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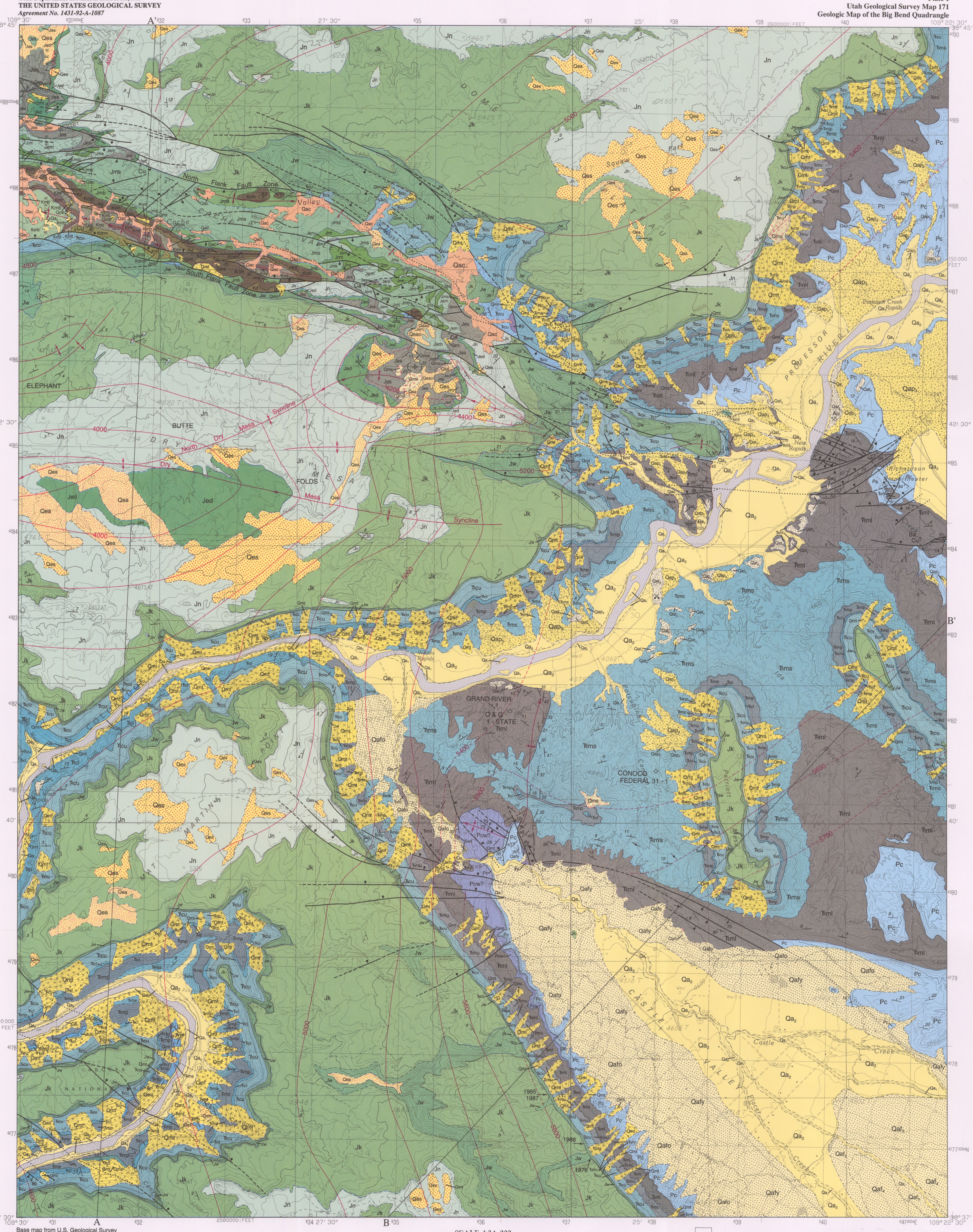


Base map from U.S. Geological Survey
Big Bend 7.5' Quadrangle, 1985

SCALE 1:24 000

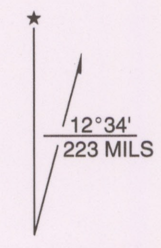
1 .5 0 1 MILES

1000 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10 000 FEET

1 .5 0 1 2 KILOMETERS

1000 0 1000 2000 METERS

CONTOUR INTERVAL 40 FEET



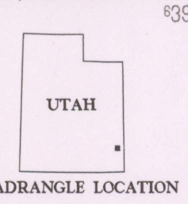
1998 MAGNETIC DECLINATION
AT CENTER OF SHEET

GEOLOGIC MAP OF THE BIG BEND QUADRANGLE, GRAND COUNTY, UTAH

by

Hellmut H. Doelling and Michael L. Ross

1998



QUADRANGLE LOCATION

1	2	3
4		5
6	7	8

1 Mollie Hogans
2 Cisco SW
3 Dewey
4 The Windows Section
5 Fisher Towers
6 Moab
7 Rill Creek
8 Warner Lake

ADJOINING 7.5' QUADRANGLE NAMES

Field work: by Doelling in 1982, 1983, 1989, and 1993,
by Ross in 1989 and 1990
Grant C. Willis, Project Manager
Lori J. Douglas, Cartographer

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DESCRIPTION OF MAP UNITS

Qa₁, Qa₂ Alluvium - *Unconsolidated deposits of poorly to moderately sorted silt, sand, and lenses of gravel; Qa₁ is located in active larger channels and floodplains; Qa₂ deposits form the first surface 6-40 feet (2-12 m) above the active channels and are characterized by weak soil development. Thickness up to 25 feet (8 m).*

Qat₃, Qat₄ Alluvial terrace-gravel deposits - *Moderately sorted, subrounded to rounded, poorly stratified gravel in a gray, calcareous, sandy matrix; forms rounded knobs on small hills along the Colorado River; variety of clast lithologies that are exotic to quadrangle; Qat₃ is about 100 feet (30 m) above the river; Qat₄ is about 130 feet (40 m) above the river. Maximum thickness 20 feet (6 m).*

Qaf₃, Qaf₄, Qafy, Qafo Alluvial-fan deposits - *Unconsolidated deposits of poorly sorted, generally unstratified, muddy to sandy cobble gravel; boulders present in proximal areas; Qaf₃ and Qaf₄ form dissected stony surfaces and subtle ridges in Castle Valley; deposits exhibit petrocalcic soils ranging from Stage I to IV; younger (Qafy) and older (Qafo) deposits form coalesced fans along the margins of Castle Valley. Typical thickness 3-40 feet (1-12 m); in Castle Valley may be up to 350 feet (107 m) thick as basin-fill deposits.*

Qap₃, Qap₄ Pediment-mantle deposits - *Poorly sorted, sandy, matrix-supported gravel; locally contains lenses of sand and/or clast-supported gravel; gravel ranges from pebbles to boulders; deposits are locally derived and have an orange-red-purple shading; detritus deposited as a relatively thin veneer on uneven pediment surfaces; mixed alluvial-fan, ephemeral stream, colluvial, and eolian processes. Deposits are subdivided based on height above current drainage and grading to alluvial terraces along the river. Maximum thickness 25 feet (8 m).*

Qmt Talus deposits and colluvium - *Generally angular rock-fall blocks, boulders, and small fragments deposited as veneers on slopes below ledges and cliffs; colluvium contains additional slopewash debris of poorly sorted rock fragments in a sandy to muddy matrix. Thickness 0 to 30 feet (0-9 m).*

Qms Landslide deposits - *Large coherent blocks to fragmented masses of bedrock and surficial debris transported downslope by mass movement. Thicknesses vary.*

Qes Eolian sand deposits - *Generally fine- to medium-grained quartzose sand forming thin,discontinuous accumulations of sand sheets and small dunes. Thickness up to 10 feet (3 m).*

Qea, Qeao Mixed eolian and alluvial sand deposits - *Thin, unconsolidated accumulations of sand deposited and reworked by eolian and alluvial processes; moderately to well sorted; generally restricted to ephemeral washes and hollows. Qeao deposits are mainly sand but contain minor clay and gravel lenses; form thick deposits capped by a Stage V petrocalcic soil suggesting an early Pleistocene age. Qeao thickness locally exceeds 160 feet (49 m).*

Qac Mixed alluvial and colluvial deposits - *Poorly sorted, unconsolidated mixtures of clay- through cobble-size detritus with random boulders; clasts vary from subrounded to angular; located along narrow ephemeral washes where colluvium is reworked and transported away by alluvial processes in active channels. Thickness up to 15 feet (4.6 m).*

Mancos Shale

Kmb Blue Gate Shale Member - *Mostly light-gray marine shale, slope former, commonly containing sandy beds which are slightly more resistant; youngest consolidated unit exposed in Cache Valley. Incompletely exposed in quadrangle; exposed thickness 500+ feet (152+ m).*

Kmf Ferron Sandstone Member - *Light-brown to medium-gray sandstone, sandy shale, marine shale, and carbonaceous shale; thin bedded; more resistant than members above and below; locally fossiliferous near top. Thickness 90-120 feet (27-37 m).*

Kmt Tununk Shale Member - *Medium-gray marine shale, slope former containing a few sandy beds, especially near the top; sandy beds are yellow gray to brown gray. Thickness about 400 feet (122 m).*

Kd Dakota Sandstone - *Light-gray to yellow-gray sandstone, conglomerate sandstone, and conglomerate with subordinate gray sandy shale and carbonaceous shale; forms ridge in Cache Valley. Thickness 40-50 feet (12-15 m).*

Kdcm Dakota Sandstone and Cedar Mountain Formation, undifferentiated - *Locally deformed and attenuated, as mapped on the south wall of Cache Valley; description same as for Kd and Kcm. Thickness indeterminable, but does not exceed thickness of combined Kd and Kcm.*

Kcm Cedar Mountain Formation - *Variegated slope-forming mudstone interbedded with ledge-forming gray and brown quartzite, conglomerate, and gritstone. Mudstone is mostly light green, gray, lavender, and white. Thickness 200-240 feet (61-73 m).*

Morrison Formation

Jmb Brushy Basin Member - *Mostly variegated to bright-green, slope-forming mudstone with thin ledges of conglomeratic sandstone, conglomerate, nodular-weathering limestone, and gritstone. Ledge formers are more abundant in the lower part of the member; locally attenuated. Thickness 300-340 feet (91-104 m).*

Jms Salt Wash Member - *Light-yellow-gray, cross-bedded, lenticular, ledge-forming sandstone interbedded with red and gray, slope-forming mudstone and siltstone. Thickness about 250 feet (76 m).*

Jmt Tidwell Member - *Red silty shale, with interbeds of fine-grained yellow sandstone and gray limestone; contains large, white siliceous concretions; lower 6 to 15 feet (1.8-4.6 m) thin to medium beds of fine- to medium-grained,non-calcareous brown sandstone and red siltstone that form a steep slope and that correlate with the Summerville Formation. Thickness 40-60 feet (12-18 m).*

Entrada Sandstone

Jem Moab Member - *Pale-orange, gray-orange, pale-yellow-brown, or light-gray, fine- to medium-grained, calcareous, massive, cliff-forming sandstone; upper surfaces prominently jointed. Thickness 90-110 feet (27-34 m).*

Jes Slick Rock Member - *Red-brown or brown, very fine- to fine-grained eolian sandstone; calcareous or iron-oxide cemented; massive, weathers to form smooth cliffs and bare rock slopes; commonly covered with self-derived sands; not as resistant as Moab Member above, but more resistant than Dewey Bridge Member below. Thickness 250-350 feet (76-107 m).*

Jed Dewey Bridge Member - *Dark-red, fine-grained, silty sandstone; mostly iron-oxide cemented; in irregularly contorted, indistinct "lumpy" medium to thick beds. Thickness 40-60 feet (12-18 m).*

Jn Navajo Sandstone - *Orange to light-gray, eolian sandstone, mostly fine grained, cemented with silica or calcite; crops out as vertical cliffs in deep canyons and as domes and rounded knolls elsewhere; contains local thin, hard, gray carbonate beds; well displayed, high-angle cross-beds. Thickness 250-400 feet (76-122m).*

Jk Kayenta Formation - *Moderate-orange-pink, red-brown, and lavender sandstone interbedded with subordinate dark-red-brown to gray-red silty mudstone, lavender-gray intraformational conglomerate, and limestone mostly of fluvial or lacustrine origin; light-orange to light-gray eolian sandstone beds more prominent in upper third; commonly micaceous; mostly cemented with calcite; resistant, forms thick step-like ledges between more massive Navajo and Wingate Sandstones; upper part less resistant and important bench former in quadrangle. Thickness 240-300 feet (73-91 m).*

Jw Wingate Sandstone - *Mostly light-orange-brown, moderate-orange-pink, or moderate-red-orange, fine-grained, well-sorted, cross-bedded sandstone; calcareous or siliceous cement; forms nearly vertical cliffs along canyon walls or thick-terraced cliff where shattered; cliff surfaces commonly coated with dark-brown desert varnish. Thickness 250-350 feet (76-107 m).*

Chinle Formation

Ŧcu Upper Member - *Moderate-red-brown or gray-red, fine- to coarse-grained sandstone and siltstone with subordinate pebblestone or gritstone, and gray limestone; slope forming with prominent ledges; slope-forming units are fine grained and generally display indistinct bedding; ledge-forming units are fine to coarse grained and platy to very thick bedded. Thickness 200-460 feet (61-140 m); sections less than 300 feet (91 m) are generally over or immediately adjacent to diapirs.*

Ŧcl Lower Member - *Mottled gray, purple, and red-brown interbedded sandstone, conglomerate, and siltstone; forms alternating ledges and slopes; contains paleosol layers exhibiting abundant and distinct vertical tubes with fossil plant remains. Thickness 0-380+ feet (0-116+ m), locally missing over or near diapirs and very thick in rim synclines.*

Moenkopi Formation

Ŧmu Pariott and Sewemup Members, undivided - *undivided where poorly exposed.*

Ŧmp Pariott Member - *Red-brown sandstone interbedded with "chocolate"-brown, orange-brown, or red siltstone, mudstone, and shale; sandstone is fine to medium grained and commonly pebbly, micaceous, poorly to well sorted, and forms a series of ledges; siltstones and mudstones form steep slopes. Thickness 0-450 feet (0-137 m).*

Ŧms Sewemup Member - *Pale-red-orange to gray-red, slope-forming siltstone with subordinate red-brown, fine-grained sandstone; thinly laminated to thin bedded; gypsum is common as irregular veinlets and thin beds; commonly cemented with gypsum; sandstone is commonly ripplemarked. Thickness 0-470 feet (0-143 m); locally missing over salt diapirs, thick elsewhere.*

Ŧml Lower member - *Red-brown and lavender, silty, ledge-forming sandstone and conglomeratic sandstone and conglomeratic sandstone interbedded with slightly darker red-brown to red-orange, slope- and recess-forming sandstone, siltstone and silty mudstone; micaceous and feldspathic; platy to medium bedded, commonly ripplemarked or mudcracked. Thickness 0-450 feet (0-137 m); may be thin or missing over salt diapirs, 270-450 feet (82-137 m) thick in outcrop.*

Cutler Formation

Pcw? White Rim Sandstone Member? - *Gray-white, quartzose, high-angle, cross-bedded sandstone interbedded with minor siltstone and arkose; massive, resistant cliff-former. Thickness 0-250 feet (0-76 m), exposures limited to southwest flank of Castle Valley.*

Pc Arkosic sandstone member - *Red-brown and red-purple, subarkosic to arkosic sandstone, conglomeratic sandstone, and conglomerate interbedded with silty and sandy mudstone and shale; thin bedded to massive, forms steep slopes, ledges, and cliffs. Thickness 0-6,235+ feet (0-1,900+ m); upper 1,000 feet (305 m) exposed at surface, probably missing over parts of diapirs.*

₽h Honaker Trail Formation (subsurface only) - *Interbedded light-gray to gray, marine limestone, micaceous sandstone, calcareous siltstone, and shale. Maximum thickness indeterminable; probably missing over parts of diapirs; 950 feet (290 m) thick in one drill hole. Symbol only on lithologic column, correlation chart, and cross sections.*

₽p Paradox Formation - *Paradox Formation caprock consists of light-gray to yellow-gray, sucrosic gypsum, gypsiferous claystone, silty shale, fine-grained sandstone, and thin-bedded carbonates; disrupted and contorted bedding in two small exposures. Estimated thickness may be as much as 1,000 feet (309 m). Subsurface consists of interbedded coarse crystalline halite and other salts, massive anhydrite, sparse gray dolomite, gray to black shale, and gray siltstone. Estimated thickness 300-9,500+ feet (90-2,900+ m).*

₽ptm Pinkerton Trail and Molas Formation,undivided (subsurface only)-*Pinkerton Trail consists of interbedded gray,marine limestone, dolomite, silty shale, and calcareous siltstone; Molas consists of red-brown to variegated siltstone, red silty shale, calcareous sandstone, and sparse gray limestone lentils. Pinkerton Trail is 120 feet (37 m) thick in Conoco Federal No. 31-1 well and estimated at 100-200 feet (30-60 m) thick across quadrangle; Molas is not present in the well and is estimated at 0-75 feet (0-23 m) across quadrangle. Symbol only on lithologic column and correlation chart.*

Ml Leadville Formation (subsurface only) - *Upper part consists of gray limestone and lower part consists of white to mottled brown dolomite. Thickness 450 feet (137 m) in Conoco Federal No. 31-1 well. Symbol only on lithologic column and correlation chart.*

Du Devonian rocks, undivided (subsurface only) - *Limestone, dolomite, silty shale, and sandstone. Thickness about 340 feet (104 m) in Conoco Federal No. 31-1 well. Symbol only on lithologic column and correlation chart.*

MAP SYMBOLS

- Contact - *dashed where approximate, dotted where concealed.*
- Normal fault - *dashed where approximate, dottted where concealed; bar and ball on downthrown side, arrow and number give dip of fault surface.*
- Anticline - *showing trace of axial plane; arrow on trace shows plunge; dashes where approximate.*
- Syncline - *showing trace of axial plane; arrow on trace shows plunge; dashes where approximate.*
- Monocline
- 23 Strike and dip of bedding - *inclined, approximated, vertical, local in folded or deformed beds.*
- Strike of vertical joint.
- 11 Strike and dip of joint.
- Collapsed depression center.
- 4500 Structure contour - *drawn on base of Wingate Sandstone; dashes where projected; 200 foot (~61 m) contour interval.*
- 4500 Closed structure contour
- Cu Ba Au Prospect, adit, and placer mine - *Cu = copper; Ba = barite; Ca = calcite; Au = gold.*
- Sand and gravel pit.
- Abandoned oil or gas well.
- 1983 Recent rock-fall location and date of movement.
- B — B′ Line of cross section

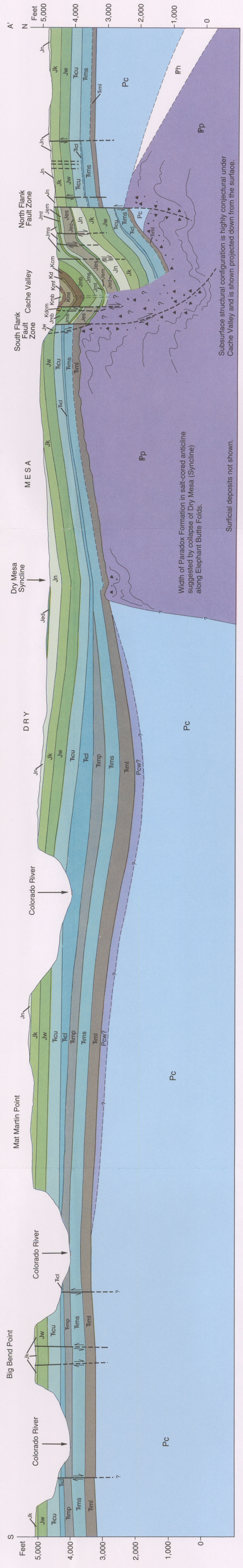
Lithologic column

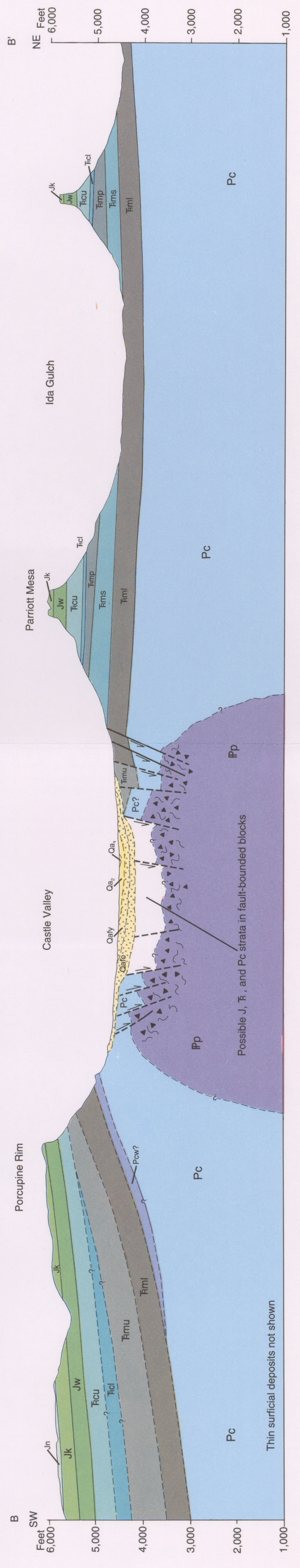
SYSTEM	SERIES	FORMATIONS AND MEMBERS		SYMBOL	THICKNESS feet (m)	LITHOLOGY
Quaternary	H. / Pleistocene	Surficial deposits		Q	0-350+ (0-107+)	Lower part unexposed
Tertiary	Pliocene ?					unconformity
Cretaceous	Upper	Mancos Shale	Blue Gate Shale Member	Kmb	500+ (152+)	Sandy beds; Light-gray shale
Cretaceous	Upper	Mancos Shale	Ferron Sandstone Member	Kmf	90-120 (27-37)	Sea shells near top
Cretaceous	Upper	Mancos Shale	Tununk Shale Member	Kmt	400 (122)	Medium-gray shale
Cretaceous	Upper	Dakota Sandstone		Kd	40-50(12-15)	unconformity
Cretaceous	Lower	Cedar Mountain Member		Kcm	200-240 (61-73)	Ridge-forming ledges; unconformity ?
Jurassic	Upper	Morrison Formation	Brushy Basin Member	Jmb	300-340 (91-104)	Green, zeolitic shale
Jurassic	Upper	Morrison Formation	Salt Wash Member	Jms	250 (76)	Lenticular channel sandstones
Jurassic	Upper	Morrison Formation	Tidwell Member	Jmt	40-60(12-18)	Large chert concretions; unconformity ?
Jurassic	Middle	Entrada Sandstone	Moab Member	Jem	90-110 (27-34)	Highly jointed; Arches
Jurassic	Middle	Entrada Sandstone	Slickrock Member	Jes	250-350 (76-107)	
Jurassic	Middle	Entrada Sandstone	Dewey Bridge Member	Jed	40-60(12-18)	Contorted bedding; unconformity
Jurassic	Lower	GLEN CANYON GROUP	Navajo Sandstone	Jn	250-400 (76-122)	Large-scale, high-angle cross-stratification; Petrified sand dunes; Thin limestone ledges
Jurassic	Lower	GLEN CANYON GROUP	Kayenta Formation	Jk	240-300 (73-91)	Ledge and bench former
Jurassic	Lower	GLEN CANYON GROUP	Wingate Sandstone	Jw	250-350 (76-107)	Prominent vertical cliff former; Desert-varnished surfaces; unconformity ?
Triassic	Upper	Chinle Formation	Upper member	Ŧcu	200-460 (61-140)	"Black Ledge" locally present; unconformity
Triassic	Upper	Chinle Formation	Lower member	Ŧcl	0-380+ (0-116+)	Silcrete horizons; Mottled siltstone and sandstone; Paleosols; unconformity
Triassic	? Middle ?	Moenkopi Formation	Pariott Member	Ŧmp	0-450 (0-137)	"Ledgy" Moenkopi
Triassic	Lower	Moenkopi Formation	Sewemup Member	Ŧms	0-470 (0-143)	Smooth slopes; Ripple marks and rain-drop imprints; Thin gypsum beds; Mud cracks
Triassic	Lower	Moenkopi Formation	Lower member (combined Ali Baba and Tenderfoot Mbrs.)	Ŧml	0-450 (0-137)	Ripple marks; Gypsum bed; unconformity
Permian	Lower	Cutler Formation	White Rim Sandstone Mbr?	Pcw?	0-250 (0-76)	White eolian sandstone
Permian	Lower	Cutler Formation	Arkosic sandstone member	Pc	1,000 (305) exposed at surface; 6,235+ (1,900+) surface and known subsurface	Subarkosic and arkosic fluvial and eolian sandstone; Thin limestone beds; unconformity
Pennsylvanian		Honaker Trail Formation		₽h	0-950+ known subsurface (0-290+)	Interbedded limestone and micaceous sandstone; unconformity
Pennsylvanian		Paradox Formation		₽p	0-100+ (0-30+) exposed as caprock; 300-9,500+ (90-2,900+) surface and known subsurface	Evaporite caprock (gypsum and shale); Marker bed-hydrocarbon potential; Sylvite and carnallite; Salt, anhydrite, shale, limestone, dolomite, siltstone
Pennsylvanian		Pinkerton Trail and Molas Formations		₽ptm	100-275 (30-83)	unconformity
Mississippian		Leadville Formation		Ml	450 (137) subsurface only	Limestone and dolomite; unconformity
Devonian	Upper ? Middle	Devonian rocks undivided		Du	340 (104) subsurface only	Limestone, dolomite, sandstone, minor shale

PRESENT ONLY IN CACHE VALLEY VICINITY

DOMINANT QUADRANGLE EXPOSURES

MOSTLY SUBSURFACE SECTION





CORRELATION OF MAP UNITS

TIME			THIS REPORT	Richmond (1962)	
QUATERNARY	HOLOCENE		Qa₁, Qa₂, Qafy, Qac, Qea, Qes, Qmt	Upper Gold Basin Formation Lower	
	PLEISTOCENE	10,000 years – Late	Qat₃, Qaf₃, Qap₃, Qafo, Qac ?, Qea ?, Qmt ?, Qms	Beaver Basin Formation	Pinedale
		Late	Qat₄, Qaf₄, Qap₄, Qafo, Qms	Upper Placer Creek Formation Lower	Bull Lake
		128,000 years – Middle	Qms		
		730,000-750,000 years – Early	Qeao, Qms	Harpole Mesa Formation	
TERTIARY	PLIOCENE		Qms ?		

