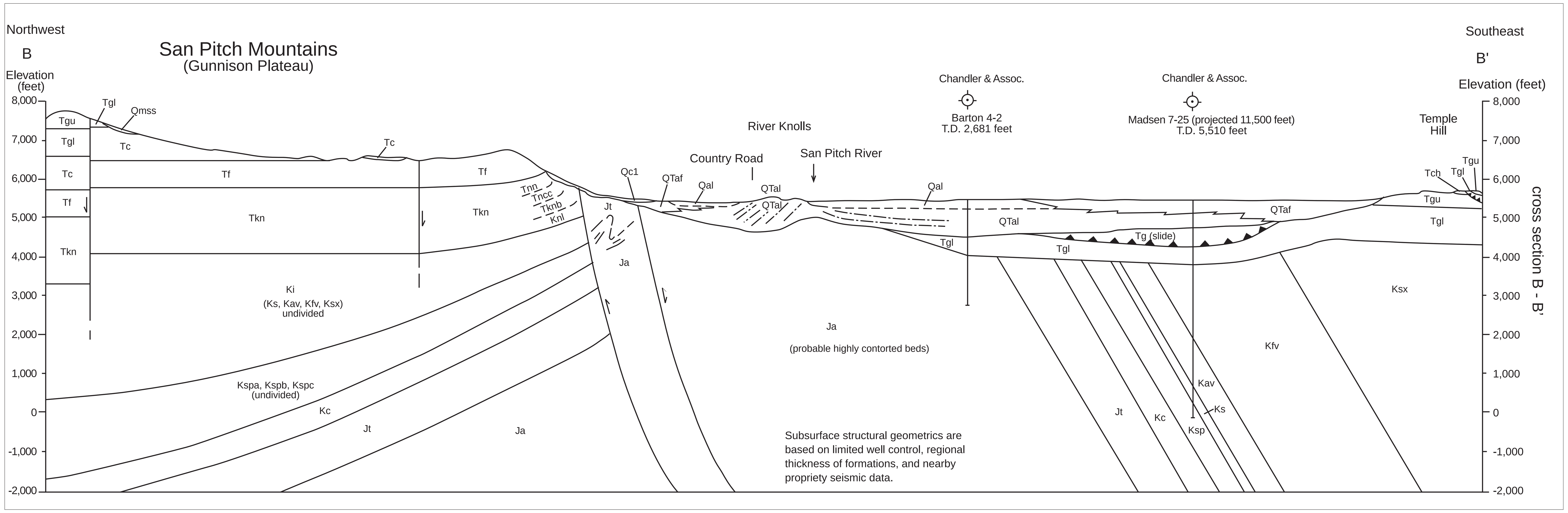
Adit | K = Kiln

STATE OF UTAH
DEPARMENT OF NATURAL RESOURCES
UTAH GEOLOGICAL SURVEY









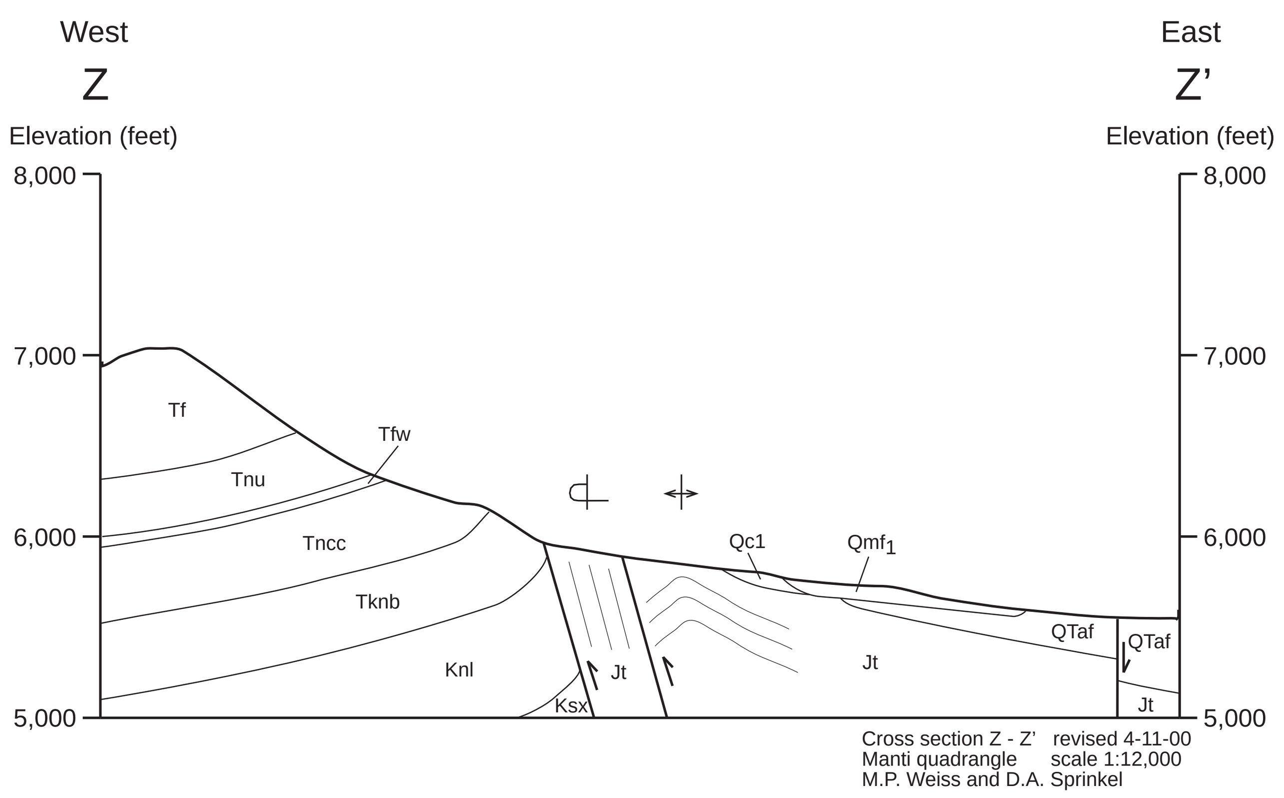


Plate 3
Utah Geological Survey Open-File Report 372
Interim Geologic Map of the Manti Quadrangle

