UTAH GEOLOGICAL SURVEY
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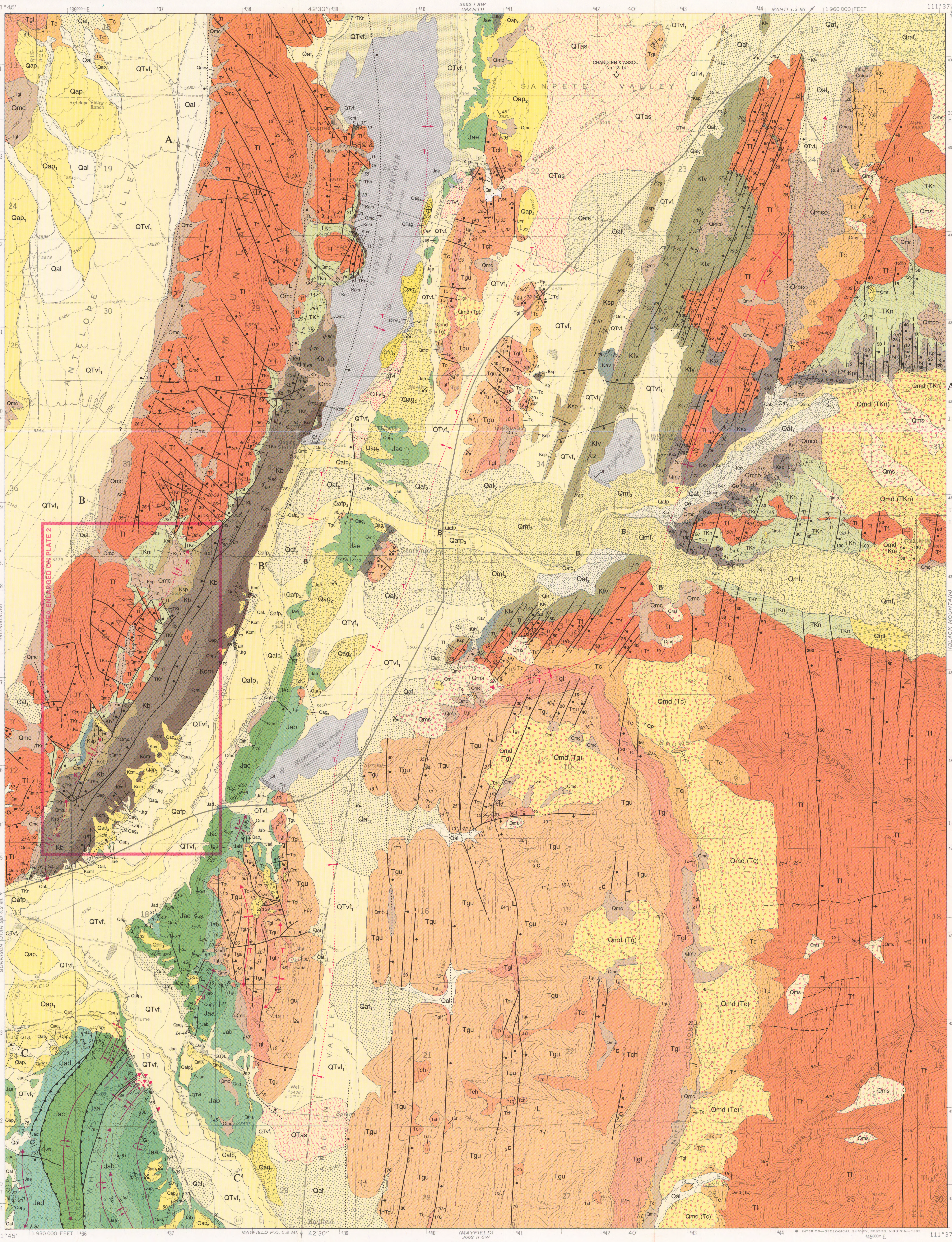
Plate 1
Utah Geological Survey Map 159
Geologic Map of the Sterling Quadrangle



Base from U.S. Geological Survey,
Sterling 7.5' Quadrangle, 1966

SCALE 1:24 000

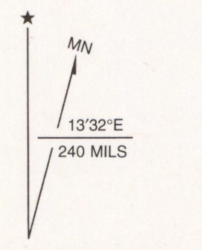
1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

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

Field work by author, 1987 and 1989
Completed April 12, 1990
Cartography by J. Parker



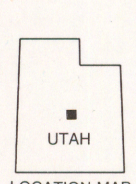
1994 MAGNETIC NORTH DECLINATION
AT CENTER OF SHEET

GEOLOGIC MAP OF THE STERLING QUADRANGLE, SANPETE COUNTY, UTAH

by

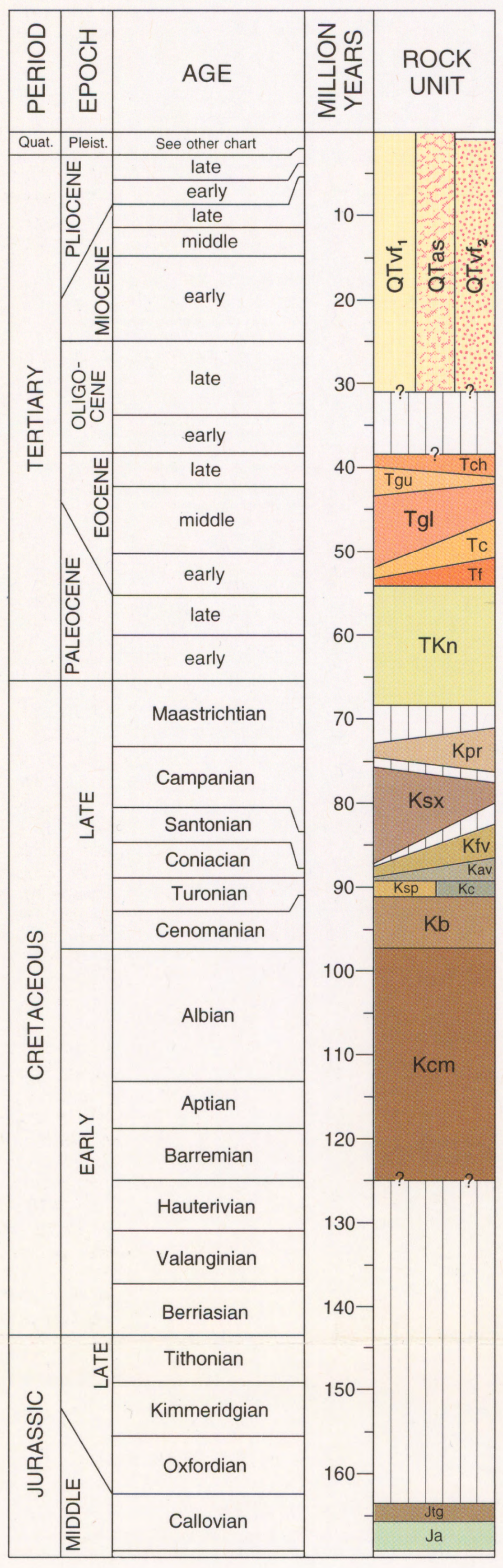
Malcolm P. Weiss

1994

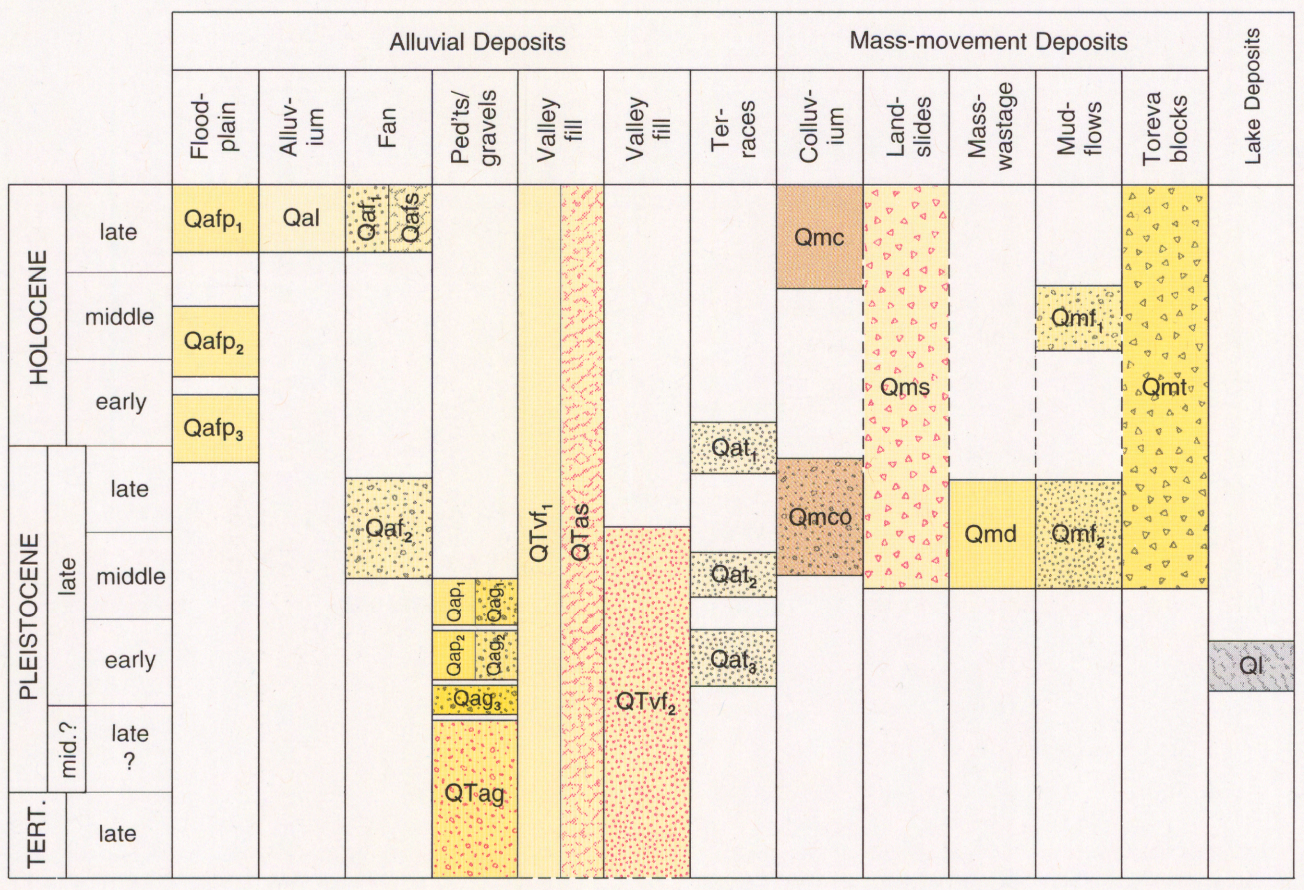


LOCATION MAP

CORRELATION OF BEDROCK UNITS



CORRELATION OF QUATERNARY UNITS

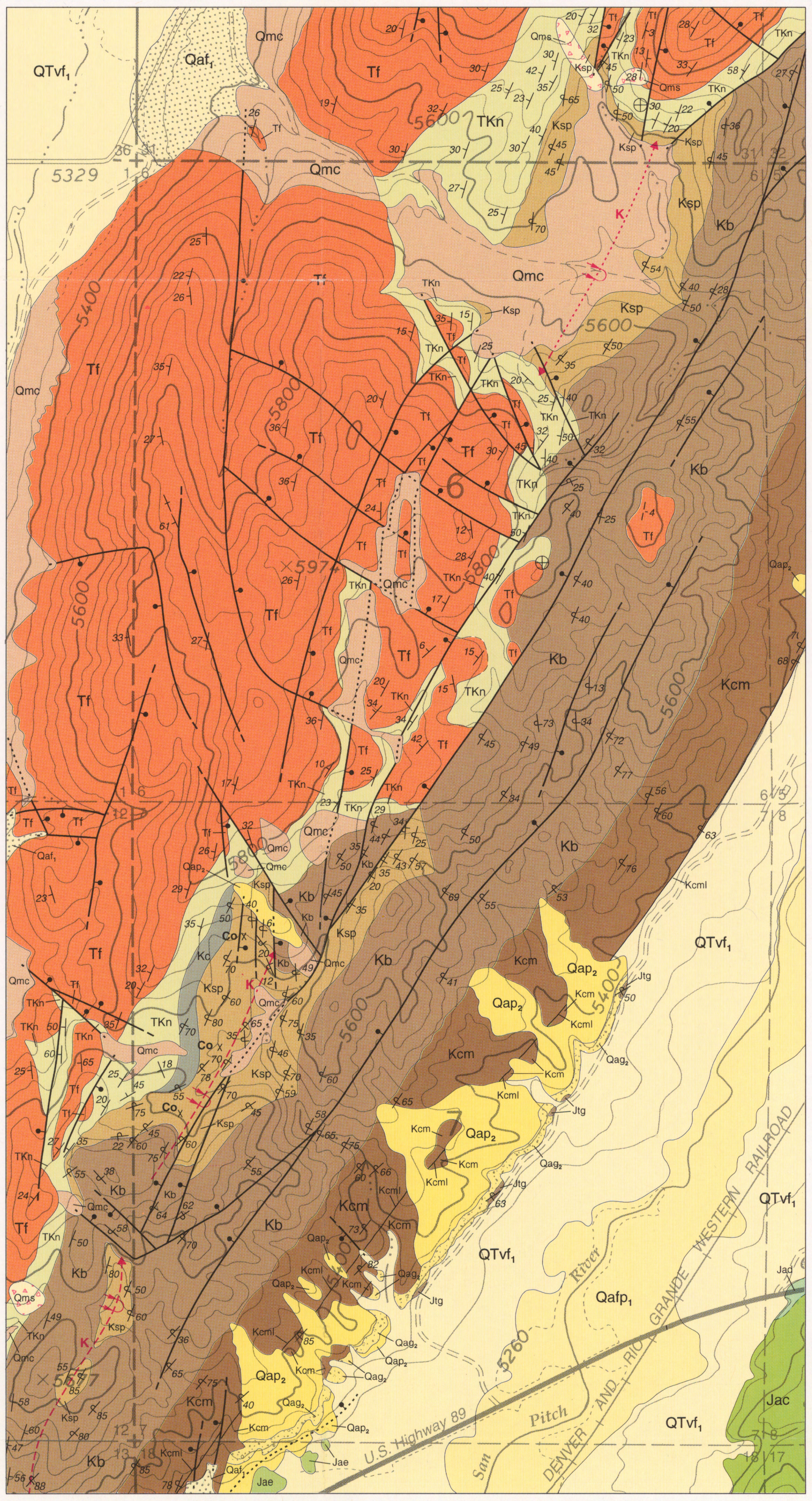


LITHOLOGIC COLUMN

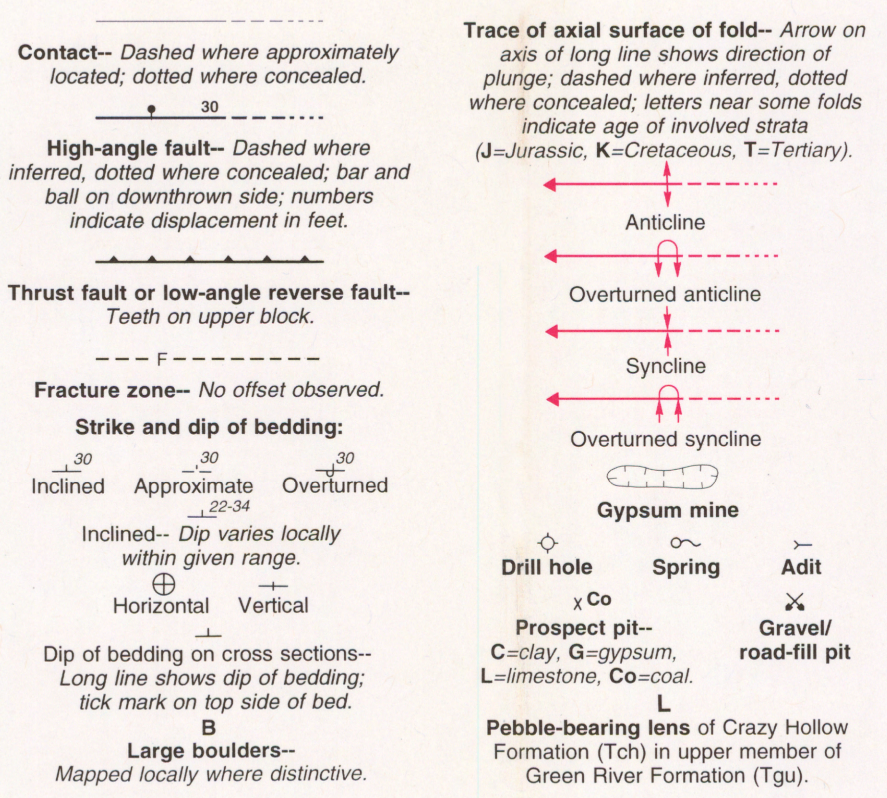
FORMATION		SYMBOL	THICKNESS Feet (Meters)
Unconsolidated deposits			0-500 (0-150)
Crazy Hollow Formation		Tch	90-120 (27-37)
Green River Fm.	Upper mbr.	Tgu	0-260 (0-80)
	Lower mbr.	Tgl	0-500 (0-150)
Colton Formation		Tc	0-500 (0-150)
Flagstaff Formation		Tf	0-250 (0-75)
North Horn Formation		TKn	0-620 (0-190)
Price River Formation		Kpr	0-300 (0-90)
Indianola Group	Sixmile Canyon Fm.	Ksx	4,000 (1,220)
	Funk Valley Fm.	Kfv	3,100 (945)
	Allen Valley Shale	Kav	620 (190)
	Conglomerate	Kc	160 (49)
	Sanpete Fm.	Ksp	2,100 (640)
	Basal Fm.	Kb	775-1,100 (235-335)
Cedar Mountain Formation		Kcm	965-1,135 (295-345)
Twist Gulch Formation		Jtg	700? (213?)
Arapien Shale	Member E	Jae	500? (150?)
	Member D	Jad	800? (244?)
	Member C	Jac	1,500? (458?)
	Member B	Jab	600? (183?)
	Member A	Jaa	900? (275?)

Query (?) indicates estimated subsurface thickness.

GEOLOGY OF SOUTHEASTERNMOST GUNNISON PLATEAU
1:12,000 SCALE ENLARGEMENT FROM PLATE 1



MAP SYMBOLS



DESCRIPTION OF MAP UNITS

QUATERNARY DEPOSITS

Qf Artificial fill (modern)-- *Earth-fill dams.*

ALLUVIAL DEPOSITS

Qafp1 Floodplain deposits (late Holocene)-- *Alluvial material; brown and brownish-gray, poorly sorted, and close in both area and level to the principal streams; coarse fraction mostly in point bars; thickness probably less than 30 feet (9 m).*

Qafp2 Older floodplain deposits (early-middle Holocene)-- *Like the modern floodplain deposits, but grayer; found as remnants 15 to 20 feet (4.5-6 m) above Qafp1; thickness is unknown.*

Qafp3 Oldest floodplain deposits (Pleistocene-Holocene)-- *Like Qafp2, but lying 30 to 40 feet (9-12 m) above Qafp1; thickness is unknown.*

Qal Alluvium (late Holocene)-- *Fluvial material; dark-brown to gray clay, silt, sand, granules, pebbles, and sparse cobbles; thin- to thick-bedded, locally massive and cross-bedded; along intermittent streams and at upper ends of fans; forms broad, even surfaces of low relief; thickness is varied, commonly less than 50 feet (15 m).*

Qaf1 / Qafs Alluvial-fan deposits (late Holocene)-- *Light-brown to brown, locally gray, unconsolidated to semi-consolidated, moderately well-sorted silt, sand, granules, pebbles, or cobbles at the mouths of canyons; commonly lobate; thickness is uncertain: large fans to 70 feet (21 m), small fans less than 30 feet (9 m); grade to alluvium upstream and valley fill downstream. Mapped as Qafs where it includes salt marsh deposits.*

Qaf2 Older alluvial-fan deposits (late Pleistocene)-- *Like the younger alluvial-fan materials, but so deeply dissected by modern drainages that the surface is no longer building; however, the surfaces do grade to modern valley-fill surfaces; to 30 feet (9 m) thick.*

Qat1 Alluvial-terrace deposits (Holocene and Pleistocene)-- *Gray and brownish-gray alluvial deposits mixed with North Horn and Flagstaff colluvium; the upper surface stands 160 to 170 feet (49-52 m) above Sixmile Creek; thickness unknown.*

Qat2 Older alluvial-terrace deposits (middle late Pleistocene)-- *Alluvial deposits of boulders, cobbles, and local sand lenses; lower edge of surface is more than 40 feet (12 m) above Sixmile Creek, and the terrace parallels the stream gradient; underlies Qmf2 and Qaf2; maximum exposure is 30 feet (9 m) thick; total thickness is unknown.*

Qat3 Oldest alluvial-terrace deposits (early late Pleistocene)-- *Like the other terrace deposits, but the surface stands 40 to 150 feet (12-46 m), distally to proximally, above Sixmile Creek; thickness is unknown.*

Qap1 Pediment-mantle deposits (middle late Pleistocene)-- *Alluvial deposits spread on stream-cut rock surfaces; brown, gray, or locally reddish brown; massive to crudely bedded; unconsolidated mixture of silt, sand, granules, pebbles, cobbles, and boulders; surfaces are even and slope from uplands (proximal) toward the streams (distal); deposits are 30 to 60 feet (9-18 m) thick; surfaces range from about 20 to 50 feet (6-15 m), distally to proximally, above Twelvemile Creek.*

