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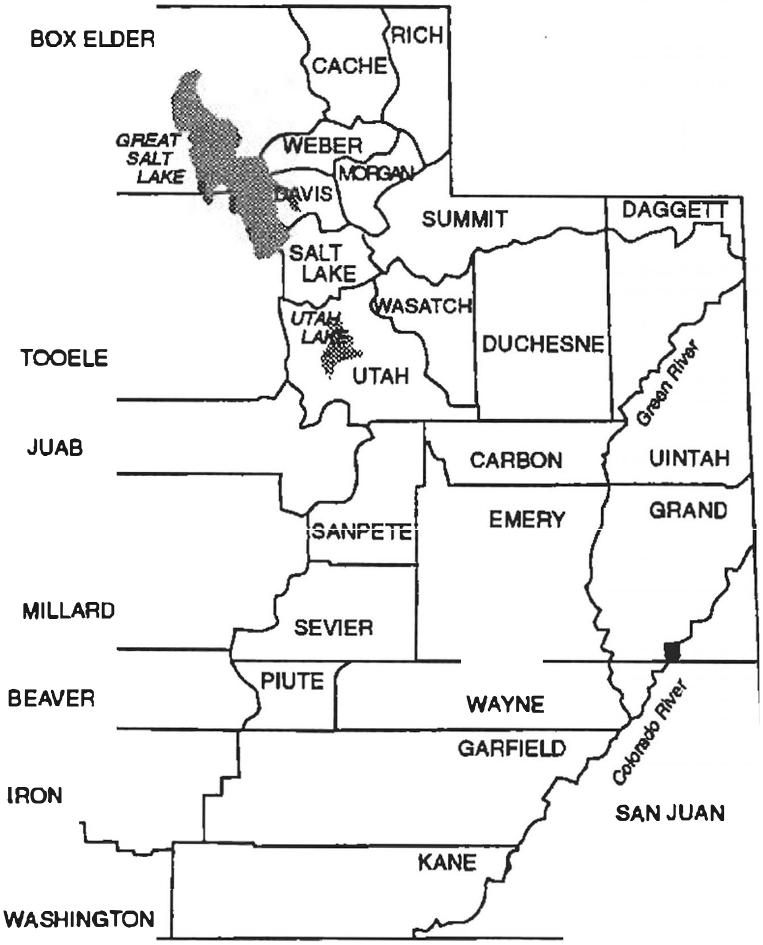

OPEN-FILE REPORT 322 **August 1995**
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

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Utah Geological Survey
a division of
Utah Department of Natural Resources
in cooperation with
U.S. Geological Survey

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

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ABSTRACT

The Moab quadrangle is located in east-central Utah on the south margin of Grand County and is named after the largest town in the region. The quadrangle is along the Colorado River in Utah's Red-Rock country and includes a small part of Arches National Park. It is in the fold and fault belt of the northern Paradox basin; an asymmetrical basin whose deepest part formed adjacent to the ancestral Uncompahgre uplift during Pennsylvanian to Late Triassic time.

Exposed strata range from Pennsylvanian to Jurassic age. These include as much as 700 feet (213 m) each of the Pennsylvanian Paradox Formation caprock and Honaker Trail Formation; 0 to 600 feet (0-183 m) of Permian Cutler Formation; 0-750 feet (0-229 m) and 100 to 700 feet (30-192 m) of the Triassic Moenkopi and Chinle Formations, respectively; and 250 to 400 feet (76-122 m) of the Wingate Sandstone, 250 to 400 feet (76-122 m) of the Kayenta Formation, 300 to 700 feet (91-213 m) of the Navajo Sandstone, 400 to 460 feet of the Entrada Sandstone, and an incomplete 70- to 80-foot (21- to 24 m) section of the Morrison Formation, all of Jurassic age. Quaternary surficial deposits include those deposited by alluvial, eolian, and mass-wasting processes.

Moab-Spanish Valley is located along the crest of the northwest-trending Moab Valley salt-cored anticline. The Moab salt-cored anticline is the dominant structural feature of the

quadrangle. The salt diapir in the core of the fold is more than 9,000 feet (2,743 m) high and is up to 2 miles (3.2 km) wide. Sedimentary rocks and structural features along its margins give evidence for Pennsylvanian to Jurassic diapirism and late Cenozoic salt dissolution. Sedimentary rocks are thin or missing over the diapir and are abnormally thick in rim synclines along the margins. Limited borehole information indicates the sides of the diapir are nearly vertical along much of its length. Valley margin strata are faulted, tilted, folded, brecciated, and replete with unconformities. 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 to the northeast. Both the main branch and west branch are normal faults with their hanging walls down to the northeast. Southeastward of its mapped exposures the trace of the faults is obscured by surficial deposits, but the displacement remains apparent along the entire length of Moab-Spanish Valley.

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

Sand and gravel, brine, stone, and perhaps 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 which underlies the quadrangle, but have not been exploited. Prospectors dug a few pits in the Honaker Trail and Chinle Formations without significant results.

Potential geologic hazards include rock falls, landslides and fractured rock, problems soils, shallow ground water, blowing sand, and evaporite dissolution. Earthquakes with low to moderate recurrence intervals are sometimes felt in the area, but are not expected to cause ground rupture or significant ground-shaking.

CONTENTS

INTRODUCTION

The Moab quadrangle is named after the city of Moab, the Grand County seat. Moab and surrounding settlements are located mainly in Moab-Spanish Valley, a northwest-trending feature divided into two parts by a low topographic saddle (figure 1). The northwest part is called Moab Valley and the southeast part is called Spanish Valley. The Colorado River flows southwesterly from the northeast to the southwest quadrants of the quadrangle in deeply incised canyons and the northern end of Moab Valley. The remainder of the quadrangle consists of mesas and benches formed on highly jointed sandstone bedrock incised by tributaries of the Colorado River.

The quadrangle is located in east-central Utah, and is served by U.S. Highway 191, a major link that connects Interstate Highway 70, 30 miles to the north to Moab City and southeastern Utah. Utah Highways 128 and 279 are joining roads that provide access up and down the Colorado River from Moab Valley, respectively (figure 1).

Elevations in the quadrangle range from about 3,940 feet (1,200 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-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 (1,340-2,134 m). The tops of mesas expose bare sandstone or thin sandy soils with stands of pinion and juniper trees at higher elevations. At lower 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 and below the cliffs.

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. It is not uncommon for the population of the quadrangle to double 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. Governmental 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 maintained in the valley and cattle are grazed on the benches.

McKnight (1940), Hemphill (1955), Miller (1959), Probandt (1959), Richmond (1962), Williams (1964), Huntoon and others (1982), and Doelling (1985) previously mapped the geology of all or parts of the Moab quadrangle at various scales. The area is included in the recently completed Moab 30 x 60-minute, 1:100,000-scale geologic map (Doelling, 1993). 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-Spanish Valley.

STRATIGRAPHY

Rock formations exposed in the Moab quadrangle range from Middle Pennsylvanian to Late Jurassic in age. Salt in the Middle Pennsylvanian Paradox Formation has undergone flowage over a long time interval to produce an elongated salt diapir beneath Moab-Spanish Valley and to completely remove salt from adjacent areas. Caprock of this diapir is present in Moab Valley. Salt movement greatly affected the Late Pennsylvanian through Triassic strata deposited in the area. Jurassic strata show less dramatic effects. Contemporaneous sedimentation and salt tectonics produced lateral variations in lithofacies, differences in unit thicknesses, and the geometry of the units (Stewart and others, 1972a).

Pennsylvanian Rocks

Paradox Formation

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 siliciclastics (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 caprock forming two northwest-trending, discontinuous belts along the southwest and northeast margins of Moab Valley (figure 2). Caprock is the residue formed at the top of leached salt diapirs (Hite and Lohman, 1973) formed as salt layers are successively dissolved and carried away by fresh 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. The mudstone and shale have disrupted and contorted bedding below a thin "popcorn"-weathering surface. Selenite and alabaster gypsum form resistant outcrops with pitted and irregular surfaces. Broken fragments and chips of mudstone, shale, silty sandstone, muddy dolomite, and micrite limestone litter the outcrop surfaces. The log from a gas storage and salt-water injection disposal well, NE 1/4 NW 1/4 section 35, T. 25 S., R. 21 E. (Great Lakes Carbon Corporation No. 1), indicates the thickness of caprock in Moab Valley is at least 400 feet (122 m) thick.

The thickness of the Paradox Formation in the Moab quadrangle area is highly variable due to salt flowage. Along the axial trace of the Moab Valley salt diapir the formation has structurally thickened to at least 9,000 feet (2,750 m) (plate 2 cross sections). The Union Oil/Cities Services, Federal-Weaver

No. 1 well (SE 1/4 NW 1/4 SE 1/4 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 (SW 1/4 NE 1/4 section 1, T. 26 S., R. 22 E.), located approximately 4 miles (6.5 km) east-northeast of Moab Valley in the Rill Creek quadrangle, penetrated only 300 feet (91 m) of salt-bearing Pennsylvanian strata (Ross and Mulvey, in preparation). The original depositional thickness of the Paradox Formation in the salt-cored anticline area in the northern Paradox basin is estimated to have been at least 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; and Woodward-Clyde Consultants, 1983). At high-stand conditions the basin was flooded with marine waters and shelf sediments. At low-stand conditions, sea-water evaporation and influx of saline ground water produced hypersaline conditions in the restricted basin. Anhydrite, halite, and potash (sylvite or carnallite) were successively precipitated.

Honaker Trail Formation

About 600 to 700 feet (183-213 m) of the upper part of the Honaker Trail Formation are exposed in the Moab quadrangle. Outcrops of the Honaker Trail consist of interbedded sandstone, limestone, and siltstone that form ledgy beds along the southwest wall of Moab Canyon in the northwest corner 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 is quartzitic and fine grained, although a few are medium grained. The grains are well to moderately sorted, and are commonly cemented with carbonate. Some sandstone beds are micaceous, others are subarkosic. Bedding is mostly medium to thick bedded. In places the beds are divided by thin siltstone or shaly partings. Crossbedding is locally displayed along the resistant ledges.

Limestone beds are gray to light gray, variably argillaceous, contain vugs filled with quartz or calcite, weather hackly, and contain fossil debris. 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. Identified fusulinids date the Honaker Trail Formation in the Moab quadrangle as Virgil (uppermost 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. Siltstones are generally lavender, purple, or green and of a deeper shade than those of adjacent sandstone beds. Siltstone is always less resistant than limestone and sandstone.

The basal contact of the Honaker Trail is not exposed in the quadrangle. The upper contact (Pennsylvanian-Permian contact with the overlying Cutler Formation is placed at the top of a light-gray, sandy limestone bed overlain by either a purple siltstone slope capped by a conspicuous white and red-brown, fine-grained sandstone bed or just 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 near shore environments during latest Desmoinesian through Virgilian time (Melton, 1972; Doelling and others, 1994).

Permian Rocks

Cutler Formation

Outcrops of the Permian Cutler Formation in the Moab quadrangle are limited to the southwest wall of Moab Canyon, and excepting Moab-Spanish Valley and its margins, is assumed to be present everywhere in the subsurface. Cutler Formation exposures, west of the Arches National Park visitor center, consist mainly of interbedded red to red-orange, mostly fine-grained subarkosic to quartzose sandstone, and red-purple arkosic, conglomeratic sandstone. The red to red-orange sandstones are generally more resistant than the red-purple sandstones. Subarkosic to quartzose sandstone is fine- to medium-grained, moderately well sorted, generally micaeous, 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 or gneissic pebbles and cobbles, commonly as much as 2 inches (5 cm) in diameter. These sandstones contain abundant visible mica and feldspar grains. Arkosic beds are commonly trough cross-bedded and have cut-and-fill features.

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

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 visitor center; one 111 feet (34 m), the other 246 feet (75 m) above the contact with the underlying Honaker Trail. The Lower Triassic Moenkopi Formation overlies the angular unconformity at the top of the Cutler. This angular unconformity dramatically thins the Cutler from northwest to southeast along the southwest wall of Moab Canyon. The Cutler is about 380 feet (116 m) thick in outcroppings south and just above the bend in U.S. Highway 191. From this location, the top of the Cutler is progressively truncated, related, in part, to movement of the Moab Valley salt diapir. The Cutler is cut out completely in the NW 1/4 section 34, T. 25 S., R. 21 E. The thickness of the Cutler Formation in the Gold Bar Canyon quadrangle to the west ranges from 900 to 1,200 feet (274-366 m) (Doelling and others, 1994). The Cutler Formation is approximately 4,550 feet (1,400 m) thick in the Burkholder No. 1-G-1 well in the adjacent Rill Creek quadrangle. These dramatic variations in the thickness of the Cutler Formation indicate salt-tectonic activity during the Permian. The outcrops in Moab Canyon and exposures at other salt-cored anticlines in the area (Dane, 1935; Cater, 1970; Doelling, 1988, Ross, in preparation) indicate the Cutler is commonly missing over the tops of salt diapirs.

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

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 reddish-brown to reddish-orange color, commonly described as "chocolate brown" in appearance (Doelling, 1988).

Moenkopi Formation outcrops extending northwest above the railroad tracks at Emkay to the edge of the quadrangle southwest of Moab Canyon are crudely divisible into three parts (not mapped): a lower steep slope, a middle ledge-former, and an upper steep slope. These divisions may correspond to Shoemaker and Newman's (1959) Tenderfoot, Ali Baba, and Sewemup Members.

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 (Doelling and Ross, 1993; 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 locally found below the conglomerate. The lenses are indistinctly bedded and form a steep smooth cliff. Scattered quartz grains in a mainly finer grained unit is characteristic of the Tenderfoot and Hoskinnini Members of the Moenkopi (Shoemaker and Newman, 1959; Stewart and others, 1972b).

The mostly thin beds of the lower steep slope become progressively thicker upsection (gradational boundary). The thicker beds form distinct ledges, which dominate the middle ledge former and set it apart from the steep slope formers above and below. Most of the descriptive elements of the lower steep slope are valid for the middle ledge former. The boundary between the middle ledge former and the upper steep slope is more abrupt. Like the lower steep slope, bedding is thin to fissile, generally thinner. Also, the upper steep slope displays a light-"chocolate-brown" rather than a medium-"chocolate-brown" coloration.

The upper contact with the Chinle Formation is an angular unconformity with slightly irregular relief. The chocolate-brown thinly bedded Moenkopi is overlain by either a white quartzose conglomeratic sandstone or mottled-textured, variegated mudstone, siltstone or sandstone of the basal Chinle. Southeast of the railroad tunnel portal, this angular unconformity at the top of the Moenkopi cuts down section to the the southeast, just like with 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. The thickness of the lower steep slope and middle ledge former are nearly constant, about 90 and 135 feet (27 and 41 m) respectively. The variation in the formational thickness is due to the degree of downcutting along the angular unconformity at the top. Southeast of the railroad tunnel portal the unconformity at the top cuts successively more section out so that in the SW 1/4 SE 1/4 NW 1/4 section 34, T. 25 S., R. 21 E. the formation is only 70 feet thick. South of the Colorado River the Chinle Formation rests directly on the Paradox Formation and the Moenkopi Formation is missing along the outcrop.

At Kane Springs Canyon (southwest corner of the quadrangle) Moenkopi exposures are of strata present above the Hoskinnini Member, which is well exposed just south of the quadrangle boundary. The Hoskinnini is the basal member of the Moenkopi throughout southeastern Utah (Stewart and others, 1972b; Huntoon and others, 1994). The exposure, above the Hoskinnini, is generally similar to the exposures southwest of Moab Canyon. The exposures, however, cannot be differentiated into parts; ledge-forming units are irregularly distributed throughout the section. 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 anticline, just west of the quadrangle. The Moenkopi, above the

Hoskinnini, is 235 feet (72 m) thick at the south edge of the quadrangle. An additional 150 feet (46 m) of strata appear eastward under the unconformity before the exposure disappears into the subsurface. The Hoskinnini Member is about 115 feet (35 m) thick just south of the quadrangle so that the maximum observable thickness of the Moenkopi Formation is 500 feet (152 m). The formation is known to be missing over the Moab salt-cored anticline, and may be as much as 750 feet (229 m) thick in the subsurface because of salt tectonism.

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

The Chinle Formation is exposed in the cliff walls bordering both sides of Moab-Spanish Valley 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 mainly 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), Hazel (1991) divided the Chinle into formal and informal units in the Moab area. They recognized the questionable use of formal members from southeastern Utah into the Moab area because of correlation problems due to lithofacies changes, unconformities, thickness variations and different source areas. Doelling and Ross (1993) and Hazel (1994) have demonstrated that lithofacies and thickness variations in the Moab and Castle Valley area were controlled by salt tectonism. Thicker packages 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 (1993) 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 thin and discontinuous.

Basal conglomeratic sandstone of the lower member is quartzose-subarkose and -sublitharenite composed of quartz, chert, and feldspar grains. 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. Cementation is mainly calcareous, but is locally siliceous. Coloration 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 is common, as are cut-and-fill features. Locally, lenses of conglomerate containing angular, dark-red-brown siltstone and mudstone clasts scoured from the underlying Moenkopi Formation are present at the base.

Siltstone and mudstone are commonly mottled yellow, purple, orange, red brown, gray, and white. Interbedded siltstone and mudstone commonly has an angular blocky to granular appearance. Mineralogical differences between the mottled strata and unaltered rocks are indicative of pedogenic alteration as are local calcareous and chert nodules. The mottled strata contain more mixed illite-montmorillonite clay and less illite clay than unaltered rocks (Stewart and others, 1972a). 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, verbal communication, December, 1993). In the Moab quadrangle outcrops of the lower member of the Chinle range from 0 to 65 feet (0-20 m) thick.

The upper member can be subdivided on geomorphic appearance into a lower slope-forming unit, middle ledge-forming unit, upper slope-forming unit, and an upper ledge-forming unit. It is important to note that each of these units has local internal variations in lithology, coloration, and thickness.