INTERIM GEOLOGIC MAP OF THE MANTI 7.5' QUADRANGLE, SANPETE COUNTY, UTAH

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OPEN-FILE REPORT 372 **SEPTEMBER 2000**
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

ABSTRACT

The Manti quadrangle lies in a region of structural transition between the extended lithosphere of the Basin and Range and the moderately deformed Colorado Plateaus Provinces. In Late Cretaceous time this region was the leading edge of the Sevier orogenic belt. Bedrock strata exposed within the quadrangle are from Middle Jurassic (Callovian) through late Eocene in age. Jurassic strata 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 (Barremian(?) to Turonian) deposited in a foreland basin associated with the Sevier orogenic belt are present in outcrop and reached by wells in the Sanpete Valley. This part of the section is less fully developed 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 in the front of the plateau.

The synorogenic North Horn Formation was deposited unconformably on older rocks between the late Campanian and early Eocene time, during intermittent Sevier and Laramide 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 pinchout in the subsurface beneath Sanpete Valley to a maximum of 945 feet (288 m) on the east flank of the range, but is even thicker in the central part of the plateau. Syndepositional shortening and uplift are recorded by intraformational unconformities and paleocurrent indicators in the North Horn beds. 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). Although the units post-date most Sevier shortening, they were deposited during what we believe to have been the latter part of the Laramide orogeny, although the evidence for Laramide deformation is not clear in the quadrangle. Minor, late-stage, west-vergent back-thrusting (Sevier orogeny) deformed North Horn, Flagstaff, and Colton strata. The mutual development of the Sanpete Valley and Wasatch monocline are in the style of Basin-and-Range extension, but their early development may have occurred during the Laramide.

Surficial deposits are mostly restricted to Sanpete Valley and to unstable slopes and stream channels in the plateau. Mass-wasting deposits are conspicuous on the slopes of the range, particularly on the fine-grained units of the North Horn, Colton and Green River Formations. Mineral resources are few in the quadrangle; sand and gravel from the Quaternary deposits 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 Gunnison Plateau (San Pitch Mountains) and most of the width of Sanpete Valley, which lies between the Gunnison and the Wasatch Plateaus. Throughout this text Athe 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 all the permanent inhabitants of the area. The lowest elevation in the quadrangle is the transient levelCabout 5,390 feet (1,643 m)C of the impounded San Pitch River 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 range 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 waterCeven in Antelope ValleyCdrains 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 range.

AgricultureCgrazing or the growing of feed for livestockCis 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 watered 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. Birsa (1973) mapped the North Horn Formation along the plateau front. Witkind and others (1987) published a 1:100,000-scale map that included the entire Manti quadrangle. Published 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), and Hells Kitchen Canyon Southeast on the west (Mattox, 1987).

Numerous topical studies have been carried out within or quite near the Manti quadrangle. Spieker (1946, 1949b), Weiss (1982a), Lawton (1985), and Weiss and Roche (1988) presented structural cross sections. Gilliland (1963) first described the anticlinal structure of Sanpete Valley and its flanking ranges; he called that structure the "Sanpete-Sevier Valley anticline.@ Gundersen and Gilliland (1967) prepared isopachous maps of the major rock units involved in the anticline, called an antiform in this report because its genesis is owed to the propagation of reverse or thrust faults, rather than draping or compression as in the case of true anticlines. 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 and Colorado Plateaus Provinces. 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).

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.

STRATIGRAPHY

Formations exposed in the Manti quadrangle are from Middle Jurassic to Eocene in age and fall into three natural 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 range 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 and Laramide orogenies. Surficial deposits within the quadrangle are largely restricted to Sanpete Valley and the major drainages of the range, but mass-wasting deposits are widespread on slopes within the range.

Jurassic System

Arapien Shale (Ja)

Only the youngest member (E) of the Arapien Shale is exposed in the quadrangle. Member E, the fifth of five members defined and described by Hardy (1952), is well exposed in the adjacent Sterling quadrangle, where it also contains salt (Weiss, 1994). The rock is a brick-red gypsiferous mudstone with minor thin layers of siltstone. Bedding is obscure and can be observed with confidence only in an anticline in SE1/4 section 4, T. 17 S., R. 2 E. 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 thickness in the vicinity is little more than 400 feet (122 m) (Willis, 1986; Weiss, 1994). The whole Arapien Shale has a total thickness of 2,700 feet (823 m) to as much as 7,000 feet (2,134 m) in wells drilled in and surrounding the Manti quadrangle (Sprinkel, 1994). The variation results from structural complications, for the soft Arapien Shale has crumpled and sheared during repeated crustal deformation.

The contact with 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 conglomerateCa thin muddy gritstoneCof 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 lies adjacent on the northwest of this one. Member E is Callovian in age, but the entire Arapien Shale is Middle Jurassic (Bathonian to Callovian) (Imlay, 1980).