SYSTEM	SERIES	MAP UNITS
		unconformity
CRETACEOUS	Upper	Kmb, Kmf, Kmt, Kd (Kdcm)
		unconformity
	Lower	Kcm (Kdcm)
		unconformity?
JURASSIC	Upper	Jmb, Jms, Jmt
		unconformity?
	Middle	Jem
		unconformity?
	Middle	Jes, Jed
		unconformity
	Lower	Jn, Jk, Jw
		unconformity?
TRIASSIC	Upper	Ŧcu
		unconformity
	Upper	Ŧcl
		unconformity
	? Middle ?	Ŧmp (Ŧmu)
	Lower	Ŧms (Ŧmu), Ŧml
		unconformity
PERMIAN	Lower	Pcw?, Pc
		unconformity
PENNSYLVANIAN		₽h
		unconformity
		₽p, ₽ptm
		unconformity
MISSISSIPPIAN		Ml
		unconformity
DEVONIAN		Du

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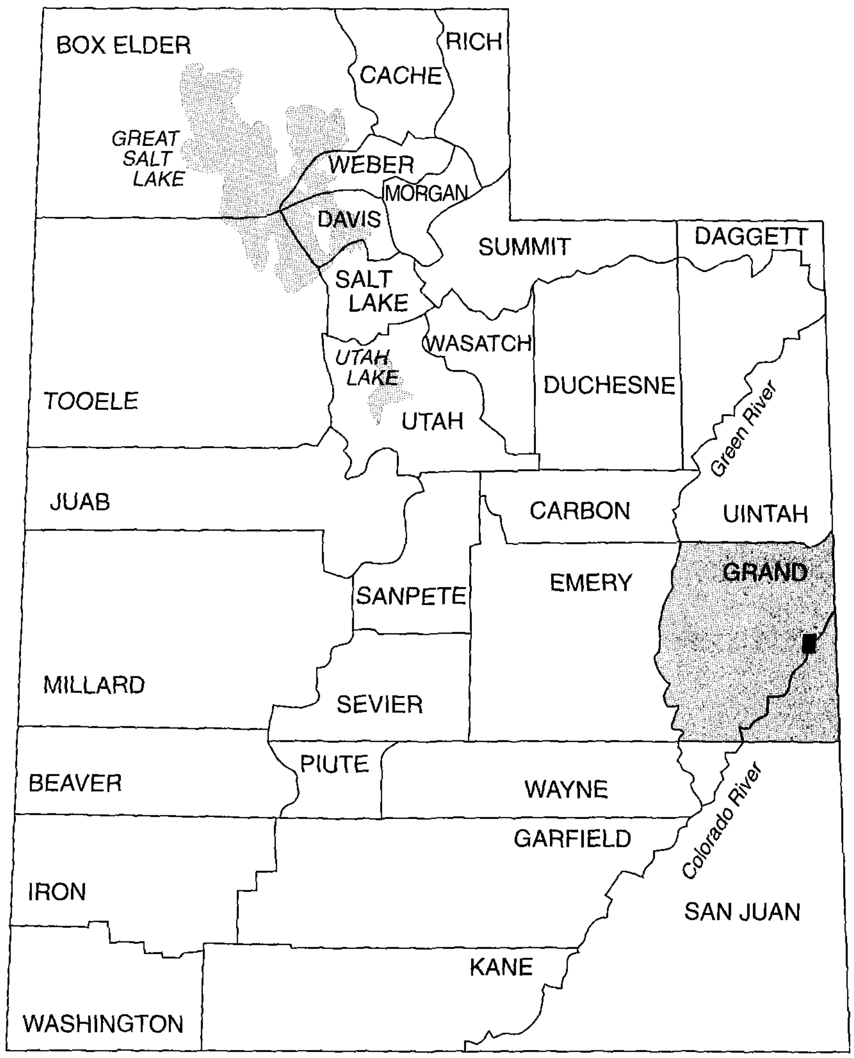

MAP 171 **1998**
UTAH GEOLOGICAL SURVEY
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Doelling and Ross
GEOLOGIC MAP OF THE BIG BEND QUADRANGLE, GRAND COUNTY, UTAH
Utah Geological Survey Map 171

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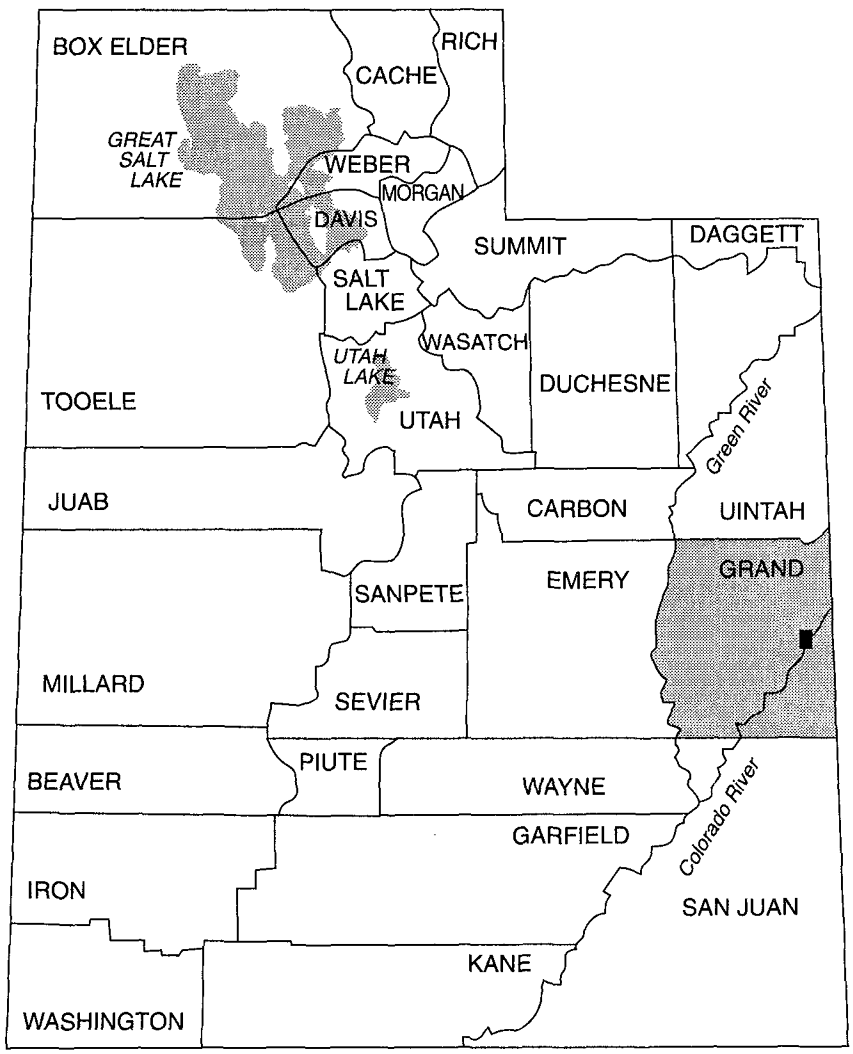

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UGS Editorial Staff

J. Stringfellow	Editor
Vicky Clarke, Sharon Hamre	Graphic Artists
Patricia H. Speranza, James W. Parker, Lori Douglas	Cartographers

10/98

GEOLOGIC MAP OF THE BIG BEND QUADRANGLE, GRAND COUNTY, UTAH

by

Hellmut H. Doelling and Michael L. Ross

ABSTRACT

The Big Bend quadrangle is named for a deeply incised meander bend in the Colorado River in southern Grand County, Utah. It is part of Utah's scenic Red-Rock country and includes the world-famous Delicate Arch and parts of Cache, Castle, and Professor Valleys. The quadrangle lies in the fold-and-fault belt of the northern Paradox basin, a northwest-trending asymmetrical basin that formed adjacent to the ancestral Uncompahgre uplift during Pennsylvanian to Late Triassic time.

Exposed strata range from Pennsylvanian to Cretaceous age. These include less than 1,000 feet (305 m) of the Pennsylvanian Paradox Formation, 0 to 1,250 feet (0-381 m) of the Lower Permian Cutler Formation, 0 to 1,370 feet (0-418 m) of the Lower Triassic Moenkopi Formation, 200 to 840 feet (0-256 m) of the Upper Triassic Chinle Formation, 250-350 feet (73-107 m) of the Lower Jurassic Wingate Sandstone, 240 to 300 feet (73-91 m) of the Lower Jurassic Kayenta Formation, 250 to 400 feet (76-122 m) of the Lower Jurassic Navajo Sandstone, 380 to 520 feet (116-158 m) of the Middle Jurassic Entrada Sandstone, 590 to 650 feet (180-198 m) of the Upper Jurassic Morrison Formation, 200 to 240 feet (61-73 m) of the Lower Cretaceous Cedar Mountain Formation, 40 to 50 feet (12-15 m) of the Upper Cretaceous Dakota Sandstone, and about 1,000 feet (305 m) of the Upper Cretaceous Mancos Shale. The quadrangle is dominated by the exposures of the Permian, Triassic and Lower Jurassic formations; younger rocks are present only in and near Cache Valley in the north part of the quadrangle. Quaternary surficial deposits were deposited by alluvial, eolian, and colluvial processes.

A thick sequence of evaporite salts and fine-grained sediments were deposited in the quadrangle during the Middle Pennsylvanian. These salt deposits of the Paradox Formation were intermittently mobilized during Pennsylvanian to Late Triassic time to form elongate salt structures. Well-developed salt structures are present under Cache and Castle Valleys. Permian and Triassic strata deposited adjacent to the growing salt-cored anticline are unusually thick in the rim synclines and are thin or missing over the crests of the salt-cored anticline.

Regionally, gentle northwest-trending Tertiary-age synclines and anticlines are superimposed over a north-dipping homocline that dips into the Uinta basin. Late Tertiary and Quaternary uplift of the Colorado Plateau, accompanied by vigorous downcutting by the Colorado River and its tributaries, allowed ground-water circulation to reach the crests of the salt-cored anticline through pre-existing fracture networks. This resulted in Pliocene-Pleistocene salt-dissolution collapse of the crests of the salt-cored anticlines. The strata were tilted and offset along numerous faults to form grabens, v-synclines, and fractured drape zones. Castle Valley filled with alluvium as its graben deepened.

The quadrangle contains sand and gravel, petroleum and potash resources, and occurrences of gold, copper, uranium, barite, gypsum, and calcite. The principal geologic hazards include debris flows, mudflows, stream flooding, rock falls, indoor radon gas, and culinary water contamination.

INTRODUCTION

The Big Bend quadrangle is in east-central Utah, approximately 12 miles (19 km) northeast of the Grand County seat of Moab (figure 1). It is named for a magnificent incised meander loop of the Colorado River in the heart of Utah's scenic Red-Rock country. The quadrangle is centered at the place where the Colorado River leaves Professor Valley and the Richardson Amphitheater and enters a narrow canyon. The landscape consists of bench and canyonland morphology common to the Colorado Plateau physiographic province. The quadrangle contains Cache Valley, which developed along an east-west-trending, salt-generated structure, and the

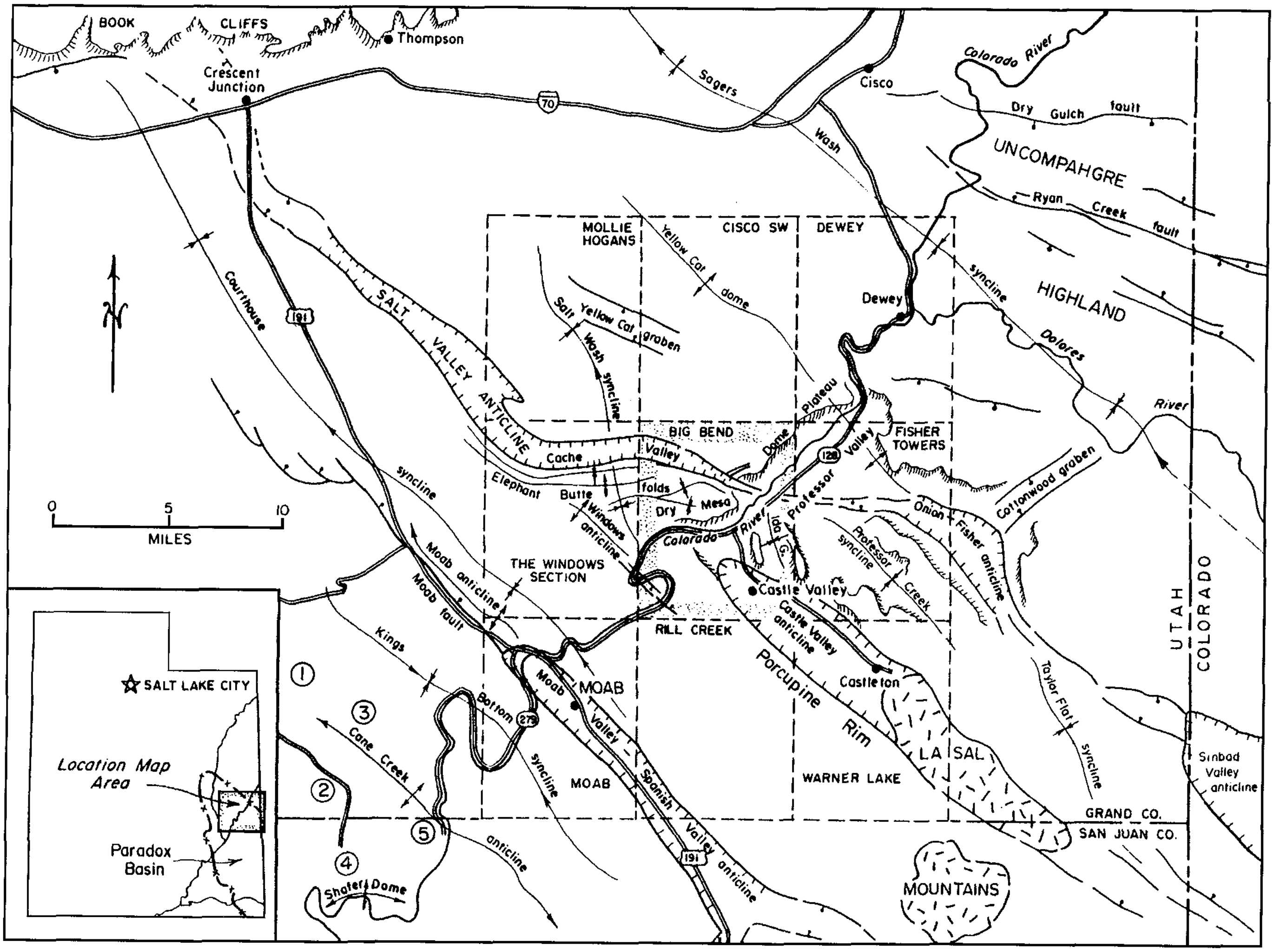


Figure 1. Map showing area of Big Bend and adjacent quadrangles in east-central Utah. Principal structural and geomorphic features, highways, and settlements are also shown. Circled numbers west of Moab represent the approximate locus of small oil fields tapping Pennsylvanian and Mississippian reservoirs: Bartlett Flat (1), Big Flat (2), Long Canyon (3), Shafer Canyon (4), and Cane Creek (5).

nose of Castle Valley, which developed along a northwest-trending, alluvium-covered, salt-cored anticline. The Colorado River flows across the quadrangle from the northeast to the southwest and has cut the Big Bend, a canyon more than 1,100 feet (335 m) deep, in the southwest corner. In the east part of the quadrangle, mesas and valleys slope northwestward from the La Sal Mountains. Remnants of former high benches form picturesque buttes, ridges, and hills in this area.

The Colorado River divides the quadrangle in half with respect to accessibility. The southeast half is reached from Moab along Utah Highway 128 (U-128) with adjoining roads providing access to Castle Valley and other places below the mesas. Access to Mat Martin Point and Porcupine Rim from Moab is from the Sand Flats road via four-wheel-drive roads. Access to Cache Valley and Dry Mesa is from Arches National Park on a four-wheel-drive road via the Delicate Arch highway. Access to the Dome Plateau is from Interstate Highway 70 (I-70) ranch exit 190, on a four-wheel-drive road extending through Yellow Cat Flat and the Poison Strip in the quadrangles to the north. These access roads are not shown on figure 1. The four-wheel- drive roads have many branches and exact routes are accurately shown only on the U.S. Geological Survey (USGS) 1:100,000-scale, 30 x 60-minute Moab topographic map. Access to the northwest bank of the river is by boat or raft.

The Big Bend quadrangle area was first mapped by Dane (1935), at a scale of 1:63,500. It was later mapped by Williams (1964) at a scale of 1:250,000 (Moab 2-degree quadrangle). Doelling (1985) included the north half of the quadrangle in his 1:50,000-scale geologic map of Arches National Park. Other publications dealing with aspects of the geology in the quadrangle are those of Cross (1907), Shoemaker and Newman (1959), Harper (1960), and Doelling (1981, 1983).

Doelling mapped much of the western half of the quadrangle, including Dry Mesa, Mat Martin Point, and Cache Valley. Ross mapped the eastern half of the quadrangle, including Castle Valley, Professor Valley, Ida Gulch, Dome

Plateau, and the canyon of the Colorado River. Doelling's field work was conducted mostly in 1982, 1983, 1989, and 1993. Ross' field work was conducted mostly in 1989 and 1990.

STRATIGRAPHY

Rock formations exposed in the Big Bend quadrangle range in age from Middle Pennsylvanian to Late Cretaceous. In addition, there are several surficial (Quaternary) deposits. Precambrian, Cambrian, Devonian, and Mississippian rocks are present in the subsurface (Hintze, 1988).

Permian to Lower Jurassic formations are extensively exposed across the quadrangle. Pennsylvanian rocks (Paradox Formation caprock) are exposed at only two locations, one in Cache Valley and the other in Castle Valley. The Middle Jurassic to Late Cretaceous formations are preserved in the collapsed graben of Cache Valley and in the eastward extensions of the Elephant Butte folds on Dry Mesa (figure 1).

Subsurface Rocks

Below Triassic strata at the surface, Permian to Cambrian rocks were encountered in the Conoco Federal 31-1 drill hole, located in the S¼ NW¼ SE¼ section 31, T. 24 S, R. 23 E. Based on well log information, the hole penetrated about 5,640 feet (1,719 m) of Permian Cutler Formation, 950 feet (290 m) of Pennsylvanian Honaker Trail Formation, 2,930 feet (893 m) of Paradox Formation, 120 feet (37 m) of Pinkerton Trail Formation; 452 feet (138 m) of Mississippian Leadville Formation, 104 feet (32 m) of Devonian-Mississippian Ouray Formation, 96 feet (29 m) of Devonian upper member and 128 feet (39 m) of McCracken Member of the Elbert Formation; and 72 feet (22 m) of part of the Devonain Aneth Shale (Cole and Moore, 1996). No Cambrian was penetrated but Hintze (1988), as compiled from various sources, indicated the Cambrian section to be 800 to 1,200 feet (244-366 m) thick in isopach maps.

The name Leadville Formation is used for rocks of Mississippian age that underlie the region (Hintze, 1988). Neff and Brown (1958) divided the Leadville into an upper limestone phase and a lower dolomite phase. The dolomite phase consists of coarsely crystalline to sucrosic, tan, brown, and gray, often cherty, massive dolomite. The limestone phase consists mostly of thick-bedded to massive limestone.

The contact between Mississippian and Pennsylvanian rocks in the area is an erosional unconformity (Hintze, 1988). The basal unit of the Pennsylvanian is the Molas Formation, which primarily consists of limestone clasts in a red muddy siltstone matrix (Wengerd, 1958). Our examination of drill cuttings from the Conoco Federal No. 31-1 well suggests the Molas Formation is not present in the well.

The Hermosa Group overlies the Molas Formation and consists of three formations, in ascending order, the Pinkerton Trail, Paradox, and Honaker Trail. The Pinkerton Trail and Honaker Trail Formations both contain predominately shallow marine limestone and fine-grained clastic deposits (Wengerd, 1958). The Paradox Formation is a sequence of cyclically bedded halite, anhydrite, carbonate, siltstone, and shale. Following the terminology of Baars and others (1967), only sediments containing evaporites are included in the Paradox Formation. Along the northeastern edge of the Paradox basin, the Paradox and Honaker Trail Formations also contain interbeds of medium, subarkosic sandstone (White and Jacobsen, 1983). Except for two small outcrops, the Pennsylvanian rocks of the Big Bend quadrangle are present in the subsurface.

