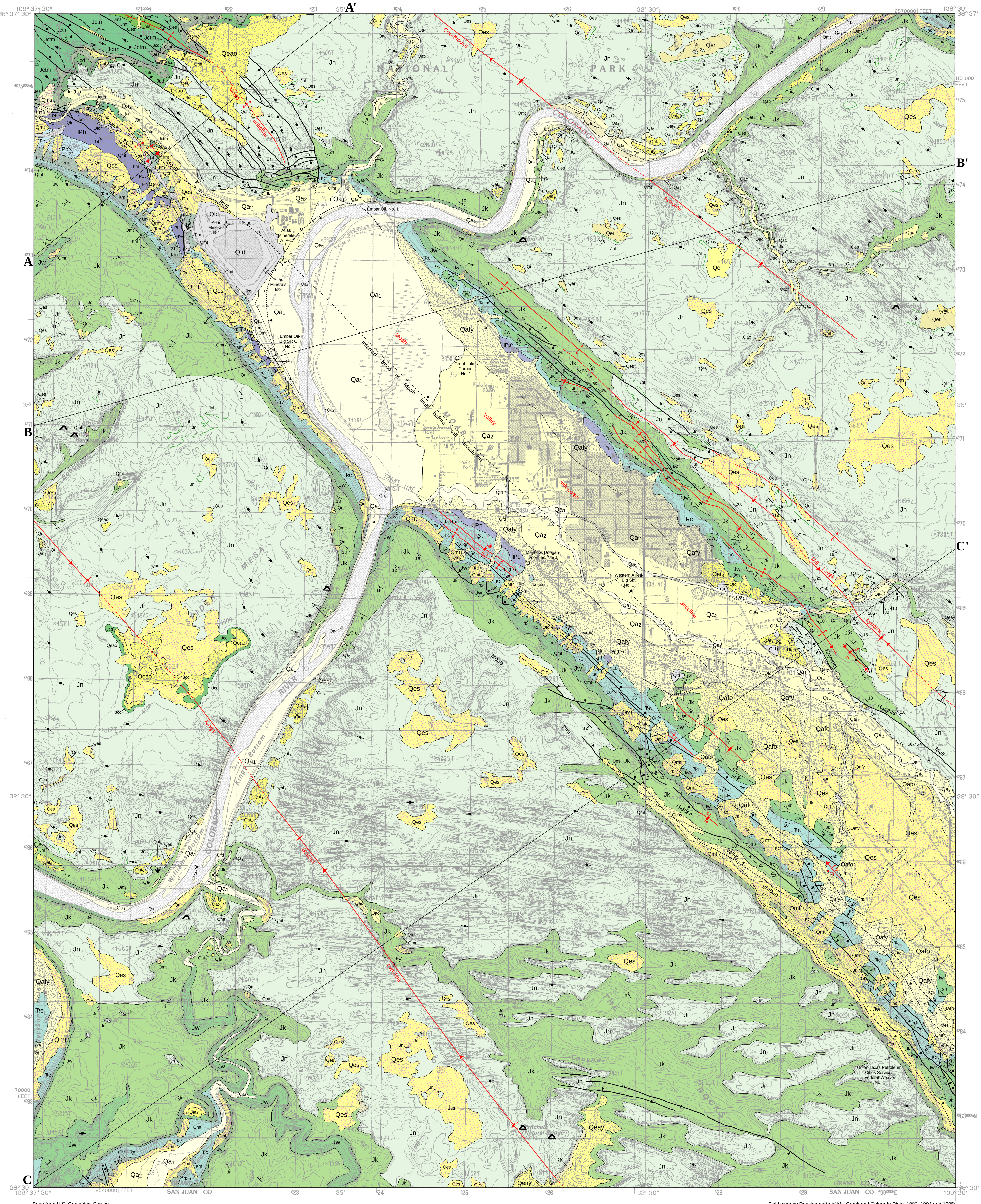
UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with
THE UNITED STATES GEOLOGICAL SURVEY

Plate 1
Utah Geological Survey Map 181
Geologic Map of the Moab 7.5' Quadrangle



Base from U.S. Geological Survey,
Moab 7.5' provisional quadrangle, 1985

SCALE 1:24,000

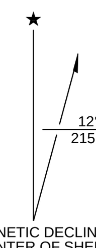
1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

Field work by Doelling north of Mill Creek and Colorado River, 1982, 1994 and 1995;
by Ross south of Mill Creek and Colorado River, 1993-1995;
and by Mulvey in Moab-Spanish Valley, 1993
Project Manager: Grant Willis



12°6'
215 mil

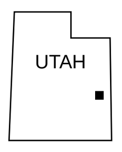
2002 MAGNETIC DECLINATION
AT CENTER OF SHEET

GEOLOGIC MAP OF THE MOAB 7.5' QUADRANGLE
GRAND COUNTY, UTAH

by

Hellmut H. Doelling, Michael L. Ross, and William E. Mulvey

2002



UTAH

DESCRIPTION OF GEOLOGIC UNITS

Quaternary Deposits

Qa_1 Modern alluvium (Holocene) - Poorly to well-sorted sand, silt, clay, and lenses of gravel in active channels and modern floodplains; as much as 20 feet (6 m) thick.

Qa_2 Older alluvium (Holocene to upper Pleistocene) - Sand, silt, minor amounts of clay, and local gravel; contains a variety of locally derived and exotic clasts; forms first surface 10 to 50 feet (3-15 m) above modern floodplains and channels; some deposit surfaces are characterized by weak soil development; as much as 30 feet (9 m) thick.

Qat_3, Qat_4, Qat_5, Qat_6 Alluvial-terrace deposits (Pleistocene) - Moderately sorted, poorly stratified gravel in a calcareous sandy matrix; contain a variety of locally derived and exotic clasts similar to Qa2; preserved as isolated remnants along major drainages; Qat3 gravels are found between 50 and 100 feet (15-30 m) above the present stream channels, some are capped by an eroded Stage II-III pedogenic carbonate soil; Qat4 gravels are between 100 and 150 feet (30-45 m) above the present stream channels; Qat5 gravels are between 200 to 240 feet (61-73 m) above the present stream channels; and Qat6 gravels are between 260 to 280 feet (79-85 m) above the present stream channels; Qat5 and Qat6 clasts are distinguishable from those of lower terraces by a well-developed rind of desert varnish; Pleistocene; as much as 60 feet (18 m) thick.

Qabf Basin-fill deposits (mostly Pleistocene) (cross section B-B' only) - Mostly alluvial deposits that fill Moab Valley; gravel, sand, silt, and minor amounts of clay encountered in drill holes; may exceed 450 feet (137 m) in thickness.

Qafy Younger alluvial-fan deposits (Holocene to upper Pleistocene) - Poorly sorted, poorly stratified, muddy to sandy cobble gravel; most clasts are locally derived and range from angular to subrounded; in distal parts locally derived subangular clasts are mixed with rounded igneous porphyry clasts; present along northeast and southwest sides of Moab and Spanish Valleys; fans have dendritic drainage patterns; located at the base of cliffs or in gullies incised in older fan deposits (Qafo); as much as 20 feet (6 m) thick.

Qafo Older alluvial-fan deposits (upper to middle Pleistocene) - Poorly sorted, poorly stratified, muddy to sandy cobble gravel; boulders present near cliffs; clasts are both locally derived and from the La Sal Mountains, and therefore range from angular to rounded; commonly covered by a mantle or veneer of sand (Qes or Qes/Qafo, respectively); fans are dissected and have limited fan morphology; present on divide between Moab and Spanish Valleys; as much as 40 feet (12 m) thick.

Qmt Talus (Holocene to upper Pleistocene) - Angular boulders, cobbles, and smaller rock fragments commonly in a finer grained matrix; derived from rock falls and forms veneers to mantles on slopes below cliffs; commonly grades downslope into alluvial-fan deposits; as much as 20 feet (6 m) thick.

Qms Landslide deposits (probably upper or uppermost middle Pleistocene) - Large mass of the Moab Member of the Curtis Formation that slid along a bedding-plane parting at its contact with the underlying Slick Rock Member; located in Moab Canyon north of U.S. Highway 191 near northwest corner of quadrangle; about 60 feet (20 m) thick.

Qc Colluvium (Holocene) - Poorly sorted gravel, sand, and silt forming thin mantles on slopes; less than 6 feet (2 m) thick.

Qes Eolian-sand deposits (Holocene) - Well-sorted, fine- to medium-grained, quartzose sand with silt; typically form thin, discontinuous sheets and small dunes, and locally fill hollows; locally as much as 30 feet (9 m) thick.

Qeay Younger eolian and alluvial deposits (Holocene) - Mainly fine- to medium-grained sand mixed with silt and sparse lenses of granules and pebbles; accumulated and reworked by eolian and alluvial processes; generally thin and restricted to ephemeral washes and hollows on benches capped by Glen Canyon Group sandstone; larger deposits floor small valleys and narrow canyons; as much as 10 feet (3 m) thick.

Qeao Older eolian and alluvial deposits (middle to lower Pleistocene) - Mainly sand and silt, but contain sparse lenses of rounded granules and pebbles and pedogenic carbonate rubble; sheet-like and locally preserved on mesas and benches; deposit on Poison Spider Mesa is capped by an eroded Stage V pedogenic carbonate; as much as 15 feet (5 m) thick.

Qer Eolian and residual deposits (Holocene to upper Pleistocene) - Mostly a mix of yellow, tan, and reddish-orange, fine-grained sand and angular limestone rubble derived from carbonate units in the Navajo Sandstone (Jnl) on which they rest; mostly less than 3 feet (1 m) thick.

Qac Alluvial and colluvial deposits (Holocene to upper Pleistocene) - Mainly sand, but commonly contain a poorly sorted mixture of pebbles, sand, silt, and clay; clasts are subrounded to angular; in ephemeral washes and on adjacent hillslopes where colluvium is reworked and transported by alluvial processes in active channels; as much as 10 feet (3 m) thick.

Qfd Fill and disturbed deposits (historical) - Clay- to boulder-size material used as railroad and road fill; mostly sand-size mill tailings and fill at the Atlas Minerals mill site; gravel pits, and larger areas disturbed by development; variable thicknesses as much as 70 feet (21 m).

Jurassic Rocks

Jms Salt Wash Member of Morrison Formation (Upper Jurassic) - Typically blocky ledges of pale-yellow-gray, cross-bedded sandstone interbedded with slope-forming, red and green mudstone and siltstone; only a small remnant is present in the northwest corner of the quadrangle; preserved thickness 30 feet (9 m).

Jmt Tidwell Member of Morrison Formation and Summerville Formation(?) (Upper and Middle Jurassic) - Red to brown, thin-bedded, silty sandstone, muddy sandstone, siltstone, and shale containing thin to nodular beds of gray limestone; large white siliceous (chert) concretions are associated with the limestone; forms gentle slope littered with limestone and chert fragments; basal 6 to 12 feet (2-4 m) is brown to red, thin-bedded, fine-grained sandstone and siltstone that forms a steep slope that correlates with the Summerville Formation; contact between this steep slope and remainder of unit (Tidwell Member) may be the J-5 unconformity; total thickness about 40 to 50 feet (12-15 m).

Jctm Curtis Formation, Moab Member (Middle Jurassic) (informal designation - see text) - Pale-gray-orange, pale yellow-brown, and light-gray, fine- to medium-grained, quartzose eolian sandstone; calcareous; forms massive cliff commonly with conspicuous joints; 60 to 100 feet (18-30 m) thick.

Jes Entrada Sandstone, Slick Rock Member (Middle Jurassic) - Red-orange to brown, thick-bedded, cross-bedded, quartzose eolian sandstone; very fine to fine grained with medium to coarse grains along cross-bed laminae; iron-oxide or calcium-carbonate cemented; forms smooth cliffs and bare rock slopes; estimated thickness 250 feet (76 m).

Jcd Carmel Formation, Dewey Bridge Member (Middle Jurassic) (formerly member of Entrada Sandstone - see text) - Red-brown, muddy to silty, fine- to medium-grained sandstone; iron-oxide or calcium-carbonate cemented; medium to thick bedded; weathers to distinct irregular and contorted rounded ledges; basal contact is the J-2 unconformity; 90 to 110 feet (27-34 m) thick.

Glen Canyon Group (Jn, Jk, Jw)

Jn / Jnl Navajo Sandstone (Lower Jurassic) - Pale-orange to light-gray to red-orange, fine-grained, quartzose eolian sandstone; calcareous and silica cemented; medium to massively bedded, commonly with large-scale sweeping cross-beds; locally contains thin, gray, cherty, sandy carbonate beds (Jnl); forms smooth vertical cliffs and rounded knolls; 300 to 700 feet (91-213 m) thick.

Jk Kayenta Formation (Lower Jurassic) - Moderate-orange-pink and red-purple sandstone, interbedded with dark-red-brown to gray-red siltstone and lesser red intraformational conglomerate and mudstone; sandstones mainly lithic arkose to feldspathic litharenite; mainly of fluvial origin; calcareous cement; pink-orange eolian sandstone beds are conspicuous in upper part; forms thick-bedded, step-like, resistant ledges and steep slopes; 250 to 400 feet (76-122 m) thick.

Jw Wingate Sandstone (Lower Jurassic) - Gray-orange-pink, gray-orange, and moderate-orange-pink to pale-red-brown, very fine- to fine-grained, quartzose to subarkosic, eolian sandstone; calcareous and siliceous; commonly forms massive cliffs along canyon walls or blocky cliffs where fractured; cliff surfaces commonly streaked with dark-brown desert varnish; 250 to 400 feet (76-122 m) thick.

Triassic Rocks

Ꞧc Chinle Formation (Upper Triassic) - Red-brown to gray-red, interbedded sandstone, conglomeratic sandstone, siltstone, and mudstone; lenticular and planar sandstone and conglomeratic sandstone are calcareous to quartzose and fine to coarse grained; indistinctly bedded bentonitic and calcareous mudstones form steep slopes separated by ledges and cliffs of sandstone and conglomeratic sandstone; two informal, unmapped members -- a discontinuous lower member of quartzose sandstone and mottled siltstone and mudstone, and an upper member that consists of a lower slope former, middle ledge former, upper slope former, and upper ledge former made up of planar flat beds of possible eolian origin; 100 to 700 feet (30-213 m) thick.

Ꞧm Moenkopi Formation (Lower Triassic) - Light- to dark-brown ("chocolate"brown), interbedded, largely fine-grained, micaceous sandstone, siltstone, mudstone, and shale; sandstone is commonly ripple marked; forms slopes separated by medium to thin continuous ledges; locally contains distinct pebble conglomerate near base; 0 to 750 feet (0-229 m) thick.

Permian Rocks

Pc Cutler Formation (Lower Permian) - Red-purple, arkosic fluvial sandstone and conglomeratic sandstone interbedded with red to red-orange, eolian sandstone; medium to thick bedded; thin beds of red-purple siltstone and light-gray, fossiliferous limestone in lower part; forms steep slopes, ledges, and cliffs; 0 to 600 feet (0-183 m) thick at the surface; may be as thick as 5,000 feet (1,524 m) in subsurface due to salt movement.

Pennsylvanian Rocks

IPh Honaker Trail Formation (Upper Pennsylvanian - Missourian-Virgilian) - Light-gray, gray-pink, gray-purple, and gray-brown interbedded sandstone, limestone, and siltstone; sandstone is fine grained and quartzose, limestone is argillaceous and fossiliferous, siltstone is commonly micaceous; thin to thick bedded; forms ledges; exposed thickness may be as much as 700 feet (213 m); subsurface thickness variable due to salt movement, but may be as much as 2,700 feet (823 m) thick.

IPp Paradox Formation (Middle Pennsylvanian - Desmoinesian) - Gray, sucrosic gypsum, gypsiferous claystone, gray to black shale, with subordinate fragments of gray, silty sandstone and carbonates as cap rock; contains cyclically bedded evaporite, dolomite, shale, and clastic beds in the subsurface; thickness highly variable due to salt movement, estimated cap rock thickness as much as 700 feet (213 m), estimated height of Moab salt diapir at least 9,000 feet (2,743 m) reaching a maximum width of 2 miles (3.2 km).

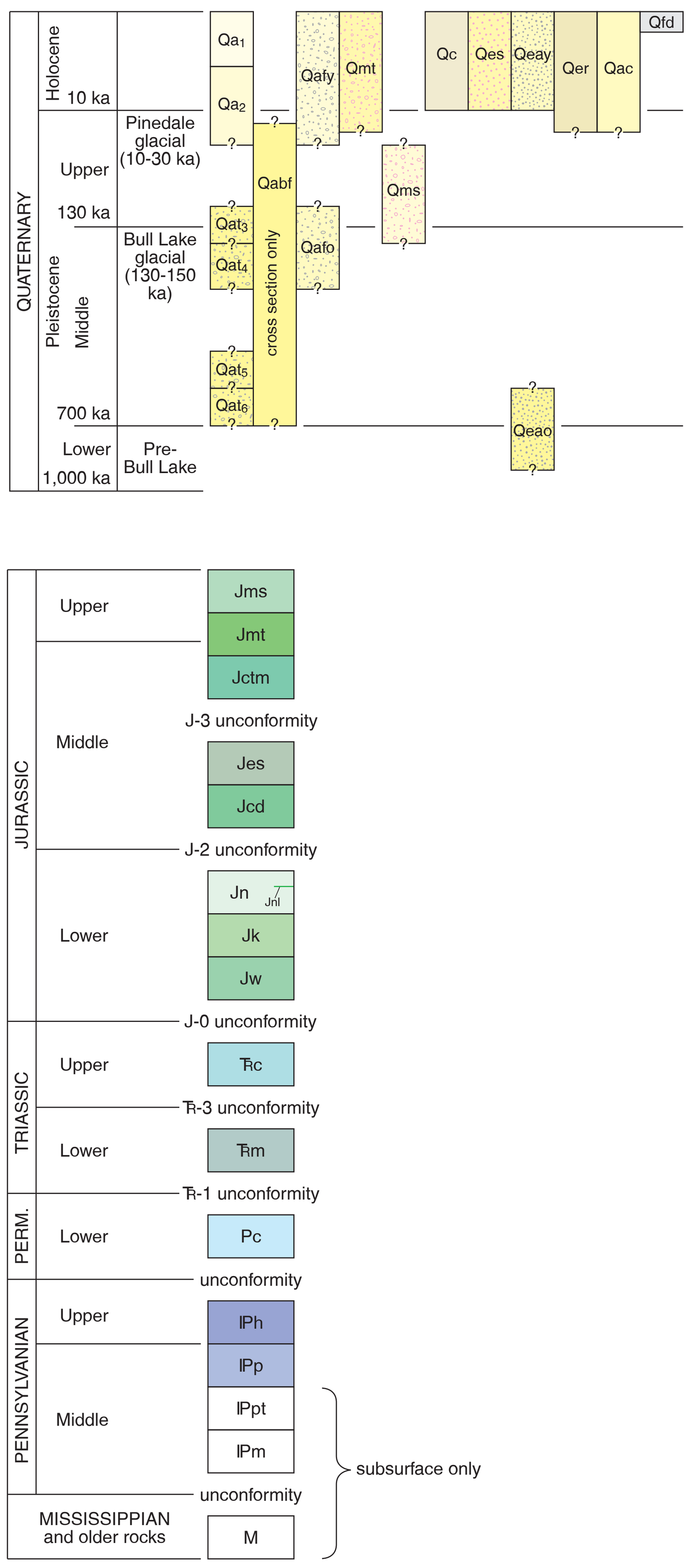
Subsurface Rocks

IPpt Pinkerton Trail Formation (Middle Pennsylvanian) - (shown on cross sections)

IPm Molas Formation (Middle Pennsylvanian) - (shown on cross sections)

M Mississippian rocks (shown on cross sections)

CORRELATION OF GEOLOGIC UNITS



LITHOLOGIC COLUMN

SYSTEM	SERIES	FORMATION AND MEMBERS		THICK-NESS feet (meters)	SYMBOLS	LITHOLOGY
QUAT.		Surficial and basin-fill deposits		up to 450± (up to 137±)	Q	Subsurface only
JURASSIC	U.	Morrison Fm.	Salt Wash Mbr.	30+ (9+)	Jms	
			Tidwell Mbr./ Summerville Fm.	40-50 (12-15)	Jmt	Red marker
	Middle	Curtis Fm.	Moab Mbr.	60-100 (18-30)	Jctm	Commonly jointed; J-3 unconformity
		Entrada Ss.	Slick Rock Mbr.	250± (76±)	Jes	Eolian cross-beds
		Carmel Fm.	Dewey Bridge Mbr.	90-110 (27-34)	Jcd	J-2 unconformity
	Lower	Navajo Sandstone		300-700 (91-213)	Jn, Jnl	Forms arches; High-angle cross-beds; Highly jointed; Thin limestone beds
		Kayenta Formation		250-400 (76-122)	Jk	Eolian marker bed; Ledge and bench
		Wingate Sandstone		250-400 (76-122)	Jw	Prominent cliff former; J-0 unconformity
TRIASSIC	Upper	Chinle Formation		100-700 (30-213)	Ꞧc	Thick beds at top "Black ledge"; Local unconformities; Ꞧ-3 unconformity
	Lower	Moenkopi Formation		0-750 (0-229)	Ꞧm	Ripple marks; Ꞧ-1 unconformity
PERMIAN	Lower	Cutler Formation		0-5,000 (0-1,524)	Pc	Arkosic sandstone; Unconformity
PENNSYLVANIAN	Upper (Missourian-Virgilian)	Hermosa Group	Honaker Trail Formation	0-2,700 (0-823)	IPh	Fossiliferous; Subsurface only
	Middle (Desmoinesian)		Paradox Formation	300-9,000+ (91-2,743+)	IPp	Gypsum and shale caprock; Salt beds; Subsurface only

SYMBOLS

Contact - Dashed where inferred

Fault - Dashed where inferred, dotted where covered, bar and ball on downthrown block where known, arrow and number indicate dip and dip direction of fault, arrows on cross section show offset, queried where existence uncertain

Inferred trace of Moab fault prior to salt dissolution

Axial trace of anticline - Dotted where covered, large arrow shows plunge and numbers are dips of bedding on limbs

Axial trace of syncline - Dashed where inferred, dotted where covered, large arrow shows plunge and numbers are dips of bedding on limbs

Axial trace of monocline - Dotted where covered, small arrows show dip of beds

Near-vertical fracture with minor brecciation

Strike and dip of beds, inclined

Strike of near-vertical joints

Adit

Dry hole, abandoned (see table 2)

Gas injection, disposal, or brine well (see table 2)