Twist Gulch Formation (Jt)

The Twist Gulch Formation crops out in patches 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 is 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; Lawton regards it as a shoreface sand (Lawton and Weiss, 1999), and it is considered a western feather edge of the marine Curtis Sandstone.

The Twist Gulch beds are also marine in origin and, although most are highly oxidized, they did not undergo the extreme evaporation and consequent deposition of halite and gypsum as in the Arapien Shale. The highly colored mudstone and siltstone beds are interpreted as tidal-flat deposits, while 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 we had ever seen, but have since found the same relation on the west side of the plateau. Although the natural basal contact with the Arapien Formation is well exposed locally, no sedimentary upper contactCunconformable regionallyCwith the Cedar Mountain Formation crops out 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 1,837 feet (566 m) thick 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 (Lawton and Weiss, 1999); the interval of Twist Gulch in this well was, however, interpreted as only 956 feet (292 m) thick by Sprinkel (1994).

The Twist Gulch is Middle Jurassic (Callovian) in age and a correlative of the Preuss Sandstone of northern Utah (Imlay, 1980). About 22 miles (35 km) southeast of the Manti quadrangle, the Twist Gulch Formation is 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). The thick interval of shoreface sandstone within the formation in the Gunnison Plateau appears to be the equivalent of the Curtis Formation, but this has not been demonstrated. In the Manti quadrangle, the beds above and below the shoreface sandstone are quite similar and not recognizable as either 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 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 both Lower and Upper Cretaceous in age (Sprinkel and others, 1999).

Cedar Mountain Formation (Kc, Ku)

The Lower Cretaceous Cedar Mountain Formation was named by Stokes (1944, 1952) in the northwestern part of the San Rafael Swell for beds of variegated mudstone with intercalated sandstone, lacustrine limestone, and a discontinuous basal conglomerate

(Buckhorn) exposed at Cedar Mountain (section 9, T. 18 S., R. 10 E., Salt Lake Meridian, Emery County, Utah). It crops out in a belt of isolated 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 crops out there as patches 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 weathers to calcareous nodules. The nodules and the Apolished stones@ (thought to be gastroliths by Stokes) in the variegated mudstone are distinctive characteristics of the unit. The Cedar Mountain Formation was deposited in a fluvial-lacustrine environment (Yingling, 1987; Schwans, 1988a, 1988b). Outcrops of the formationCand the other Lower Cretaceous unitsCare so small that they cannot be fully labeled on Plate 1, at a scale of 1:24,000; they are labeled Ku.

The Cedar Mountain Formation unconformably overlies the marginal marine beds of the Middle Jurassic Twist Gulch Formation (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. A basal Cedar Mountain conglomerate with interbedded sandstone dips about 20^{o} less than the underlying fine-grained, reddish-orange sandstone beds of the Twist Gulch. The upper contact is accordant, 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 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 he reported only 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 Unit 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 incomplete section exposed in the Manti quadrangle is 62 feet (19 m).

The age span of the Cedar Mountain Formation has been difficult to determine because the biostratigraphic and radiometric data have come mostly from the upper half of the formation. Its age (including the age of the correlative Burro Canyon Formation) in the San Rafael Swell is Barremian(?) to late Albian (Early Cretaceous) (Katich, 1951, 1956; Craig, 1981; Tschudy and others, 1984). In Salina Canyon, the Cedar Mountain is likely 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). 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 Barremian(?) to middle Albian in age. The Barremian(?) age is based on the age of the Cedar Mountain and Burro Canyon Formations in east-central Utah (Tschudy and others, 1984). 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 accordantly 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 conglomerates and interbedded mudstone and sandstone that overlies the Cedar Mountain Formation accordantly and underlies 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 ACedar Mountain@ of 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 from the mountain front area by erosion.

Where more fully exposed, the San Pitch rests accordantly 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, in press). 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 finally grades into the unnamed member of 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, as is also seen in the subsurface of the Manti quadrangle. The upper contact is placed, regionally, at the base of a distinctive, light-colored 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 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). That between members A and B is placed below the first carbonate-pebble conglomerate, which separates the reddish-brown, channel-form conglomerate beds of member A from the lighter-colored tabular conglomerate, sandstone, and mudstone beds of member B (Sprinkel and others, 1999). Member C is mostly of mudstone with cobbles and boulders; it overlies 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 and carbonates (about 50 percent of the first and 45 percent of the latter). 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 are 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 real because of shearing. 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). Some outcrops of the memberCand the other Lower Cretaceous unitCare so small that they cannot be fully labeled on Plate 1, at the scale of 1:24,000; they are labeled Ku.

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 cobblesCto nearly 100 percentCwhich is not common in members A and C. The carbonate clasts are mostly dolostone cemented in a dolomite to dolomitic matrix. This quality gives member B the appearance of being grayer and lighter in color than the underlying conglomerate beds of member A. Member B also contains 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 seen in 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 beds 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). Some outcrops of the member - and the other Lower Cretaceous units - are so small that they cannot be fully labeled on Plate 1, at scale of 1:24,000; they are labeled Ku.

Funk Valley Formation (Kfv)

Interbedded fine-grained, yellowish-gray sandstone and gray siltstone and shale of the lower third of the Funk Valley Formation forms a small outcrop near the southeast corner of the Manti quadrangle. The rock is dipping steeply, and only about 200 feet (61

m) of beds are 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 shore-face sands (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.