The thickness of the Paradox Formation in the area is extremely variable due to salt flowage. Near the center of Castle Valley and just east of the quadrangle, the Grand River Oil and Gas Sid Pace No. 1 well (NE¼ SE¼ section 16, T. 25 S., R. 23 E.) penetrated an incomplete section of about 5,400 feet (1,646 m) of evaporites and mudstone on the flank of the Castle Valley salt anticline. The Conoco Federal No. 31-1 well, along the northeast flank of the anticline, penetrated 2,930 feet (893 m) of salt-bearing strata. The Union of California Burkholder No. 1 well (SW¼ NE¼ section 1, T. 26 S., R. 22 E.), southwest of Castle Valley and just off the quadrangle, drilled through about 2,850 feet (869 m) of Pennsylvanian rock, of which only 300 feet (91 m) contained salt-bearing strata. Elston and others (1962) estimated the original thickness of the Paradox Formation in the northern Paradox basin to have been at least 5,000 feet (1,524 m).

The Honaker Trail Formation consists of fossiliferous carbonates, cherty limestone, siltstone, and sandstone based on nearby outcrops and drill-hole information. Interbeds of arkosic sandstone, purple siltstone, and shale become more numerous in the northeast part of the Paradox basin near the ancestral Uncompahgre highland source area (Doelling, 1988). Regionally, the unit is 0 to 2,000 feet (0-610 m) thick; it is generally believed to be missing over the salt-cored anticlines, but is expected to be present in areas between them.

The depositional history of the Hermosa Group may be summarized as follows (Wengerd and Matheny, 1958; Woodward-Clyde Consultants, 1983; Baars, 1987): during Atokan (early Middle Pennsylvanian) time, silty shales and fossiliferous carbonates in the Pinkerton Trail Formation were deposited across the region in a shallow marine shelf environment. By Desmoinesian (Middle Pennsylvanian) time the Paradox basin began to subside and was periodically restricted from the open marine shelf that had shifted to the south-southwest. Halite, sylvite, carnallite, gypsum, and anhydrite were precipitated in the restricted hyper-saline environment that developed. Open marine shallow-shelf conditions were re-established in Upper Desmoinesian (late Middle Pennsylvanian) time and continued to Virgilian (Late Pennsylvanian) time, and marine carbonates and clastics of the Honaker Trail Formation were deposited.

Pennsylvanian Rocks

Paradox Formation (IPp)

The two small exposures of Paradox Formation caprock in the quadrangle are resistant, rounded hills consisting of massive sucrosic gypsum, clayey gypsum, silty shale, sandstone, limestone, and dolomite. Caprock is the residue after the more soluble salts have been removed from the formation. The clayey gypsum beds are disrupted and contorted beneath a thin, popcorn-like weathered surface and are associated with resistant and pitted, sucrosic, whitish-gray gypsum. Broken fragments and blocks of silty shale, fine-grained quartzose sandstone, micritic limestone, and dolomite are generally scattered across the outcrops. Caprock exposures are predominantly light gray to yellow gray, but may be black to green gray.

The Paradox Formation caprock is well displayed near the northwest nose of the Castle Valley salt-cored anticline in the NE¼ SW¼ NE¼ section 1, T. 25 S., R. 22 E. (plate 1). There, gypsum, carbonate rocks, and shale that may be fault gouge have been cemented with calcite and silica into a coherent mass more resistant than the surrounding rock. Halite is not present at the surface; however, a small spring at this location is extremely salty. Halite crystals encrust the area around the spring.

The second exposure is located in the W½ SW¼ SE¼ section 13, T. 24 S., R. 22 E., in Cache Valley. There, caprock appears to be conformably overlain by the Triassic Chinle Formation on the west side of the exposure and is cut off by a fault on the east side that places it against the Triassic Moenkopi Formation.

Permian Rocks

Cutler Formation

Rocks of the Permian Cutler Formation in the Paradox basin are a complex sequence of intertonguing continental red-bed, eolian, paralic (coastal), and shallow marine deposits that unconformably overlie the Hermosa Group (Campbell, 1979). The Permian rocks represent a large alluvial-fan complex shed from the ancestral Uncompahgre highland that intertongues with coastal-plain deposits to the southwest, in the Canyonlands area southwest of Moab. In the Big Bend quadrangle, we recognize two units in the Cutler Formation; an informal arkosic sandstone member (Pc), which is predominant, and a sandstone member that may correlate with the White Rim Sandstone (Pcw?) (figure 2). Uplift of the salt-cored anticlines during the Permian affected the deposition of the Cutler Formation. Thicker sequences of sediments were deposited in basins or synclines peripheral to the growing salt structures. The uplifted areas over the crests of the salt-cored anticlines received thinner sequences or the sediments were removed by pre-Moenkopi erosion (Doelling, 1988).

The Cutler Formation in the Big Bend quadrangle was deposited in the medial to distal parts of a large alluvial-fan complex emanating from the Precambrian metamorphic and granitic terrain of the ancestral Uncompahgre uplift. The fluvial system consisted of braided streams on the fan surface that changed to braided, meandering streams away from the fan (Campbell, 1979; Campbell and Steele-Mallory, 1979). The toe of the fan was near sea level, periodically allowing marine conditions to influence sedimentation. Toward the end of Cutler deposition, a marginal-marine eolian environment was present, represented by the White Rim Sandstone Member.

Arkosic sandstone member (Pc): The arkosic sandstone member consists primarily of subarkosic to arkosic sandstone, conglomeratic sandstone, and conglomerate interbedded with silty and sandy mudstone. Subordinate lithologies are quartzose sandstone, cherty limestone, and hard, dense mudstone. Because of lithologic heterogeneity and variable cementation, the member's outcrop appearance ranges from near-vertical cliffs to alternating ledges and slopes that form step-like escarpments. Outcrops are red brown, red purple, red orange, and maroon, with subordinate brown-orange, pale-red, gray, gray-red, and gray-white coloration.

Arkosic sandstone is fine to very coarse grained and micaceous. Grains are generally subangular to subrounded and individual beds vary from poorly to well sorted. Many beds of arkosic sandstone display small-scale trough cross-bedding and cut-and-fill structures with basal gravel lenses, suggesting deposition by fluvial processes. Gravel beds range from moderately sorted granule and pebble conglomerate to poorly sorted cobble conglomerate. Maximum clast size is about 10 inches (25 cm), with 0.4 to 2.4-inch (1-6-cm) clasts most common. Smaller grains are mostly quartz, feldspar, and mica; pebbles and cobbles are granite, gneiss, schist, and quartzite. Horizontal stratification and variable bed thickness are common for the conglomeratic beds. Subarkosic to quartzose sandstone is composed mostly of fine to medium, subrounded, moderately well-sorted grains. Tabular-planar cross-stratification and laminations with inverse graded bedding in some beds suggest deposition by eolian processes (Campbell, 1979). These sandstones are generally orange to red in contrast to the red-purple shades of the fluvial

Figure 2. View to the southwest of Porcupine Rim from Castle Valley. White Rim Sandstone Member? of Cutler Formation pinches out to southeast (left). Note ancient paleovalleys cut in the Wingate and Kayenta Formations along Porcupine Rim.

sandstones. The mudstones and siltstones are micaceous and generally show little stratification.

The maroon sandstone and conglomeratic sandstone beds are interbedded with brown silty mudstone and siltstone beds in the upper part of the Cutler Formation at Ida Gulch and in Professor Valley along the Colorado River. The bases of the sand-rich beds are scoured into the mudstones and contain mudstone rip-up clasts and basal gravel lenses. The sand-rich beds are interpreted to be fluvial braided channel deposits incised into overbank mudstones.

On the north side of Castle Creek, at the northwest nose of the Castle Valley salt-cored anticline, is an area of complexly deformed Cutler Formation that contains interesting petrologic features and sedimentary structures. Pebbles and cobbles of angular to subrounded, pale-gray mudstone and sandstone clasts lie in disturbed beds in fluvial cross-beds. The clasts may be detritus from the Hermosa Group or from the lower part of the Cutler Formation shed off the crest of the growing salt structure. Two small syndepositional faults were observed in the Cutler red beds at this location (see structure discussion). These structural and sedimentolog ical features, combined with the variable thickness of the formation, support the concept of episodic growth of the Castle Valley salt anticline during deposition of the Cutler Formation.

The arkosic sandstone member in the Big Bend quadrangle varies from thin or missing over the salt-cored anticlines to very thick in adjacent peripheral basins and rim synclines (see cross sections, plate 2). A maximum of about 1,000 feet (305 m) is present in surface exposures. Harper (1960) measured an incomplete 931-foot (284-m) section of the Cutler in section 9, T. 25 S., R. 23 E. We interpret the Conoco Federal No. 31-1 well as having penetrated about 5,640 feet (1,719 m) of the arkosic sandstone member. The member is up to about 6,235 feet (1,900 m) thick.

White Rim Sandstone Member? (Pcw?): A conspicuous gray-white, massive sandstone, as much as 250 feet (76 m) thick, caps the arkosic sandstone member of the Cutler Formation in the northwest corner of Castle Valley. The sandstone gradually thins to the southeast due to erosional truncation below the Triassic Moenkopi Formation along the southwest flank of Castle Valley (figure 2 and plate 1). Exposures in section 18, T. 25 S., R. 23 E., suggest a gradual change from an alluvial-fan environment to predominantly eolian conditions. There the lower part of an incomplete section of Cutler is "typical" red-purple and maroon sandstone and conglomerate. This lower interval contains trough cross-stratified arkosic sandstone and gravel lenses (lags?) in scour surfaces. It grades upward into the conspicuous gray-white quartzose sandstone that is interbedded with minor siltstone and arkose. Primary sedimentary structures of this uppermost unit include large-scale, relatively high-angle (20°-30°) cross-bed sets. Quartz grains in this unit are frosted. Crude dune forms mark its exhumed upper surface. Just to the north of these outcrops, the Grand River Oil and Gas No. 1 well, drilled in the SW¼NW¼NE¼ section 36, T. 24 S., R. 22 E., penetrated about 250 feet (76 m) of quartzose sandstone having frosted grains.

The massive eolian sandstone at Castle Valley resembles the White Rim Sandstone Member, which is the uppermost member of the Cutler Formation west and southwest of Moab. However, the eolian sandstone at Castle Valley cannot be physically connected with White Rim exposures in the Canyonlands area. The Cutler Formation is well exposed in Moab Canyon, between Castle Valley and the Canyonlands, and the White Rim Sandstone is not present there (Doelling and others, 1994). Baars (1987) presented an isopach map of the White Rim Sandstone showing a thin finger, approximately 200 feet (61 m) thick, extending from the main area of deposition along the southwest flank of the Salt Valley salt-cored anticline and just reaching the Big Bend area of the Colorado River from the southwest.

The Cutler Formation in Castle Valley is unconformably overlain by the Triassic Moenkopi Formation. The unconformity is angular and is well exposed in Ida Gulch and below Porcupine Rim. At Ida Gulch, Cutler Formation beds below the unconformity trend N. 85° W. and dip 9° NE., and are medium- to coarse-grained arkose with numerous conglomerate lenses. The unconformity is a subtle, low-relief surface with little channelization. The basal Moenkopi Formation bed above the contact is a coarse-grained arkosic sandstone overlain by fine-grained sandstone and silty mudstone. The Moenkopi Formation in this area strikes N. 80° W. and dips 5° NE. The angular discordance between the Cutler and Moenkopi Formations appears to increase toward the axis of the Castle Valley salt-cored anticline, since dips in the Cutler increase from 9 to 20 degrees, while the attitude of the Moenkopi Formation remains constant. On the northeast side of Castle Valley the unconformity is poorly exposed in the slope approximately 20 feet (6 m) below a prominent gypsum bed in the Moenkopi Formation.

Triassic Rocks

Moenkopi Formation

The Moenkopi Formation of Early and Middle(?) Triassic age is missing over the Uncompahgre Plateau to the east-northeast, and regionally thickens westward toward the Cordilleran miogeocline (Baars, 1987; Doelling, 1988). It is primarily a sequence of intertonguing deltaic and coastal deposits that represent the initial Mesozoic marine transgression in the Colorado Plateau region (Stewart and others, 1972a). Regionally, it consists of interbedded, orange-brown to red-brown, thinly laminated to thin-bedded, micaceous mudstone, siltstone, and fine-grained sandstone. Subordinate lithologies include shale, gypsum, sandstone, and conglomerate. The formation is characterized by ubiquitous oscillation ripples and mudcracks (Stewart and others, 1972a; Molenaar, 1987, Doelling, 1988).

Shoemaker and Newman (1959) investigated the Moenkopi in the salt-anticline region and divided the formation into four members, in ascending order, the Tenderfoot, Ali Baba, Sewemup, and Pariott Members. The lower three members are widely distributed throughout the salt-anticline region, all commonly exhibiting lateral variations in lithology and thickness. The Pariott Member is present near Castle Valley and in Sinbad Valley.

Thick sequences of Moenkopi sediments were deposited in localized basins (rim synclines) peripheral to the growing salt structures. The uplifted areas, over the crests of the salt-cored anticlines, either received thin sequences of sediment or the sediments were removed by pre-Chinle erosion (Stewart and others, 1972a; Doelling, 1988). At Hill 5163, near the northwest nose of the Castle Valley salt-cored anticline, the entire Moenkopi is only 550 feet (168 m) thick. The thickness of the Moenkopi increases dramatically eastward across the north-trending monocline toward Porcupine and Parriott Mesas, where the measured section is 958 feet (292 m) thick (Shoemaker and Newman, 1959). Most of this change in thickness occurs in the Sewemup and Pariott Members. Under Porcupine Rim, at the south edge of the quadrangle, the Moenkopi is about 600 feet (183 m) thick. However, the Union of California Burkholder No. 1 well, between the Castle Valley and Moab Valley salt-cored anticlines, penetrated about 1,600 feet (488 m) of Moenkopi.

We divided the Moenkopi Formation into a mostly ledge-forming lower member (composed of the Tenderfoot and Ali Baba Members) (TRml), the slope-forming Sewemup Member (TRms), and the ledge-forming Pariott Member (TRmp) (figure 3).

Lower member of the Moenkopi Formation (TRml): This member consists mainly of lavender, silty sandstone and conglomeratic sandstone interbedded with red-brown to red-orange sandstone, siltstone, and silty mudstone. Sandstone beds form rough cliffs and ledges. Siltstones and mudstone form rubble-covered steep slopes or recesses between ledges.

The sandstone appears arkosic and micaceous, with a distinct speckled appearance. Clasts are poorly to well-sorted, fine- to coarse-grained, subangular to subrounded quartz, feldspar, mica, and opaque minerals. The sandstone is calcareous and moderately to well indurated. Sandstone beds range from thin to massive, as great as 30 feet (9 m) thick. The lower contacts of many sand bodies exhibit scoured surfaces. Many sandstone beds contain small-scale cross-stratification. Sandstone beds with conglomerate lenses are lavender to pale red brown, exhibit scoured basal contacts, and contain granules, pebbles, and a few cobbles of Precambrian granite and gneiss. However, some conglomerate lenses on the immediate limb of the Castle Valley salt-cored anticline are rich in gypsum, mudstone, sandstone, limestone, and chert clasts. These particular conglomerates are matrix-supported and clasts are randomly oriented.

Intervening siltstones are moderate-red-orange to red-brown slope or bench formers. Siltstones are thinly laminated to thin bedded and are commonly marked by parallel oscillation and interference ripple marks, and are generally closely interbedded with siltstone and mudstone exhibiting cuspate ripple marks and mudcracks (Stewart and others, 1972a). Ripple-laminated beds typically occur in sets that range from a few inches to several feet thick. Mudstone and shale range from fissile to homogeneous structureless beds of variable thickness.

The outcrop thickness of the lower member of the Moenkopi ranges from 270 to 450 feet (82-137 m), but may be thin or missing over the crests of salt-cored anticlines in the Big Bend quadrangle. Shoemaker and Newman (1959) measured a complete 444-foot (135-m) section of the lower member on the south side of Parriott Mesa in section 5, T. 25 S., R 23 E. They differentiated the unit into a 220-foot (67-m) Tenderfoot Member and a 224-foot (68-m) Ali Baba Member. The thickness of the lower member ranges from 280 to 290 feet (85-88 m) below the Dome Plateau on the northwest side of the Colorado River and is 270 feet (82 m) thick at Hill 5163, in section 36, T. 24 S., R. 22 E. It is about 360 feet (110 m) thick below Porcupine Rim.

The contact between the lower member and Sewemup Member is placed at a color change from darker brown beds below to lighter brown beds slightly above the highest prominent ledge-forming sandstone of the lower member of the Moenkopi. This contact is at the same stratigraphic position as the contact between the Ali Baba and Sewemup Members of Shoemaker and Newman (1959). The color change has been equated to an increase in gypsum in the Sewemup Member siltstones and mudstones (Stewart and others, 1972a).

Sewemup Member (TRms): The predominant lithology of the Sewemup Member is pale-red-orange to gray-red, slope-forming, micaceous siltstone. The siltstone is thinly laminated to thin bedded and exhibits distinct oscillation ripples. Subordinate sandstone is generally red brown to light brown, fine grained, and micaceous. Thin to thick beds of pale-lavender, coarse-grained sandstone to conglomeratic

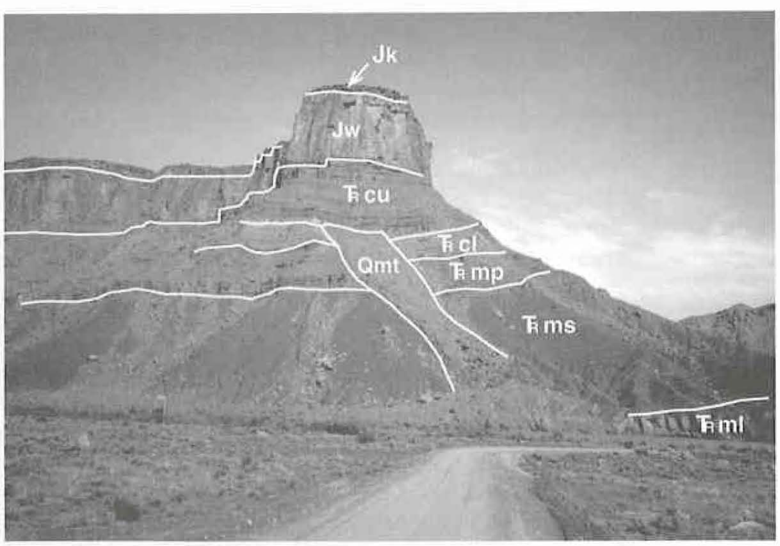


Figure 3. *View to north of the eastern end of Dry Mesa. TRml = lower member of Moenkopi Formation, TRms = Sewemup Member of Moenkopi Formation, TRmp = Pariott Member of Moenkopi Formation, TRcl = lower member of Chinle Formation, TRcu = upper member of Chinle Formation, Jw = Wingate Sandstone, Jk= Kayenta Formation, and Qmt = talus.*

sandstone are present. North of Castle Valley, sandstone beds in the Sewemup Member become conglomeratic and increase in thickness and abundance, so that the lithologic character becomes nearly identical to that of the lower member of the Moenkopi Formation (Shoemaker and Newman, 1959). However, the color change and predominance of slope-forming beds still allow placement of the lower Sewemup contact. Mudstone is dark red brown, slope forming, thinly laminated to structureless, and may be indistinctly bedded. Gypsum is common as irregular veinlets and thin discontinuous beds as much as 0.4 inches (1 cm) thick.

The Sewemup Member is nearly 380 feet (116 m) thick on the south side of Parriott Mesa (Shoemaker and Newman, 1959); 440 feet (134 m) thick near Rocky Rapids on the north side of the Colorado River in section 19, T. 24 S., R. 23 E. (figure 3); and about 200 feet (61 m) thick below the Dome Plateau in the northeast corner of the quadrangle. At Hill 5163, at the north end of Castle Valley, the combined Sewemup-Pariott Member thickness is only 280 feet (85 m). The thickness range of the Sewemup is 0 to 470 feet (0-143 m) across the Big Bend quadrangle.

Pariott Member (TRmp) and Sewemup and Pariott Members, undivided (TRmu): The ledge-forming Pariott Member caps the Sewemup Member and consists mainly of red-brown to lavender sandstone interbedded with "chocolate"-brown, orange-brown, and red siltstone and mudstone. Both the Pariott Member and lower member contain abundant, sand-rich, ledge-forming beds. Orange and red mudstone units in the Pariott Member are distinctive and resemble the overlying Chinle Formation (Shoemaker and Newman, 1959). Sandstone is fine to medium grained, micaceous, poorly to well sorted, and exhibits small-scale trough cross-stratification. Many sandstone bodies are lenticular and exhibit a fining-upward sequence. The basal sandstone of the Pariott Member varies from fine to coarse grained with lenses of pebble conglomerate. The base of the bed is scoured and contains abundant cross-bedding. At Parriott Mesa a muddy, discontinuous gypsum bed is present near the base. The bed is about 6 feet (2 m) thick with nodular gypsum at the base grading to thinly laminated, muddy siltstone. Veinlets of gypsum criss-cross the bed and detrital quartz grains are scattered throughout the bed.

The Pariott Member appears to be present only in the vicinity of the Big Bend quadrangle and adjacent to the Sinbad Valley salt-cored anticline in Colorado (Shoemaker and Newman, 1959). The unit may have been more extensive before erosion, prior to deposition of the overlying Chinle Formation. The unit is 0 to 450 feet (0-137 m) thick in the quadrangle. Shoemaker and Newman (1959) measured a thickness of 135 feet (41 m) on the south side of Parriott Mesa in the type section. The thickest measurement made at a surface exposure is 386 feet (118 m) above Rocky Rapids in section 19, T. 24 S., R. 23 E. (figure 3). There the unit appears to thicken westward under Dry Mesa. The Pariott Member thins northeastward under the Dome Plateau and becomes unrecognizable in the northeast corner of the quadrangle where equivalent strata are included in the Sewemup Member. A nearly complete section of 222 feet (68 m) of Pariott Member was measured near the roadside park at the Big Bend. The Pariott Member is present under Porcupine Rim, but is too poorly exposed to obtain an accurate measurement or to map it separately from the Sewemup Member.

Chinle Formation

In the salt anticline region the Chinle Formation generally forms red ledgy slopes covered with rubble below the massive cliffs of the Wingate Sandstone (Doelling, 1988). We divided the Chinle Formation into lower and upper members. The lower member includes quartzose conglomerate and sandstone, siltstone, and mudstone that are characteristically mottled white, gray, red, purple, green, yellow, and black. The upper member is a red-bed sequence of lithic pebble conglomerate, calcareous sandstone, and silty mudstone.

Throughout most of the quadrangle, the contact between the Moenkopi Formation and Chinle Formation is an erosional surface with minor relief and varies from a disconformity to a slight angular unconformity near the salt structures. The contact is at the base of a distinct light-green-gray to orange-pink to pale-red-brown quartzose sandstone and conglomeratic sandstone at the base of the lower member of the Chinle Formation. The sandstone characteristically forms a prominent white band on the steep slopes of the Triassic strata. The underlying Moenkopi Formation is generally browner, bedding is regular and distinct, and the rocks are finer grained. The overlying Chinle is redder, bedding is irregular and less distinct, and the sandstones are coarser grained.