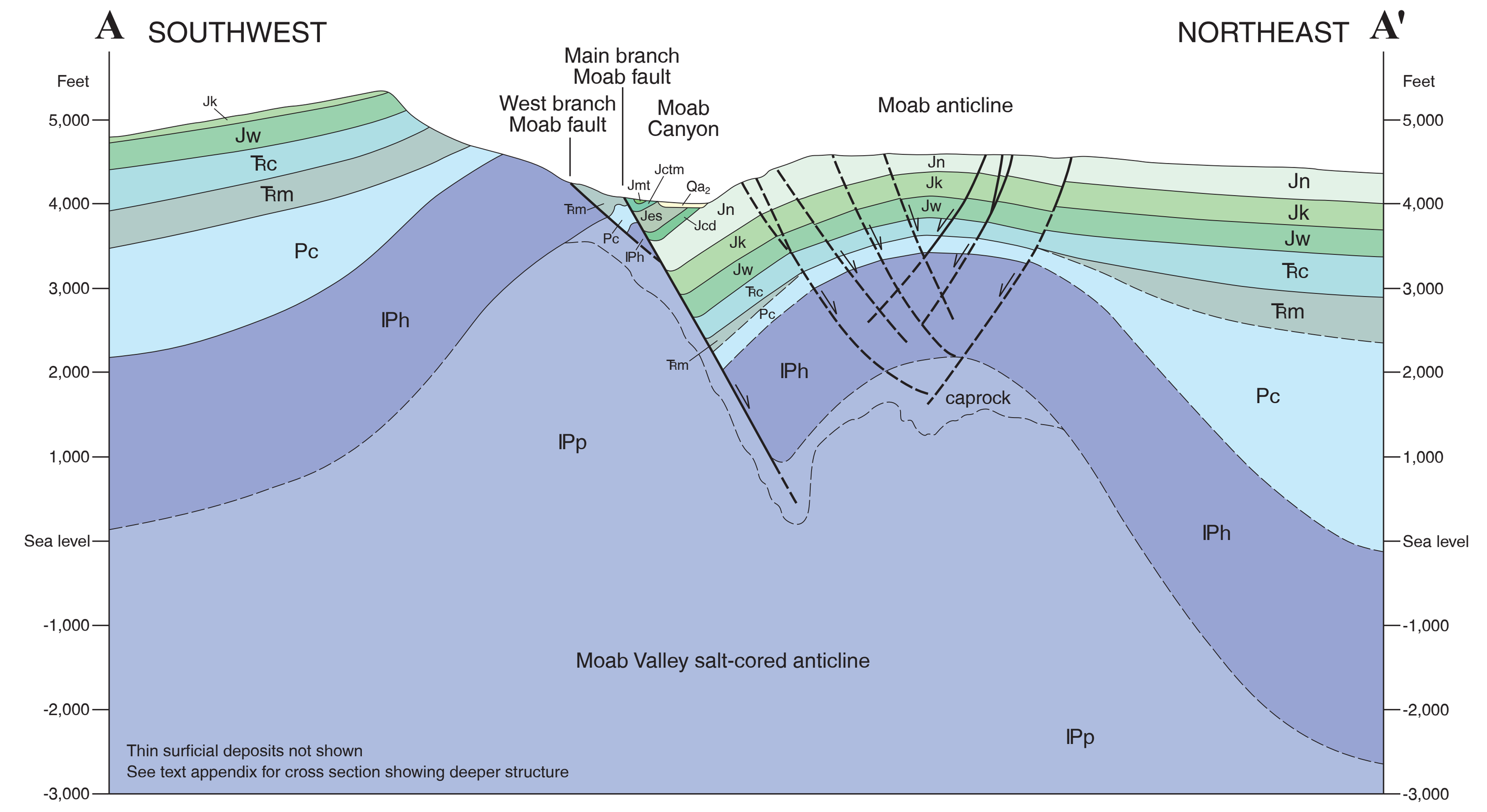
Shallow borehole (only holes referred to in text figure 7 shown)

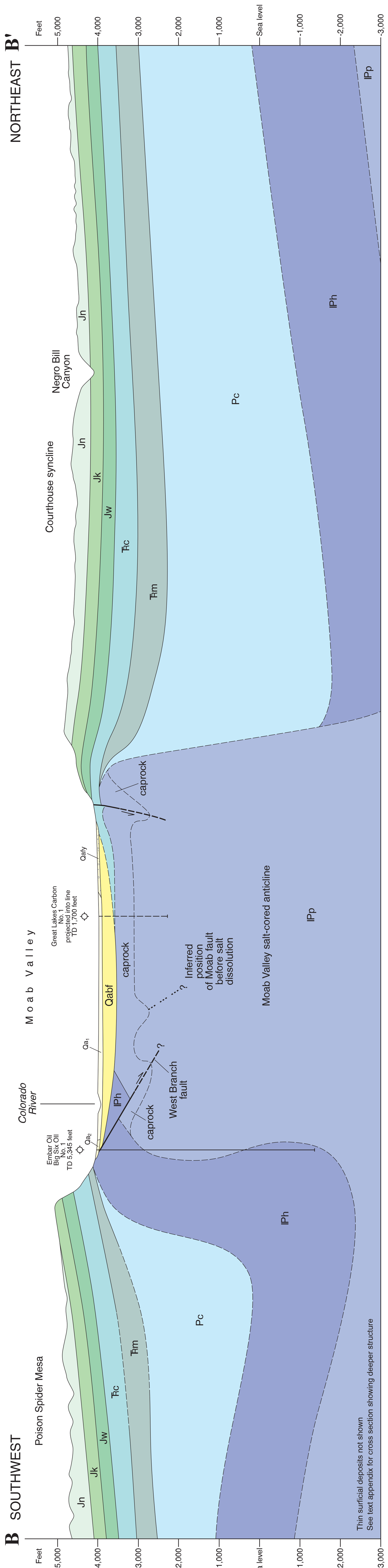
Gravel pit

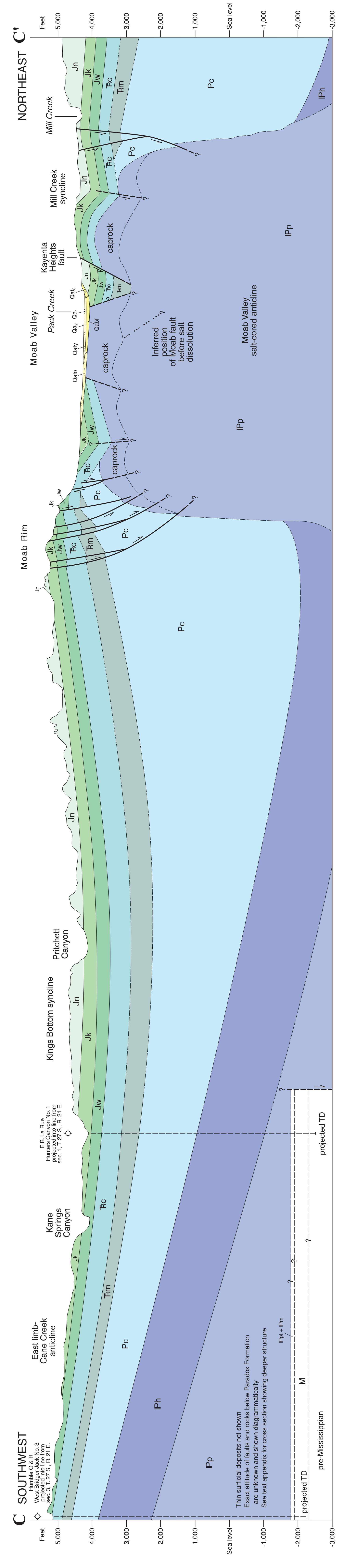
Natural stone arch or bridge

Dinosaur trackway

Ꞧc(bx) Brecciated rock (bx) - Pattern over affected unit added to map unit label







GEOLOGIC MAP OF THE MOAB 7.5′ QUADRANGLE, GRAND COUNTY, UTAH

by

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State Contract 95-0846
STATEMAP Agreement No. 1434-94A-1256

ISBN 1-55791-580-6

MAP 181
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
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the U.S. Geological Survey

2002

UTAH GEOLOGICAL SURVEY

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ABSTRACT

The Moab 7.5′ quadrangle is in Utah's red-rock country in east-central Utah. It is crossed by the Colorado River, and includes a small part of Arches National Park. The quadrangle is in the fold and fault belt of the salt-cored anticline region in the northern Paradox basin. The Paradox basin was an asymmetrical basin whose deepest part formed adjacent to the ancestral Uncompahgre uplift during Pennsylvanian to Late Triassic time.

Exposed bedrock strata in the Moab quadrangle range from Pennsylvanian to Jurassic in age. These include as much as 200 feet (60 m) and 700 feet (213 m) of the Pennsylvanian Paradox Formation cap rock and the Honaker Trail Formation, respectively; 0 to 600 feet (0-183 m) of the Permian Cutler Formation; 0 to 500 feet (0-152 m) of the Lower Triassic Moenkopi Formation; 100 to 640 feet (30-195 m) of the Upper Triassic Chinle Formation; 250 to 400 feet (76-122 m) of the Wingate Sandstone, 250 to 400 feet (76-122 m) of the Kayenta Formation, and 300 to 700 feet (91-213 m) of the Navajo Sandstone, all Lower Jurassic; 90 to 110 feet (27-34 m) of the Dewey Bridge Member of the Carmel Formation, about 250 feet (76 m) of the Slick Rock Member of the Entrada Sandstone, and 60 to 100 feet (18-30 m) of the Moab Member of the Curtis Formation, all Middle Jurassic; and an incomplete 70- to 80-foot (21-24 m) section of the Upper Jurassic Morrison Formation. Quaternary alluvial, eolian, and mass-movement deposits are also locally present.

The Middle Jurassic below the Summerville Formation in the Moab area consists of three units, Dewey Bridge, Slick Rock, and Moab, that have long been considered members of the Entrada Sandstone. The Dewey Bridge Member was recently reassigned as a member of the Carmel Formation, and the Moab unit is now considered a member of the Curtis Formation (informally pending formal reclassification); they are discussed and mapped in this way in this document.

Moab and Spanish Valleys are located along the crest of the northwest-trending Moab Valley salt-cored anticline, the dominant structural feature of the quadrangle. The salt diapir in the core of the fold is at least 9,000 feet (2,743 m) high and 2 miles (3.2 km) wide. Sedimentary rocks and structural features along the anticline margins are evidence of Pennsylvanian to Jurassic salt diapirism and late Cenozoic salt dissolution. Sedimentary rocks are thin or missing over the diapir and are abnormally thick in synclines along the margins. Limited borehole and geophysical information indicate that the sides of the diapir are nearly vertical along much of their length. Valley margin strata are faulted, tilted, folded, and brecciated. Unconformities are common. Strata dip away from the anticline into the broad troughs of the Courthouse syncline on the northeast and the Kings Bottom syncline on the southwest. The axial traces of these synclines are parallel to the trend of the salt-cored anticline.

The Tertiary-age Moab fault displaces strata along the southwest flank of the Moab Valley salt-cored anticline a maximum of about 2,400 feet (732 m) in the northwest quarter of the quadrangle. In this area the fault consists of two northwest-striking branches that dip northeast. Both branches are normal faults. Southeast of their mapped exposures the fault traces are obscured by surficial deposits, but the displacement remains apparent along the entire length of Moab and Spanish Valleys.

The northeast limb of the Cane Creek anticline is present in the southwest corner of the quadrangle (cross section C-C′). The Cane Creek anticline is also a Pennsylvanian to Jurassic salt-cored anticline, but is non-diapiric.

Sand, gravel, brine, stone, and a little gold have been produced from the quadrangle. Shows of oil and gas have been encountered in the few tests made for petroleum and natural gas. Potash and magnesium salts are believed present in the Paradox Formation that underlies the quadrangle, but have not been exploited. Uranium prospectors dug a few pits in the Honaker Trail and Chinle Formations without significant results. The Colorado River, Mill Creek, Pack Creek, and the creek in Kane Springs Canyon, and three primary ground-water aquifers are important sources of irrigation and culinary water.

Geologic hazards include rock falls, landslides, debris flows, stream flooding, problem soils, shallow ground water, blowing sand, and evaporite dissolution. Earthquakes of low to moderate magnitudes are sometimes felt in the area, but are not expected to cause ground rupture or significant ground shaking.

INTRODUCTION

The Moab 7.5′ quadrangle is in east-central Utah and is named after the city of Moab, the Grand County seat. Moab and surrounding settlements are located in Moab and Span-

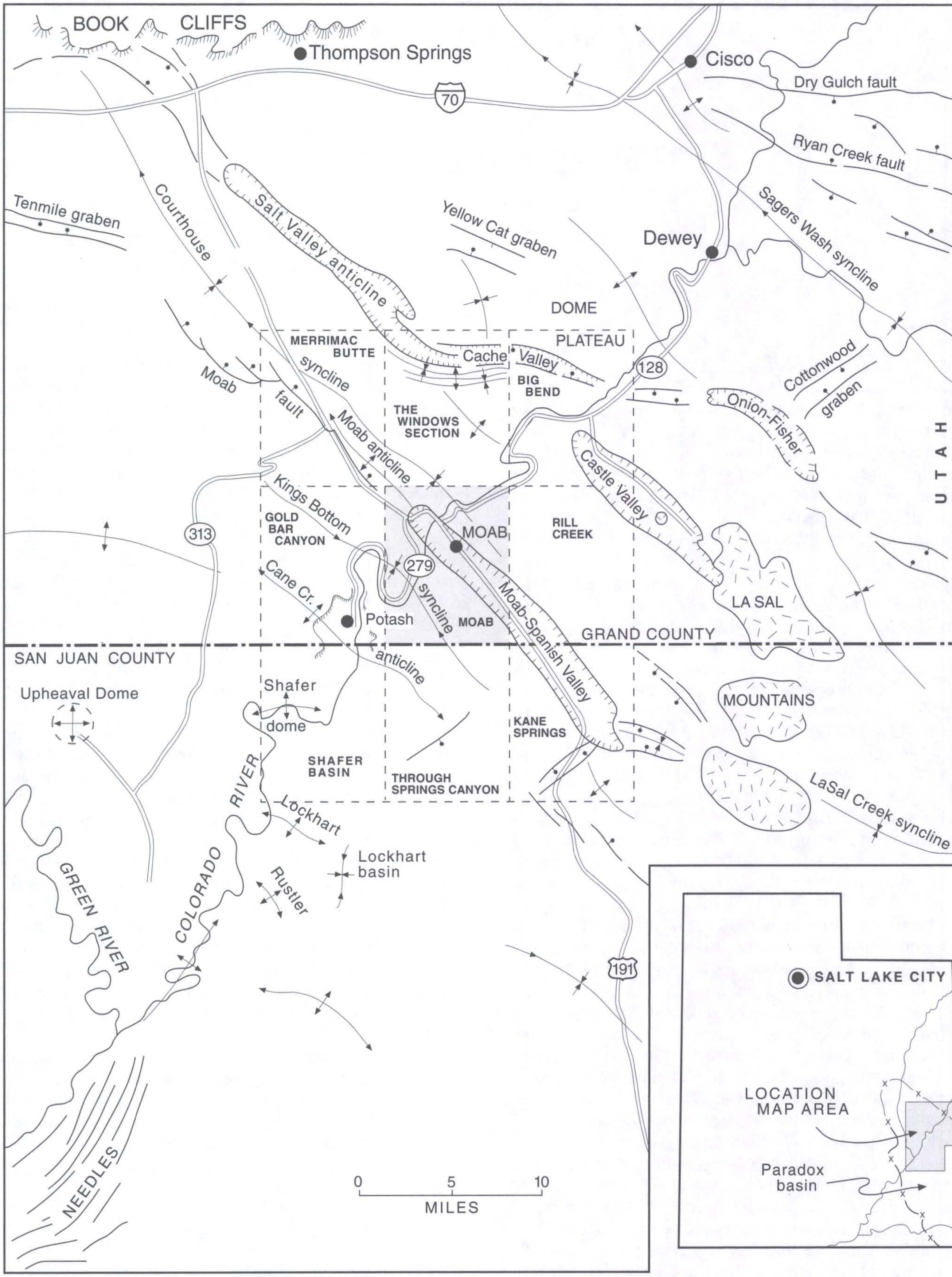


Figure 1. Structural and geographic features in east-central Utah in the vicinity of the Moab 7.5-minute quadrangle. The eight quadrangles which border it are also shown and named. The Moab quadrangle is located in the Paradox basin within the Colorado Plateau physiographic province.

ish Valleys, northwest-trending features divided by a low topographic saddle (figure 1). The northwest part is Moab Valley and the southeast part is Spanish Valley. The Colorado River flows northeast to southwest across the quadrangle in deeply incised canyons and through the northern end of Moab Valley. The remainder of the quadrangle consists of benches of highly jointed sandstone bedrock incised by canyons formed by tributaries of the Colorado River.

The quadrangle is served by U.S. Highway 191, a major link that connects Interstate Highway 70, 30 miles (48 km) to the north, to Moab and southeastern Utah. Utah Highways 128 and 279, respectively, parallel the Colorado River upstream and downstream (respectively) from Moab Valley (figure 1).

Elevations in the quadrangle range from about 3,940 feet (1,201 m) along the Colorado River to slightly more than 7,000 feet (2,134 m) along the Moab Rim in the southeastern corner of the quadrangle (plate 1). Moab and Spanish Valley elevations range from 3,950 to 4,700 feet (1,204-1,433 m) and bench elevations increase southward from about 4,400 feet to 7,000 feet (1,341-2,134 m). The bench tops expose bare sandstone or thin sandy soils. Pinion and juniper trees are common on benches at higher elevations. At lower bench elevations, desert shrubbery and grasses are common. Bitterbrush, blackbrush, Mormon tea, prickly pear cactus, rice grass, and scattered juniper trees are common in the canyons.

The principal industry of Moab is tourism based on outdoor activities such as hiking, bicycling, back-roads driving, river running, and sightseeing at the nearby national and state parks. The population of the quadrangle commonly doubles during the tourist season and for special events. The southern boundary of Arches National Park follows the Colorado River and Moab Canyon in the northern part of the quadrangle. Government agencies dealing with land management maintain offices in the city. Moab is also a hub for nearby mining and oil and gas exploration activities. Orchards and croplands are in the valleys and cattle graze on the benches.

McKnight (1940), Hemphill (1955), Miller (1959), Probandt (1959), Richmond (1962), Williams (1964), Huntoon and others (1982), and Doelling (1985, 2001) mapped the geology of all or parts of the Moab quadrangle at various scales. Richmond (1962) and Harden and others (1985) mapped and described Quaternary deposits in the area. For this investigation Doelling mapped the bedrock areas north of Mill Creek and the Colorado River, Ross mapped the bedrock areas south of these drainages, and Mulvey and Ross mapped the Quaternary deposits of Moab and Spanish Valleys.

STRATIGRAPHY

Rock formations exposed in the Moab 7.5′ quadrangle range from Middle Pennsylvanian to Late Jurassic. Thick salt layers in the Middle Pennsylvanian Paradox Formation have "flowed" into an elongated salt diapir beneath Moab and Spanish Valleys over a long time interval. Salt beds are completely removed from adjacent areas. Salt movement greatly affected the Late Pennsylvanian through Triassic strata deposited in the area. Jurassic strata show less dramatic effects. Salt movement produced lateral variations in lithofacies and differences in thickness, and also affected the distribution of contemporaneous units (Stewart and others, 1972a). Quaternary sediments were deposited by alluvial, eolian, and mass-movement processes. As much as 500 feet (152 m) of basin fill (mostly alluvium) is present in Moab Valley.

Pennsylvanian Rocks

Paradox Formation (IPp)

The Paradox Formation is overlain by the Honaker Trail Formation and underlain by the Pinkerton Trail Formation; the three units make up the Hermosa Group (Baars and others, 1967). The Paradox Formation is a sequence of cyclically bedded evaporites (anhydrite, halite, and potash), dolomite, organic-rich carbonaceous shale, and fine-grained siliciclastic sediments (Hite and Lohman, 1973). The halite-bearing cyclic units have been divided into 29 to 33 cycles (Hite, 1960; Raup and Hite, 1992; Williams-Stroud, 1994).

The Paradox Formation is exposed in the quadrangle as elongated mounds and irregular ridges of cap rock that form two northwest-trending, discontinuous belts along the southwest and northeast margins of Moab Valley (figure 2). Cap rock is the residue (insoluble parts of the Paradox Formation) formed at the top of leached salt diapirs (Hite and Lohman, 1973) as salt is successively dissolved and carried away by ground water. Outcrops are a characteristic grayish white to light gray with patchy areas of dark gray, pale yellowish gray, and pale greenish gray. At these outcrops, gypsiferous mudstone, black shale, and sucrosic gypsum are complexly folded with disrupted and contorted bedding below a thin "popcorn"-weathering surface. Selenite and alabaster gypsum form resistant outcrops with pitted and irregular surfaces. Fragments and chips of mudstone, shale, silty sandstone, muddy dolomite, and micrite limestone and dolomite litter the outcrop surfaces. The log from a gas-storage and salt-water-injection-disposal well, NE1/4NW1/4 section 35, T. 25 S., R. 21 E. (Great Lakes Carbon Corporation No. 1), shows the well penetrated at least 400 feet (122 m) of cap rock in Moab Valley. We estimate the cap rock may locally be as much as 700 feet (213 m) thick, and as much as 200 feet (60 m) is exposed in the quadrangle.

The thickness of the Paradox Formation beneath the Moab quadrangle area is highly variable due to salt flowage. Along the Moab Valley salt diapir, the formation is thickened to at least 9,000 feet (2,743 m) (plate 2, cross sections A-A′, B-B′, and C-C′). The Federal-Weaver No. 1 well (SE1/4NW1/4SE1/4 section 31, T. 26 S., R. 22 E.), located along the southwest side of Moab Valley, penetrated only 500 feet (152 m) of salt-bearing Pennsylvanian strata. The Union of California, Burkholder No. 1-G-1 well (SW1/4NE1/4 section 1, T. 26 S., R. 22 E.), located approximately 4 miles (6.4 km) east-northeast of Moab Valley in the Rill Creek quadrangle, penetrated only 300 feet (91 m) of salt-bearing Pennsylvanian strata. The original depositional thickness of the Paradox Formation in the salt-cored anticline area in the northeastern Paradox basin was probably about 5,000 feet (1,524 m) (Elston and others, 1962; Hite and Lohman, 1973).

The Paradox Formation was deposited in a periodically restricted part of the Paradox basin (Wengerd and Matheny, 1958; Woodward-Clyde Consultants, 1983). At highstand conditions the basin was covered by marine waters and shelf

Figure 2. Cap rock of the Pennsylvanian Paradox Formation exposed along the southwest flank of Moab Valley. Cap rock is the residue formed at the top of leached salt diapirs as salt layers are successively dissolved and carried away by fresh ground water. Gypsiferous mudstone, sucrosic gypsum, and gray shale are complexly folded and contorted in outcrops.

sediments. At low-stand conditions, sea-water evaporation produced hypersaline conditions in the restricted basin. Anhydrite, halite, and potash (sylvite and carnallite) were successively precipitated.

Honaker Trail Formation (IPh)

About 600 to 700 feet (183-213 m) of the upper part of the Honaker Trail Formation is exposed in the Moab 7.5′quadrangle. Outcrops of the Honaker Trail consist of interbedded sandstone, limestone, and siltstone that form ledges along the southwest wall of Moab Canyon in the northwest part of the quadrangle. Sandstone and red-purple siltstone beds are common near the top of the exposure, whereas sandy limestone beds are common at the base of the exposure.

Sandstone beds are gray white, gray pink, gray lavender, gray purple, gray brown, red brown, and light brown. Most sandstone beds are quartzitic and fine grained, although a few are medium grained. The grains are well to moderately sorted, and are commonly cemented with calcium carbonate. Some sandstone beds are micaceous, whereas others are subarkosic. Bedding is mostly medium to thick bedded. In places the beds are divided by thin siltstone or shaly partings. Cross bedding is locally displayed along the resistant ledges.

Limestone beds are gray to light gray and variably argillaceous, contain vugs filled with quartz or calcite, weather hackly, and contain broken fossils. They are mostly thin to medium bedded and resistant. Types of limestone include biomicrite, biosparite, sandy sparite, and micrite (Melton, 1972). Fossils include horn corals, various brachiopods, bryozoa, crinoid columnals, various spines and spicules, fusulinids, and rare trilobites. We collected fusulinids from the top of the Honaker Trail Formation in the Moab quadrangle that are Virgilian (latest Pennsylvanian in age; Fusulinid Biostratigraphy, Inc., written communication, 1991).

Micaceous siltstone commonly forms thin beds and partings between limestone and sandstone beds. Thicker beds are locally present. Siltstone beds are generally lavender, purple, or green and of a deeper shade than those of adjacent sandstone beds. Siltstone beds are less resistant than limestone and sandstone beds.

The basal part of the Honaker Trail Formation is not exposed in the quadrangle. The thickness of the Honaker Trail may be as much as 2,700 feet (823 m) in the subsurface, but is highly variable due to movement of salt. The upper contact with the overlying Cutler Formation is placed at the top of a light-gray, sandy limestone bed and below a purple siltstone slope capped by a conspicuous white and red-brown, fine-grained sandstone bed. Where the siltstone is absent, it is placed just below the white and red-brown sandstone. This contact with the Cutler Formation may be a paraconformity.

The Honaker Trail Formation was deposited in shallow marine shelf and nearshore environments during latest Desmoinesian through Virgilian time (Late Pennsylvanian) (Melton, 1972; Doelling and others, 1994).