Cretaceous and Tertiary 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 range 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 members (Lawton and others, 1993; Lawton and Weiss, 1999). The formation thins markedly southward from the Wales area, however; only the four upper members (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 it increases westward into the body of the plateau. The four older (lower) members of the North Horn are present in the subsurface in the quadrangle. The whole formation is shown on cross-sections A-A= and B-B,= and labeled TKn; on cross-sections X-X,= Y-Y,= and Z-Z,' the four upper members are labeled individually and the lower four are grouped as Alower North Horn@ and labeled Knl. Within the Dry Canyon graben, at the north edge of the quadrangle, only two members, 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). 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) penetrated 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). Lawton reported dinosaur bones are present within the formation to a level at least 980 feet (300 m) above the base of the section just south of Wales Canyon (SE1/4 section 26, T. 15 S., R. 2 E.) (Lawton and Weiss, 1999). Because only the younger members are present in the Manti quadrangle, the formation is presumed to be only

Maastrichtian to early Eocene in age in this area.

<u>Big Mountain member (TKnb):</u> In its type area, five miles (8 km) north of here, the Big Mountain member is divisible into four submembers, 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 Areef@ of light-gray sandstone with local streaks of pebble- and cobble-conglomerate that weathers to yellowish gray. The member is well cemented by calcite, contains but little 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 member at several sites in section 9, T. 17 S., R. 2 E. The logs are in tangled arrays over several square meters 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, are known to have 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 member 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 member 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 member is Maastrichtian in age, based on palynomorphs from a mudstone lens at its base in NE1/4SW1/4 section 9, T. 16 S., R. 2 E. (Lawton and Weiss, 1999, Appendix 1).

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

Tertiary System

North Horn Formation (Tncc, Tns, Tnu)

<u>Coal Canyon and calcareous siltstone members (Tncc, Tns):</u> The Coal Canyon member is poorly exposed in patches in the Manti quadrangle and is too thin to map; therefore it is mapped together with the calcareous siltstone member as Tncc. Where typically developed farther 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. The foresets indicate transport toward the west and northwest, in marked contrast to the eastward dispersal of the underlying Big Mountain sediments. The foreset 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 elevation of the antiform. The unit is Paleocene in age, from its gradation to and intertonguing with the upper part of the calcareous siltstone unit (Lawton and Weiss, 1999).

The Coal Canyon lithofacies is represented above the great wall of Big Mountain sandstone between the SW1/4 section 4 and the NW1/4 of section 16, T. 17 S., R. 2 E. by patches of the same type of pebbly sandstone beds, foreset toward the west, as are found farther north. Their historical meaning is thus uniform along the mountain front. 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 member (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 member. The whole unit is weak and weathers to steep vegetated slopes. Over the wall of Big Mountain sandstone, where patches of the Coal Canyon member 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 of itself 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 upward-fining (Lawton and Weiss, 1999).

The environments of deposition of the calcareous siltstone member 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 members aggregate from 0 to 400 feet (0-122 m) of thickness in the Manti quadrangle. Within the Dry Canyon graben the Coal Canyon member is absent and the calcareous siltstone member (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 intervalCCoal Canyon plus the calcareous siltstone units (Tncc)Cis 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 member is very thick. Locally there it lies on the Coal Canyon member, but elsewhere intertongues with both the Big Mountain and Coal Canyon members. Thus its age in that area is both Cretaceous and Tertiary and it is so mapped

(Lawton and Weiss, 1999). In the Manti area only the upper part of the calcareous siltstone member is present, lying on the patches of the Coal Canyon member over the much diminished Big Mountain member. 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). Accordingly, that part of the calcareous siltstone member in the Manti quadrangle is believed to be only Paleocene in age.

The patchy Coal Canyon member and the calcareous siltstone member (Tncc) lie on the massive ledge of the Big Mountain member 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 (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 member (Tns, Tncc) and the upper redbed member (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 member pinches out (Lawton and Weiss, 1999). Northward thickening of the Wales Tongue is complementary to the northward thinning of the upper redbed member.

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. 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 member 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 member 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 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 member, but is overlain sharply and unconformably by the upper redbed member outside of the Dry Canyon graben. In the graben it is overlain conformably by the main body of the Flagstaff Limestone.

<u>Upper redbed member (Tnu):</u> The upper redbed member is the uppermost of the mappable elements of the North Horn Formation. The name is used here to be consistent with the map of the Wales quadrangle, where a lower redbed member is also present low in the formation (Lawton and Weiss, 1999). The upper redbed member 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 elementsCthe main body and the Wales TongueCof 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 more gray. 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 are formed on cores of 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 member are much oxidized to red, but may well have been partly red to begin withCas red mud and silt reworked from the Arapien Shale and the Twist Gulch Formation. If so, the presence of such sediment would imply a pulse of the elevation of the SSVA and renewed reverse faulting on its west flank during mid-Flagstaff time.

The upper redbed member 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 180-200 feet (55-61 m) thick in the interior of Maple Canyon.

The upper redbed member 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. Its exposed thickness in the quadrangle is between 528 and 640 feet (161-197 m) everywhere except 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.). 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 the 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 also 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. 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.

Many thin beds of glassy micritic limestone and fine sparite are interspersed among the fine clastics, and these also exhibit a similar variety of colors. But most limestone beds are of 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 is about equally intrasparites and intrarudites. 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. Grains of weathered feldspar (subequal plagioclase and K-feldspar) are next most abundant to 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 overrode the lacustrine and palustrine Flagstaff carbonates came from the southeast (Stanley and Collinson, 1979; Dickinson and others, 1986).

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. 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.

The Colton Formation contains a fauna similar to that of the Flagstaff Limestone and is thereby also Eocene in age. As a great thickness of mostly fluviatile clastics, it blotted out Lake Flagstaff and its marshes, but the transition was gradual. The transition from the terrestrial deposits of the Colton to the lacustrine regime of Lake Uinta, in which the Green River Formation was deposited, was also a gradual change of conditions. The Green River beds, like those of the Flagstaff Limestone, include both lacustrine and palustrine sediments.