Qap2 Older pediment-mantle deposits (early late Pleistocene)-- *Deposits like Qap1, but deformed by tilting (35-45 degrees) or by elevation above the younger surfaces by as much as 70 feet (21 m); deposits are about 40 feet (12 m) thick; above the water table the deposits are well cemented in some layers, and are yellowed by limonite.*

Qag1 Stream gravel (middle late Pleistocene)-- *Limestone and chert cobbles and pebbles from the Flagstaff Limestone; found in streaks and patches within and bordering the younger pediments (Qap1); 10 to 20 feet (3-6 m) thick and at the same elevations as Qap1.*

Qag2 Older stream gravel (early late Pleistocene)-- *Moderately sorted cobble and pebble gravels with little sand, mostly limestone and chert of the Flagstaff Limestone; less than 15 feet (5 m) thick west of river and averaging 30 to 40 feet (9-12 m) east of river.*

Qag3 Alluvial (?) gravel (middle to early late Pleistocene)-- *Gray and brownish gray, mostly pebble gravels with some fines; poorly bedded with numerous poorly sorted layers; mostly limestone and chert from the Flagstaff; 20 feet (6 m) thick at maximum.*

MASS-MOVEMENT DEPOSITS

Qmc Colluvium (Holocene)-- *Gravity and slopewash sediments; gray to brown; unconsolidated to semi-consolidated; deposits mantle lower valley walls and accumulate at the base of some steep cliffs; grades to alluvium, valley fill, or fans as slopes lessen; thickness ranges from 0 to 50 feet (0-15 m).*

Qmco Older colluvium (late Pleistocene)-- *Gray, but otherwise like Qmc; occurs as sharply dissected aprons of weakly consolidated, mostly Flagstaff Limestone debris; larger in area than Qmc and 0 to 100 feet (0-30 m) thick.*

Qms Landslide deposits (Holocene and late Pleistocene)-- *Gravity deposits; brown to dark-brown and gray fragments of diverse sizes and shapes; hummocky topography with concentric ridges; includes small toreva blocks; thickness ranges from 0 to perhaps 60 feet (18 m).*

Qmd Debris-flow deposits (late Pleistocene)-- *Brown to gray masses of broken rock of diverse sizes and shapes; non-stratified; locally includes small earthflows and rock falls; hummocky and irregular surface; thickness ranges widely, but does not exceed about 300 feet (90 m). Mapped in three subdivisions, according to source: Qmd (Tg), Qmd (Tc), and Qmd (TKn).*

Qmf1 Mudflow deposits (middle Holocene)-- *Gray and brownish-gray, very poorly sorted, angular debris moved by mudflow; fine material is from the North Horn and most of the coarse material is Flagstaff Limestone; hummocky surface; thicknesses range up to 200 to 300 feet (60-90 m).*

Qmf2 Older mudflow deposits (late Pleistocene)-- *Similar to Qmf1 in texture and composition but much longer; dissected by both Funk and Sixmile Creeks; thickness ranges from 0 to 150 feet (45 m).*

Qmt Toreva blocks (Holocene-late Pleistocene)-- *Masses of rock that slumped with little internal disturbance; small toreva blocks are lumped with colluvium and are probably Holocene in age; large blocks are probably older; thickness is unknown.*

LACUSTRINE DEPOSITS

Ql Lake deposits (early late Pleistocene)-- *Marl, clay, thin sands, and some pebble bands; fossiliferous; little cementation; base not exposed, but apparently lies on Arapien Shale; overlain by Qag2; 12.8 feet (3.9 m) exposed.*

QUATERNARY AND TERTIARY DEPOSITS

QTag Older alluvial(?) gravel (middle Pleistocene)-- *Material and structure like Qag3, but has been turned on edge, in angular unconformity beneath Qag3; maximum thickness exposed is less than 50 feet (15 m). Regionally this unit is older.*

QTvf1 Valley-fill deposits (Holocene at surface; Tertiary at depth)-- *Gray and brownish-gray, poorly sorted, unconsolidated alluvial and colluvial debris in large valleys; grades to fans, colluvial and alluvial deposits at valley margins; probably 0 to 700 feet (0-215 m) thick.*

QTas Salt marsh deposits on valley fill (Holocene at surface; Tertiary at depth)-- *Same material as QTvf1, and has a concordant surface, but is water-saturated and contains local pond sediments; thickness like QTvf1; probably 0 to 700 feet (0-215 m) thick.*

QTvf2 Older valley-fill deposits (late Pleistocene at surface; Tertiary at depth)-- *Material and origin like those of QTvf1, but surface is 15 to 30 feet (4.5-9 m) higher than the younger valley fill and associated deposits; probably 0 to 700 feet (0-215 m) thick.*

TERTIARY ROCKS

Tch Crazy Hollow Formation (late Eocene)-- *Red to reddish-brown mudstone; red, light-yellow-brown, and locally white sandstone, shaly siltstone, and some conglomerate; sandstone and conglomerate that are not red are marked by grains and pebbles of black chert, giving a "salt and pepper" look; locally contains lenses of dense, micritic, light-gray, pink, or dark-gray to black limestone; mostly fluvial, but locally pond or lacustrine deposits; thickness is 0 to 120 feet (37 m).*

Green River Formation (Eocene)

Tgu --Upper member-- *White to yellowish-gray, thin-bedded, platy, micritic, well-cemented limy mudstone, and ostracodal and oolitic limestone interbedded with thin shale layers; yellowish-orange near the top, with silicified stromatolite beds and some tuffs; interfingers with Crazy Hollow Formation. Maximum thickness in quadrangle is 180 to 260 feet (55-80 m).*

Tgl --Lower member-- *Light-gray and greenish-gray, shaly mudstone with thin layers of limestone, some siltstone, and minor sandstone; 0 to 300 feet (0-90 m) thick in central area and to 500 feet (150 m) thick in the southeast corner; pinches out over Jurassic rocks.*

Tc Colton Formation (early Eocene)-- *Claystone and mudstone variegated in shades of reddish brown, light gray, violet, or light greenish gray; locally includes beds of yellowish-gray to yellowish-brown siltstone and sandstone; sparse, thin beds of platy, light-gray, micritic, lacustrine limestone; pinches out over the disturbed belt of Mesozoic rocks, but is 280 feet (85 m) thick in the central area and about 500 feet (150 m) thick in the southeast.*

Tf Flagstaff Limestone (Eocene)-- *Light-gray to yellowish-gray limestone; pinkish or grayish orange near base where unconformable on Jurassic or Cretaceous beds; numerous shale partings and mudstone interbeds; micritic beds are slabby limestone; finely sacharoidal, massive beds are commonly dolomitic or dolomite; deposits in northwestern part of quadrangle are fractured, high-calcium micrites; thin- to thick-bedded, locally massive; contains oncolites locally near the base; contains subordinate, interbedded, dark-gray, gray, and greenish-gray shale; forms resistant ledges and prominent hogbacks; ranges widely in thickness from 0 to 400 feet (0-122 m); average maximum thickness is about 250 feet (75 m).*

TERTIARY AND CRETACEOUS ROCKS

TKn North Horn Formation (Maastrichtian to early Eocene)-- *Claystone, sandstone, conglomeratic sandstone, conglomerate, and sparse limestone; units alternate irregularly; mudstones are thick-bedded to massive; sandstones range from thin to thick bedded and many are cross-bedded; fine to medium grained; limestone beds are thin, dense, and locally arenaceous; the formation slumps, slides, and flows easily; ranges in thickness from pinchout to 620 feet (190 m).*

CRETACEOUS ROCKS

Kpr Price River Formation (Late Cretaceous)-- *Gray to light-gray or yellowish-brown conglomerate, conglomeratic sandstone, and sandstone, with minor shale; thin to thick bedded; locally massive; commonly well cemented; coarse conglomerates contain well-rounded clasts of light-brown and purple quartzite, and red-and-white striped quartzite, light-gray quartz, light-gray chert, and sparse dark-bluish-gray limestone; sandstones are fine to coarse grained; forms steep slopes and low cliffs; ranges in thickness from 0 to 300 feet (90 m).*

Indianola Group

Ksx Sixmile Canyon Formation (Late Cretaceous)-- *Three intergrading parts are distinguished: a lower interval (slightly more than half the formation) of sandstone with some conglomerate and conglomeratic sandstone; a middle interval (slightly less than one-fourth) of finer sandstone, shale, carbonaceous shale, and coal; and an upper interval (slightly less than one-fourth) of coarser sandstone with minor conglomerate and a few coal beds; the formation is perhaps 4,000 feet (1,220 m) thick.*

Kfv Funk Valley Formation (Late Cretaceous)-- *Three intergrading parts are distinguished: 900 to 1,000 feet (275-304 m) of thick beds of sandstone interbedded with shale; 1,300 feet (395 m) of an easily weathered, finer grained, muddy sandstone with 550 feet (165 m) of mudstone near the middle; and an upper sandstone unit like the lower one, but 800 to 900 feet (245-275 m) thick.*

Kav Allen Valley Shale (early Late Cretaceous)-- *Gray, fossiliferous, marine shale with thin layers of bentonitic mudstone, siltstone, and limy siltstone; thickness is 620 feet (190 m).*

Kc Conglomerate beds (early Late Cretaceous)-- *A massive, well-cemented, gray conglomerate present only locally on top of the Sanpete Formation west of the San Pitch River; gray in outcrop with colored Precambrian quartzite clasts; outcrop is only about 1,500 feet (455 m) long with an exposed thickness of 160 feet (49 m).*

Ksp Sanpete Formation (early Late Cretaceous)-- *Grayish-orange weathering, marginal marine sandstone with shale interbeds, some 100 feet thick; sand has a range of grain sizes and sorting is moderate to good; rock is reasonably well cemented, and limonitic; particularly west of the San Pitch River; thickness is about 2,100 feet (640 m).*

Kb Basal formation of Indianola Group, new unit (early Late Cretaceous)-- *Reddish-brown and gray, thick-bedded to massive, well-cemented conglomerate with interbeds of sandstone and some mudstone; granules, pebbles, and well-rounded cobbles and boulders 3 to 6 feet (1-2 m) in diameter of white, red, red-striped, purple, green, grayish-green, and light-brown quartzite; light-brown to tan-gray chert, white quartz, and some gray and dark-bluish-gray limestone; thickness 775 to greater than 1,100 feet (235-335 m). Equals "Gunnison Formation" of Roche (1985), upper Pigeon Creek of Schwans (1989), and upper Cedar Mountain of Witkind and others (1986).*

Kcm / Kcml Cedar Mountain Formation (Early Cretaceous)-- *Mudstone, variegated in shades of red-orange, yellowish-gray, gray, purple, and green; massive to thick bedded; a few lenses and thin layers of limy sandstone occur; limy mudstone beds with lime nodules and oncolites are a signature of the unit; a few pebble and cobble conglomerate layers 10 to 30 feet (3-9 m) thick are present near the base and close to the top; exposed thickness is 965 to 1,135 feet (295-345 m). A conspicuous layer, 20 to 40 feet (6-12 m) thick, of white-weathering, pale-pink limestone (Kcml) lies near the base of the unit.*

JURASSIC ROCKS

Jtg Twist Gulch Formation (Middle Jurassic)-- *Reddish-brown shale and silty mudstone with some thin to thick beds of reddish-gray to light-gray, gritty sandstone that weathers light brown; feldspathic; unfossiliferous; about 3,000 feet (915 m) thick regionally and 1,667 feet (510 m) locally.*

Ja Arapien Shale (Middle Jurassic)-- *Mudstone, calcareous, commonly light-gray, with red, salt-bearing beds and lenses; in places entirely drab gray, elsewhere wholly reddish brown; thin to medium bedded; evenly bedded; locally amorphous; has intercalated thin, lenticular beds and seams of yellowish-gray to light-brown siltstone and sandstone; sparse limestone beds have few fossils; contains thick beds of rock salt (halite), gypsum, and minor evaporites; abundant selenite crystals; formation is complexly deformed, with much shearing; erodes to badland topography with gullied surfaces; thickness uncertain. Unit is divisible into five intergrading members:*

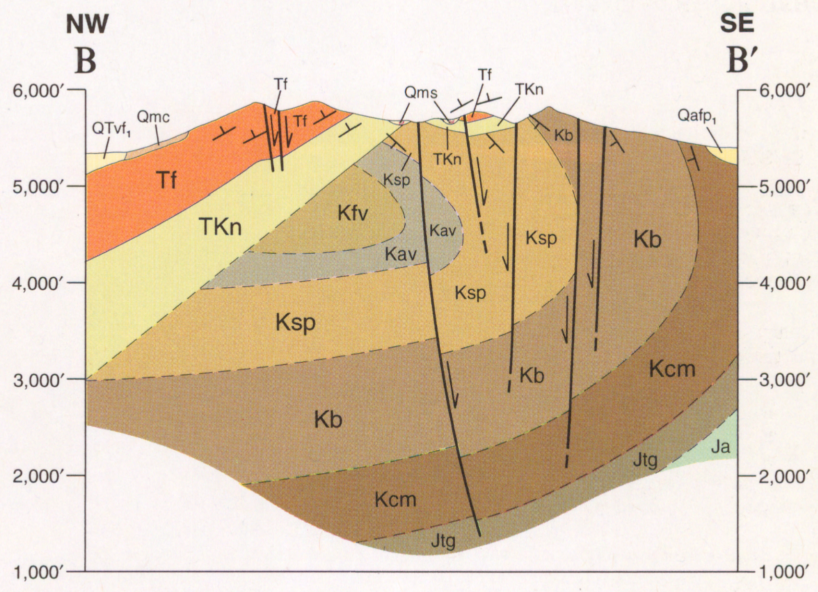
Jae --Member E: *Brick-red, silty shale; locally salt-bearing; bedding obscure where deformed; exposed thickness incomplete, about 500 feet (150 m) locally.*

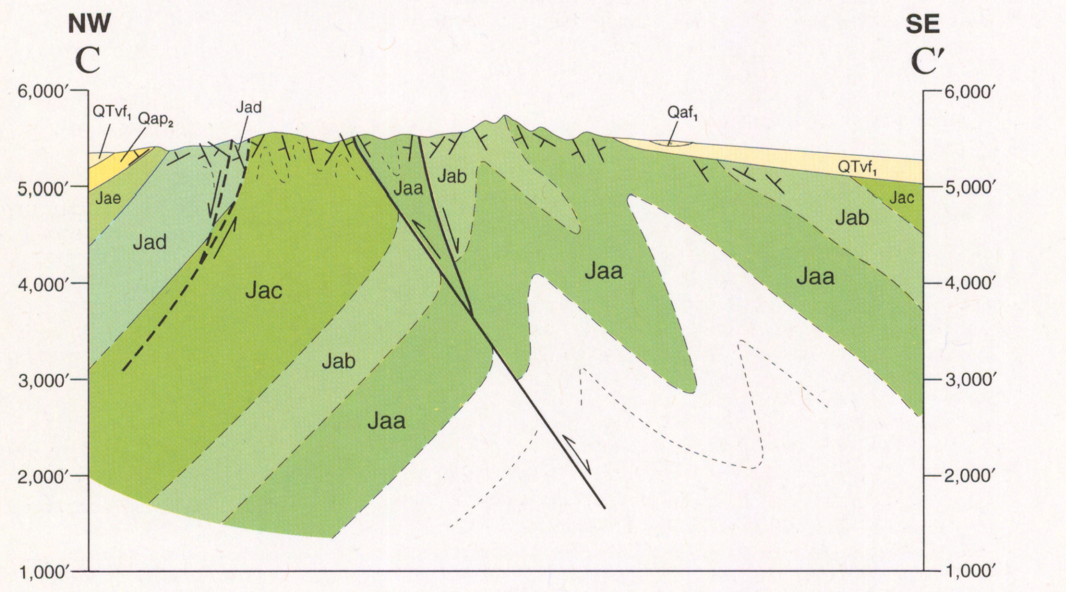
Jad --Member D: *Alternate layers of bluish-gray and red, gypsiferous shale; locally blotchy because of lenticular beds and facies changes; about 800 feet (244 m) exposed locally.*

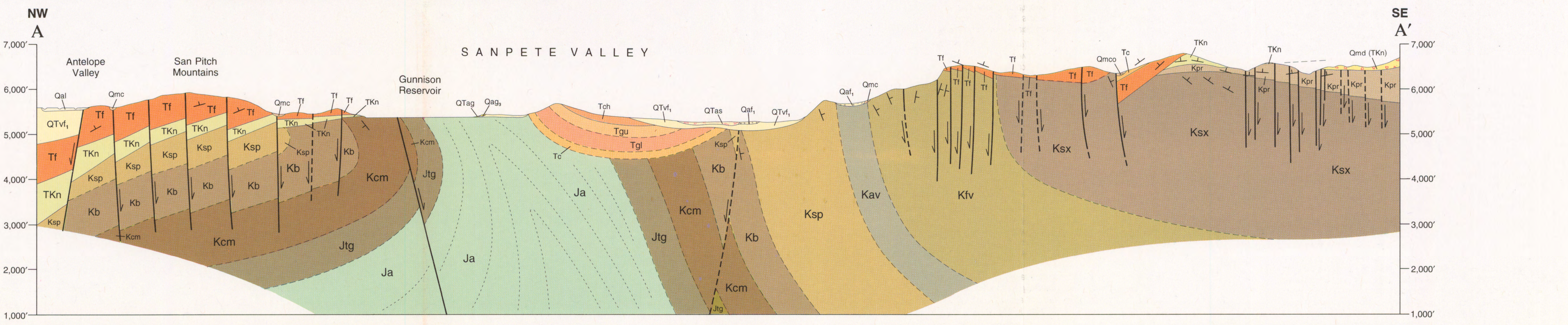
Jac --Member C: *Light-gray, calcareous shale and limy mudstone; all thin-bedded; contains a few thin and medium beds of dense, sandy, fossiliferous limestone, and local pods of gypsum; local thickness may be about 1,500 feet (458 m).*

Jab --Member B: *Bluish-gray and red, gypsiferous shale; blotchy and streaked like member D, but has more red mudstone with local pods of halite; minimum local thickness is 425 feet (130 m) but may reach 600 feet (183 m).*

Jaa --Member A: *Light-yellowish-gray shale and thin-bedded limestone; some red gypsiferous shale, and light-gray, argillaceous limestone with large local pods of gypsum concentrated near the top; local thickness indeterminate, but about 900 feet (275 m).*







GEOLOGIC MAP OF THE STERLING QUADRANGLE, SANPETE COUNTY, UTAH

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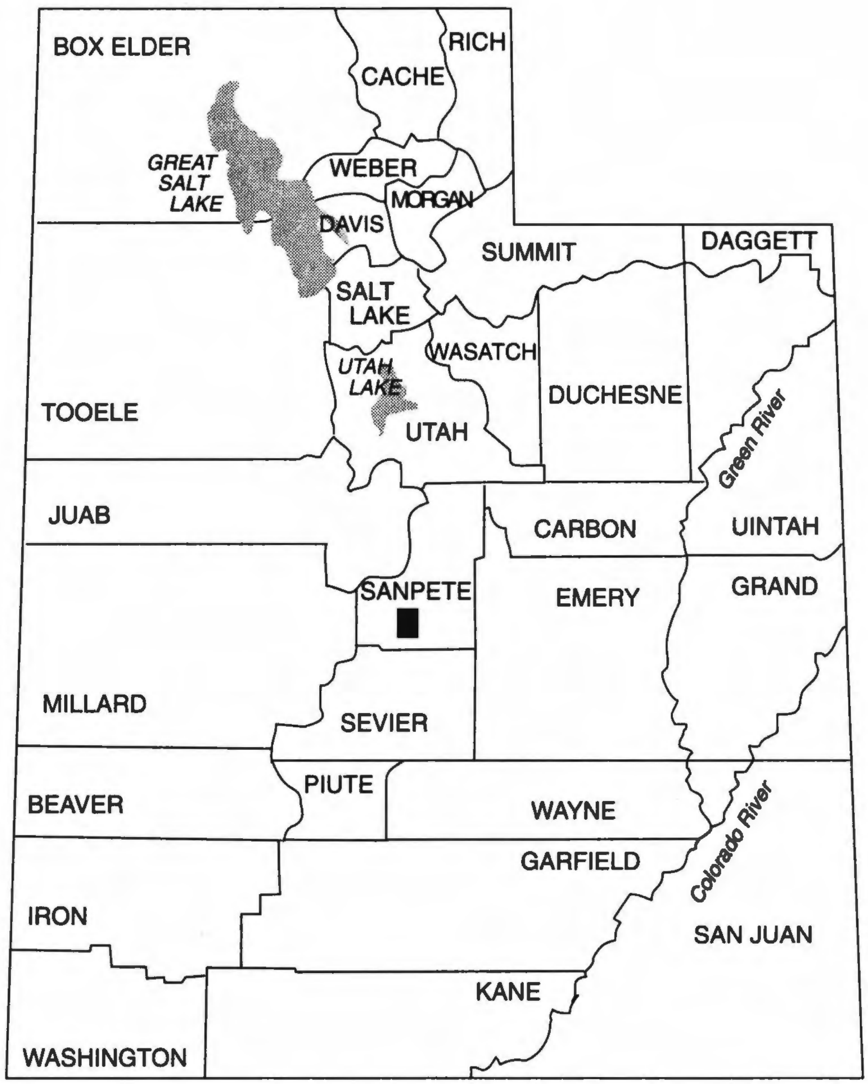

MAP 159 **1994**
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

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GEOLOGIC MAP OF THE STERLING QUADRANGLE, SANPETE COUNTY, UTAH

by
Malcolm P. Weiss
Department of Geology
Northern Illinois University

ABSTRACT

The Sterling quadrangle lies across the junction of Sanpete and Sevier Valleys and at the point of closest approach of the Wasatch and Gunnison Plateaus. The geology of the Sterling quadrangle is complex stratigraphically, structurally, and by the abundance and variety of unconsolidated Quaternary deposits. The complexities result from the quadrangle's position on a part of the Sanpete-Sevier antiform that is elevated and exposed at the surface, and also because local diapirism of the Arapien Shale has interacted with climatic changes to multiply the type and number of Quaternary deposits.