Permian Rocks

Cutler Formation (Pc)

Outcrops of the Permian Cutler Formation in the Moab 7.5′ quadrangle are limited to the southwest wall of Moab Canyon. The Cutler is presumed to be present everywhere in the subsurface, except in and near the margins of Moab and Spanish Valleys. Cutler Formation exposures consist mainly of interbedded red to red-orange, mostly fine-grained, subarkosic to quartzose, eolian sandstone; red to purple arkosic sandstone; and conglomeratic fluvial sandstone. The red to red-orange sandstones are generally more resistant than the red-purple arkosic sandstones. Subarkosic to quartzose sandstone is fine to medium grained, moderately well sorted, generally micaceous, and displays tabular planar cross-bedding and horizontal bedding. The arkosic sandstones are poorly sorted and are medium to coarse grained. Conglomeratic beds and lenses contain granitic and gneissic pebbles and cobbles, commonly as much as 2 inches (5 cm) in diameter. These sandstones contain abundant visible mica and feldspar grains and are medium to thick bedded. Arkosic beds are commonly trough cross-bedded and have cut-and-fill features.

A few siltstone and limestone beds are present in the Cutler Formation, especially in the lower part of the outcrop. Siltstone is generally purple, red, or green, thin bedded, and forms slopes. Limestone is light gray, thin to medium bedded, and forms ledges. Limestone beds commonly contain fossils.

Doelling and others (1994) divided the Cutler Formation into informal upper and lower members in the adjacent Gold Bar Canyon quadrangle. The division was based on the presence of limestone beds in the lower member (Loope and others, 1990). Two limestone beds were noted in the Cutler outcrops southwest of the Arches National Park visitor center: one 111 feet (34 m) and the other 246 feet (75 m) above the contact with the underlying Honaker Trail. We chose not to subdivide the Cutler in the Moab quadrangle because the limestone beds are inconspicuous.

The Lower Triassic Moenkopi Formation overlies an angular unconformity at the top of the Cutler Formation (Ꞧ-1 unconformity of Pipiringos and O'Sullivan, 1978). This angular unconformity progressively cuts into (thins) the Cutler from northwest to southeast along the southwest wall of Moab Canyon. The thinning is related, at least in part, to movement of the Moab Valley salt diapir. The Cutler is about 380 feet (116 m) thick in outcrop south and just above the largest bend in U.S. Highway 191. It is cut out completely in the NW1/4 section 34, T. 25 S., R. 21 E. In comparison, the Cutler Formation is 900 to 1,200 feet (274-366 m) thick in the Gold Bar Canyon quadrangle to the west (Doelling and others, 1994), and approximately 4,550 feet (1,387 m) thick in the Burkholder No. 1-G-1 well in the Rill Creek quadrangle to the east. The Cutler probably ranges from absent up to 5,000 feet (0-1,524 m) thick in the subsurface in the Moab quadrangle; outcrops are up to 600 feet (0-183 m) thick. These dramatic variations in the thickness of the Cutler Formation indicate salt tectonic activity during the Permian. The thin to missing outcrops in Moab Canyon and relationships exposed at other salt-cored anticlines in the Paradox basin indicate that the Cutler is commonly missing over the tops of the salt diapirs (Dane, 1935; Cater, 1970; Doel-ling, 1988, Ross, in preparation).

The Cutler Formation in the Moab region consists of intertonguing fluvial redbeds, eolian sandstones, and sparse shallow marine carbonates. These sediments were deposited in a transition zone between alluvial-fan environments along the southwest flank of the ancestral Uncompahgre highland, eolian environments of the Cedar Mesa Sandstone to the south-southwest, and shallow marine environments to the west-northwest of Moab (Mack, 1977; Campbell, 1980; Stanesco and Campbell, 1989).

Triassic Rocks

Moenkopi Formation (Ꞧm)

The Lower Triassic Moenkopi Formation crops out along the southwest wall of Moab Canyon and Moab Valley northwest of The Portal of the Colorado River and in Kane Springs Canyon. It mostly consists of interbedded siltstone, fine-grained sandstone, and mudstone, in contrast to the coarser-grained, sandy lithologies of the Cutler Formation. The Moenkopi has an overall light- to dark-brown color commonly described as "chocolate" brown (Doelling, 1988).

Outcrops of Moenkopi Formation in the northwest part of the quadrangle are crudely divisible into three parts: a lower steep slope, a middle series of ledges, and an upper steep slope. These divisions may correspond to Shoemaker and Newman's (1959) Tenderfoot, Ali Baba, and Sewemup Members. The Tenderfoot Member in the Moab area (probably the lower slope) is thought to correlate with the Hoskinnini Member, which is the basal member of the Moenkopi throughout southeastern Utah (Shoemaker and Newman, 1959; Stewart and others, 1972b). Within the Moab quadrangle, we did not use these formal member names because the members thin and thicken dramatically near the salt structures, making contact picks and correlations uncertain.

The lower steep slope consists of interbedded medium-"chocolate"-brown, silty sandstone, sandy mudstone, fissile siltstone, and shale. Bedding is distinct, thin, and relatively continuous. Sandstone and siltstone are micaceous and well indurated. Ripple marks are particularly common in the thin-bedded, fine-grained sandstones. Locally, just above the base of the lower steep slope is a conspicuous, poorly sorted, gray conglomerate bed. The conglomerate contains angular gypsum clasts and pebbles of siltstone, limestone, sandstone, chert, granite, and quartz in a sandy matrix. The sedimentary rock clasts may be intraformational and suggest erosion of Moenkopi beds off the crestal portion of the Moab Valley salt diapir. Similar conglomerate beds have been noted adjacent to the Castle Valley salt diapir in the Big Bend quadrangle (Doelling and Ross, 1998; Ross, in preparation). The bed is as much as 4 feet (1.2 m) thick and has a scoured basal surface. Also, poorly sorted, sandy mudstone and silty, micaceous sandstone lenses containing scattered medium to coarse grains of rounded and frosted quartz are commonly found below the conglomerate. The lenses are indistinctly bedded and form a steep, smooth cliff. Scattered coarse quartz grains in a mainly finer grained unit are a distinct characteristic of the Tenderfoot and Hoskinnini Members of the Moenkopi in other areas (Shoemaker and Newman, 1959; Stewart and others, 1972b).

The lithologic descriptions of the middle slope are the same as for the lower steep slope, except for thicker beds. Thin beds in the lower steep slope become progressively thicker upsection and grade into the middle slope. The thicker beds form distinct ledges, which dominate the middle series of ledges and set it apart from the steep slope formers above and below.

The boundary between the middle series of ledges and the upper steep slope is more abrupt. Like in the lower steep slope, bedding in the upper steep slope is thin to fissile, but generally thinner. Also, the upper steep slope is a light "chocolate" brown rather than a medium "chocolate" brown.

The upper contact with the Chinle Formation is an angular unconformity with irregular relief (Ꞧ-3 unconformity of Pipiringos and O'Sullivan, 1978). The "chocolate"- brown, thin-bedded Moenkopi is overlain by either a white quartzose conglomeratic sandstone or mottled-textured, variegated mudstone, siltstone or sandstone of the basal Chinle. Near the railroad-tunnel portal, this angular unconformity cuts down section to the southeast into the Moenkopi, just like the angular unconformity on the underlying Cutler.

Northwest of the railroad-tunnel portal at Emkay, the Moenkopi Formation ranges from 280 to 340 feet (85-104 m) in thickness. Thicknesses of the lower steep slope and middle series of ledges are nearly constant, about 90 and 135 feet (27 and 41 m), respectively. Changes in the formational thickness are due to paleo-erosion at the angular unconformity below the Chinle. Southeast of the railroad-tunnel portal the Moenkopi was deeply eroded below the unconformity, so that in the SW1/4SE1/4NW1/4 section 34, T. 25 S., R. 21 E. the formation is only 70 feet (21 m) thick. South of the Colorado River the Chinle Formation rests directly on the Paradox Formation and outcrops of the Moenkopi Formation are missing.

In Kane Springs Canyon (southwest corner of the quadrangle) Moenkopi exposures consist of strata above the Hoskinnini Member (the basal Moenkopi member in areas to the south), which is well exposed just south of the quadrangle boundary. Outcrops in Kane Springs Canyon are generally similar to the exposures southwest of Moab Canyon; however, they cannot be differentiated into subunits. Ledge-forming beds are irregularly distributed throughout the section, and locally thick, possibly eolian, beds are also present.

The angular unconformity at the top of the Moenkopi Formation cuts down section toward the crest of the Cane Springs (named for Cane Springs which is different than Kane Springs) anticline, located just west of the quadrangle. The Moenkopi strata above the Hoskinnini Member are 235 feet (72 m) thick at the southwest corner of the quadrangle. An additional 150 feet (46 m) of post-Hoskinnini strata are exposed beneath the unconformity east of the crest of the anticline. The Hoskinnini Member is about 115 feet (35 m) thick just south of the quadrangle. Thus, the maximum observable thickness of the entire Moenkopi Formation in Kane Springs Canyon is 500 feet (152 m). The formation is missing over the Moab salt-cored anticline. It may be as much as 750 feet (229 m) thick in places in the subsurface because of thicker deposition in areas of salt withdrawal during deposition.

The Moenkopi Formation is a sequence of redbeds deposited in fluvial, mudflat (tidal?), sabkha, and shallow marine environments (Stewart and others, 1972b; Dubiel, 1994).

Chinle Formation (Ћc)

The Chinle Formation is exposed in the cliff walls bordering both sides of Moab and Spanish Valleys and in the northeast and southwest corners of the quadrangle. In the salt-cored anticline region, the Chinle Formation forms gray-red to red-brown, ledgy slopes covered with rubble below the massive cliffs of the Wingate Sandstone. The formation consists of interbedded fluvial sandstone, mudstone, siltstone, and pebble conglomerate; the mudstone and siltstone form slopes separated by continuous to discontinuous ledges and cliffs of sandstone and conglomerate. Baker (1933), Dane (1935), O'Sullivan (1970), Stewart and others (1972a), O'Sullivan and MacLachlan (1975), Blakey and Gubitosa (1983), and Hazel (1991) divided the Chinle into formal and informal units in the Moab area. They recognized the questionable use of formal member names (used in areas to the south) in the Moab area because lithofacies changes, unconformities, thickness variations and different sediment source areas make correlations between outcrops uncertain. Doelling and Ross (1998) and Hazel (1994) demonstrated that lithofacies and thickness variations in the Moab and Castle Valley areas were controlled by salt tectonism (figure 1). Thicker intervals of sandstone and conglomerate are concentrated in the rim synclines between salt structures rather than across the crestal areas.

Based on stratigraphic relations in the adjacent Big Bend quadrangle, Doelling and Ross (1998) divided the Chinle Formation into informal lower and upper members. The two members are separated by an unconformity that appears to be regional in extent. Both members are present in the Moab quadrangle, but were not differentiated on the map because the lower member outcrops are too thin and discontinuous to map separately.

Basal conglomeratic sandstone of the lower member is quartzose subarkose and sublitharenite composed of quartz, chert, and feldspar. The sandstone is generally poorly sorted and consists of angular to subrounded, medium- to very coarse-grained sand, granules, and pebbles. Locally, the sandstone is moderately sorted and fine to medium grained. Sandstone varies from friable to well indurated. Cement is mainly calcareous, but is locally siliceous. Color is generally gray orange pink to gray pink, but is locally yellow gray, very pale orange, and pale yellow brown. Small-scale trough cross-bedding and cut-and-fill features are common. Locally, lenses of basal conglomerate contain angular, dark-red-brown siltstone and mudstone rip-up clasts scoured from the underlying Moenkopi Formation.

Siltstone and mudstone in the lower member are commonly mottled yellow, purple, orange, red brown, gray, and white. They commonly have an angular blocky to granular appearance. The mottled strata contain more mixed illite-montmorillonite clay and less illite clay than unaltered rocks (Stewart and others, 1972a). These mineralogical differences between the mottled strata and unaltered rocks are indicative of pedogenic alteration. Oxidation and reduction of the sediments during rise and fall of the ground-water table during or shortly after deposition of the sediments may have contributed to the mottled coloration (R.F. Dubiel, U.S. Geological Survey, verbal communication, December, 1993). In the Moab quadrangle at the surface exposures, the lower member of the Chinle is from 0 to 65 feet (0-20 m) thick.

The upper member consists of a lower slope-forming interval, middle ledge-forming interval, upper slope-forming interval, and an upper ledge-forming interval. It is important to note that each of these intervals is locally variable in lithology, color, and thickness.

The lower slope-forming interval consists of red-brown, gray-red, and green gray, interbedded siltstone, mudstone, and sandstone that weathers as a steep slope. Thin, discontinuous ledges of sandstone and conglomeratic sandstone are locally present. Bedding in the slopes is characteristically indistinct. Siltstone and mudstone are commonly micaceous and are fissile to blocky weathering. Quartzose sandstones are fine to medium grained with ripple laminations and small-scale cross beds. Conglomeratic sandstone is intraclastic, calcareous, and typically forms lenses with scoured bases.

The thickness of the lower slope-forming interval varies considerably, is dependent on its position in relation to salt-cored anticlines, and may locally be missing over them. In measured sections, it varies from 0 to 234 feet (0-71 m) thick. It is 28 to 234 feet (9-71 m) thick on the southwest side of Moab Valley north of The Portal, about 125 feet (38 m) thick near Jackass Canyon in the northeast corner of the quadrangle, and 176 feet (54 m) thick in Kane Springs Canyon to the southwest. The contact with the middle ledge-forming interval is commonly gradational and partly accounts for the variation in the thickness of the lower slope-forming interval.

The middle ledge-forming interval strata are brown-gray, green-gray, and red brown conglomeratic sandstone and sandstone interbedded with red-brown siltstone and mudstone. These strata form thick to massive ledges separated by narrow, steep slopes. The interval is a series of fluvial-channel sequences that commonly consist of a basal intraclastic conglomeratic sandstone that grades upward through cross-bedded sandstone, siltstone, and mudstone. Pebble conglomerate forms lenses above scour surfaces, and contains abundant petrified wood and vertebrate fossil fragments. Fine- to medium-grained sandstone is calcareous and quartzose. Siltstones vary from horizontally laminated and ripple laminated to structureless. Mudstone is calcareous. The uppermost massive conglomeratic sandstone ledge is coated with dark-brown desert varnish and is informally referred to as the Black Ledge (Stewart and others, 1972a). The middle ledge-forming unit includes the Black Ledge and the underlying upper part of the Kane Springs strata of Blakey and Gubitosa (1983) and Hazel (1991).

The measured thickness of the middle ledge-forming unit ranges from 50 to 155 feet (15-47 m); the thicker sections are generally found where the lower slope-forming unit is thin. At Jackass Canyon the middle ledge-forming unit is 55 feet (17 m) thick, southwest of the Moab salt-cored anticline and north of The Portal it is 85 to 153 feet (26-47 m) thick, and at Kane Springs Canyon it is 55 to 89 feet (17-27 m) thick.

The upper slope-forming unit consists of alternating and indistinctly bedded, red-brown to gray-red siltstone, mudstone, and sandstone similar to the lower slope-forming unit. Fine- to medium-grained sandstone and conglomeratic sandstone form thin- to medium-bedded ledges that disrupt the slope. Calcareous sandstone is fine to medium grained and includes sparse lenses of coarse grains. This sandstone is predominantly sublitharenite, consisting of quartz, chert, carbonate rock fragments, and minor mica. Grains are subangular to subrounded and moderately to well sorted. Primary sedimentary features include horizontal bedding, small-scale trough cross bedding, and asymmetrical ripple laminations. Siltstone is muddy, calcareous, indistinctly bedded, and laminated to structureless. Lithic pebble conglomeratic sandstones contain gray-red to light-gray calcareous siltstone and mudstone fragments, dull-gray carbonate clasts, pale-red-brown chert, and minor quartz. Grains are angular to rounded and range in size from coarse sand to pebbles. Grain sorting is generally poor. Cementation is calcareous and hematitic. The lithic pebble conglomerate is believed to be intraformational because siltstone and mudstone clasts resemble lithologies in the Chinle Formation and carbonate clasts may have been derived from pedogenic carbonate layers or nodules. The lithic pebble conglomerates are reworked floodplain and lacustrine deposits (Blakey and Gubitosa, 1983).

The measured thickness of the upper slope-forming unit ranges from 95 to 210 feet (29-64 m). In Jackass Canyon it is 138 feet (42 m) thick and in Kane Springs Canyon it is 113 feet (34 m) thick. North of The Portal on the southwest side of the Moab salt-cored anticline the upper slope-forming unit thickens southeasterly from 115 to 207 feet (35-63 m).

The upper ledge-forming unit consists of thick-bedded to massive, light-brown to red-orange, very fine- to fine-grained sandstone. The sandstone is horizontally laminated and faint cross-bedding is locally present. Sandstone ledges are interbedded with pale-red to red-brown siltstone and mudstone. The mudstone commonly has mudcracks. The sandstone originated as eolian sand sheets deposited prior to the development of the Wingate desert (Blakey and Gubitosa, 1983; Dubiel and others, 1989).

The upper ledge-forming unit is present at most locations in the Moab quadrangle, but is locally missing due to nondeposition or erosion. The maximum observed thickness is 45 feet (14 m). It thickens eastward in Kane Springs Canyon from 25 to 41 feet (8-13 m), is 9 feet (3 m) thick at Jackass Canyon, and is 40 to 45 feet (12-14 m) thick where observed along the southwest flank of the Moab Valley salt-cored anticline north of The Portal.

The upper Chinle contact is placed at the top of a dark-red-brown, platy to very thin-bedded, recess-forming siltstone, overlain by orange-brown, thick, planar bedded, massive beds of the Wingate that contain pull-apart structures, clay galls, and pebbles. The contact is an unconformity that regionally truncates older strata (J-0 unconformity of Pipiringos and O'Sullivan, 1978).

Exposed thicknesses of the Chinle Formation range from 100 to 640 feet (30-195 m). The Chinle may be thicker in the subsurface adjacent to Moab and Spanish Valleys; thicknesses are expected to range from 100 to 700 feet (30-213 m) in the Moab quadrangle. The Chinle is about 640 feet (195 m) thick in the Burkholder No. 1-G-1 well and is as much as 800 feet (244 m) thick 6 miles (9.7 km) up the Colorado River in the Big Bend quadrangle (Doelling and Ross, 1998). At Kane Springs Canyon the Chinle thickens eastward from 288 to 419 feet (88-128 m). At Jackass Canyon the Chinle is more than 317 feet (97+ m) thick. At the northwest corner of the quadrangle, opposite the Arches National Park visitor center, the Chinle is 341 feet (104 m) thick and at The Portal it is 639 feet (195 m) thick.

The Chinle Formation in the salt-cored anticline region was deposited primarily in alluvial-channel and floodplain environments; eolian environments developed towards the end of deposition (Dubiel, 1994).

Jurassic Rocks

Jurassic strata in the Moab quadrangle include, in ascending order, the Wingate Sandstone, Kayenta Formation, Navajo Sandstone, Carmel Formation, Entrada Sandstone, Curtis Formation, and Morrison Formation. The lower three formations are assigned to the Glen Canyon Group (Gregory and Moore, 1931) and are shown as partly Triassic in age on some previous geologic maps (Williams, 1964; Doelling, 1985). We follow the work of Pipiringos and O'Sullivan (1978), Peterson and Pipiringos (1979), and Imlay (1980), and consider the Glen Canyon Group to be entirely Early Jurassic in age (figure 3).

Wingate Sandstone (Jw)

The Wingate Sandstone generally forms a prominent gray-pink to red-brown smooth cliff along the walls of Moab Valley, Spanish Valley, the canyons of the Colorado River, and some of its tributaries in the quadrangle. In places, the cliffs are streaked and stained dark brown or black by desert varnish, or are horizontally banded. Where it is highly fractured, the Wingate forms rocky cliffs along the margins of Moab and Spanish Valleys.

The Wingate Sandstone is a relatively homogenous unit that consists of gray orange to gray-orange-pink and moderate-orange-pink to pale-red-brown, very fine- to fine-grained sandstone. Sandstone is quartzose subarkose, containing quartz, feldspar, and traces of chert and accessory minerals (Lohman, 1965; Cater, 1970). Sand grains are moderately to well sorted, subangular to rounded, and commonly frosted, suggesting eolian transportation. Sandstone is moderately to well indurated with calcareous and siliceous cement, and is commonly stained with iron oxide.

Bedding is thin to massive, but the Wingate weathers to thick, massive ledges and cliffs. Primary sedimentary features include horizontal stratification; planar tabular, wedge-planar, and trough cross-bedding; and local asymmetrical ripple laminations. Cross-bed sets range from small to large scale.

The contact with the overlying Kayenta Formation is an irregular, sharp surface that locally is erosional with scouring and cut-and-fill features. Along Hunter Canyon, relief along the contact varies from 3 to 18 feet (1-6 m) and fluvial sandstone lenses fill scours in the massive eolian sandstone beds. A cap of somewhat lighter sandstone, as much as 10 feet (3 m) thick, is locally found at the top of the Wingate. Nation (1990) and Blakey (1994) interpreted the contact as being unconformable and Baker and others (1936) interpreted the contact as being conformable. A hiatus of limited extent seems reasonable considering the aforementioned scouring and sandstone cap. At outcrops, Kayenta beds are more reddish or pale purplish, lithologically more heterogenous, and contain fluvial sedimentary features. The Wingate-Kayenta contact is locally difficult to identify because the basal beds of the Kayenta are thick bedded to massive and are nearly the same color as the underlying Wingate. In these places we placed the contact where the vertical cliff ends and is replaced by thick ledges.

The Wingate Sandstone is 250 to 400 feet (76-122 m) thick in the area around Arches National Park (Doelling, 1981). In the Moab quadrangle, a similar variation in thickness is related to movement of the salt into the Moab Valley salt diapir and Cane Creek anticline. Measurements of the Wingate along the northeast side of Moab Valley indicate thinning over the salt diapir. The Wingate Sandstone is 286 feet (87 m) thick in the SE1/4 section 26, T. 25 S., R. 21 E., and 250 feet (76 m) thick on the west side of Courthouse Wash in the SW1/4SE1/4 section 22, T. 25 S., R. 21 E. Both measurements were in highly fractured sections. We estimate the Wingate may be as much as 400 feet (122 m) thick in the axis of the Kings Bottom syncline due to syndepositional salt flowage out of the rim syncline. The Wingate is 315 feet (96 m) thick at the confluence of Kane Springs Canyon and Hunter Canyon (Nation, 1990) and 300 feet (91 m) thick at Jackass Canyon.

The Wingate Sandstone in the salt-cored anticline region consists of eolian dune and interdune sediments deposited in desert environments that covered this part of the Colorado Plateau in the Early Jurassic (Blakey and others, 1988; Nation, 1990; Blakey, 1994).

Kayenta Formation (Jk)

The Kayenta Formation forms irregular, step-like, ledgy cliffs overlying the massive cliffs of the Wingate Sandstone. Much of the formation is resistant to erosion and forms bare-rock surfaces. Soft siltstone and sandstone are present in the upper third of the unit where a prominent bench commonly appears.

The Kayenta Formation consists mainly of broad lenses of fluvial sandstone and siltstone interbedded with lesser amounts of fluvial conglomerate, eolian sandstone, and lacustrine calcareous mudstone. The overall color of the Kayenta is generally dark brownish red, but the color of individual lenses and beds varies considerably; some are purple, lavender, red, brown, tan, orange, white, or gray. Most of the sandstone lenses are moderately orange pink or red purple and the muddy siltstones are dark red brown to gray red.

Sandstones in the Kayenta are very fine to medium grained and moderate to well sorted. Sand is subangular to subrounded quartz, chert, feldspar, mica, and opaque minerals. The majority of the Kayenta sandstone is classified as lithic arkose to feldspathic litharenite (Luttrell, 1987). The moderately to well-indurated sandstone is primarily calcareous, but silica, iron oxide, and clay are also cementing agents. Bedding ranges from thinly laminated to thick bedded. Sandstone beds are lenticular and tabular, commonly with scoured basal surfaces. Locally lenses display cut-and-fill features, current ripple marks, and rare slump features. Small-scale cross-beds, horizontal laminae, and low-angle cross laminae are common. Overturned cross-beds are common in structurally deformed fluvial sandstones of the Kayenta along the flanks of Moab Valley.