Lower member (TRcl): From the Dry Wash area (section 9, T. 24 S., R. 23 E.) westward along the Colorado River canyon below Mat Martin Point to the Big Bend, a thick package of light-green-gray, orange-pink, to pale-red-brown, interbedded quartzose sandstone and conglomerate, and minor siltstone and mudstone makes up the lower member of the Chinle Formation. The upper part of this package is mottled white, light gray, red, purple, yellow, orange, and red brown. Sandy units form thin to massive ledges and cliffs separated by narrow steep slopes of muddy and silty units. The irregular topography and mottled coloration give the rocks a distinct rough appearance.

The lower member consists primarily of fine- to coarse-grained quartzose sandstone and conglomeratic sandstone. The sandstone contains poorly to moderately sorted, subangular to rounded, fine- to coarse-grained quartz. Locally, it contains quartz pebbles as much as 2.5 inches (6 cm) in diameter. Some conglomeratic sandstones contain both quartz and chert pebbles. Sandstone is calcareous and cementation ranges from friable to well indurated. Sandstone exhibits small- to medium-scale cross-stratification and both fining- and coarsening-upward sequences. Siltstone and mudstone contain scattered grains of fine- to coarse-grained quartz sand.

Distinct horizons containing sedimentary features indicative of paleosols are present throughout the sequence. Calcareous and chert nodules are commonly present. Near Salt Wash Rapids, a 12- to 18-inch (30-46-cm) cherty horizon is present that may be a pedogenic silcrete or silicified pedogenic carbonate horizon. Interbedded silty mudstone commonly exhibits an angular blocky to granular appearance. Mineralogical differences between the mottled strata and unaltered rocks are indicative of pedogenic alteration. Another factor that may have contributed to the mottled coloration of the beds is oxidation and reduction of the sediments during rise and fall of the ground-water table during or shortly after deposition of the sediments (R.F. Dubiel, verbal communication, December, 1993).

These colorful rocks contain networks of vertical tubular features. The tubular features range from pencil width to 20 inches (50 cm) in diameter. The features include single tubes that branch downward into several tubes, and anastomosing networks of tubes. The tubular features are generally filled with sandstone, siltstone, and mudstone and a color alteration halo is present around them. The tubular features are interpreted to be a combination of crayfish burrows, root tracings, and lungfish burrows (R.F. Dubiel, US Geological Survey, verbal communication, December, 1993).

Strata of the lower member vary widely in thickness. They also exhibit unconformable relations both internally and with the overlying and underlying stratigraphic units, indicating that the lower member was deposited during a period of active salt tectonics. Thickness of the lower member of the Chinle Formation varies from 0 to more than 380 feet (0-116+ m) (figure 4). Mottled beds are present below the cliffs of the Dome Plateau immediately north of the northern fault of the Cache Valley graben in Professor Valley, but these beds thin northeastward. The lower member thins and disappears southeastward along Porcupine Rim and along the northeast side of Castle Valley. In some places the lower

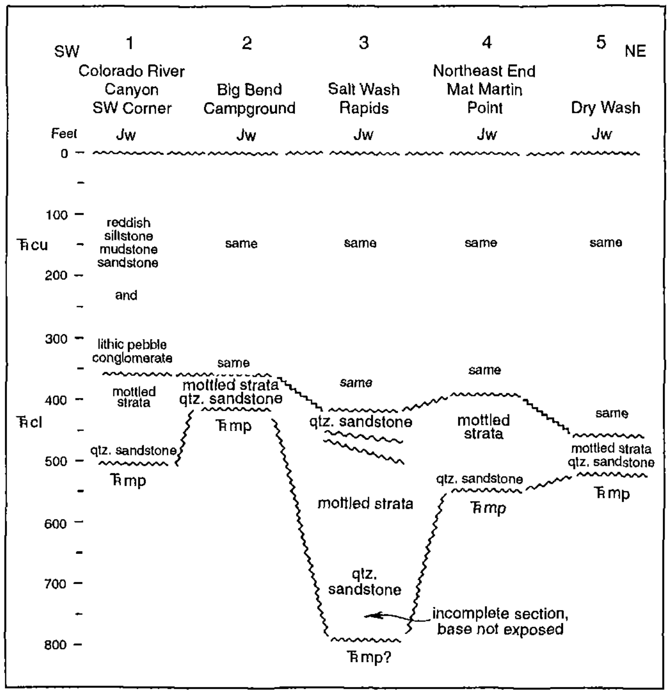


Figure 4. Schematic stratigraphic sections of the Chinle Formation showing variation in thickness of the informal members in the Big Bend-Mat Martin Point area. Sections are hung on the base of the Wingate Sandstone (Jw).

member is present but very thin, and has been mapped together with the upper member (plate 1).

The variation in thickness of the lower member is probably due to a combination of variable depositional thickness and erosion at the unconformity between the lower and upper members of the Chinle. At Salt Wash Rapids (location 3, figure 4), the lower member strikes from N. 23° E. to N. 75° E. and dips from 15° to 20° NW., and is abruptly truncated by gently dipping (<5°) beds of the upper member (figure 5). This angular unconformity removes most of the mottled strata of the lower member at the Big Bend campground (location 2, figure 4). The thickness increases again between locations 2 and 1, figure 4. At location 1 the dip on the lower member is 10° to 13° SW., about 5° to 7° greater than the upper member.

Baker (1933) assigned our informal member to the Shinarump Conglomerate Member of the Chinle Formation. Dane (1935) called these rocks the "basal gritstone" of the Chinle. Shoemaker and Newman (1959) suggested the mottled strata and quartzose conglomeratic sandstone below the angular unconformity at Salt Wash Rapids represent a preserved remnant of Middle Triassic rocks removed by erosion in the unconformity between the Chinle and Moenkopi Formations. Stewart and others (1972b) called the rocks "mottled strata" and used the term for mottled rocks that occur predominantly in the basal part of the Chinle Formation at locations throughout the Colorado Plateau. O'Sullivan and MacLachlan (1975) suggested that the mottled strata in the Big Bend quadrangle may be correlative with the Temple Mountain Member of the Chinle Formation in the San Rafael Swell. We suggest that our lower member is correlative with the informally named "basal white gritstone" of the Chinle Formation in the salt-cored anticline region (Dane, 1935; Stewart and others, 1972b). Our upper and lower Chinle Formation members are separated by an unconformity that varies from a disconformity to an angular unconformity because of salt movement.

Upper member(Ћcu): The upper member of the Chinle Formation is composed predominantly of moderate-red-brown and pale- or gray-red, fine-grained sandstone and siltstone. Sandstone generally exhibits indistinct bedding and occurs as lenses or layers that interfinger with siltstone beds. The fine-grained, calcareous sandstone consists of well-sorted, subangular to subrounded quartz grains and minor mica. Primary sedimentary features include horizontal stratification and medium- to small-scale, low-angle trough cross-stratification and asymmetrical ripple laminations. Siltstone is generally structureless and indistinctly bedded.

Throughout the lower two-thirds of the upper member, thin beds to thick lenses of lithic pebble conglomerate are common. Lithic pebbles are reddish siltstone and mudstone, and gray carbonate and chert. Pebbles are subangular to rounded and are intraclastic, resembling other lithologies in the upper member of the Chinle Formation. Lithic pebble conglomerate varies from clast-supported to matrix-supported with a moderately sorted sandy matrix. A distinction between the upper and lower members is that lithic pebble conglomerates have not been recognized in the lower member. The lithic pebble conglomerates are interpreted to represent the cannibalization of floodplain deposits in the upper Chinle Formation (Blakey and Gubitosa, 1983).

The "Black Ledge" of the upper Chinle Formation (not mapped) is present along the Colorado River canyon from the southwest corner of the quadrangle to the Big Bend, but not farther to the east-northeast. The "Black Ledge" forms a prominent rough cliff, covered with desert varnish, that thins to the northeast and appears to bifurcate into thin-bedded sandstone layers interbedded with siltstones. It consists of pale-red, red-brown, and red-gray, fine-grained sandstone interbedded with lenticular conglomeratic sandstone and thin siltstone and shale beds. The interval 10 to 30 feet (3-9 m) below the "Black Ledge" locally exhibits soft-sediment deformation structures consisting of tight to open disharmonic folds with local slip surfaces.

At most locations near the top of the upper member of the Chinle Formation 3 to 35 feet (1-12 m) thick lenses of light-brown to red-orange, very-fine to fine-grained sandstone are present. The sandstones are thin to thick bedded and horizontally laminated to structureless. Faint cross-bedding is present locally. These sandstone lenses are interbedded with pale-red to red-brown siltstone and mudstone. The sandstones are interpreted to be eolian sand sheet deposits (Blakey and Gubitosa, 1983; Dubiel and others, 1989).

The thickness of the upper member of the Chinle Formation varies from 200 to 460 feet (61-140 m) in the Big Bend quadrangle. The thinnest complete sections were measured on the south flank of Cache Valley where the lower part of the lower member is truncated by a fault. There the upper member varies from 200 to 250 feet (61-76 m) thick and reflects preservation of a thinner section over the Cache Valley salt-cored anticline. At most other exposures, the upper member ranges from 330 to 460 feet (101-140 m) thick (figure 4). The thickest section was measured on the south side of Dry Wash, below Dry Mesa, in the SE¼ NE¼ section 24, T. 24 S., R. 22 E. (location 5, figure 4). The upper Chinle thins to 300 feet (91 m) in exposures below the Dome Plateau in the northeast corner of the quadrangle.

Figure 5. *View to north across the Colorado River at Salt Wash Rapids area. Ꞧcl = lower member of Chinle Formation, Ꞧcu = upper member of Chinle Formation, Jw = Wingate Sandstone, Jk = Kayenta Formation, and Qmt = talus. Note angular unconformity at Ꞧcl -Ꞧcu contact.*

Jurassic Rocks

Wingate Sandstone (Jw)

The Wingate Sandstone is the most prominent formation in the Big Bend quadrangle. It is the lower formation of the Glen Canyon Group which, in ascending order, consists of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. These formations are considered Early Jurassic in age (Pipiringos and O'Sullivan, 1978), but no fossils or other evidence pertinent to constraining their age were found. Mostly composed of sandstone, the Glen Canyon Group is generally cliff forming throughout the Big Bend quadrangle.

The Wingate Sandstone forms the prominent cliff along most of the major canyons and valleys in the quadrangle (figures 2, 3, and 5). It is a red-brown, nearly vertical cliff, and is commonly streaked and stained to a darker brown or black by desert varnish. Erosion of the Wingate is characterized by thick slabs that separate from the cliff along vertical joints as the formation is undercut by mass wasting of the less resistant underlying Chinle Formation. Wingate Sandstone rubble covers slopes below the cliffs. In several places, notably on the north rim of the eastern part of Cache Valley, the Wingate is shattered because of salt-dissolution-induced collapse. Here, a very ledgy and steep, blocky outcrop replaces the usual cliff.

The Wingate Sandstone is mostly light-orange-brown, moderate-orange-pink, moderate red-orange, pink-gray, or pale-red-brown, fine-grained, well-sorted, cross-bedded sandstone. High-angle cross-beds indicate the Wingate is dominantly an eolian unit. Generally it appears massive and uniform from top to bottom; partings and other dividing features are present, but are difficult to see at most locations. They are most evident near the base of the unit.

The lower contact with the Chinle Formation is generally sharp and is interpreted as a disconformity (Pipiringos and O'Sullivan, 1978). Locally, angular discordance is present, but this is due to soft-sediment deformation (folding) in the uppermost Chinle Formation beds. Generally, the eolianite sandstone at the top of the Chinle resembles the Wingate, but the sandstone in the uppermost Chinle is thick bedded rather than massive.

Although the Wingate Sandstone is prominently exposed in the quadrangle, the vertical outcrop habit restricts suitable locations for section measurement. No drill-hole data are available in the quadrangle and the following thickness range is an estimate. Regionally the Wingate is 250 to 400 feet (76-122 m) thick (Doelling, 1981). In the Big Bend quadrangle area the average thickness of the Wingate is about 300 feet (91 m) ranging from 250 to 350 feet (76-107 m).

Kayenta Formation (Jk)

The Kayenta Formation overlies the Wingate and is the middle unit of the Glen Canyon Group. The Kayenta commonly forms thick ledges above the Wingate Sandstone cliff and caps mesas (figures 3 and 5). However, in some places such as on the Dry Mesa side of the Colorado River canyon, the Kayenta merges with the Wingate Sandstone to form a vertical cliff. Although individual beds and lenses of the formation can be found in various hues, the overall color of the Kayenta is red brown and lavender. Prominent benches generally form on top of the thicker sandstone lenses. Bare rock outcrops are common; where present, unconsolidated deposits overlying the Kayenta are typically thin.

The Kayenta is dominated by fluvial sandstone, but eolian and lacustrine sandstone, siltstone, and limestone interbeds or lenses are present, especially in the upper third of the formation. Most of the fluvial sandstone tends to be moderate orange pink with dark-red-brown to gray-red, silty mudstone interbeds. The lenses normally exhibit low-angle cross-bedding, and display channeling, current ripple marks, and slump features. The grain size of the fluvial sandstones varies, ranging from very fine to medium. Very fine flakes of mica are common in some of the sandstone beds and cementation is principally calcareous. Other lithologic types in the Kayenta include: intraformational pebble conglomerate; cliff-forming, light-colored eolian sandstone; slope-forming, red-brown to dark-red-brown sandy siltstone; very-fine-grained silty sandstone; and rare, thin beds of gray lacustrine limestone. These other lithologic types are more common in the upper third of the formation.

The lower part of the formation is dominated by very thick to massive fluvial sandstone lenses. Sparse, very thin partings of dark-red-brown siltstone locally separate the sandstone lenses, which collectively form a vertical cliff above the Wingate cliff. The middle part of the Kayenta contains medium to thick sandstone beds, sporadic intraformational conglomerate lenses, and abundant siltstone partings that form benches between the lenses, giving the outcrop a step-like configuration. The upper part is generally slope forming with scattered thick lenses of fluvial or eolian sandstone. Much of the rock is red-brown, fine-grained, silty sandstone and sandy siltstone. A few 2-inch- (5-cm-) thick beds of gray limestone that represent local lacustrine deposition are present in the sequence. Contacts between fluvial and eolian lenses are generally sharp. In the Big Bend quadrangle, the Kayenta ranges from 240 to 300 feet (73-91 m) thick.

Navajo Sandstone (Jn)

The Navajo Sandstone is the uppermost formation of the Glen Canyon Group and is the classic example of an eolian-deposited formation. This massive, cross-bedded sandstone unit is often described as fossil or petrified sand dunes. The outcrops form cliffs and large rounded cupola or dome-like features. Large areas of unconsolidated sand commonly fill hollows on Navajo outcrops. Thick eolian beds near the top of the Kayenta are similar to those in the Navajo and are thought to intertongue laterally with the Navajo Sandstone. In most places in the quadrangle, we placed the contact over a nearly white eolian sandstone bed (Kayenta) and under light-brown, normally less resistant eolian sandstone (Navajo).

The Navajo Sandstone is mostly orange, light-brown to light-gray, fine-grained sandstone cemented with silica or calcite. Medium to coarse grains of quartz sand are common along cross-bed laminae. Even though the Navajo is a well-cemented cliff former, the sandstone is somewhat friable in hand specimen. The sandstone is generally massive and divided into 15- to 25-foot (4.6-7.6-m) thick cross-bed sets. Cross-bedding angles locally exceed 30 degrees.

Thin, gray, commonly cherty lacustrine limestone beds are present locally in the Navajo Sandstone. In the Big Bend quadrangle they are present on Dry Mesa, Mat Martin Point, and the Dome Plateau. Thin, red, silty sandstone partings separate the 1- to 4-inch- (2.5-10-cm-) thick limestone beds that aggregate from 1 to 4 feet (0.3-1.2 m) thick. Areally these lacustrine or playa limestones extend to as much as several hundred acres (80+ hectares). At their margins the limestone beds become silty and sandy and eventually thin into partings between the massive sandstone horizons. In the Big Bend quadrangle, these limestone beds are most common in the upper third of the Navajo Sandstone. The limestone outcrops commonly form a resistant bench covered with a dark sandy or rubbly soil.

Scattered erosional remnants of the Navajo Sandstone are present on most of the larger mesas in the quadrangle, but the only complete section is on the north flank of the Cache Valley graben. Here, the formation is about 400 feet (122 m) thick. The upper contact is an unconformity with little relief, which is overlain by the Dewey Bridge Member of the Entrada Sandstone.

Entrada Sandstone

The Entrada Sandstone is preserved in the Cache Valley graben and as erosional remnants on Dry Mesa. The Entrada Sandstone is divided into the Dewey Bridge, Slick Rock, and Moab Members (ascending order) in east-central Utah (Wright and others, 1962). The formation is Middle Jurassic in age (Hintze, 1988) and averages about 400 feet (122 m) thick in the quadrangle.

Dewey Bridge Member (Jed): The contact between the Navajo Sandstone and the Dewey Bridge Member of the Entrada Sandstone is usually easily recognizable and is placed where light-colored sandstone is overlain by dark-red or medium-red, muddy, less resistant sandstone. Locally, this change is not pronounced, and lower sandstones of the Dewey Bridge, although slightly darker than those of the Navajo, are also resistant. These lower Dewey Bridge beds are generally lighter in color than the remainder of the member because they are cemented with more calcite than iron oxides, because they contain an abundance of lighter colored, reworked Navajo sand grains, and because of a decreased percentage of muddy matrix. The Navajo-Dewey Bridge contact is a major regional unconformity that separates Lower Jurassic strata from Middle Jurassic strata across the Colorado Plateau (Pipiringos and O'Sullivan, 1978).

The Dewey Bridge Member is generally poorly exposed and forms an earthy slope or a conspicuous red-brown recess between the overlying Slick Rock Member and the underlying Navajo Sandstone. The Dewey Bridge Member is best exposed in the southeast and northwest parts of the Cache Valley graben.

The Dewey Bridge Member is interpreted as deposited on broad tidal flats marginal to a shallow sea (Carmel sea) located to the west (Wright and others, 1962). It is a soft, red, muddy sandstone with irregular contorted bedding. The sandstone is generally fine grained and silty, poorly cemented with iron oxides or calcite, and is divided into indistinct "lumpy" medium to thick beds. The Dewey Bridge is 40 to 60 feet (12-18 m) thick in the vicinity of Cache Valley.

Slick Rock Member (Jes): The Slick Rock Member of the Entrada Sandstone generally forms vertical, lightly banded cliffs. In the Cache Valley area, exposures are shattered or broken into blocks by salt-dissolution-induced fracturing. The rock along the fractures is commonly bleached. The lower contact in the Big Bend quadrangle is generally gradational over a few feet and is picked at the top of the last "lumpy" dark-red-brown bed of the Dewey Bridge Member.

The Slick Rock Member is a massive, well-indurated, red-orange or brown, very fine- to fine-grained sandstone with sparse medium to coarse sand grains. The Slick Rock is eolian and exhibits high-angle cross-bedding like the Wingate and Navajo. However, unlike the Navajo, the sandstone is better sorted and cross-bed laminae do not etch out as well upon weathering, hence producing noticeably smoother outcrops. Cementation is generally calcareous or with iron oxides.

Exposures of the Slick Rock Member are limited to the west end of the north flank and the east end of the south flank of Cache Valley. There the member is 250 to 350 feet (76-107 m) thick. Accurate measurements are difficult to obtain because the unit is a massive cliff and generally not scalable. In other localities, it is so fractured and broken that a complete section is difficult to find.

Moab Member (Jem): The uppermost member of the Entrada Sandstone in the Cache Valley area is very-pale-orange, gray-orange, pale-yellow-brown, or light-gray, fine- to medium-grained, calcareous, massive, cliff-forming, quartzose sandstone. It is generally well indurated and exhibits low-angle eolian cross-bedding. The lower contact is a prominent parting filled with a few inches of red sandy siltstone.

The Moab Member is generally lighter in color than the Slick Rock Member and weathers to a granular surface rather than a smooth one. The Moab Member resembles the Navajo Sandstone, but is not as thick and does not exhibit high-angle cross-bedding. The unit weathers to form rounded, bare rock surfaces, and because of the prominent jointing, develops huge "pillows" or "biscuits" on its upper surfaces. Delicate Arch, the most famous arch in Arches National Park, formed in the lower part of the Moab Member and the upper part of the Slick Rock Member.

The Moab Member ranges from 90 to 110 feet (27-34 m) thick in Cache Valley.

Morrison Formation

The Morrison Formation consists of three members in the Big Bend quadrangle. They are, in ascending order, the Tidwell, Salt Wash, and Brushy Basin Members. Exposures are confined to the Cache Valley graben. In addition, a rubble breccia composed of landslide deposits containing unmistakable Morrison rocks is present on the south flank of the graben. The Morrison Formation is considered to be Late Jurassic in age (Dane, 1935; Williams, 1964). About 6 to 15 feet (1.8-4.6 m) of brown, thin-bedded, commonly ripple-marked, fine-grained sandstone at the base of the Middle Jurassic Summerville Formation is included with the Morrison Formation in this report. The complete Morrison Formation (with the Summerville) is 590 to 650 feet (180-198 m) thick in Cache Valley.

Tidwell Member (Jmt): The lower member of the Morrison Formation in the Cache Valley graben is easily recognized; its dark-red or lavender color and large, white, siliceous concretions contrast sharply with the Moab Member of the Entrada Sandstone below and the Salt Wash Member above. Tidwell Member outcrops are prevalent along the trail to Delicate Arch and near the Delicate Arch viewpoint parking lot. Fault-repeated outcrops of the Tidwell are also present in the eastern part of the graben. Locally, at the base of the mapped unit (in the very thin Summerville Formation), is a 1- to 2-foot (0.3-0.6-m) thick, resistant, platy weathering, well-bedded, reworked, fine-grained, light-brown sandstone. The lower 6 to 15 feet (1.8-4.6 m) (Summerville Formation) is slightly more resistant than the remainder of the unit. An unconformity may exist between the Summerville and the Tidwell Member of the Morrison Formation. Such is the case in western Grand County (Doelling, 1993) and in the San Rafael Swell (Trimble and Doelling, 1978).

A zone of sandy, nodular, gray limestone and huge concretions of white to light-pink chalcedony is present above the lower 6 to 15 feet (1.8-4.6 m). Concretions approach 20 feet (6 m) in diameter; however, most are 5 to 10 feet (1.5-3.0 m) in diameter. Most of the Tidwell consists of red and lavender shaly, thin, or nodular beds of silty, limy, fine-grained sandstone and siltstone. Thin beds of nodular limestone are present between the concretionary zone and the top of the unit. Locally, these sandy limestone beds are as much as 3 feet (0.9 m) thick.

The thickness of the Tidwell Member in Cache Valley is 40 to 60 feet (12-18 m). The lower 6 to 15 feet (1.8-4.6 m) of the mapped unit was probably deposited on a tidal flat, whereas most of the unit was probably deposited on gently sloping floodplains and in shallow lakes on the floodplain. The origin of the large siliceous concretions is a puzzle, but they may be diagenetic.

Salt Wash Member (Jms): The Salt Wash Member of the Morrison Formation consists of resistant sandstone deposited in anastomosing fluvial channels alternating with overbank deposits of finer grained sandstone, siltstone, mudstone, or claystone. Exposures of this member are most widespread in the central part of the Cache Valley graben, where they are shattered and faulted by collapse due to salt dissolution.

The Salt Wash Member consists of sandstone, conglomeratic sandstone, mudstone, siltstone, shale, claystone, and conglomerate. Lenticular outcrops of sandstone, conglomeratic sandstone, and conglomerate are generally light gray to light brown on fresh surfaces and weather to white or yellow-gray hues. The lenses represent ancient river channels (Trimble and Doelling, 1978), with individual channels locally traceable for a few hundreds of feet. Sedimentary features, such as meanders, bars, trough cross-stratification, and cut-and-fill, are readily identifiable. The cementation is generally calcareous and the grain size varies within individual lenses as well as from lens to lens. Grains are well to poorly sorted. The less resistant mudstone, siltstone, shale, and claystone are generally sandy and weather into recesses or earthy slopes.