The bedrock units exposed in the quadrangle total about 18,500 feet (5,640 m) in thickness, and are divisible into three packages: (1) Middle Jurassic marine mudstones and sandstones, (2) Early and Late Cretaceous piedmont and coastal-plain conglomerate and sandstone, interleaved with some marine shale tongues, and (3) latest Cretaceous through Eocene terrestrial basin-filling deposits of both alluvial and lacustrine origin. Twenty-seven units of unconsolidated deposits are mapped: three are of Tertiary-Quaternary age and the others are Quaternary in age.

The major structure of the Sterling area is the Sanpete-Sevier antiform, a welt of Jurassic and Cretaceous rocks that was raised and compressed during the Sevier orogeny. The thickness of the Jurassic Arapien Shale, the oldest unit within the antiform, was increased many times by stacked thrust sheets. Concurrently, Cretaceous piedmont clastics derived from the Sevier orogenic belt were folded over the welt of Arapien beds in the antiform. The Mesozoic strata in the antiform were deeply eroded toward the end of the Cretaceous and, as the Sevier orogeny waned, were covered by terrestrial basin-fill deposits of Maastrichtian, Paleocene, and Eocene age. The terrestrial beds are thin over and near the antiform, lie unconformably upon it, and contain several unconformities; to both flanks these strata thicken and become mutually conformable. Five formations make up the basin-fill package; three are mostly alluvial, but the second and fourth in the stack are thick lacustrine deposits.

During later Tertiary regional extension, other large structures developed, such as the Wasatch monocline and Sanpete Valley, by which the Wasatch and Gunnison Plateaus were delineated. Many high-angle normal faults appear to have formed coincidentally to the regional extension. The Arapien evaporites stacked in the Sanpete-Sevier antiform have risen diapirically at times between latest Cretaceous and the present. This is shown by unconformities within and between basin-fill units and by deformed Quaternary alluvial deposits. Buoyancy of the Arapien Shale has also raised the south end of Sanpete Valley, inhibiting drainage of the San Pitch River.

Since the Eocene Epoch, the Sterling quadrangle has undergone erosion of the bedrock units and accumulation of unconsolidated deposits, including up to 700 feet (215 m) of fill in Sanpete Valley. Several varieties of alluvial, colluvial, mass-

movement, and lacustrine deposits are present. Episodes of high rainfall during the Pleistocene led to movements of large masses of rock and earth in the Sterling quadrangle, including a large mudflow from Sixmile Canyon.

Coal, salt, sand, and gravel have been produced in the quadrangle. Gypsum is now being mined and minable limestone is present. Suitable petroleum source beds and reservoir rocks exist at depth, but have not been tested.

The quadrangle lies in the Intermountain seismic belt, and historic earthquakes have occurred in surrounding areas. One Quaternary fault scarp, probably early Holocene, is known. Landslides are numerous, but are in remote areas. Flooding by the three major drainages is the most frequent and costly geologic hazard.

INTRODUCTION

Sterling, the small ranching and recreation village near the center of the quadrangle, is about 112 miles (180 km) south of Salt Lake City, near the center of the state. U.S. Highway 89 traverses the quadrangle from north to south, connecting Manti and Gunnison, and Utah Highway 137, from Mayfield to Gunnison, crosses the southwest corner of the quadrangle. The abandoned railway from Thistle to Marysvale extends across the area, close to the San Pitch River.

The Sterling quadrangle is located astride the southern end of Sanpete Valley and includes the margins of the Gunnison Plateau (San Pitch Mountains) and the Wasatch Plateau to west and east, respectively. The flanking plateaus are part of the High Plateaus Section of the Colorado Plateaus Province but are very close to the Great Basin, which begins at the west edge of the Gunnison Plateau. Because it is near the boundary between the plateau region and the basin, the quadrangle contains many geologic aspects common to each, making it geologically fascinating but difficult to analyze.

The topographic relief of the Sterling quadrangle is moderate. The highest elevation is nearly 8,900 feet (2,710 m), on the Wasatch monocline at the southeast edge of the map area. The lowest is 5,250 feet (1,590 m), along the San Pitch River, in the southwest. The Sterling region is well-watered, for the San Pitch River, Sixmile Creek, and Twelvemile Creek all cross the quadrangle. The river is dammed to form Gunnison Reservoir, part of the flow of Sixmile Creek is diverted to support Palisade Lake, and Ninemile Reservoir is filled by springs. Most of the water is exported southward to northern Sevier Valley. Culinary water for the city of Gunnison, for example, comes from a spring southeast of Sterling.

A 7.5-minute quadrangle such as Sterling is conveniently divided into nine rectangles by joining intervals of 2½ degrees of latitude and longitude. The rectangles are named Northwest Rectangle (NWR), North-Central Rectangle (NCR), and so on through the whole quadrangle (figure 1). Locations of features discussed in the text are specified by such rectangles or by a rectangle and cadastral survey section within that rectangle.

A few early reports, such as the study of coal in Sixmile Canyon by Richardson (1906), described the geology of the Sterling quadrangle, but the first thorough analyses of stratigraphy and structure in the area were by Spieker (1946, 1949). Since the Ohio State University Geology Field Station was established (at Ephraim in 1947) hundreds of students have mapped parts of the quadrangle, mostly north of Ninemile Canyon and east of the San Pitch River. Several of them subsequently mapped parts of the quadrangle as graduate students (Babisak, 1949; Fagadau, 1949; Johnson, 1949; Wilson, 1949; Gilliland, 1951; Hardy, 1952; and Birsa, 1973). Hardy's study of the Arapien Shale, particularly, has endured and has been fundamental to all subsequent studies in the region. All the reports mentioned contributed to the compilation of the Manti 1:100,000 scale map (Witkind and others, 1987), which includes the Sterling quadrangle. A preliminary map of the quadrangle was prepared by Taylor (1980).

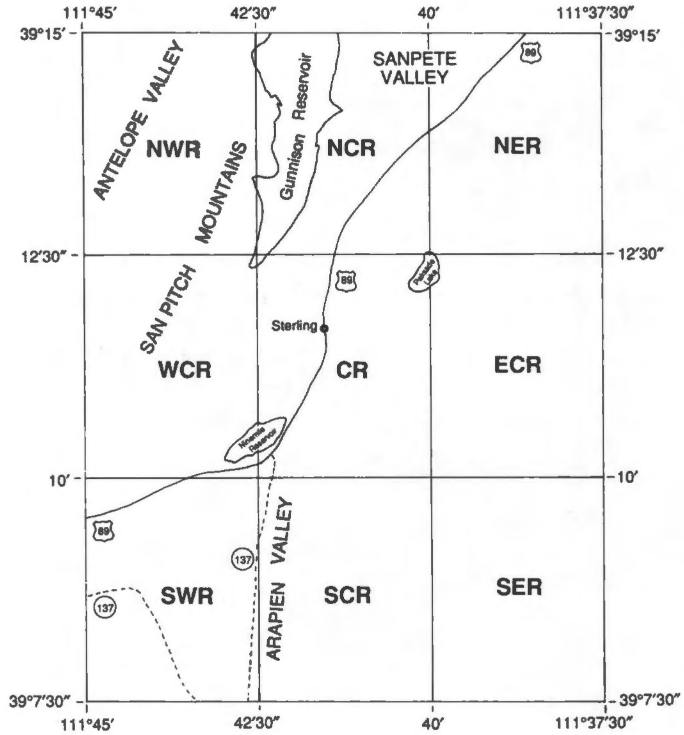

Figure 1. Sterling 7½ - minute quadrangle divided into rectangles.

STRATIGRAPHY

General

The consolidated rocks exposed in the Sterling quadrangle range in age from Middle Jurassic to latest Eocene, and have an aggregate thickness of about 18,500 feet (5,640 m). A large number of mostly unconsolidated Quaternary deposits occur in the area as well; many of their relationships are uncertain because stream and mass-wasting deposits from Sixmile Canyon have a complex association with San Pitch River deposits.

The consolidated rocks are conveniently considered in three packages: (1) a severely deformed mass of the Middle Jurassic Arapien Shale and Twist Gulch Formation extends as a locally elevated welt across the entire quadrangle from south to north, just west of the center of the quadrangle, (2) a thick sequence of mostly coarse clastics of latest Early Cretaceous and Late Cretaceous age dips away from the Jurassic welt, west beneath the Gunnison Plateau and east under the Wasatch Plateau, and (3) a thick sequence of late- and post-orogenic fluvial and lacustrine beds of Maastrichtian to Eocene age overlies both of the first two rock packages, unconformably along the axis of Sanpete Valley, but conformably east and west of the axis.

Jurassic System

Thick marine mudstones and evaporites of the Jurassic units form a complex, crudely antiformal welt that extends from beyond Sigurd, 35 miles (55 km) south of Sterling, to Thistle, 55 miles (90 km) north, and crosses the quadrangle along the White Hills (SWR) and the Gunnison Reservoir (NCR). The White Hills are the north end of a belt of good bedrock exposures that are the type area for the Arapien Shale (Hardy, 1952). Although Spieker (1946) originally subsumed the Arapien and Twist Gulch Formations under the name Arapien, most workers have considered them separate formations. Witkind and Hardy (1984) formally adopted the Arapien and Twist Gulch as separate formations according to the rules of the North American Commission on Stratigraphic Nomenclature.

Arapien Shale (Ja)

Although Spieker (1946) first defined the Arapien, the definitive description of the formation was by Hardy (1952), who divided the unit into five mappable members. Although named "shale" and commonly weak and flaky, much of the formation is not true shale, but rather is thin-bedded mudstone, calcareous mudstone, muddy limestone, and siltstone, with minor volumes of calcareous sandstone. Gypsum and halite occur in several of the members, often in pods a few hundreds of feet (100-150 m) thick at the axes of folds. Standlee (1982) reported a total thickness of 5,580 feet (1,700 m) for an undisturbed section of the Arapien in a well in the southern Gunnison Plateau. The Arapien Shale is Callovian in age.

Member A (Jaa): The basal unit, member A, is exposed along the axial belt of an overturned, faulted anticline that crosses Twelvemile Creek (SWR) and extends north into a highland, where the member plunges steeply to the north beneath members B and C. Member A consists of gray shale, thin-bedded limestone, and limy mudstone that weather into light-brownish-gray chips, as well as local masses of gypsum and red shale. Little red shale occurs in the quadrangle, but a large mass of gypsum occurs near the top of the member just south of Utah Highway 137; open-pit mining began there in 1989. Hardy (1952) cited a minimum thickness of 745 feet (227 m) from the area just south of the quadrangle. The true thickness is not determinable in the quadrangle because of folding and faulting; a value of 900 feet (275 m) is used in the cross sections.

Member B (Jab): The next unit, member B, is shale and mudstone that is conspicuously and irregularly colored bluish gray and red. The two colors may be interlayered, as along Utah 137, or patchy and blotchy, as both north and south of U.S. 89 near Ninemile Reservoir. The blotchy mixture of colors may be the result of folding and shearing during deformation. The upper part of the member is solid red and contains gypsum and halite locally, as in the west-facing cliffs beneath the Green River Formation and east of the San Pitch River (WCR). Where salt is close to the surface, the soil absorbs moisture and appears darker than surrounding dry areas; a whitish film of salt coats the salty patches when dry. Hardy (1952) cited a minimum thickness of 250 feet (76 m) in the region of Twelvemile Creek, but a minimum of 425 feet (130 m) crops out along Utah 137. An estimated thickness of 600 feet (183 m) is used in the cross sections.

Member C (Jac): Member C, the least colorful part of the Arapien, is well exposed along Utah 137 and to either side of U.S. 89. It is mostly light-gray calcareous shale and mudstone and muddy micritic limestone, all of which weather to light-yellowish-gray chips. Thin and medium beds of hard, dense, sandy limestone and limy sandstone that contain some fossils and weather brownish gray also occur. Hardy (1952) compiled a faunal list and fossil locality register. The member contains important masses of gypsum regionally, but none is exposed in the Sterling quadrangle. Member C is typically bare of vegetation, although no part of the formation harbors much life. Hardy (1952) gave a thickness of 1,450 feet (442 m) along Twelvemile Creek, which is reasonable for the thickness in that vicinity, even though only about 850 feet (260 m) of unrepeated thickness is exposed along Utah Hwy 137 (SWR). Willis (1986) cited a thickness of 1,000 feet (305 m) near Salina, 20 miles (32 km) south of Twelvemile Creek. Member C is estimated to be about 1,500 feet (458 m) thick in the quadrangle area.

Member D (Jad): Member D is mostly bluish gray, but the upper part is bicolored red and bluish gray like member B; the color bands are 15 to 30 feet (5-10 m) thick where undisturbed, but elsewhere are blotchy due to lensing of beds and to deformation. The color and tone are conspicuously different from member C on both the outcrops and on aerial photos. Member D consists mostly of gypsiferous shale and mudstone, but also contains some thin and medium beds of limy sandstone. A minimum thickness of 770 feet (235 m) crops out in the faulted, sheared belt in the SWR, and a thickness of 800 feet (244 m) is used in cross section C-C′. Willis (1986) cited a thickness of 2,000 to 4,000 feet (610-1,220 m) near Salina.

Member E (Jae): Member E is at the top of the Arapien Shale and is a conspicuous unit of brick-red gypsiferous and salty mudstone with streaks and pods of siltstone. No gray beds occur. Salty zones develop the same dark-and-moist or dry-and-white surfaces as those in member B. Bedding is obscure in member E; where recognizable it is contorted. Member E is the thinnest unit of the Arapien; too little is exposed in the Sterling quadrangle to estimate the thickness. Hardy (1952) cited 165 feet (50 m) at Salina, but Willis (1986) gives 200 to 400 feet (60-120 m) in the same area. The broad welt of salty red mudstone west of Sterling is mapped as member E; because of outcrop width, a thickness of about 500 feet (150 m) is assumed for cross section C-C'. A water well drilled in 1989 in the center of N½ SW¼ section 33 (CR) cut 250 feet (75 m) of red mudstone and stopped in massive salt. The top of member E is regionally accordant and gradational with the overlying Twist Gulch Formation, which is similarly colored; the latter is distinctly brownish red, has no salt or gypsum, and contains conspicuous thin and medium beds of light-brown or reddish-brown silty sandstone and reddish-brown siltstone.

Twist Gulch Formation (Jtg)

A few small outcrops of Twist Gulch Formation occur along the west side of the San Pitch River in the WCR, and a poorly exposed patch lying southwest of Sterling Cemetery (CR) exposes about 350 feet (105 m) of strata. Most of the Twist Gulch is soft, thin-bedded, and reddish-brown mudstone that weathers to a reddish-brown soil. The siltstone and sandstone beds are weakly cemented. The sandstone contains about 5 percent feldspar, in contrast to nearby Cretaceous sandstones, which have only minor feldspar and are highly quartzose or lithic sandstones (Weiss and Roche, 1988). The Twist Gulch was correlated with the Entrada and Carmel Formations by Willis (1986; see also Imlay, 1980). Although many outcrops of the Twist Gulch lie along the west edge of Sanpete Valley, none display the whole formation. The entire unit is exposed along the northwest face of the Gunnison Plateau, where it is 1,667 feet (508 m) thick (Auby, 1987, 1991). I use 700 feet (213 m) for the cross sections. The Twist Gulch Formation is Callovian in age.

At one locality in the Sterling quadrangle (NW¼SW¼ section 5, WCR) and at several locations along the west side of the Gunnison Plateau, the Twist Gulch is overlain unconformably by conglomerates of the Cedar Mountain Formation (Auby, 1987, 1991; Biek, 1987, 1991). The unconformity appears to represent a hiatus equal to the Late Jurassic plus the earliest Cretaceous (Neocomian) (Weiss and Roche, 1988, figure 2).

Cretaceous System

The Cretaceous system is represented by a thick wedge of mostly coarse clastics that comprise the Cedar Mountain Formation, Indianola Group, and Price River Formation. The great volume of sediment was shed eastward from the Sevier orogenic belt (Armstrong, 1968; Lawton, 1982), and subsequently thrusted, folded, and faulted. The total thickness of the clastic wedge is about 9,600 feet (2,925 m) in the quadrangle; the wedge thins gradually eastward and the rocks fine rapidly eastward. The sedimentologic history of this wedge is described by Lawton (1986), Schwans (1988), and Heller and Paola (1989). The rocks range in age from later Early Cretaceous (Barremian-Aptian) to Late Cretaceous (Campanian).

Cedar Mountain Formation (Kcm, Kcml)

The Cedar Mountain Formation consists mostly (80-90 percent) of variegated red, reddish-brown, purple or violet, and yellowish-gray mudstone beds. Thin to thick beds and lenses of sandstone and pebbly sandstone with abundant lithic grains, pebble conglomerates with some cobbles, dark-gray mudstone, and beds of limestone and limy mudstone are also present. The larger clasts are, in about equal parts, quartzite and carbonates (limestone and dolomite). One thick (15 to 25 feet [4.5-8 m]) unfossiliferous bed of white-weathering, gray limestone that grades along strike from micrite (south) to sparite (north) lies low in the formation just west of the San Pitch River (WCR) and is mapped as Kcml. The limy mudstone beds are grayish or whitish, less oxidized than the redbeds, and commonly contain both oncolites and irregular nodules of limestone. The Cedar Mountain is also characterized by gastroliths (rounded and polished quartzite pebbles thought to have been the "grit " in the crops of large reptiles). The basal beds are colored mudstones with local conglomerate lenses.

Beds of the Cedar Mountain were assigned to the Morrison Formation in the Jurassic System when first described by Spieker and Reeside (1926), and subsequently called Morrison (?) Formation by Spieker (1946). The latter usage persisted for about 40 years, until discovery that the dark-gray mudstones and limy mudstones contain Cretaceous palynomorphs and a few Cretaceous molluscs and leaves (Stuecheli, 1984). Stokes (1972) had predicted that these beds are the Cedar Mountain by the presence of gastroliths and limestone nodules. Witkind and others (1986) considered the unit Early Cretaceous in age, although the non-diagnostic palynomorphs (all non-marine) range from Jurassic to Early Cretaceous.

Three different patterns of new nomenclature have developed. The rocks are here mapped as Cedar Mountain Formation following the usage of Weiss and Roche (1988). Witkind and others (1986) called these beds the lower part of their Cedar Mountain Formation. Schwans (1988) named these same beds the lower member of his newly described Pigeon Creek Formation.

Diagnostic late Albian and early Cenomanian palynomorphs lie immediately above the Cedar Mountain; by these and the Jurassic/Cretaceous palynomorphs in the Cedar Mountain itself, the formation is considered to be later Early Cretaceous in age (Weiss and Roche, 1988). The Cedar Mountain Formation has been identified as late Early Cretaceous in Salina Canyon, as well, by Willis and Kowallis (1988).

The entire unit is exposed in the west half of section 5 (WCR) where it is about 965 feet (295 m) thick. Folding may have attenuated the mudstones there, for an incomplete thickness of about 1,135 feet (345 m) occurs in NE¼SW¼ section 7 (WCR). Small outcrops are scattered along the east side of the Gunnison Plateau and the entire formation is exposed on the northwest flank of the plateau (Auby, 1991).

Indianola Group

The major thickness of the Cretaceous synorogenic clastic wedge (Lawton, 1982) is included in the Indianola Group, which extends roughly north-south across central Utah over about the same distance as the marine Jurassic sediments described earlier. Spieker (1946) named the group and its four classic formations:

the Sanpete Formation, the Allen Valley Shale, the Funk Valley Formation, and the Sixmile Canyon Formation. Type sections of all four lie in the Sterling quadrangle. Two additional informal formations of the Indianola Group, a basal formation and unnamed conglomerate beds, are mapped in this quadrangle.

Basal formation of Indianola Group (Kb): The upper part of an interval of redbeds and coarse conglomerates exposed beneath the Sanpete Formation on the west side of the San Pitch River are herein mapped as the basal formation of the Indianola Group. Spieker (1946, 1949) considered the redbeds and conglomerates the Jurassic Morrison(?) Formation. Discovery of Cretaceous fossils in these beds and assignment of their lower part to the Cedar Mountain Formation (Weiss and Roche, 1988) required a new name for the upper part. Witkind and others (1986) included the upper part in the Cedar Mountain, although one of those coauthors disagreed with the assignment. Schwans (1988) called it the upper member of his Pigeon Creek Formation. Weiss and Roche (1988) considered it to be a previously unrecognized basal element of the Indianola Group, but avoided giving it a new formation name, pending development of a consensus among students of the geology of central Utah. For this quadrangle, this unit is mapped as the basal formation of the Indianola Group (Kb). The rationale for this decision is that the basal formation is overlain by a sandstone unit that closely resembles the type Sanpete Formation.

Half the volume of this unit is mudstone and the rest is conglomerate and minor sandstone. Much of the conglomerate is clast-supported with a sandstone matrix. The mudstone is like the red mudstone in the Cedar Mountain Formation. The unit is roughly divisible into three subequal units: (1) a lower red, pebble conglomerate, fine-grained sandstone, and mudstone unit, with oncolites locally, (2) a middle unit of pale-red mudstone, yellowish-gray sandstone and mudstone, pebble conglomerate, and reddish-gray conglomerate, and (3) an upper unit of red, sandy mudstone with numerous large cobbles and some boulders.