Finely laminated and locally ripple-laminated, very fine-grained sandstone and siltstone are interbedded with calcareous mudstone. The calcareous mudstone is thinly laminated to structureless and is locally cherty and sandy. The mudstone commonly forms beds 1 to 10 feet (0.3-3 m) thick.

Lenses of conglomeratic sandstone and conglomerate are commonly present at the base of sandstone beds. The conglomerate and conglomeratic sandstone are poorly sorted with angular to subrounded granules and pebbles of equant to bladed, reddish-brown to grayish-red purple siltstone and mudstone. Clast lithology, color, and shape (flat-pebble) suggest they are intraformational. Beds are 1 to 5 feet (0.3 1.5 m) thick.

Near the top of the Kayenta is a conspicuous, smooth-weathering, pink-orange cliff of eolian sandstone ("e" on figure 3). The sandstone consists of well-sorted quartzose sandstone having large-scale cross-beds with high-angle (30-35°) foresets. The eolianite resembles the overlying Navajo Sandstone. Between the thick eolianite and the base of the Navajo, the Kayenta consists of interbedded fluvial sandstones and thinner eolianites. These eolian sandstones are thought to intertongue laterally into the Navajo Sandstone (Blakey, 1994). Theropod dinosaur tracks are locally present in the stratigraphic interval between the thick eolianite and the lower beds of the Navajo Sandstone.

The contact between the Kayenta and the overlying Navajo is placed at the top of a gray-pink, thick-bedded to massive ledge that commonly is lighter colored than the beds above and below it. The upper surface of the ledge is sharp and nearly horizontal. The ledge is 10 to 20 feet (3-6 m)

Figure 3. The Early Jurassic Glen Canyon Group as exposed at The Portal of the Colorado River. The Wingate Sandstone (Jw) is a massive-weathering formation about 300 feet (91 m) thick at this location. The Kayenta Formation (Jk) is the ledgy unit in the middle and the Navajo Sandstone (Jn) forms the top of the section. "e" indicates an eolian marker sandstone in the Kayenta Formation; "b" indicates flat-bedded basal beds of the Navajo Sandstone.

thick, and is preferentially cemented, ranging from friable to well indurated. The variable cement and color give the ledge a unique "rotted" or "sculptured" weathered appearance. The ledge contains a mixture of various lithologies and depositional facies more characteristic of the Kayenta than the overlying Navajo.

The Kayenta Formation is 250 to 400 feet (76-122 m) thick in the Moab quadrangle. It is 293 feet (89 m) thick just west of Courthouse Wash in the SW1/4SE1/4 section 22, T. 25 S., R. 21 E.; 331 feet (101 m) thick between Negro Bill and Jackass Canyons along the Colorado River in the NW1/4SE1/4 section 19, T. 25 S., R. 22 E.; and 306 feet (93 m) thick immediately west of The Portal. We estimate that the Kayenta may be as much as 400 feet (122 m) thick in the axis of the Kings Bottom syncline, due to salt flowage, and thins to approximately 250 feet (76 m) across the crest of the Moab Valley salt-cored anticline.

Most of the Kayenta Formation in the salt-cored anticline region was deposited in sandy fluvial systems with sources in the ancestral Rocky Mountains of eastern Utah and western Colorado (Luttrell, 1987). Eolian environments near the top of the formation indicate a gradual change in climate and depositional environments (Blakey, 1994).

Navajo Sandstone (Jn, Jnl)

The light-gray, pale-orange, and red-orange Navajo Sandstone is exposed on most of the benches of the quadrangle. The lower part of the Navajo consists of interbedded sets of flat- and cross-bedded sandstone ("b" on figure 3). The upper part of the Navajo consists of massive beds of large-scale cross-bedded sandstone that weather to rounded cliffs and domes.

The Navajo Sandstone consists of fine-grained quartz sand that is well sorted, subrounded to very well rounded, and frosted. Thin laminae of medium- to coarse-grained sand are common along the foresets of cross-beds. The Navajo is friable to moderately indurated and cementation is commonly calcareous and locally siliceous. The Navajo Sandstone is characterized by large, sweeping, tangential cross-beds with foresets that may dip more than 30 degrees. The sweeping cross-beds are preserved in massive sets 15 to 25 feet (5-8 m) thick.

Sparse, thin beds of gray to pink-gray, silty to sandy, micritic limestone (Jnl) are locally interbedded with the sandstone. Limestone horizons rarely exceed 4 feet (1.2 m) in thickness. Limestone beds commonly contain small nodules of authigenic jasper (red chert). They grade laterally into red sandstone or siltstone beds that form bounding surfaces between cross-bed sets. The cherty limestones commonly form a resistant bench covered with a dark sandy or rubbly soil (Qer).

The upper contact of the Navajo is a regional unconformity (J-2 unconformity of Pipiringos and O'Sullivan, 1978) that truncates Lower Jurassic strata, cutting deeper from west to east across the Colorado Plateau. Middle Jurassic strata of the San Rafael Group overlie the unconformity on the Colorado Plateau (Peterson and Pipiringos, 1979; Peterson, 1988).

The thickness of the Navajo Sandstone is 300 to 700 feet (91-213 m) in the Moab quadrangle. It is estimated to be at least 700 feet (213 m) thick along the axis of the Kings Bottom syncline at Poison Spider Mesa. The Navajo is approximately 400 feet (122 m) thick across the crest of the Moab Valley salt-cored anticline in sections 22 and 27, T. 25 S., R. 22 E., and varies from 165 to 450 feet (50-137 m) thick in the vicinity of Arches National Park (Doelling, 1988; Doelling and Morgan, 2000). Local areas of thickening and thinning of the Navajo adjacent to and over the salt-cored anticlines may be due to flowage of the salt during the latest Early Jurassic.

The main part of the Navajo Sandstone was deposited in an eolian environment (Peterson and Pipiringos, 1979; Blakey and others, 1988; Blakey, 1994) characterized by dune (cross-bedded sandstones) and interdune (cherty, sandy limestones and horizontally bedded sandstones) deposits. The basal flat beds were deposited primarily as eolian sand reworked in a sabkha environment (Sansom, 1992).

Reclassification of Middle Jurassic Carmel, Entrada, and Curtis Formations

The Middle Jurassic below the Summerville Formation in the Moab area consists of three units, the Dewey Bridge, Slick Rock, and Moab, that have generally been assigned as members of the Entrada Sandstone (for example: Wright and others, 1962; Doelling, 1985; Peterson, 1988; Doelling and Ross, 1998). Dewey Bridge strata were originally classified as part of the Carmel Formation (Dane, 1935; McKnight, 1940), until Wright and others (1962) reassigned them to the Entrada Sandstone based on lithologic criteria. However, over the past several years, continued work in the area has made it apparent to the lead author and other workers that the Dewey Bridge Member is an eastern extension of the Carmel Formation (O'Sullivan, 2000), and that the Moab Member is an eastern extension of the Curtis Formation as generally mapped in the San Rafael Swell and Green River area (Doelling, 2001). O'Sullivan (2000) recently formally reassigned the Dewey Bridge Member back to the Carmel Formation. For this map, the Moab Member is considered an informal member of the Curtis Formation pending formal reclassification. The full combined thickness of the three units at exposures measured northeast of the Arches National Park visitor center is about 425 feet (130 m).

Dewey Bridge Member of the Carmel Formation (Jcd): (newly assigned to the Carmel Formation [O'Sullivan, 2000]); assigned as a member of the Entrada Sandstone on the preliminary version of this map [Doelling and others, 1995]). The Dewey Bridge Member is red-brown, muddy to silty, mostly fine- to medium-grained sandstone with irregular, contorted to "lumpy" bedding. It weathers to distinct irregular and contorted rounded ledges. The unit is medium to thick bedded and cemented with iron oxide or calcite. Regionally, the Dewey Bridge Member can be divided into lower and upper parts (not mapped on the Moab quadrangle). The lower part of the member is dominated by yellow-gray, planar-bedded, mostly fine-grained sandstone. Angular, white and gray chert fragments are commonly embedded in the sandstone immediately above the lower contact. The upper part of the member is mostly a red-brown, muddy, fine- to medium-grained sandstone, with the irregular, contorted to "lumpy" bedding. The member is 104 feet (32 m) thick in the cliff along the Arches National Park roadway above the park visitors center. The upper part is 84 feet (26 m) thick and the lower part is 20 feet (6 m) thick. The thickness in the quadrangle probably ranges from 90 to 110 feet (27-34 m). An incomplete, unmeasured exposure of the Dewey Bridge Member is also present along the axial trace of the Kings Bottom syncline on Poison Spider Mesa. The upper contact with the Slick Rock Member is irregular and probably conformable.

Slick Rock Member of the Entrada Sandstone (Jes): The Slick Rock Member crops out in the northwest corner of the quadrangle, mostly across the Moab anticline in Arches National Park. The member forms a smooth, banded sandstone cliff in the middle of the Entrada section. Highly fractured outcrops of Slick Rock are also present southwest of U.S. 191 along the Moab fault. The Slick Rock Member is estimated to be at least 250 feet (76 m) thick in the quadrangle. The contact with the overlying Moab Member is sharp and is placed along a bedding parting that is overlain by slightly coarser grained and lighter colored sandstone. The upper contact of the Slick Rock is thought to be the J-3 unconformity of Pipiringos and O'Sullivan (1978).

The Slick Rock Member is composed of thick-bedded, red-orange to brown, eolian sandstone. The sandstone is very fine to fine grained with sparse medium to coarse sand grains generally aligned along cross-bed laminae; it displays distinct high-angle cross-stratification and planar bedding. The sandstone is well indurated with calcareous and iron-oxide cement, but the normally smooth-weathering sandstone weathers to rubbly slopes where fracture density increases near the Moab fault zone.

Moab Member of the Curtis Formation(Jctm): (tentative assignment pending formalization; assigned as a member of the Entrada Sandstone on the preliminary version of this map [Doelling and others, 1995]). The Moab Member correlates with the Curtis Formation of western Grand County (Doelling, 2001). It is conspicuous, resistant eolian sandstone that forms the capping surface of Slick Rock Member of the Entrada Formation outcrops in the northwest corner of the quadrangle. The Moab Member ranges from 60 to 100 feet (18-30 m) thick. The upper contact is sharp and drawn where the light sandstone of the Moab Member is overlain by the red siltstone of the combined Summerville Formation and Tidwell Member of the Morrison Formation. The base of the Summerville/Tidwell unit commonly consists of a few inches to a foot (5-30 cm) of reworked Moab Member sandstone.

The Moab Member is a pale-orange, gray-orange, pale-yellow-brown, or light-gray, fine- to medium-grained, calcareous, massive, cliff-forming, quartzose sandstone. The sandstone is typically well indurated, exhibits low-angle cross stratification, and is typically highly jointed in outcrop. It resembles the Navajo Sandstone in color, cementation, and weathering characteristics. Navajo and Moab Member cross-bed laminae etch out similarly.

Morrison and Summerville? Formations

The Upper Jurassic Morrison Formation consists of three members in the Moab area: the Tidwell, Salt Wash, and Brushy Basin. The Tidwell and basal part of the Salt Wash Members are only exposed in the northwest corner of the Moab quadrangle; the Brushy Basin Member is not exposed in the quadrangle. Morrison Formation exposures are preserved along the down-dropped margins of small-displacement faults. The Tidwell Member, as mapped, includes a thin bed that may be Middle Jurassic Summerville Formation at its base.

Tidwell Member and Summerville? Formation (Jmt): This thin red member is an excellent marker unit. In the Moab quadrangle the mapped unit is 40 to 50 feet (12-15 m) thick. This unit was formerly mapped as the Summerville? Formation (Dane, 1935; McKnight, 1940; Williams, 1964), but only the lower 6 to 12 feet (2-4 m) correlate with that formation in the San Rafael Swell. After discussion with R.B. O'Sullivan, USGS (2001, personal communication), the senior author is now considering that these 6 to 12 feet (2-4 m) of strata may more accurately be an upper horizon of the Curtis rather than a remnant of the Summerville? Formation. Most of the unit correlates with gypsiferous and silty beds at the base of the Salt Wash in western Grand County (Doelling, 2001). The contact between these two parts may be the J-5 unconformity of Pipiringos and O'Sullivan (1978). The upper contact appears conformable with the overlying Salt Wash Member.

The lower part of the mapped unit (Summerville? Formation) consists of brown to red, thin-bedded, fine-grained sandstone and siltstone that forms a steep 6- to 12 foot (2-4 m) high slope in the quadrangle. The uppermost foot (30 cm) is resistant and exhibits ripple-marked, platy-weathering sandstone.

The remainder and dominant part of the unit consists of thin-bedded, red to brown, silty sandstone, muddy sandstone, sandy siltstone, shale, and thin to nodular beds of gray limestone. The lowermost limestone bed generally contains very large, white siliceous concretions that have diameters of several feet. The limestone-bearing, dominant part of the unit is less resistant than the lower 6 to 12 feet (1.8-3.6 m) and forms a more gentle slope commonly littered with limestone nodules and broken pieces of the white concretions.

Salt Wash Member (Jms): Only a remnant of the Salt Wash Member of the Morrison Formation remains in the Moab quadrangle. In adjacent areas the member consists of blocky ledges of pale-yellow-gray, cross-bedded sandstone and conglomeratic sandstone interbedded with green and red slope-forming mudstone and siltstone. The sandstone is generally poorly sorted and fine to coarse grained. The maximum exposed thickness in the Moab quadrangle is no more than 30 feet (9 m).

Quaternary Deposits

Quaternary deposits in the Moab quadrangle are grouped into alluvial, eolian, mass-movement, colluvial, mixed depositional environment, and human-made. The Moab quadrangle, as well as the Colorado Plateau in general, is an area primarily undergoing erosion. Therefore, most Quaternary deposits are relatively thin. However, the mouth of Moab Canyon, Moab Valley, and Spanish Valley are areas of subsidence caused by removal of salt from the underlying Moab Valley salt-cored anticline in which surficial sediments have accumulated to greater thickness. Quaternary deposits in Moab Valley near the Colorado River may exceed 450 feet (137 m) in thickness.

Alluvial Deposits

Modern alluvium (Qa_1): Stream deposits along larger, active drainages and their floodplains have been mapped as modern alluvium (Qa_1). Along the Colorado River the unit occurs as channel-fill and low terrace deposits of sand, silt, and clay, with local lenses of gravel. Bars in the river channel consist of well-sorted, fine- to medium-grained sand interbedded with pebble and cobble gravel. These gravels are composed of locally derived rocks and exotic clasts from outside the immediate area. Exotic clasts are various Tertiary igneous rocks, Paleozoic and Mesozoic sedimentary rocks, and Precambrian igneous and high-grade metamorphic rocks.

Deposits along Mill Creek, Pack Creek, and Kane Springs Creek consist mainly of silty sand with abundant pebble and cobble gravel in active channels. The deposits occur as low terraces, bars, levees, and overbank fills. Clasts consist of locally derived sedimentary rocks and intrusive igneous rocks from the La Sal Mountains. Modern alluvium is Holocene in age and is as much as 20 feet (6 m) thick.

Older Alluvium (Qa_2): Alluvium forming the first surface above the modern floodplain of the larger, active drainages is mapped as older alluvium (Qa_2). The unit forms surfaces approximately 10 to 50 feet (3-15 m) above active channels. In Moab Valley, Qa_2 deposits are part of a thick section of basin-fill alluvium (Qabf, cross section only). Deposits of Qa_2 grade upslope into younger alluvial-fan deposits (Qafy) along the valley margins. The ephemeral stream deposits (modern alluvium) of Moab Wash in Moab Canyon are too small to map separately and are included in the Qa_2 deposits. In Moab Valley and Mill Creek, gravel clasts are dominated by trachyte porphyry from the La Sal Mountains, with lesser amounts of locally derived sandstones from the Chinle Formation and Glen Canyon Group. Along the Colorado River, Qa_2 deposits contain primarily exotic igneous and metamorphic rocks from up-river source areas, trachyte porphyry from the La Sal Mountains, and Glen Canyon Group sandstones.

Qa_2 alluvium consists of sand, silt, clay, and local gravel, similar to modern alluvium (Qa_1). Qa_1 and Qa_2 deposits contain larger percentages of fine-grained materials than older alluvium (Harden and others, 1985). Weak soil development at the surface and buried soil horizons are characteristic of Qa_2 alluvium (Harden and others, 1985). Qa_2 deposits are as much as 30 feet (9 m) thick. Qa_2 alluvium is late Pleistocene to early Holocene in age.

Alluvial-terrace deposits (Qat_3, Qat_4, Qat_5, Qat_6): Older alluvium is preserved on isolated terraces along the Colorado River, Mill Creek, Pack Creek, Kane Springs Creek, and Courthouse Wash. The deposits typically consist of moderately sorted, subrounded to rounded, crudely stratified, calcareous, sandy cobble gravel. The description of the terrace alluvium is nearly the same as the alluvium in the modern deposits (Qa_1); however, fine-grained materials are commonly removed from deposit surfaces by wind or sheet wash, making the coarse constituents appear prominent. Materials contained in the terrace deposits are indicative of the source areas. Streams that head in the La Sal Mountains are dominated by clasts of porphyritic intrusive rock, but sandstone clasts of the Glen Canyon Group are also common. Terrace deposits along the Colorado River contain both locally derived and exotic clasts similar to modern alluvium (Qa_1). Terrace deposits along Courthouse Wash, which erodes much sandstone bedrock, consist mainly of sand.

Alluvial terrace deposits are subdivided based on relative ages; height above present channel level and stage of soil development were used to determine relative age. Qat_3 deposits are found 50 to 100 feet (15-30 m) above the present stream channel. Calcic soil horizons developed on Qat_3 deposits range from coatings on gravel clasts and a uniform white appearance of the matrix (Stage II) to a cemented and plugged horizon (Stage III). Thick, zoned carbonate rinds on the bottoms of some clasts and the locally variable development of calcic soil horizons at individual locations suggest that the soil carbonate has undergone dissolution and reprecipitation.

Qat_4 deposits are 100 to 150 feet (30-46 m) above present stream channels. No soil profiles were found on these deposits in the quadrangle; however, similar deposits in the adjacent Spanish Valley area display a continuous, plugged calcic soil horizon (Stage III) (Harden and others, 1985).

Qat_5 and Qat_6 deposits are 200 to 240 feet (61-73 m) and 260 to 280 feet (79-85 m), respectively, above the modern stream channels, and, where preserved, have stage III+ to IV soil development. Larger clasts in these deposits are distinguishable from those of lower terraces by a well-developed rind of desert varnish.

Alluvial terrace deposits are commonly less than 30 feet (9 m) thick. Exposures of Qat_3 deposits at the mouth of Mill Creek Canyon are 60 feet (18 m) thick, but their bases are not exposed. Qat_3 deposits are interpreted to be equivalent to Bull Lake deposits (late, middle Pleistocene age) in the Rocky Mountain region (plate 2). Older alluvial terrace deposits (Qat_{4-6}) are middle Pleistocene in age.

Basin-fill deposits (Qabf): Shown only in the subsurface on cross section B-B′, these deposits fill Moab Valley beneath a cover of late Pleistocene to Holocene surficial deposits. Meager drill-hole information indicates the deposits are gravelly and dominated by alluvium. They also contain sand, silt, and minor clay. The deposits contain river and stream alluvium, fan alluvium, and possibly some eolian interbeds. The Great Lakes Carbon Corporation No. 1 well, SW1/4NE1/4 section 34, T. 25 S., R. 21 E., penetrated more than 300 feet (91+ m) of basin-fill deposits in Moab Valley. Another drill hole, near the tailings pond in section 27, T. 25 S., R. 21 E., penetrated 406 feet (124 m) of basin-fill deposits. The deposits may be more than 450 feet (137 m) thick and are Pleistocene in age.

Younger alluvial-fan deposits (Qafy): Younger alluvial-fan deposits (Qafy) form gentle to moderate, apron-like slopes along the northeast and southwest sides of Moab Valley. The surfaces of the younger alluvial fans have dendritic drainage patterns and the deposits grade and interfinger upslope into talus (Qmt) or head in gullies in older fan deposits (Qafo). Younger fans grade downslope into alluvium (Qa_2 and presumably Qabf in subsurface) filling the valley. At the distal margins of the fans, fan detritus mixes with alluvium brought into the valley by Mill Creek and Pack Creek. The contact between Qafy and Qa_2 is arbitrarily placed at the change in orientation of contours in the valley.

Younger alluvial-fan deposits commonly consist of poorly sorted, poorly stratified muddy to sandy cobble gravel. Boulders are common in proximal areas of the fans. Gravel beds are both clast-supported and matrix-supported. In the distal parts of the fans locally derived subangular clasts are mixed with rounded igneous porphyry clasts.

Younger alluvial fans are commonly active and age-correlative with Qa_1 and Qa_2 deposits (late Pleistocene to Holocene). Locally, Qafy surfaces are inactive. Pedogenic carbonate in these deposits consists of thin coatings on the base of clasts and sparse carbonate nodules in fine-grained material (Stage I). Deposits are up to 20 feet (6 m).

Older alluvial-fan deposits (Qafo): Older alluvial-fan deposits (Qafo) underlie a gently sloping bench that extends northeastward from the southwest side of Moab and Spanish Valleys and separates the two valleys. Older alluvial-fan deposits are dissected by younger drainages and have limited fan morphology. The older fan deposits rest on deformed bedrock units in the valley and the deposits are commonly mantled by a layer of unstratified, windblown sand (Qes).

Older alluvial-fan deposits commonly consist of poorly sorted, poorly stratified, muddy to sandy cobble gravel. Boulders are common in proximal areas. Locally derived, angular to subangular gravels are mixed with rounded gravels of intrusive porphyry from the La Sal Mountains in the distal parts of the deposits.

No pedogenic carbonate soils were noted in ravine exposures of the Qafo deposits. However, locally the surface of the older fan deposits is littered with angular chips and fragments of pedogenic carbonate, suggestive of a soil horizon. Harden and others (1985) determined that older fan deposits grade to the position of Qat_3 surfaces in Moab and Spanish Valleys and concluded that the Qat_3 deposits and equivalent Qafo deposits are correlative to Bull Lake-age deposits (late middle Pleistocene) in the Rocky Mountain region. We show the Qafo deposits as middle to late Pleistocene (plate 2). Older fan deposits are up to 40 feet (12 m) thick.

Mass-Movement Deposits

Talus (Qmt): Talus (Qmt) consists of gravity-induced rockfall blocks mixed with slopewash material. Talus forms cones and sheets on the steep slopes below most cliffs in the quadrangle. The deposits are commonly gradational and interfinger with alluvial-fan deposits (Qafy) at their downslope extent. The generally gradational contact between talus and alluvial-fan deposits is placed at the break from steep to moderate slopes, which roughly coincides with a decrease in clast size and angularity, and an increase in sorting.

Talus contains poorly sorted, angular boulders, cobbles, and smaller rock fragments in a matrix of sand, silt, and clay. Locally, talus deposits may display weak discontinuous bedding parallel to slope, but most are structureless (Richmond, 1962). Individual block size ranges to as much as 15 feet (4.6 m) in diameter. Locally, talus deposits have been modified by erosion, sheetwash, and rock creep. Deposits range from a thin veneer to 20 feet (6 m) thick, and their surfaces vary from relatively smooth to scoured by shallow gullies. Talus deposits are probably late Pleistocene to latest Holocene in age.

Landslide deposit (Qms): A single landslide deposit (Qms) has been mapped in the Moab quadrangle, but several faulted blocks of Chinle Formation and Wingate Sandstone along the Moab Rim may have a landslide component to their deformation. Near the west edge of the map, on the north side of U.S. Highway 191, a mass of Moab Member of the Curtis Formation has slid approximately 300 feet (91 m) south on a shale parting at its contact with the underlying Slick Rock Member. The landslide is a translational slide whose scarp was possibly controlled by northwest-striking joints in the Moab Member.

The age of movement of the landslide must postdate incision of Moab Canyon to near its current level of erosion, because the landslide moved across and covered both branches of the Moab fault and slid into the Moab Canyon drainage. Later erosion cut the toe of the slide away and exposed bedrock below it on the north wall of the drainage. The slide is probably late or latest middle Pleistocene in age and up to about 60 feet (20 m) thick.