The Salt Wash Member is about 250 feet (76 m) thick in the Cache Valley area. The lower contact with the Tidwell Member appears to be gradational and interfingering and is probably unconformable. In Cache Valley, the contact is placed where the red slopes of the Tidwell are capped by the first thick, cliff-forming, light-colored channel sandstone lens of the Salt Wash.

Brushy Basin Member (Jmb): Whereas the Salt Wash Member is dominated by cliff-forming channel sandstone, the Brushy Basin Member is dominated by slope-forming floodplain and lacustrine deposits. The member is exposed in the more deeply collapsed parts of the Cache Valley graben. The member is easily recognized by its bright green or blue-green color.

The contact between the Salt Wash and Brushy Basin Members is placed where the ledge-forming sandstones of the Salt Wash give way to the slope-forming mudstones of the Brushy Basin. Locally, however, resistant sandstone and conglomerate lenses are also present in the Brushy Basin Member. These are more common in the lower part of the member, and where present, are generally more conglomeratic and weather darker in color.

The Brushy Basin generally consists of variegated muddy siltstone and claystone, and lesser amounts of sandstone, conglomeratic sandstone, and limestone. In Cache Valley, the slope formers are dominated by bright green and maroon hues. Clay present in the mudstone swells when wetted and shrinks when dried and provides typical "popcorn" textured outcrops. The bentonitic clay is derived from the hydrolysis and devitrification of volcanic ashes (Stokes, 1952a). Some of the volcanic ash is altered to zeolite minerals, which produce the bright green or blue-green color (Tripp and Mayes, 1989).

Sandstone, conglomeratic sandstone, conglomerate, and limestone occur throughout the member, but are more prevalent in the lower half. Grain size varies considerably within individual lenses and from lens to lens, ranging from very fine to very coarse sand and granules to small cobbles. Most of these ledge-forming lenses are a shade of white, gray, or brown. The coarser grained and better indurated units are generally cross-bedded.

In Cache Valley, the lower 55 feet (17 m) of the Brushy Basin consists of 60 percent slope-forming rocks interbedded with 40 percent ledge-forming units. Above this is a 40-foot (12-m) thick, lenticular conglomeratic sandstone that grades laterally into light-colored, fine-grained sandstone interbedded with variegated shale or mudstone. This is overlain by 30 feet (9 m) of mostly maroon mudstone capped by a ledge of brown-gray, nodular-weathering limestone. Next is a 100-foot (30-m) unit of bright-green earthy mudstone or shale with thin fingers of white, fine-grained sandstone that is entirely slope forming in its outcrop habit. It is capped by a gray-green, brown-weathering ridge- or ledge-forming sandstone about 10 feet (3 m) thick. Finally, the uppermost unit is a green and tan shale or mudstone with a few ledges of "lumpy," fine-grained, cream-colored sandstone and brown-weathering, nodular, gray limestone about 80 feet (24 m) thick. The Brushy Basin Member is 300 to 340 feet (91-104 m) thick in Cache Valley.

Cretaceous Rocks

Cedar Mountain Formation (Kcm)

The Cedar Mountain Formation appears similar to the Brushy Basin Member of the Morrison Formation. This similarity makes recognizing the contact between the two formations difficult. The contact is mapped at the base of a thick 10- to 20-foot (3- to 6-m) thick ledge or cliff of lenticular conglomerate and quartzose sandstone. The conglomerate and sandstone are considered equivalent to the Buckhorn Conglomerate in Emery County (Trimble and Doelling, 1978).

The Cedar Mountain Formation consists of one or two cliff-forming units of sandstone, quartzitic sandstone, conglomeratic sandstone, gritstone, and conglomerate, separated by thick slope-forming mudstone and muddy sandstone. The resistant units are similar in texture and coloration to their Brushy Basin counterparts. The mudstone is also similar to mudstone in the Brushy Basin, but the coloration is generally not as bright. Gray-green and lavender mudstone is present in the Cedar Mountain Formation, but maroon mudstone is rare. Nodular, brown-weathering, gray, sandy limestone horizons are commonly encountered in the slope-forming parts of the Cedar Mountain Formation.

In sections 9 and 10, T. 24 S., R. 22 E., south of Delicate Arch, the lowermost unit of the Cedar Mountain Formation (Buckhorn equivalent) consists of 15 feet (4.6 m) of lenticular, fine- to coarse-grained, pebbly conglomerate and quartzitic sandstone that form a very prominent ridge or cliff. This lower unit is overlain by 90 feet (27 m) of slope-forming, pastel-green shale interbedded with sporadic thin to medium lenses of tan, green, or gray, medium-grained, well-indurated sandstone or pebbly sandstone. The next 40 feet (12 m) are similar, but the overall color is light gray. For another 85 feet (26 m) the color alternates between lavender and gray, and thin zones of nodular sandy limestone become more numerous.

The Cedar Mountain Formation is 200 to 240 feet (61-73 m) thick in Cache Valley. Like the Brushy Basin Member of the Morrison Formation, it is regarded as a swampy floodplain deposit (Stokes, 1952b). The Cedar Mountain is considered Early Cretaceous (Albian) in age (Hintze, 1988).

Dakota Sandstone (Kd)

The Dakota Sandstone is mostly a prominent, yellow-brown weathering, resistant sandstone, conglomeratic sandstone, and conglomerate that crops out as hogbacks in Cache Valley. Fresh colors are yellow-gray, gray-orange, and brown. The conglomeratic beds contain mostly cobble- and pebble-sized clasts interbedded with medium-to coarse-grained sandstone. Cementation is generally calcareous and the lenses are cross-stratified. Rare fossil wood and leaf impressions are present in the more resistant beds. A lower slope-forming unit of soft, yellow-gray mudstone commonly rests on the light-gray and lavender mudstone of the Cedar Mountain Formation. Close examination of the mudstone slope reveals the presence of siltstone, claystone, and fine- to medium-grained, poorly cemented sandstone, carbonaceous shale, and white marl.

The contact with the Cedar Mountain Formation is an unconformity (Hintze, 1988). The exact position of the contact is difficult to find; however, the color difference between mudstones is helpful. The Dakota Sandstone ranges from 40 to 50 feet (12-15 m) thick. Variations in thickness are commonly at the expense of the slope-forming lower unit. The hard, ridge-forming part ranges from 15 to 25 feet (4.6-7.6 m) thick. The Dakota was deposited on a broad coastal plain in front of the advancing Mancos sea. The Dakota is Late Cretaceous (Cenomanian) in age (Hintze, 1988).

Mancos Shale

The Mancos Shale is the youngest formation in the Big Bend quadrangle. Regionally, it is about 3,600 feet (1,097 m) thick (Willis, 1994), but only the lower 1,000 feet (305 m) are preserved in Cache Valley. Members present in these exposures are, in ascending order, the Tununk Shale Member, the Ferron Sandstone Member, and the lower part of the Blue Gate Shale Member.

Tununk Shale Member (Kmt): The Tununk Shale is present only in the western part of the Cache Valley graben in sections 8, 9, and 10, T. 24 S., R. 22 E. The contact with the Dakota Sandstone is gradational over a narrow interval. The Tununk is a medium-gray, blue-gray, steel-gray, or lead-gray fissile shale that forms a soft slope. It is generally poorly exposed. Some shaly horizons are silty or sandy and are slightly more resistant, but these rarely show in the Cache Valley outcrops. Most of the shale is slightly calcareous.

The Tununk Shale Member is estimated to be 400 feet (122 m) thick in the quadrangle, but may be locally attenuated because of salt-dissolution-related deformation. The member becomes sandy near the top. The Tununk is considered late Cenomanian to mid-Turonian in age (Molenaar and Cobban, 1991). It was deposited in an epicontinental sea that covered the central part of the North American continent in Late Cretaceous time.

Ferron Sandstone Member (Kmf): The Ferron Sandstone is the most resistant part of the otherwise soft Mancos Shale in Cache Valley. Although the Tununk Shale becomes increasingly sandy toward its top, the contact with the Ferron Sandstone Member is an erosional sequence boundary (Molenaar and Cobban, 1991). The sand content of the Ferron makes it more resistant and gives it a brown-gray color. In Cache Valley the Ferron forms low ridges and rounded hills. Regionally, the Ferron forms a low double cuesta of sandy shale separated by a soft swale of very carbonaceous, dark shale (Doelling, 1988). In Cache Valley the outcrops have weathered unevenly and the double cuesta is not always recognizable, probably because of steep dips and structural complications.

Most of the Ferron Sandstone Member is platy or thin-bedded, brown-gray, very-fine-grained sandstone. The middle part of the member (about 20 to 30 feet [6-9 m] thick) consists of dark-gray and black carbonaceous shale. The lower cuesta of the Ferron Sandstone is 35 to 40 feet (11-12 m) thick, and the upper is about 35 to 50 feet (11-15 m) thick.

The thickness of the Ferron Sandstone ranges from 90 to 120 feet (27-37 m) in the Big Bend quadrangle. It grades upward into the Blue Gate Shale Member. Broken megafossils (mostly shellfish) commonly litter the surface at the top of the upper cuesta. The Ferron is Turonian in age (Molenaar and Cobban, 1991) and is interpreted as deposited in a shallow, shoaling sea.

Blue Gate Shale Member (Kmb): This unit is similar to the Tununk Shale Member, but generally is a lighter gray in outcrop. Like the Tununk, there are sandy layers that are more tan and slightly more resistant than the encasing gray marine shale. The outcrop area in Cache Valley is one of low rolling hills. The estimated thickness of the incomplete Blue Gate Shale Member in Cache Valley is about 500 feet (152 m).

Quaternary Deposits

Quaternary sediments in the Big Bend quadrangle consist of alluvial, eolian, and landslide deposits. Most range from middle Pleistocene to Holocene in age.

Alluvium (Qa_1, Qa_2)

Holocene alluvium in and along the Colorado River and major stream channels is mapped either as Qa_1 or Qa_2. Alluvium mapped as Qa_1 is confined to active channels and floodplains. Bars and levees along the Colorado River consist of moderately sorted sand and pebbly gravel. However, some bars are dominantly subangular to rounded cobbles and boulders. Alluvium (Qa_1) mapped in the stream channels of Castle and Placer Creeks consists of poorly sorted sand, silt, and gravel.

Slightly older alluvium (Qa_2) comprises the valley-fill material present at the surface in lower Castle Valley. Castle Creek has incised about 20 feet (6 m) into Qa_2 alluvium below its confluence with Placer Creek. Qa_2 deposits in Castle Valley consist mainly of sand, silt, and clay, with sparse gravel lenses. However, the amount of gravel in these deposits increases up-gradient. Qa_2 deposits along the Colorado River form the first surface about 20 feet (6 m) above the modern floodplain. The alluvium consists of sand and silt, with sparse gravel lenses. The deposits represent a combination of river and local alluvial-fan deposition.

Richmond (1962) and Harden and others (1985) observed that Qa_2 alluvium characteristically displays weak soil development. Exposures of Qa_2 along lower Castle Creek contain several weak buried A horizons. Minor disseminated pedogenic carbonate (weak Stage I) may be present at some locations (Harden and others, 1985).

Alluvial Terrace-Gravel Deposits (Qat_3, Qat_4)

Terrace-gravel deposits are common along the Colorado River. In the quadrangle, the highest terrace deposits (Qat_4) are rounded knobs of gravel capping benches and small hills about 130 feet (40 m) above the present river level. Qat_3 deposits exhibit a similar morphology about 100 feet (30 m) above the river.

The deposits consist of subrounded to rounded, poorly stratified, clast-supported gravel in a gray, calcareous sandy matrix (Colman and Hawkins, 1985). Clasts are mostly 2 to 6 inches (5-15 cm) in diameter with the largest about 12 inches (30 cm). The gravel contains Precambrian granitic and high-grade metamorphic rocks; Tertiary(?) basaltic, intermediate, and silicic igneous rocks; and late Paleozoic to Mesozoic sedimentary rocks. Locally, lenses of cross-bedded, moderately sorted, fine- to medium-grained sand are associated with the gravels.

Alluvial-fan Deposits (Qaf_3, Qaf_4, Qafy, Qafo)

In Castle Valley, alluvial-fan deposits form apron-like slopes inclined down the valley from the La Sal Mountains and from the cliffs that surround the valley. Alluvial-fan deposits of Qaf_3 and Qaf_4 consist of poorly sorted, unstratified to poorly defined subhorizontally bedded, sandy cobble gravel. Some gravel beds are clast-supported, and some layers having imbricated clasts, suggesting stream-channel origin. Some gravel beds are matrix-supported and structureless, suggesting a debris-flow origin. Local, small and irregular accumulations of boulders on the Qaf_3 and Qaf_4 surfaces are suggestive of sieve deposits.

In general, Qaf_3 deposits form a dissected, stony surface that grades inconspicuously into the Qa_2 surface. Qaf_3 deposits become more extensive and better developed up the valley. Soils associated with Qaf_3 deposits exhibit weak argillic horizons in fine-grained alluvium and calcic horizons in gravelly alluvium. The calcic horizons range from continuous coatings on clast bottoms (Stage I) to continuous carbonate coatings on clasts and disseminated carbonate in the matrix with sparse nodules (weak Stage III).

Qaf_4 deposits are preserved in two low-relief, subtle ridges in the southeast corner of the quadrangle. They are capped by the eroded remnants of a pedogenic carbonate soil horizon. The calcic horizon varies from coalesced carbonate nodules to pebble coatings cemented in a plugged horizon (Stage IV). This calcic horizon can be traced up-valley into the Warner Lake quadrangle where it caps a broad whaleback feature. Another well-indurated calcic horizon, having Stage IV morphology, is poorly exposed along the base of the dry wash that separates the two Qaf_4 deposits. This calcic horizon cannot be traced up-valley to older alluvial-fan surfaces.

Harden and others (1985) suggested, on the basis of calcic soil development, that alluvial deposits equivalent to Qaf_3 are correlative with Pinedale-age deposits of the Rocky Mountain region. Further, they concluded that alluvial deposits equivalent to Qaf_4 are correlative to Bull Lake-age deposits.

The coalesced alluvial fans along the southwest margin of Castle Valley grade upslope into talus (Qmt) and downslope into alluvium (Qa_2). Younger alluvial fans (Qafy) head in gullies of older fan deposits (Qafo) and bury older fans downslope. Remnants of successively older beheaded fans stand above the younger fans. Younger alluvial fans (Qafy) are active and correlate with Qa_1 and Qa_2 deposits. However, local areas of Qafy are inactive and possibly correlate with Qaf_3 deposits. Older alluvial fans (Qafo) are inactive and correlate with Qaf_3 and Qaf_4 deposits.

The Qaf_3 and Qaf_4 deposits consist of poorly sorted, angular to subangular boulders, cobbles, and gravels in a crudely bedded, sandy matrix. Sedimentary features in the deposits such as cut-and-fill structures and structureless matrix-supported gravel layers suggest unchannelized slope-wash, channelized debris flows, and ephemeral stream action.

Information from water-well logs (Utah Division of Water Rights, unpublished data) and cuttings from two petroleum wells (Utah Geological Survey Core Library, unpublished data) suggest that at least 350 feet (107 m) of gravelly alluvium is present beneath Castle Valley. The thickness of alluvial-fan deposits along the margin of the valley ranges from 6 to 40 feet (1.8-12 m) based on exposures and water-well logs.

Pediment-Mantle Deposits (Qap_3, Qap_4)

Continuous and discontinuous deposits of locally derived alluvial material extend from surrounding bedrock exposures toward the Colorado River. These deposits are the erosional remnants of mixed alluvial-fan and ephemeral stream deposits forming relatively thin gravel veneers on pediment surfaces (Colman and Hawkins, 1985). Locally, they contain eolian and sheetwash sand material.

We divided these alluvial pediment-mantle deposits into two units (Qap_3 and Qap_4) based on relative height above the present drainage channels and relationship to alluvial-terrace deposits along the river. The relative elevations of the deposits are similar to those of the correlative alluvial-terrace gravels.

Pediment-mantle deposits (Qap_3, Qap_4) consist predominantly of poorly sorted sandy gravel. Locally, sand-rich and clast-supported gravel lenses are present. Clast size ranges from pebbles to boulders. Matrix material consists of red-brown, calcareous sand and silt. Clasts consist of lithologies common to the Permian and Mesozoic formations in the immediate source areas. Well-rounded Precambrian igneous and metamorphic clasts derived from the Permian Cutler Formation or from alluvial-terrace gravels are locally present. Along the river, pediment-mantle deposits are locally interbedded with river-terrace gravels. Along the west side of the Colorado River, at New Rapids, a 10-foot (3-m) bed of Qat_4 river gravel is overlain by detritus of Qap_4. The basal portion of the Qap_4 deposit is an irregular 6- to 20-foot (2-6-m) layer of bouldery gravel. The bouldery gravel is overlain by a sand-rich unit that weathers to earthy, rounded hills and slopes.

Talus Deposits and Colluvium (Qmt)

Talus deposits and colluvium are found on steep slopes below most cliffs. Talus and colluvium exhibit gradational contacts; therefore, they are lumped together as a single map unit. Talus deposits consist of gravity-produced rock-fall blocks, boulders, and smaller fragments. Colluvium consists mostly of slopewash material charaterized by poorly sorted, angular to subangular rock fragments in a matrix of coarse to fine sand, silt, and clay. Some colluvium may display a weak discontinuous bedding parallel to slope, but most is structureless (Richmond, 1962). Colluvium generally supports vegetation, whereas talus contains little fine material between blocks and supports little vegetation.

The best preserved Qmt deposits are cones and sheets on the slopes of Triassic formations beneath the overlying Jurassic Glen Canyon Group sandstone cliffs. The deposits range from a thin veneer to a layer 10 feet (3 m) thick. The deposits may show relatively smooth concave surfaces locally scored by shallow gullies. The deposits are commonly gradational and interfinger with alluvial-fan material (Qafo and Qafy) at their downslope extent. The contact between the Qmt deposits and alluvial-fan deposits is placed at a break in slope.

Landslide Deposits (Qms)

The remnants of an old rotational slump are present at the northwest end of Castle Valley in section 31, T. 24 S., R. 23 E. The extremely eroded condition of the landslide and its height about 700 feet (213 m) above the river suggest early Pleistocene or older age. The landslide is developed in the upper part of the Moenkopi Formation and involves both the Moenkopi and Chinle Formations. The basal slip surface is locally visible and well preserved. The direction of landslide movement was north-northeast, nearly parallel to the local dip direction. Dips of the rock in the landslide steepen toward the main scarp. Slump material is significantly disrupted near the basal slip surface.

Jumbled and slumped landslide masses of the Moab Member of the Entrada Sandstone, and Tidwell and Salt Wash Members of the Morrison Formation are present in a salt-"collapse" basin in the northeast part of Dry Mesa, S½, sections 13 and 14, T. 24 S., R. 22 E. Morrison Formation debris in this deposit was derived from outcrops that existed on Dry Mesa during active salt-dissolution. Presently, the nearest outcrops of the Morrison Formation are found in Cache Valley at elevations lower than those of the landslide deposit. A thick deposit of mixed eolian and alluvial sand, capped by a Stage V petrocalcic soil, partially covers the landslide deposit. Oviatt (1988) estimated the soil to be early Pleistocene in age, making the landslide material even older. Similar thick, deformed, mixed-eolian and alluvial-sand deposits contain the Bishop (740 ka) and Lava Creek B (620 ka) ashes in Salt Valley and Fisher Valley (Colman and Hawkins, 1985; Oviatt, 1988). Colman and Hawkins (1985) indicated their lower basin-fill deposits (deposits beneath the Bishop ash) may be as old as Pliocene. We assume the landslides are early Pleistocene in age, but possibly as old as Pliocene.

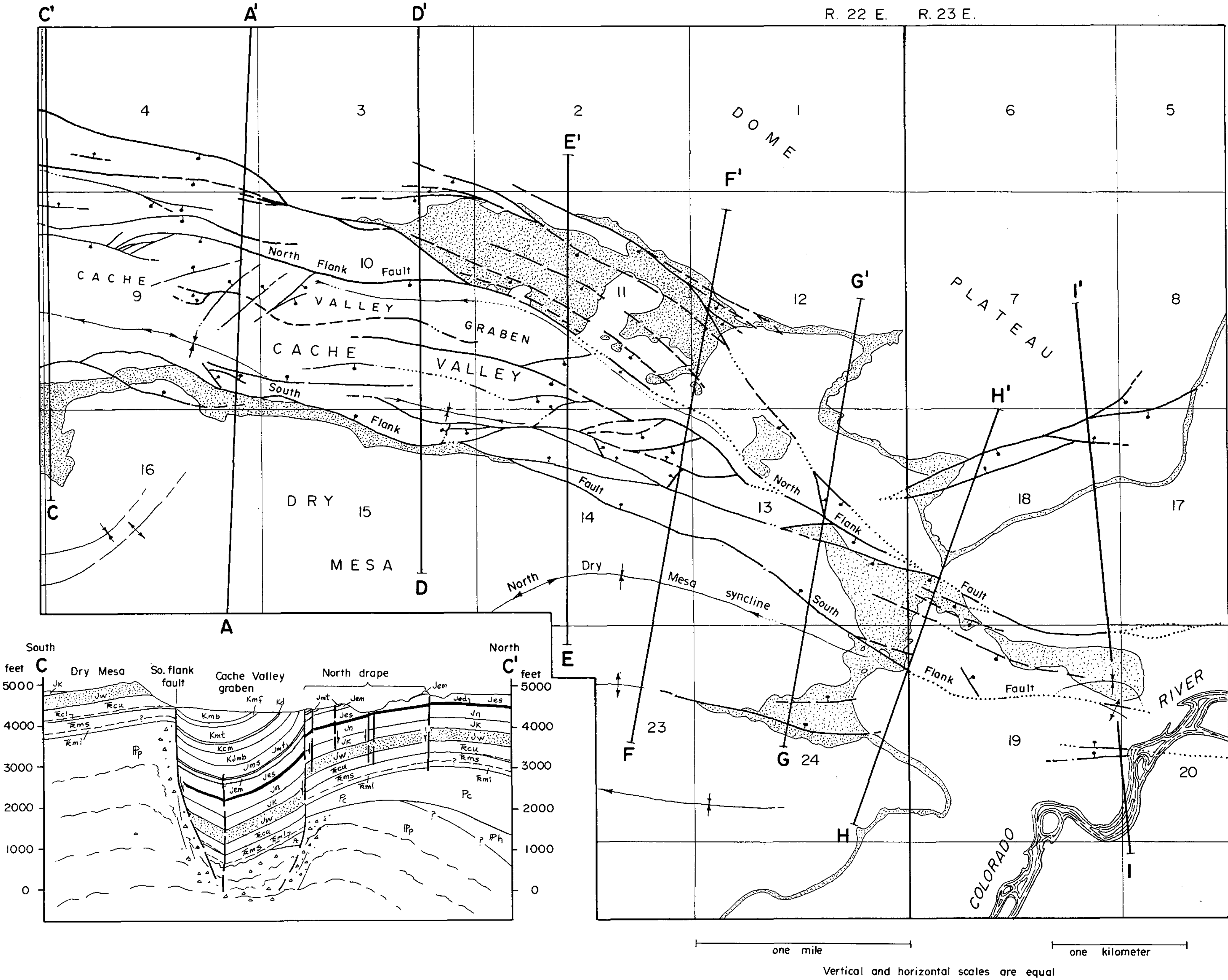
Along the eastern rim of the Dome Plateau, in section 8, T. 24 S., R. 23 E., an extremely large block of Wingate and Kayenta is detached from the plateau by a long arcuate fissure, about 2 to 30 feet (0.6-9.1 m) wide. The fissure appears to penetrate through the Jurassic units and root in the Chinle Formation. The fissure may have developed along joints. The resulting large block of detached sandstone does not presently exhibit any significant vertical displacement or evidence of rotational movement, but could develop into a slump block.