The upper unit is clast-supported and weakly cemented in the north, where rocky ridges contain many large, well-rounded, smooth quartzite boulders 3 to 6 feet (1-2 m) in diameter. Closer to U.S. 89, this unit is less well cemented, has smaller diameter large clasts, and forms stony slopes of red soil littered with cobbles.

The conglomerate in the basal formation consists mostly of pebbles and cobbles, but boulders prevail in some beds. These clasts are of quartzite and carbonate (limestone and dolomite) as in the Cedar Mountain Formation. Fine-grained, olive-green quartzite pebbles, not known in other units, occur in the lower part of the formation. The sandstones exhibit parallel, cross- and graded-bedding locally. Sandstone and mudstone increase somewhat northward.

The basal conglomerate bed of the basal formation unconformably overlies the Cedar Mountain Formation. The hiatus probably is small, for similar lenses and sheets of conglomerate occur in the Cedar Mountain and are numerous throughout the basal formation. The basal formation is accordant (and probably conformable) with the Sanpete Formation west of the San Pitch River.

A few thin lenses of dark-gray mudstone have yielded palynomorphs of Albian to Coniacian age. Witkind and others (1986) tabulated a number of fossil forms, and concluded that the unit is Early Cretaceous.

The real thickness of the formation cannot be determined in the quadrangle because the beds west of the San Pitch River are overturned and cut by a number of faults subparallel to bedding. A complete thickness to the south is 775 feet (235 m), but a minimum thickness beneath overlapping North Horn beds is about 1,100 feet (335 m) near the Gunnison Reservoir Dam. I suspect that the basal formation both underlies the Sanpete Formation and, by fining of lithofacies eastward, may be partly laterally equivalent to the Sanpete.

A tiny outcrop of the basal formation lies in Allen Valley on the border of sections 27 and 34 (NCR). It is adjacent to sandy, light soil which is on strike with the lower part of the type Sanpete Formation. This outcrop was discovered by student mappers in 1953, and dubbed the Morrison (?) Formation; the soil is red, with numerous pebbles and small cobbles of quartzite and carbonate. The Eocene Colton Formation crops out nearby, but no such clasts occur in the Colton of Sanpete Valley. The mapped attitude (plate 1) was recorded by students in those early years when the knoll was uncultivated. Aerial photos clearly show the tonal contrast between the red conglomeratic mudstone of the basal formation and the light sandy soil on the Sanpete Formation. Though the outcrop has since deteriorated by cultivation, I believe the color change is the contact of the basal formation with the Sanpete Formation.

Sanpete Formation (Ksp): This formation consists mostly of gray sandstone that weathers light yellowish brown to yellowish brown. Fine-grained, moderately cemented sandstone is interbedded with medium-grained, poorly cemented sandstone, some sandy gray shale, and shale partings; some pebbly sandstone and minor conglomerate also occur. All weather to shades of yellowish brown. Pebbles in the unit are mostly quartzite, like the types occurring in the Cedar Mountain and basal formations. At the type locality of the Sanpete Formation, the lowland between Sterling and Manti, nonresistant covered intervals suggest that important thicknesses of shale occur within the unit. West of the San Pitch River the formation is better cemented, more ferruginous, breaks into angular chunks, and weathers to a darker limonitic color. The unit is transitional, stratigraphically upward and by lithofacies change eastward, between the piedmont conglomerate and mudstone of the basal formation and the open marine shale and mudstone of the overlying Allen Valley Shale.

Several prospects in coaly, dark-gray shale exposed in NW¼ section 7 (WCR) have yielded numerous non-marine palynomorphs that suggest an age of middle Albian to middle Cenomanian (record on file at Utah Geological Survey). Lawton (1985) believes the Sanpete is Cenomanian/Turonian in age.

Spieker (1946) believed the only fully exposed thickness of the Sanpete Formation is in Salina Canyon and gave it 1,350 feet (410 m). If we use the basal Indianola/Sanpete contact on the border of sections 27/34 (NCR), the thickness of the Sanpete Formation in its type area is 2,100 feet (640 m). Only about 400 feet (120 m) of the unit is exposed west of the San Pitch River, where the base is exposed but the top is an unconformity. A thickness of 1,500 feet (457 m) is used in cross sections A-A′ and B-B′.

Conglomerate beds (Kc): A thick, well-cemented pebble and cobble conglomerate lies on top of the Sanpete Formation in NW¼ section 7 (WCR), but not elsewhere. The outcrop is 1,500 feet (460 m) long, covered at both ends by Tertiary beds, and appears to be a channel deposit. Although it appears to mark the top of the Sanpete Formation, the latter is so cut by faults farther east that one cannot presume an orderly succession from the basal formation through the Sanpete Formation to this conglomerate. So it is possible that the conglomerate is a local unit within the Sanpete, but T.F. Lawton (personal communication, 1990) pointed out that no such conglomerate occurs in wells in Sanpete Valley. Alternatively, the conglomerate may be a Price River Formation remnant (Weiss, 1982a, figures 11, 12) or a basal North Horn ledge lying below an intraformational angular unconformity.

The channel conglomerate is clast-supported toward the base and matrix-supported otherwise. It is medium gray, with much gray sandstone near the top. Framework grains are well rounded, and are mostly pebbles with scattered cobbles. The clasts are quartzite and carbonate rocks like those of the older conglomerates; the ratio of quartzite to limestone and dolomite is about 3 to 2. These clasts eroded from Precambrian and lower Paleozoic formations in the thrust sheets of the Sevier orogenic belt. The unit is well cemented and weathers to smooth, steep surfaces. The top of the unit is hidden beneath the unconformably overlapping North Horn Formation. A thickness of about 160 feet (49 m) is exposed.

Allen Valley Shale (Kav): The Allen Valley is a gray, marine shale with thin sandstone beds and some sandy and silty shale and mudstone. Thin layers of bentonite and thin beds of sandy limestone bearing a variety of molluscs are also present. It weathers yellowish brown. Because the rock is weak, the formation is poorly exposed everywhere. Spieker (1946) cited only two exposures, the type area and Salina Canyon, but a third exists southeast of Sterling, in NE¼SE¼ section 4 (CR). *Collignoniceras woolgari* is present at the type locality and also in the Tununk Shale Member of the Mancos Shale (T.F. Lawton, personal communication, 1990), a correlation also made by Willis (1986). Nikravesh (1963) studied the foraminifera of the type section. Lawton (1985) considered the formation Turonian in age.

The type locality of the Allen Valley Shale is a poorly exposed outcrop in SW¼ SW¼ section 26 (NCR) (Allen Valley is actually the next valley west of this outcrop, in NW¼ section 34 [CR]) (E.M. Spieker, personal communication, 1957, 1961). Spieker (1946) cited 620 feet (190 m) for the thickness of this unit at the type section, and newer measurements compare closely. In wells in Sanpete Valley, the formation is consistently about 600 feet (183 m) thick (T.F. Lawton, personal communication, 1990).

Funk Valley Formation (Kfv): The Funk Valley consists of sandstone with interbedded mudstone, siltstone, and shale, but their proportions are not uniform throughout. The rock is light yellowish gray and most weathers to yellowish gray. The interbedding of soft, fine beds with better cemented sandy beds gives the unit a rough, ragged outcrop. Upward-coarsening sequences are present in many beds of the unit.

The type locality surrounds Palisade (formerly Funk) Lake (CR) and clearly shows the three-part nature of the formation in the Sterling area: (1) a lower interval of interbedded sandstone and shale that weathers rusty orange, (2) a middle zone of very muddy sandstone and shale, and (3) an upper part consisting of fissile, friable sandstone with minor mudstone and shale interbeds. Spieker (1946) gave thicknesses of 700 feet (215 m), 650 feet (200 m), and 900 feet (275 m), respectively for the three parts, a total of 2,250 feet (685 m). More recent measurements and calculations from outcrop width give about 3,100 feet (945 m) for the total thickness; the soft, readily weathered, finer grained middle unit is about 1,300 feet thick (395 m). T.F. Lawton (personal communication, 1990) reported that five coalbeds, one more than 20 feet (6 m) thick, are present in the upper, nonmarine part of the Funk Valley in the J.W. Irons #1 well near Moroni, 19 miles (32 km) north of the type locality. No coalbeds are present at the type locality, and Lawton believes the upper surface of the Funk Valley Formation in the Sterling quadrangle is unconformable. The Funk Valley is Turonian/Coniacian in age and a correlative of the Ferron Sandstone and Bluegate Shale Members of the Mancos Shale (Lawton, 1985). Weiss and Roche (1988) believed it is partly lower Santonian in age.

Funk Valley sandstone was formerly exposed in lower Warm Springs Canyon in NW¼NW¼ section 24 (NER), but has since been covered by fallen blocks of Flagstaff Limestone.

Sixmile Canyon Formation (Ksx): This unit is conspicuously coarser than the Funk Valley, and contains several beds of coal that indicate a marginal sea and alluvial-plain origin. The type section lies along the north side of Sixmile Creek, in sections 35 and 36 (ECR). The formation is composed mainly of gray, medium-grained, quartzose sandstone and pebbly sandstone, with some fine- and coarse-grained beds. Stringers and lenses of pebble conglomerate are concentrated in the lower half of the formation. Above the middle of the formation is an interval of fine-grained, light-yellowish-gray, white-weathering sandstone with some shale and beds of coal that have been mined. Above the coal-bearing zone is an interval of sandstone and pebbly sandstone interbedded with thin sandy shale that is almost cyclic in character. The sand is varied in texture, but is not as coarse as the lower part of the formation nor as fine as the coal-bearing zone. The formation weathers to rounded, ragged surfaces.

The Sixmile Canyon beds are concordant with, but conspicuously coarser than, the upper Funk Valley, although no channeling was observed. The absence of coal in the highest Funk Valley beds (T.F. Lawton, personal communication, 1990) and the textural change suggest the contact is unconformable. The formation is truncated and overlain unconformably by the Price River Formation. Both the upper Sixmile Canyon (down to the coal-bearing zone) and the Price River are overlapped unconformably by the North Horn Formation and the Flagstaff Limestone.

Spieker (1946) cited 2,000 feet (610 m), 300 feet (90 m), and 425 feet (130 m), respectively, for the three parts. Students have obtained a total thickness of about 3,000 feet (915 m). A computation from outcrop widths and the changing dips gives 4,180 feet (1,275 m); 4,000 feet (1,220 m) is here assumed for the full thickness. Lawton (1985) correlated the Sixmile Canyon with the upper formations of the Mancos Shale and the lower formations of the Mesaverde Group on the east side of the Wasatch Plateau, and assigned an age of Santonian and Campanian.

Price River Formation (Kpr)

The Price River Formation along Sixmile Creek consists mostly of medium and thick beds of medium- and coarse-grained sandstone and pebbly sandstone with some quartzite and chert pebble conglomerate. Medium and thick beds of the conglomerate occur, but stringers of pebbles also lie in some sandstone units. A few thin and medium beds of dark-gray shale and red mudstone are interbedded, especially in the upper part. The sandstone is light yellowish brown or light yellowish gray, but many of the beds weather to the grayish-orange color of limonite stain. The sandstone beds break into smooth surfaces, square corners, and bold cliffs at joint faces. The small exposure of the Price River in Funk Canyon consists almost entirely of quartzite conglomerate with pebbles and small cobbles. The small outcrops high on the south wall of Sixmile Canyon (ECR) are also conglomeratic.

The Price River lies unconformably, with small angular disparity, on the Sixmile Canyon Formation near the east edge of the quadrangle. It overlaps the upper part of the Sixmile Canyon nearly as far west as the coalbed outcrops. Although Lawton (1985) correlated overlying beds with the Price River of the Book Cliffs, he denied the unconformity and included them with his Sixmile Canyon Formation. He believes that several unconformities lie in the interval surrounding the Sixmile Canyon-Price River contact (T.F. Lawton, personal communication, 1990).

Thickness of the Price River Formation in the Sterling quadrangle ranges from zero to a maximum of 300 feet (0-90 m) in the narrows of Sixmile Creek, near the east edge of the quadrangle. The Price River is truncated toward the west by the west-dipping beds of the lower North Horn Formation, both north and south of Sixmile Creek. Price River beds near the quadrangle have yielded late Campanian palynomorphs (Fouch and others, 1983).

Cretaceous and Tertiary Systems

Deposits of latest Cretaceous and Tertiary age lie unconformably on deformed older rocks. They represent a long period of terrestrial basin filling, with sediments overlapping and pinching out against topographic highs formed by the older strata. The topographic highs were described and illustrated by Weiss (1969, figure 9). He described them as islands in Tertiary Lake Flagstaff and Lake Uinta. The modern hills composed of Funk Valley Formation between the towns of Sterling and Manti (CR and NER) are the remains of an island in Tertiary Lake Flagstaff referred to here as Sterling island. The hills of Arapien Shale to the west and south of Ninemile Reservoir (WCR and SWR) are remnants of an island in both Lake Flagstaff and Lake Uinta referred to here as Ninemile island.

North Horn Formation (TKn)

The North Horn Formation in the Sterling quadrangle consists mostly of colored mudstone, sandstone, some conglomerate, and a little limestone. The beds are all terrigenous in origin; the limestone beds formed in lakes and ponds. The regionally useful four-part division of the North Horn (Spieker, 1946, 1949) is not expressed in the incomplete sections of the Sterling area. From the quadrangle, the formation thickens rapidly eastward up the Wasatch monocline and northward along the east front of the Gunnison Plateau. Changes of facies accompany the thickening so that "normal" sections of the North Horn are found only a few miles east and north of the quadrangle.

Mudstones of the North Horn are typically brick red to pinkish or violet red, but some are reddish brown and brownish gray. Siltstone shows the same range of reds and browns. Sandstones are the same reddish brown and, locally, are gray weathering to grayish orange because of limonite. Conglomerate lenses are common minor parts of the North Horn. The clasts are mostly well-rounded pebbles of the same kinds of quartzite, limestone, and dolomite present in older formations. Most beds are thin or medium in thickness. Bedding is irregular, with many lenses and rapid facies changes. Very little limestone is found in the Sterling quadrangle; however, the formation contains oncolites that formed on nuclei of pebbles or broken pieces of bottom mudstone. Some lie in the highest beds southeast of the quadrangle; elsewhere they are locally common, especially near the base of the North Horn in section 29 (NWR), and throughout the entire unit in SW¼SE¼ section 31 (WNR). Such accumulations of cemented algal material are signs of pond or lake conditions.

The thickness of the North Horn varies markedly within the quadrangle. The minimum is zero because the North Horn laps onto the Price River and Sixmile Canyon Formations from the east and the basal Indianola Group and Cedar Mountain Formation from the west. The greatest thickness west of the San Pitch River is about 180 feet (55 m) in section 31 (WCR). It is 570 feet (175 m) in the north wall of Funk Canyon (ECR) and about 620 feet (190 m) in the north wall of Sixmile Canyon near the east edge of the quadrangle (NER). These values are only fractions of the unit's regional thickness.

Fossils occur sparsely in the North Horn; those most readily found are gastropods in limy beds. Vertebrate remains mark the formation as both Cretaceous and Tertiary (Spieker, 1946). The North Horn is Maastrichtian through lowest Eocene in age in this region, although only as young as Paleocene farther northeast (Lawton, 1985). Paleomagnetic work by Hobbs (1989) suggested the uppermost North Horn may be early Eocene near Wales, 20 miles (32 km) north of Sterling.

Beneath a brown pebbly sandstone bed near the base of the North Horn Formation, close to U.S. Highway 89 at the west edge of the quadrangle (center of NE¼ section 13, SWR), is a severely folded mass of dark-red, reddish-gray, and purplish-red sandstone with some pebbles that has been assigned to various formations over the years. Although the brown pebbly sandstone has a steep west dip, the reddish sandstone rolls over from a west dip to an east dip, and is offset against a fault with the basal formation of the Indianola Group forming the hanging wall on the east. Spieker (1949) included the reddish sandstone in his Morrison (?) Formation, with the brown pebbly North Horn sandstone unconformably over it. Weiss (1982a) showed the reddish beds to be lower North Horn with an angular unconformity between them and the brown pebbly sandstone. Witkind, in Witkind and Sprinkel (1982, figure 11 and p. 323) called the reddish beds Price River. Weiss and Roche (1988) showed them as part of the new basal Indianola unit (labeled "Kinu" in their figure 5), cut off from the main body of the formation on the east by a fault. Many unpublished opinions assign the reddish beds to the North Horn, often with an angular unconformity between the reddish and the brown beds, as did Weiss (1982a). In my view, the reddish sandstone represents an informal lower North Horn Formation and the brown pebbly sandstone represents an informal middle North Horn Formation. The reddish sandstone of the lower North Horn Formation is crumpled and overridden from the east by the thrusted basal formation of the Indianola Group. The brown pebbly sandstone of the middle North Horn Formation unconformably lies on the lower North Horn Formation, the thrust fault, and the basal formation of the Indianola Group.

A complication exists a little higher in the North Horn Formation at this same locality: the brown, pebbly sandstone beds, agreed by all observers to be North Horn, dip much more steeply (73° W) than the yellowish-brown sandstone beds (38° W) higher up the slope at about the middle of the North Horn section. This discordance suggests angular unconformity between the brown sandstones and the middle beds of the North Horn, for a total of two unconformities within the formation. The distortion of the reddish sandstone is readily explained by motion on the adjacent fault. The unconformities may be of the progressive syntectonic type described by Riba (1976). Multiple unconformities of the same type occur in the North Horn at Big Mountain, 18 miles (30 km) north along the mountain front (T.F. Lawton, personal communication, 1990).

Tertiary System

Flagstaff Limestone (Tf)

Regionally, the North Horn Formation grades upward into the lowest beds of the lacustrine Flagstaff Limestone. The upper beds of the North Horn are less oxidized, more limy, and less sandy than the rest of the formation. This change is not readily observed in the Sterling quadrangle because of thinning and pinching-out of the formations. A normal North Horn-Flagstaff transition can be seen only high on the north wall of Sixmile Canyon, in section 30 (NER). For the same reason, "normal" Flagstaff beds are not widespread in the quadrangle, and unusual nearshore lithofacies occur, particularly at Sterling island (CR and NER). Further, the regionally valid members of the Flagstaff, established by Stanley and Collinson (1979), are not applicable in the Sterling quadrangle.

"Typical" thicknesses and lithofacies of the Flagstaff Limestone occur in the lower flank of the Wasatch monocline south of Forbush Cove (ECR) and east of North Hollow (SER). There, great thicknesses of thin- and medium-bedded limestone and some dolomite are interbedded with very thin to thin beds of gray shale and mudstone. The carbonates are light gray and light brownish gray, but weather to very light gray or yellowish gray and appear white at a distance. The abundant carbonate beds make the Flagstaff a resistant, strongly jointed unit; thus, it tends to form tall cliffs which are readily seen within the mouth of Twelvemile Canyon, about 5 miles (8 km) east of Mayfield (SER). About 400 feet (122 m) of the Flagstaff Limestone are exposed in upper Forbush Cove. A section measured in Twelvemile Canyon is 810 feet (245 m) thick, and one measured near the mouth of Manti Canyon, a mile away from the northeast corner of the quadrangle, is 423 feet (130 m) thick. This lithofacies of the Flagstaff contains a few channel sandstone lenses regionally, although none were observed in this quadrangle.

Nearly typical beds of Flagstaff Limestone sheath the west flank of the long ridge west of the San Pitch River and Gunnison Reservoir, where they dip west into Antelope Valley and are cut by many faults and closely spaced fractures, mostly healed by calcite. The transition from the upper North Horn reddish mudstones to limestone occurs there in a short interval. In this area as well, the Flagstaff contains mostly micritic limestone high in calcium and relatively free of mud and beds of mudstone or shale. In northern Antelope Valley, several thin lenses of sandstone occur on stripped slopes of the uppermost Flagstaff, and the limestone is partly silicified in the soil zone. Large oncolites are abundant in the basal beds in sections 31 and 32 (WCR). Closer to the river, the Flagstaff overlaps the North Horn and lies in angular unconformity on the basal formation of the Indianola Group (section 6, WCR) and the Cedar Mountain Formation (sections 21, 28, NCR). The Flagstaff forms a dip slope into Antelope Valley. An unknown thickness, probably small, of Flagstaff beds is eroded away. Thicknesses in this area range from about 55 feet (17 m) in eastern section 6 (WCR) to a maximum of about 250 feet (75 m) in western section 6.

A third lithofacies of the Flagstaff Limestone lies in a north-northeast belt from near the spring in section 4 (CR), across the Palisade Lake area, to near U.S. Highway 89 in section 13 (NER). Along this belt, the Flagstaff lies unconformably (at about 90 degrees) on the Funk Valley Formation and, in SE¼ section 4 (CR), on the Sanpete and Allen Valley Formations, which formed ancestral Sterling island. Weakly cemented Cretaceous-derived sand and shale made the Flagstaff sediment very sandy and silty, but it is now strongly cemented by calcite. Thin and medium beds of sandy and silty limestone alternate with thin layers of silty and sandy shale. The beds are very poor in fossils, but a few small, dense oncolites occur. Eastward from Palisade Lake these beds thicken, become more calcareous, and grade to the more typical Flagstaff rock type where the formation paves the Wasatch monocline north of Sixmile Canyon. The complete thickness of the Flagstaff in lower Snows Canyon (section 3, CR) is 195 feet (60 m). In Warm Springs Canyon (NW¼ section 24, NER) where the Colton beds have been removed, the Flagstaff is 145 feet (45 m) thick.