The lower slope-forming unit consists of red-brown, gray-red, and green-gray, interbedded siltstone, mudstone, and andstone that weathers as a steep slope with thin, discontinuous edges of sandstone and conglomeratic sandstone. 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 crossbeds. Conglomeratic sandstone is intraclastic, calcareous, and typically forms lenses with scoured bases.

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

The middle ledge-forming unit consists of brown-gray, green-gray, and red-brown conglomeratic sandstone and sandstone interbedded with red-brown siltstone and mudstone. These strata consist of thick to massive ledges separated by thin beds that form steep slopes. The unit 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 vertibrate fragments. Fine- to medium-grained sandstone is calcareous and quartzose. Siltstones vary from horizontally laminated, 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 thickness of the middle ledge-forming unit ranges from 50 to 155 feet (15-47 m) where measured; 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 include sparse lenses of coarse grains. These sandstones are predominantly sublitharenites, consisting of quartz, chert, carbonate rock fragments, and minor mica. Grains are subangular to subrounded and moderate to well sorted. Primary sedimentary features include horizontal bedding, small-scale trough cross-bedding, and assymetrical ripple laminations. Siltstone is muddy, calcareous, indistinctly bedded and laminated to structureless. Lithic pebble conglomerates contain gray-red to light-gray calcareous siltstone and mudstone fragments, dull-gray carbonate, 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. 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. The lithic pebble conglomerates are interpreted to represent the cannibalization of flood plain and lacustrine deposits in the Chinle Formation (Blakey and Gubitosa, 1983).

The thickness of the upper slope-forming unit ranges from 95 to 210 feet (29-64 m) where measured. 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 sandstones are horizontally laminated and faint cross-bedding is sometimes present. These sandstone ledges are interbedded with pale-red to red-brown siltstone and mudstone. Mudstones often have mudcracks. The sandstones are interpreted to be eolian sand sheets deposited prior to the development of the Wingate Sandstone erg (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. The maximum observed thickness is 45 feet (14 m). It thickens eastward in Kane Springs Canyon from 25 to 41 feet (7.6-12.5 m), it is 9 feet thick (3 m) at Jackass Canyon, and is 40 to 45 feet (12-14 m) thick where observed along the southwest flank of the Moab salt-cored anticline north of The Portal.

The upper Chinle contact was chosen at the top of a dark red-brown, platy to very thin bedded, recess-forming siltstone above which orange-brown, thick, flat, massive beds of the Wingate are present. The base of the Wingate contains pull aparts, mud galls, and pebbles. The contact is an unconformity that regionally truncates older strata (J-0 unconformity of Pipiringos and O'Sullivan, 1978).

Measured sections indicate the exposed thickness of the Chinle Formation is approximately 100 to 640 feet (30-195 m) in the Moab quadrangle. The Chinle may be thicker in the subsurface adjacent to the valley. The Chinle is approximately 640 feet (195 m) thick in the Burkholder No. 1-G-1 well (Ross and Mulvey, in preparation) and is as much as 800 feet (244 m) thick 6 miles (9.7 km) up the Colorado River (Doelling and Ross, 1993). 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, with eolian environments developing towards the end of deposition (Dubiel, 1994).

Jurassic Rocks

Jurassic strata in the Moab quadrangle include (ascending) the Wingate Sandstone, Kayenta Formation, Navajo Sandstone, Entrada Sandstone, 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). The age of the Glen Canyon Group is considered to be Early Jurassic (Pipiringos and O'Sullivan, 1978; Peterson and Pipiringos, 1979; and Imlay, 1980) (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 and 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 and are locally horizontally banded. Locally, the Wingate forms rocky cliffs along the margin of the Moab-Spanish Valley where it is highly fractured.

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 subarkosic, containing quartz, feldspar, and traces of chert and accessory minerals (Lohman, 1965; Cater, 1970). Sand is moderate to well sorted and grains are subangular to rounded, with quartz grains commonly frosted suggesting eolian transport. Sandstone is calcareous and siliceous and commonly stained with iron oxide. Cementation is moderate to well indurated.

Bedding is thin to massive, but the Wingate weathers to thick, massive ledges and cliffs. Primary sedimentary features noted include: horizontal stratification, planar-tabular, wedge-planar, and trough cross-bedding. Sets range from small to large-scale. Assymetrical ripple laminations may be present.

The contact with the overlying Kayenta Formation is an irregular and 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 scour into massive eolian sandstone beds. Also, 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) as conformable and gradational. An hiatus of limited extent seems reasonable. At outcrops, Kayenta beds are more reddish or pale purplish, lithologically more heterogenous, and contain fluvial sedimentary features. The Wingate-Kayenta contact is sometimes difficult to identify from a distance along the massive cliffs because the basal beds of the Kayenta are thick bedded to massive, and are the same color as the underlying Wingate. In this case, the contact is placed 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 SE 1/4 section 26, T. 25 S., R. 21 E., and 250 feet (76 m) thick on the west side of Courthouse Wash in the SW 1/4 SE 1/4 section 22, T. 25 S., R. 21 E. Both measurements were taken 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 thick at Jackass Canyon.

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

Kayenta Formation

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 ledgy bare-rock surfaces. Soft siltstone and sandstone is present in the upper third of the unit where a prominent bench usually 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 red, but individual lenses and beds vary considerably; some are purple, lavender, red, brown, tan, orange, white, or gray. Most of the sandstone lenses are moderate 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 moderate- 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. Some lenses display cut-and-fill features, current ripple marks, and rare slump features. Small-scale cross-bedding and horizontal to low-angle laminated bedding are common. Overturned cross-bedding is a sedimentary structure that is common in the fluvial sandstones of the Kayenta along the flanks of Moab Valley.

Finely laminated and locally ripple-laminated, very fine-grained sandstone and siltstone is interbedded with calcareous mudstone. The calcareous mudstones are thinly laminated to structureless and locally are cherty and sandy. These lithologies commonly form 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. Conglomerate is poorly sorted and consists of angular to subrounded granules and pebbles of equant to bladed, reddish brown to grayish red purple siltstone and mudstone in a sandy matrix. Clast lithology, coloration, 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 (figure 3). The eolianite 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 (plate 1).

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 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) thick, and is preferential cemented, ranging from friable to well indurated. The variable cementation and coloration give the ledge a unique "rotted or sculptured" weathering appearance (figure 4). 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. The Kayenta is 293 feet (89 m) thick just west of Courthouse Wash in the SW 1/4 SE 1/4 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 NW 1/4 SE 1/4 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.

The Kayenta Formation in the salt-cored anticline region was deposited in sandy fluvial systems that were sourced 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

The light-gray, pale-orange, and red-orange Navajo Sandstone is exposed on most of the mesas of the quadrangle. The lower part of the Navajo consists of interbedded sets of flat- and cross-bedded sandstone (figure 3). The upper part of the Navajo consist 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 both calcareous and, locally siliceous. The Navajo Sandstone is characterized by large, sweeping, tangential cross beds with foresets that may dip more than 30°. The sweeping crossbeds are preserved in massive sets 15 to 25 feet (4.6-7.6 m) thick.

Sparse, thin beds of gray to pink-gray, silty to sandy, micritic limestone are locally interbedded with the sandstone (Jnl). Limestone beds commonly contain small nodules of authigenic jasper (red chert). Limestone beds grade laterally into red sandstone or siltstone which form bounding surfaces between large 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 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. The Navajo 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. The thickness of the Navajo varies from 250 to 450 feet (76-137 m) in the vicinity of Arches National Park (Doelling, 1988). Local areas of thickening and thinning of the Navajo adjacent and over the salt-cored anticlines may be due to flowage of the salt during the latest Early Jurassic.

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.

Entrada Sandstone

The Middle Jurassic Entrada Sandstone in the Moab area consists of three members (ascending), the Dewey Bridge, Slick Rock, and Moab. The full thickness of the Entrada Sandstone, at exposures measured northeast of the Arches National Park visitor center, is about 425 feet (130 m). An incomplete exposure of the Dewey Bridge Member is also present along the axial trace of the Kings Bottom syncline on Poison Spider Mesa.

Dewey Bridge Member (Jed): Dewey Bridge Member strata were formerly mapped as the Carmel Formation (Dane, 1935; McKnight, 1940) in the Arches National Park area, but Wright and others (1962) proposed a change based on lithologic criteria. However, outcrops of the Dewey Bridge are laterally continuous and correlative with the Carmel Formation to the west (Doelling, 1993)

The Dewey Bridge is a red-brown, muddy, mostly fine-grained sandstone with 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 contact with the Slick Rock Member is irregular and probably conformable.

Slick Rock Member (Jes): The Slick Rock Member crops out only 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 about 250 feet (76 m) thick in the quadrangle. The contact with the overlying Moab Tongue is sharp and is placed along a bedding parting that is overlain by slightly coarser and lighter-colored sandstone of the Moab Member. 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 sandstone. The sandstone is very fine to fine grained with sparse medium to coarse sand grains; it displays distinct high-angle cross-stratification and planar bedding. The sandstone is well indurated with calcareous cement, but weathers to rubbly slopes where fracture density increases near the Moab fault zone.

Moab Member (Jem): The Moab Member of the Entrada Sandstone is a conspicuous, resistant sandstone that forms the capping surface of Entrada outcrops in the northwest corner of the quadrangle. The Moab Member ranges from 60 to 100 feet (18-30 m) thick. The Moab Member correlates with the Curtis Formation of western Grand County (Doelling, 1993). The upper contact is sharp and drawn where the light sandstone of the Moab Member is overlain by the red siltstone of the Tidwell Member of the Morrison Formation. The base of the Morrison 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 sandstone. The sandstone is usually well indurated, exhibits low-angle cross stratification, and is usually highly jointed in outcrop. The sandstone resembles the Navajo in color and cementation with differential etching of cross-bed laminae.

Morrison Formation

The Upper Jurassic Morrison Formation consists of three members in the Moab area (ascending), the Tidwell, Salt Wash, and Brushy Basin. Only the Tidwell and basal part of the Salt Wash Members are exposed in the northwest corner of the Moab quadrangle. The Morrison Formation exposures are preserved along the down-dropped margins of small displacement faults.

Tidwell Member (Jmt): This thin red member is an excellent marker unit. In the Moab quadrangle it is 48 feet (14.6 m) thick. This unit was formerly mapped as the Summerville Formation (Dane, 1935; McKnight, 1940, and Williams, 1964). The Tidwell Member can easily be subdivided into two units, the lower of which correlates with the Summerville Formation and the upper of which correlates with gypsiferous and silty beds at the base of the Salt Wash in western Grand County (Doelling, 1993). 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 lowermost part of the mapped unit correlates with the Summerville Formation and consists of brown to red, thin-bedded sandstone and siltstone that forms a steep slope 6 to 12 feet (1.8-3.6 m) high 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, and shale containing thin to nodular beds of gray limestone. The lowermost limestone bed generally contains very large, white siliceous concretions which have diameters of several feet (as much as a meter or more). The limestone-bearing 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 light-colored sandstone and conglomeratic sandstone interbedded with green and red siltstone slopes. The sandstone is generally poorly sorted and fine to coarse grained. The maximum exposed thickness on the Moab quadrangle is a few tens of feet (as much as 8 m).

Quaternary Deposits

Quaternary deposits in the Moab quadrangle are grouped into alluvial, eolian, mass-movement, colluvial, mixed depositional environment, and human-made deposits. The Moab quadrangle, as well as the Colorado Plateau in general, is an area primarily undergoing erosion. Therefore, most Quaternary deposits are relatively thin and temporary in nature. However, the mouth of Moab Canyon, Moab Valley, and Spanish Valley are areas of surficial sediment accumulation and subsidence caused by removal of salt from the underlying Moab Valley salt-cored anticline. Quaternary deposits in Moab Valley near the Colorado River are several hundred feet (about 135 m) thick.

Alluvial Deposits

Modern alluvium (Qal): Alluvium along larger, active drainages and their floodplains have been mapped as modern alluvium (Qal). 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 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 consist of 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 it is as much as 20 feet (6 m) thick.

Alluvium (Qa): Alluvium forming the first surface above the modern floodplain of the larger, active drainages is mapped as alluvium (Qa). The unit forms a terrace surface approximately 10 to 50 feet (3-15 m) above active channels. In Moab Valley, Qa deposits overlie a thick section of older basin-fill alluvium (Qabf, cross-section only). Alluvium filling Moab Valley ranges from 20 to 450 feet (6-137 m) thick. Deposits of Qa grade upslope into younger alluvial-fan deposits (Qafy) along the valley margins. The ephemeral stream deposits of Bloody Mary Wash with Moab Canyon are included in the Qa deposits.

Qa alluvium consists of sand, silt, clay, and local gravel, similar to modern alluvium (Qal). Qal & Qa 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 alluvium (Harden and others, 1985). Qa deposits are as much as 30 feet (9 m) thick. Qa alluvium is late Pleistocene to early Holocene in age and is probably equivalent to Pinedale-age deposits of the Rocky Mountain region.

Alluvial terrace deposits (Qat3, Qat4, Qat5, Qat6): Older alluvium is preserved in isolated terraces along the Colorado River, Mill Creek, Pack Creek, Kane Springs Creek, and Courthouse Wash. The deposits typically consist of poorly sorted, subrounded to rounded, crudely stratified, sandy cobble gravel. The alluvium is mostly the same as that contained in the modern deposits, however, fine-grained materials are commonly removed from their surfaces by wind or by sheet wash making the coarse constituents appear prominent. Contained materials 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 (Qal) 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. Qat3 deposits are found 50 to 100 feet (15-30 m) above the present stream channel. Calcic soil horizons developed on Qat3 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 the soil carbonate has undergone dissolution and reprecipitation. Qat4 deposits are found 100 to

150 feet (30-45 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). Qat5 and Qat6 deposits are 200 to 240 feet (61-73 m) and 260 to 280 feet (79-86 m), respectively, above the modern stream channels. 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. Qat3 deposits at the mouth of Mill Creek canyon are 60 feet (18 m) thick at the surface, but bases are not exposed. Qat3 deposits are interpreted to be equivalent to Bull Lake deposits (middle to early late Pleistocene age) in the Rocky Mountain region (plate 2). Alluvial terrace deposits (Qat4-6) are middle to early Pleistocene in age.

<u>Basin-fill deposits (Qabf):</u> These deposits fill Moab Valley beneath a cover of late Pleistocene to Holocene surficial deposits. Meager drill-hole information indicates the deposits are graveliferous and dominated by alluvium. It is assumed the deposits contain river and stream alluvium, fan alluvium, and possibly some eolian interbeds. The Great Lakes Carbon Corporation No. 1 well, SW 1/4 NE 1/4 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., reportedly penetrated 406 feet

(124 m) of basin-fill deposits. The deposits may be as much as 450 feet thick (137 m) under Moab Valley.

Younger alluvial-fan deposits (Qafy): Younger alluvial fan deposits (Qafy) form apron-like slopes along the northeast and southwest sides of Moab Valley. The surfaces of the younger alluvial fans have dentritic drainage patterns and the deposits grade upslope into bedrock, talus (Qmt), or head in gullies of older fan deposits (Qafo). Younger fans grade downslope into alluvium (Qa and Qabf in cross-section) 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 is arbitarily placed at the change in orientation of contours in the valley.

Younger alluvial fan deposits consist of poorly sorted, generally unstratified 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.

In general, younger alluvial fans are active and correlative with Qal and Qa deposits (late Pleistocene to Holocene age). Locally, Qafy surfaces are inactive. Pedogenic carbonate in these deposits consist 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) thick at the surface, but Qabf equivalents are probably thicker.

Older alluvial-fan deposits (Qafo): Older alluvial fan deposits (Qafo) underlie a valleyward-sloping bench that extends northeastward from the southwest side of Moab and Spanish Valleys. This bench 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 well into the valley and the deposits are commonly mantled by a layer of unstratified (windblown) sand.

Older alluvial fan deposits consist of poorly-sorted, generally unstratified, muddy to sandy cobble gravel. Boulders are common in proximal areas. Angular to subangular gravels are mixed with rounded gravels of La Sal intrusive porphyry 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. Older fan deposits grade to the position of the Qat3 surfaces in Moab and Spanish Valleys (Harden and others, 1985). They concluded that the Qat3 deposits and equivalent Qafo deposits are correlative to Bull Lake-age deposits in the Rocky Mountain region. Older fan deposits are up to 40 feet (12 m) thick at the surface.

Mass-Movement Deposits

Talus (Qmt): Talus deposits (Qmt) consist of gravity-induced rock-fall 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 (Qafo and Qafy) at their downslope extent The contact between talus and alluvial fan deposits is placed at a break in slope.

Talus consists of 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 is 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 being relatively smooth to being scoured by shallow gullies. Talus deposits are probably late Pleistocene to latest Holocene in age.

<u>Landslide deposit (Qms)</u>: 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 Entrada Sandstone has slid approximately 300 feet (91 m) southward on a shale parting at its contact with the underlying Slick Rock Member. The landslide is a translational slide whose head scarp was possibly controlled by northwest-striking joints in the Moab Member.

The age of movement of the landslide must post-date incision of Moab Canyon 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 Pleistocene in age.

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 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 interpreted to be Holocene in age.

Eolian Deposits

Eolian sand deposits (Qes): Well sorted, unstratified to cross-bedded sand deposits cover surfaces and fill hollows locally across the quadrangle. The sand is derived from the weathering of Lower and Middle Jurassic sandstone formations. Qes deposits typically form relatively thin and discontinous 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 on the canyon wall southwest of the Arches National Park visitor center.

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 observed thickness of 30 feet (9 m) was noted. Eolian sand deposits are interpreted to be latest Pleistocene to Holocene in age because of their thinness, transitory nature, and lack of soil development.

Mixed Depositional Environment Deposits

Eolian-alluvial deposits (Qea): 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 (Qea). Larger deposits of this type are mapped flooring Hidden Valley and canyons near Pritchett Natural Bridge. The deposits form irregular thin blankets with scattered surface rills and gulleys.