Colluvium (Qc)

Colluvium consists of poorly sorted slopewash detritus that is derived from, and forms an apron on, the slopes beneath alluvial-terrace deposits. Colluvium consists of rounded to subangular gravel, sand, and silt of the same lithologic composition as the source deposit. Colluvium is generally less than 6 feet (2 m) thick and deposits are mostly Holocene in age.

Eolian Deposits

Eolian sand deposits (Qes): Well-sorted, nonstratified to cross-bedded sand deposits cover surfaces and fill hollows across the quadrangle. The sand is derived from Lower and Middle Jurassic sandstone formations. Qes deposits typically form relatively thin and discontinuous sheets and small dunes. Dune deposits may be larger and thicker on the lee-side slopes of cliffs. Some especially prominent sand deposits are present at the base of the canyon wall southwest of the Arches National Park visitor center in the northwest part of the quadrangle.

Eolian sand deposits are generally light red orange to light red brown and consist of fine- to medium-grained quartzose sand and silt. Deposits are generally less than 6 feet (2 m) thick, but a maximum thickness of 30 feet (9 m) was observed. Eolian sand deposits are Holocene in age.

Mixed-Depositional-Environment Deposits

Younger eolian and alluvial deposits (Qeay): Many of the canyons and ephemeral washes carved in the mesas of the Glen Canyon Group sandstones contain small deposits of unconsolidated sand of mixed eolian and alluvial origin (Qeay). Larger deposits of this type are mapped in Hidden Valley and canyons near Pritchett Natural Bridge. The deposits form irregular thin blankets with scattered surface rills and gullies.

The deposits mainly consist of fine- to medium-grained sand mixed with silt and sparse lenses of granules and pebbles. Deposits are better packed and grain size is more heterogeneous in drainages. Deposits in interfluve areas consist of loose sand with wind-ripple laminations and small dunes. The deposits accumulate and are reworked by wind, sheetwash, and ephemeral runoff. The transitory character of the deposits and lack of soil development suggest they are Holocene in age. Deposits are as much as 10 feet (3 m) thick.

Older eolian and alluvial deposits (Qeao): The overall character of older eolian and alluvial deposits (Qeao) is similar to the younger Qeay deposits except that the older deposits exhibit extensive soil development indicative of an older age. Their surfaces are currently being modified and eroded, and the deposits are sheet-like and locally preserved on mesas and benches. The deposits mostly consist of well-sorted, fine- to medium-grained sand, silt, and pedogenic carbonate rubble. Soil development varies from weak to strong for individual deposits in the quadrangle. The large older eolian and alluvial deposit on Poison Spider Mesa includes sparse granules, pebbles, and lenses of pebbly gravel and is capped by an eroded Stage V(?) pedocalcic soil. Holocene eolian sheet sand covers part of this older deposit.

The older eolian and alluvial deposits in the quadrangle range in age from early to middle Pleistocene based on their varying degrees of Stage III to V pedocalcic soil development. Maximum thickness of these deposits is 15 feet (5 m).

Eolian and residual deposits (Qer): Thin, sheet-like deposits of windblown fines mixed with weathered bedrock are mapped on some of the resistant beds of limestone (Jnl) found in the Navajo Sandstone. The deposits consist of sand, silt, and angular rock fragments from the sandy limestone beds. Deposits are yellow, tan, and reddish orange depending on the color of the source materials. Some of the deposits have weak pedocalcic soils. The deposits are believed to be of latest Pleistocene to Holocene age. Deposits are mostly less than 3 feet (1 m) thick.

Alluvial and colluvial deposits (Qac): The drainages of Negro Bill Canyon, Pritchett Canyon, and Courthouse Wash contain mixed alluvial and colluvial deposits (Qac). The active channels contain deposits of poorly sorted, crudely stratified sandy gravel that grade up the steep side slopes into bouldery rubble and sandy slopewash deposits derived from the adjacent bedrock outcrops. At Negro Bill Canyon and Courthouse Wash, Qac deposits are mostly sand and small sandstone fragments derived from adjacent outcrops of Navajo Sandstone. These unconsolidated deposits also include silt and clay, and are as much as 10 feet (3 m) thick. Deposits are probably of late Pleistocene to Holocene age.

Fill and Disturbed Deposits (Qfd)

We mapped the larger deposits of human-placed fill and disturbed ground in the quadrangle, but not in the urbanized or developed areas. Mapped deposits include the railroad fill on the south wall of Moab Canyon, the large tailings pile at the Atlas Minerals industrial site, large gravel pits near Moab, and fill used in road construction across washes. The railroad fill consists primarily of angular bedrock (Honaker Trail and Moenkopi Formations) material blasted from outcrops along the railroad grade and removed from the tunnel constructed through Poison Spider Mesa. The tailings pile at the Atlas site consists of approximately 11 million cubic yards (8.4 million m^3) of uranium mill tailings (sand-size and smaller material) and sandy fill. Fill used in road construction consists of boulder- to sand-size material. The thickness of these accumulations is up to 70 feet (21 m).

STRUCTURAL GEOLOGY AND GEOLOGIC HISTORY

Sedimentary strata in this part of the Colorado Plateau are folded into northwest-trending anticlines and synclines, and are cut by normal faults and joints that mainly trend northwest (figure 1). Several folds and one major fault extend diagonally northwest-southeast across the Moab 7.5' quadrangle. The most prominent of these structural features is the Moab Valley salt-cored anticline. The crest of the salt-cored anticline is deformed, having been displaced by a large extensional fault and then structurally collapsed due to partial dissolution of the salt core. Erosion of the deformed crestal rocks formed Moab and Spanish Valleys.

In Pennsylvanian to Permian time the fault-generated and intermittently subsiding Paradox basin formed on the southwest side of the ancestral Uncompahgre uplift (figure 1) (Baars, 1966; Cater, 1970; Stevenson and Baars, 1987).

Clastic, carbonate, and evaporite sediments were deposited across the basin at this time. Evaporite deposits, containing a large percentage of halite, were primarily deposited in the Paradox Formation during the Middle Pennsylvanian (Hite, 1960).

From Middle Pennsylvanian to Late Triassic time, salt beds (mostly halite) in the deepest part of the basin flowed toward discontinuities in the floor of the Paradox basin caused by faults in the pre-Paradox Formation rocks (Joesting and Case, 1960; Baars, 1966; Stevenson and Baars, 1987; Huntoon and others, 1994) (appendix A-A′, B-B′, C-C′). The salt thickened at these discontinuities to form northwest-trending elongate salt diapirs. During salt movement, Late Pennsylvanian through Triassic strata were locally thinned, folded, brecciated, truncated by erosion, or were not deposited across the crests of the salt diapirs. Local basins, called rim synclines, developed on the sides of the salt diapirs as the underlying salt flowed out of these areas into the diapirs. These basins filled with thick Late Pennsylvanian to Late Triassic sediments. Salt continued to move during the Jurassic and Cretaceous, locally affecting the thickness and lithofacies of Jurassic and Cretaceous strata adjacent to and over salt diapirs within the basin (Shoemaker and others, 1958; Cater, 1970).

West-southwest regional compression affected the region during the Late Cretaceous to early Tertiary Laramide orogeny (Cater, 1970; Heyman and others, 1986). Hypothetically, strata were folded into broad northwest-trending anticlines and synclines (Cater, 1970; Doelling, 1985, 1988). Anticlines were superimposed over the pre-existing salt-cored anticlines. Broad, shallow synclines formed between the anticlines and, in some cases, were also superimposed on pre-existing rim synclines.

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 fault movement postdates the Laramide episode of folding. This period of Tertiary extensional faulting has been related to regional relaxation of stress after Laramide compressional folding (McKnight, 1940), possible reactivation of subsurface faults in the pre-Paradox rocks (Doelling, 1988)(appendix), regional extension during the Cenozoic (Ge and Jackson, 1994), and epeirogenic uplift of the Colorado Plateau during the late Tertiary (Parker, 1981; Ross, 1998).

The Moab region was epeirogenically uplifted in late Tertiary time as part of the Colorado Plateau (Hunt, 1956; 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 diapirs through existing fracture systems. The ensuing dissolution of salt caused local areas of collapse, with tilting, faulting, and subsidence of the overlying strata during late Tertiary and Quaternary time (Shoemaker and others, 1958; Colman, 1983; Harden and others, 1985; Doelling, 1988; Oviatt, 1988; Ross, in preparation).

Moab Valley Salt-Cored Anticline

The Moab Valley salt-cored anticline trends roughly N. 45° W. across the quadrangle under Moab and Spanish Valleys. It plunges to the northwest of Moab Valley and is recognizable for another 7 miles (11 km) as the Moab anticline (McKnight, 1940; Doelling, 1988). To the southeast, the Moab Valley salt-cored anticline is linked to a string of salt features totaling about 72 miles (116 km) in length (Williams, 1964). Moab and Spanish Valleys are 1 to 1.5 miles (1.6-2.4 km) wide and about 15 miles (24 km) long, extending beyond the quadrangle to the south and southeast (figure 4). The valleys are separated by a topographic saddle south of the Mill Creek Canyon. The topographic expression

Figure 4. *View southeastward into Moab and Spanish Valleys. The Colorado River is in the foreground and the La Sal Mountains are in the background. A salt diapir 9,000 feet (2,743 m) thick and two miles (3.2 km) wide underlies the valleys and is covered with basin-fill deposits, collapsed bedrock, and Paradox Formation cap rock.*

of Moab and Spanish Valleys is the result of an early episode of diapiric salt growth in the Paradox Formation and a later episode of salt-dissolution-induced structural collapse and erosion along the crest of the salt-cored anticline during the late Cenozoic. Because salt dissolution has occurred throughout the Quaternary, imperceptible salt dissolution is probably continuing today.

Moab Valley salt-cored anticline structural features are complex and, for discussion, are grouped into the (1) Moab and Spanish Valleys salt diapir; (2) salt dissolution-induced basin along the crest of the diapir; (3) deformational belts on the southwest and northeast sides of the valleys; (4) structural features on the flanks of the diapir; and (5) the Moab anticline extension.

Moab and Spanish Valleys Salt Diapir

Geophysical data, well log information, and this mapping provide some control on the shape of the Moab and Spanish Valley salt diapir (plate 2, cross sections). Closely spaced gravity contours (Case and Joesting, 1972) along the margins of Moab Valley indicate that the salt core is steep-walled and that the nose plunges to the northwest. Well logs from the Federal-Weaver No.1 well and sample descriptions of the Embar Oil-Big Six Oil Cos. well, SW1/4SE1/4NW1/4 section 34, T. 25 S., R. 21 E., reported by Baker (1933) and McKnight (1940), indicate the southwest margin of the Moab and Spanish Valleys salt diapir may be nearly vertical at these locations. Near-vertical dips of Chinle outcrops and structural deformation at the Chinle-Paradox cap rock contact appear to be on trend with the vertical margin. The northeast margin of the salt diapir probably parallels and underlies the trace of the northeasternmost fault or anticline on the northeast side of the valleys (plates 1 and 2). This interpretation is based on gravity data and the location of the belt of salt-dissolution induced faults and folds on the northeast side of the valley (cross sections B-B′ and C C′). Therefore, the width of the Moab and Spanish Valley salt-cored anticline is about 2 miles (3.2 km) at cross sections B-B' and C-C′.

Sparse local petroleum-well data indicate the height of the Moab and Spanish Valleys salt diapir. The Federal-Weaver No. 1 well (SW1/4NE1/4 Section 28, T. 26 S., R. 22 E.) penetrated the Mississippian Leadville Limestone at about 4,500 feet (1,400 m) below sea level (depth used on cross section C-C′) The Burkholder 1-G-1 well, northeast of Moab Valley, (section 1, T. 26 S., R. 22 E., Rill Creek quadrangle) penetrated the Leadville Limestone at approximately 5,300 feet (1,600 m) below sea level. The base of the salt is generally less than 200 feet (61 m) above the top of the Leadville (appendix) and suggests that the diapir has a height (post-salt-dissolution collapse) of about 9,000 feet (2,743 m) at Moab Valley (cross sections B-B′ and C-C′). The difference in elevation of the Leadville tops in the wells suggests a buried fault in the subsalt rocks. The elongate shape and steep margins indicate that the Moab and Spanish Valley salt diapir is a salt wall.

Salt-Dissolution-Induced Basin Along Crest of Diapir

Moab and Spanish Valleys are filled with basin-fill alluvium (Qabf) interpreted to be mainly of Quaternary age. Logs from several water wells (Utah Division of Water Rights, unpublished data) at the southeast end of the Spanish Valley adjacent to Pack Creek, SW1/4 section 7, T. 25 S., R. 22 E., indicate only 56 to 123 feet (17-37 m) of unconsolidated basin-fill alluvium above gray shale and gypsum of the Paradox cap rock. In the central part of the valley, the Great Lakes Carbon Corp. State No. 1 well penetrated approximately 320 feet (98 m) of basin-fill alluvium, about 45 feet (14 m) of sandstone (collapsed bedrock?), 140 feet (43 m) of black shale, and 395 feet (120 m) of cap rock before reaching the first salt horizon in the Paradox Formation at a depth of about 900 feet (275 m) (figure 5). In the northwest part of the valley, along the northwest side of the Colorado River, NE1/4SW1/4 section 27, T. 25 S., R. 21 E., Atlas Minerals ATP-1 borehole penetrated approximately 406 feet (124 m) of basin-fill alluvium from the surface to total depth (Canonie Environmental, 1994) indicating that alluvial basin fill exceeds 406 feet (124 m). Two additional boreholes (1 and 2, figure 6), drilled farther to the west-northwest on the Atlas Minerals site, indicate that Quaternary basin-fill deposits abruptly thin to about 100 feet (30 m) and rest on post-Paradox Formation bedrock beneath the site.

This limited subsurface information suggests that basin-fill deposits (Qabf) form a wedge that overlies cap rock, thickening to the northwest beneath the surface of Moab Valley, and are juxtaposed against post-Paradox bedrock that is overlain by a thinner sequence of basin-fill alluvium (figure 6). We interpret the northwest boundary (no longer present) of the basin-fill wedge to be a buried salt-dissolution-induced fault(?) that has offset and lowered the basal surface of the basin-fill deposits a minimum of 400 feet (122 m). The exact position or trend of this fault(?) is unknown. In fact, it may not be a fault at all, but a dramatic thinning of units northwest of the bend in the Colorado River. The "front" of bedrock on the north side of U.S. Highway 191 opposite the Atlas minerals mill might illustrate what the buried fault(?) or escarpment "front" might be like.

Evidence for a buried fault near the northwest end of Moab Valley includes previously cited well data, as well as hydrologic data. The base of the alluvial basin fill beneath the Colorado River, in Moab Valley, is at least 400 feet (122 m) lower than the bedrock thresholds for the Colorado River channel on the northeast and southwest sides of the valley. Alluvium could not be deposited at elevations much lower than the river's current elevation, about 3,950 feet (1,204 m) above sea level, unless the valley subsided. The buried fault(?) is a boundary separating an area of lesser subsidence northwest of the river from an area of greater subsidence southeast of the river. The greater amount of subsidence southeast of the river may be due, in part, to perennial surface-water infiltration and greater ground-water flow entering the valley from the east-southeast, causing more dissolution.

Salt-dissolution-induced subsidence in Moab and Spanish Valleys has been active during the Quaternary (Pleistocene to the present). Quaternary alluvial deposits, interpreted as middle Pleistocene and younger, have a complex morphology and distribution (Richmond, 1962; Harden and others, 1985) consistent with salt dissolution. Mill Creek, from its confluence with the Colorado River to the eastern side of Moab Valley, lacks terraces that are present along the drainage above the valley. The lack of terraces along Mill

Creek in Moab Valley suggests aggrading conditions under which Mill Creek sediments are being deposited in a subsiding basin. The presence of Holocene-age alluvial fans on the valley margins suggest response to a lowering base level. We interpret this change in base level to be due to dissolution of the salt diapir underlying Moab Valley.

Southwest-Valley-Margin Deformation Belt

Structural features along the margins of Moab and Spanish Valleys formed through both salt-diapiric and salt-dissolution processes. Salt diapiric features are common at the northwest end of the southwest valley margin, but salt-dissolution-induced features are not evident in this area, probably due to erosion by the Colorado River.

Lower Jurassic strata southwest of the valley margin dip away from the valley at angles of 10 to 15 degrees. Below the Poison Spider Mesa rim, along the Potash Road (Utah Highway 279 in section 34, T. 25 S., R. 21 E.), strata of the upper Chinle Formation dip 15 to 17 degrees southwest. Dips progressively increase down section across several angular unconformities until in some areas, the basal strata of the Chinle and uppermost beds of the Moenkopi are nearly vertical. These angular unconformities are known as progressive unconformities.

Chinle outcrops immediately southeast of The Portal have progressive unconformities and also contain intraformational conglomerates (figure 7). Some conglomerate beds in the upper Chinle contain distinctive sedimentary rock fragments eroded from nearby steeply tilted older Chinle strata. Valleyward of these outcrops, the Chinle is folded into an anticline-syncline pair, and strata are discolored, brecciated, and fractured. Rocks in the core of the anticline are an intensely brecciated and discolored mixture of Paradox Formation cap rock and Chinle lithologies. The axial trace of the anticline trends to the northwest directly into a small ridge of cap rock. Chinle beds in contact with cap rock are locally cut out along strike, indicating discordance between the cap rock and the Chinle. The syncline is between the anticline and a larger ridge of cap rock (figure 2), on which the Chinle again is in contact with cap rock. Similar areas of brecciation and changes in dip are present at the cap rock-Chinle outcrops on the northeast side of the valley.

These outcrops probably represent the structural configuration of the upper surface of the diapir that has not been significantly modified by later salt-dissolution-induced collapse. Steepening of dips and progressive angular unconformities within Chinle strata, the unconformity between the Chinle and Paradox cap rock, and the nature of the contact between the Chinle and Paradox cap rock indicate that the Moab Valley salt diapir completely penetrated pre-Chinle strata in the central part of the valley (cross sections B-B′ and C-C′, plate 2) and partially penetrated and deformed the Chinle.

A belt of salt-dissolution-induced, northwest-trending faults, fractures, and folds extends from The Portal southeastward along the southwest side of Moab Valley beyond the quadrangle boundary. Vertical to steeply northeast-dipping and N. 45° W. -striking joints are closely spaced (about 5 feet [1.5 m] apart) along the belt. The spacing abruptly increases to the southwest beyond the southwesternmost fault in the cliff wall. The southwesternmost fault and other

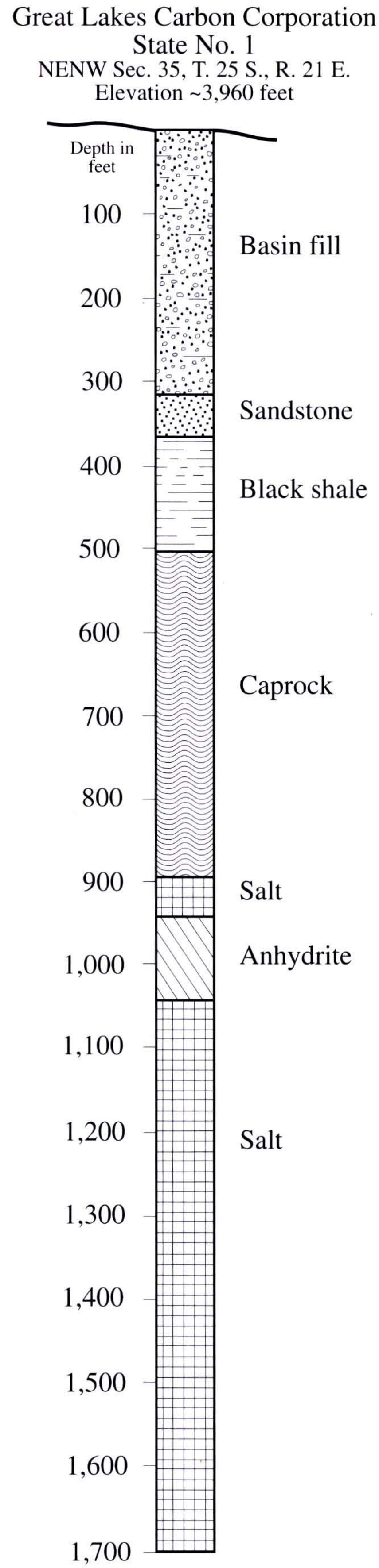
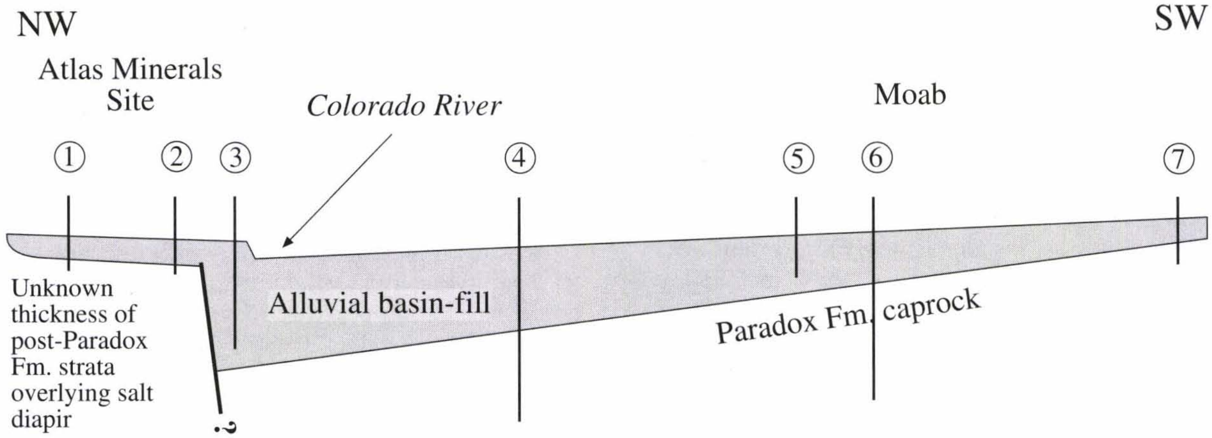


Figure 5. *Log of the Great Lakes Carbon Corporation State No. 1 well, NE1/4NW1/4 section 35, T. 25 S., R. 21 E.*



Thickness of alluvial basin-fill in selected wells:	Thickness
1. Atlas Minerals B-4 borehole	99 feet
2. Atlas Minerals B-3 borehole	108 feet
3. Atlas Minerals ATP-1 borehole	>406 feet
4. Great Lakes Carbon Corp. brine disposal well	320 feet
5. Water wells in section 1, T. 26S., R. 21E.	>100 feet
6. Western Allied - Bix Six Oil Cos., oil & gas well	200 feet
7. Several water wells in sec. 7, T. 26 S., R. 22 E.	56-123 feet

Figure 6. *Northwest-southeast diagrammatic cross section through Moab Valley (not to scale). Basin-fill alluvium dramatically thickens toward the Colorado River and abruptly thins at the north-northwest end of the valley. The abrupt thinning of alluvium is interpreted to be the result of movement along a salt-dissolution-related fault or fault zone. Location of wells shown on geologic map (plate 1). Deep wells listed in table 2.*

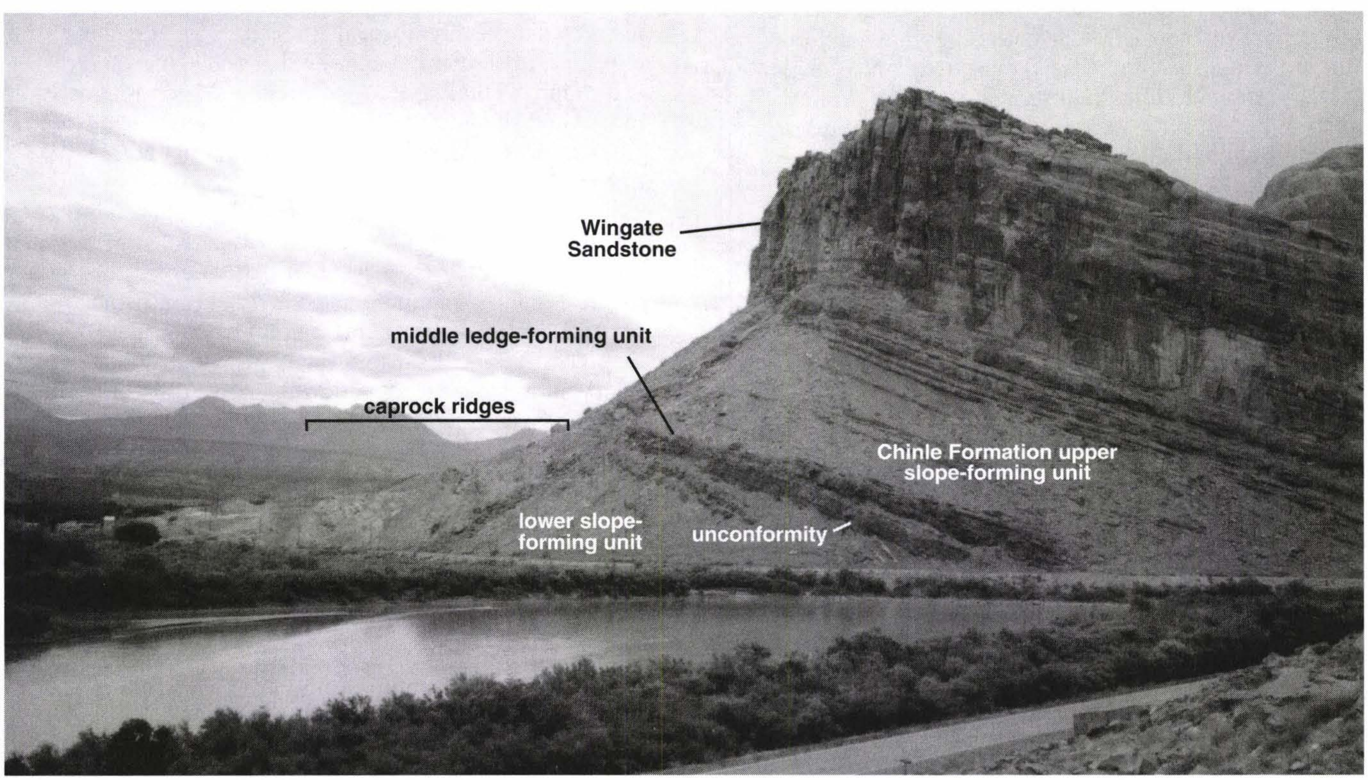


Figure 7. *Bluff forming the south buttress of The Portal (the cliffs flanking the river canyon mouth) are Wingate Sandstone. Progressive unconformities are common in the lower slope-forming unit of the Chinle Formation and intraformational conglomerate is common in the upper slope-forming unit. The Chinle Formation is in contact with cap rock ridges of the Middle Pennsylvanian Paradox Formation on the left. Upper Pennsylvanian, Permian, and Lower Triassic rocks are unconformably "cut out" over the top of the Moab Valley salt-cored anticline.*

high-angle normal faults in the belt are primarily down-to-the-valley and form an anastomosing pattern along which the dominant displacement is transferred from fault segment to fault segment. This transfer is accomplished by complex fault relays, fold ramps, and block rotations. Overall displacement is greatest in the southeast corner of the map area and gradually decreases northwest as the faults die out in hinge zones. The fault zone is a "scissor" structure opening to the southeast.