The Flagstaff Limestone is the most fossiliferous of the formations exposed in the quadrangle, although fossils are common only in a few beds. Ostracodes are locally abundant, but the most common specimens are molluscs (mainly gastropods). LaRocque (1960) published the most complete account of Flagstaff paleontology. The Flagstaff ranges in age regionally from later Paleocene to early Eocene (Lawton, 1985). Paleomagnetic indications that the upper North Horn is early Eocene in the east-central Gunnison Plateau (Hobbs, 1989) suggest that the Flagstaff of the Gunnison Plateau is all Eocene in age.

Colton Formation (Tc)

The Colton separates the two great lacustrine sequences, the Flagstaff and Green River formations, and intertongues and is gradational with both. Most of the Colton beds are mudstones highly colored by various degrees of oxidation of iron; shades of red or pink predominate, but violet and purple, shades of green, and olive or brownish-olive beds also occur. The upper part is red. The colors contrast strongly with the light-gray Flagstaff and the greenish basal Green River beds. Colton colors are less bright and conspicuous in the NE rectangle but are bright again not far north of Manti. The mudstone is all weakly cemented and slumps and erodes readily.

The next most abundant rock types are sandstone and siltstone; some are reddish or greenish, but many are brownish gray. Colton sandstone is thin to medium bedded and contains a few percent of feldspar (mostly K-spar), in marked contrast to the quartzose and lithic sands of the North Horn and Flagstaff. The feldspar in the terrigenous sediment that filled Flagstaff Lake came from granitic crustal rocks far to the southeast (Stanley and Collinson, 1979; Dickinson and others, 1986). Most sandstone beds in the Colton are sheetlike, but others are channel fills that thin to both sides and are flat on the top. Such channel fills range from about 100 to 300 feet (30-90 m) in width, and may be as much as 30 feet (9 m) thick.

Limestone and calcareous mudstone also occur in the Colton. They may be faintly violet or pink, but are always light colored because of the low oxidation state of the contained iron. The limestones are all muddy, thin- and medium-bedded, dense micrite with conchoidal fracture; some are fossiliferous--with the same genera seen in the Flagstaff. The limestone and limy mudstone beds were deposited in small lakes and ponds that formed from time to time on the irregular floor of the basin. Most beds in the Colton are only local in extent, and facies changes are numerous (Volkert, 1980).

The weak Colton mudstone moves readily by gravity, especially when wet, so exposures are generally poor. The Colton is very thick regionally, 853 feet (260 m) nearby in the Gunnison Plateau, but is thin in the Sterling quadrangle because of deposition over the welt of Mesozoic beds (Ninemile and Sterling islands). The Colton is locally absent; for example, it is overstepped northwestward by the Green River in the center of the quadrangle. The thickest local interval is about 500 feet (150 m) in North Hollow. The unit is about 280 feet (85 m) thick in section 34 north of Sterling, and it pinches out between the Arapien and the overlapping Green River in the hill south of Ninemile Reservoir. The Colton probably was once nearly co-extensive with the Flagstaff Limestone, and thus it has been stripped from most of the area of the Wasatch Plateau.

The lower part of the Colton is late Paleocene in age in the Book Cliffs and Uinta Basin (Fouch and others, 1983), but developed in the Sanpete area only during the early Eocene (Fouch and others, 1983). This implies a westward spread of the fluvial/alluvial lithofacies as it encroached into Flagstaff Lake and accords with a proposed southeastern source of the feldspar in the Colton sands. However, places exist where the Colton Formation is absent, and where local lacustrine conditions persisted from Flagstaff Lake into Lake Uinta. The closest such location to Sterling is near the middle of the west side of the Gunnison Plateau, 11 miles (18 km) to the northwest, where the Green River Formation lies on the Flagstaff Limestone. Davis (1967) described several other such localities north of Sanpete County.

Green River Formation

The lacustrine sediments that accumulated in Eocene Lake Uinta, which are several thousand feet thick in northeastern Utah, are all assigned to the Green River Formation (Weiss and others, 1990). In the Uinta Basin the formation is divisible into several members, but in central Utah only two are mappable: (1) a lower one of mostly mudstone and shale, and (2) an upper one mostly of limestone (Millen, 1982). Neither member is named. Because the two are gradational over a short interval and are difficult to distinguish at poor exposures, they are separated by a dashed line on the map.

The lower member has never been dated specifically, but the lower part of the Green River, in general, is early Eocene (Fouch and others, 1983). The upper part of the Green River is placed in the middle Eocene by Fouch and others (1983). Radiometric evidence cited by Weiss (1982b) suggests that the upper part of the lower member in Sanpete Valley is latest middle Eocene. Farther south, in Sevier Valley, Willis (1986) reported late Eocene radiometric ages for the Aurora Formation, which overlies the Green River there. Bryant and others (1989a) described and dated Green River tuffs in the Uinta Basin, where the Green River terminated about the same time.

Lower member (Tgl): The lower member consists mostly of thin-bedded, highly calcareous mudstone and shale, some siltstone, and numerous thin beds of muddy micritic limestone. The mudstone and shale are greenish gray and weather to light greenish gray; the limestone beds weather to very light gray to almost white. The member slumps readily on moderate slopes, disrupting the more resistant upper member. All exposures of the lower member are on antidip slopes and are grayish green in color. The member thins over Ninemile island north and south of U.S. 89, where it lies on Arapien Shale. There, it cannot be clearly distinguished from the feather edge of the upper member (section 17, SWR). Green River beds lying on the Arapien contain no clasts of Arapien rock; the change from red, oxidized mudstone of the Arapien to green mudstone is rather sharp. These facts argue that the Green River is unconformable over the Arapien and the contact is not a thrust fault nor a diapiric intrusion of the Arapien.

Normal thicknesses of the whole Green River occur only in the southeastern quadrant of the quadrangle; the lower member there ranges from 300 to about 500 feet (90-150 m) thick. A mile (1.6 km) northeast of Sterling the lower member is about 280 feet (85 m) thick. In section 17 (SWR), it ranges from zero to about 50 feet (15 m) thick, as it thins over an irregular surface of Arapien Shale, part of Ninemile island.

Upper member (Tgu): The upper member of the Green River consists of thin, slabby beds of muddy, micritic limestone and some ostracode biomicrite, separated by partings and thin beds of calcareous mudstone and shale. The limestone beds are very light gray, light yellowish gray, and brownish gray, but weather to almost white so that bold cliffs of white show over the greenish slopes of the lower member. Many of the limestone beds contain a few fossils, but more conspicuous organic remains are ostracodal and stromatolitic limestones that occur mostly in the upper part of the member.

Near the top of the upper member, perhaps the upper 50 to 100 feet (15-30 m), the nature of the limestone changes and other types of rock occur in small volumes. The limestone is yellowish brown, silty, stromatolitic, and also silicified, especially in the southeast near Twelvemile Creek. Some thin beds of tuff are interbedded, as are local lenses of kaolinite with chert nodules. Lenses of black chert pebbles typical of the overlying Crazy Hollow Formation are mapped (L symbol on plate 1), indicating that the formations intertongue over a short interval.

The upper member of the Green River is covered only locally by beds of the Crazy Hollow. In the SCR and SER, it ranges in thickness from pinchout over Jurassic rocks to 180 to 260 feet (55-80 m). About 250 feet (75 m) of upper member beds, without a cover of Crazy Hollow, lie above Snows Canyon (section 3, CR).

Crazy Hollow Formation (Tch)

The Crazy Hollow Formation is widespread in central Utah, but not recognized outside the region. As a non-lacustrine fill of the southwest arm of Lake Uinta, it corresponds to the Uinta Formation of the Uinta Basin, but no genetic nor temporal identity is presumed. Because of the diversity of rock types, patchy occurrence (Norton, 1986), and the abundance of channel-like deposits in the region, it seems probable that the Crazy Hollow never formed a continuous sheet over central Utah as did the subjacent units.

The principal rock type in the formation regionally is red mudstone, but little occurs in the Sterling quadrangle except in sections 22 and 27 (NCR). The next most abundant Crazy Hollow rock type is considered to be the signature of the formation--lithic sandstone and pebble conglomerate of black, white, and gray chert; the white and black sand grains inspire the common term "salt-and-pepper" sandstone. This rock type is both abundant and widespread in the quadrangle; in the SCR it is pebbly (clasts are up to 4 inches [10 cm] across) at many places. Thin lenses of such pebbly sandstone, with some red mud, are present high in the Green River beds, and a knoll of Crazy Hollow in the middle of the SE¼ section 22 (SCR) is capped by a layer 15 feet (5 m) thick of yellowish-brown, silty Green River limestone. This confirms the interfingering of the two formations. Limestone of several sorts, formed in ponds and small lakes, is present in the Crazy Hollow regionally. Only one example, a bed of brownish-black, micritic, nearly pure limestone 1 to 2 feet (0.5 m) thick, is present in the quadrangle (NW¼ section 22, NCR). It contains a small fauna of freshwater, long-ranging gastropods.

No consolidated sedimentary rocks overlie the Crazy Hollow, so all thicknesses cited are minima. In the SCR and north of the railway grade in the NCR, the Crazy Hollow is 90 feet (27 m) thick. South of the railway grade it is 120 feet (37 m) thick. Norton (1986) cited much greater thicknesses of 300-365 feet (90-110 m) in Sevier County.

The Crazy Hollow was called Oligocene in age (Weiss, 1982b), but its intimate relationship to the Green River Formation argues that it is late Eocene. Possible correlatives of the Crazy Hollow in southern Juab Valley are overlain by volcanics having ages of 30-35 million years (Witkind and Marvin, 1989).

Tertiary and Quaternary Systems

No post-Eocene Tertiary deposits are exposed in the Sterling quadrangle even though Oligocene and Miocene volcanic and volcaniclastic beds are exposed nearby in Sevier and Juab Counties. The valley-fill deposits lying in Sanpete Valley, however, are of such thickness that the lower levels are surely older than Quaternary. They are considered both Tertiary and Quaternary (QT) even though the age of their base is not known.

Alluvial Valley-Fill Deposits

The broad, gently sloping surfaces of the valley floors have several sources of sediment: alluvium from through-going streams, fans on the margins, sheetwash, mudflows, and colluvium. The shapes of clasts--pebbles, cobbles, and boulders--vary with the source of material. Alluvial materials are well rounded and smooth, mudflow debris contains both angular fragments and smooth stream gravels, and colluvial materials have angular clasts. Valley fill may be regarded as a coalescence of large alluvial fans and has been mapped using that term (Witkind and others, 1987), but here the term valley fill is used.

Older valley-fill deposits ($QTvf_2$): The material of this deposit is generally like that of the more widespread younger valley-fill deposits ($QTvf_1$), but is locally more gravelly. Though the southernmost of the four mapped patches is poorly exposed, its surface is scattered with angular pebbles and cobbles. The two middle patches (SE¼ section 28 and NW¼ section 33, NCR) are stream gravels of rounded pebbles, cobbles, and some sand; they may represent material reworked by an ancestral San Pitch River. The surfaces with $QTvf_2$ are elevated 15 to 30 feet (4.5-9 m) above the younger valley-fill surfaces ($QTvf_1$) and other associated deposits. No substantial difference of thickness or age at depth between the younger and older valley fill is presumed; the *surface* of $QTvf_2$ is older, perhaps late Pleistocene.

Valley-fill deposits ($QTvf_1$): The exposed part of this unit consists of gray and brownish-gray, poorly sorted, unconsolidated clastic material (except over member E of the Arapien Shale where it is thin and reddish). The debris has accumulated in large structural lowlands to form modern, gently sloping surfaces that are concave in profile. The deposits grade laterally into colluvium, alluvial-fan, and floodplain deposits. Thicknesses are unknown, but oil wells near Manti and Ephraim appear to have penetrated 700 to 900 feet (215-275 m) of unconsolidated material without encountering a base. The age of the valley fill is late Holocene (modern) at the surface and late Tertiary at depth.

The depositional surface continues from the southwest nearly to the mouths of Ninemile and Twelvemile Canyons, but is sharply dissected by the San Pitch River because the river erodes more readily below the Gunnison dam. In sections 5, 7, and 8 (WCR), the valley-fill surface is lower east of the river than on the west for two reasons: (1) the valley profile is skewed lower to the east, and (2) the river has migrated in recent times so as to cut into a higher part of the surface.

Around the Gunnison Reservoir is a swampy area between the area shown as water on the map and the 5,390-foot (1,643 m) contour. This area is mapped as $QTvf_1$, but the 5,390 (1,643 m) contour does not coincide with the unit boundary at some places on the east side of the reservoir because wave-cut cliffs are cut in higher, older deposits ($QTvf_2$ and Qag_3).

Salt marsh deposits on valley fill (QTas): The rock material, age, and thickness of this unit is similar to neighboring valley-fill deposits ($QTvf_1$), but the valley floor here is waterlogged and contains local pond sediments. Saturation north of Sterling (sections 14, 15, 22, 23, and 27, NCR and NER) is caused by the discharge of mineral springs in the nearby Sanpete and Funk Valley Formations and by a threshold of Crazy Hollow strata in the W½ section 22 (NCR). Saturation north of Mayfield (sections 20 and 29, SWR) occurs because of springs and partial damming between adjoining alluvial fans. The salt-marsh areas are moist even in dry seasons. They support reeds and marsh hay, and accumulate whitish coatings of sulfates in the dry areas. Marshes north of Sterling are conspicuously saline because of the sulfur springs that issue from the Indianola bedrock.

Older alluvial (?) gravel (QTag): Texture, composition, and bedding of this deposit are like those of Qag_3, but this deposit has thin beds of soft sandstone and siltstone locally. The later beds and local angular clasts have the aspect of valley-fill deposits. Beds of this unit have been turned on edge, and lie in angular unconformity beneath Qag_3. The maximum exposed thickness is less than 50 feet (15 m); the setting of this deposit suggests that the original thickness was not much greater. I believe it is late middle Pleistocene in age in the Sterling quadrangle. It is correlated with part of a more extensive unit in the Manti quadrangle, thus the QTag designation (Weiss and Sprinkel, in progress).

Quaternary System

Eleven types of deposits of Quaternary age are present in the quadrangle, and 24 different units are mapped on plate 1. The units are described in groups, according to type, and from oldest to youngest within each group. The variety of units derives from the interaction of geomorphic processes with the complex tectonic history of the Sterling area.

Alluvial deposits are those directly related to streams and stream action. The larger clasts of pebbles, cobbles, and boulders are typically well rounded by the streams that carried and deposited them. The relative ages of some deposits are readily apparent, but obscure in others. The relative ages as now understood are shown in the correlation diagram (plate 2).

Alluvial-Terrace Deposits

Sixmile Canyon has had a complex history of filling by mudflow and debris-flow deposits that have subsequently been cut or modified by Sixmile Creek, a sequence of events explained later in this report. Three flat surfaces, incised by Sixmile Creek, are mapped as alluvial terraces. Their surfaces slope gently both toward and parallel to Sixmile Creek.

Oldest alluvial-terrace deposits (Qat_3): The composition appears similar to younger terrace deposits (described below), but Qat_3 stands 40 to 150 feet (12-46 m), distally to proximally, above Sixmile Creek. The thickness is unknown. These terraces are estimated to be early late Pleistocene in age. This deposit might be conceived as an equivalent of Qat_2, except that the north edge of Qat_3 is about 20 feet (6 m) higher than the base of map unit Qmf_2 (which is equal to the top of Qat_2) across Sixmile Creek (section 3, CR).

Older alluvial-terrace deposits (Qat_2): This unit is similar in composition to Qat_1, but it has less colluvial debris and contains some cross-bedded sand lenses. The material is well compacted and weakly bound with calcite-cemented mud (Wallace, 1964). Cobbles and boulders represent each of the nearby formations, but most are Flagstaff Limestone. The lower edge of the terrace stands more than 40 feet (12 m) above Sixmile Creek, but the thickness is not known. The deposit is believed to be continuous with small exposures of similar material that lie beneath Qmf_2 and that becomes more sandy downstream. Several exposures, too small to map at this scale, occur on the inner walls of Sixmile Creek, as far west as NW¼SW¼ section 33 (CR), where this deposit underlies Qaf_2. The best such exposure, and currently the best exposure of Qat_2, is nearly 30 feet (9 m) thick in NW¼NE¼ section 3 (CR), where it has a calcified red soil at the top. The deposit seems to have formed during the middle late Pleistocene, was then buried by Qmf_2 and Qaf_2, and was finally exhumed during the early Holocene. Wallace (1964) also described the burial of Qat_2 by Qmf_2, but considered Qat_2 to have been a watery mudflow material; instead it is a coarse stream gravel like that in modern Sixmile Creek.

Alluvial-terrace deposits (Qat_1): This unit consists of gray and brownish-gray, poorly sorted debris, mostly from the North Horn and Flagstaff formations. Angular colluvial material is conspicuous. Its surface stands about 160 to 170 feet (49-52 m) above Sixmile Creek; the thickness is unknown. Its correlation with surfaces or deposits in Sanpete Valley is uncertain, but this deposit formed behind a dam formed by an older mudflow (Qmf_2), and is of late Pleistocene or early Holocene age. Its formation behind the mudflow dam in Sixmile Canyon explains its youth and its height (see "Correlation and Analysis of Quaternary Units").

Alluvial Gravel and Pediment-Mantle Deposits

Alluvial (?) gravel (Qag_3): These deposits consist of a clast-supported framework of gray and brownish-gray pebbles with considerable finer matrix that is poorly bedded and has numerous poorly sorted layers. Large clasts are mostly limestone and chert from the Flagstaff. Mostly rounded, some may be early San Pitch River gravels, but the mass may be partly valley fill. The deposits are perhaps 20 feet (6 m) thick. They lie at a lower level than Qag_2 because of diapiric collapse of the Arapien Shale. They overlie older gravels (QTag) in angular unconformity at about 90 degrees. Their correlation is uncertain, but they are believed to be early late Pleistocene or possibly middle Pleistocene.

Older pediment-mantle deposits (Qap_2): Pediment-mantle deposits are sheets of alluvium spread on bedrock surfaces cut by streams. These deposits are similar to the younger pediment-mantle deposits, but the surfaces were formed at, or raised to, higher elevations and are tilted locally. The deposits are up to 40 feet (12 m) thick. Along the San Pitch River the pediments are 70 to 270 feet (21-82 m), distally to proximally, above the river. Along Twelvemile Creek the surfaces are 125 to 220 feet (38-67 m), distally to proximally, above the creek. Elsewhere (SWR) these deposits are only 20 to 30 feet (6-9 m) thick, but are elevated and are tilted 35-45 degrees. Near Twelvemile Creek most clasts are of Flagstaff Limestone, but quartzite clasts from Mesozoic beds prevail in the deposits west of the San Pitch River. The gravel pit in section 30 (SWR), which is now disrupted by a gypsum mine, exposes 0 to 12 feet (0-4 m) of sandy siltstone above about 30 feet (9 m) of sandy gravel. Where elevated above the water table (SWR), these beds are light yellow. Beds 1 to 2 feet (0.5 m) thick are cemented with limonite locally, but most are uncemented or weakly cemented with sandy mud. These beds may be a correlative of the Axtell Formation (Spieker, 1949), but contain no volcanic clasts. They are early late Pleistocene in age, judging from their elevation above modern drainages.

Pediment-mantle deposits (Qap_1): These deposits are brown to gray, (locally reddish brown), massive to crudely bedded mixtures of silt, sand, and gravel (to small boulder size). Pediment mantle is as much as 60 feet (18 m) thick in the NWR and 30 to 60 feet thick (9-18 m) in the WCR. Their surfaces are generally even and slope toward the streams and gently downstream. The surfaces range from about 20 to 50 feet (6-15 m), distally to proximally, above Twelvemile Creek. The pediment surfaces are locally uneven and elevated where the irregular surface of the diapiric Arapien Shale is at shallow depth. Clean cobble gravels in the pediment-mantle deposits are mapped separately as Qag_1. These deposits are early and middle late Pleistocene.

Older stream gravel (Qag_2): These deposits consist of coarse, cleanly washed, moderately well-sorted cobble, pebble, and small boulder gravels with little matrix. West of the San Pitch River they are point-bar deposits associated with older pediment-mantle deposits (Qap_2), are weakly cemented locally, and are less than 15 feet (5 m) thick. They thin to the north. The deposits contain many clasts of Flagstaff Limestone, as well as quartzites from nearby Cretaceous beds. Large volumes of similar gravel, at similar elevations, lie on the Arapien Shale along the east side of the San Pitch River (sections 5 and 33, WCR and CR), and are considered to be genetically and temporally related to deposits west of the river. However, those lying east of the river are dominated by limestone and chert from the Flagstaff Limestone. Because the large patches of gravel lie unconformably on irregular surfaces of the Arapien Shale, thickness ranges from 0 to 40 feet (0-12 m). The age is the same as Qap_2, and the unit probably is also coeval with the Axtell Formation.

Stream gravel (Qag_1): The pediment deposits locally contain cleanly washed cobble and pebble gravels of Flagstaff limestone, dolomite, and chert, and Green River chert. Because they lie east of the San Pitch River, they contain no quartzite from Mesozoic beds. The deposits are light gray, the color of the prevalent Flagstaff Limestone clasts, and they contain no limonite cement. The gravels occur in small patches or streaks, and are considered to be point-bar deposits in the streams that formed the pediment-mantle deposits (Qap_1). Except for the large linear deposit at the northwest corner of Mayfield (SCR), which fines northwestward, the upper surfaces are at levels similar to the enclosing pediment mantle. More such gravels may remain to be discovered. Thicknesses range from 10 to 20 feet (3-6 m). The age is the same as the associated pediment mantle (Qap_1).