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 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 but 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 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 monocline, on the east side of Sanpete Valley, but have only a small area of outcrop out in this quadrangle, in Temple Hill at the north edge of the city of Manti.

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 are glassy. Some beds are dolomitic limestone or dolomite, and those also have a higher content of siliceous clastics than the limestones (Millen, 1982). The shale unit is generally ascribed to sedimentation in Lake Uinta (e.g., Stanley and Collinson, 1979), but the abundance of siliceous mud suggests that the prevailing environment may have been palustrine (Platt and Wright, 1992). Whichever the case, the iron in the entire member is in a reduced state; the environment was always strongly reducing in nature.

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

Limestone member (Tgu): The limestone member consists of finely crystalline, yellowish- or gray-weathering sparite in thin to thick beds, very light-gray micritic limestone, and pale-yellowish-gray micritic dolomite. The member forms a resistant cap and cliffs that are especially conspicuous above the soft lower 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 itself.

A truly lacustrine origin for the limestone member is traditional and probably also correct. The features of the Flagstaff Limestone that point to a palustrine origin (Platt and Wright, 1992) are not prevalent in the limestone member of the Green River Formation. Over much of the area underlain by the limestone member there is no covering formation and it is therefore much reduced in thickness. In the southwestern quadrant of the quadrangle and at nearby sites just to the west, where the member is capped by the Crazy Hollow Formation, the limestone member ranges from about 220 to 400 feet (67-122 m) in thickness.

Tuff beds in the limestone member at the northern end of the Wasatch Plateau have been dated by zircon fission-tracks from 44.9 " 2.1 to 42.3 " 2.0 Ma old (Bryant and others, 1989). Sheliga (1980) got ages of 43.1 to 46.4 Ma by ^{40}Ar/^{39}Ar dating of biotite and other minerals from the uppermost part of the limestone member near Ephraim, just east of this quadrangle.

Like the shale member below it, the 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 there have different names.

Crazy Hollow Formation (Tch)

As the Flagstaff lacustrine/palustrine environment was swamped by the mostly fluviatile lithofacies of the Colton Formation, so was the basin of the diminishing Lake Uinta 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 on the other hand is found only in central Utah and, although widespread there, it is patchy in occurrence and its lithofacies differ markedly over even short distances. The Crazy Hollow Formation is the youngest and last sedimentary accumulation in the region, except for unconsolidated Pliocene-Pleistocene deposits that were reworked from bedrock units.

In the Sanpete Valley area the Crazy Hollow contains red mudstone, thin, gray pond limestone, light-gray sandstone, and the lithologic "signature@ of the formationC"salt-and-pepper sandstone"Cwhich contains abundant grains (including pebbles) of black chert and light-gray chert (Norton, 1986). The Crazy Hollow Formation is present above the Green River limestone member in patches 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.

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 patches 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 monocline; Temple Hill is an example and a number of cuestas extend north along the foot of the monocline from this vicinity. The Crazy Hollow lithofacies there are dominantly sandstone and pebbly sandstone. On Temple Hill the Crazy Hollow beds are salt-and-pepper sandstone, both with and without pebbles of black chert.

The variety of lithofacies, erratic thicknesses, and patchy occurrences of Crazy Hollow beds indicate a highly varied fluviatile environment, with local pond or paludal carbonate lenses. Because no superjacent deposits protect the Crazy Hollow, all thicknesses are incomplete. The thickest remnant in the quadrangle, in the southwest quadrant, is 70 feet (21 m) thick.

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; Norton, 1986; Mattox and Weiss, 1989; Weiss, 1994). 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 pebblesCevenly bedded floodplain and cross-bedded channel deposits, like modern stream alluviumCis preserved beneath an isolated giant boulder from the Big Mountain member of the North Horn Formation 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, for the boulder is firmly trapped in place by debris to each side. Erosion subsequent to the placement of the boulder has been diverted around it and also 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 shall call it Plio-Pleistocene.

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 flood-plain 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) lie locally over the upper edges of the old alluvial fans, and debris-flow deposits (Qmf1, Qmf2) 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. They thin out upstream to zero thickness, and at the lower edge they may be as thick as the valley fill deposits (QTal plus Qal); this can be as much as 925 feet (285 m). A thickness of 250 feet (75 m) was recorded for the 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 gravelCto bouldersClie like hemi-cones 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 structurallyCprobably by solution of buried Arapien saltCwhich initiated a new development of fan deposits. 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 compacted but mostly uncemented brown and brownish-gray mud, silt, sand, and gravel of pebbles and cobbles. The sediment is of alluvial, mudflow, and debris-flow origin and great thicknesses of it occupy the axial region of Sanpete Valley. The deposits were derived from both the Gunnison and Wasatch Plateaus and grade laterally at depth into the older fan deposits (QTaf). At the surface the deposits are overlain by younger alluvium (Qa) along the lower San Pitch River.

The distinction between deposits mapped as QTal or Qal is an arbitrary one, for the chronological boundary cannot be known accurately. Older material fills the major volume of the bedrock depression beneath Sanpete Valley, and has been elevated and tilted locally (probably 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 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, 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. Both Qal and Qsm are considered Holocene in age.

The older valley fill (QTal) is exposed in the 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 valley fill (Qal), and cross sections display Qal above a maximum depth of about 165 feet (50 m) below the valley floor. The thickness of the entire valley fill ranges from zero to a maximum of about 500 feet (0-153 m) at the west side of the valley (Robinson, 1971); the thickness is generally less on the eastern side of the valley, for the bedrock of the Wasatch monocline rises eastward. The thickness probably also 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). Locally, however, the valley fill (QTal plus Qal) is 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.).