Eolian Sand Deposits (Qes)

Small dunes and thin sheets of eolian sand (Qes) are present on sandstone plateaus in the quadrangle. The relatively thin, discontinuous deposits are commonly present in narrow canyons, erosional surface depressions, and on the lee sides of irregular bedrock prominences. Most eolian deposits support sparse vegetation and are partially stabilized.

Mixed Eolian and Alluvial Sand Deposits (Qea, Qeao)

Many deposits of unconsolidated sand have a mixed eolian and alluvial origin (Qea). Most of the sand was wind deposited, but alluvial processes, such as sheetwash and ephemeral stream flow, reworked the eolian material. Generally, these deposits are restricted to areas affected by occasional sheetwash runoff. Most of these deposits are probably Holocene in age. However, on the southwest side of Cache Valley, calcic soil development on mixed eolian and alluvial sand deposits (Qeao) suggests an early Pleistocene age. The calcic soil reaches carbonate morphologic Stage V and is developed on a surface mantled with eolian sand that truncates gently dipping strata of Jurassic age (Oviatt, 1988). The older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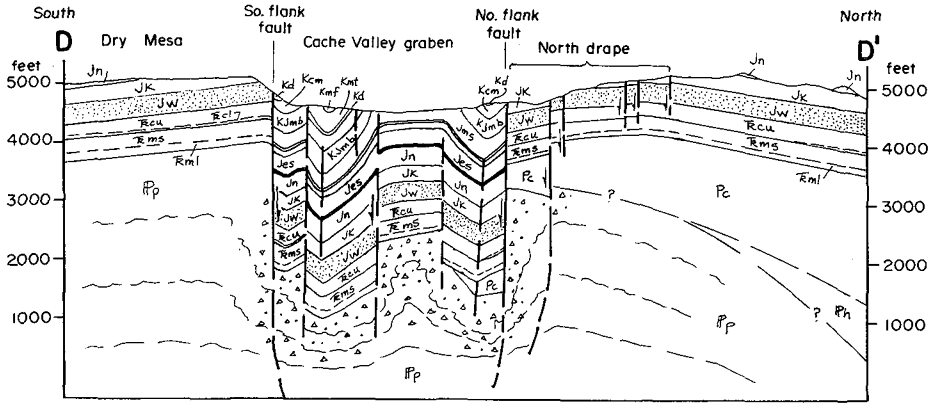
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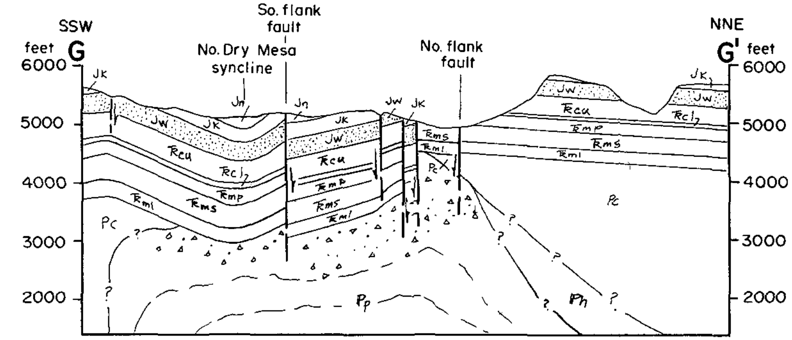
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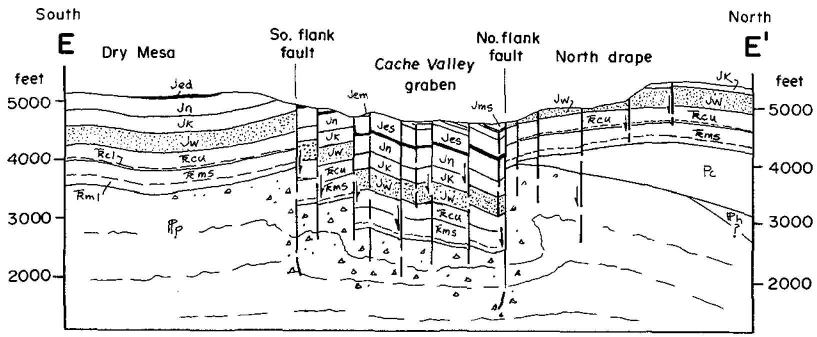
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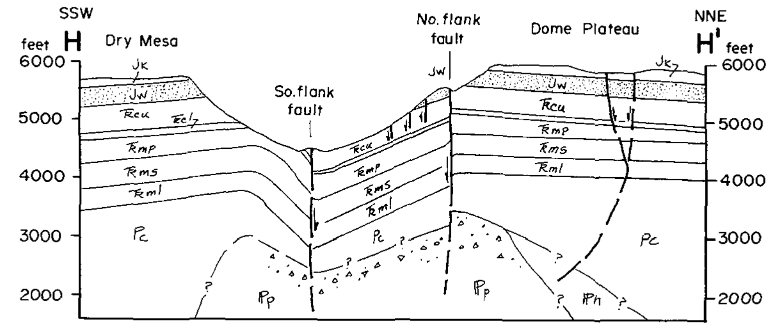
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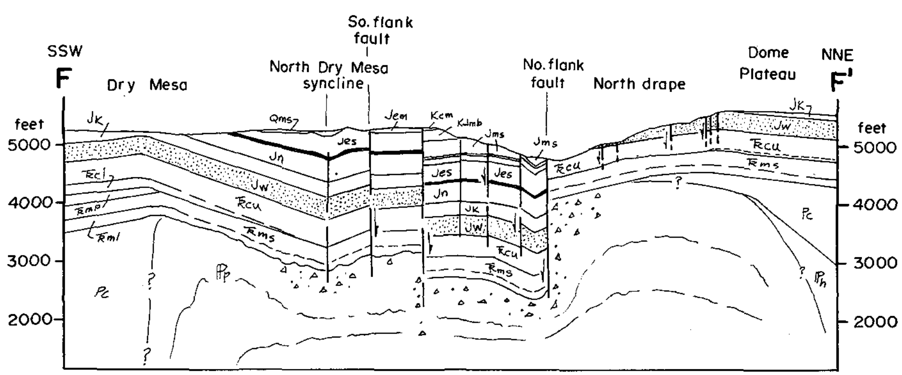
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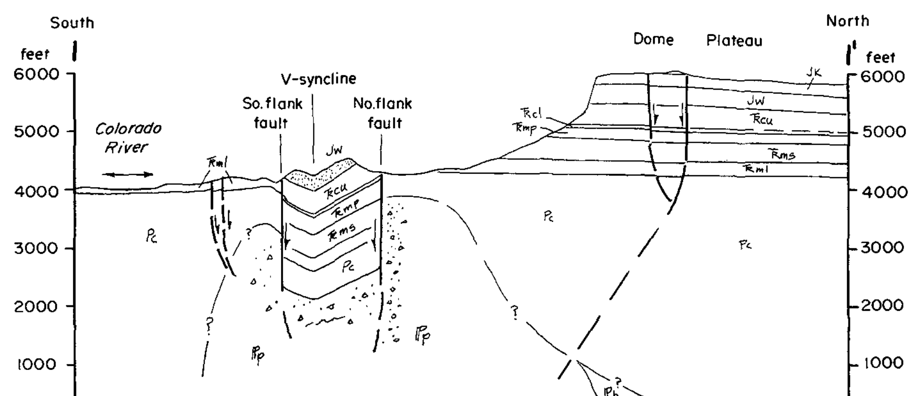
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mixed eolian and alluvial deposits are about 160 feet (49 m) thick, consisting of horizontally bedded sand and silt with minor clay and gravel lenses. These deposits fill an approximately 500-foot (152-m) wide paleocanyon. No buried soils or unconformities have been observed in the finer grained fill material, suggesting the sediments accumulated rapidly and nearly continuously (Oviatt, 1988).

Mixed Alluvial and Colluvial Deposits (Qac)

Areas of mixed alluvial and colluvial deposits parallel the ephemeral washes of Cache Valley. The active channels are choked with sand and angular cobble and boulder alluvium derived from adjacent bedrock outcrops. Deposits that cover wider areas consist of sand and mud derived from local bedrock sources. The deposits are probably Holocene and late Pleistocene in age and are as much as 15 feet (4.6 m) thick.

STRUCTURAL GEOLOGY

The Big Bend quadrangle is located in the Paradox fold-and-fault belt at the junction of three major salt-tectonic structures: the collapsed Castle Valley salt-cored anticline, Cache Valley graben, and Professor Valley graben (mostly in Fisher Towers quadrangle). Regionally, Mesozoic and Tertiary strata dip gently northward from the La Sal Mountains-Moab region toward the Book Cliffs and into the Uinta basin (Williams, 1964). The salt-tectonic features and related structures on their flanks disrupt the otherwise simple homocline.

All three of the salt-tectonic features have a graben developed over a buried core of thick salt (salt wall). Strata flanking the Cache Valley and Professor Valley structures do not dip as anticlines and therefore cannot be described as salt-cored anticlines. The thickness of Paradox Formation salt in the subsurface is diminished or missing adjacent to the salt walls of all three features.

Cache Valley Graben

The Cache Valley graben extends west-northwest from the Colorado River and connects with the Salt Valley salt-cored anticline, which trends northwesterly (figure 1). The major displacing faults on the south and north margins of the graben are herein grouped into the South Flank fault zone and the North Flank fault zone, respectively.

Strata in the Cache Valley graben preserve the youngest consolidated rocks in the quadrangle. We give structural interpretations in a series of cross sections drawn across the graben on figure 6. Bedding attitudes vary from horizontal to vertical, generally striking in linear belts subparallel to graben escarpments and faults. Competent units form hogbacks that are shattered by many fractures. Less competent units are locally folded, but most are broken and tilted.

V-synclines have developed at the north and south margins of the Cache Valley graben leaving a broad, shattered syncline in the middle. A v-syncline is a salt-dissolution-induced chevron fold with a v-shaped cross section (Doelling, 1985, 1988). Dips on the north side of the north v-syncline range to as much as 20 degrees and dips on the south side range to as much as 40 degrees. Dips on the south v-syncline are steep, commonly approaching 80 degrees on each side of the axial trace. Both synclines are well developed in section 10, T. 24 S., R. 22 E. (see figure 6, cross section D-D′).

The depth of structural collapse in the graben generally increases westerly from the drainage divide between Salt Wash and the Colorado River and easterly from the drainage divide toward the Colorado River (figure 7). Salt Wash flows south perpendicularly across Cache Valley just west of the west margin of the quadrangle.

South Flank Fault Zone

Strata forming the south escarpment of the Cache Valley graben are about 500 feet (152 m) higher than those forming the north escarpment at the west margin of the quadrangle (figure 6, cross section C-C′). This apparent displacement across the graben decreases eastwardly (figure 6, cross section D-D′ to cross section G-G′). Along the west margin of the quadrangle the South Flank fault zone is a simple normal fault with a few splays. Eastwardly, in sections 13 and 14, T. 24 S., R. 22 E., it breaks up into many branching faults where each block of strata between faults dips successively more steeply into the graben and forms a "roll over." Nearly all observable fault planes dip at high angles (>45°). The maximum apparent displacement across the South Flank fault zone is about 3,300 feet (1,006 m).

North Flank Fault Zone

The north escarpment of the Cache Valley graben is formed by a fault zone that parallels the South Flank fault zone. The North Flank fault zone is as much as a half mile (0.8 km) wide and contains numerous subparallel and branching faults. The fault zone forms a "roll over" along the west half of the Cache Valley graben in the quadrangle, and becomes a simple normal fault with a few splays in the east half (see cross sections, figure 6). The dips on the fault blocks in the "roll over" steepen to as much as 45 degrees. The apparent displacement into the graben varies along strike reaching a maximum of about 1,400 feet (427 m) in section 11, T. 24 S., R. 22 E. Rocks along the northern escarpment also plunge gently westward toward the Salt Wash syncline, the axial trace of which is located 1 mile (1.6 km) west of the quadrangle.

Elephant Butte Folds

The Elephant Butte folds extend into the quadrangle from the west and gently warp strata on Dry Mesa just south of the Cache Valley graben. In the quadrangle, the Elephant Butte folds trend generally east-west and plunge gently westward

Figure 7. *East end of the Cache Valley graben at the Colorado River. Pc = arkosic member of Cutler Formation, Ŧml = lower member of Moenkopi Formation, Ŧmu = upper member of Moenkopi Formation, Ŧc = Chinle Formation, Jw = Wingate Sandstone, Jk = Kayenta Formation. Note that the Wingate Sandstone, which forms the high cliff in the background, has collapsed nearly to river level due to salt dissolution of the subsurface Paradox Formation. A characteristic v-syncline is present at the deepest part of the collapsed rock sequence.*

toward the north-south axis of the Salt Wash syncline (Doelling, 1983, 1985). The axial trace of the syncline follows Salt Wash, a drainage that flows southward across the Cache Valley graben and Elephant Butte folds 1 mile (1.6 km) west of the quadrangle's west margin.

The principal Elephant Butte fold on Dry Mesa is a syncline (Dry Mesa syncline) that divides Dry Mesa approximately in half. The Dry Mesa syncline is a broad fold with dips on the south limb ranging up to 5 degrees and dips on the north limb ranging up to 7 degrees. The Navajo Sandstone and Dewey Bridge Member of the entrada Sandstone are exposed in the trough of the shallow Dry Mesa syncline.

Another syncline (North Dry Mesa syncline) has an arcuate axial trace and is located 0.5 mile (0.8 km) south of the Cache Valley graben in the east part of the mesa. At its west end the axial trace of the syncline plunges southwesterly toward the axis of the Dry Mesa syncline. The eastern part of the North Dry Mesa syncline is doubly plunging [along its east part] and forms a structural depression (plate 1). The depression is located in the SW¼ section 14, T. 24 S., R. 22 E., and is about 1 mile (1.6 km) long and 0.5 mile (0.8 km) wide. Dips on the flanks of the depression range to 40 degrees. The Navajo Sandstone and Entrada Sandstone are preserved in the depression. Thick Pleistocene unconsolidated deposits and a large landslide composed of Morrison Formation blocks are also present in the depression.

Between the Dry Mesa syncline and the North Dry Mesa syncline is a high-angle normal fault that dies out into a fault-propagation anticline. Dip in the strata changes sharply across the fault, as if someone had broken a board in two. Bedding on the south side of the fault dips [range] from 5 to 10 degrees to the southwest and bedding on the north side of the fault dips [range] from 12 to 20 degrees to the north.

Castle Valley Salt-Cored Anticline

The Castle Valley salt-cored anticline trends about N. 50° W. and plunges to the northwest. The southeast extension of the structure is complicated by late Oligocene intrusions of the north La Sal Mountains. The elongate oval-shaped valley formed over the salt core is approximately 10 miles (16 km) long and 3 miles (4.8 km) wide. In general, Jurassic rocks form massive cliffs that rim the valley and dip away from the structure at angles of 5 to 10 degrees. Older strata below the cliff rim dip progressively more steeply away from the valley axis. At the northwest end of the valley, the anticline is slightly asymmetrical with the southwest limb exhibiting an overall steeper dip (plate 2, cross-section B-B′).

Regional gravity studies show closely spaced gravity contours along the margins of the salt-cored anticline, suggesting it has steep walls. Modeling of the data suggests about 7,000+ feet (2,134+ m) of structural relief on the salt wall (Case and others, 1963; Case and Joesting, 1972). Two petroleum wells near Castle Valley that postdate the gravity studies penetrate pre-Paradox Formation rocks. Formational tops from the wells and new surface mapping allow a better estimate of the height and shape of the Castle Valley salt wall.

The Union of California Burkholder No. 1 well, drilled in section 1, T. 26 S., R. 22 E., southwest of Castle Valley, penetrated the top of the Mississippian Leadville Limestone 6,081 feet (1,853 m) below sea level. The Mississippian Leadville and pre-Paradox Formation Pennsylvanian rocks (Molas and Pinkerton Trail Formations) formed the basin floor on which the Paradox Formation and later Paleozoic units were deposited. The Leadville Formation makes a good marker horizon to determine the approximate amplitude of the Paradox basin salt walls that core the anticlines.

We interpret the Pinkerton Trail and Leadville Formations to be nearly horizontal in the subsurface (figure 8). Dipmeter data for the Leadville from the Conoco Federal No. 31-1 well indicate nearly flat-lying strata. Apparent offset in the pre-Paradox Formation rocks between the two wells is interpreted as resulting from offset along a northwest-trending fault with about 1,000 feet (305 m) of displacement. This sub-Paradox Formation fault is on strike with, and may be a continuation of, a larger displacement, high-angle fault along the southwest margin of the Paradox Valley salt-cored anticline in Colorado (Case and others, 1963; Baars, 1966, Cater, 1970). The approximate structural relief on the Castle Valley salt wall is a minimum of 9,500 feet (2,896 m); however, the crest of the wall is altered from its original shape due to salt-dissolution (figure 8).

The Conoco Federal No. 31-1 well penetrated the Paradox Formation 2,982 feet (909 m) below sea level, indicating a steep northeast margin for the Castle Valley salt wall. We interpret the southwest margin of the wall to be nearly identical with the northeast margin because of a similar gravity profile. Thick sections of Permian and Triassic strata are located in the rim synclines that flank the Castle Valley salt anticline (figure 8).

Significant angular unconformities (5 degrees or greater) are exposed in the Cutler Formation, within the upper part of the lower member (Ali Baba Member) of the Moenkopi Formation and between the lower and upper members of the Chinle Formation adjacent to the Castle Valley salt anticline. At several locations along the southwest side of Castle Valley, southeast of the quadrangle, the Cutler Formation and Paradox Formation caprock contact is vertical to slightly overturned (85° NE), suggesting the salt wall penetrated the Honaker Trail and Cutler Formations and possibly the Moenkopi Formation (plate 2, cross section B-B'). Younger formations were probably folded over the salt wall and thinned over the crest.

At the northwest nose of the Castle Valley structure is a small, northwest-plunging anticline in the Cutler Formation. Within a cliff face, indistinct stratification of conglomeratic sandstone define the gentle fold. The axial trace of the anticline is subparallel with the axial trace of the Castle Valley salt-cored anticline.

Hill 5163 Monocline

A north-striking, north-plunging, east-dipping monocline extends from the northwest nose of the Castle Valley salt-cored anticline in section 36, T. 24 S., R. 22 E. The stratigraphic thickness of the Moenkopi Formation, especially the upper two members, changes dramatically across the monocline. The Moenkopi nearly doubles in thickness from 550 feet (168 m) at Hill 5163 to approximately 958 feet (292 m) at the south end of Parriott Mesa (Shoemaker and Newman, 1959). In addition, lithofacies of Cutler strata also change across the monocline. The White Rim Sandstone Member(?) is about 240 feet (73 m) thick as measured on the west side of the monocline (and in cuttings from the Grand River Oil and Gas No. 1 well, SW¼ NW¼ NE¼ section 36, T. 24 S., R. 22 E.), but is absent on the east side. The variations in stratigraphic thickness and lithofacies across the monocline and the presence of small syndepositional faults in the Cutler Formation indicate the monocline formed during movement of the salt.

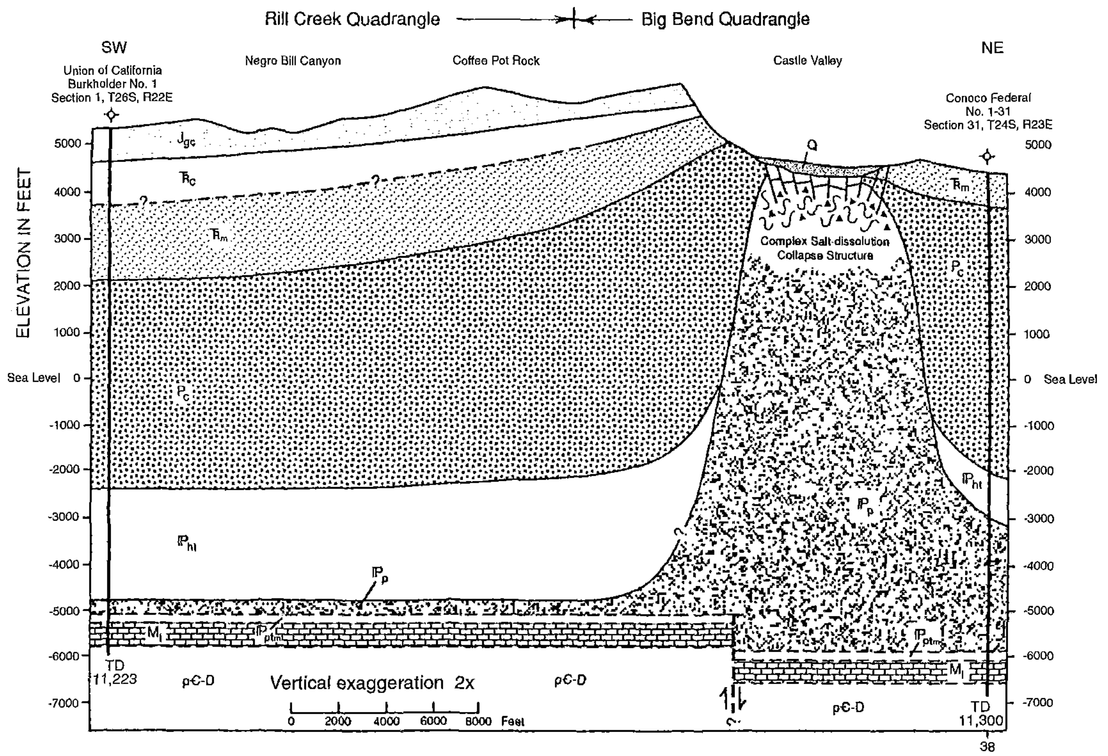

Figure 8. Diagrammatic and vertically exaggerated cross section across the north end of the Castle Valley salt-cored anticline. The cross section shows the estimated height of the Castle Valley salt structure and the dramatic variation in thickness of the Pennsylvanian to Triassic formations. The occurrence and structural configuration of bedrock units over the crest of the salt-cored anticline are unknown. Jgc = Glen Canyon Group; TR c = Chinle Formation, TR m = Moenkopi Formation, Pc = Cutler Formation, IPht = Honaker Trail Formation, IPp = Paradox Formation, IPpt = Pinkerton Trail and Molas Formations, Ml = Leadville Limestone, and p€-D = Precambrian, Cambrian, and Devonian rocks, undivided.

Castle Valley Faults

High-angle normal fault systems are present on both sides of Castle Valley. The fault zone along the southwest side of the valley is covered by surficial debris of the coalesced alluvial fans below Porcupine Rim. Shallow water-well data, our mapping in this quadrangle, and our unpublished mapping in the Rill Creek and Warner Lake quadrangles indicate the position of the fault zone. At its location, less than 50 feet (15 m) of surficial deposits that cover bedrock abruptly thickens into thick deposits of valley-fill alluvium (plate 2, cross-section B-B′).