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 (3m) thick.

Older eolian-alluvial deposits (Qeao): The overall character of older eolian and alluvial deposits (Qeao) is similar to the younger Qea deposits except they exhibit the soil development indicative of an older age. Their surfaces are currently being modified and eroded. The deposits mostly consist of 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 pebbles and lenses of pebbly gravel and is capped by an eroded Stage V petrocalcic soil. The elevation of the deposit is about 700 feet (213 m) above the Colorado River. 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 late Pleistocene based on their varying degrees of petrocalcic soil development. Maximum thickness of these deposits is 15 feet (4.6 m).

Eolian-residual deposits (Qer): Thin, sheet-like deposits of windblown fines mixed with weathered bedrock have been mapped on some of the resistant beds of limestone 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 petrocalcic soils. The deposits are believed to be of Pleistocene age. Deposits are mostly less than 3 feet (1 m) thick.

Alluvial-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 these deposits are mostly of sand and small sandstone fragments because the adjacent outcrops are Navajo Sandstone. The unconsolidated deposits are as much as 10 feet (3 m) thick. Deposits are probably of late Pleistocene to Holocene age and equivalent to Qa1 and Qa alluvium.

Fill and Disturbed Deposits (Qfd)

We mapped the larger areas of man-made fill and disturbed ground in the quadrangle, but not the urbanized or developed areas. We did map 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 the 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 grade of the railroad 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 cubic meters) 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 variable 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. Several folds and one major fault extend diagonally northwest-southeast across the Moab quadrangle. The most prominent of these structural features is a salt-cored anticline. The crest of the salt-cored anticline is faulted by a large extensional fault and has collapsed due to partial dissolution of the salt core. Erosion and burial of the deformed crestal rocks has 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 (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).

In the deepest part of the basin, salt beds (mostly halite) began to flow to discontinuities in the floor of the Paradox basin caused by faults in the pre-Paradox Formation rocks (Baars, 1966; Joesting and Case, 1960; Stevenson and Baars 1987). The salt thickened at these discontinuities to form northwest-trending elongate salt diapirs. Synchronous with this period of salt movement, Late Pennsylvanian through Triassic strata were locally thinned, folded, brecciated, truncated and removed by erosion, or possibly never deposited across the crests of the salt diapirs. Local basins, called rim synclines, developed on the sides of the salt diapirs as the underlying salt flowed into the diapirs. These basins were filled with a thick complement of late Pennsylvanian to Triassic sediments. The salt continued to move and have a more localized effect on the thickness and lithofacies of Jurassic and Cretaceous strata at some of the salt diapirs within the basin (Shoemaker and others, 1958; Cater, 1970)

Approximately west-southwest regional compression effected the region during the Late Cretaceous to Early Tertiary Laramide orogeny (Cater, 1970; Heyman and others, 1986). It is hypothesized that strata were folded into broad northwest-trending anticlines and synclines (Cater, 1970; Doelling, 1985, 1988). Anticlines may have been superimposed on the pre-existing salt-cored anticlines and gentle synclines formed between them, and in some cases superimposed, in part, on the 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 they post-date 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), regional extension during the Mesozoic to Cenozoic (Ge and Jackson, 1994), and epeirogenic uplift of the Colorado Plateau during the Late Tertiary (Parker, 1981; Ross, in press).

The Moab region was epeirogenically uplifted in late Tertiary time as part of the Colorado Plateau (Hunt, 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 (tilting and faulting) and subsidence of the overlying strata during late Tertiary and Quaternary time (Shoemaker and others, 1958; Coleman, 1983; Harden and others, 1985; Doelling, 1988; Oviatt, 1988; Ross, in preparation)

Folds

Moab Valley Salt-Cored Anticline

The Moab Valley salt-cored anticline trends roughly N 45° W across the quadrangle under Moab and Spanish Valleys (Moab-Spanish Valley). It plunges to the northwest, northwest of Moab Valley, and is recognizable for another 7 miles (11 km) as the

Moab anticline (McKnight, 1940; Doelling, 1988). Moab-Spanish Valley is 1 to 1.5 miles (1.6-2.4 km) wide and about 15 miles (2 km) long extending beyond the quadrangle to the south and southeast (figure 5). The Moab Valley salt-cored anticline continues southeasterly where it is linked to a string of salt features totaling about 72 miles (116 km) in length (Williams, 1964). Moab Valley is separated from Spanish Valley by a topographic saddle south of the canyon of Mill Creek. The topographic expression of Moab-Spanish Valley 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.

Moab Valley salt-cored anticline structural features are complex and may be grouped into the salt diapir of Moab-Spanish Valley, the deformational belts on the northeast and southwest sides of the valley, the flanks, and the northward-extending Moab anticline.

Salt diapir of Moab-Spanish Valley: Geophysical data, well log information, and our new mapping allow for a better understanding of the shape of the Moab Valley salt diapir. 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, SW 1/4 SE 1/4 NW 1/4 section 34, T. 25 S., R. 21

E., reported by Baker (1933) and McKnight (1940), indicate the southwest margin of the Moab Valley salt diapir may be nearly vertical at these locations. Chinle outcrops that show near-vertical dips and show structural deformation at the Paradox caprock contact appear to be on line with the vertical margin.

The northeast margin of the salt diapir probably parallels and underlies the trace of the northeasternmost fault-anticline (plate 1). This interpretation is based on gravity data and location of the belt of salt-dissolution-induced faults and folds on the northeast side of the valley (cross sections B-B′ & C-C′). Therefore, the width of the Moab Valley salt diapir is about 2 miles (3.2 km) wide at cross sections B-B′ and C-C′.

Sparse local petroleum well data indicate the height of the Moab Valley salt diapir. The Federal-Weaver No.1 well penetrated the Mississippian Leadville Limestone at about 4,500 feet (1.4 km) below sea level (see cross section C-C′). The Burkholder 1-G-1 well northeast of Moab Valley penetrated the Leadville Limestone at approximately 5,300 feet (1.6 km) below sea level. The base of the salt is generally less than 200 feet above the top of the Leadville 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′ & C-C′). The difference in elevation of the Leadville tops in the wells suggest a buried fault in the subsalt rocks.

Moab-Spanish Valley is filled with basin-fill alluvium (Qabf) estimated to be mainly of Quaternary age. Logs from several water wells (Utah Division of Water Rights, unpublished data), at the southeast end of the valley adjacent to Pack Creek, SW 1/4 section 7, T. 25 S., R. 22 E., report only 70 to 100 feet (21-30 m) of unconsolidated basin-fill alluvium before penetrating gray shale and gypsum of the Paradox caprock. In the central part of the valley, the Great Lakes Carbon Corp. No. 1 well penetrated approximately 320 feet (98 m) of basin-fill alluvium, about 45 feet (14 m) of sandstone (collapsed bedrock?), and 520 feet (158 m) of caprock before reaching the first salt of the Paradox Formation at a depth of about 900 feet (275 m) (figure 6). In the northwest part of the valley, along the northwest side of the Colorado River, NE1/4 SW1/4 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 that amount at that location. everal additional boreholes (1 and 2, figure 7) drilled farther to the west-northwest on the Atlas Minerals site indicate that the thickness of Quaternary basin-fill deposits abruptly thins to about 100 feet (30 m) before penetrating post-Paradox Formation bedrock beneath the site.

This dispersed and limited subsurface information suggests that basin-fill deposits (Qabf) form a wedge that overlies caprock and thickens to the northwest beneath the surface of Moab Valley and that the wedge is juxtaposed against post-Paradox bedrock that is overlain by a thinner sequence of basin-fill alluvium (figure 7). The northwest boundary of the basin-filling alluvial wedge is interpreted 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 basis for this structural interpretation is the fact that 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. Surficial sediments cannot be deposited at elevations lower than the river's current elevation, about 3,950 feet (1,204 m) above sea level, unless the valley is currently undergoing subsidence. The arcuate fault(?) is a boundary separating a lesser subsided area northwest of the river from a greater subsided area southeast of the river. The greater amount of subsidence southeast of the river may be due, in part, to perennial surface-water and greater ground-water flow entering the valley from the east-southeast.

The buried arcuate fault(?) may continue in the subsurface along the sides of Moab Valley, but with decreasing offset toward the southeast. Alternatively, the fault may end abruptly and basin-fill alluvium (Qabf) gradually thins along the sides of the valley (cross-section B-B').

Salt-dissolution-induced subsidence has continued from the Pleistocene into the early Holocene. 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 suggest 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: The margins of Moab-Spanish Valley show a variety of structural features that reflect both salt-diapiric and salt-dissolution origins. In some cases they cannot be differentiated. The deformation present along the northwest half of the southwest Moab valley margin is dominated by salt diapiric features. This lack of salt-dissolution-induced deformation is probably the result of erosion of the faulted and folded rocks by the Colorado River beyond the southwest margin of the salt diapir.

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.), upper strata of the Chinle Formation dip 15 to 17 degrees southwest. Dip attitudes progressively increase downsection across several angular unconformities until the basal strata of the Chinle and uppermost beds of the Moenkopi are vertical. These angular unconformities are known as progressive unconformities.

Chinle outcrops immediately southeast of The Portal have progessive unconformities and contain intraformational conglomerates (figure 8). Some conglomerate beds in the younger Chinle contain distinctive sedimentary rock fragments eroded from steeply tilted older strata. Valleyward of these Chinle outcrops, the Chinle is folded into an anticline and syncline, and strata are discolored, brecciated and fractured. Rocks in the core of the anticline are an intensely brecciated and discoled mixture of caprock and Chinle lithologies. The axial trace of the anticline trends to the northwest directly into a small ridge of caprock. Chinle beds in contact with caprock are locally cut-out along strike indicating discordance between the caprock and the Chinle. The syncline is a downwarp between the anticline and a larger ridge of caprock (figure 2), on which the Chinle again is in contact with caprock. Similar areas of brecciation and changes in dip are present at the caprock-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 caprock, and the "intrusive" nature of the contact between the Chinle and Paradox caprock indicate 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 continued to "intrude" and deform 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 (≤5 feet [1.5 m] apart) along the belt. The spacing abruptly increases to the southwest beyond the southwesternmost fault in the cliff wall. This fault and other 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 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 this side of the valley. Hidden Valley is in a narrow graben (Hidden Valley graben) 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-propagated assymetrical synclines trend northwest along the top of the ridge. Rocks along the ridge are extensively fractured and sandstone along the faults are locally bleached, enriched in hematite, and recemented. The horst block is marked by a conspicuous ledge-forming conglomeratic sandstone in the Chinle for approximately 3 miles (4.8 km) along the southwest side of Moab Valley. Valleyward of the horst, strata begin to rollover to the northeast along a fault-propagated monocline (cross-section C-C'). The monocline is marked by a series of flatirons in the Chinle, Wingate, and Kayenta Formations (figure 9). The apparent thickness of the strata in these outcrops is thinner than normal, probably from a combination of 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 assymmetrical 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 cover these bedrock units as they extend into the valley. The topographic saddle that separates Moab Valley from Spanish Valley is formed by these surficial deposits resting 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 increases to 4,500 feet (1,370 m) wide toward the southeast at Mill Creek. The strata "roll over" from their original northeastward dip and are warped into alternating anticlines and synclines (figure 10). Many of the axial traces of the anticlines change to high-angle normal faults that are down-to-the-valley. The arrangement suggests the anticlines are fault-propagated folds.

Synclines, typically asymmetric chevron folds, parallel the faults and anticlines. These folds are referred to as V-synclines in previous maps and reports in the Moab area (Doelling, 1983, 1985, 1988). Many of these synclines doubly-plunge toward drainages that cross their axes. A good example is the Mill Creek syncline (cross section C-C'). A down-to-the-southwest normal fault is interpreted in the hinge of the fold because many folds of this type in the region have faults along their hinges (Doelling, 1988; Doelling and Ross, 1993). A cluster of intersecting fracture zones is present at the eastern edge of the map along the axial trace of the Mill Creek syncline. The fractures are networks of closely-spaced and anastomosing cataclastic shear bands cutting brecciated Navajo Sandstone. The features form resistent 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 this 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 shear bands commonly criss-cross the sandstones of the Glen Canyon Group. Shear bands show a variety of orientations and geometries and higher-angle bands cross-cut lower-angle bands. Shear-band networks typically parallel the traces of large faults.

The Kayenta Heights fault, south of Mill Creek, shows many of these fault-related features. The fault dips 50-75 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 foot wall, with an estimated displacement of 400 feet (122 m). A small, inconspicuous deposit of alluvial Qat3 terrace gravel is on the hanging wall adjacent to the fault, but not in direct contact with the fault trace. No deposits of Qat3 gravel are found on footwall outcrops near the fault.

Deformation on down-to-the-valley 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 the salt-cored anticlines in the region and Doelling (1983, 1988) has attributed them to greater amounts of salt-dissolution occuring at depth where the crossing drainages intersect northwest-striking, open fractures. The open fractures probably originated as joints.

Structural features on the flanks: Since Upper Pennsylvanian through Upper Triassic strata are missing or thinned over the crest of the Moab Valley salt diapir, a reciprocal thickening of relative-age 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 Burkholder 1-G-1 well (Rill Creek quadrangle) which 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 (Ross and Mulvey, in preparation). Salt flowed into the Moab Valley salt diapir and into the Castle Valley salt diapir, 8 miles (13 km) northeast of Moab Valley, from this intervening, rim-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 the Moenkopi and Chinle Formations may each thicken to as much as 700 feet (213 m) in the rim syncline on this side of the salt diapir.

Moab anticline: The axial trace of the 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° on each flank (figure 11). Its southwest flank is cut by the paralleling Moab fault, a tectonic feature of relatively large displacement.

The crest of the anticline is cut by several faults and closely spaced joints that parallel the axis of the fold. The faults, in a zone one mile (1.6 km) in width, are all located northeast of the Moab fault and most have displacements of 60 feet (18 m) or less (cross section A-A'). The northeasternmost fault increases in displacement southward to at least 500 feet

(152 m) at the north edge of Moab Valley (plate 1). The faults generally dip 40 to 80° toward the axial plane of the anticline. Faults are commonly recemented and their traces often stand as ribs. The northeasternmost fault has an apparent offset of at least 500 feet (152 m), juxtaposing the base of the Navajo almost against the base of the Wingate.

Several cross faults are present at the south end of the Moab anticline marginal to Moab Valley. These faults dip at high angles, mostly northward, at 60 to 80°. The cross faults, together with a slight valleyward dip on some of the strata suggest collapse into Moab Valley. The cross fault zones 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°, but little movement has been noted on them. This joint set ends abruptly about a half mile north of Moab Valley.

Kings Bottom Syncline

The Kings Bottom syncline is a N 45° W, doubly plunging fold located 1.5 miles (2.4 km) southwest of Moab-Spanish Valley. The axial trace of the syncline plunges approximately 3-5 degrees from both directions toward its intersection with the Colorado River. Glen Canyon Group strata dip to as much as 17° SW on the northeast limb and as much as 10° NE on the southwest limb. The hinge of the syncline is broad and the Navajo Sandstone appears to thicken into the hinge, suggesting the fold is, in part, a rim syncline formed by salt removal underneath the depression of the syncline. This interpretation is supported by thickness of strata encountered in the 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'. Honaker Trail Formation through the Wingate Sandstone are thicker than sections adjacent to the Cane Creek anticline on the southwest and the Moab Valley salt-cored anticline on the northeast.

Courthouse Syncline

The northwest-trending Courthouse syncline parallels the Moab Valley salt-cored anticline on its northeast side. The axial trace of the syncline plunges gently to the northwest. Maximum dips on the southwest limb reach 8 or 9 degrees as they do on the northeast limb in the quadrangle. The hinge of the fold flattens out to the southeast where it becomes impossible to trace. The syncline continues northward, 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 present in the southwest corner of the quadrangle. Strata dip between 5 to 10 degrees in Mesozoic strata and increase to 10 to 15 degrees in late Paleozoic strata in the quadrangle (cross-section C-C′). Wingate through Honaker Trail strata 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 fixed by buried faults that cut Mississippian and older rocks, but do not continue above the lower part of the Paradox Formation (cross-section A-A′, Doelling and others, 1994). Such buried faults probably extend across the Moab quadrangle and lower pre-Paradox rocks in a series of down-to-the-northeast, fault-blocks (cross-section C-C′).

Moab Fault

The Moab fault, in the quadrangle, 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, termed 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(s) is evident along the entire length of the Moab Valley salt-cored anticline. The fault traces do not cut any Pleistocene or Holocene sediments in the quadrangle. Movement on the fault is believed to have occurred in 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 12). At the south end of this outcrop the west branch of the Moab fault, strikes about N 80° W and dips 60-68° NE; slickensides rake 60° to the east. Strata near the top of the Honaker Trail Formation, are exposed in the footwall, the Moenkopi Formation and the Cutler Formation are exposed in the hanging wall. An 8- to 10-foot (2.4-3 m) zone of attenuated and shattered Honaker Trail limestone and sandstone dips with the fault in the fault zone, behind which the strata strike N. 45° W and dip 10 degrees NE in the footwall. Moenkopi strata in the narrow fault block strike roughly parallel to the faults and generally dip 20 to 25° N., but dip as much as 40° or more due to drag folding along the west branch fault. 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 this outcrop, strikes about E-W and dips about 68° north. Slickensides are not exposed. The Slick Rock Member of the Entrada Sandstone is juxtaposed against the Moenkopi Formation. The Entrada has been drag folded and is 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.

The traces of both branches of the Moab fault curve to the southeast, cross U.S. Highway 191 and strike N 45-70° W. in section 28, T. 25 S., R. 21. E. Entrada Sandstone is juxtaposed against the lower member of the Chinle Formation across the main branch of the Moab fault and 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. Entrada strata are quite 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 appear to strike E-W. The main branch of the Moab fault strikes N 70° W and the dip is not discernible. In the footwall 10 to 15 feet (3-4.6 m) of mottled siltstone and quartzose sandstone beds of the lower member of the Chinle strike N 70° W and dip 30 degrees or more northeastward. Strata of the underlying Moenkopi strike N 60-70° W and dip an average of 25 degrees northeast between the main branch fault and surficial units covering the west branch fault. The railroad tracks are constructed on the Pennsylvanian Honaker Trail Formation at this place showing that the west branch fault is covered by surficial units.