Alluvial-Fan Deposits

Older alluvial-fan deposits (Qaf_2): These deposits are like Qaf_1 (described below) in form and material but are deeply dissected by modern drainages and are no longer active; however, the surfaces do merge with younger fans toward the center of the valley. These fans are probably not more than 30 feet (9 m) thick and are middle to late late Pleistocene in age.

Alluvial-fan deposits (Qaf_1; Qafs): Masses of light-brown and light-gray, locally weakly consolidated, moderately well-sorted silt, sand, pebbles, and cobbles accumulated at the mouths of canyons, where the gradient lessens in a short distance. The deposits are lobate or fanshaped in plan and have a profile steeper than the surface onto which they spread. They grade to alluvium upstream and valley-fill or floodplain deposits downstream. Most are dissected to a small degree by modern stream courses. Very small fans are included with colluvium (Qmc) on the map. The toe of one fan north of Sterling (SE¼ section 22, NCR) is saturated with mineral water from nearby springs and includes marsh deposits, and is shown as part of the adjacent salt marsh (Qafs). Thicknesses of fans are uncertain: the large ones in Arapien and Sanpete Valleys are up to 70 feet (21 m) thick; smaller ones are no more than 30 feet (9 m) thick. They are late Holocene in age.

General Alluvial and Floodplain Deposits

Oldest floodplain deposits ($Qafp_3$): These are flat-topped deposits like $Qafp_1$ and $Qafp_2$ (described below) but stand 30 to 40 feet (9-12 m) above the San Pitch River. The thickness is probably less than the relative elevation, but poor exposure of the flanks makes this a presumption. The surface is also cut into the older alluvial-fan (Qaf_2) unit. The deposits are early Holocene and possibly latest Pleistocene.

Older floodplain deposits ($Qafp_2$): These deposits are similar to $Qafp_1$, but with the organic matter leached. They are remnants of floodplains of a former gradient of the San Pitch River, 15 to 20 feet (4.5-6 m) above its modern level. Their flat surfaces parallel the modern floodplain. The thickness is unknown, but is probably similar to the younger deposits. The age is early to middle Holocene.

This unit and $Qafp_3$ are terraces in form but are associated only with the San Pitch River; other terraces, described previously, are related to Sixmile Creek. No way is known to correlate the two sets, so, to distinguish them, this set is called floodplain deposits.

Floodplain deposits ($Qafp_1$): This unit includes both channel and overbank deposits of poorly sorted, well-rounded, brown and brownish-gray, clastic debris lying close, in both area and level, to large modern streams. The coarse fraction formed mostly on point-bars, and the clast types differ among the drainages. Along Sixmile Creek clasts are Flagstaff limestone, dolomite, and chert and North Horn sandstone; along Twelvemile Creek they are the same Flagstaff rocks and Green River chert; along the San Pitch River they are mostly Flagstaff limestone and quartzite from the Cedar Mountain and basal formation of the Indianola Group. Much organic material is included in the floodplain deposits. The thickness is unknown, but probably is less than 30 feet (9 m). The age is late Holocene.

Alluvium (Qal): Sediments along small streams and in dry channels correspond genetically and in age to floodplain deposits of larger streams and are mapped as alluvium. The material is dark brown to gray, thin to thick bedded, locally cross-bedded, and poorly sorted — from clay to boulders. Thicknesses range widely, but are commonly less than 50 feet (15 m). The age is late Holocene.

Mass-Movement Deposits

Colluvium is the term applied to aprons of broken rock and soil that accumulate by falling, downslope creep, sheetwash, and rillwash. Colluvium is mapped on slopes where the debris apron is thick enough to obscure the bedrock and also where pond-like deposits of slopewash debris accumulate in closed depressions among fault blocks and in the sags on mass-wasting deposits.

Deposits of earth or rock that slide, flow, or slump downslope are mass-wasting deposits. All are characterized by poor sorting and angular clasts. The younger deposits have a high organic content. Talus deposits are mapped as colluvium. Landslide deposits lie on steep slopes, are long and narrow, and may be lobate at the lower end. Debris-flow deposits are irregular in area, may be very large, and may have other mass-wasted deposits, such as landslides, on their surface. Mudflow deposits are also elongate and of large volume; because they accumulated on lower slopes than landslides, they are considered to have been watery when in motion. Toreva blocks are slumped masses that retain coherent bedding. Small slump blocks are mapped with colluvium.

Older colluvium (Qmco): This material is similar to Qmc, but is more gray due to leaching of organic material. Aprons of Qmco are formed mostly of debris from the Flagstaff Limestone, are weakly consolidated, are deeply dissected, and cover larger areas than Qmc. In Round Valley (SE¼ section 23, NER) both ages of colluvium cover most of the bottom of the basin because the soft, muddy sandstone of the Funk Valley Formation erodes easily; thus ridges of Qmco stand above gullies floored by Qmc. Qmco deposits are from 0 to 100 feet (0-30 m) thick. No longer active, they are late Pleistocene in age.

Colluvium (Qmc): Gray to brown, heterogeneous mixtures of fragments of many sizes and shapes (mostly angular) mantle lower valley walls, the bases of steep cliffs, and closed depressions. Formed on moderate dip slopes and steep antidip slopes, the deposits grade to the gentle slopes of valley fill, alluvium, or fans. Deposit thicknesses range from 0 to 50 feet (0-15 m), and are Holocene in age. Similar deposits, called "slope deposits" by Baum and Fleming (1989), are mostly less than 16 feet (5 m), but locally are 80 feet (25 m) thick in nearby canyons of the Wasatch monocline.

Older mudflow deposits (Qmf_2): This deposit is like Qmf_1 in texture and topography, but it had a much higher fluid content, for it ran out of Forbush Cove nearly 3 miles (4.8 km) into Sanpete Valley. It is older than Qmf_1 because it has been incised in lower Forbush Cove, where Qmf_1 lies within it and at a lower level. Average clast size increases rapidly eastward, toward the source. Several large blocks of Flagstaff Limestone lie on the deposit and are mapped (map symbol "B"); the largest (16x38x9 feet [5x11.5x3 m]) is in NW¼ section 2 (ECR). The thickness of Qmf_2 varies with position along its length: it is 100 to 130 feet (30-40 m) near the junction of Funk and Sixmile Creeks; 150 feet (46 m) farther up Funk Creek (NW¼NW¼ section 2, ECR), 390 feet (120 m) in SW¼NW¼ section 2 (ECR), about 75 feet (23 m) northeast of Sterling, on the Sixmile Road; and about 50 feet (15 m) just east of Sterling. Qmf_2 is middle and later late Pleistocene in age.

This unit is the "bouldery deposit" of Wallace (1964), who studied it and related deposits in Sixmile Canyon. The substrate over which Qmf_2 spread is the matrix-poor cobbly deposit Qat_2, and the contact is exposed in NW¼NE¼ section 3 (CR). Qaf_2 also lies next to the toe of Qmf_2 and contains the farthest-traveled giant boulder (18x33x9 feet [5.5x10x3 m]), in NE¼NW¼ NE¼ section 5 (WCR).

Mudflow deposits (Qmf_1): This deposit consists of gray and brownish-gray, very poorly sorted, angular debris of rock and earth lying in valleys. The surface of this deposit is irregular, hummocky, and has poorly integrated drainage. The abundant finer fractions – mud and sand – are from the North Horn Formation. Most large clasts, including limestone boulders to 18 feet (5.5 m) long, are from the Flagstaff Limestone. The deposit in Funk Canyon (ECR) is exposed at two places where it is 200 to 300 feet (60 - 90 m) thick. It is middle Holocene in age. Qmf_1 appears to have been a linear mass of debris that moved forward as a unit into a lowland.

Debris-flow deposits (Qmd): These are masses of brown to gray, heterogeneous debris of earth, broken rock, and vegetation. They are irregular in shape, and lie on moderate slopes. Small earthflows and rockfalls contained within these masses are not mapped. Three formations undergo mass-wasting readily, so the debris-flow deposits are mapped in three units; each resembles its source formation in color and texture, but bedding is disturbed or destroyed. These masses are active periodically but most of the movement probably occurred during the middle and late late Pleistocene.

Debris-flow deposits of North Horn Formation (Qmd (TKn)): This unit consists of debris-flow deposits from, and lying on, the North Horn Formation. Much Flagstaff Limestone is included in these deposits, which are conspicuous and voluminous on the shaded south slopes of Sixmile Canyon (NER and ECR). Their thickness is not measurable without drilling, but is probably about 200 feet (61 m).

Debris-flow deposits of Colton Formation (Qmd(Tc)): This unit consists of debris-flow deposits from, and lying on, the Colton Formation. The colors appear like "in-place" Colton rock, but bedding is absent. In North Hollow (SER) the masses are about 180 feet (55 m) thick.

Debris-flow deposits of Green River Formation (Qmd(Tg)): This unit consists of debris-flow deposits from, and lying on, the Green River Formation. The main Green River unit involved is the lower mudstone member, which fails readily when wet. The limestone upper member coheres better, but the limestone is jointed so great blocks may tilt and slide on the lower member. This condition is well developed in section 10 (CR), but the isolated blocks are not mapped. The thickness is about the same as the lower Green River member, perhaps 300 to 400 feet (90-122 m).

Landslide deposits (Qms): Such deposits are brown to gray mixtures of soil and rock fragments of many sizes and shapes; resistant rock types form angular fragments. Deposits are elongate and lie on steep slopes that permit repeated sliding; a hummocky surface is common in the lower parts. Landslides are concentrated in the North Horn Formation, the shaly upper beds of the Flagstaff Limestone, and in the lower member of the Green River Formation. Thickness ranges widely, but probably does not exceed 60 feet (18 m). The small slides are all Holocene, but the large ones have been active repeatedly, probably including during the wet episodes of the late Pleistocene. Several large landslides that initiated or reactivated in Ephraim Canyon during the 1983-85 wet cycle are described by Baum and Fleming (1989). Similar slides occur in Sixmile Canyon, east of this quadrangle.

Toreva blocks (Qmt): Toreva blocks occur in two settings in the quadrangle: blocks of Flagstaff Limestone that have slumped onto North Horn beds and blocks of upper Green River limestone that have slumped onto mudstones of the lower member. A large example of the latter, contained in a large landslide (SW¼SE¼ section 4, CR), has been rotated far from its original attitude in the cliffs above. Because toreva blocks slump on a curved surface, concave upward, their thickness is problematic. The smaller ones may well be only Holocene in age, but the larger are probably late Pleistocene.

Lake Sediments

Lake deposits (Ql): Lacustrine deposits are evenly and thinly bedded, mostly fine-grained, fossiliferous muds and sands in the Sterling quadrangle. Three small deposits, only about 5 acres (2 ha) in total area, are exposed. The two smaller ones are in abandoned railroad cuts in NE¼SE¼ section 21 (NCR); the largest one lies in an embayment east of the railroad grade in NW¼SE¼ section 28 (NCR). The largest deposit was studied in detail by Roy (1962), who erroneously cited section 12 as its location. The two small deposits appear to lie on member E of the Arapien Shale, and are not overlain by other deposits. The base of the large deposit is covered, but it is capped by Qag_2. These three outcrops probably are remnants of more widespread sediments deposited when the San Pitch River was ponded.

Roy (1962) measured and described 13 beds in the lacustrine deposits totalling 12.8 feet (3.9 m) thick. Most beds are clay, but sand, marl, and fine pebble layers also are present. Oddly, the marls are unfossiliferous; fossils are concentrated in the clay beds low in the deposit and in a 2-foot-thick (0.6 m) sand near its top. Roy identified 17 species of molluscs: 2 freshwater clams, 9 freshwater snails, and 6 terrestrial snails. He concluded that because all but one of the species is still living in Utah, the deposit must be relatively young: comparison with the fauna and sedimentation rate of Great Salt Lake (Eardley and Gvosdetsky, 1960) suggested an age of about 200,000 years. I believe the unit is late late Pleistocene in age. If the lake was dammed by mass-wastage owing to late Pleistocene pluvial events, this estimate is accurate, but the cause of the lake is not yet established.

CORRELATION AND ANALYSIS OF QUATERNARY UNITS

The "Correlation of Quaternary Units" chart (plate 2) displays the 27 units according to estimates of their ages and their mutual relations in the field. In this section groups of deposits of various types thought to be correlative in time are described, from youngest to oldest in each group. Wallace (1964) studied the alluvial and mass-wasting deposits of lower Sixmile Canyon and their effects on the San Pitch River. Such units mapped for this report are not all congruent with his. Therefore comparisons are drawn and a new sedimentary history developed.

Late Holocene

Deposition is active on these nine mapped units: $Qafp_1$, Qal, Qaf_1, Qafs, $QTvf_1$, QTas, Qmc, Qms, and Qmt. Thus, at least the upper part is late Holocene in age. Four of these units have been deposited over long periods, such that the lower parts may be as old as late Pleistocene (Qms, Qmt) or Tertiary ($QTvf_1$, QTas).

The 1983-85 wet cycle caused many new and renewed landslides in central Utah. Only a few of these affected the Sterling quadrangle, mostly by stripping vegetation and thin soil from the upper beds of the Flagstaff Limestone on the Wasatch monocline (SER).

Middle Holocene

Two units of this age were mapped, Qmf_1 and $Qafp_2$. Qmf_1

is the younger of two giant mudflow deposits, for it lies in a cavity cut into the older one (Qmf_2) by Funk Creek. Although erosion, slumps, and small rockfalls affect Qmf_1 today, it is not an active mudflow; thus it is older than the currently developing deposits.

Small remnants of an older floodplain ($Qafp_2$) lie in San Pitch Valley (WCR). Differences in elevation compared to $Qafp_1$ and $Qafp_3$ seem too large to be mere unpaired fluvial terraces, so it is suggested that $Qafp_2$ represents a former level of the San Pitch River that formed about the time of mudflow Qmf_1.

Early Holocene

The surfaces of two mapped deposits ($Qafp_3$, Qat_1) are of this age. $Qafp_3$ incises and, thus, is younger than units Qmf_2 and Qaf_2. Qat_1 was built behind a dam formed in Sixmile Creek by Qmf_2. Both $Qafp_3$ and Qat_1 seem to bridge the Pleistocene-Holocene boundary. The high elevation of Qat_1 is explained by its formation in a temporary lake behind the dam.

Middle Late and Late Late Pleistocene

Six types of deposits are believed to have developed under unusually wet conditions because very large volumes of rock and earth were moved. The widespread wet conditions known to have occurred during the pluvial interval of the late Pleistocene suggest medial and late late Pleistocene ages for these deposits. The six deposits are: Qaf_2, Qmco, Qms, Qmd, Qmf_2, and Qmt. Four kinds of mass-wasting deposits (Qmco, Qms, Qmd, and Qmt) developed on steeper slopes and on north-facing canyon walls along the Wasatch monocline. Movement of landslides (Qms) and toreva blocks (Qmt) continues intermittently today, but on a smaller scale.

Two deposits (Qmf_2 and Qaf_2) are related genetically and discussed together. The mudflow (Qmf_2) developed in the following sequence: (1) it surged westward from the area now called Forbush Cove, (2) it spread a short distance down an old valley connecting the cove with Snows Canyon (NW¼ section 2, ECR), (3) it filled a bedrock gap between Forbush Cove and Sixmile Creek (NW¼NW¼ section 2, ECR), (4) it spilled into Sixmile Canyon, overspreading the surface of terrace Qat_2, (5) it dammed Sixmile Creek and the opening now occupied by Palisade Lake, forming an early version of the lake (the dam has since been enhanced artificially), (6) it followed the canyon southwestward toward the gap in the basal Funk Valley Formation and onto Qat_3 in SE¼NW¼ section 3 (CR), and (7) it deflected westward into Sanpete Valley as far as the west edge of Sterling. As the mudflow thinned and lost velocity in its distal reaches, watery fines from the mass spread farther to form the older alluvial fan (Qaf_2). The mudflow carried the largest boulders (B-symbol on map) found in any deposits of the quadrangle.

The debris dam across Sixmile Creek trapped water and large volumes of alluvial and colluvial debris to form the high terrace (Qat_1) that remains today only on the south side of the canyon (ECR). Most terrace material came from the weak North Horn Formation, which is broadly exposed on the south wall of the canyon. A corresponding terrace may never have formed on the resistant north wall composed of the Sixmile Canyon Formation. Sixmile Creek soon cut the debris dam formed by Qmf_2 and exhumed and incised the older terrace (Qat_2).

The history of the older mudflow (Qmf_2) was the focus of a study by Wallace (1964); my history is similar to his, with two important exceptions. First the older fan (Qaf_2) west of Sterling is fan-shaped and intimately related to the mudflow (Qmf_2). Wallace believed that this deposit consisted of alluvium spread by Sixmile Creek after it cut through the mudflow dam upstream. On the contrary, as the dam was incised, a new stream profile was established, one which incised both Qmf_2 and Qaf_2 and formed the oldest floodplain surface ($Qafp_3$).

The second exception concerns a sinuous, sloping lowland that stretches from Funk Canyon to Snows Canyon, mostly in the S½ of NW¼ section 2 (ECR). It is now partly floored by Flagstaff Limestone and partly by thin colluvial and landslide deposits. The shape and trend of this valley suggest that Funk Creek formerly flowed through it to Snows Canyon; therefore Sixmile Creek must have pirated Funk Creek at some time. Wallace (1964) believed that the mudflow plugged the old valley and diverted Funk Creek into Sixmile Creek. Although Qmf_2 deposits do obtrude a little way into the old valley (S½NW¼ section 2, ECR), the piracy of Funk Creek occurred long before the mudflow moved. In NW¼ section 2 (ECR) an exposure of Qmf_2 extends nearly 400 feet (120 m) above Funk Creek. Further, where Funk Creek turns 90 degrees (NW¼NW¼ section 2, ECR), Qmf_2 still fills the gap the creek had already cut through the bedrock wall into Sixmile Canyon. After the mudflow (Qmf_2), Funk Creek dissected the flow and also cut a new rock gap, still in use, into Sixmile Canyon.

Early Late and Middle Late Pleistocene

Most of the remaining Quaternary units cannot be correlated with confidence, nor are their ages readily distinguished. A few are paired. Most of these deposits do not show evidence of the very wet conditions that correlated the younger deposits described above. Several deposits were influenced by local diapirism of the Arapien Shale, making comparative elevations meaningless for correlation. They will be discussed in order of increasing apparent relative age.

Four map units appear to be early to middle late Pleistocene in age: $QTvf_2$, Qap_1, Qag_1, and Qat_2. Qap_1 and Qag_1 are physically associated and are of the same age. Association of these deposits with the other two units is not certain, but all are older than Qmf_2.

Three higher units are somewhat older; probably early late Pleistocene in age: Qat_3, Qap_2, Qag_2. Qat_3 probably is not much older than Qat_2, but no evidence bears on the relationship. Qap_2 and Qag_2 are physically associated and are of the same age.

Middle Pleistocene and Early Late Pleistocene

Three small deposits remain that cannot be related even indirectly to those already described. The three are the lake beds

(Ql) and two gravels (Qag_3 and QTag). The gravels are juxtaposed and can be ordered in time, but their relationship to other deposits is unknown. Ql is not associated with either Qag_3 or QTag, although it does underlie a widespread younger gravel (Qag_2). Roy (1962) studied the stratigraphy and paleontology of the lake beds, which appear to be late Pleistocene. Wallace (1964) considered Qag_2 to have been deposited during a large mudflow (Qmf_2) event and suggested the mudflow event had caused the lake by damming of the San Pitch River, but this is not possible because Ql underlies Qag_2.

STRUCTURE

General

The Sterling area contains many unusual and puzzling structures and relationships, such as multiple unconformities, gravel beds unconformable on older gravel beds, contorted mudstone beds, moderation of steep dips to nearly flat dips over short distances, a large monocline, and great thicknesses of overturned piedmont fan deposits.

Folds

Only the larger folds in the Sterling quadrangle are described. The small anticlines and synclines in the Arapien Shale in the SWR (cross section C-C′) are not discussed.

Sanpete-Sevier Antiform

Both Sanpete and Sevier Valleys are underlain by a long, linear upwarp of Mesozoic beds that was named the Sanpete-Sevier Valley anticline by Gilliland (1963). The structure appears to be anticlinal at some places, but it is so sheared and crushed in the Sterling area, where Sanpete Valley is narrowest, that it is better called an antiform--a welt of strata upwarped by an unknown mechanism or combination of mechanisms. A culmination of the antiform occurs in the Sterling area, for it is lower elsewhere in Sanpete and Sevier Valleys.

The west flank of the antiform, shown in cross sections A-A′ and B-B′, consists of Cretaceous clastic formations that are overturned to the west, as they are along most of the Gunnison Plateau front (Weiss, 1982a). The overturned beds form a tight, overturned syncline in the ridge between Antelope Valley and the San Pitch River (WCR). The beds of the west flank flatten within a very short distance to the west, however, and reappear with moderate east dips on the west side of the Gunnison Plateau (west of the quadrangle) (Standlee, 1982; Lawton, 1985; Mattox, 1987). Both this syncline and the rest of the west flank of the Sanpete-Sevier antiform are cut by several high-angle normal faults parallel to the strike of the bedding.

The east flank of the antiform is just east and northeast of Sterling where strata of the Indianola Group flatten from very steep east dips near the structure to very low east dips within 3 miles (5 km) to the east.