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 Asalt-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 and body of the deposit are continuous with fan (QTaf) and valley-fill materials (Qal); the Aspring 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 alluvium (Qa)

Stream alluvium consists of floodplain and channel deposits of brown and yellowish-gray mud, silt, sand and gravel to boulder size that lie in the major canyons and along the lower San Pitch River. The deposits are unconsolidated and uncemented, locally cross-bedded, and closely associated with stream courses. They grade laterally to 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 large angular blocks of bedrock unitsCmostly the Flagstaff limestone. These were deposited very rapidly during catastrophic discharge from steep gulches and the major streams. The steeper the drainage profile, the larger and more angular are the boulders deposited. These deposits have rough surfaces because of the large boulders and blocks;

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 15 feet (0-5 m)

The younger debris-flow deposits (Qmf_1) continue to form today, contribute to the alluvial fans (QTaf) andCultimatelyCto the valley fill (Qal), and are Holocene in age. The older ones (Qmf_2) have a more subdued relief, 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 rock to boulder size that mantle steep, unstable slopes. They are deposited by gravity, a piece at a time, from weathered bedrock above, and may grade downslope to alluvial or fan deposits. Thicknesses of each type are generally 0 to 20 feet (0-5 m), but reach 50 feet (15 m) locally. Slopes in soft beds are usually covered by some debris from higher outcrops, but colluvium is mapped only where the debris is extensive or obscures bedrock unit contacts. Colluvial slopes have smooth, almost mathematic, curves in profile.

The youngest deposits (Qc_1) are still accumulating today and 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)

Landslide and slump deposits are mass-movement deposits that were moved by gravity on steep slopes, usually when soaked with water. Soil, vegetation, and bedrock all move in this way. The deposits are masses of soil, mud, sand, and blocks of rock that may be crudely rounded. Trees and other vegetation may be churned into the mass of rock material. The material is generally brown or gray, except where highly colored by muds from the Colton Formation. Two typesClandslides (Qmsl) and slumps (Qmss)Care mapped in the quadrangle. Some of each type have undergone repeated movements over numerous wet seasons, and the two types are not entirely mutually exclusive. Parts of a slump mass may slide from time to time and small slumps may occur locally on a slide deposit.

Landslides deposits (Qmsl) are elongate with a high length-width ratio, lie in gulches or depressions on steep slopes, and are known to move rapidly, even catastrophically. A failure scarp and depression may stand at the top of a slide, and a lobe of crumpled mud and rock, indicating recent movement, may be at the lower end. Landslide deposits are 0 to 50 feet (15 m) thick.

Slump deposits (Qmss) are broader and irregular in shape, often wider along a hillside than long downslope. A failure scarp or Aheadwall@ in undisturbed bedrock may stand at the top of a slump. Slump masses may be furrowed or ridged parallel to the slope and have a bulge at the toe where the mass shoves against lower material; their surfaces are usually hummocky. Slumps generally move slowly, a bit at a time, by creep of the mass rather than by rapid flow. Slump deposits may reach thicknesses of 200 feet (61 m).

STRUCTURAL GEOLOGY

The Manti quadrangle contains compressive structures that resulted from the Sevier orogeny, Laramide structures from mixed vertical and horizontal stresses, younger structures of relaxation and sagging that formed during Basin-and-Range extension, and local diapirism of evaporites in the labile Arapien Shale. The gross structure of the quadrangle includes the east limb of the large synforms of the Gunnison Plateau (San Pitch Mountains), the zone of imbricate reverse faults along the east margin of the plateau, and a large fault-propagation fold (the Sanpete-Sevier Valley antiformCSSVA) that underlies the down-dropped Sanpete Valley block.

There are two synforms in the body of the plateau. A shallow one in the Tertiary beds is rather open, has a moderate closure, and its axis is subparallel to and near the west edge of the quadrangle. A deeper synform has greater closure, its east limb is overturned, and its axis lies along the eastern front of the plateau. Both synforms are part of the upper plate of the Gunnison thrust system, and contain Jurassic, Cretaceous, and Tertiary strata deposited both before and during folding (Villien and Kligfield, 1986; Lawton and Trexler, 1991). The Jurassic and older Cretaceous beds make up most of the deeper synform. Growth strata of the North Horn Formation, deposited during folding, lie in the transition zone from the lower to the upper synform; younger beds complete the shallow, upper synform in the central part of the plateau (Mattox, 1987; Lawton and Weiss, 1999). The overturned east limb of the lower synform is intimately related to a zone of imbricate reverse faults in the steep, west-verging west limb of the SSVA.

Five structural elements are present in the rocks of the quadrangle, and are listed below in order of decreasing age, although elements 2 and 3 are coeval. They are: 1) a zone of imbricate reverse faults forms a belt of up-folded and reverse-faulted Jurassic-through-Eocene rocks that forms the western limb of the SSVA and lies along the eastern foot of the range; 2) west-trending normal faults 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 a) divide the Gunnison Plateau (San Pitch Mountains) from Sanpete Valley and b) form the divide graben in the interior of the plateau. In the west, the system cuts the Late Eocene Crazy Hollow Formation; along the margin of Sanpete Valley the system cuts deposits of Quaternary age; 4) diapirism of the labile mudstone and evaporites in the Arapien Shale has elevated local blocks of the formation near to the south edge of the quadrangle. Other raised blocks expose only Quaternary valley-fill deposits, and 5) Temple Hill, a large slide block off the Wasatch monocline

Zone of Imbricate Reverse Faults

Faults

The rocks of the Gunnison Plateau and Sanpete Valley are part of the upper plate of the Gunnison thrust that 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 Sanpete-Sevier Valley antiform (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 (cross-sections X-X,′ Y-Y,′ and Z-Z′). The principal faults are shown in cross-sections A-A′ and B-B.′ The vertical displacement of Jurassic beds now at the surface from their pre-back-thrusted place at depth exceeds 10,000 feet (3,050 m) (Lawton and Weiss, 1999).