The Hidden Valley area is an example of the complexity of deformation along the southwest side of Moab Valley. Hidden Valley is in a narrow graben (Hidden Valley graben, plate 1) filled with sandy surficial sediments. Its southwest edge is a massive cliff of Glen Canyon Group sandstone. Hidden Valley is separated from Moab Valley by a narrow, ridge-forming horst. Two fault-induced asymmetrical synclines trend northwest along the top of the ridge. Rocks along the ridge are extensively fractured and sandstone along the faults is locally bleached, enriched in hematite, and recemented. The horst block is marked by a ledge-forming conglomeratic sandstone in the Chinle that is conspicuous for approximately 3 miles (4.8 km) along the southwest side of Moab Valley. Valleyward of the horst, strata begin to "roll over" to the northeast along a fault-induced monocline (cross section C-C′). The monocline is marked by a series of hogbacks in the Chinle Formation, Wingate Sandstone, and Kayenta Formation (figure 8). The strata in these outcrops appear thinner than normal, probably from a combination of depositional thinning over the crest of the salt diapir and structural thinning due to bedding-plane slip as the units were extended and folded during salt-dissolution-induced collapse. An asymmetrical syncline in the Kayenta and Wingate is locally found valleyward of the large monocline. A thin veneer of older-alluvial-fan and eolian-sand deposits covers these bedrock units as they extend into the valley. The topographic saddle that separates Moab Valley from Spanish Valley occurs where these surficial deposits rest on the highly fractured Glen Canyon Group strata.

Northeast-Valley-Margin Deformation Belt

A belt of faulted and folded bedrock extends along the northeast flank of Moab Valley. The belt is 2,000 feet (610 m) wide at its northwest end and widens to 4,500 feet (1,370 m) toward the southeast at Mill Creek. The strata "roll over" from their northeast dip and are warped into alternating anticlines and synclines (figure 9). Many of the anticlinal axial traces change to high-angle normal faults that are down-to-the-valley. This arrangement suggests the anticlines are fault-induced folds.

Synclines that typically are asymmetric chevron folds parallel the faults and anticlines. These folds are referred to as V-synclines in previous maps and reports (Doelling, 1983, 1985, 1988). Many of these synclines doubly plunge toward drainages that cross their axes. A good example is the Mill Creek syncline (plate 1 and plate 2, cross section C-C′). Intersecting fracture zones are present at the eastern edge of the map along the axial trace of the Mill Creek syncline. The fracture zones are networks of closely spaced, anastomosing, cataclastic bands and fractures cutting brecciated Navajo Sandstone. These fracture zones form resistant ridges, 0.5 to 2 feet (15-61 cm) wide, that meander across the landscape. The larger fractures are small faults with approximately 3 feet (1 m) of offset.

The northeastern belt contains numerous northwest-striking faults, many of which are too small to map at 1:24,000 scale. Fault blocks are tilted both northeast and southwest. Rocks along many of the faults and associated fractures are bleached and are either more friable or better cemented than "normal" outcrops. Fault gouge and narrow breccia zones mark many fault traces. Cataclastic bands commonly criss-cross the sandstones of the Glen Canyon Group. The bands show a variety of orientations and geometries and typically parallel the traces of large faults. Higher-angle bands cross-cut lower-angle bands.

The Kayenta Heights fault (plate 1, cross section C-C′), south of Mill Creek, shows many of these fault-related features. The fault dips 50 to 75 degrees southwest, and offset increases to the northwest along the fault. At the mouth of Mill Creek Canyon, the Navajo Sandstone in the hanging wall is juxtaposed against the Wingate Sandstone in the footwall, indicating an estimated displacement of 400 feet (122 m).

Deformation on down-to-the-valley normal faults, V-synclines, and anticlines is apparently greater where the northeast belt is crossed by short drainages. These local areas of greater deformation are present along the crests and flanks of many of the salt-cored anticlines in the region. Doelling (1983, 1988) has attributed them to greater amounts of salt-dissolution occurring at depth where the crossing drainages intersect northwest-striking, open fractures. The open fractures probably originated as joints.

Structural Features on the Flanks

Because Upper Pennsylvanian through Upper Triassic strata are missing or thinned over the crest of the Moab Valley salt diapir, a reciprocal thickening of the same strata is expected in the rim synclines that flank the margins of the salt diapir. This increase in thickness is dramatically documented on the northeast side of the valley in the Courthouse rim syncline, where the Burkholder 1-G-1 well (Rill Creek quadrangle) penetrated about 640 feet (195 m) of Chinle, 1,830 feet (558 m) of Moenkopi, 4,550 feet (1,387 m) of Cutler, and 2,380 feet (725 m) of Honaker Trail Formations before penetrating only 300 feet (91 m) of salt-bearing strata of the Paradox Formation. Salt flowed into the Moab and Spanish Valleys salt diapir and into the Castle Valley salt diapir, 8 miles (13 km) northeast of Moab Valley, from this intervening syncline area during the Late Pennsylvanian to Late Triassic time interval.

Strata thickness also increases on the southwest side of Moab Valley. The Cutler and Honaker Trail Formations are about 5,400 feet (1,646 m) and 1,500 feet (457 m) thick, respectively, above a 700-foot (213-m) thick section of Paradox in the Federal-Weaver No.1 well (cross section C-C′). The Chinle is nearly 640 feet (195 m) thick in a measured section containing progressive unconformities just northwest of The Portal. We estimate that the Moenkopi and Chinle Formations may each thicken to as much as 700 feet (213 m) in the Kings Bottom rim syncline on this side of the salt diapir.

Moab Anticline

The Moab anticline is the northwestward extension of the Moab Valley salt-cored anticline. The axial trace of the

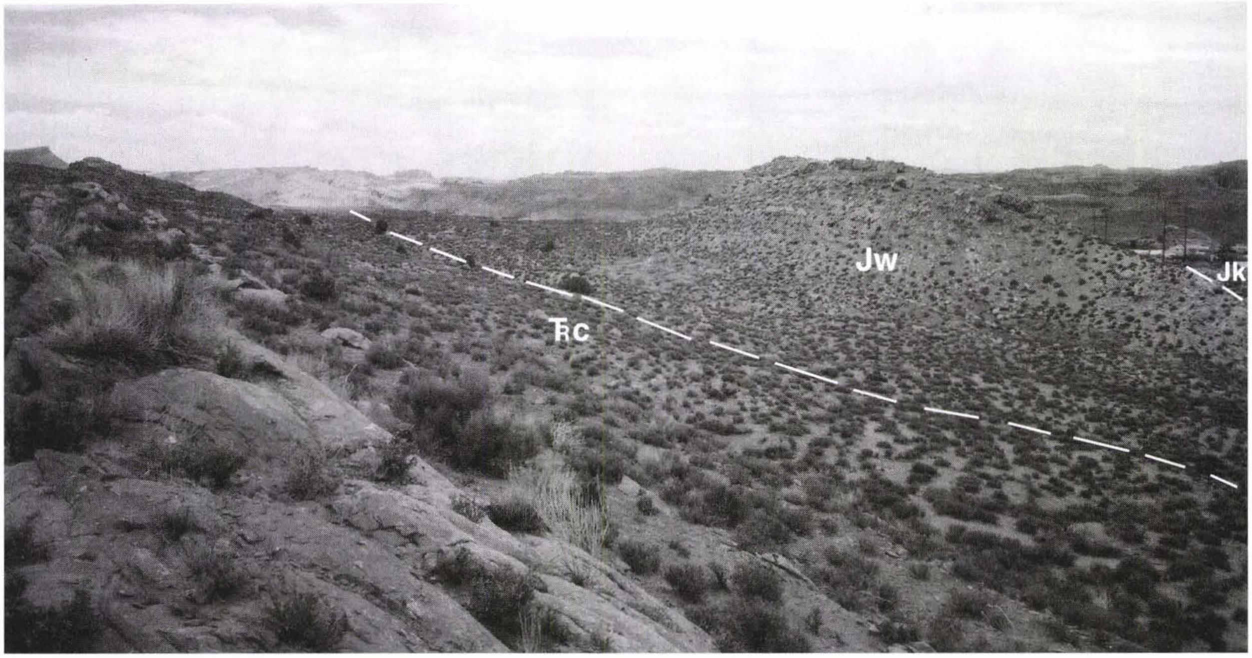


Figure 8. *Hogback of the Wingate Sandstone (Jw) on the southwest side of Spanish Valley. The Wingate Sandstone, Chinle Formation (Ŧc), and Kayenta Formation (Jk) have collapsed due to salt dissolution and are tilted valleyward. Rocks in these tilted blocks are highly fractured. About 3 miles (5 km) southeast of The Portal.*

Figure 9. *Deformed and fractured Glen Canyon Group formations. Strata "roll over" from their northeast dip and are warped into alternating anticlines and synclines along the northeast valley-margin deformation belt. About 1.5 miles (2.4 km) northwest of Mill Creek.*

Moab anticline curves from N. 55° W. just north of the Colorado River to N. 35° W. at the north edge of the quadrangle. The anticline gently plunges and flattens to the northwest. As viewed north from the river the anticline is nearly symmetric, dipping to a maximum of about 38 degrees on each flank (figure 10). Its southwest flank is cut by the subparallel Moab normal fault, a tectonic feature of relatively large displacement.

The crest of the anticline is cut by several faults and closely spaced joints that are subparallel to the fold axis. The faults, in a zone 1 mile (1.6 km) wide, are all located northeast of the Moab fault and most have displacements of 60 feet (18 m) or less (cross section A-A′). Displacement on the northeasternmost fault increases southward to about 500 feet (152 m) at the north edge of Moab Valley, nearly juxtaposing the base of the Navajo against the base of the Wingate (plate

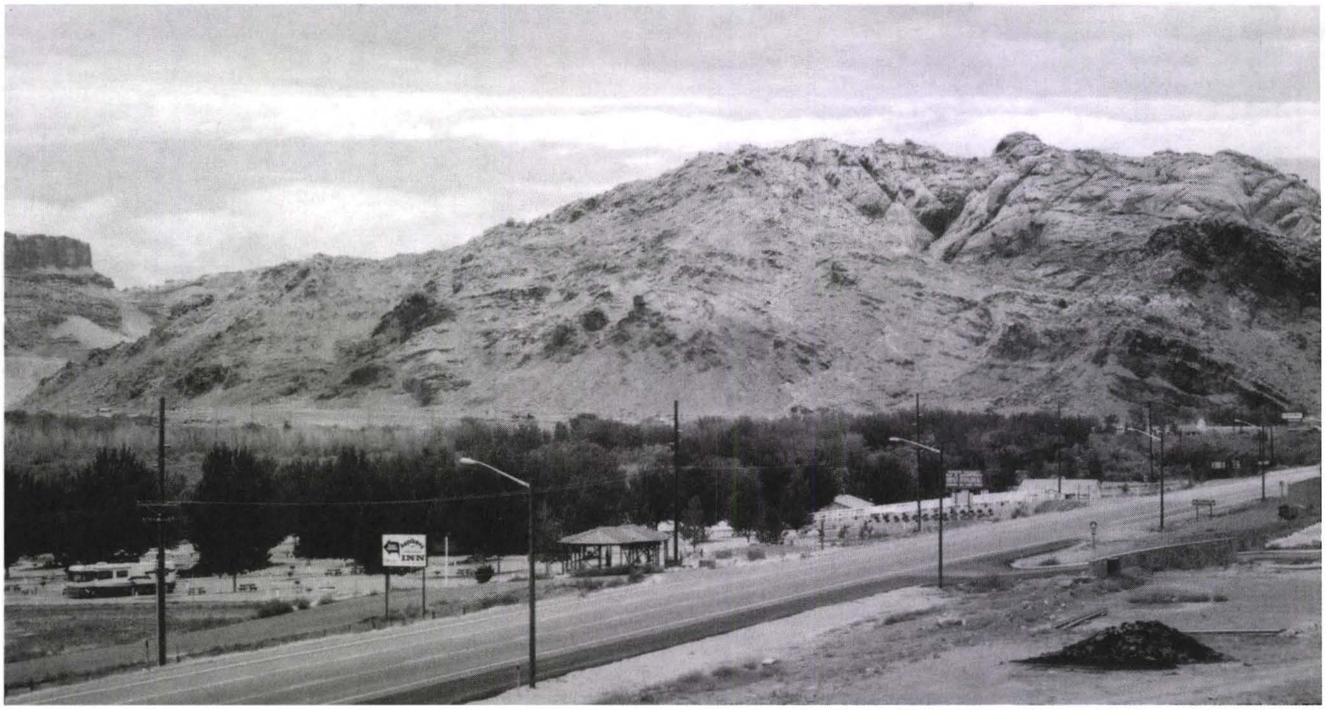


Figure 10. View of the Moab anticline at the north end of Moab Valley. Highly fractured and faulted rocks of the Chinle, Wingate, Kayenta, and Navajo Formations are exposed at this end of the anticline. The anticline gradually flattens and disappears about 7 miles (11 km) to the northwest. Strata on each limb dip as much as 38 degrees.

1). The faults generally dip 40 to 80 degrees toward the axial plane of the anticline. Fault breccia is commonly recemented and resistant so that erosional remnants commonly stand as "ribs."

Several cross faults are present at the south end of the Moab anticline, at the north end of Moab Valley. These faults dip at high angles, mostly northward, at 60 to 80 degrees, and are displaced down to the south. The cross faults appear to have rotated fault planes, given the slight valleyward dip on some of the strata and a gap between hanging wall and footwall that decreases downward. This suggests collapse into Moab Valley. The cross-fault zones also display highly shattered bedrock, local open fractures, and no signs of cementation. A set of closely spaced joints cross cuts the anticline, dipping valleyward from 35 to 55 degrees. This joint set ends abruptly about a 1/2 mile (0.8 km) north of Moab Valley.

Folds

Kings Bottom Syncline

The Kings Bottom syncline is a N. 45° W.-trending, doubly plunging fold located about 2 miles (3 km) southwest of Moab and Spanish Valleys. The hinge line of the syncline plunges approximately 3 to 5 degrees from both directions toward its intersection with the Colorado River. Glen Canyon Group strata dip to as much as 17 degrees southwest on the northeast limb and as much as 10 degrees northeast on the southwest limb. The Navajo Sandstone thickens in the broad hinge of the syncline, suggesting the fold is, in part, a rim syncline formed by removal of salt from underneath the syncline. This interpretation is supported by thickness of strata encountered in the E.B. LaRue, Hunters Canyon No. 3 well located in section 1, T. 27 S., R. 21 E., and projected into the plane of cross section C-C′. The stratigraphic section between the Honaker Trail Formation and Wingate Sandstone is thicker in the well than equivalent sections adjacent to the Cane Creek anticline to the southwest and the Moab Valley salt-cored anticline to the northeast.

Courthouse Syncline

The northwest-trending Courthouse syncline parallels the Moab Valley salt-cored anticline on its northeast side. The hinge line of the syncline plunges gently to the northwest. Except locally near the Moab anticline, maximum dips on the southwest and northeast limbs reach 8 or 9 degrees in the quadrangle (cross section B-B′). The hinge of the fold flattens to the southeast where it becomes impossible to trace. The syncline continues northwest, out of the quadrangle, into the Book Cliffs. A bend of the Colorado River follows the axial trace of this syncline for about 4,500 feet (1.4 km) about 2 miles (3.2 km) upstream from Moab Valley.

Cane Creek Anticline

The northeast limb of the Cane Creek anticline is in the southwest corner of the quadrangle (figure 1). Mesozoic strata dip between 5 and 10 degrees, and dips increase to between 10 and 15 degrees in upper Paleozoic strata on the fold limb in the quadrangle (southwest part of cross section C-C′). Wingate through Honaker Trail strata are thinner over the crest of the anticline based on measured sections in the quadrangle and data projected into the line of cross section C-C′ from the Humble O & R, West Bridger Jack No. 3 well, section 3, T. 27 S., R. 21 E., approximately 1.5 miles (1 km) south of the quadrangle boundary. The Paradox Formation is thicker in the crest of the anticline because of salt flowage (Doelling and others, 1994). The position and trend of the anticline were probably controlled by buried faults that cut, but do not continue above, the lower part of the Paradox Formation (cross section A-A′ in Doelling and others, 1994). Such buried faults, down-to-the-northeast, probably extend across the Moab quadrangle and bound blocks of lower Paradox and older rocks (cross section C-C′).

Moab Fault

The Moab normal fault consists of two branches that offset strata on the southwest limb of the Moab Valley salt-cored anticline in the northwest quadrant of the quadrangle. The two branches, the west branch and main branch, merge to the northwest and are buried by Quaternary deposits upon entering Moab Valley to the southeast. The fault traces can only be mapped in the northwest quadrant of the quadrangle, but displacement attributed to the fault is evident along the entire length of the Moab Valley salt-cored anticline. The fault does not cut any exposed Pleistocene or Holocene sediments in the quadrangle. Movement on the fault is believed to have occurred during Tertiary time (McKnight, 1940).

Both branches of the Moab fault are well exposed in a steep slope 800 feet (244 m) west of the Arches National Park visitors center (figure 11). At the south end of this exposure the west branch of the Moab fault strikes about N. 80° W. and dips 60° to 68° NE.; slickensides rake 60 degrees to the east. Strata near the top of the Honaker Trail Formation are exposed in the footwall, and the Moenkopi and Cutler Formations are exposed in the hanging wall. An 8- to 10-foot-thick (2.4-3 m) zone of attenuated and shattered Honaker Trail limestone and sandstone dips with the fault in the fault zone. Strata strike N. 45° W. and dip 10° NE. in the footwall. Moenkopi strata in the narrow fault block between the two branches strike roughly parallel to the faults and generally dip 20° to 25° N., but locally dip more than 40 degrees due to drag folding along the west branch. The width of the Moenkopi outcrop between the two branches is about 230 feet (70 m). The main branch of the Moab fault, at the north end of the exposure, strikes about east-west and dips about 68° N. Slickensides are not exposed in the main branch, where the Slick Rock Member of the Entrada Sandstone is juxtaposed against the Moenkopi Formation. The Entrada is drag folded, shattered, and recemented in the hanging wall. The estimated displacement across both branches of the fault is 2,400 feet (732 m) using formational thicknesses measured in section 20, T. 25 S., R. 21 E.

Both branches of the Moab fault curve to the southeast, cross U.S. Highway 191 and strike N. 45° to 70° W. in section 28, T. 25 S., R. 21. E. In section 28 the Entrada Sandstone is juxtaposed against the lower member of the Chinle Formation across the main branch of the Moab fault. The west branch of the fault is covered by eolian sand and talus southwest of the Arches National Park entrance, between U.S. Highway 191 and the Potash railroad. Strata are highly shattered adjacent to the fault, and parts of the Slick Rock and Moab Members are most likely present in the shattered band of yellow and red sandstone outcrops immediately southwest of U.S. Highway 191. Here, yellow sandstone beds dip 15° S. and strike east-west. The main branch of the Moab fault strikes N. 70° W. and the dip is not discernible.