The core of the antiform is exposed in two places. Near Sterling it is represented by a welt of member E of the Arapien Shale and a thin section of the Twist Gulch Formation. Between Ninemile Reservoir and the south edge of the quadrangle, the exposed core is an overturned and thrust-faulted anticline composed of all five members of the Arapien Shale (section C-C′). The anticline incorporates a number of subsidiary folds, particularly in member C. The west side of the steeply plunging nose of the anticline is cut by a high-angle reverse fault (sections 18, 19, SWR). This fault may represent a late episode of local deformation of the Arapien, as mentioned by Standlee (1982). The two exposures of the core of the Sanpete-Sevier antiform are separated by a fault north of Ninemile Reservoir.

Two processes have been proposed for formation of the Sanpete-Sevier antiform, diapirism (Witkind, 1982) and thrusting (Standlee, 1982; Lawton, 1985). The antiform is here considered to be the result of lateral compression associated with thrusting during the Cretaceous Sevier orogeny. Standlee (1982, figure 14) and Lawton (1985, figure 6) have shown that the Navajo Sandstone (which underlies the structure) is gently folded, but not broken, as far east as the western part of the Wasatch Plateau, and that abnormal thicknesses of Arapien Shale accumulated above the Navajo near the axis of the antiform. As no anticline affects the Navajo, the thickening of the overlying Arapien was from stratigraphic duplication by thrusts. Thus, simple diapiric upwelling of evaporites in the Arapien cannot be the sole mechanism responsible for the antiform. However, the thick accumulation of Arapien mudstone, salt, and gypsum has contributed to later local diapirism that continues to the present.

Within the thrust model, two mechanisms have been suggested for the formation of the antiform. A choice cannot be made between them based on surface geology of the Sterling area alone. In the first model, Standlee (1982) suggested "back-thrusting," whereby multiple thrusts in the Arapien Shale created a welt of mudstone and evaporites, and that continued compression caused a back thrust that overturned rocks now at the edge of the Gunnison Plateau. Lawton (1985) suggested a slightly different model in which the antiform is a "triangle zone," a prism of Arapien Shale piled up by multiple thrusts that overturned the beds of its west flank.

I believe that the steep flank beds of the antiform and the overturned west flank resulted from crushing during thrusting. Later diapirism of the thickened Arapien Shale elevated the structure and led to erosion of older Cretaceous beds. Younger Cretaceous and Tertiary beds were later deposited across the structure. The antiform has experienced subsequent local uplift from time to time as demonstrated by the north-south arching of the Quaternary gravels (Qag_2). The highest point or culmination is close to the mouth of Sixmile Creek.

Wasatch Monocline

Of regional magnitude similar to the antiform, the west-dipping Wasatch monocline bounds the west flank of the Wasatch

Plateau for about 70 miles (112 km). It is best developed in southern Sanpete County, including the Sterling area. Only the lower reaches of the fold are included in the Sterling quadrangle; the west-dipping limb continues 5 miles (8 km) east of the quadrangle before the strata flatten out on top of the Wasatch Plateau. The monocline is typically expressed at the surface by the Flagstaff Limestone, and locally by the Green River Formation. The Colton Formation is easily eroded and has been removed from all but the toe of the monocline. The monocline is cut by many antithetic normal faults. South of Sixmile Canyon the faults trend nearly north-south and are parallel to the strike of the beds. To the north, beds in the monocline strike about 30 degrees east of north and the antithetic faults strike only about 20 degrees east of north. This kink in the monocline is probably associated with several other changes of structure near Sixmile Creek. East of the quadrangle, the higher part of the monocline is cut by a graben.

No consensus has developed to explain the formation of the Wasatch monocline. Spieker (1949) ascribed it to differential subsidence. Neither Standlee (1982) nor Lawton (1985) discussed the monocline in detail, but Standlee's figure 14 implies that a listric, down-to-the-east normal fault occurred along a preexisting back-thrust. Witkind and Page (1984) stated that diapiric collapse by loss of salt and gypsum from the Arapien Shale dropped the western edge of the Wasatch Plateau into the area that is now Sanpete Valley.

Witkind and Page's hypothesis may work for most of Sanpete and Sevier Valleys, but it does not explain the termination of the lower edge of the monocline against the Sanpete-Sevier antiform in this quadrangle. Near Sixmile Canyon, the Wasatch Plateau approaches the Gunnison Plateau most closely and the strike of the Wasatch Plateau changes by about 25 degrees. At that point, the toe of the monocline abuts culminations on the Sanpete-Sevier Valley antiform; specifically, it abuts the Late Cretaceous beds that formed Sterling island in Flagstaff and Uinta Lakes (CR and NER) and the Arapien Shale that formed Ninemile island (sections 17 and 20, SWR) during part of the history of those lakes (Weiss, 1969). These islands were elevated both before and since the times of the Tertiary lakes, for a syncline in Tertiary beds lies between them and the lower slopes of the Wasatch monocline. In contrast, Witkind and Page (1984, figure 4) postulated a simple collapse of the monocline into the zone of the Sanpete-Sevier Valley antiform.

Synclines

Several synclines are mapped in the quadrangle; four are discussed here. Two extend through the middle of the quadrangle, parallel to the north-south structural trend. Neither is very conspicuous because flank beds are exposed only in patches. The longer syncline lies in Sanpete and Arapien Valleys and stretches from section 22 (NCR) to section 29 (SWR). At its north end, Colton, Green River, and Crazy Hollow beds are deformed; at the south end only the upper member of the Green River Formation is folded.

A second syncline lies at the foot of the Wasatch monocline. Its northern end is in section 24 (NER). It continues southward as a shallow, asymmetrical fold to the right-angle bend of Snows Creek in SE¼ section 3 (CR). The Flagstaff Limestone forms its west flank, and Flagstaff and some Colton beds in the Wasatch monocline form its east flank. South of Snows Canyon the syncline is shallow and poorly developed, and it bends westward around the south end of Sterling island. This area is highly faulted. The faults and mass-wastage deposits obscure the west limb, which is expressed by sandy Flagstaff beds. The east limb is poorly developed, but there is a sense that the upper member of the Green River Formation slopes west-northwestward here, rather than directly west as it does in the Wasatch monocline at Ninemile Canyon. East of Sterling island, closure on the syncline has been accentuated by faulting approximately along its axis. Although many of the faults are displaced down-to-the-west (perhaps caused by diapiric collapse in the valley), most faults show down-to-the-east displacements, like the antithetic faults that cut the Wasatch monocline. On and near Sterling island all the faults are bedding-plane faults that displace units of the Indianola Group.

A tightly folded, overturned syncline occurs in older Cretaceous units in the ridge west of the San Pitch River, but it is only intermittently exposed. It lies low on the west limb of the Sanpete-Sevier antiform.

A short, shallow syncline occurs in section 17 (SWR). It folds the upper member of the Green River Formation, and is separated from the big syncline in Arapien Valley by a short anticline. The syncline is cut by several faults parallel to its length, and is the result of differential movement of the underlying Arapien Shale.

Anticlines

An anticline that affects only beds of Tertiary age lies along the Gunnison Reservoir from about the north edge of the quadrangle to the mouth of Sixmile Creek. It is represented by only a few outcrops. Because of the great disparity of elevation, a high west limb and low east limb, it may better be called an antiform. The west limb is formed mostly of Flagstaff Limestone, with local patches of North Horn beds. The east limb is expressed by the Colton, Green River, and Crazy Hollow Formations at the north end and by small exposures of the upper member of the Green River at the south end. A difference in the dip of the two limbs is ascribed to local, post-Eocene diapirism along the welt of Arapien Shale that lies beneath and east of the reservoir. The difference in elevation of the two sides results from the frontal fault (Gunnison fault of Weiss, 1982a) of the Gunnison Plateau, which has a large displacement farther north but decreases to zero within the Sterling quadrangle.

A small anticline extends north-south for about 1 mile (1.6 km) in section 17 (SWR) at the top of the steep west flank of the syncline in Arapien Valley. It is also a consequence of diapirism by the Arapien beds.

The west flank of the Sanpete-Sevier antiform is the tight, overturned syncline mapped west of the San Pitch River. The Mesozoic beds of the west limb of the syncline are upright and nearly horizontal to east-dipping (sections 12 and 13, SWR and WCR). Because Mesozoic strata near Mellor Canyon in the

Gunnsion quadrangle dip westward (Mattox, 1992), the strata must reverse dip direction between the two areas, forming an open anticline. The axis is probably under Antelope Valley.

Faults and Fractures

Rocks in the Sterling quadrangle are much broken by faults and fractures, and one instance of faulted unconsolidated deposits is known (W½ section 33, CR). Most of the faults are high-angle normal faults associated with the extension that formed the Great Basin. Several thrust faults have been fundamental to the development of structure in the area; some of these are exposed at the surface and others are known only from subsurface data. Several high-angle faults separate major blocks within the quadrangle, but show little direct evidence of their existence. Because the numerous high-angle normal faults are superposed on the folds and larger faults, they will be described last.

Thrust Faults

The basic elements of the structure of the quadrangle are the thrust faults that formed during the Sevier orogeny, and which are evidenced mainly by subsurface data (Standlee, 1982; Lawton, 1985). The principal displacement was by plates of Arapien Shale, Twist Gulch Formation, and some Cretaceous rocks sliding eastward on multiple imbricate thrusts in the ductile Arapien Shale. An unknown number of splays occurred within the Arapien that heaped up a welt of Arapien and Twist Gulch beds (Standlee, 1982, figure 14; Lawton, 1985, figure 6).

Local thrusts of several orientations also occur in the Arapien Shale. An anticline, overturned to the west and thrust westward and upward, is exposed in the core of the Sanpete-Sevier antiform in the White Hills (SWR) (Section C-C′). The thrust may be consonant with the back thrusts suggested by Standlee (1982). North of Twelvemile Creek the thrust surface turns into a high-angle reverse fault. Steeply west-dipping thrusts (or high-angle reverse faults) occur on the west flank of the antiform (Section C-C′). Although they are consonant with close compression and shearing of the formation and with overturning of the antiform, they may have been formed during diapiric uplift of the Arapien core of the Sanpete-Sevier antiform.

Major High-Angle Normal and Reverse Faults

"Major" faults are those that separate major blocks within the quadrangle, not just those with great length or large stratigraphic separation. For example, some of the antithetic faults cutting the Wasatch monocline extend for miles, but they are no different from the many subsidiary antithetic faults in style or mechanism. "Major" faults will be described from west to east across the quadrangle.

The westernmost structure is a large down-to-the-west fault along the east side of Antelope Valley, at the foot of a Flagstaff Limestone cuesta (NWR). The fault is present in the quadrangle near the north edge and is the east boundary fault of the "Divide graben" of Mattox (1987). The graben carries the resistant upper member of the Green River Formation. Due to differential erosion, the upper member forms the crest of the southern part of the Gunnison Plateau. In the Sterling quadrangle the stratigraphic separation on the fault decreases southward to zero in section 31 (WCR) where Tertiary beds flanking Antelope Valley are in proper stratigraphic position. The west boundary of the Divide graben is a zone of normal faults just outside the northwest corner of the Sterling quadrangle. The graben resulted from fracture of the plateau slab during basin-and-range extension.

The east front of the Gunnison Plateau is an erosional fault-line scarp, and locally a fault scarp, along most of the length of the plateau. The throw is great in the north and diminishes southward to zero in the Sterling quadrangle, probably not far south of Gunnison Reservoir. The fault is called the Gunnison fault in the sections published by Weiss (1982a). Although a high-angle normal fault at the surface, the Gunnison fault is best explained as an east-directed listric normal fault along bedding planes in the Arapien Shale of the Sanpete-Sevier antiform (Standlee, 1982; Lawton, 1985). It may have formed coincidently with the formation of the Wasatch monocline during the extension that formed the Great Basin.

In the NW¼ section 18 (SWR), a high-angle fault is inferred between the small exposures of the Arapien Shale and the Cedar Mountain Formation because the area separating the two outcrops cannot accommodate the regional stratigraphic thickness of the Jurassic Twist Gulch Formation. This relationship is best explained by west-directed shortening along a concealed fault, with the Arapien on the hanging wall overriding the Cedar Mountain Formation.

A north-northwest-trending fault with very limited exposure (section 5, WCR) divides the northern and southern elements of the Jurassic beds in the core of the Sanpete-Sevier antiform. It probably extends northward beneath the San Pitch River Valley (where it may become the Gunnison fault), and southward beneath Arapien Valley. Northeast of the fault, the exposed units are member E of the Arapien Shale and the Twist Gulch Formation. Member E is so distorted that various attitudes may be measured on the few distinguishable layers, but the Twist Gulch dips steeply eastward just west of Sterling. The welt of Arapien member E continues northward for about 9 miles (14 km), into the Manti quadrangle. Southwest of the fault, the exposed Jurassic core consists of the overturned and faulted anticline already described. The southern area was raised by diapiric action with respect to the northern, and the northern area seems to have been less tightly folded. Major movement on the fault, which may have been a high-angle reverse motion, was completed prior to deposition of the Green River Formation, for the Green River lies unconformably on member B of the Arapien Shale south of the fault and upon member E north of the fault.

A major fault is displaced down-to-the-east along the east edge of Arapien Valley. It is probably continuous, but is mapped only where evidence for it is certain (W½ section 9, CR and E½ sections 20 and 29, SCR). Springs issue from the fault at two places; the northern spring is a major source of water for Ninemile Reservoir.

The easternmost major normal fault is similar to the one in

Arapien Valley in that it is down-to-the-east like the antithetic faults of the Wasatch monocline. It is exposed in section 25 (NER), but probably extends nearly to the north edge of the map.

Minor High-Angle Normal Faults

High-angle normal faults abound over most of the bedrock surface of the quadrangle, except in exposures of the Arapien Shale in the White Hills. Some faults are present within member E of the Arapien in the central part of the map area, but the Arapien is so ductile that the faults can be observed only where overlying brittle units such as Colton and Green River beds are involved. The high-angle normal faults may be grouped into three sets.

The first set is the most widespread and includes faults of the greatest length, the antithetic faults on the Wasatch monocline. These faults tend generally to parallel the strike of the monocline. Where the brittle Flagstaff and upper Green River beds are thin, the antithetic faults parallel bedding in the subjacent steeply dipping Indianola units.

A second set of abundant faults, most of which are much shorter than those in the monocline, cuts the Tertiary and Cretaceous beds west of the San Pitch River in the ridge that forms the southeastern corner of the Gunnison Plateau (cross-section A-A′). Of these, the faults of greatest length and throw are those that cut the Indianola units parallel to the strike of the beds. These faults have displaced the overturned flank of the Sanpete-Sevier antiform down to the west. The origin of these faults, by analogy with structures farther north along the Gunnison front (Weiss, 1982a), is believed to have been reverse faulting of the Sanpete-Sevier antiform against the resistant upturned edge of the Cretaceous clastic wedge. Later, reactivated extensional movement along the same planes of weakness faulted the younger North Horn and Flagstaff beds as well. Numerous cross faults are associated with the later movements, perhaps related to buoyant Arapien evaporites and mudstone. A conspicuous cluster of normal faults oblique to both sub-groups of this group cuts the Flagstaff Limestone in the NWR. The trend of these faults is not easily explained except perhaps by warping of the limestone, which is particularly well cemented and brittle.

The third set of high-angle normal faults have in common their north-central and south-central locations in the quadrangle and the fact that they cut thin sections of Tertiary units that lie on weak Mesozoic units. West of the San Pitch River the faults cut the North Horn and Flagstaff Formations; east of the river they cut the Colton, Green River, and Crazy Hollow Formations. All these faults are believed to have developed as the subjacent Arapien Shale swelled and sagged due to local diapirism and dissolution throughout the Tertiary Period. Some faults close to the west shore of Gunnison Reservoir may have developed in part by stream undercutting of the Cedar Mountain Formation. A fault crossed by the abandoned railroad grade in the W½ section 22 (NCR), brought Cedar Mountain beds close to Crazy Hollow beds, with a small block of Green River between. Nearby outcrops of member E of the Arapien suggest that the Cretaceous section has been sheared and thinned by this fault. This fault is a down-to-the-east, high-angle reverse fault (but is included in this group because of similar genesis) that formed by mid-Tertiary diapirism in the Sanpete-Sevier antiform near the reservoir. As such, it is a mirror-image of the down-to-the-west faults in the Cretaceous units west of the river.

One fault cuts several Quaternary deposits near the boundary of sections 32 and 33 (CR). It is recognized by a steep scarp that cannot be explained by sedimentary processes. A small patch of Green River Formation west of the fault near the south end lies much lower than another Green River outcrop just a half mile (0.8 km) to the east. The east side of the fault was probably raised by diapiric action of the shallow Arapien Shale.

Fracture Zones

At several places on the flank of the Wasatch monocline, Flagstaff Limestone beds have been fractured for some distance. These long zones of broken rock are readily permeable to ground water, and thus support thicker and more luxuriant vegetation than neighboring areas. The lines of more dense vegetation are conspicuous on the ground and on aerial photographs.

Unconformable Surfaces

Most Quaternary deposits are unconformable on bedrock or even on other Quaternary units, and many intraformational disconformities occur in bedrock units, especially in the Cedar Mountain Formation and the Indianola Group. Most of these do not require description. However, some unconformable surfaces between and within formations have implications for the diastrophic history of the Sterling quadrangle and are briefly described from oldest to youngest. Many are surfaces in Cretaceous and Tertiary rocks that are angular unconformities near and over the Sanpete-Sevier antiform, grade within a short distance east or west into disconformities, and then, a little farther on, into conformable formational contacts. This relationship developed because sedimentation was syntectonic and the antiform was a source of sediment that spread both east and west.

Channel gravels at the base of the Cedar Mountain Formation lie disconformably on the top of the Twist Gulch Formation (SW¼ section 5, WCR). These gravels signaled the intensifying Sevier orogeny, sedimentologic aspects of which are treated by Schwans (1988). The great volume of conglomerate in the basal formation of the Indianola Group is disconformable on the Cedar Mountain Formation, and is evidence of the peak of the Sevier orogeny, also described by Schwans (1988).

The coarse basal part of the Sixmile Canyon Formation is disconformable on the Funk Valley, and the Price River Formation pinches out on the Sixmile Canyon Formation with a small intervening angular discordance (12-18 degrees) and a local basal conglomerate. East of the Sanpete-Sevier antiform, these units thicken, are finer grained, and become mutually conformable. Elevation and tilting of the antiform resulted in erosion of its upper surface and in the local unconformities.

The North Horn Formation lies in angular unconformity on the Cedar Mountain, basal Indianola, Sanpete, and Indianola channel conglomerate units in the SWR, WCR, NWR, and NCR parts of the quadrangle. In Sixmile Canyon (section 25, NER), the North Horn lies with an angular discordance of nearly 40 degrees on the Price River and the upper part of the Sixmile Canyon Formations. Angular unconformities within the North Horn Formation (SWR), and between the Flagstaff and the North Horn Formations(SWR), show that deformation and syntectonic sedimentation persisted into earliest Tertiary time.

The Flagstaff Limestone lies unconformably on eight different formations along the flanks of the Sanpete-Sevier antiform and on ancestral Sterling island. It lies with angular unconformity on six of the eight and overlaps wedge edges of the other two. Angular relations between the Flagstaff and the Cedar Mountain, basal Indianola, Sanpete, and North Horn Formations exist in the hills west of the San Pitch River (SWR, WCR, NWR and NCR). In NE¼ section 13 (SWR), resistant limestone of the Flagstaff dips 12 degrees less than sandstone in the middle of the North Horn. In Sixmile Canyon, the Flagstaff overlies the feather edge of the North Horn. On Sterling island (CR, ECR, NER) the Flagstaff overlaps thin edges of the Price River and North Horn Formations to lie across upturned edges of the Sixmile Canyon, Funk Valley, Allen Valley, and Sanpete Formations.

Both the Colton and Green River Formations also unconformably overlie older units; again the angular unconformities are on upturned beds of the Sanpete-Sevier antiform. Not far east and west of the antiform both formations are gradational and conformable, mutually and with their adjacent units. Near the antiform, the Colton is unconformable upon member B (section 17, SWR) and probably member E (section 28, NCR) of the Arapien Shale. It probably also lies unconformably on the basal formation of the Indianola Group (boundary of sections 27 and 34, NCR), but the contact is not exposed. The Green River is unconformable on member B of the Arapien Shale (sections 8 and 17, SWR and section 32, CR), and on the Twist Gulch Formation (sections 4 and 33, CR). The Crazy Hollow Formation oversteps the Green River Formation locally and lies with angular unconformity on member B of the Arapien Shale (section 5, WCR) and on member E (section 22, NCR).

Pebbly sandstone beds of the Crazy Hollow suggest a disconformity where they lie on the Green River, but the pebble beds are only locally developed. In many areas outside of the quadrangle, the Green River is succeeded by limestone beds, or sandy and pebbly Crazy Hollow rock is interbedded with the upper part of the Green River (Weiss, 1982b; Norton, 1986; Mattox and Weiss, 1989). This intertonguing relationship of the two formations is shown in this quadrangle as well (SCR) by lenses of Crazy Hollow chert pebbles within the uppermost Green River, and by a bed of Green River silty limestone that lies low in the Crazy Hollow (section 22, SCR).

Two unconformable surfaces within the Quaternary units are especially significant. In SE¼ section 28 (NCR) gravels (Qag_2) overlie lake deposits (Ql) disconformably, and in SE¼ section 21 (NCR) gravels (Qag_3) lie nearly horizontally over gravels (QTag) that dip as much as 85 degrees east (compare with Witkind, 1981, figure 3). The first instance resulted from the complex interaction of sediments from Sixmile Canyon with those of the San Pitch Valley. The second suggests the intensity of young, local diapiric elevation, tilting, and collapse within the Sanpete-Sevier antiform. It is also possible that QTag slumped off the antiform, and was later covered by Qag_3, a possibility suggested by T. F. Lawton (personal communication, 1990).