Along the line of cross-section A-A', The Navajo Sandstone, northeast of the faults, strikes N 45° W and dips 35-38° SW (figure 13). 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 filled with the Tidwell Member of the Morrison Formation. The plunge on the syncline is estimated to be at least 9 degrees southeastward. Entrada Sandstone between the hinge and the fault dip steeply northeastward. This steep dip is partly due to drag along the fault. The syncline probably formed over of a zone of salt-dissolution that parallels the fault as attested by the shattered nature of the Entrada Sandstone. The Moenkopi Formation is exposed in the footwall of the main branch fault which trends N 52° W and dips 60° NE. The displacement along the fault is estimated to be about 1,750 feet (533 m). The Moenkopi dips about 15° NE in the footwall of the main branch fault. 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 at this place. 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 gouge. The Honaker Trail dips 25° southwest in the footwall. No exposure of the main branch of the Moab fault trace is available southwest of this traverse. We assume that the buried trace continues to the arcuate fault (?) at the north end of Moab Valley.

The trace of the west branch of the Moab fault can be followed into the NW 1/4 section 34, T. 25 S., R. 21 E., where it becomes 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 15-25° SW as do Honaker Trail strata in the footwall. The fault is marked by the peculiar 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 14-16). 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. The reader must visit this place in order to believe it.

In the SW1/4 NW1/4 NW1/4 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 reducing ground water adjacent to the Moab Valley salt wall. Shortly southeast of this outcrop the west branch of the Moab fault is covered by Quaternary deposits in Moab Valley.

The boreholes drilled on the Atlas Minerals property at the northwest end of the valley indicate that most of the tailings pile rests on a relatively thin package of surfical deposits overlying post-Paradox bedrock (figure 7). This bedrock in lithologic logs consists of clayey siltstone; moderately fractured, red-gray sandstone; indurated siltstone; and red-gray sandstone (Woodward-Clyde Federal Services, unpublished data). 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 45-50° W strike from its last mapped surface exposure. Southeast of the Colorado River and the buried salt-dissolution-induced arcuate fault it appears that basin-fill alluvium (Qabf) directly overlies caprock along the length of Moab Valley. Erosion has apparently removed all post-Paradox 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 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 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 E-W. Near Kings Bottom along the Colorado River the joints rotate clockwise to about N 65° W and continue on Poison Spider Mesa where they gradually rotate 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 45-65° W. On the northeast flank of the salt-cored anticline joints trend N 60-70° W.

ECONOMIC GEOLOGY

Potash, Salt, and Magnesium

Potash and halite deposits underlie the Cane Creek anticline and Moab-Spanish Valley. Potash and halite have been commercially extracted from the Paradox Formation along the Cane

Creek anticline by solution 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 (Doelling and others, 1994; Ritzma, 1969).

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-Spanish Valley. Potash- and magnesium-bearing sylvite and carnallite, are probably present in the Paradox Formation underlying the valley. 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 brine contained about 310,000 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. Daily brine production in 1965 was between 400 and 3,000 barrels (64 and 477 m3). 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 SW1/4 SW1/4 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 at an approximate depth of 2,000 feet (610 m). 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 another salt-bed cavern in the halite for the purpose of storing liquefied petroleum gas (Hite, 1964). Brines are reinjected into the cavern to recover the gas.

Sand and Gravel

Alluvium along the Colorado River (Qal & Qa) and older terrace deposits (Qat) contain sand and gravel suitable for construction of highways and other construction. The basin-fill (Qabf) under Moab Valley may also contain important resources. The Utah Department of Transportation (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. No attempt was made to calculate reserves, but they are large. Such sand and gravel was put to use in the construction of Utah Highway 279 that connects Moab with Potash.

Petroleum

The Moab quadrangle is in a region historically productive for oil and gas (Morgan, 1993). 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 has been 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 noted that all of these Moab Valley wells had shows of oil and gas, presumably from the Paradox Formation in the salt diapir.

The Union Oil/Cities Services, 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 mineral 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 where given a low certainty rating.

Gold

Alluvium (Qal & Qa) 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 found 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 twice-background radiation (about 180 total count 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 to the north along the trend of the Moab fault (Finch, 1954).

Decorative and Building Stone

Blocks and slabs of locally derived stone have been 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 steppe climate area (mid-latitude steppe) 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) per year (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 is sourced 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 a mile (1.6 km) downstream from the Dolores River confluence was 8,057 cfs (228 m3/s) or 5,833,000 acre-feet (7,200 hm3) per year (Hendricks, 1964). An 11-year average flow on Mill Creek, measured prior to construction of the Kens Lake diversion, was 14.3 cfs (405 l/s) or 10,360 acre-feet (12.8 hm3) per year. A 5-year average flow on Pack Creek, measured near the eastern edge of the map, averaged 4.02 cfs (113.8 l/s) or 2,912 acre-feet (3.6 hm3) per year.

Three ground-water regimes are operative in the Moab quadrangle. The first involves bedrock aquifers and aquicludes above the level of the Moenkopi Formation, the second involves those below or the deep ground-water regime. The third involves the unconsolidated units of the quadrangle.

The three principal consolidated-rock aquifers of the first regime are Navajo, Kayenta, and Wingate Formations. These are recharged on the benches by rainfall or snow, especially under sandy surficial deposits (Blanchard, 1990). Water from these aquifers 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-Spanish Valley in the neighboring Rill Creek quadrangle. These wells produce about 2,200 acre-feet (2.7 hm3) of water per year. The area laps onto the northwest valley-margin deformation belt along which there are many springs. Many springs emerge from the fracture zones along the belt. Blanchard (1990) noted that movement of the upper ground-water system is generally to the west and west-northwest. Recently horizontal bore holes 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 about 80 gallons per minute (5 liters per second) (R.R. Norman, verbal communication, March, 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 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 second or deep ground-water regime may be 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 the carbonate units below the Paradox Formation. The recharge area for the upper unit probably includes the La Sal Mountains. The transmissivity of the upper hydrostratigraphic unit is largely unknown and untested, but permeabilities of Permian strata are low and largely controlled by the presence of local faults and joints (Huntoon, 1985). The amount of water is expected to be small and not as good in quality as that in beds above the Moenkopi Formation. Permian and Pennsylvanian strata below the level of the Colorado River are generally saturated with sodium chloride brines. The middle unit consists of horizons acting as aquicludes alternating with others of variable water-bearing capacity. Where water is found it is generally very salty.

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

Unconsolidated aquifers include the water-bearing surficial deposits of the quadrangle. Larger, unconsolidated sand patches (Qes, Qea, 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. Dissolved solid content is usually 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

The geologic hazards for the Grand County part of Moab-Spanish Valley has been summarized and described in a report and maps by Mulvey (in press).

Debris Flows and Stream Flooding

Erosion by running water is the most active and potentially damaging hazard in the quadrangle. The sparsely vegetated steep slopes and deep, narrow washes are subject to 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 are shallow along their travel paths. Easily erodible bedrock, and abundant unstable slope debris (Qmt) provide ample material for debris flows.

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

Rock Falls

Rock falls occur sporadically throughout the rugged topography of southern Grand County. In the quadrangle, rock fragments from the Glen Canyon Group, Chinle, Moenkopi, Cutler, and Honaker Trail Formations produce rock fall debris. 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-Spanish Valley are active rock fall areas. Some areas of development are within the danger zones, especially along the southwest cliff bordering Moab-Spanish Valley. Rock fall debris may travel great distances down slope by rolling, bouncing, and sliding. The potential large size of some debris and relatively high velocity of 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 Soils

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 clay minerals and the soils derived from them are capable of absorbing large quantities of water (Schulz, 1963; Stewart and others, 1972a; 1972b). The "popcorn" surface of weathered Moenkopi and Chinle outcrops is indicative of the shrinking and swelling nature of the formations.

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

Gypsiferous soil and rock (caprock outcrops) present 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 (Mulvey, in press). Dissolution of gypsum and ground settlement may take place when water is introduced into the subsurface through irrigation, landscaping, or wastewater disposal. If thick gypsum beds are present, underground solution cavities may develop and collapse forming sinkholes. Gypsum is a weak material with low bearing strength, and can cause foundation problems for heavy structures.

Fine-grained soils and surficial deposits are prone to piping and rapid erosion (Mulvey, in press). 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/semi-arid climates where fine-grained, non-cemented, Holocene-age alluvium is incised by ephemeral stream channels.

Landslides and Fractured Bedrock

Blocks of bedrock can slide and damage structures. Only one landslide was mapped on the quadrangle, others are too small. They are most prone to occur where heterogeneous rocks dip valley- or canyon-ward. Excavators should be careful not to remove rock debris that supports valley-ward dipping strata. Brittle rocks can slide over fine-grained partings, beds, and bedding-plane fractures. Land- and block-sliding are more likely to occur during "wet" seasons or years and in areas where rocks are highly shattered and fractured. Areas to watch in the Moab area are along the deformed belts on both sides of Moab-Spanish Valley.

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 the unconsolidated alluvium covering the floor of Moab Valley from the Colorado River southeastward to and extending along the drainage of Pack Creek. Ground water at shallow depths 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 (1971) indicates 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, is an area of potential ground-water contamination. The bedrock in the area is highly fractured along which springs and wells are locally used. Improper waste water disposal could contaminate this valuable ground-water source. 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.

Blowing Sand

Sand blowing across and accumulating on back roads occasionally causes problems. Motorists using the back roads should be cautious when proceeding into areas of sheet or dune sands. Loss of traction in sandy areas becomes more pronounced during the hot 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). Historical seismicity in the Moab area consists of small- to moderate-magnitude activity with diffusely distributed epicenters and low to moderate re-occurrence 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, 1991).

Wong (1984) and Wong and Humphrey (1989) studied seismicity in the Paradox basin from 1979 to 1987 in connection with nuclear waste-disposal investigations. This investigation 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).

Human Activities

Geologic-hazard discussions generally focus on how the geology may adversely affect the activities of human beings. Human activity can adversely affect the environment (in this case the geology), which in time will be detrimental to humans. We have already discussed the probability of contamination of the ground-water reservoirs by human activities. Another concern is 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 are underway to evaluate the hazard (1995)

The Moab quadrangle and surrounding area are experiencing the effect of greatly increased recreational activity. Especially significant are bicycling, motor-biking, four-wheeling, and camping activities. Such hazard is minimized when confined to designated areas, such as existing roadways, trails, and camping areas. Unfortunately signs of abuse are emerging everywhere. Abuse includes blazing new trails, especially across fine-grained deposits. Especially abusive are trails cut over mounds, up or down hills, and across soft grassy surficial deposits. The scars do not quickly disappear and invite gullying and other forms of ugly erosion.

Litter is now found in the most remote areas. Litter along highways and mines can be cleaned up because it is localized. Litter left by careless tourists, especially non-degradable litter, may degrade the natural beauty of the region forever. Land-management personnel designate camping areas in an effort to localize disturbances. Many tourists, in an effort to escape camping fees, or for other reasons, camp in undesignated areas, leaving blackened hearths, garbage, and human waste that cannot be effectively cleaned up.

SCENIC GEOLOGY

The Moab quadrangle contains magnificent red-rock canyonland vistas. The Colorado River and its tributaries have incised deep canyons in colorful rocks 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-Spanish Valley 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 (figure 17). Four are named on the Moab 7.5-minute topographic map and more are present. We show several others on our geologic map, not shown on the topographic map (plate 1) and some are every "bit" as spectacular and worthy of visitation as most in the park.

The Behind the Rocks area between Kane Springs Canyon and Moab-Spanish Valley 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, but is worthy of the adventurous traveler.

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 eolianite sandstone near the top of the Kayenta Formation up to and including the lower part of the Navajo Sandstone.

ACKNOWLEDGMENTS

We thank Fitzhugh D. Davis 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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DESCRIPTION OF MAP UNITS

Quaternary Deposits

Qal - Modern Alluvium - Poor to well sorted sand, silt, clay, and lenses of gravel in active channels and covering modern flood plains. Holocene. Deposits are as much as 20 feet (6 m) thick.

Qa - Alluvium - Gravel, sand, silt, and minor amounts of clay; covers valley floors and forms isolated terraces or surfaces 10 to 50 feet (3-15 m) above modern floodplains and channels; the surfaces of some deposits are characterized by weak soil development; in Moab Valley and Mill Creek, trachyte porphyry clasts from the La Sal Mountains are the dominant rock type, with lesser amounts of locally derived sandstones from the Chinle Formation and Glen Canyon Group; along the Colorado River Qa terraces contain primarily exotic igneous and metamorphic rocks from source areas up river, trachyte porphyry from the La Sal Mountains, and Glen Canyon Group sandstones. Early Holocene to late Pleistocene. Deposits are as much as 30 feet (10 m) thick.

Qat3, Qat4, Qat5, Qat6 - Alluvial-Terrace Deposits - Moderately sorted, poorly stratified gravel in a gray, calcareous sandy matrix; contain a variety of locally derived and exotic clasts similar to Qa; 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 found between 100 and 150 feet (30-45 m) above the present stream channels; Qat5 gravels are found between 200 to 240 feet (61-73 m) above the present stream channels; and Qat6 gravels are found between 260 to 280 feet (79-86 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. Deposits are as much as 60 feet (20 m) thick.

Qabf - Basin-Fill Deposits - Mostly alluvial deposits that fill Moab Valley; gravel, sand, silt, and minor amounts of clay; no surface exposures, but intercepted in drill holes and covered by Holocene surficial deposits. Tertiary(?) and Pleistocene. Deposits may exceed 450 feet (137 m) in thickness.

Qafy - Younger Alluvial-Fan Deposits - Poorly sorted, generally unstratified, muddy to sandy cobble gravel; clasts locally derived and range from angular to subrounded; found along northeast and southwest sides of Moab-Spanish Valley; fans have dendritic drainage patterns and typical fan shap; form gentle to moderate apron-like slope at the base of cliffs or head in gullies of older fan deposits (Qafo). Holocene to Late Pleistocene. Deposits as much as 20 feet (6 m) thick.

Qafo - Older Alluvial-Fan Deposits - Poorly sorted, generally unstratified, muddy to sandy cobble gravel; boulders present near cliffs; clasts are locally derived and range from angular to subrounded; commonly covered by a veneer of sand (Qes); fans are dissected and have limited fan morphology; form gentle to moderate apron-like slopes at the base of cliffs; found on southwest side of Moab-Spanish Valley. Late and middle Pleistocene. Deposits as much as 40 feet (12 m) thick.

Qmt - Talus - Angular boulders, cobbles, and smaller fragments commonly in a fine-grained matrix; derived from rockfalls and form relatively thick veneers on slopes below cliffs; commonly grade downward into alluvial-fan deposits. Holocene to Pleistocene. Deposits as much as 20 feet (6 m) thick.

Qms - Landslide Deposit- Large mass of the Moab Member of the Entrada Sandstone that slid along a bedding plane parting of muddy sandstone at its contact with the underlying Slick Rock Member; located in Moab Canyon along U.S. Highway 191. Probably late Pleistocene. About 60 feet (20 m) thick.

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

Qes - Eolian Sand Deposits - Fine- to medium-grained, quartzose sand; typically form thin, discontinuous sheets and small dunes. Holocene. Locally as much as 30 feet (10 m) thick.

Qea - Eolian-Alluvial Deposits - Mainly moderately to well sorted quartzose sand deposited and reworked by eolian and alluvial processes; generally thin and restricted to ephemeral washes and hollows on mesas and benches capped by Glen Canyon Group sandstone. Holocene. Deposits as much as 10 feet (3 m) thick.

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

Qer - Eolian-Residual Deposits - Mostly mix of red fine-grained sand and angular limestone rubble derived from carbonate units in the Navajo Sandstone over which they are deposited. Holocene to late Pleistocene. Mostly less than 3 feet (1 m) thick.

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

Fill and Disturbed Deposits - Clay- to boulder-size material used as railroad and road fill; sand-size mine tailings at the Atlas Minerals site; sand and gravel pits, and larger areas disturbed by development. Latest Holocene. Variable thicknesses as much as 70 feet (21 m).

Jurassic Rocks

Morrison Formation

Jms - Salt Wash Member - Blocky ledges of pale-yellow-gray, cross-bedded sandstone interbedded with slope-forming, red and gray mudstone and siltstone; only a small remnant is present in the northwest corner of the quadrangle. Late Jurassic. Preserved thickness is 30 feet (10 m).

Jmt - Tidwell Member - Red to brown, thin-bedded, silty sandstone, muddy-limy sandstone, siltstone, and shale containing thin to nodular beds of gray limestone; large white siliceous concretions are associated with the limestone; forms gentle slope littered with limestone and chert fragments; lower 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 the lower steep slope and remainder of Tidwell may be the J-5 unconformity. Late to Middle Jurassic. Total thickness is 40 to 50 feet (12-15 m)

Entrada Sandstone

Jem - Moab Member - Pale-gray-orange, pale-yellow-brown, and light-gray, fine- to medium-grained, quartzose eolian sandstone; calcareous; forms massive cliff commonly with conspicuous joints. Middle Jurassic. Thickness is 60 to 100 feet (20-30 m).

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

Jed - Dewey Bridge Member - Red-brown, muddy to silty, fine- to medium-grained sandstone; iron-oxide or calcareous cemented; medium to thick bedded; weathers to distinct irregular and contorted rounded ledges; basal contact is the J-2 unconformity. Middle Jurassic. Thickness is 90 to 110 feet (27-33 m).

Glen Canyon Group

Jn, Jnl - Navajo Sandstone - Pale-orange to light-gray, 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. Lower Jurassic. Thickness is 300 to 700 feet (91-213 m).