These imbricate reverse (or thrust) faults in the face of the mountain 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 range, 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 members 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 apparent on the 1:12,000-scale geologic map in sections 9 and part of 16, but there is little evidence south of there for the same pair. We therefore mapped them as joining together in the NE1/4NW1/4 of section 16. Two faults are present for very short distances 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 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), and 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 plunge of the plateau carries this fault beneath Sanpete Valley south of township T. 17 S., R. 2 E.

We believe there is also a blind reverse fault west of this one that butts into the Big Mountain member of the North Horn Formation (see cross-sections A-A,′ B-B,′ and X-X′). This sort of relationship is exposed at the south end of the plateau, in the Christianburg area (Sprinkel and others, 1999). The upward and westward shear 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 will be described separately.

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 bedsCArapien and Twist GulchCare 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 (N1/2 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 (N1/2 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 here 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 AS,@ 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 graben and in the Wales quadrangle (Lawton and Weiss, 1999).

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 wall of the Dry Canyon graben, and are mirrored in the north wall 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 N1/2 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 drop Green River beds beside 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 three 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. T. F. Lawton has suggested that a lateral ramp of the Gunnison thrust plate extended east-west about here, at right angles to the sedimentary strike of the later Cretaceous and Paleocene formations, and that upon Neogene extension the ramp yielded by collapse 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 (San Pitch Mountains) is separated from Sanpete Valley, along its entire eastern front, by a normal fault zone that creates the topographic differential between the range and the valley. The range-front fault zone was called the Avalley fault@ by Fong (1995) and the AGunnison fault@ by Weiss (1982a). The magnitude of displacement is greatest near the north end of the plateau and the height of the range-front scarp 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 to both north and south of here, but it cuts Quaternary deposits (QTaf) in sections 2, 16, and 21, T. 17 S., R. 2 E. Low scarps of 2 to 6 feet (0.6-2 m) are present locally, 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 materials and agricultural disturbance. Even Holocene surfaces are cut in the Wales quadrangle, where displacement of deposits of Quaternary age on this fault system is 6 to 8 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 was an integral part of the formation of the Wasatch monocline, across Sanpete Valley to the east. The experiments of Withjack and others (1995) produced conditions very similar to those beneath Sanpete Valley and low on the Wasatch monocline, except that there was no antiform in their down-faulted block (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

An alternative 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 and Laramide orogenies or Basin-and-Range extension. Instead they were caused by the vertical action of diapirism of the evaporites and labile mudstone of the Arapien Shale, followed by solution collapse (Witkind, 1982, 1983, 1992, 1994; Witkind and Page, 1984). Several reasons make it clear that regional diapirism and collapse cannot be the cause of the major tectonic and sedimentary history of the Sanpete-Sevier Valley region: 1) overturning of fault-repeated strata and consistent west-vergence of faults and folds requires crustal shortening not predicted by the diapirism model; 2) the Arapien Shale does not breach the crest of the antiform in Sanpete Valley, i.e., it does not extrude through younger units except at the western margin of the antiform, in the zone of imbricate reverse faults; and 3) major regional deformation caused by the Sevier and Laramide orogenies and Basin-and-Range extension are well documented in the region.

Local diapirism of the Arapien Shale, however, has occurred, and has modified structures at several places in both Sanpete and Sevier Valleys (Willis, 1986; Weiss, 1994). Local diapirism of the Arapien in the Manti quadrangle caused the upwelled Arapien Shale near the south edge (NW1/4 section 15, T. 18 S., R. 2 E.). This example continues into the Sterling quadrangle where it is more conspicuous (Weiss, 1994). The elevation and tilting (as much as 50^{o} west) of old valley-fill deposits (QTal) to form the river knolls is believed to be evidence of local diapirism of the Arapien Shale as well, although no subsurface data are available to confirm that. Significantly, these manifestations of local diapirism are present (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. The authors recognize local diapirism of the Arapien Shale during late Tertiary and Quaternary time, but do not subscribe to the hypothesis that regional diapirism is the sole cause of the tectonic development of the area since the Cretaceous.

Temple Hill

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 monocline.

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 lies 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, 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 disturbedCit is a toreva block in the classic sense. A normal fault does cut the synclinal mass on the northeast, outside this quadrangle.

The slide surface 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 slidesCboth smaller and largerCwhere 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 are considered to have formed during pluvial intervals in the Pleistocene, when the Colton and Green River mudstones on the flank of the monocline were so weak and heavy that they could not support themselves on the monoclinal slope (Weiss, 1994).

As the Dry Canyon graben, the divide graben, initiation of the Wasatch monocline, and initiation of the range-front fault zone are all ascribed to Neogene (Basin-and-Range) extension, the differences in their timing cannot have been very great. However, the displacement of the range-front fault zone and the lower limb of the monocline continue today. The Temple Hill slide 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 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 SSVA (anticline of Gilliland, 1963). The fold arose as a back-thrusted welt on the upper plate of the Gunnison thrust. The evidence for the initial growth of the fold in Campanian time is found in the Wales quadrangle (Lawton and Weiss, 1999) and presumed herein. The North Horn Formation is much thicker there 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 timeCinto 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. Lawton (Lawton, 1985; Lawton and Weiss, 1999) believes that most of the structural relief was developed during Campanian time. 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, 1998). 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. It may have been late Sevier movement or early Laramide movement, from west-verging shear or by lateral vectors of vertical movements.