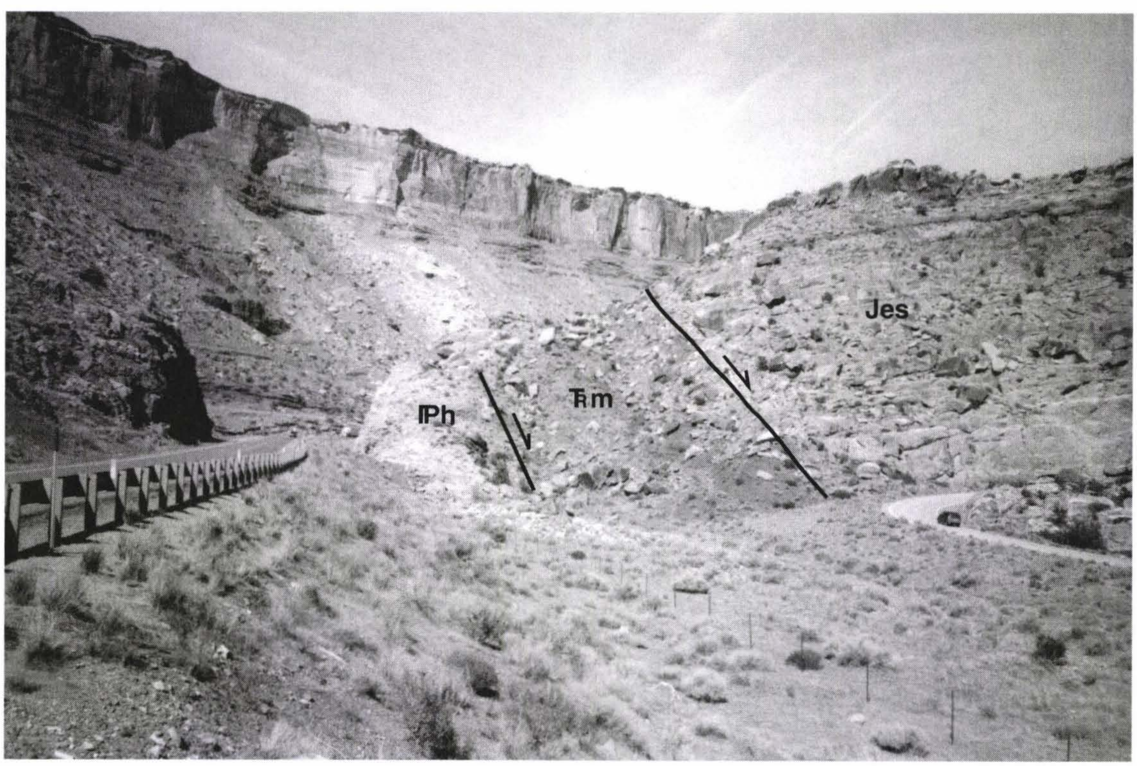


Figure 11. *View of both branches of the Moab fault west of the Arches National Park visitor center. The main branch, juxtaposing the Slick Rock Member of the Entrada Sandstone (Jes) against the Moenkopi Formation (TRm), is to the right. The west branch, juxtaposing the Moenkopi Formation (TRm) against the Honaker Trail Formation (IPh), is to the left. The total displacement at this location is estimated to be 2,400 feet (732 m).*

Along the line of cross section A-A', the Navajo Sandstone strikes N. 45° W. and dips 35° to 38° SW. northeast of the faults (figure 12). Immediately southwest of U.S. Highway 191, shattered Entrada outcrops dip 23° SW. A synclinal axis is present in the hanging-wall rocks immediately northwest of the main branch of the Moab fault. The hinge of the syncline is cored with the Tidwell Member of the Morrison Formation. The plunge on the syncline is at least 9 degrees southeastward. Entrada Sandstone between the hinge and the fault dips steeply northeastward. This steep dip is partly due to drag along the fault. The syncline probably formed over a zone of salt dissolution that parallels the fault and shattered the Entrada Sandstone. The displacement along the main branch, which trends N. 52° W. and dips 60° NE., is estimated to be about 1,750 feet (533 m). The Moenkopi Formation is exposed in the footwall of the main branch and dips about 15° NE. The dip gradually decreases toward the Potash railroad tracks. Between the railroad tracks and the west branch of the Moab fault Moenkopi strata dip as much as 25° SW. We interpret a northwest-trending anticlinal axis beneath the railroad tracks. The west branch fault strikes about N. 42° W. and dips about 45° NE. The displacement on the west branch fault is estimated to be about 600 feet (183 m). A 20- to 25-foot (6-7.6 m) thick mass of attenuated, northeast-dipping Honaker Trail and Cutler Formation rock forms the fault breccia. The Honaker Trail dips 25 degrees southwest in the footwall. No exposure of the main branch of the Moab fault is found southwest of this traverse. We think the buried trace continues to the southeast, at least to the buried salt dissolution-induced fault(?) at the north end of Moab Valley (plate 1).

The trace of the west branch of the Moab fault can be followed into the NW1/4 section 34, T. 25 S., R. 21 E., where it is buried by surficial deposits. The final dip angle is 35 degrees valleyward. From Emkay southward, shattered Moenkopi or Chinle strata in the hanging wall dip 15° to 25° SW., as do Honaker Trail strata in the footwall. The fault is marked by an unusual zone of attenuated brittle rocks that follows the trace along its entire length in the Moab quadrangle. This zone is well displayed along the railroad grade between the tunnel portal and Emkay (figures 13-15). Brittle rocks of the Cutler and Honaker Trail Formation are dragged downward, attenuated, and smeared along subsidiary faults in a reversed-dip zone as much as 70 feet (21 m) thick (Baars and Doelling, 1987). We followed attenuated beds for 50 feet (15 m) or more continuously up the zone to the place in which they resume their proper position in the footwall.

In the SW1/4NW1/4NW1/4 section 34, T. 25 S., R. 21 E., a short ridge of gray shale in the hanging wall of the west branch of the Moab fault is juxtaposed against the Honaker Trail Formation. We interpret the shale as Moenkopi Formation that has been bleached by ground water adjacent to the Moab Valley salt diapir. Just southeast of this outcrop the west branch of the Moab fault is covered by Quaternary deposits in Moab Valley.

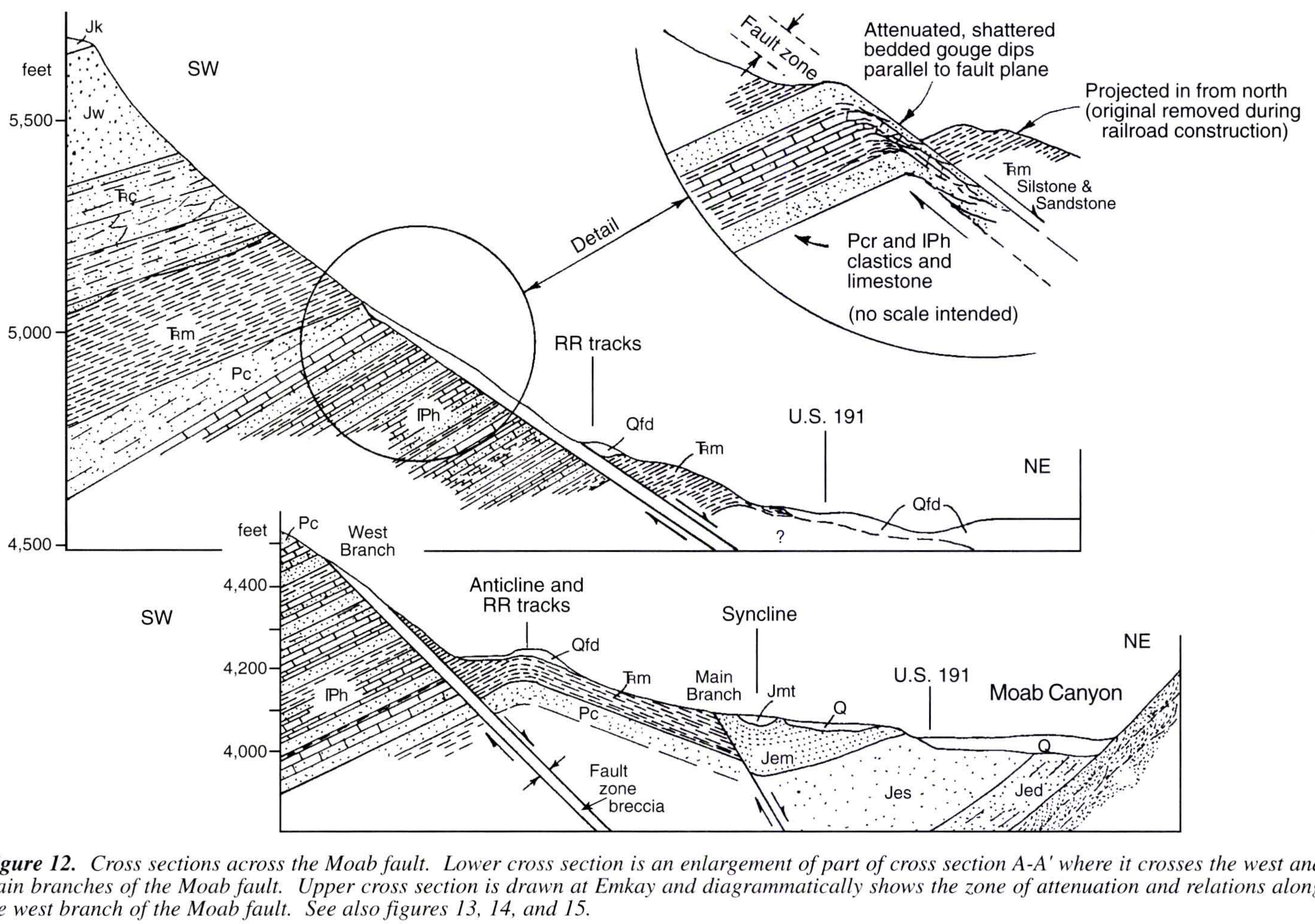


Figure 12. Cross sections across the Moab fault. Lower cross section is an enlargement of part of cross section A-A' where it crosses the west and main branches of the Moab fault. Upper cross section is drawn at Emkay and diagrammatically shows the zone of attenuation and relations along the west branch of the Moab fault. See also figures 13, 14, and 15.

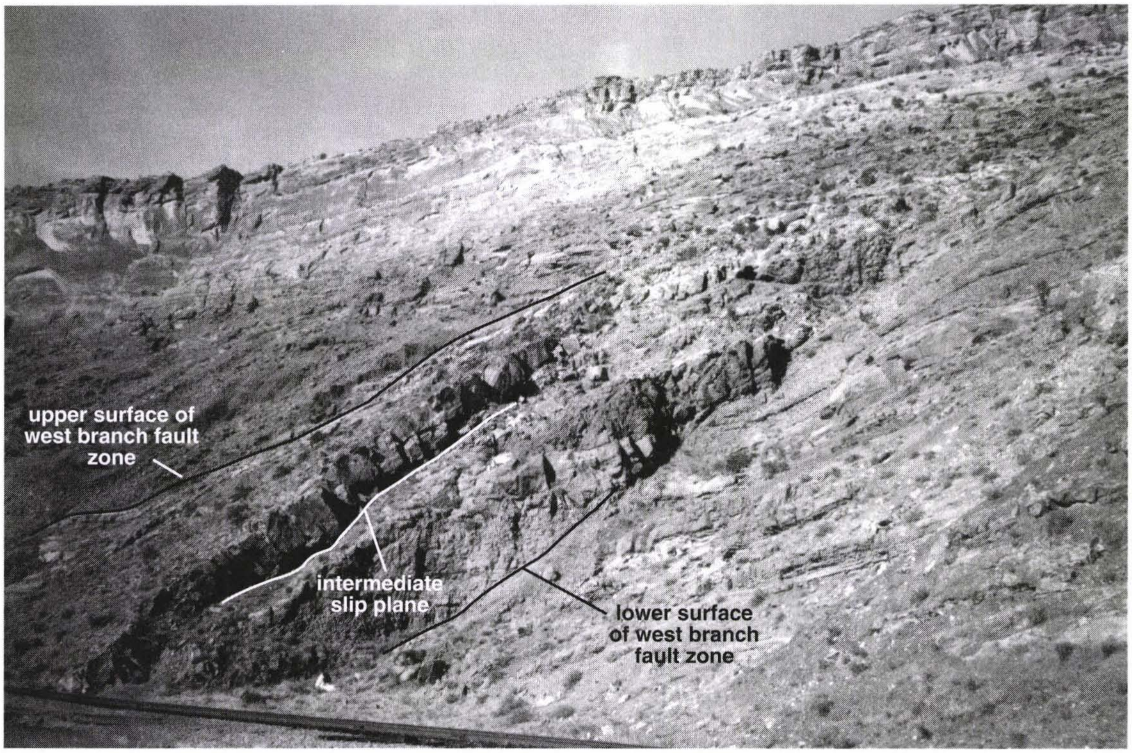


Figure 13. View to southwest of west branch fault zone of Moab fault near portal of the railroad tunnel at Emkay siding. See detail on figure 12. Most of the zone consists of attenuated strata that partly dip parallel to the fault zone.

Figure 14. View to northwest of an outcrop of the Moenkopi Formation (ledgy beds) in the hanging wall of the west branch of the Moab fault at Emkay. The smooth slope to the left is the upper surface of the fault exposed during railroad construction.

Figure 15. Sandstone bed "roll over," attenuation, and dip change along the west branch of the Moab fault. The dark sandstone on the skyline is sandstone that "rolled over" higher in the section. See also figures 12 and 13.

The boreholes drilled on the Atlas Minerals property at the northwest end of Moab Valley indicate that most of the mill tailings pile on this property rests on a relatively thin sequence of surficial deposits overlying post-Paradox bedrock (figure 6). In lithologic logs, this bedrock consists of clayey siltstone, moderately fractured red gray sandstone, indurated siltstone, and red-gray sandstone (Woodward-Clyde Federal Services, 1996). The encountered lithologies suggest that the buried trace of the main branch of the Moab fault is located as shown on plate 1, maintaining an approximate N. 40° to 50° W. strike southeast of its last mapped surface exposure. Cooksley Geophysics Inc. (1995), using seismic evidence, placed the buried fault trace about 500 feet (152 m) northeast of where we projected it. They assumed a vertical fault in their interpretation whereas we assumed a 60° NE. dip on the fault.

Southeast of the Colorado River and the buried salt-dissolution-induced fault(?), basin-fill alluvium (Qabf) directly overlies Paradox cap rock along the length of Moab Valley. Erosion has apparently removed most post-Paradox bedrock strata and salt dissolution has modified the upper surface of the diapir since the last episode of movement on the Moab fault. Therefore, the Moab fault is not expected to be preserved along the crest of the Moab Valley salt-cored anticline southeast of the Colorado River. It might be preserved beneath surficial deposits in the saddle between Moab and Spanish Valleys where post-Paradox strata cover a large part of the diapir (plate 1 and cross section C-C′). Surface and limited subsurface data from water wells (not on map) in the center of the valley suggest that the Moab fault is not preserved at this location. Along cross section C-C′ the base of the Navajo is at an elevation of about 5,300 feet (1,615 m) on the Moab Rim; across the valley its elevation is about 4,300 feet (1,311 m). The difference in elevation at similar positions on the flanks of the salt wall suggest a minimum offset of 1,000 feet (305 m) on the inferred Moab fault at this location.

Joints

Closely spaced, nearly vertical joints are prominent in the massive sandstone formations of the Glen Canyon Group in the Moab quadrangle (plate 1). Weathering and erosion have carved eye-catching sandstone fins that add scenic value and interest to the region. The most spectacular of these are in the Navajo Sandstone between Kane Spring Canyon and the southwest rim of Moab Valley on the bench locally known as "Behind the Rocks." These joints do not parallel the Moab salt-cored anticline, Moab fault, or Kings Bottom syncline, but trend N. 75° W. to N. 90° W. Near Kings Bottom along the Colorado River the joints veer clockwise to about N. 65° W. and continue on Poison Spider Mesa where they gradually bend to a N. 35° W. trend.

Near-vertical joints subparallel the Courthouse syncline and Moab Valley salt-cored anticline on the benches northeast of Moab Valley. Northeast of Negro Bill Canyon the trend of joints is N. 45° to 65° W. On the northeast flank of the salt-cored anticline joints trend N. 60° to 70° W.

ECONOMIC GEOLOGY

Potash, Salt, and Magnesium

Potash and halite deposits underlie the Cane Creek anticline and Moab and Spanish Valleys. They have been commercially extracted from the Paradox Formation along the Cane Creek anticline by dissolution mining in the adjacent Gold Bar Canyon quadrangle. In the Cane Creek anticline 65 to 75 percent of the Paradox Formation consists of salt deposits, which contain potentially commercial quantities of potash, magnesium, bromine, boron, and lithium (Ritzma, 1969; Doelling and others, 1994).

The Moab Valley salt-cored anticline consists of a salt wall estimated to be at least 9,000 feet (2,750 m) high beneath Moab and Spanish Valleys. Potash- and magnesium-bearing sylvite and carnallite are probably present in the Paradox Formation underlying the valleys. However, sufficient information is not currently available to accurately appraise the extractability or value of the salts and associated economic elements.

Fresh water was pumped into a massive salt bed in the Moab Valley salt-cored anticline to produce brine from a second well. The injection well was originally drilled for oil in 1943 (Dougan and Voorhies No. 1) and was recompleted as a brine well in 1960. The boreholes, located in SW1/4SW1/4 section 1, T. 26 S., R. 21 E., reached the first salt bed at a depth of 900 feet (174 m), but produced from another bed at an approximate depth of 2,000 feet (610 m). The brine contained about 310,000 parts per million (ppm) sodium chloride and 1,200 ppm calcium sulfate (Mayhew and Heylmun, 1965). The Atlas Minerals uranium mill used the brine in their operation north of Moab until they shut down. Daily brine production in 1965 was between 400 and 3,000 barrels (64 and 477 m^3).

Brine production forms large caverns in the salt beds (Mayhew and Heylmun, 1965). The Great Lakes Carbon Corp./Suburban Natural Gas Co. wells were drilled in Moab Valley, sections 26 and 35, T. 25 S., R. 21 E., to create a salt-bed cavern in the halite for the purpose of storing liquefied petroleum gas (table 2) (Hite, 1964). To recover the gas, brines are reinjected into the cavern.

Sand and Gravel

Alluvium along the Colorado River (Qa_1 and Qa_2) and older terrace deposits (Qat) contain sand and gravel suitable for highway and other construction. The basin fill (Qabf) under Moab Valley may also contain important sand and gravel resources. The Utah Department of Highways (about 1967) conducted tests at several localities in the Moab quadrangle (table 1). The quality of the sand and gravel in the terraces and alluvium along the river is not expected to vary greatly from the test results in table 1. No attempt was made to calculate reserves, but they are large. Similar sand and gravel was used in the construction of Utah Highway 279 that connects Moab with Potash.

Petroleum

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

Drilling records (Hansen and others, 1955; Heylmun and others, 1965) indicate that six wildcat wells were drilled in the Moab quadrangle prior to 1945 (table 2). Except for the brief lithologic descriptions of depth intervals from the Embar Oil-Big Six Oil Cos. well reported in Baker (1933) and McKnight (1940), and the Big Six-Western Allied Oil Co. well in section 12, T. 26 S., R. 21 E. reported in Baker (1933), no subsurface information is available for these early wells. However, Baker (1933) noted that early wells had shows of oil and gas, presumably from the Paradox Formation in the salt diapir.

The Union Texas Petroleum/Cities Services Oil Company, Federal-Weaver No. 1 well was first drilled in 1972-73 to a true vertical depth (TVD) of 7,622 feet (2,323 m). It was later deepened to a TVD of 9,650 feet (2,941 m) by Cities Services in 1974-75. The hole was dry and was abandoned.

Colombia Gas Development Co. completed the Kane Springs Federal 27-1 oil well in the Bartlett Flat field in 1991 in the adjacent Gold Bar Canyon quadrangle and sparked a renewal of interest in oil and gas development in the area. This well and others were drilled horizontally into the fractured Paradox Formation Cane Creek zone and produced oil and gas from this self-sourced reservoir (Morgan, 1993; Doelling and others, 1994).

Recent studies of economic resources have been conducted by the U.S. Geological Survey and U.S. Bureau of Mines in the Negro Bill Canyon (Bartsch-Winkler and others, 1990) and Behind the Rocks (Patterson and others, 1988) Wilderness Study Areas (WSA) that extend, in part, into the Moab quadrangle. The potential for oil and gas was rated high for the Behind the Rocks WSA and moderate for the Negro Bill Canyon WSA, but both areas were given a low certainty rating.

Gold

Alluvium (Qa_1 and Qa_2) and older terrace deposits (Qat) along the Colorado River contain "flour" and rare flakes of gold. A very small but unknown quantity of gold may have been recovered in the quadrangle from past operations. The gold occurs in placer deposits in black, magnetite-bearing, coarse sand lenses in the Colorado River gravels. The upstream ends of bars and higher-level terraces may be slightly richer (Butler, 1920, p. 638). Some gravel deposits prospected for gold have subsequently been exploited for sand and gravel.

Uranium and Associated Mineral Occurrences

Prospecting for uranium and associated minerals during past uranium "booms" was not particularly successful in the Moab quadrangle. A few short inclined adits were dug in favorable Chinle beds and in other formations that were locally radioactive. Many of these workings are in the south half of section 28, T. 25 S., R. 21 E., on the southwest side of Moab Valley. At least three such workings were driven into subarkosic clastic beds in the Honaker Trail Formation which display about double the normal background radiation (about 180 total counts on a scintillation counter). Similarly sized workings, in the lower Chinle Formation, display only background radiation.

Uranium and copper have been produced from basal Chinle Formation beds about 8 miles (13 km) to the north of the quadrangle along the trend of the Moab fault (Finch, 1954).

Decorative and Building Stone

Blocks and slabs of locally derived stone are used by Moab residents as facing, pavement, and garden stones for homes and offices. Ripple-marked sandstone from the Moenkopi and other formations, rounded metamorphic and igneous cobbles from alluvial sources, and flat slabs of fossiliferous limestone from the Honaker Trail Formation have been collected for such purposes.

WATER RESOURCES

The Moab quadrangle lies in a mid-latitude steppe climate area receiving an average of 7 to 10 inches (18-25 cm) of precipitation per year. Average annual evaporation rates are 40 to 42 inches (102-107 cm) (Iorns and others, 1964). The Colorado River, Mill Creek, Pack Creek, and Kane Springs Canyon drainages are perennial streams that provide water for irrigation in the quadrangle. Mill Creek water originates in the La Sal Mountains and provides the water supply for the city of Moab. The water is removed upstream of the quadrangle. A few catchment basins have been constructed to utilize rainfall for watering cattle on the benches.

A 49-year average flow for the Colorado River 1 mile (1.6 km) downstream from the Dolores River confluence was 8,057 cubic feet per second (228 m^3/s) or 5,833,000 acre-feet (7,192,100,000 m^3) per year (Hendricks, 1964). An 11-year average flow on Mill Creek, measured prior to construction of the Kens Lake diversion, was 14.3 cubic feet per second (405 L/s) or 10,360 acre-feet (12.77 hm^3) per year. A 5-year average flow on Pack Creek, measured near the eastern edge of the map, was 4.02 cubic feet per second (113.8 L/s) or 2,912 acre-feet (3.59 hm^3) per year (Hendricks, 1964).

Three ground-water regimes are present in the Moab quadrangle. The first involves bedrock aquifers and aquicludes above the Moenkopi Formation, the second involves those below the Moenkopi Formation, and the third involves the unconsolidated Quaternary deposits in the quadrangle.

The three principal bedrock units of the first regime are the Wingate, Kayenta, and Navajo Formations (Glen Canyon Group). These are recharged, especially under sandy surficial deposits on the benches, by rainfall or snow (Blanchard, 1990). Water from these units is used by the City of Moab and the Grand County Water Conservancy District from wells scattered in parts of sections 15, 22, and 23, T. 26 S., R. 22 E., on the northeast canyon wall of Moab and Spanish Valleys in the neighboring Rill Creek quadrangle. These wells produce about 2,200 acre-feet (2.7 hm^3) of water per year. The well area laps onto the northwest valley-margin deformation belt, along which there are numerous springs that emerge from fracture zones. Blanchard (1990) noted that movement of water in aquifers above the Moenkopi Formation is generally to the west and west-northwest. Recently, horizontal boreholes were drilled across the fractures of the belt in S1/2 section 26, T. 25 S., R. 21 E., to provide water for a local water park. These wells flow at a rate of about 80 gallons per minute (304 L/min) (R.R. Norman, verbal com-

Table 1.
Sand and gravel tests run by the Utah Department of Highways on terrace and alluvial deposits (Qat and Qa_1) in the Moab 7.5' quadrangle (Utah Department of Highways, about 1967).

	NAME AND LOCATION			North Mill Creek NE 7-26S-22E	South Mill Creek E 7-26S-22E	Negro Bill SW 19-25S-22E	U-128 bend SW 24-25S-22E
TEST DATA - REPRESENTATIVE SAMPLE	THICKNESS OF MATERIAL			50 feet	50 feet	10 feet	—
	DEPTH OF OVERBURDEN 0-1 foot			0-1 foot	0	—	
	DATE SAMPLED			1958	1955	1958	1958
	TYPE OF SAMPLE			Cutbank			
	DEPTH OF SAMPLE						0-3 feet
	SIEVE ANALYSIS	Before Crushing	> 3 inches	7.9%	19%	3.1%	11.7%
			> 1 inch	44.0%	53.0%	49.1%	37.2%
		Percent passing after crushing to 1 inch maximum size	1 inch	100%	100%	100%	100%
			1/2 inch				
			No. 4	43.2%	46.4%	34.4%	46.2%
			No. 10	36.9%	37.2%	27.1%	39.4%
			No. 40	30.6%	29.4%	20.0%	33.5%
			No. 200	5.4%	8.0%	3.4%	9.2%
	LIQUID LIMIT			18.4	19.2	16.3	17.6
	PLASTICITY INDEX			NP (not plastic)	NP	NP	NP
	SWELL			.023	.014	.008	.013
	A.A.S.H.O. CLASSIFICATION			A-1-a	A-1-a	A-1-a	A-1-a
	IMMERSION COMPRESSION AVERAGE P.S.I.	LIME	WO/				
			W/				
	ABRASION 500 REVOLUTIONS			26.4%	24.1%	26.3%	20.0%
	SODIUM SULFATE LOSS		+4				
			-4				

Table 2.
Oil, gas, and brine wells in the Moab 7.5' quadrangle.