Jk - Kayenta Formation - Red-brown, pale-red, gray-red, and pale-red-purple sandstone, interbedded with dark-red-brown to gray-red intraformational conglomerate, siltstone, mudstone, and silty limestone; mainly of fluvial and lacustrine origin; pale-gray-orange eolian sandstone beds are conspicuous in upper part; litharenites; calcareous; forms thick-bedded, step-like, resistant ledges and steep slopes. Lower Jurassic. Thickness is 250 to 400 feet (76-122 m).

Jw - Wingate Sandstone - Gray-orange-pink, gray-orange, and light-brown, fine-grained, quartzose, eolian sandstone; calcareous and siliceous cement; commonly forms massive cliffs along canyon walls or blocky cliffs where fractured;

cliff surfaces commonly streaked with dark-brown desert varnish. Lower Jurassic. Thickness is 250 to 400 feet (76-122 m).

Triassic Rocks

Trc - Chinle Formation - Red-brown to gray-red, interbedded sandstone, conglomeratic sandstone, siltstone, and mudstone, with subordinate gray, sandy limestone; lenticular and sheet-like sandstone and conglomeratic sandstone are calcareous to quartzose; fine to coarse grained; bentonitic and calcareous mudstones form steep slopes separated by ledges and cliffs of sandstone and conglomeratic sandstone; indistinctly bedded; has a discontinuous lower member of light-gray, quartzose sandstone and mottled siltstone (not mapped); upper member is divisible into a (ascending) slope former, ledge former, slope former, and sheet-like flat beds of possible eolian origin. Upper Triassic. Thickness ranges from 100 to 700 feet (30-192 m).

Trm - Moenkopi Formation - 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; local lenses of Hoskinnini

Member(?) at base. Lower Triassic. Thickness ranges of 0 to 750 feet (0-229 m).

Permian Rocks

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

Pennsylvanian Rocks

IPh - Honaker Trail Formation - Light-gray, pink-gray, 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 cliffs, ledges, and steep slopes. Upper Pennsylvanian (Missouri-Virgil) Outcrop thickness may be as much as 700 feet (213 m), but may be as much as 2,700 feet (823 m) thick in subsurface due to movement of salt diapirs.

IPp - Paradox Formation - Gray, sucrosic gypsum, gypsiferous claystone, gray to black silty shale, with subordinate gray, fine-grained sandstone and carbonates; mostly gypsiferous claystone is infolded and contorted with resistant and pitted sucrosic gypsum as caprock; contains thick salt beds in the subsurface. Middle Pennsylvanian (Desmoines). Estimated caprock thickness is as much as 700 feet (213 m); estimated height of Moab salt diapir is 9,000 feet (2,743 m) reaching a maximum width of 2 miles (3.2 km).

Figure Captions

Figure 1. Map showing 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 Plateaus Physiographic Province.

Figure 2. Caprock of the Pennsylvanian Paradox Formation exposed along the southwest flank of Moab-Spanish Valley. Caprock is the residue formed at the top of leached salt diapirs, formed 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.

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 (91 m) thick. The Kayenta Formation is the ledgy unit in the middle and the Navajo Sandstone forms the top of the section. Jke represents an eolian marker sandstone in the Kayenta Formation. Jnb represents flat-bedded basal beds of the Navajo Sandstone.

Figure 4. Gray-pink, preferentially cemented sandstone ledge at the top of the Kayenta Formation. The variable cementation and

coloration give the ledge a unique "rotted or sculptured" weathering appearance.

Figure 5. View southeastward into Moab-Spanish Valley. The Colorado River is in the foreground, the La Sal Mountains appear in the background. A salt diapir 9,000 feet (2,743 m) high and two miles (3.2 km) wide underlies the valley and is covered with basin-fill deposits, collapsed bedrock, and Paradox Formation caprock.

Figure 6. Log of the Great Lakes Carbon Corporation State No. 1 well, NE 1/4 NW 1/4 section 35, T. 25 S., R. 21 E.

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Figure 10. Deformed and fractured Glen Canyon Group formations. Strata "roll over" from their original northeastward dip and are warped into alternating anticlines and synclines along the northeast valley-margin deformation belt.

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Table Captions

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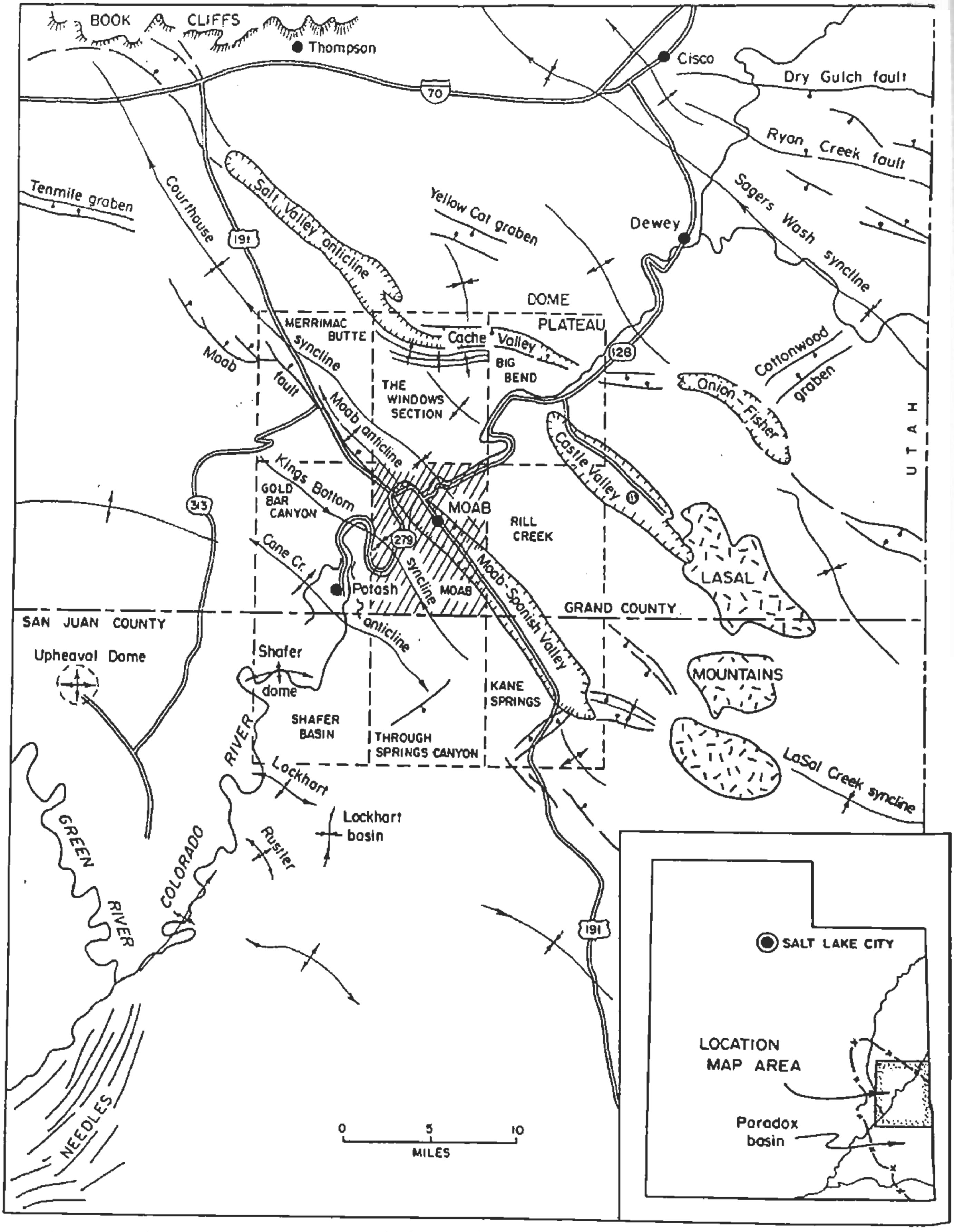

Figure 1. Map showing structural and geographic features in east-central Utah in the vicinity of the Moab 7.5-minute quadrangle. The eight quadrangles which border it are also shown and named. The Moab quadrangle is located in the Paradox basin within the Colorado Plateaus Physiographic Province.

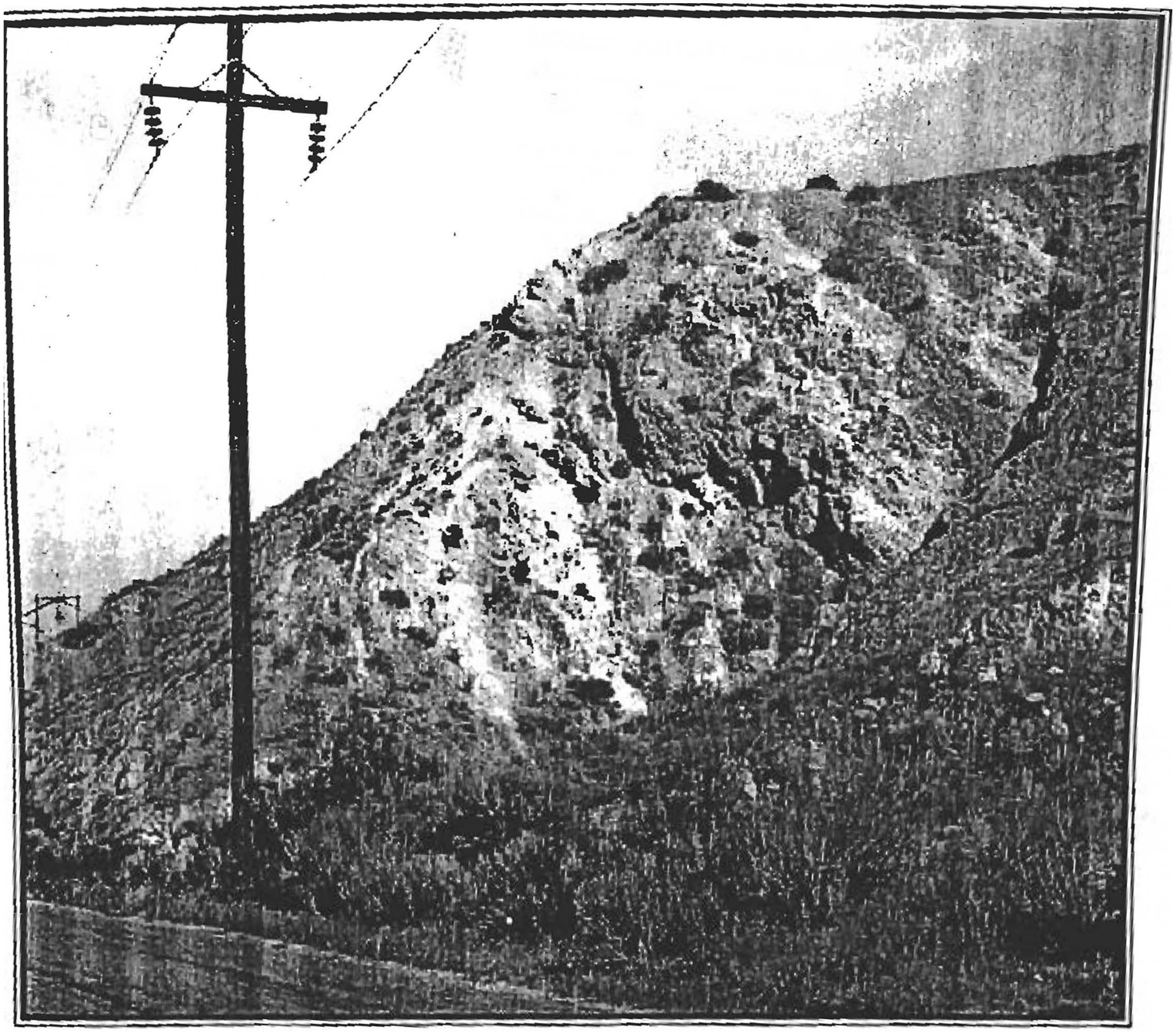

Figure 2. Caprock of the Pennsylvanian Paradox Formation exposed along the southwest flank of Moab-Spanish Valley. Caprock is the residue formed at the top of leached salt diapirs, formed as salt layers are successively dissolved and carried away by fresh ground water. Gypsiferous mudstone, sucrosic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

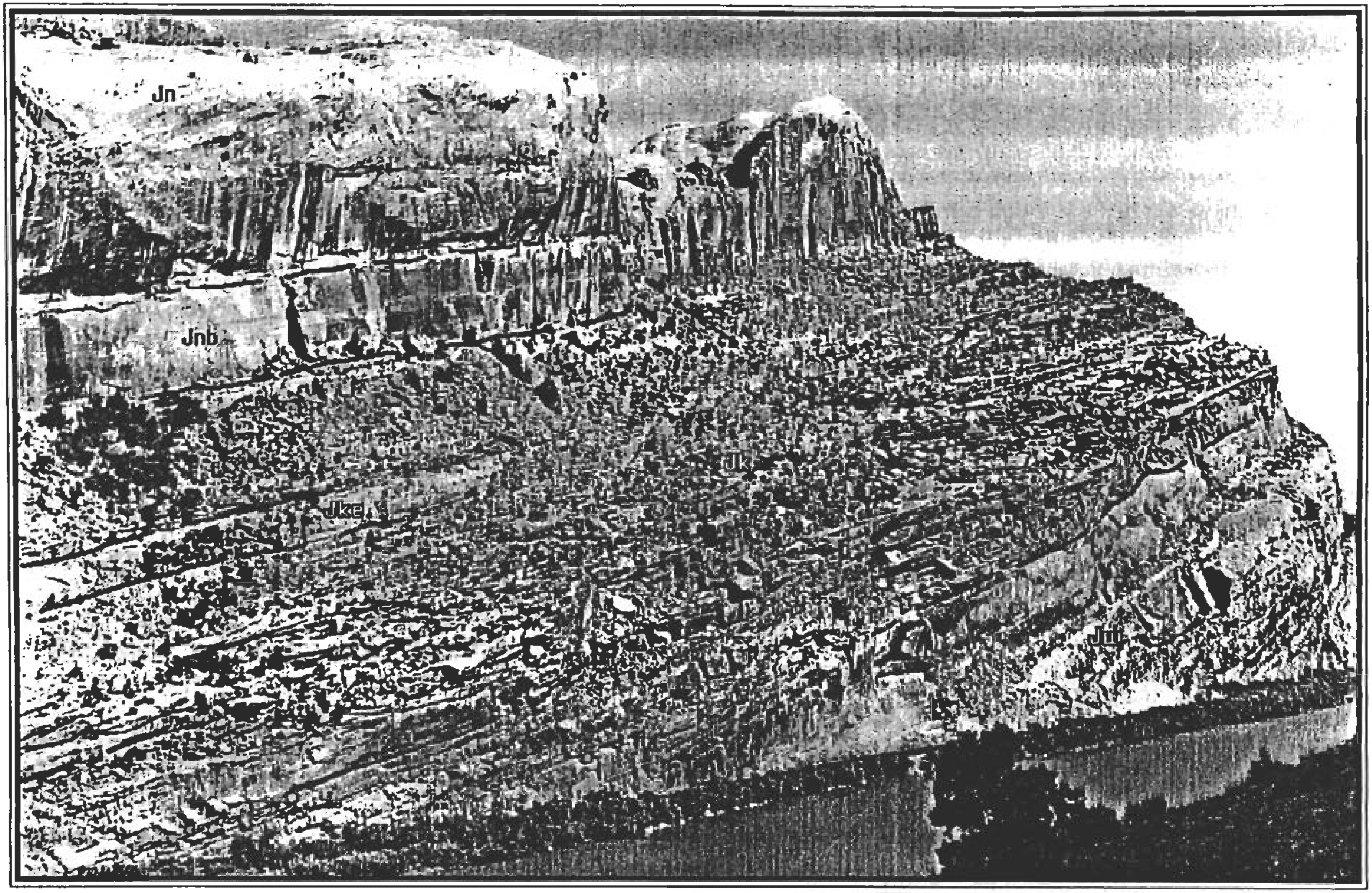

Figure 3. The Early Jurassic Glen Canyon Group as exposed at The Portal of the Colorado River. The Wingate Sandstone (Jw) is a massive-weathering formation about 300 (91 m) thick. The Kayenta Formation is the ledgy unit in the middle and the Navajo Sandstone forms the top of the section. Jke represents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