East-trending normal faults

East-trending normal faults, including 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, as imagined by Lawton (Lawton and Weiss, 1990, figure 4). Lawton=s evidence for this scheme is the thin North Horn-Colton section in the graben, contrasted with thicker sections north and south of the graben. He suggests that 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 practiced.

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 Temple itself 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 Temple itself.

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 is too difficult of access to be developed readily.

Petroleum

Although no petroleum or natural gas has been economically produced in Sanpete County, exploration for it 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 is 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 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 the early 1960s. The stated objective was silver.

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 permanent streams on the entire east face of the Gunnison Plateau. Manti Creek discharges abundant surface water from high on the Wasatch Plateau; although it supplies the city of Manti, it provides for only a small fraction of the area of the quadrangle. 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 load the valley-marginal fans and the central-valley fill with large reserves of subsurface water.

The water table everywhere in the valley is less than 60 feet (18 m) below the surface and the interbedding of permeable with impermeable layers produces both confined and unconfined aquifers (Robinson, 1971). A number of flowing wells provide water for stock and irrigation over the width of Sanpete Valley.

GEOLOGIC HAZARDS

Three types of hazards are enduring threats to man, livestock, and cultural installations in the Manti quadrangle. In decreasing order of potential for damage, 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. Dirt and gravel roads are only briefly disturbed; the debris flow on the Maple Canyon fan (Qmf1) 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 fan there stands high enough above Manti Creek so that most discharge can be safely directed. The periodic flooding of the central and northern portions of Sanpete Valley is an inconvenience to owners of the grazing rights thereon, but an important replenishment of the groundwater supply. Such lakes also depress the value of water rights temporarily!

Landsliding and land slumping are constant threats on the steep slopes on the plateau face and on the 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 shale member of the Green River Formation. Areas underlain by the Arapien and Twist Gulch Formations are similarly susceptible, but those areas are small and their slopes are short, so that erosion by this means is minimal. Slides and slumps interrupt mountain roads, but affect few other cultural features.

Seismic activity along the range-bounding fault zone is a potential source of earthquakes in the Manti quadrangle. Low scarps in the youngest Quaternary deposits show that geologically recent movement has occurred and is therefore 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). Scarps are not fresh, suggesting a long recurrence interval, so that future earthquakes are also not likely to be frequent. Central Utah, generally, has a history of few earthquakes, mostly small-to-moderate in strength, and most of which occurred in Sevier Valley, farther south than Manti. Liquefaction of saturated alluvial deposits along the San Pitch River may disrupt irrigation ditches and weirs. The things at the most serious risk are masonry buildings in the City of Manti, which is built on an alluvial fan made of uncemented sediments; most such structures have survived without problems for a century and a quarter.

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Figure 1. Synformal 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 (SE1/4 NW1/4 section 9, T.17 S., R. 2 E.). The mine tunnel was cut about 50 feet (15 m) into the hard San Pitch conglomerate. A compressed air tank about 24 inches (0.6 m) in diameter serves as scale. The photo was taken about 1965; the adit is now filled with talus and the anticline is covered.

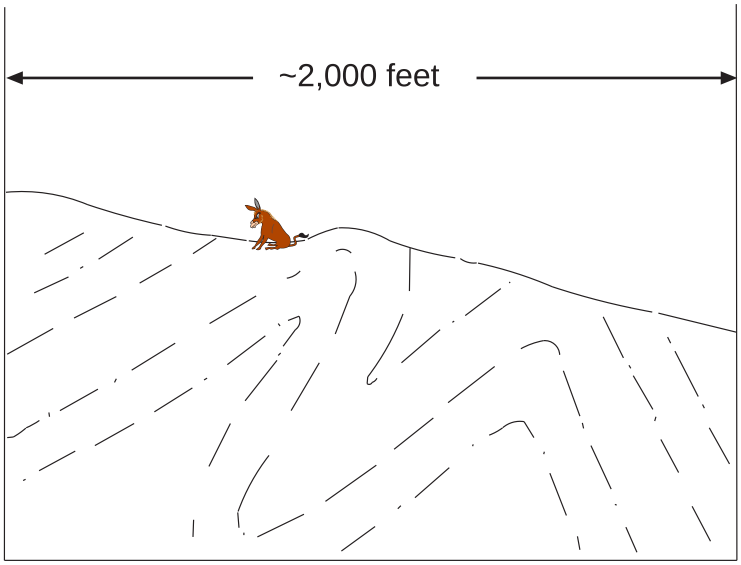

Figure 2. Sketch of a complete z-fold in the Twist Gulch Formation south of Maple Canyon in section 28 T. 17 S., R. 2 E. The z-fold likely formed by east-directed compression during the Sevier orogeny. Sketch is not drawn to scale.

Table 1. Simplified Logs of Exploratory Wells in the Manti Quadrangle.

Operator	Well Name	API Number	Location	Ground Elevation (feet)	Formation Name	Drilled Depth (feet)	Elevation (feet)	Thickness (feet)
Mobil Oil Corporation	Larson #1	43-039-30008	SW¼SE¼ section 1 T. 17S, R. 2E	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	SW¼SE¼ section 1 T. 17S, R. 2E	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	SW¼NE¼ section 25 T. 17S, 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	NW¼NW¼ section 2 T. 18S, 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	