The fault system along the northeast flank of Castle Valley is well exposed in the Moenkopi Formation below Parriott Mesa. Faults cut the rocks into long, narrow blocks in a zone paralleling the valley axis. The outermost fault trends N. 65° W. and dips valleyward 70° SW. The strike of this fault rotates counter-clockwise to nearly east-west at its northwest end. The fault displaces strata 60 to 70 feet (18-21 m). Valleyward of this fault are numerous closely spaced fractures (faults and joints) with similar trends. The high-angle faults strike N. 40° W. and dip 8° SW and rotate blocks valleyward, displacing strata progressively downward toward the valley axis. Block rotation appears to increase valleyward. Individual faults exhibit small displacement, but the overall offset across the fault zone is significant. The Moenkopi Formation in the fault zone is extensively fractured and highly weathered to red-brown mounds and ridges. The discontinuous fractures have a complicated anastomosing pattern in the zone. The bounding fault can be traced southeastward to fractured and valleyward rotated exposures of Cutler Formation. These faults are similar to fault zones along the margins of most salt-cored anticlines in the region.

At the northwest end of the valley is a somewhat fan-shaped pattern of high-angle normal faults. Most of the faults trend west-northwest. Only significant faults are shown on the map; some splay into additional faults with small displacements (about 1 to 2 feet [0.3-0.6 m]). Smaller fractures are marked by linear brecciated zones and siliceous/calcareous veins. Numerous microcrystalline quartz-barite-calcite veins are present in the White Rim Sandstone Member (?) of the Cutler Formation. South of Castle Creek, the larger west-northwest-trending faults form a sequence of down-to-the-north blocks. North of Castle Creek, the faults form narrow step-down grabens that are sporadically cross cut by irregularly trending faults. In this area, the complex structure (numerous fractures and steeply dipping beds) and poorly bedded, massive conglomeratic sandstone of the Cutler Formation make determining the position of some faults rather tenuous. Several large faults at the northwest end of Castle Valley extend as much as 0.5 mile (0.8 km) from the Castle Valley salt-cored anticline to the Porcupine Rim cliff and cut Glen Canyon Group formations. Displacements on the mesa amount to as much as 40 feet (12 m). Bleaching, caused by ground-water flow, is evident along some of the faults.

Cross-cutting relations constrain the relative timing of several faults in this area. Several small syndepositional faults occur within the arkosic facies of the Cutler Formation. These normal faults offset strata for a short distance and then are terminated by gravel-filled Cutler Formation channel deposits exhibiting no displacement. Another normal fault cuts off a part of a gravel-filled channel with no offset of overlying beds. Two larger northwest-trending and steeply southwest dipping (70-75° SW) normal faults (plate 1) in the Permian Cutler Formation do not offset the overlying Triassic Moenkopi Formation.

A vertical fault trends directly into the axis of the Hill 5163 monocline. On the upthrown side near the fault, competent thicker sandstone beds in the Moenkopi Formation are slightly faulted and the interbedded, incompetent beds are folded, suggesting bending or squeezing. This fault appears to have formed during the folding of the monocline.

Richardson Amphitheater Faults

The Richardson Amphitheater faults at Stearns Creek generally trend west-northwest across the northern half of the quadrangle and join the Cache Valley graben and Professor Valley graben (located in the Fisher Towers quadrangle to the east). The Richardson Amphitheater faults are high-angle normal faults. The complex criss-cross fault pattern masks a narrow step-down graben with an overall east-west trend. The graben is cut and segmented by numerous faults that form small elongate blocks that have each rotated independently. The faults are steeply dipping to vertical, closely spaced, have small displacements, and some exhibit opposite sense of movement on either side of a crossing fault (figure 9).

Numerous other fractures too small to map on plate 1 are present in this faulted area. The northwest-trending fractures are consistent and regularly spaced. Slickensides displaying a variety of vertical, dip-slip, and horizontal orientations are common in this area. Coarse crystalline barite-calcite veins are commonly associated with the faults. The veins range from small (a few millimeters thick) to large (many centimeters thick) and generally run parallel or subparallel to the faults. Also present are bleached zones and stratigraphic horizons associated with fractures in the lower member of the Moenkopi Formation that attest to ground-water activity.

Big Bend Fault Zone

A northwest-trending zone of high-angle normal faults cross the Colorado River at the Big Bend. The faults trend between N. 35° W. and N. 70° W. and are vertical to steeply dipping (mostly greater than 80°). The faults form horsts and grabens, but the overall structure is a step-down graben with displacement greatest toward the center. Offset ranges to as much as a few tens of feet, with the graben-bounding faults having about 40 feet (12 m) of offset. The faults continue northwestward into Arches National Park along the southwest flank of the Windows anticline (Doelling, 1985).

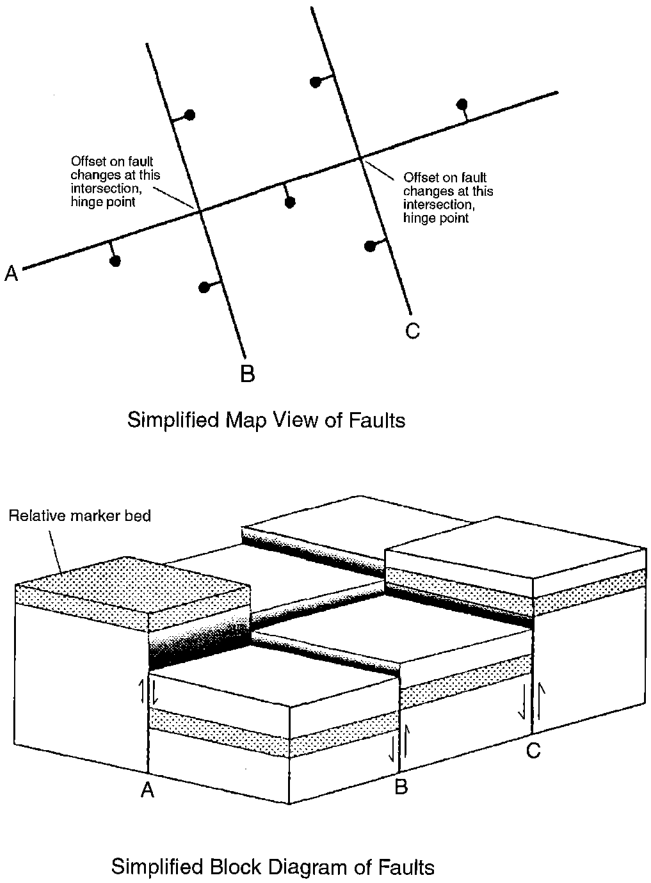

Figure 9. Simplified block diagram of faults of the New Rapids area. The diagram illustrates the hinge point and opposite offset along the same fault. Each fault block behaves independently during structural collapse.

GEOLOGIC HISTORY OF THE PARADOX BASIN

In Pennsylvanian time the fault-generated and intermittently subsiding Paradox basin formed on the southwest side of the ancestral Uncompahgre uplift (Baars, 1966; Cater, 1970; Stevenson and Baars, 1987). Clastic, carbonate, and evaporite sediments were deposited across the basin. In the deepest part of the basin, salt beds (mostly halite) began to flow to discontinuities in the floor of the Paradox basin caused by faults in the pre-Paradox Formation rocks (basement faults) (Baars, 1966; Joesting and Case, 1960; Stevenson and Baars, 1987). The salt thickened at these discontinuities to form elongate salt walls. From the Late Pennsylvanian to at least the Late Triassic, salt previously deposited adjacent to the walls continued to move into the walls intermittently in response to the movement of the basement faults.

Late Pennsylvanian through Triassic strata were locally thinned, folded, brecciated, truncated, and removed by erosion, or possibly never deposited, across the crests of the salt walls. Local basins, called rim synclines, developed on the flanks and between salt walls as the underlying salt flowed into the walls. These basins were filled with abnormally thick complements of Late Pennsylvanian to Triassic sediments. The transition zones between the thick strata in the rim synclines and the thin or missing strata overlying the salt walls are structurally deformed and locally faulted. Many angular unconformities are present in the marginal strata, with dips increasing progressively downward.

After Late Triassic time, salt continued to move (where not depleted under the rim synclines), causing more thinning and thickening of Jurassic and Cretaceous strata at some of the salt walls. The Paradox basin area continued to subside and receive sediments into Late Cretaceous time and perhaps through Early Tertiary time. The youngest sediments preserved in the Paradox fold and fault belt are Pliocene to Holocene in age, and these unconformably overlie rocks of Late Cretaceous age. Depositional and structural events between the Late Cretaceous and Pliocene are difficult to interpret because time-constraining rocks from much of the Tertiary interval are missing from the area. Post-Late-Cretaceous structures are complicated because they are commonly superimposed on the earlier salt structures and are in turn masked by more recent salt-dissolution-induced structures. The following paragraphs summarize our interpretations of Late Cretaceous to Holocene events that affected the Big Bend quadrangle and the Paradox fold and fault belt.

Approximately west-southwest regional compression affected the region during the Late Cretaceous to Early Tertiary Laramide orogeny (Cater, 1970; Heyman and others, 1986). Strata probably were folded into broad northwest-trending anticlines and synclines (Cater, 1970; Doelling, 1985, 1988). Anticlines were superimposed on the pre-existing salt-cored anticlines and gentle synclines formed between them. In some cases the broad synclines were superimposed, at least in part, on the pre-existing rim synclines. This folding was not superimposed on the more east-west-trending salt structures, such as the Cache Valley structure.

Mostly northwest-striking normal faults, such as the Moab fault, Lisbon Valley fault, and Salt Valley fault, cut the folds (McKnight, 1940; Williams, 1964; Parker, 1981; Doelling, 1988), indicating they post-date the Laramide episode of folding. The 500 feet (152 m) of apparent displacement across the Cache Valley graben along the west margin of the Big Bend quadrangle may have been produced by a normal fault. This period of Tertiary extensional faulting has been related to regional relaxation of stress after Laramide compressional folding (McKnight, 1940), possible reactivation of some of the subsurface faults in the pre-Paradox rocks (Doelling, 1988), regional extension during the Mesozoic to Cenozoic (Ge and Jackson, 1994), and epeirogenic uplift of the Colorado Plateau during the late Tertiary (Parker, 1981; Ross, in press).

The Moab region was epeirogenically uplifted in late Tertiary time as part of the Colorado Plateau (Hunt and Waters, 1958; Lucchitta, 1979; Fleming, 1994). Subsequent erosion cut deeply into the strata and carved the extensive canyons of the Canyonlands region. This erosion allowed fresh ground water to locally reach the upper parts of the salt structures through existing fracture systems (extensional faults and joints opened during folding and uplift). The ensuing dissolution of salt caused local areas to collapse (tilting and faulting) and subsidence of the overlying strata during late Tertiary and Quaternary time (Shoemaker and others, 1958; Colman, 1983; Doelling, 1983, 1988; Harden and others, 1985; Oviatt, 1988).

ECONOMIC GEOLOGY

Sand and Gravel

Colorado River alluvium and terrace alluvium contain materials suitable for use in contructing highways. The Utah Department of Transportation (UDOT, about 1967) sampled these deposits at three localities in the quadrangle. Analytical work showed the material is suitable for use as base and surfacing gravel and for concrete and asphalt mixtures (table 1). The quality of the sand and gravel in the terraces and alluvium along the river is not expected to vary. The three river terraces tested contained 80,000, 460,000, and 290,000 cubic yards of gravel, respectively. Many other potentially suitable deposits were not evaluated, but the total sand and gravel resource is large. The pit in the NE ¼ section 30, T. 24 S., R. 23 E., is intermittently active; the gravel is used for road repair.

Copper and Uranium

Small copper workings are present along the north flank fault zone of Cache Valley. One prospect is in the E½ NE¼ section 9, T. 24 S., R. 22 E., along a fault just outside Arches National Park. The copper shows are on the downthrown side of the fault, which trends nearly east-west and dips 75° south, placing the Salt Wash Member of the Morrison Formation (south side) against the Navajo Sandstone. Copper carbonates (malachite, azurite), copper pitch, and limonite occur at the prospect. No mineralization is evident in the Navajo Sandstone. The mineralization is partly controlled by fractures and partly by a favorable sandstone horizon in the Salt Wash Member adjacent to the fault. Minerals generally coat fractures, but some are disseminated in the sandstone. The mineralization gradually dies out south of the fault where adjacent green siltstone and mudstone become red.

The small prospect or mine at this locality consists of a shaft 10 by 5 by 15 feet (3 x 1.5 x 4.6 m) deep that is cut into a thick lens of sandstone in the Salt Wash Member of the Morrison Formation. A 30-foot (9.1-m) adit intersects the shaft from the east. At a lower elevation and 270 yards (247 m) to the west, another adit has been driven southward in the Navajo Sandstone, crossing the fault about 50 feet (15 m) from the portal. An incline connects with this adit south of the fault and extends upward and eastward at an angle of 30 degrees. The incline crosses the first adit and continues eastward about 10 feet (3 m) to the surface. The length of the incline between the surface and the adit is about 35 feet (10.7 m). The incline follows the dip of the Salt Wash bedding. A 0.5 ton (0.4 tonne) stockpile containing about 0.5 percent copper is present next to the surface opening of the incline. A sandstone lens above a green siltstone parting is irregularly mineralized with copper and is 1 to 3 feet (0.3-0.9 m) thick.

Copper mineralization is also present in slickensided, brecciated, conglomeratic sandstone in the Cedar Mountain-Dakota Formation undifferentiated unit in the South Flank fault zone along the south side of Cache Valley. The rock is highly fractured and dips as much as 80 degrees northward. Mineralization consists of copper oxides, mostly malachite, with a little copper pitch and cuprite. The minerals coat fracture surfaces, pebbles, and grit in the conglomerate. Mineralization appears to die out 75 feet (23 m) north of the fault zone. Workings consist of some shallow pits and dog holes.

Minor shows of copper occur in other places in the thicker lenses of Salt Wash sandstone in Cache Valley. Malachite

MATERIAL					TEST DATA - REPRESENTATIVE SAMPLE															
								SIEVE ANALYSIS												
								BEFORE CRUSHING		PERCENT PASSING AFTER CRUSHING TO 1" MAXIMUM SIZE										
USE OF MATERIAL	TYPE OF DEPOSIT	PRESENT ESTIMATED QUANTITY (CU. YDS.)	THICKNESS OF MATERIAL	DEPTH OF OVERBURDEN	DATE SAMPLED	TYPE OF SAMPLE	DEPTH OF SAMPLE	>3"	>1"	1"	½"	No. 4	No. 10	No. 40	No. 200	LIQUID LIMIT	PLASTICITY INDEX	SWELL	A. A. S. H. O. CLASSIFICATION	ABRASION 500 REV.
B.G., S.G.	River Terrace	80,000	8	0	1958	Cut Bank	0-10	2.3	21.5	100		51.3	41.8	29.5	8.6	16.4	NP	.012	A-1-a	20.9
B.G., S.G.	River Terrace	460,000	12	0-1	1958	Cut Bank	0-12	23.4	46.7	100		42.3	34.3	21.6	5.4	17.5	NP	.010	A-1-a	29.3

Table 1. *Sand and gravel tests run by the Utah Department of Transportation (UDOT) on Colorado River alluvium in 1962 (UDOT, about 1967). Thickness and depths are in feet, most other analyses are in percent. Sample 1 is located in the W½ SW¼ section 33, T. 24 S., R. 22 E.; sample 2 is located in the W½ NE¼ section 35, T. 24 S., R. 22 E.; and sample 3 is located in the NE¼ section 30, T. 24 S., R. 23 E. B.G., S.G. indicate base gravel and surfacing gravel.*

coats bedding planes and is found in thin stringers. The control appears to be strictly stratigraphic. Volumetrically there is little copper in comparison to sandstone. The potential for finding a large deposit of copper in Cache Valley is considered low.

The Salt Wash Member of the Morrison is an important host of uranium mineralization in the region (Doelling, 1969). Most of the Salt Wash Member in Cache Valley shows background radiation with a counter, but radiation is higher near yellow and brown limonite stains and where dark streaks are found in sandstone channels. Radiation and shows of copper generally increase at the base of these sandstone channels. Nevertheless, the potential for finding economical uranium deposits in Cache Valley is considered low.

Gold

The gravels of the Colorado River and the terrace alluvium contain small amounts of flour gold and rare gold flakes. A small, but unknown quantity of gold may have been recovered in the quadrangle from placer mining operations carried out near Salt Wash Rapids, New Rapids, and other locations along the Colorado River. The gold occurs in black, magnetite-bearing, coarse, sandy streaks in the river alluvium. The gold content in the sandy streaks is usually uniformly distributed vertically through the river bed alluvium (Qa_1) and terrace alluvium (Qat_2, Qat_3). However, the upstream ends of the gravel bars and higher terraces may be slightly richer in gold content (Butler, 1920).

Petroleum

Three oil exploration wells were drilled in the Big Bend quadrangle: the Conoco Federal No. 31-1 well, SE¼ NW¼ SE¼ section 31, T. 24 S., R. 23 E.; the Grand River Oil and Gas No. 1 well, NW¼ NE¼ section 36, T. 24 S., R. 22 E.; and the Grand River Oil and Gas Sid Pace No. 1 well, NE¼ SE¼ section 16, T.25 S., R.23 E. (just east of quadrangle). In the Conoco well, hydrocarbon shows were encountered in the clastic units interbedded with the salts of the Pennsylvanian Paradox Formation and in the Mississippian Leadville Formation, and carbon dioxide shows were present in the Leadville Formation. All three wells were abandoned as dry holes.

The Big Bend quadrangle is in a region historically productive for oil and gas (Morgan, 1993). Fields in the vicinity are located primarily to the west and include Bartlett Flat, Big Flat, Long Canyon, Cane Creek, and Shafer Canyon. Production in these fields has been from the Cane Creek zone of the Paradox Formation and from the Mississippian Leadville Formation (Morgan, 1993; Doelling and others, 1994).

Evaporites

Gypsum beds are present in the Moenkopi Formation and in the caprock of the Paradox Formation. The gypsum beds in the Moenkopi are thin and have not been mined in the quadrangle. Gypsum beds in the Paradox Formation caprock are impure.

Potash (sylvite), carnallite, and halite are known to occur in the Paradox Formation. Potash is solution mined from the Cane Creek anticline 16 miles (26 km) west of Moab (Doelling and others, 1994). These salts are present in the Castle Valley and Cache Valley salt-cored structures. A shallow petroleum drill hole in the Castle Valley salt-cored anticline southeast of the quadrangle confirmed the presence of potash deposits (Hite and Lohman, 1973). The internal structure of the salt is normally very complex, and much exploratory drilling will be necessary to define the resource. The Paradox Formation is presumed too deep and thin for economical extraction under other areas in the quadrangle.

Barite

A few prospect pits have been dug into barite veins associated with the Richardson Amphitheater faults in the vicinity of Stearns Creek. The Moenkopi Formation is bleached to light gray or yellow gray and shows of calcite, barite, quartz, malachite, and hematite are present. Breit and others (1990) showed that barite fracture fillings are associated with faulting and the barite solutions originated in the Paradox Formation. The occurrences are small. No analyses testing the purity of the barite are available.

Calcite

Acicular calcite is present along several of the faults in Cache Valley. The shattered Moab Member of the Entrada Sandstone commonly contains thin calcite veins along fractures which locally thicken to as much as 5 feet (1.5 m). A small mine was opened to exploit the calcite in the NE¼ NE¼ NW¼ section 14, T. 24 S., R. 22 E. A 15-foot (4.6-m) adit was driven into a cliff at a bearing of N. 35° E., and intersected a fault trending N. 63° W. that juxtaposes the Slickrock Sandstone and the Moab Member. The calcite vein is 1 to 5 feet (0.3-1.5 m) thick along the fault. The acicular calcite in the vein is partly brecciated. Shattered blocks of sandstone are also found as vein-filling material. The vein extends 120 feet (36.6 m) along the fault at this locality.

GROUND WATER

Bedrock aquifers in the Big Bend quadrangle are largely untested. Sandstone formations of the Glen Canyon Group are considered the most important bedrock aquifers of the region (Feltis, 1966; Blanchard, 1990); however, only remnants of these units are present in the quadrangle. Most Glen Canyon Group exposures are severed from recharge areas by deeply eroded canyons. Nevertheless, small springs issue intermittently from these formations at many localities. The potential for obtaining small amounts of water is good. The quality of water from these aquifers is generally good, with concentrations of dissolved solids averaging less than 220 mg/l. The water type is calcium bicarbonate or calcium magnesium bicarbonate, and the water is moderately hard to hard (Blanchard, 1990). Recharge to the mesas southwest of Castle Valley may be much better because of their connection with recharge areas around the La Sal Mountains.

Triassic formations are generally regarded as aquicludes and rarely yield water. The Permian Cutler Formation yields water to wells on the southwest side of Castle Valley. According to Blanchard (1990), 30 wells had been drilled that produced from 20 to 40 gal/min (1.3-2.5 l/sec) without measurable drawdown, with dissolved solids concentrations ranging from 1,420 to 3,450 mg/l. These wells had concentrations of selenium that exceeded state of Utah drinking-water standards. Water from the Cutler Formation is expected to be slightly saline to saline in quality throughout the Big Bend quadrangle.

Deep ground-water aquifers have been subdivided into three hydrostratigraphic units, each possessing similar hydrogeologic characteristics (U.S. Department of Energy, 1984). The upper hydrostratigraphic unit consists of Permian rocks and the upper two-thirds of the Honaker Trail Formation. The middle unit includes the remainder of the Honaker Trail Formation and the Paradox Formation. The lower unit includes all the carbonate rock units below the Paradox Formation. The recharge for the upper unit includes the La Sal Mountains. The water yields from the upper unit are expected to be small and of variable quality, tending to be saline. The middle unit consists of horizons acting as aquicludes alternating with others horizons of variable water-bearing capacity. When water is found it is generally very saline. The lower hydrostratigraphic unit consists of carbonates with good porosity and permeability. Oil-well data generally indicate large quantities of salty water.

Ground water is also present in surficial deposits of the quadrangle. More than 100 wells have been drilled in unconsolidated deposits in Castle Valley. Sampled wells indicated dissolved solids concentrations ranging from 169 to 1,020 mg/l (Sumsion, 1971). Recharge to the Castle Valley wells is assumed to be in upvalley locations along Placer and Castle Creeks, which originate in the La Sal Mountains. Mixing with subsurface spring sources in the Cutler Formation, and possibly the salt wall, probably accounts for the more saline water. Similarly, water from the Colorado River recharges gravelly aquifers under adjacent bottom land. Unconsolidated sand on the benches collects rainwater and snowmelt that may provide small amounts of water for stock.

GEOLOGIC HAZARDS

Geologic hazards in the Big Bend quadrangle are typical of those in the canyon country of southeast Utah. They include erosion, debris flows, alluvial-fan flooding, stream flooding, rock falls, problem soils, indoor radon gas, and earthquake hazards. The environmental problem of culinary water contamination from septic systems and other human-caused events is also a concern. See Mulvey (1992) for a detailed discussion of the geologic hazards in Castle Valley.

Erosion, Debris Flows, Alluvial-Fan Flooding, and Stream Flooding

Erosion by running water is the most active and potentially damaging hazard in the quadrangle (Mulvey, 1992). The sparsely vegetated steep slopes and deep, narrow ephemeral stream channels are subject to rapid erosion from waters generated by cloudburst storms and spring runoff.