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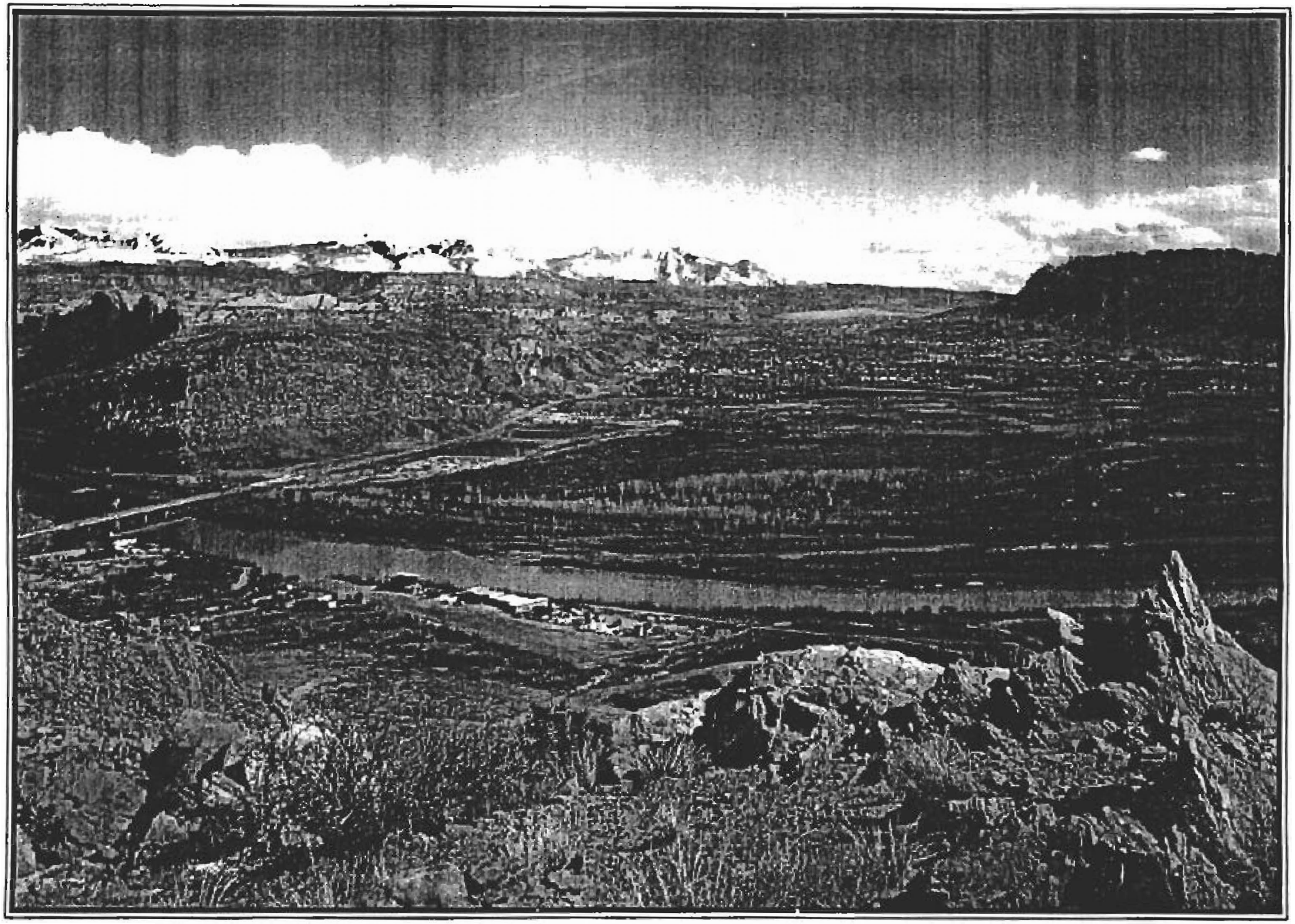

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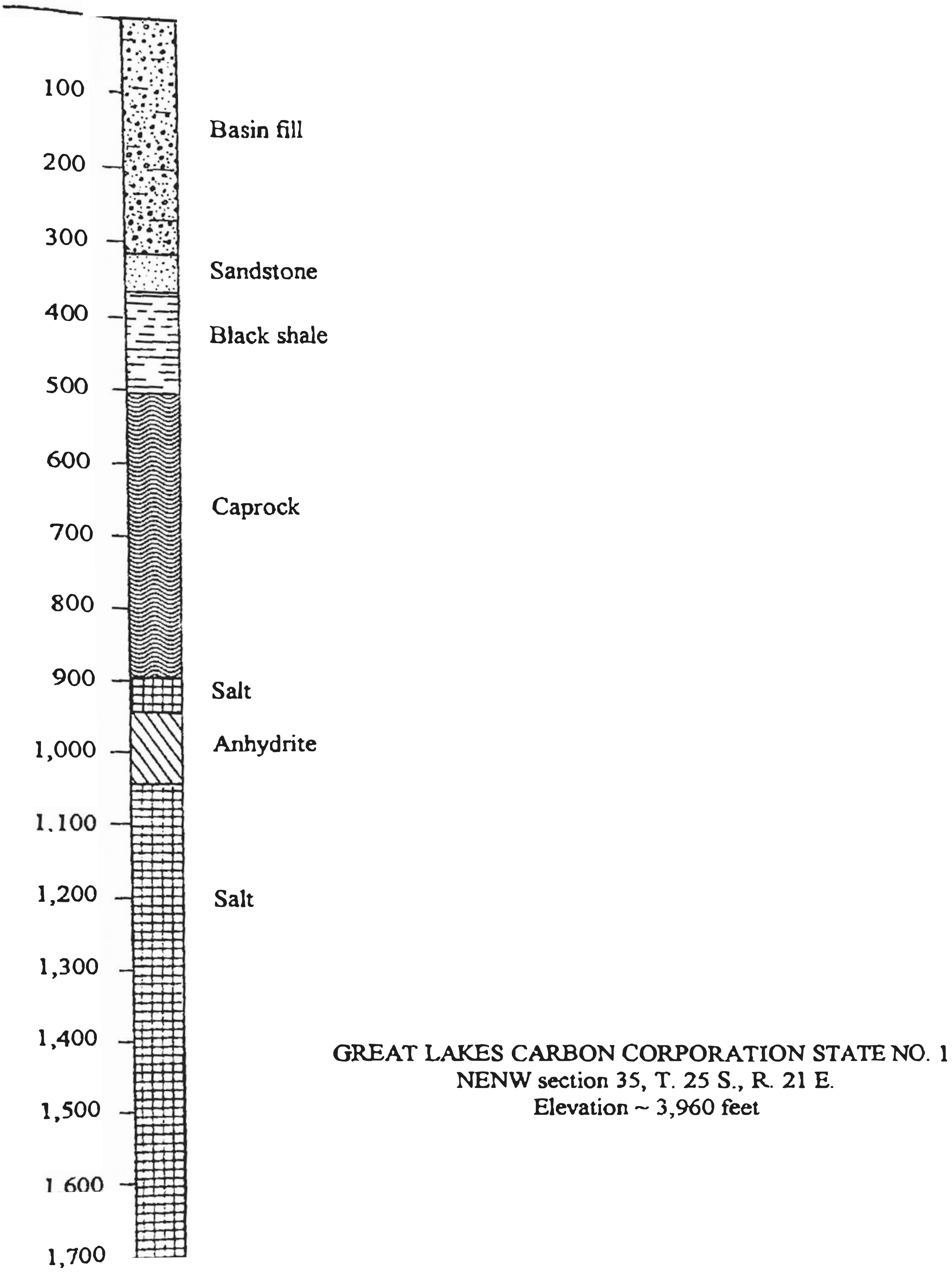

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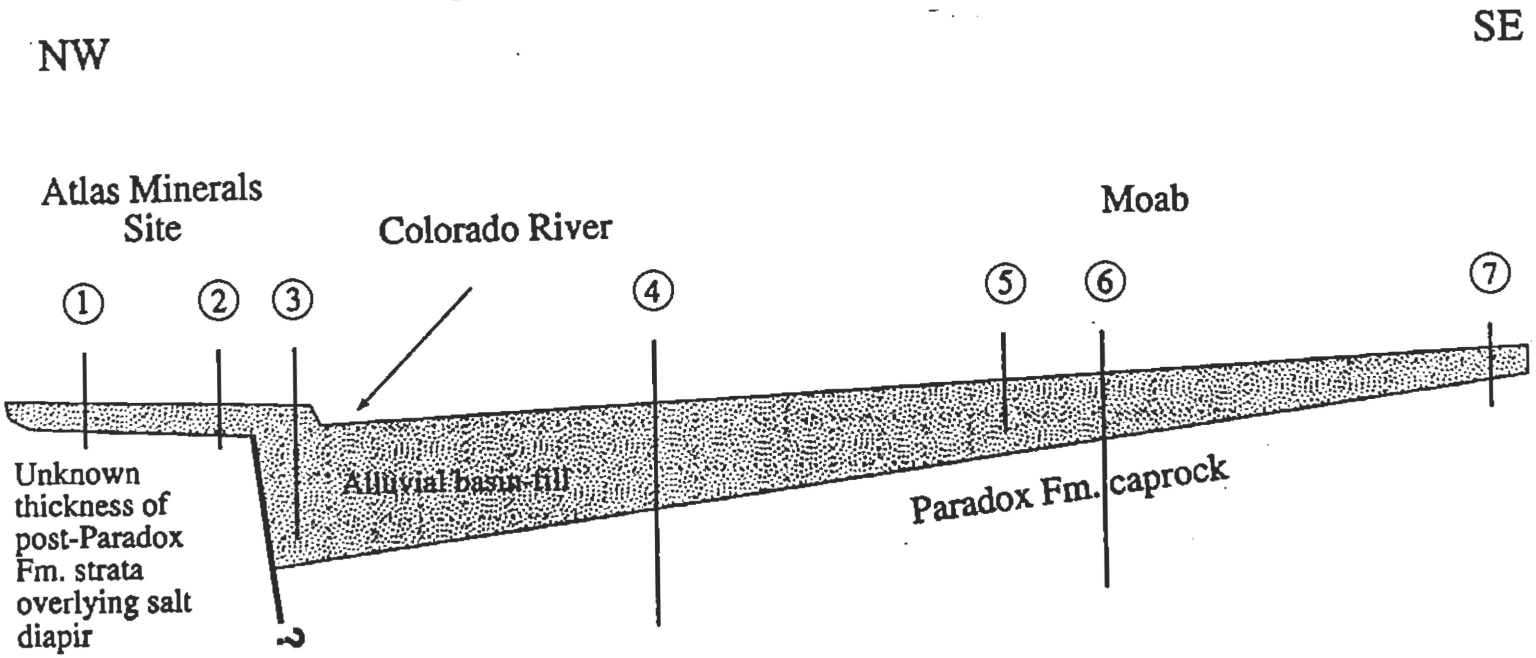
NW-SE Diagramatic Cross-section through Moab Valley



Thickness of alluvial basin-fill in selected wells:	Thickness
1. Atlas Minerals B-4 borehole	99 feet
2. Altas 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.26 S., R.21 E.	>100 feet
6. Western Allied - Big Six Oil Cos. oil & gas well	200 feet
7. Several water wells in section 7, T.26 S., R.22 E.	56-123 feet

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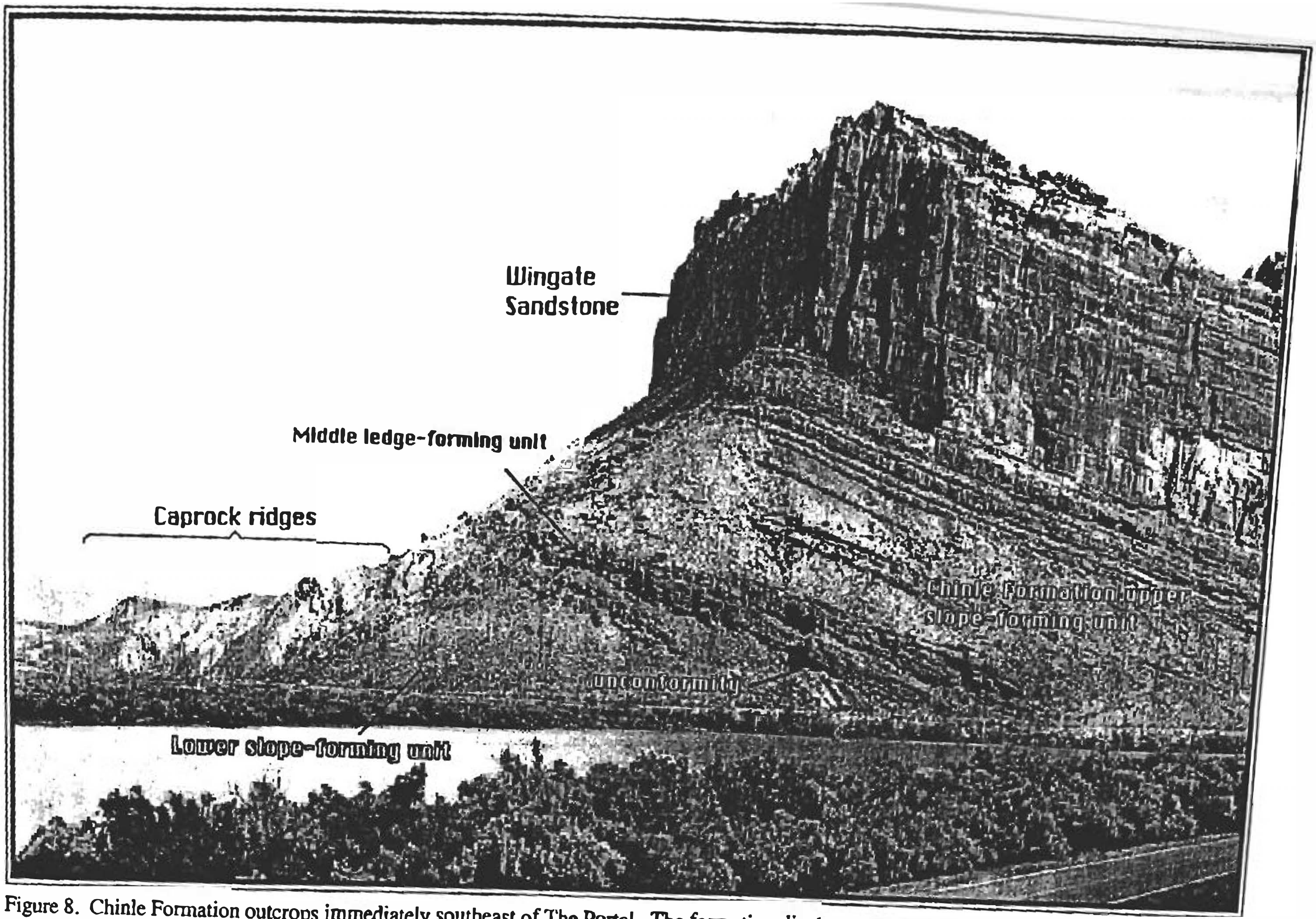

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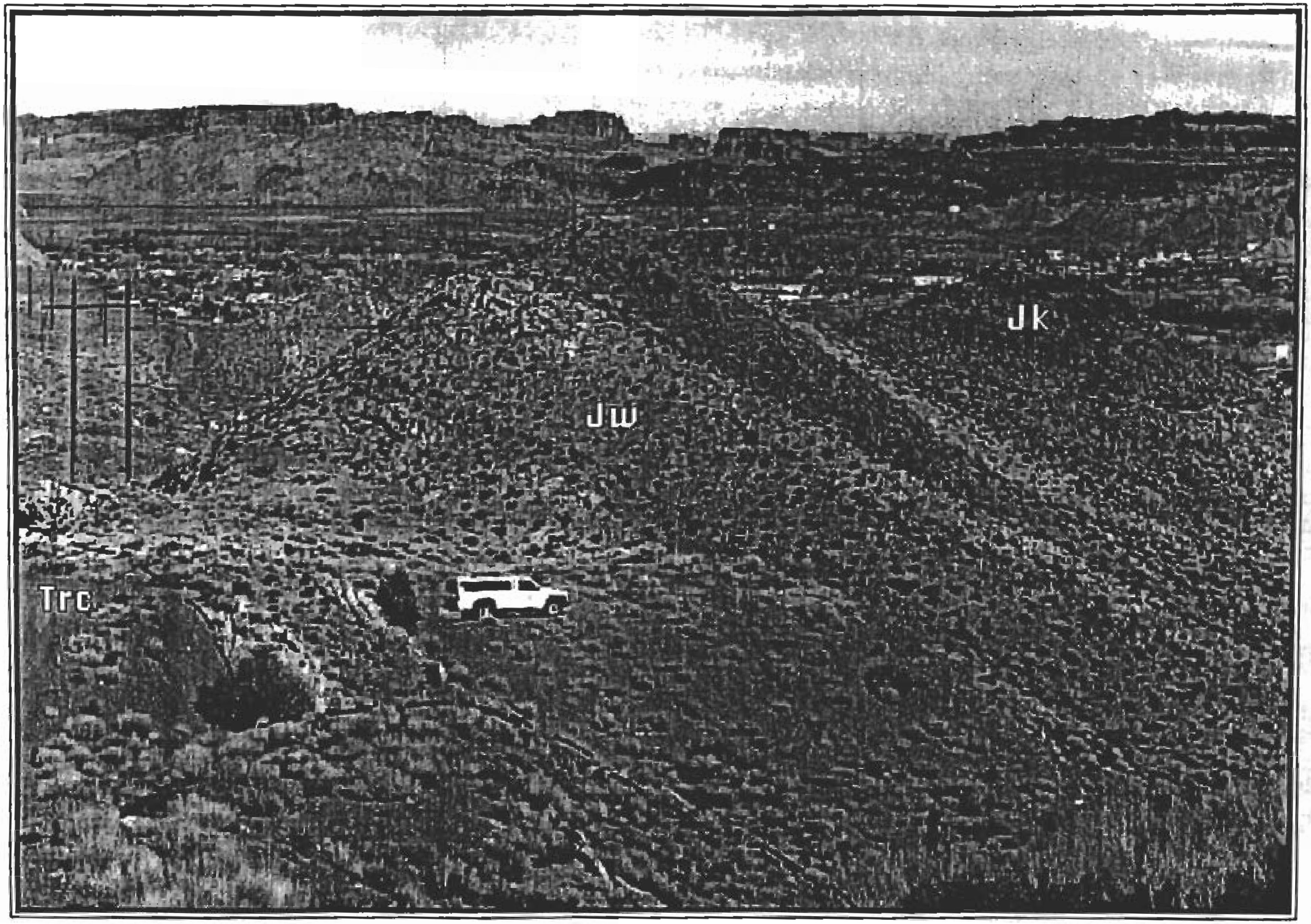