LOCATION SECTION, TOWNSHIP, RANGE API NUMBER	OPERATOR AND WELL	COMPLETION OR ABANDONMENT DATE	TOTAL DEPTH (feet)	REMARKS
1. NENE 27, 25S 21E 43-019-11562-0000	Embar Oil Co., No. 1	1926	300	Abandoned.
2. SENW 34, 25S, 21E Oil Companies, No. 1	Embar Oil - Big Six Oil Companies, No. 1	3-2-28	5,345	Oil and gas shows at various depths, from 2,380 to 4,880 feet; abandoned.
3. SWNE 34, 25S, 21E 43-019-20407-0000	Great Lakes Carbon Corp., No. 1	1-?-43	3,367	Initially a potash test hole, then abandoned; re-entered to TD of 1,700 feet and used as brine disposal well by gas storage company. Because of problems with original site information the location of the well may be 1,300 feet west of the location on the map (plate 1); abandoned.
4. SWSW 1, 26S, 21E	E.J. Mayhew, Doogan Voorhies, No. 1	1-2-43 5-20-60	2,027	Initially a 1,150-foot-deep exploration well, then abandoned; re-entered and deepened as a brine well by Moab Brine Co.; abandoned.
5. NENWNE 12, 26S, 21 E	Western Allied - Big Six Oil Companies No. 1	1920	2,450	200 feet of valley-fill alluvium overlying Paradox Fm. caprock and salt; oil shows at 1,380 to 1,420 feet; abandoned.
6. SWNW 8, 26S, 22E	Utah Oil Development Co., No. 1	7-?-27	1,525	Shows of oil reported; TD in salt; abandoned.
7. SWNE 28, 26S, 22E 43-019-30113-0000 43-019-30113-0001	Union Texas Petroleum Cities Services Oil Co., Federal-Weaver No. 1	3-17-73 7-10-75	8,286 10,721	Deviated well initially by Union Petroleum, re-entered and deepened to 10,721 feet; abandoned.

munication, 1995).

Springs and seeps, issuing from the Glen Canyon Group, are common in the Moab quadrangle. Notable springs include Matrimony Spring, which issues from the base of the Wingate Sandstone on the south side of the Colorado River just east of Moab Valley, and a spring along the Kane Springs Canyon road just below the mouth of Hunter Canyon, which issues from the Wingate Sandstone. The spring water is of good quality, generally containing less than 220 ppm of dissolved solids. The water type is classed as calcium bicarbonate or calcium magnesium carbonate, and the water is moderately hard to hard (Blanchard, 1990).

The deep ground-water regime (aquifers below the Moenkopi Formation) is divided into three hydrostratigraphic units (U.S. Department of Energy, 1984). The upper unit consists of Permian rocks and the upper two-thirds of the Pennsylvanian Honaker Trail Formation. The middle unit includes the remainder of the Honaker Trail Formation and the Paradox Formation. The lower unit includes all carbonate units below the Paradox Formation. The recharge area for the upper hydrostratigraphic unit probably includes the La Sal Mountains. The transmissivity of this unit is largely unknown and untested, but permeabilities of Permian strata are low and are largely controlled by the presence of local faults and joints (Huntoon, 1985). Therefore, the amount of water in the upper hydrostratigraphic unit is expected to be small and of lower quality than that in beds above the Moenkopi. Permian and Pennsylvanian strata below the level of the Colorado River are generally saturated with sodium chloride brines. The middle unit consists of layers acting as aquicludes alternating with others of variable water-bearing capacity. Water in the middle unit is generally very salty.

The lower hydrostratigraphic unit consists of carbonates with good porosity and permeability. Oil-well data generally indicate large quantities of salty connate water. The saltiness may reflect original seawater or mixing of salines from the middle hydrostratigraphic unit.

The third ground-water regime includes water-bearing surficial deposits of the quadrangle. Larger, unconsolidated sand deposits (Qes, Qeay, Qeao, and others) that fill the hollows on the plateau offer opportunity for ground-water development. Yields are expected to be small, but possibly enough for watering stock. Springs and wells in thicker alluvial deposits may yield good-quality calcium bicarbonate or sodium bicarbonate type water. Total dissolved solids content in wells and springs is typically less than 500 ppm (Doelling, 1969). Wells with larger yields might be developed in Colorado River alluvium and in the basin fill above the Moab Valley salt-cored anticline.

GEOLOGIC HAZARDS

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

Flooding and erosion by running water are the most active and potentially damaging hazards in the quadrangle. The sparsely vegetated steep fan slopes (Qafy) and deep, narrow washes (Qa_1) are subject to flooding and rapid erosion from waters generated by cloudburst storms and spring snowmelt runoff. Debris flow, 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 channels and deposit debris where slope gradients decrease or channels become more shallow. Easily erodible bedrock and abundant unstable slope debris (Qmt) provide ample material for debris flows. Human activity can increase erosion by creating tracks and trails that channel runoff, and damaging or removing vegetation that anchors soils and slows runoff.

Flooding of the Colorado River occurs during years of unusually high spring runoff because the river is unregulated by engineered structures upstream of the quadrangle. Much of the northern part of Moab Valley (Qa_1) was flooded during the 1983 runoff (personal observations of the first author). The flooding eroded river banks and adjacent roads.

Rock Falls

Rock falls occur sporadically throughout the rugged topography of southern Grand County. In the quadrangle, rock fragments from the Glen Canyon Group and Chinle, Moenkopi, Cutler, and Honaker Trail Formations produce rock-fall debris (Qmt). The most susceptible cliffs or slopes are those broken by fractures that subparallel cliff faces.

The high cliffs that line the deeper canyons and Moab and Spanish Valleys are active rock-fall areas. Some areas of development are within the danger zones, especially along the southwest cliff bordering Moab and Spanish Valleys. Rock-fall debris may travel great distances down slope by rolling, bouncing, and sliding. The potentially large size of some debris and relatively high velocity of movement present a hazard that can easily and quickly destroy houses and buildings. The large boulders in Qmt deposits attest to previous rock-fall events. The Chinle-Moenkopi slope below the cliff is generally littered with large blocks of the Wingate Sandstone.

Problem Soil and Rock

Expansive soil and rock contain clay minerals capable of absorbing large quantities of water. In the Moab quadrangle, the Moenkopi and Chinle Formations consist mostly of fine-grained sandstone and siltstone, but include some clay horizons. The "popcorn" surface of weathered Chinle (T̶Rc) and Paradox (IPp) outcrops is indicative of the shrinking and swelling nature of the formations and their derived bentonitic soils (Schultz, 1963; Stewart and others, 1972a, 1972b).

Alluvial-fan sediments derived from the Moenkopi and Chinle Formations are susceptible to the development of collapsible soils. These soils are subject to volumetric changes that could damage structures built upon them. The existence of collapsible soils in Moab and Spanish Valleys and surrounding areas is undocumented, but susceptible sediments are present.

Fine-grained soils and surficial deposits are prone to piping and rapid erosion. 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 surface. The removal of fine particles increases void space thereby producing a "pipe" and promoting enhanced erosion. Piping is common in arid and semi-arid climates where fine-grained, non-cemented, Holocene alluvium (some Qa_2)is incised by ephemeral stream channels.

Gypsiferous cap rock (IPp) and Moenkopi Formation (Trm) and derived soils are a potential hazard in the Moab quadrangle. They may subside and collapse due to dissolution of gypsum, which creates a loss of internal structure and volume within the deposit. Structures built over dissolution areas may experience ground settlement and differential subsidence. Ground settlement may take place when water is introduced into the subsurface through irrigation, landscaping, or waste-water disposal. If thick gypsum beds are present, underground dissolution cavities may develop and collapse, forming sinkholes. Gypsum is a weak material with low bearing strength, and can cause foundation problems for heavy structures.

Landslides

Only one landslide was mapped in the quadrangle (Qms); others are present, but are too small to be mapped. They are most likely to occur in clay-rich rocks (Chinle, Kayenta, Carmel, and Morrison Formations) that dip toward valleys or canyons. Excavators should be careful not to remove rock debris that supports such dipping strata. Brittle rocks can slide over fine-grained partings and beds, and over bedding-plane fractures. Landsliding is more likely to occur during periods of above average precipitation in areas where rocks are highly fractured. In the Moab area, deformed belts on both sides of Moab and Spanish Valleys are particularly susceptible to landslides.

Shallow Ground Water

In the Moab quadrangle, shallow ground water (water at depths of 10 feet [3 m] or less) is present in an unconfined aquifer in unconsolidated alluvium (Hecker and Harty, 1988). This aquifer covers the floor of Moab Valley from the Colorado River southeastward to, and extending along, the drainage of Pack Creek. Shallow ground water can flood basements, damage underground utilities, and affect land use. Detailed information on the hydrologic characteristics of the unconfined aquifer is not available; however, Sumsion (1970) indicated that the average thickness of the saturated alluvium is 70 feet (21 m).

Potential Ground-Water Contamination

The valley-margin deformation belts, especially the northeast belt, are areas of potential ground-water contamination. Contaminant flow caused by improper waste water disposal could contaminate springs and wells in these areas through the fractures. Contamination can occur with poor septic systems, application of fertilizers to lawns, and other household discharges. The possibility of contamination is enhanced as urban development proceeds and increases in the deformed belts.

Of concern are the uranium tailings and radioactive mill scrap north of the Colorado River in Moab Valley. Leakage of contaminants into surface and ground waters is expected to be diluted by the Colorado River, but studies continue to evaluate the hazard.

Blowing Sand

Sand blowing across and accumulating on back roads occasionally causes loss of traction and blockage. Motorists using the back roads should be cautious when proceeding into areas of sheet or dune sands (Qes). Loss of traction in sandy areas becomes more pronounced during the hot, dry, summer months when even gentle slopes of sand cannot be traversed in a motor vehicle.

Earthquakes

The northern Paradox basin shows little natural earthquake activity (Smith and Sbar, 1974; Wong and Humphrey, 1989). Wong (1984) and Wong and Humphrey (1989) studied seismicity in the Paradox basin from 1979 to 1987 in connection with nuclear-waste-disposal investigations. These investigations noted very low-level earthquake activity along the Colorado River from its confluence with the Green River northward to Amasa Back (ending just west of the Moab quadrangle).

Historical seismicity in the Moab area consists of small- to moderate-magnitude earthquakes with diffusely distributed epicenters and low to moderate recurrence intervals (Wong, 1984). Earthquakes greater than magnitude 4 (large enough to be felt) are uncommon, and no faults indicating Holocene movement have been found. The quadrangle is in Uniform Building Code zone one, indicating low potential for earthquake damage (International Conference of Building Officials, 2000).

SCENIC GEOLOGY

The Colorado River and its tributaries have incised deep canyons in the colorful rocks of the Moab quadrangle and have carved many spectacular vistas. Utah Highway 279 is a beautiful drive along the Colorado River extending 15 miles (24 km) downstream from Moab to Potash. Utah Highway 128, a designated Scenic Byway, is a counterpart extending upstream 45 miles (72 km) from Moab to Interstate Highway 70. Spectacular cliff-top views of Moab and Spanish Valleys and the deeper canyons are afforded the hardy traveler who takes the time to climb the high rims.

The south part of Arches National Park is in the quadrangle. This part of the park offers a Courthouse Wash hike, lovely Entrada Sandstone cliffs, and the Three Penguins monument, but no arches. Nevertheless, several spectacular arches, mostly formed in the Navajo Sandstone, are present in the quadrangle outside of the park (figure 16). Four are named on the Moab 7.5-minute topographic map and more are present. We show several others on our geologic map (plate 1) that are not shown on the topographic map, and some are as spectacular as most in the park.

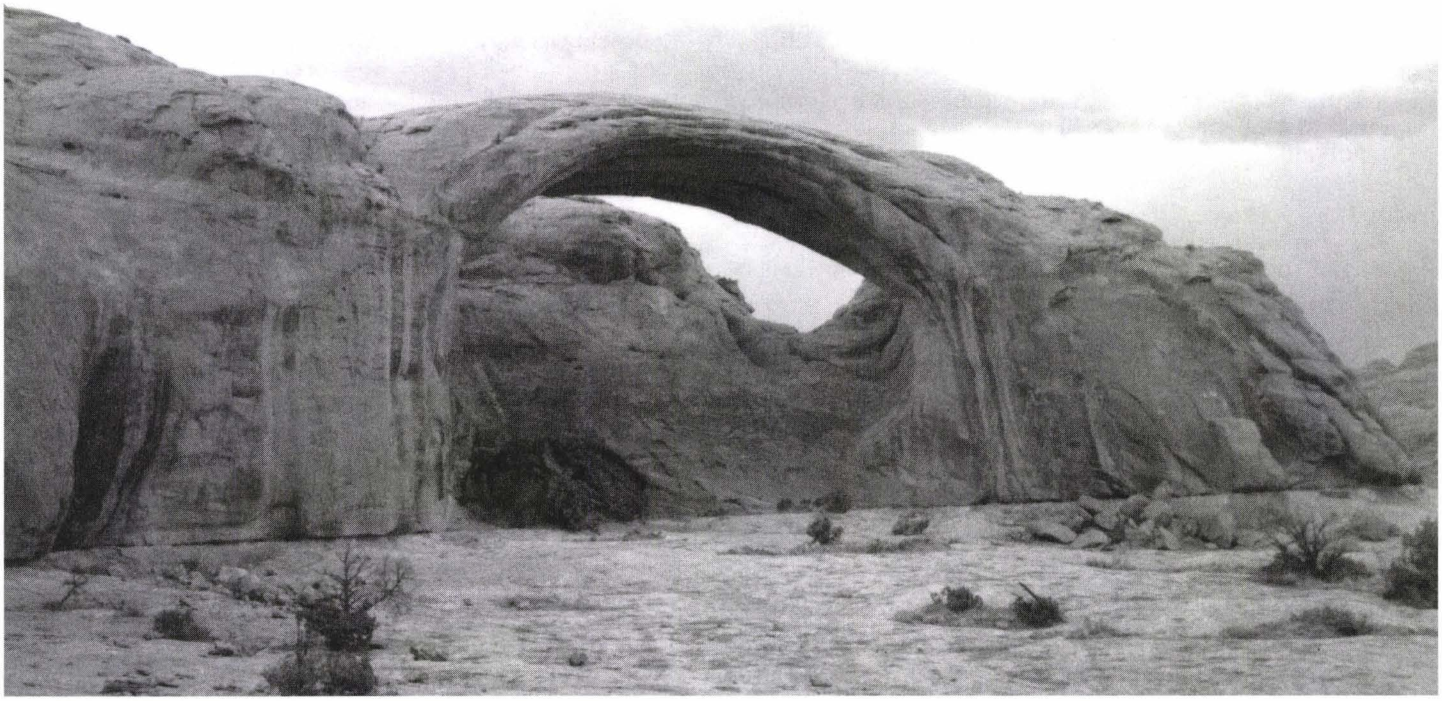


Figure 16. *Pritchett Arch, a free-standing arch, spans 130 feet (40 m), is 45 feet (14 m) wide, and is 90 feet (27 m) high. Pritchett Arch is one of several magnificent stone arches in the Moab quadrangle. Most, like Pritchett Arch, are cut in the Navajo Sandstone.*

The Behind the Rocks area between Kane Springs Canyon and Moab and Spanish Valleys consists of Navajo Sandstone that is deeply eroded along closely spaced, near-vertical joints to form a series of enormous, fin-like ridges and narrow canyons. This spectacular area is extremely rugged and traversed by few trails.

Dinosaur tracks can be inspected in the cliffs above Williams Bottom along the Colorado River (section 21, T. 26 S., R. 21 E.). The track site is marked by a sign along Utah Highway 279. Early Jurassic Theropod dinosaur tracks can be found throughout the stratigraphic section from the thick eolian sandstone near the top of the Kayenta Formation up to and including the lower part of the Navajo Sandstone.

ACKNOWLEDGMENTS

We thank Jeff McCleary of Woodward-Clyde Federal Services and Barry Solomon, Fitzhugh D. Davis, J. Wallace Gwynn, and Grant C. Willis of the Utah Geological Survey for critically reviewing the map and manuscript and making valuable suggestions. We appreciate the work of Kent Brown, who annotated the map and helped us digitize geologic contacts. Additional thanks go to G.E. Christenson, J.K. King, and C.D. Morgan of the Utah Geological Survey, Andrew Foxford of the University of Liverpool, and Loren Morten of the Utah Department of Environmental Quality for invaluable discussion on various aspects of the geology in the quadrangle.

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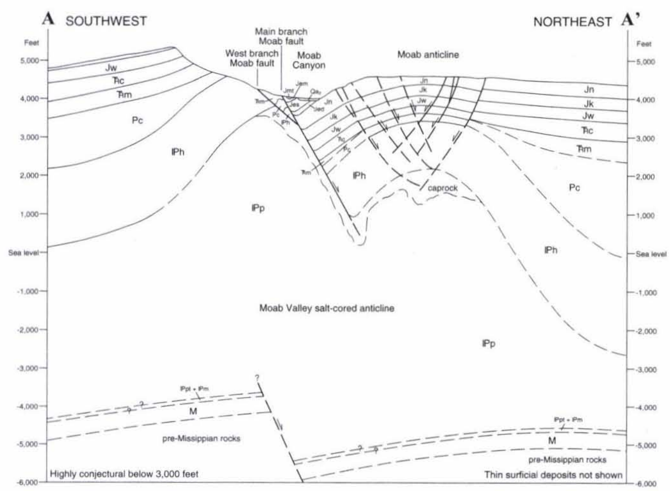
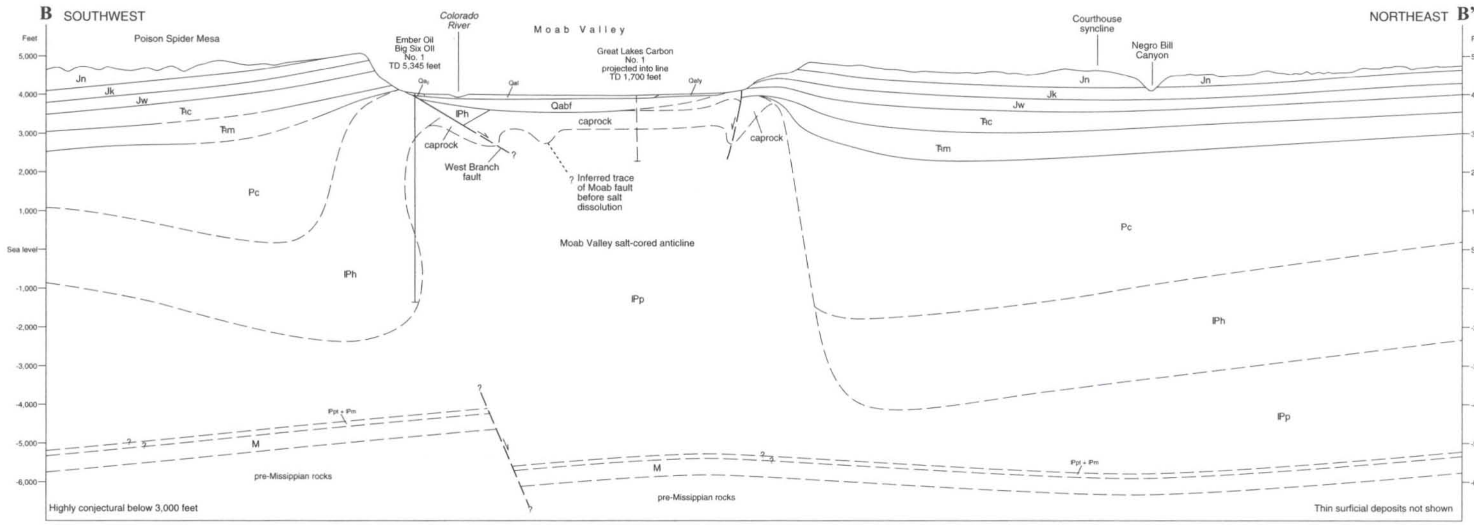
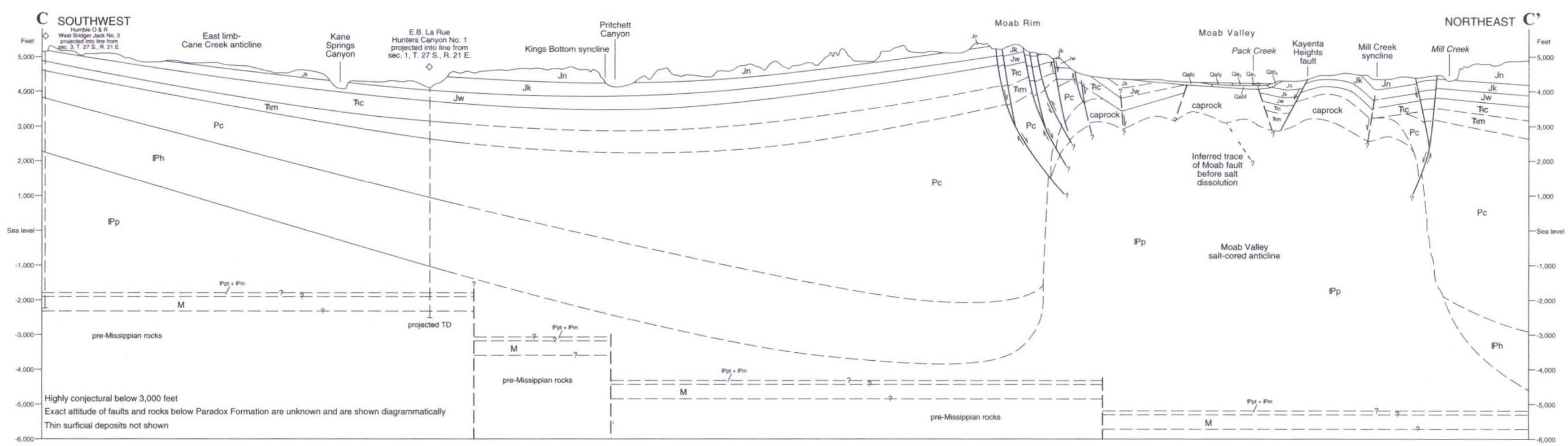
APPENDIX

Cross sections A-A′, B-B′, and C-C′ (plate 2) showing postulated deeper structures.




B SOUTHWEST
NORTHEAST B'
Feet
Poison Spider Mesa
Colorado River
Moab Valley
Ember Oil Big Six Oil No. 1 TD 5,345 feet
Great Lakes Carbon No. 1 projected into line TD 1,700 feet
Courthouse syncline
Negro Bill Canyon
caprock
West Branch fault
Inferred trace of Moab fault before salt dissolution
Moab Valley salt-cored anticline
pre-Missippian rocks
Highly conjectural below 3,000 feet
Thin surficial deposits not shown


C SOUTHWEST
NORTHEAST C'
Feet
Humble O & R West Bridger Jack No. 3 projected into line from sec. 3, T. 27 S., R. 21 E.
East limb-Cane Creek anticline
Kane Springs Canyon
E.B. La Rue Hunters Canyon No. 1 projected into line from sec. 1, T. 27 S., R. 21 E.
Kings Bottom syncline
Pritchett Canyon
Moab Rim
Moab Valley
Pack Creek
Kayenta Heights fault
Mill Creek syncline
Mill Creek
caprock
Inferred trace of Moab fault before salt dissolution
Moab Valley salt-cored anticline
projected TD
pre-Missippian rocks
Highly conjectural below 3,000 feet
Exact attitude of faults and rocks below Paradox Formation are unknown and are shown diagrammatically
Thin surficial deposits not shown