Debris flow (including mudflow), debris flood (hyperconcentrated stream flow), and normal stream flow form a continuum of sediment/water mixtures. Debris flows and floods generally remain confined to stream channels in high-relief areas, but may exit the channels and deposit debris where slope gradients decrease (that is, on alluvial fans) along their travel paths. The heterogeneous lithologies and weathering characteristics of the Moenkopi, Chinle, Wingate, and Kayenta Formations are conducive to the accumulation of talus and colluvium on slopes, providing ample material for debris flows. Overland sheetflow and/or floodwaters may scour material from the ground surface and stream channels, thereby increasing the proportion of bed/suspended load until the mixture becomes a debris flow (Mulvey, 1992).

Alluvial fans on the southwest side of Castle Valley are particularly susceptible to debris-flow, mud flow, and flooding hazards. The Colorado River canyon, with numerous steep gulleys that drain to the river, and is also susceptible, especially near Utah Highway 128(U-128). Ephemeral stream channels are also potential debris-flow carriers.

Stream flooding may originate by direct precipitation, melting snow, or a combination of both. Primary drainage channels, such as Castle Creek, Placer Creek, and Professor Creek are generally deeply incised (10 to 30 feet [3-9 m]), and seasonal snowmelt or cloudburst runoff are contained. Flooding of the adjoining areas is possible, but unlikely due to the depth of incision. Flood damage along primary drainage channels is generally confined to stream bank undercutting (Mulvey, 1992).

Flooding of the Colorado River occurs during unusually high spring runoff years. The river undercut its banks in June of 1983, when a section of U-128 was washed out at the bend below Whites Rapids. The pavement section in the west-bound lane, embankments, and culverts were washed out along the highway for a distance of about 300 feet (91 m) (Davis, 1989). Large amounts of fill and riprap material were hauled in to repair the roadway. The damage cost was more than $200,000.

Rock Falls

Rock falls occur sporadically throughout the rugged topography of southern Grand County. In the quadrangle, rock fragments from Kayenta, Wingate, Chinle, and Moenkopi Formations cliffs commonly produce rock-fall debris. The most susceptible cliffs or slopes are those broken by fractures that are subparallel to cliff faces.

Porcupine Rim, along the southwestern margin of Castle Valley, is an area of chronic rock-fall activity. Since 1978 five major rock falls have occurred along this escarpment (plate 1). Northwest-trending joints and fractures are common in the massive cliffs of the Kayenta and Wingate Formations, which are slowly being undercut by erosion of the less resistant Chinle Formation. Homes built at the foot of the Porcupine Rim slopes are especially susceptible to the hazard.

Rock-fall debris may travel great distances down slope by rolling, bouncing, and sliding. The potential large size of some debris and relatively high velocity of travel present a hazard to engineered structures and personal safety for the southwest side of Castle Valley. Rock-fall debris is present below all of the massive cliffs throughout the quadrangle and is a constantly threatening geologic hazard along U-128 in the narrow canyon of the Colorado River. Each year rock debris must be cleared away by the Utah Department of Transportation to keep the highway safe for travelers.

Problem Soils

The bentonitic clay minerals of the Moenkopi, Chinle, Morrison, Cedar Mountain, and Mancos Formations, and the soils derived from them, are capable of absorbing large quantities of water (Schultz, 1963; Stewart and others, 1972a, 1972b). As the moisture content of these units changes, the clay minerals expand and contract, producing as much as a 10 percent volume change (Shelton and Prouty, 1979). The "popcorn" surface of weathered Moenkopi and Chinle outcrops is indicative of the shrinking and swelling nature of the formations. These formations commonly exhibit this surface texture in the Porcupine Canyon, Castle Valley, and Ida Gulch areas.

Alluvial fans composed of sediments derived from the Moenkopi and Chinle Formations are favorable for the development of collapsible soils (Mulvey, 1992). These soils are subject to volumetric changes that could damage structures built upon them. The existence of collapsible soils in Castle Valley and surrounding areas is undocumented, but geologic conditions are favorable for their development.

Fine-grained soils and surficial deposits (Qa_2), prone to piping and rapid erosion, cover much of the lower part of Castle Valley. Cloudburst storm floods can quickly remove large volumes of material. Piping is subsurface erosion by ground water that flows into permeable noncohesive layers in unconsolidated sediments, removes fine sediments, and exits at a spot where the layer intersects the ground surface. The removal of fine particles increases void space thereby producing a "pipe" and promoting enhanced erosion. Piping is common in arid/semi-arid climates where fine-grained, noncemented, Holocene-age alluvium is incised by ephemeral stream channels. Several large pipe-related erosional gulleys are present in Qa_2 sediments along Castle Creek below its confluence with Placer Creek.

Indoor Radon Gas

Radon is naturally occurring radioactive gas derived from the decay of uranium in geologic materials. When inhaled, radon decay particles may cause lung cancer. Radon gas is very mobile and may migrate through void space in rock and soil and be captured in poorly ventilated buildings thereby causing a health hazard.

A potential radon health hazard depends on three factors: (1) a source of radon, (2) depth to ground water, and (3) permeability of the substrata (B.J. Solomon UGS, verbal communication 1992). Many of the sedimentary rocks in the Big Bend quadrangle are potential sources of radon. The igneous rocks of the La Sal Mountains contain small amounts of uranium making them a potential radon source. The Morrison Formation contains small uranium deposits in the Warner Lake quadrangle to the southeast. The Chinle Formation, which crops out in the Colorado River canyon walls, is locally radioactive, even though no uranium deposits have been discovered in the quadrangle. The surficial deposits in Castle Valley, and other places in the Big Bend quadrangle, are derived from these sources and have the potential to produce concentrations of radon gas.

Areas with ground-water levels deeper than 30 feet (10 m) have a higher potential for radon gas movement to the surface or into basements of homes. The gravelly to sandy alluvium of Castle Valley is poorly lithified and highly permeable, allowing easy migration of the gas. The permeability of the local bedrock units is highly variable and is controlled by lithology and degree of cementation. Sprinkel and Solomon (1990) and Black (1993) discussed the radon hazard in Utah in greater detail.

Earthquake Hazard

Seismicity in the Paradox basin can be characterized as having a low rate of occurrence, being widespread with a few small areas of concentration, and consisting of small-to-moderate magnitude events (Wong and Humphrey, 1989). The closest area of concentrated seismic activity to the Big Bend quadrangle is associated with the Cane Creek mine at Potash, about 12 miles (19 km) southwest of the quadrangle. This seismicity is believed to be induced by underground solution mining of potash salts in the Paradox Formation (Wong and Humphrey, 1989). The strongest recorded earthquake in the area occurred in February 1967 (magnitude 3.8) near Upheaval Dome, about 26 miles (42 km) southwest of the quadrangle. The 1994 Uniform Building Code (UBC) includes this area in Seismic Zone 1, a zone of least earthquake hazard in Utah (International Conference of Building Officials, 1994).

SCENIC RESOURCES

The Big Bend quadrangle displays world-famous, redrock Canyonland vistas. The Colorado River has incised a large meander loop in the southwest corner of the quadrangle creating scenic vertical cliffs in the Glen Canyon Group. Utah Highway 128 is a beautiful 35-mile (56-km) river drive from

Moab to the Dewey Bridge. The buttes and mesas between Castle Valley and the Richardson Amphitheater are picturesque, and are often photographed for postcard art and filmed for television commercials. Excellent views of Castle Rock, the Priest and Nuns, and the La Sal Mountains are visible from Castle Valley. Several classic Hollywood western movies were filmed in the Big Bend and adjacent quadrangles.

Many spectacular vistas of the canyons, Professor Valley, Richardson Amphitheater, and Castle Valley are available from the mesas, but these are difficult to access. They can be reached by hiking, mountain biking, or with four-wheel drive vehicles. The cliff tops are generally 1,000 to 2,000 feet (305-610 m) above the valley and canyon bottoms.

Delicate Arch and Arches National Park

Delicate Arch is a well-known symbol for Utah and appears on Utah's centennial automobile license plates. The arch is located in the Big Bend quadrangle, SW¼ NW¼ SW¼ section 4, T. 24 S., R. 22 E., in Arches National Park. According to Stevens and McCarrick (1988), it is the best known arch in the world. It is considered the most beautiful arch in Arches National Park. The light opening is 46 feet (14 m) high and 32 feet (10 m) wide. The pedestals of the arch are carved from the Slick Rock Member and the span from the Moab Member of the Entrada Sandstone.

Several smaller arches are present on the quadrangle in the Delicate Arch area, which tourists rarely see. These include the free-standing Frame and Echo Arches; the cliff-wall Diving Board and Goosehead Arches; and the pothole Tapered Arch, all cut in the Entrada Sandstone. Still other small arches are present to the east in Winter Camp Wash canyon. These include Cliff Top, Winter Camp, Donut, Mirror, and Solo Arches, cut in the Kayenta and Navajo Sandstone.

Cache Valley

The salt dissolution features exposed in Cache Valley are among the best in the Paradox basin. "Collapsed" formations, tilted strata, v-synclines, and faults are well exposed to view and study. The nearly 2,000-foot (610-m) displacement of the Wingate Sandstone and older formations into the graben west of New Rapids is plainly visible from the Colorado River and represents a geologic event of immense proportions.

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REFERENCES

Baars, D.L., 1966, Pre-Pennsylvanian paleotectonics, Paradox basin: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2082-2111.

—1987, Paleozoic rocks of Canyonlands country, *in* Campbell, J.A., editor, Geology of Cataract Canyon and vicinity: Four Corners Geological Society Guidebook, Tenth Field Conference, p. 11-17.

Baars, D.L., Parker, J.W., and Chronic, John, 1967, Revised stratigraphic nomenclature of the Pennsylvanian System, Paradox basin: American Association of Petroleum Geologists Bulletin, v. 51, no. 3, p. 393-403.

Baker, A.A., 1933, Geology of the Moab district, Grand and San Juan Counties: U.S. Geological Survey Bulletin 841, 84 p.

Black, B.D., 1993, The radon-hazard-potential map of Utah: Utah Geological Survey Map 149, 12 p., 1 pl., scale 1:1,000,000.

Blakey, R.C., and Gubitosa, Richard, 1983, Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona, *in* Reynolds, M.W., and Dolly, E.D., editors, Mesozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 2, p. 57-76.

Blanchard, P.J., 1990, Ground-water conditions in the Grand County area, Utah, with emphasis on the Mill Creek-Spanish Valley area: Utah Department of Natural Resources, Technical Publication No. 100, 69 p.

Breit, G.N., Goldhaber, M.B., Shawe, D.R., and Simmons, E.C., 1990, Authigenic barite as an indicator of fluid movement through sandstones within the Colorado Plateau: Journal of Sedimentary Petrology, v. 60, no. 6, p. 884-896.

Butler, B.S., 1920, Ore deposits of Utah: U.S. Geological Survey Professional Paper 111, 672 p.

Campbell, J.A., 1979, Lower Permian depositional system, northern Uncompahgre basin, *in* Baars, D.L., editor, Permian land: Four Corners Geological Society, 9th Annual Field Conference Guidebook, p. 13-21.

Campbell, J.A., and Steele-Mallory, B.A., 1979, Depositional environments of the uranium-bearing Cutler Formation, Lisbon Valley, Utah: U.S. Geological Survey Open-File Report 79-994, 35 p.

Case, J.E., and Joesting, H.R., 1972, Regional geophysical investigations in the central Colorado Plateau: U.S. Geological Survey Professional Paper 736, 31 p.

Case, J.E., Joesting, H.R., and Byerly, P.E., 1963, Regional geophysical investigations in the La Sal Mountain area, Utah and Colorado: U.S. Geological Survey Professional Paper 316-F, p. F91-F116.

Cater, F.W., 1970, Geology of the salt anticline region in southwestern Colorado: U.S. Geological Survey Professional Paper 637, 80 p.

Cole, R.D., and Moore, G.E., 1996, Stratigraphic and sedimentologic characterization of McCracken Sandstone Member of Elbert Formation (Upper Devonian) at Lisbon Field, Paradox Basin, San Juan County, Utah, *in* Hoffman, A.C. Jr., Lund, W.R., and Godwin, L.H., editors, Geology and resources of the Paradox Basin: Utah Geological Association Guidebook 25, p. 119-132.

Colman, S.M., 1983, Influence of the Onion Creek salt diapir on the late Cenozoic history of Fisher Valley, southeastern Utah: Geology, v. 11, p. 240-243.

Colman, S.M., and Hawkins, F.F., 1985, Surficial geologic map of the Fisher Valley-Professor Valley area, southeastern Utah: U.S. Geological Survey Miscellaneous Investigations Map I-1596, scale 1:24,000.

Cross, Whitman, 1907, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Journal of Geology, v. 15, p. 634-679.

Dane, C.H., 1935, Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U.S. Geological Survey Bulletin 863, 184 p.

Davis, F.D., 1989, Water-related geologic problems of 1983 in southeastern Utah: Utah Geological and Mineral Survey Open-File Report 149, 92 p.

Doelling, H.H., 1969, Mineral resources, San Juan County, Utah and adjacent areas - uranium and other metals in sedimentary host rocks: Utah Geological and Mineral Survey Special Studies 24, pt. 2, 64 p.

—1981, Stratigraphic investigations of Paradox basin structures as a means of determining the rates and geologic age of salt-induced deformation: Utah Geological and Mineral Survey Open-File Report 29, 88 p.

—1983, Observations on Paradox basin salt anticlines, in Averett, W.R., editor, Northern Paradox basin-Uncompahgre uplift: Grand Junction Geological Society, 1983 Field Trip Guidebook, p. 81-90.

—1985, Geologic map of Arches National Park and vicinity, Grand County, Utah: Utah Geological and Mineral Survey Map 74, 15 p., scale 1:50,000.

—1988, Geology of Salt Valley anticline and Arches National Park, Grand County, Utah, *in* Salt deformation of the Paradox region: Utah Geological and Mineral Survey Bulletin 122, p. 7-58.

—1993, Interim geologic map of the Moab 30' x 60' quadrangle, Utah and Colorado: Utah Geological Survey Open-File Report 287, 3 pl., 16 p., scale 1:100,000.

Doelling, H.H., Yonkee, W.A., and Hand, J.S., 1994, Geologic map of the Gold Bar Canyon quadrangle, Grand County, Utah: Utah Geological Survey Map 155, 26 p., scale 1:24,000.

Dubiel, R.F., Good, S.C, and Parrish, J.M., 1989 Sedimentology and paleontology of the Upper Triassic Chinle Formation, Bedrock, Colorado: The Mountain Geologist, v. 26, no.4, p. 113-126.

Elston, D. P., Shoemaker, E.M., and Landis, E.R., 1962, Uncompahgre front and salt anticline region of Paradox basin, Colorado and Utah: American Association of Petroleum Geologists Bulletin, v. 46, p. 1857-1878.

Feltis, R.D., 1966, Water from bedrock in the Colorado Plateau of Utah: Utah State Engineer, Technical Publication No. 15, 82 p.

Fleming, R.F., 1994, Cretaceous pollen in Pliocene rocks: Implications for Pliocene climate in the southwestern United States: Geology, v. 22, p. 787-790.

Ge, Hongxing, and Jackson, M.P., 1994, Crestal grabens above the Paradox salt diapirs - a consequence of regional extension and superposed salt dissolution: Geological Society of America Abstracts with Programs, v. 26, no. 6, p. 13.

Harden, D.R., Biggar, N.E., and Gillam, M.L., 1985, Quaternary deposits and soils Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 43-64.

Harper, M.L., 1960, The areal geology of Castle Creek Valley, Utah: Lubbock, Texas, Texas Technological College, M.S. thesis, 121 p.

Heyman, O.G., Huntoon, P.W., and White-Heyman, M.A., 1986, Laramide deformation of the Uncompahgre Plateau - geometry and mechanisms, *in* Stone, D.S., and Johnson, K.S., editors, New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 65-76.

Hintze, L.F., 1988 (revised 1993), Geologic history of Utah: Brigham Young University Geology Studies Special Publication 7, 202 p.

Hite, R.J., and Lohman, S.W., 1973, Geologic appraisal of Paradox basin salt deposits for waste emplacement: U.S. Geological Survey Open-File Report 73-63, 75 p.

Hunt, C.B., and Waters, A.C., 1958, Structural and igneous geology of the La Sal Mountains, Utah: U.S. Geological Survey Professional Paper 294-I, p. 305-364.

International Conference of Building Officials, 1994, Uniform building code: Whittier, California, International Conference of Building Officials, 1,050 p.

Joesting, H.R., and Case, J.E., 1960, Salt anticlines and deep-seated structures in the Paradox basin, Colorado and Utah, *in* Geological Survey research, 1960: U. S. Geological Survey Professional Paper 400-B, p. B252-B256.

Lucchitta, Ivo, 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent Colorado River region: Tectonophysics, v. 61, p. 63-95.

McKnight, E.T., 1940, Geology of area between Green and Colorado Rivers, Grand and San Juan Counties, Utah: U.S. Geological Survey Bulletin 908, 147 p.

Molenaar, C.M., 1987, Mesozoic rocks of Canyonlands country, *in* Campbell, J.A., editor, Geology of Cataract Canyon and vicinity: Four Corners Geological Society Guidebook, Tenth Field Conference, p. 19-24.

Molenaar, C.M., and Cobban, W.A., 1991, Middle Cretaceous stratigraphy on the south and east sides of the Uinta Basin, northeastern Utah and northwestern Colorado: U.S. Geological Survey Bulletin 1787-P, 34 p.

Morgan, C.D., 1993, Horizontal drilling technology re-opens old play: Utah Geological Survey, Survey Notes, v. 25, no. 3-4, p. 1-7.

Mulvey, W.E., 1992, Geologic hazards of Castle Valley, Grand County, Utah: Utah Geological Survey Open-File Report 238, 31 p.

Neff, A.W., and Brown, S.C., 1958, Ordovician-Mississippian rocks of the Paradox basin, *in* Sanborn, A.F., editor, Guidebook to the geology of the Paradox basin: Intermountain Association of Petroleum Geologists, 9th Annual Field Conference Guidebook, p. 102-108.

O'Sullivan, R.B., and MacLachlan, M.E., 1975, Triassic rocks of the Moab-White Canyon area, southeastern Utah: Four Corners Geological Society Guidebook, 8th Annual Field Conference, p. 129-141.

Oviatt, C.G., 1988, Evidence for Quaternary deformation in the Salt Valley anticline, southeastern Utah, *in* Salt deformation in the Paradox basin: Utah Geological and Mineral Survey Bulletin 122, p. 61-76.

Parker, J.M., 1981, Lisbon field area, San Juan County, Utah, *in* Wiegand, D.L., editor, Geology of the Paradox basin: Rocky Mountain Association of Geologists Guidebook, p. 89-101.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, western interior United States--a preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Richmond, G.M., 1962, Quaternary stratigraphy of the La Sal Mountains, Utah: U.S. Geological Survey Professional Paper 324, 135 p.

Ross, M.L., in press, Geology of Tertiary intrusive centers of the La Sal Mountains, Utah - influence of pre-existing structural features on emplacement and morphology, *in* Friedman, J.D., and Huffman, A.C., editors, Laccolithic complexes of southeastern Utah--time of emplacement and tectonic setting: U. S. Geological Survey Bulletin.

Schultz, L.G., 1963, Clay minerals in Triassic rocks of the Colorado Plateau: U.S. Geological Survey Bulletin 1147-C, 71 p.

Shelton, D.C., and Prouty, Dick, 1979, Nature's building codes, geology, and construction in Colorado: Colorado Geological Survey Special Publication 12, 72 p.

Shoemaker, E.M., Case, J.E., and Elston, D.P., 1958, Salt anticlines of the Paradox basin, *in* Sanborn, A.F., editor, Guidebook to the geology of the Paradox basin; Intermountain Association of Petroleum Geologists , 9th Annual Field Conference Guidebook, p. 39-59.

Shoemaker, E.M., and Newman, W.L., 1959, Moenkopi Formation (Triassic? and Triassic) in salt anticline region, Colorado and Utah: American Association of Petroleum Geologists Bulletin, v. 43, no. 8, p. 1835-1851.

Sprinkel, D.A., and Solomon, B.J., 1990, Radon hazards in Utah: Utah Geological Survey Circular 81, 24 p.

Stevens, D.J., and McCarrick, J.E., 1988, The arches of Arches National Park, a comprehensive study: Moab and Orem, Utah, Mainstay Publishing, 169 p.

Stevenson, G.M., and Baars, D.L., 1987, The Paradox basin - a pull-apart basin of Pennsylvanian age, *in* Campbell, J.A., editor, Geology of Cataract Canyon and vicinity: Four Corners Geological Society Guidebook, 10th Field Conference, p. 31-50.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972a, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 691, 191 p.

—1972b, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 690, 336 p.

Stokes, W.L., 1952a, Uranium-vanadium deposits of the Thompson area, Grand County, Utah, with emphasis on the origin of carnotite ores: Utah Geological and Mineral Survey Bulletin 46, 51 p.

—1952b, Lower Cretaceous in Colorado Plateau: American Association of Petroleum Geologists Bulletin, v. 36, p. 1766-1776.

Sumsion, C.T., 1971, Geology and water resources of the Spanish Valley area, Grand and San Juan Counties, Utah: Utah Department of Natural Resources, Technical Publication No. 32, 45 p.

Trimble, L.M., and Doelling, H.H., 1978, Geology and uranium-vanadium deposits of the San Rafael River mining area, Emery County, Utah: Utah Geological and Mineral Survey Bulletin 113, 122 p.

Tripp, B.T., and Mayes, B.H., 1989, Zeolite occurrences of Utah: Utah Geological and Mineral Survey, Survey Notes, v. 23, no. 3, p. 2-13.

U.S. Department of Energy, 1984, Draft environmental assessment, Davis Canyon site, Utah: Washington, D.C., U. S. Department of Energy, Office of Radioactive Waste Management, variously paginated.

Utah Department of Highways, about 1967, Materials inventory, Grand County: Utah State Department of Highways Materials and Research Division, Materials Inventory Section, 15 p.

Wengerd, S.A., 1958, Pennsylvanian stratigraphy, southwest shelf, Paradox basin, *in* Sanborn, A.F., editor, Guidebook to the geology of the Paradox basin: Intermountain Association of Petroleum Geologists, 9th Annual Field Conference Guidebook, p. 109-133.

Wengerd, S.A., and Matheny, M.L., 1958, Pennsylvanian System of Four Corners region: American Association of Petroleum Geologists Bulletin, v. 42, no. 9, p. 2048-2106.

White, M.A., and Jacobsen, M.I., 1983, Structures associated with the southwest margin of the ancestral Uncompahgre uplift, *in* Averett, W.R., editor, Northern Paradox basin-Uncompahgre uplift: Grand Junction Geological Society, 1983 Field Trip Guidebook, p. 33-39.

Williams, P.L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-360, scale 1:250,000.

Willis, G.C., 1994, Geologic map of the Harley Dome quadrangle, Grand County, Utah: Utah Geological and Mineral Survey Map M-157, 18 p., scale 1:24,000.

Wong, I.G., and Humphrey, J.R., 1989, Contemporary seismicity, faulting, and the state of stress in the Colorado Plateau: Geological Society of America Bulletin, v. 101, p. 1127-1146.

Woodward-Clyde Consultants, 1983, Geologic characterization report for the Paradox basin study region, Utah study areas: Walnut Creek, California, Woodward-Clyde Consultants, v. VI, 120 p.

Wright, J.C., Shawe, D.R., and Lohman, S.W., 1962, Definition of members of Jurassic Entrada Sandstone in east-central Utah and west-central Colorado: American Association of Petroleum Geologists Bulletin, v. 46, no. 11, p. 2,057-2,070.