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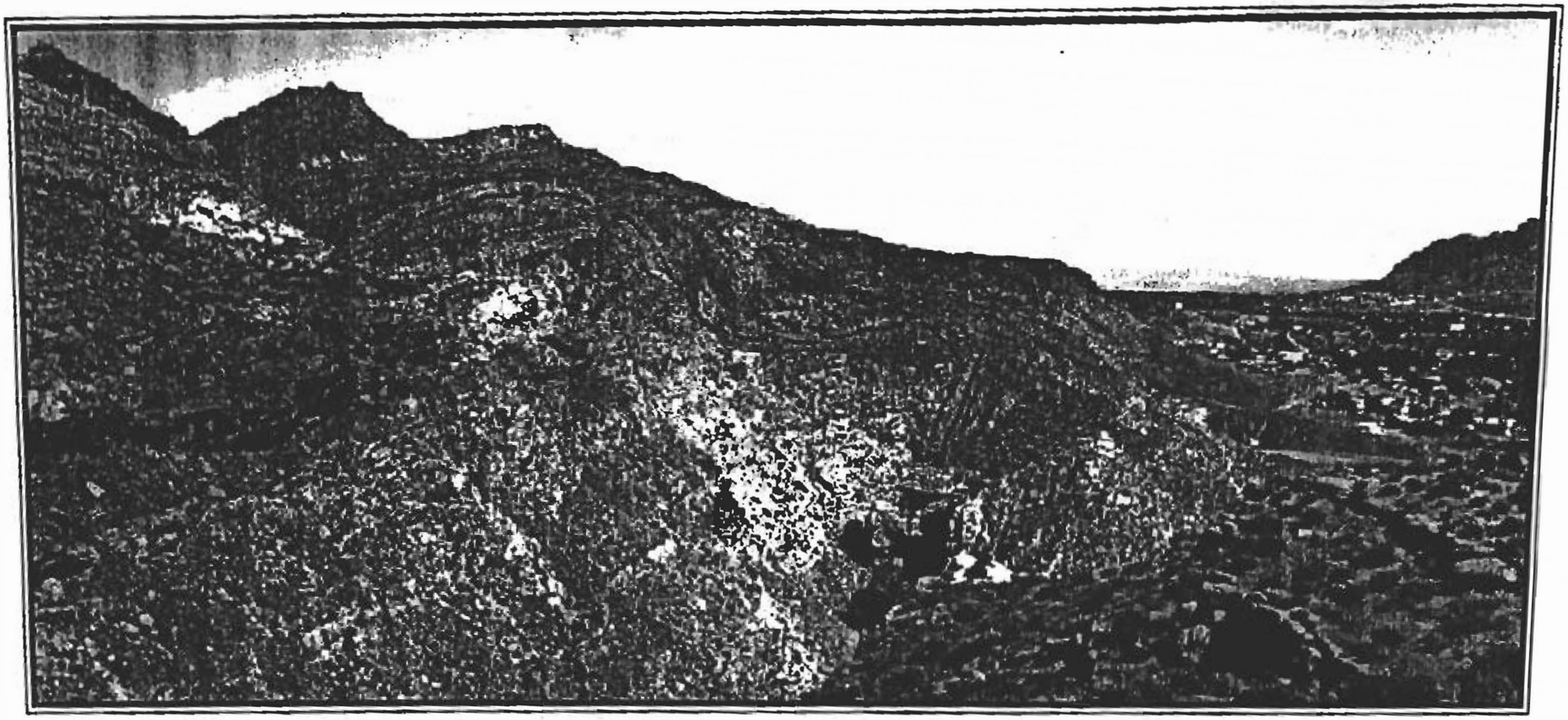

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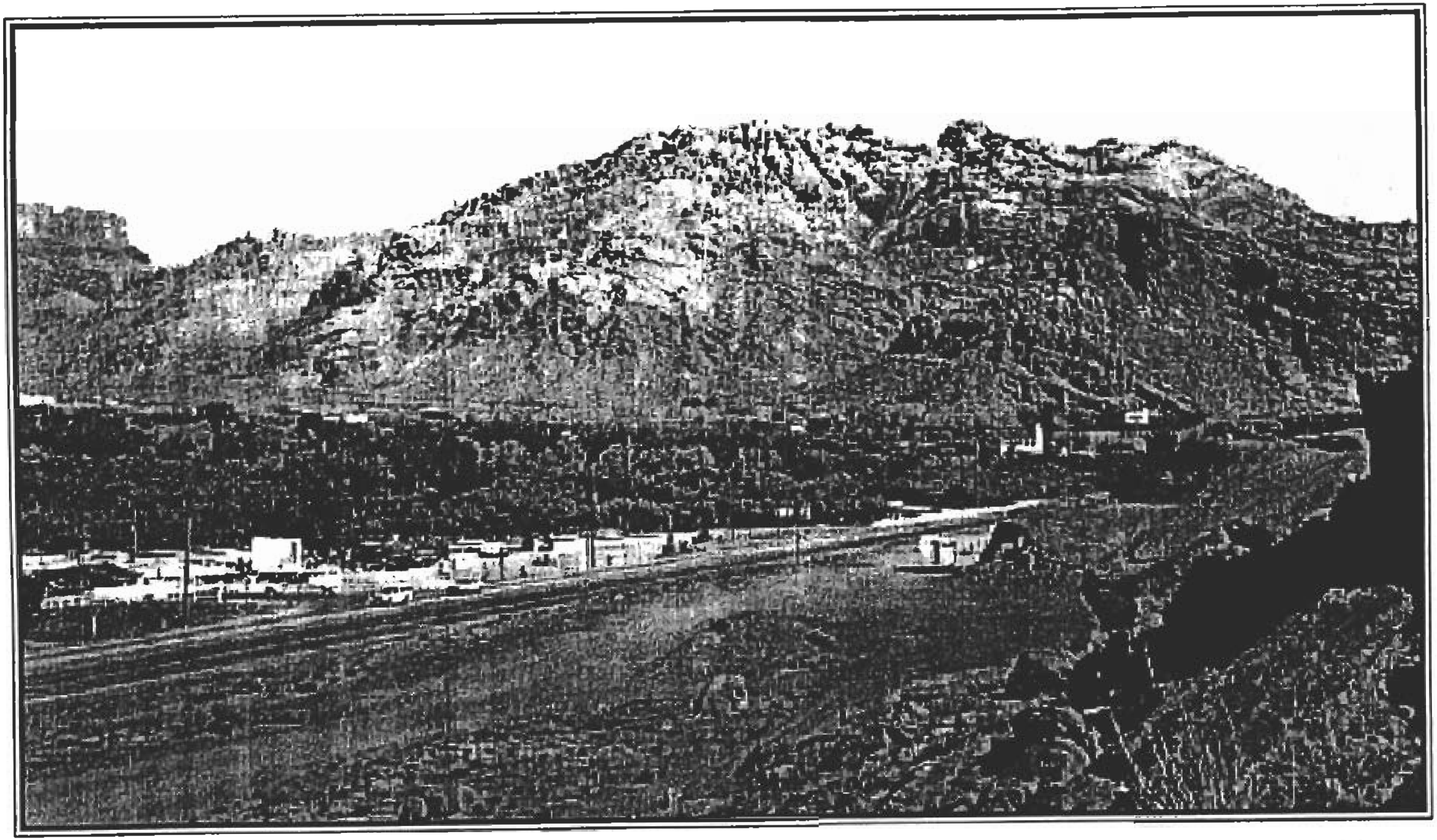

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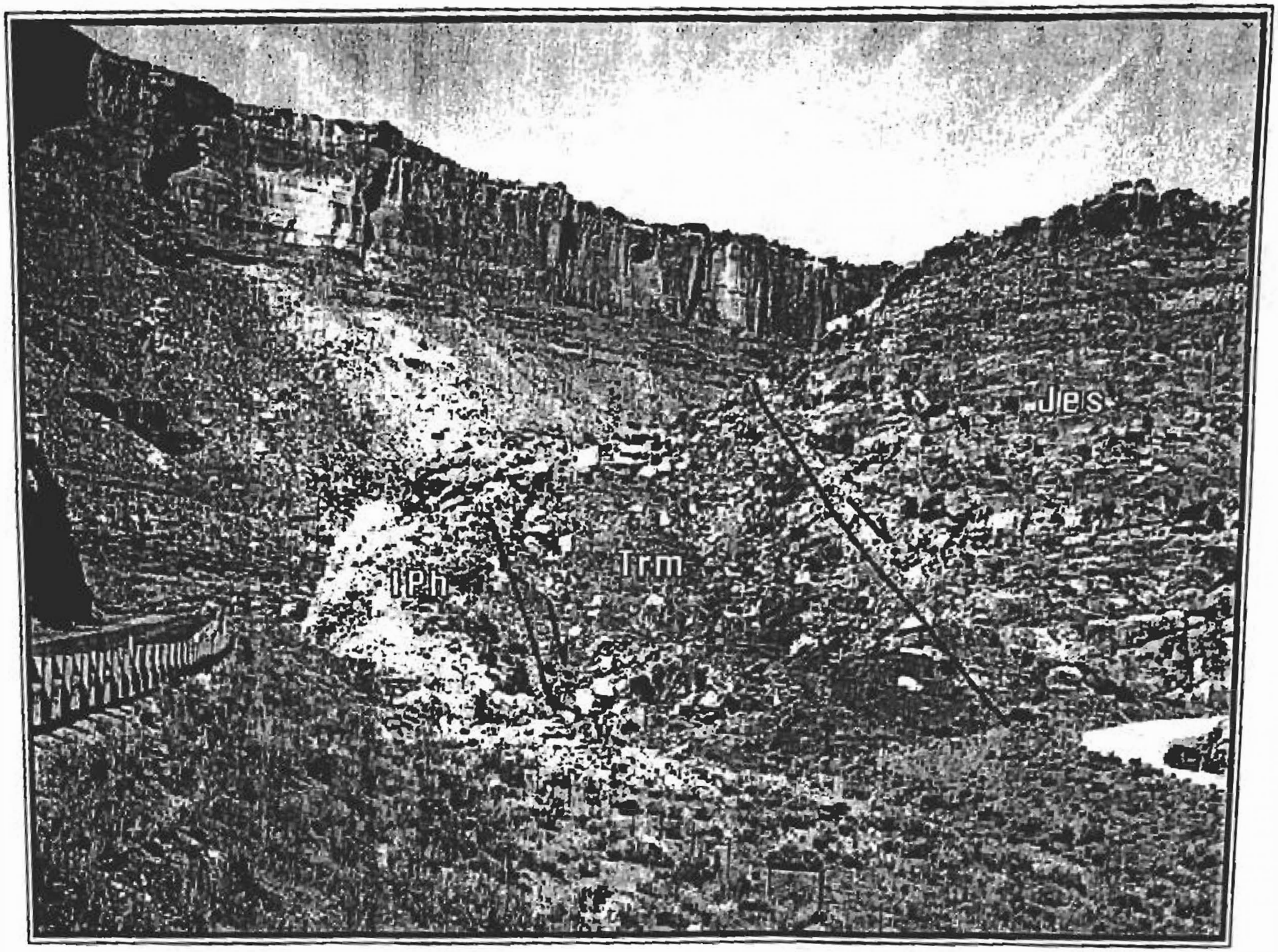

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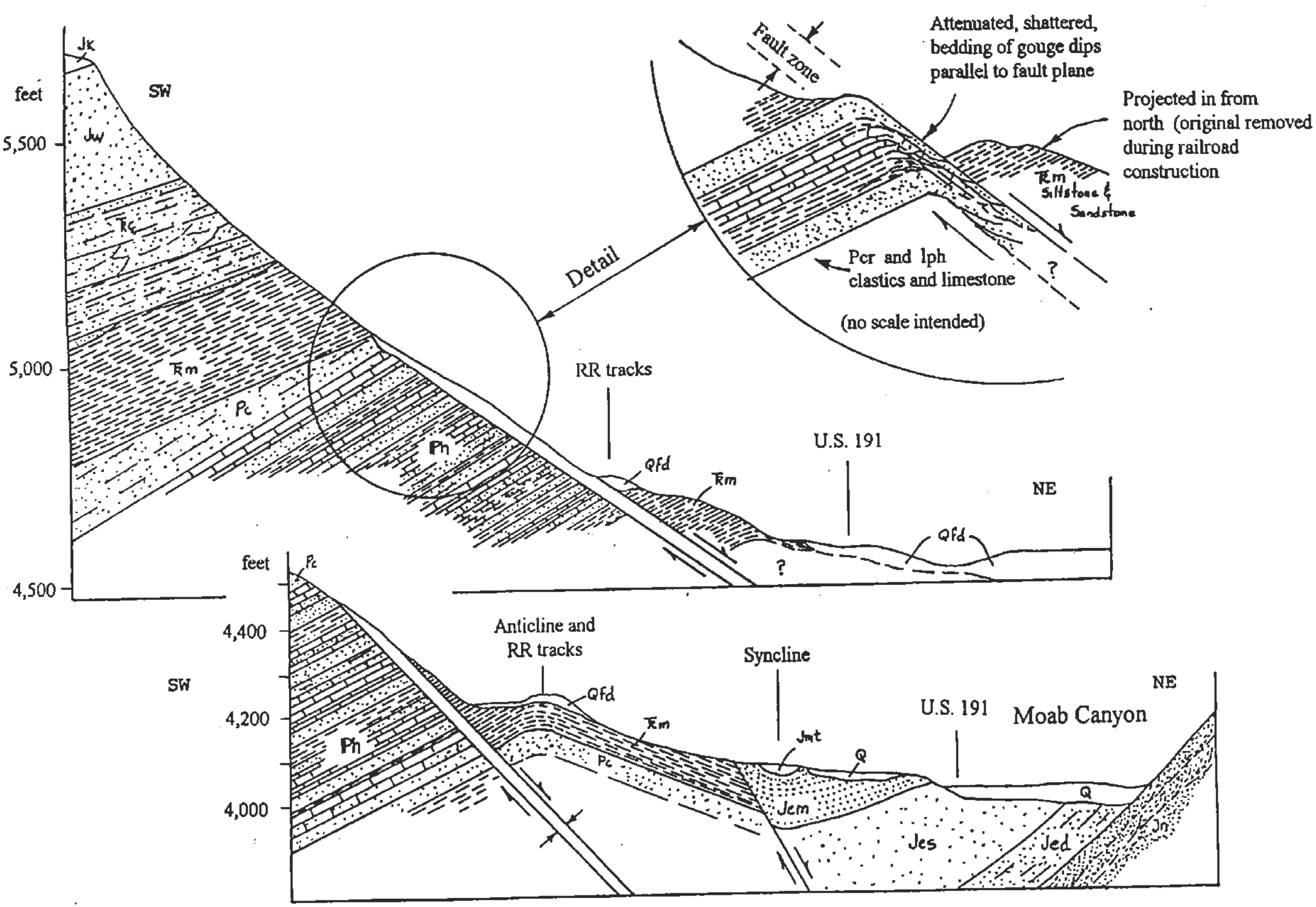

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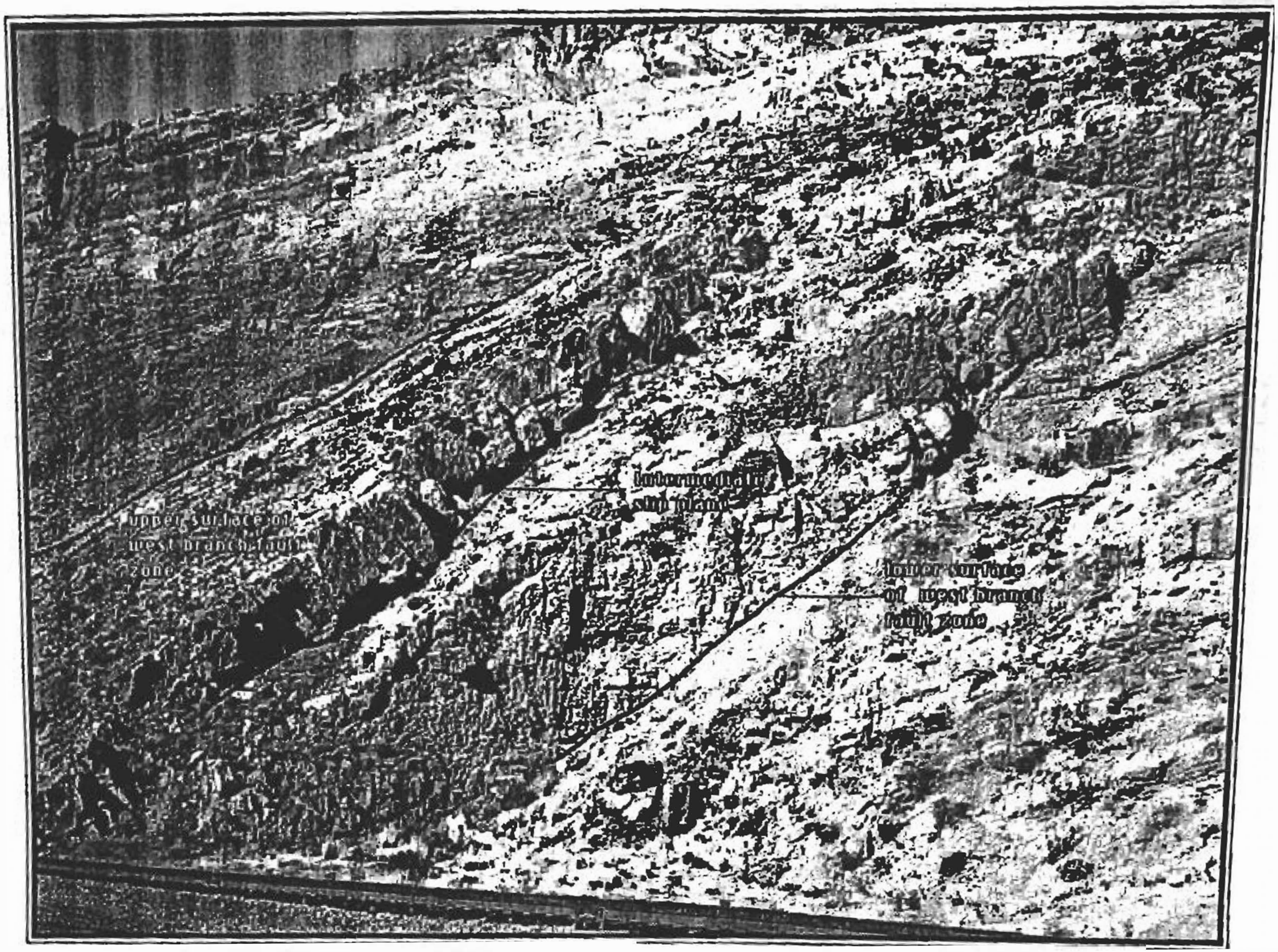