Tectonic Mechanisms

Spieker (1946, 1949) explained most of the complex structural phenomena in the Sanpete and Sevier Valleys area by invoking repeated episodes of crustal compression and differential elevation of crustal blocks. The first geophysical seismic traverse of the Gunnison Plateau was made in 1957, but only better equipment and techniques of the 1970s provided extensive subsurface data that allow a revised interpretation (Armstrong, 1968; Standlee, 1982; Lawton, 1985).

Gilliland (1963) suggested that the Sanpete-Sevier Valley anticline formed by regional compression assisted by diapirism of Arapien mudstones in the axial region of the fold. In several reports, Witkind (1982) and Witkind and Page (1984) developed that idea into a mechanism to explain vertical movements (both up and down) in central Utah. Witkind postulated episodic upwelling by salt and gypsum in the Arapien Shale to form long, linear welts, followed by dissolution of the evaporites and collapse of overlying strata. Upwelling produced folds and unconformities; solution-collapse produced the Wasatch monocline, disturbed strata, and much normal faulting.

I believe that elevation and tilting by diapirism and collapse by solution have occurred locally and many times in central Utah, but that the process has operated upon structural features and zones of weakness already produced by thrusting and folding during the Sevier orogeny. Erosion of elevated areas produced unconformable relations. The surface geology alone cannot demonstrate this conclusion, but subsurface data (Standlee, 1982; Lawton, 1985) argue strongly against the development and oscillation of the Sanpete-Sevier antiform by diapirism alone. The surface geology accords neatly with the published subsurface data. The great prism of Arapien Shale in the antiform was developed during the Sevier orogeny, and contacts of Tertiary formations with the Arapien Shale show no evidence of intrusion by the Arapien against them; shearing motion was confined within the Arapien Shale.

GEOLOGIC HISTORY

Many of the events that formed the Sterling quadrangle have already been described. A summary follows (table 1). For additional information on the correlation of the bedrock units, see Weiss and Roche (1988) and on regional relations of rock units, see Fouch and others (1982, 1983).

Consolidated Units

The oldest rocks exposed in the Sterling quadrangle are the marine Middle Jurassic Arapien Shale and marginal marine Twist Gulch Formations; the former is markedly evaporitic and the latter feldspathic. No rocks of the Late Jurassic and earliest

Cretaceous are known in the area. Beginning in medial Early Cretaceous time, orogenic compression from the west began to affect central Utah (Lawton, 1987; Weiss and Roche, 1988). Sheets of Precambrian, Paleozoic, and early Mesozoic rocks were thrust eastward and stacked in the Sevier orogenic belt, which lay about 25 miles (40 km) west of Sterling. Concealed thrusts and thrust-related folds reach as far east as the western Wasatch Plateau. Correlating well logs with surface structure and proprietary seismic data, Standlee (1982) and Lawton (1985) have detailed this structural foundation of central Utah.

Enormous volumes of quartzose and lithic sediment were shed off the orogenic welt into the foreland basin along the margin of the Cretaceous interior seaway. In the Sterling area this material was deposited as piedmont fans and alluvial plains marginal to that seaway. In the early stages, perhaps Barremian to early Albian, sediment came from fine-grained lower Mesozoic strata, which explains the high ratio of mudstone to conglomerate in the Cedar Mountain Formation. Large clasts in Cedar Mountain and Indianola sediments are Precambrian and Cambrian quartzite and middle Paleozoic limestone and dolomite, and were derived as those sources were exposed in the Sevier orogenic belt. Coarse deposits of late Albian to Cenomanian age are conspicuous in the basal formation of the Indianola Group.

The remaining formations of the Indianola Group record the filling of the western margin of the seaway, a process that was not continuous. Marine sediments reached westward into the Sterling quadrangle and formed the Allen Valley Shale and the shaly part of the Funk Valley Formation. Littoral sands were interbedded with coal swamps during the middle Campanian Sixmile Canyon sedimentation.

Heller and Paola (1989) argued that Lower Cretaceous gravels widespread in the Intermountain West were not a consequence of the Sevier orogeny, but were from regional uplift in the area of the Great Basin. Although they did not consider central Utah in particular, if their hypothesis is applied to the Sterling area, the unit derived by regional uplift might be the Cedar Mountain Formation and that arising from the Sevier orogeny would be the basal formation of the Indianola Group.

A late Campanian episode of compression from the Sevier orogeny, perhaps with back thrusting, ended Indianola sedimentation, folded the Indianola and older beds forming the Sanpete-Sevier antiform, and elevated them. Sterling and Ninemile islands were two ancestral highlands formed by this deformation. Diapirism by the Arapien Shale in the antiform may have occurred also, but no direct evidence of such is known. Erosion of the up-bent beds supplied sediment to the Price River Formation, which pinches out against Sterling island from the east. This late compression from the Sevier orogenic belt may also have shifted Cretaceous proximal piedmont lithofacies eastward, because Indianola beds west of the San Pitch River seem too coarse to have graded into the sandstone sections north of Sterling in not quite 2 miles (3 km). The Sanpete-Sevier antiform continued to provide sediment until early Tertiary time, though the Sevier orogeny had ended.

The post-orogenic sediments of Maastrichtian through Eocene age have a much different character. These younger deposits are terrestrial, contain large volumes of freshwater limestone, and have coarse clastics near the base that were reworked from Cretaceous units. These sediments filled basins between the diminished Sevier orogenic belt and Laramide uplifts farther east and southeast in Utah (Dickinson and others, 1988). The sequence is regionally conformable on the Price River Formation and consists of three fluvial-alluvial units (North Horn, Colton and Crazy Hollow Formations) that are separated by two lacustrine units (Flagstaff and Green River Formations). Each of the five formations pinches out over the Sanpete-Sevier antiform and thickens both east and west of it. Although mutually conformable regionally, unconformities and overlaps interrupt the sequence locally on and near the Sanpete-Sevier antiform and demonstrate the intermittent local elevation of the antiform by diapirism.

The changes between alluvial and lacustrine conditions were all gradational, alternating from fluvial-dominated basin floors dotted with ponds and small lakes to giant lakes.

Feldspathic sands common in the Colton Formation were transported from Laramide uplifts of basement rock far to the southeast (Dickinson and others, 1986). Prior to this, sediment had come only from the west or from local areas. The change suggests that the Sevier orogenic belt had worn down and no longer dominated the basin fill.

The stratigraphy of the Green River Formation is simpler in central Utah than in the Uinta Basin, where several members of complex lithofacies have been mapped (Weiss and others, 1990). Saline and highly organic rocks so abundant in the Uinta Basin do not occur in the central Utah arm of Lake Uinta. Both climate change and drainage are believed to have terminated Lake Uinta (Dickinson and others, 1988; Hansen, 1990). Crazy Hollow sedimentation appeared first in the latest stages of Lake Uinta and gradually became the prevailing sediment on the basin floor. Volcanic rocks lie on the Crazy Hollow elsewhere in central Utah, but in the Sterling quadrangle the late Eocene Crazy Hollow is the youngest exposed consolidated rock unit.

Unconsolidated Deposits

The history of the unconsolidated deposits is a climatic history (Thompson, 1990), and much of it is implicit in the chapter on correlation of Quaternary units. Here the diastrophic aspects of late Tertiary and Quaternary history are summarized.

The thickness of the valley fill and associated salt-marsh deposits is a consequence of the formation of the Wasatch monocline, probably by eastward listric faulting during regional extension, which began 10 to 12 million years ago (Bryant and others, 1989b). The small difference in levels of the older and younger valley fills is ascribed to diapiric swelling of the Sterling area. The old gravel (QTag) was rotated about 90 degrees westward during diapiric elevation of the mass of Arapien Shale east of it. The same motion tilted back the cuesta of Colton and Green River Formations, and raised the Arapien nearby in fault contact against the Crazy Hollow Formation. T.F. Lawton (personal communication, 1990) suggested that QTag may have rotated by slumping off the welt of Arapien Shale. More or less continuous solution of the subjacent evaporites is presumed, but the collapse of overlying deposits must have been intermittent.

Table 1.
Diastrophic events that have shaped the Sterling quadrangle.

TIME	PROCESS	RESULT
late Holocene	stability (?)	surface accumulation; incision by drainages
mid-Holocene	diapiric elevation	slight ponding of Sanpete Valley to north; $Qafp_2$ cut
	solution	minor lowering
early Holocene	diapiric elevation	slight ponding of Sanpete Valley to north; $Qafp_3$ cut
late late Pleistocene	slight diapiric elevation	Qaf_2 cut and also the younger pediment Qap_1 - Qag_1
	solution	sagging of syncline of Tg?
middle late Pleistocene	diapiric elevation	cutting of older pediment Qap_2 - Qag_2?
	solution	sagging of syncline of Tg?
early late Pleistocene	diapiric elevation	dislocation of QTag & formation Qag_3
Late Pliocene to middle Pliocene	stability	formation of QTag
early Oligocene?	faulting collapse	Sanpete Valley dropped against Gunnison Plateau and Wasatch monocline?
late Eocene	elevation	planing of Tg and deposition of Tch on Ja
early late Eocene	elevation	rising White Hills and Tg cover (SWR, WCR)
early Eocene	*elevation	Tg overlaps Tc and laps onto Ja
early Eocene	*elevation	Tc unconformable on Ja and possibly Kb
Maastrichtian/Paleocene	elevation	Sterling island raised; no TKn and only younger Tf deposited; TKn formed off island
late Campanian	elevation and compression	Sterling and Ninemile islands formed; truncation of Ki (Indianola Group); rapid overlap by Kpr
early Campanian	compression	tighten Sanpete-Sevier Valley antiform; deform Ja at White Hills & Ninemile Reservoir; move Ki west facies (Indianola Group) eastward
late (?) Albian	compression	thrust west plate over eastern; rumpled the Sanpete-Sevier Valley antiform; initiate deposition of Ki
Barremian/Albian	compression	initiate Sevier orogeny and depostion of Kcm

** May not be two separate motions but a persistent high antiform onto which the two formations lapped.*

Perhaps QTag is an example of such a collapse; if so, it is unique in the Sterling quadrangle. The low elevations of Qag_3 and QTag compared to younger deposits is ascribed to their lowering by solution of evaporites from the shallow Arapien Shale.

Pediment mantle and associated gravel deposits are conspicuous in the Sterling quadrangle, but not beyond it. Their very presence shows the work of local diapirism, and the distinction of two different ages (Qap_1-Qag_1 and Qap_2-Qag_2) shows intermittent diapiric activity. Further, Qag_2 east of the San Pitch River is arched north-south today. It is significantly higher near the Gunnison Dam than at its north and south ends, which suggests some diapiric swelling since its deposition. Directly north of the Sterling quadrangle, Sanpete Valley is broad and swampy, and the San Pitch River meanders. Low welts of Arapien Shale and knolls of tilted gravel parallel the river for several miles. Both conditions suggest Quaternary diapiric action that raised the Arapien, tilted the young gravels, and elevated the south end of Sanpete Valley. A general trend of elevation there during the Quaternary is also suggested by the abandoned floodplains ($Qafp_2$ and $Qafp_3$) now dissected by younger surfaces.

ECONOMIC GEOLOGY

Several kinds of mineral deposits occur in the Sterling quadrangle, but only three are of current economic significance: gypsum, limestone, and sand/gravel. Mining of gypsum from members A and B of the Arapien Shale in section 30 (SWR) began in 1989. The deposit is nearly at the surface and was partly covered by the older pediment mantle (Qap_2). No other large deposits of gypsum have been observed in the quadrangle.

Limestone suitable for crushing for fill and road metal is widely available in the Flagstaff Limestone and the upper Green River Formation. Chert in the latter, however, is a serious drawback for some uses. Local fracturing lowers the value of the limestone, although ostracodal and oolitic limestone of the upper Green River is used elsewhere in Sanpete Valley. The local Green River beds are too fractured and siliceous for satisfactory building stone. The Flagstaff Limestone beds west of the San Pitch River are high-calcium rock and are closely fractured. In years past, there were many test pits in sections 20, 21, and 29 (NWR and NCR), probably for the former sugar mill in Centerfield, Sevier County. The pits were all refilled and graded early in the 1980s. Flagstaff Limestone was burned for lime in pioneer days. Pratt and Callaghan (1970) gave analyses of Flagstaff and Green River samples from several localities in the quadrangle.

Sand and gravel is widely available from many of the Quaternary deposits, particularly the alluvial materials. They can be used for fill or subgrade metal where good sorting is not a requirement. The alluvial deposits do not contain large volumes of clean sand, so screening may be required. Rather clean gravels of smoothly rounded pebbles and cobbles occur in units Qag_1 and Qag_2. Large areas of the latter occur in easily reached benches only about a mile (1.6 km) west and northwest of Sterling. Both benches have been exploited for fill and road metal in the past, but no major extractions have been made recently.

Salt was mined west of Sterling cemetery (CR) in pioneer days. The only other outcrop of salt is in member B of the Arapien Shale in sections 17 and 18 (SWR), but it is inconveniently located compared to larger known deposits in Sevier County.

Coal in the Sixmile Canyon Formation was important until about World War I. Several mines supported the town of Morrison along Sixmile Creek (SE¼ section 35, ECR) (Richardson, 1906; Pratt and Callaghan, 1970).

Prospect pits near the Green River-Crazy Hollow contacts (SCR) (C-symbol on map) are in non-plastic clayey material; the objective was fullers earth, but none was found (Pratt and Callaghan, 1970, p. 35, 52).

There is no current production of oil or gas from the Sterling quadrangle nor from the immediate area. However, the presence of source and reservoir rocks in the Cretaceous section, and the thrusted and diapiric structures, make this an interesting area for future exploration. Pratt and Callaghan (1970) described the older wildcat wells. Stark and Gordon (1982) supplied a statistical summary of exploratory drilling in Sanpete County. Most exploration has occurred in northern Sanpete Valley, the Gunnison Plateau, and the northern Wasatch Plateau.

WATER RESOURCES

As is the case with so many parts of the Intermountain West, water resources are the most valuable assets of the Sterling quadrangle, and all of the water rights are fully appropriated. The San Pitch River has been dammed and the water diverted for irrigation of northern Sevier Valley near Gunnison and Centerfield. Sixmile Creek maintains Palisade Lake, a recreation site. Together with discharge from the old Morrison coal mine, it contributes to the San Pitch River below the dam and thence to irrigation in northern Sevier Valley. Ninemile Reservoir is filled by springs and provides a habitat suitable for game fish. The reservoir feeds a highline canal that waters the northeastern corner of Sevier Valley. Twelvemile Creek is also tributary to the San Pitch River and thus provides water to northern Sevier Valley. Whatever is not used for irrigation goes via the San Pitch River to the Sevier River and then into the Sevier Bridge Reservoir.

Until the 1970s, Sixmile and Twelvemile Creeks and the San Pitch River fed ditches that irrigated fields in the Sterling quadrangle. Now, however, most farmers use piped distribution systems and irrigate by sprinkling. Ground water is pumped from wells and surface water is piped from higher elevations. Use of the confined-water system has permitted an increase of irrigated acreage of about 30 percent. The surface-water supply is thus applied more efficiently, but pumpage from alluvial fans and the valley fill has increased from former times. A large spring near Sterling (center of SE¼ section 4, CR) is the source of culinary water for the city of Gunnison, to which the water is piped.

GEOLOGIC HAZARDS

Three kinds of geologic hazards are of concern in the Sterling quadrangle: earthquakes, floods, and landslides. The area lies within the Intermountain seismic belt, but Sanpete Valley is considered less active than the Wasatch fault zone to the west and the east-central Wasatch Plateau to the east (McKee and Arabasz, 1982). Small tremors are frequent in both of those zones and quakes of moderate severity occur every few years, but none have affected the Sterling area recently. Moderate quakes with local damage in Sanpete Valley have been concentrated in the Manti Canyon area, just north of the Sterling quadrangle (Pratt and Callaghan, 1970). One fault scarp cuts Quaternary deposits in sections 32 and 33 (CR), but it is not known to be associated with an historic earthquake.

Floods are the most frequent threat to property and persons in the Sterling area. Gunnison Reservoir is typically less than full, so it operates as a safety catchment for floods on the San Pitch River. Sixmile and Twelvemile Creeks, however, have no flood-control structures. Both have catchments of many square miles on the flank and top of the Wasatch Plateau. These areas receive large volumes of snow each year and frequent violent orographic rainstorms in warmer seasons. In addition, the formations below the Flagstaff Limestone in the Wasatch Plateau are all permeable and can store an enormous volume of ground water. When spring snowmelt and rainfall combine with ground-water discharge, Sixmile and Twelvemile Creeks flood dangerously. When rock and soil are saturated the lag time between rainfall and flood runoff is very short. Irrigation developments in the narrow parts of the canyons and the bottom lands along the creeks are particularly subject to washout. In May of 1984, the foundation of the U.S. 89 bridge over the San Pitch River was severely weakened by deep, turbulent water.

Many acres of mass-wastage deposits occur in the Sterling quadrangle, but most are old and stable. Further, all landslides are on slopes at moderate and high elevations and far from dwellings and fixed agricultural installations. Even the wet years of 1983-1985 caused relatively little slide action in the area. The Arapien Shale includes some expandable clays that make the soil unstable when wet and may cause construction problems.

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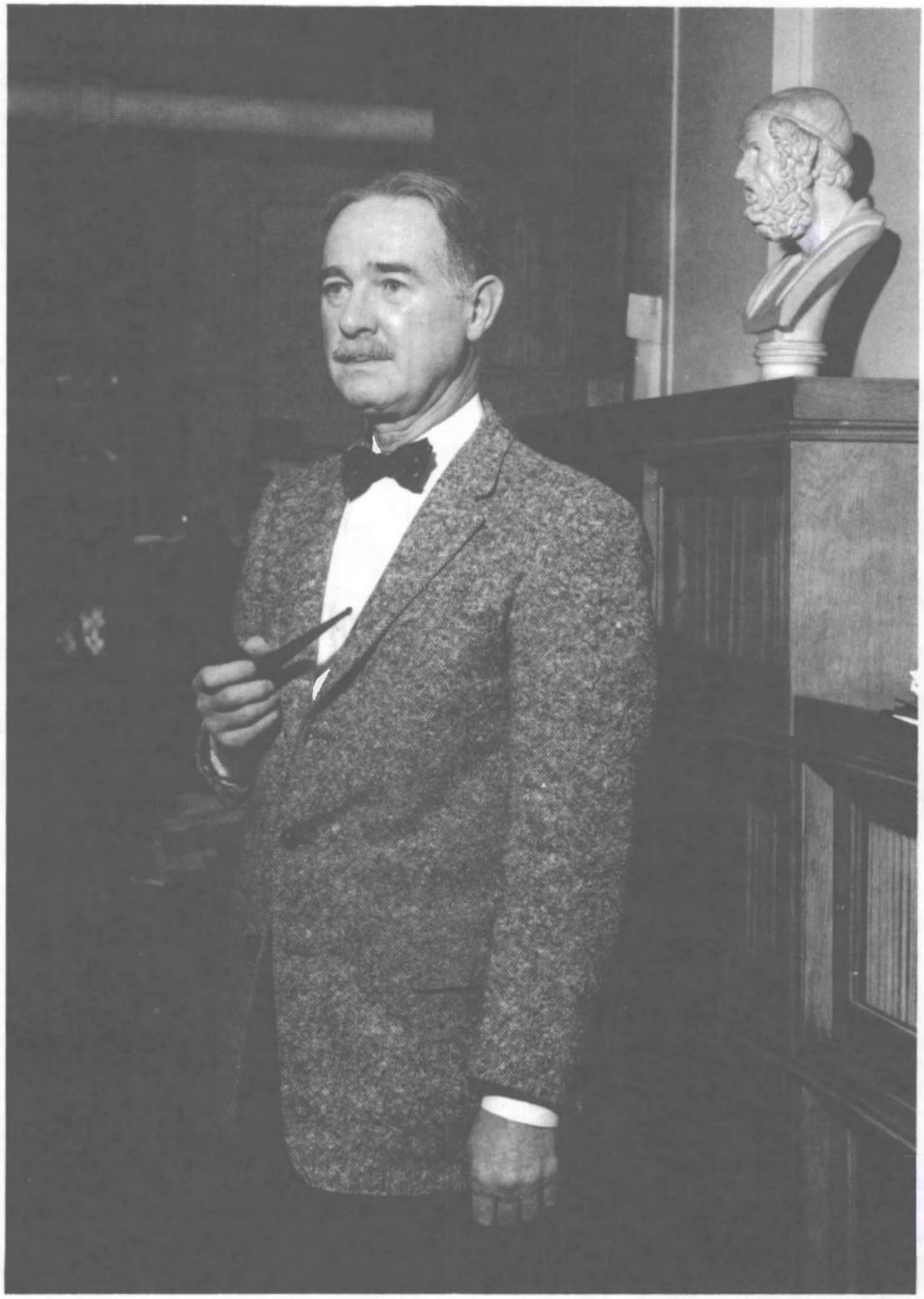

DEDICATION -

This map and report are dedicated to the memory of the late EDMUND MAUTE SPIEKER, a pioneer student of the geology of the High Plateaus region, ingenious explainer of difficult and unusual geology, and inspiring teacher who filled me with respect and admiration for central Utah, its geology, and his work upon it.