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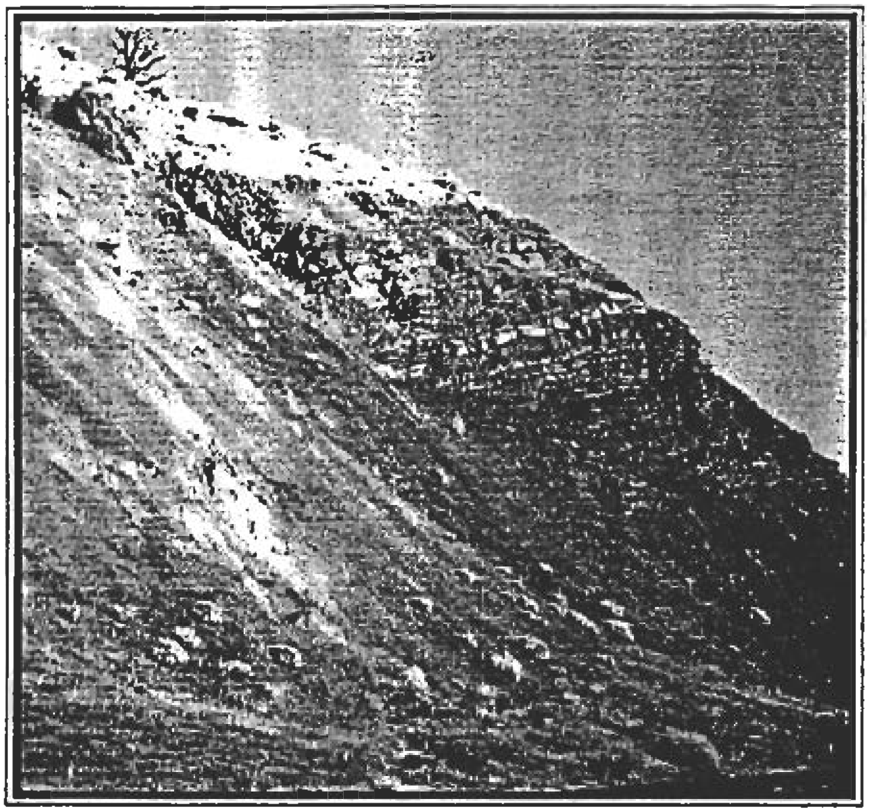

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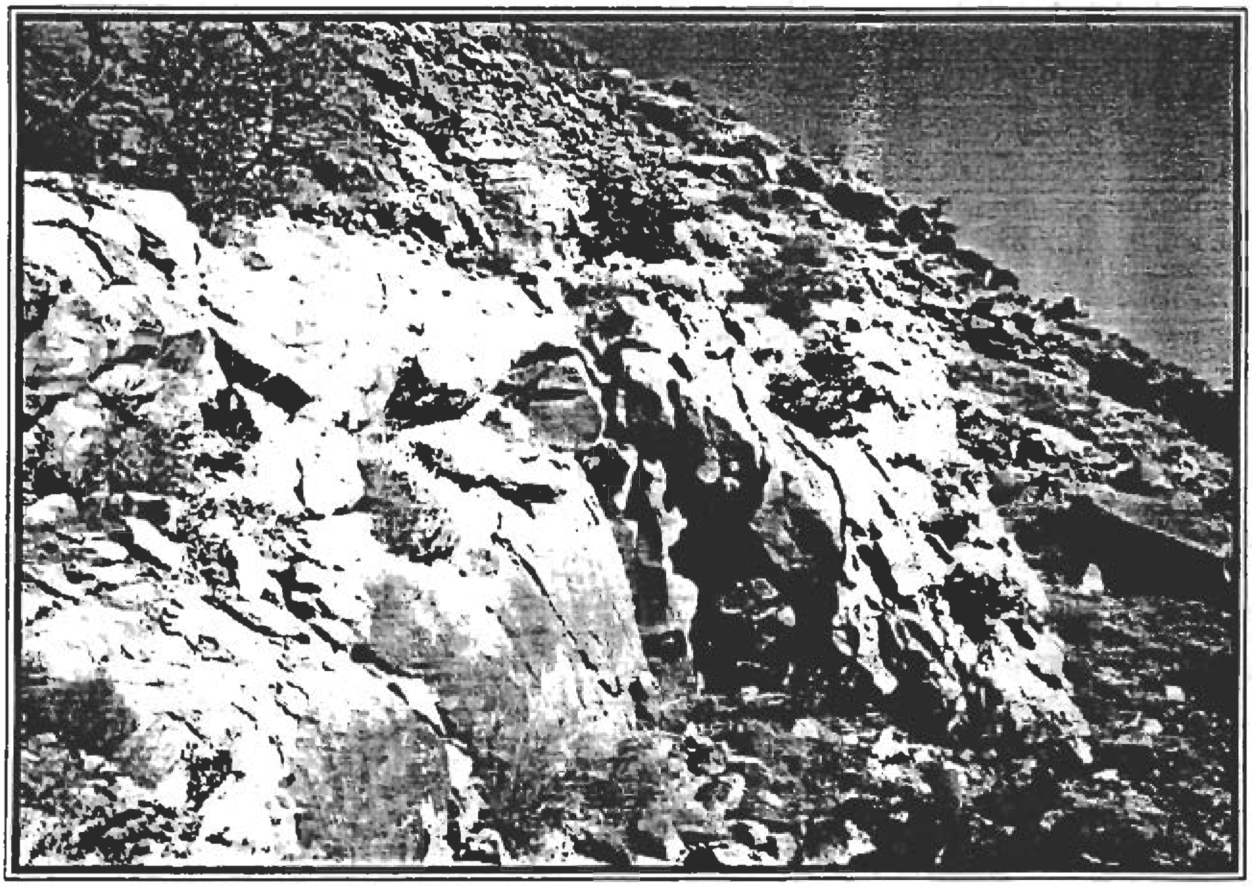

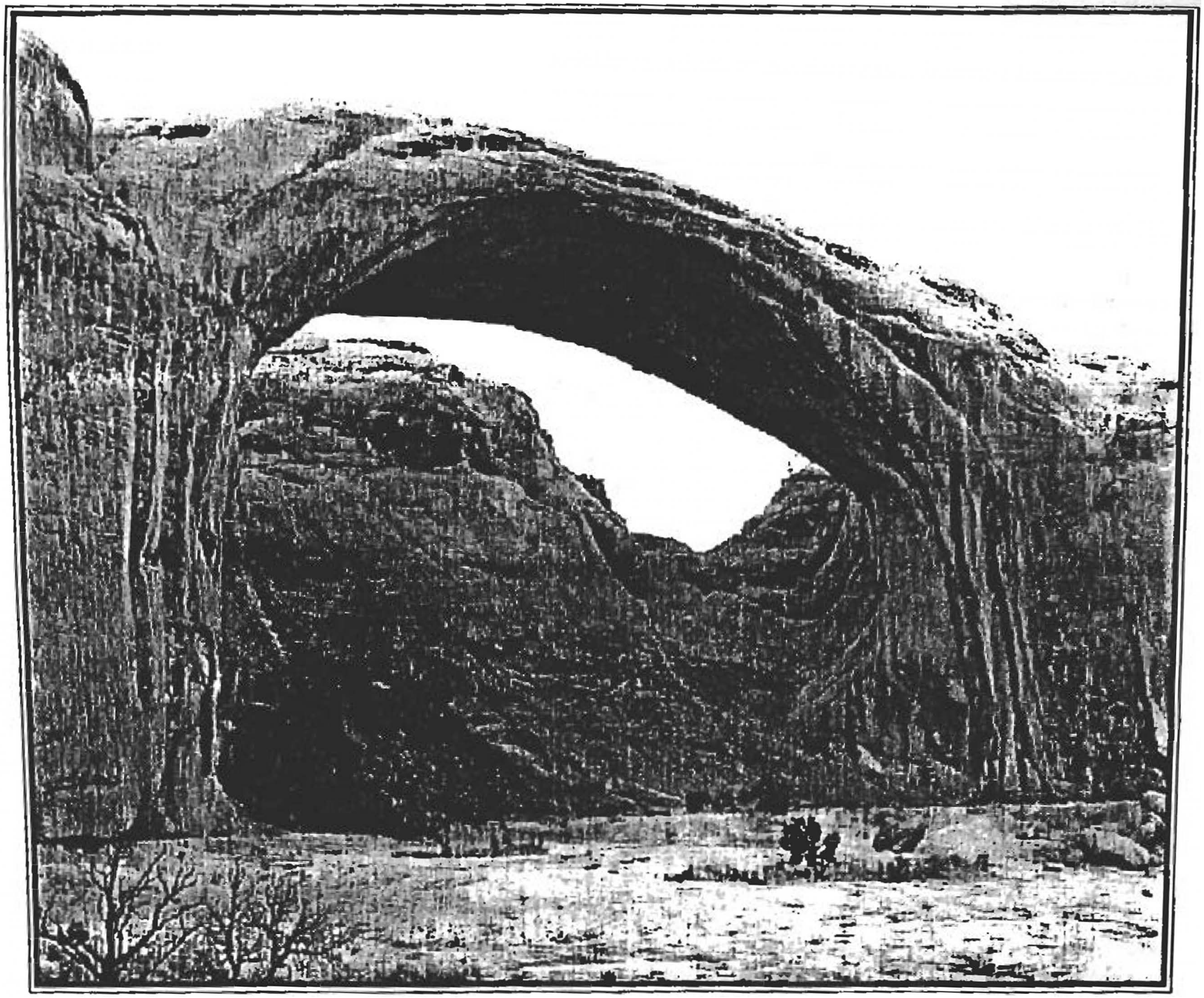

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	NAME AND LOCATION			North Mill Creek NE 7-26S-22E	South Mill Creek E 7-26S-22E	Negro Bill SW19-25S-22E	U-128 bend SW24-25S-22E
TEST DATA - REPRESENTATIVE SAMPLE	THICKNESS OF MATERIAL			50 feet	50 feet	10 feet	—
	DEPTH OF OVERBURDEN			0 - 1 foot	0 - 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	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-b
	IMMERSION COMPRESSION AVERAGE P.S.L.	LIME	WO/				
			W/				
	ABRASION 500 REVOLUTIONS			26.4 %	24.1 %	26.3 %	20.0 %
	SODIUM SULFATE LOSS		+4				
			−4				

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

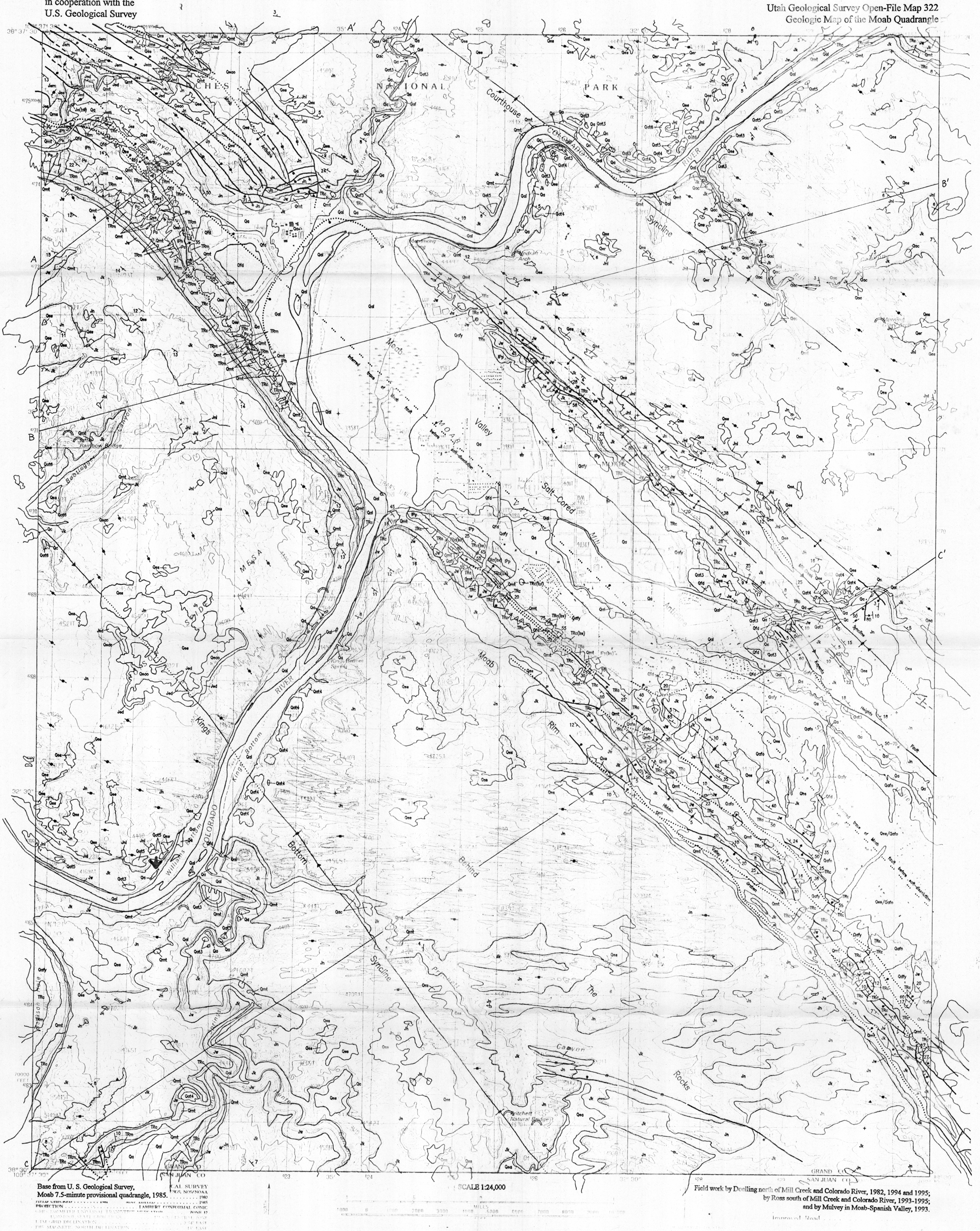
Table 1

Table 2. Oil & Gas and Brine wells in the Moab quadrangle.

LOCATION SECTION, TOWNSHIP, RANGE, API NUMBER	OPERATOR AND WELL NUMBER	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 43-019-11563-0000	Embar Oil - Big Six Oil Companies, No. 1	3-2-28	5,345	Oil and gas shows at various elevations from 2,380 to 4,880 feet; Abandoned.
3. SWNE 34, 25S, 21E 43-019-20407-0000	Great Lakes Carbon Corp., No. 1	1-7-43	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 43-019-10696-0000	E.J. Mayhew, Doogan - Voorhies, No. 1	1-2-43 5-20-60	2,027	Initially a 1,150-foot exploration well, then abandoned; Re-entered and deepened as a brine well by Moab Brine Co.; Abandoned
5. NENWNE 12, 26S, 21E 43-019-11580-0000	Western Allied - Big Six Oil Companies, No. 1	1920	2,450	200 feet of valley-fill alluvian overlying Paradox Fm. caprock & salt; oil shows at 1,380 to 1,420 feet; Abandoned
6. SWNW 8, 26S, 22E 43-019-11582-0000	Utah Oil Development Co., No. 1	7-7-27	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 Oil; Re-entered and deepened to 10,721 feet; Abandoned.

Utah Geological Survey
Department of Natural Resources
in cooperation with the
U.S. Geological Survey

Plate 1
Utah Geological Survey Open-File Map 322
Geologic Map of the Moab Quadrangle



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

PROJECTION . . . . LAMBERT CONFORMAL CONIC

To place on the predicted North American Datum of 1983, move the projection lines as shown by dashed corner ticks (5 meters north and 60 meters east)
There may be private inholdings within the boundaries of any Federal and State Reservations shown on this map.
Gray tint indicates area in which selected buildings are shown.
All marginal data and lettering generated and positioned by automated type placement procedures.

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.

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

Interim Geologic Map of the Moab Quadrangle, Grand County, Utah

by

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

1995

Utah Geological Survey
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Interim Geologic Map of the Moab Quadrangle, Grand County, Utah

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1995

Plate 2
Utah Geological Survey Open-File Map 322
Geologic Map of the Moab Quadrangle

DESCRIPTION OF MAP UNITS

Quaternary Deposits

Qal **Modern Alluvium** - Poor to well sorted sand, silt, clay, and lenses of gravel in active channels and covering modern flood plains. Holocene. Deposits are as much as 20 feet (6 m) thick.

Qa **Alluvium** - Gravel, sand, silt, and minor amounts of clay; covers valley floors and forms isolated terraces or surfaces 10 to 50 feet (3 to 15 m) above modern floodplains and channels; the surfaces of some deposits is characterized by weak soil development; in Moab Valley and Mill Creek, trachyte porphyry clasts from the La Sal Mountains are the dominant rock type, with lesser amounts of locally dreived sandstones from the Chinle Formation and Glen Canyon Group; along the Colorado River Qa terraces consist primarily of exotic igneous and metamorphic rocks from source areas up river, trachyte porphyry from the La Sal Mountains, and Glen Canyon Group sandstones. Early Holocene to late Pleistocene. Deposits are as much as 30 feet (10 m) thick.

Qat_3 Qat_4 Qat_5 Qat_6 **Alluvial-Terrace Deposits** - Moderately sorted, poorly stratified gravel in a gray, calcareous, sandy matrix; contain a variety of locally derived and exotic clasts similar to Qa; preserved as isolated remnants along major drainages. Qat_3 gravels are found between 50 and 100 feet (15 to 30 m) above the present stream channels, some are capped by an eroded Stage II-III pedogenic carbonate soil. Qat_4 gravels are found between 100 to 150 feet (30-45 m) above the present stream channels; Qat_5 gravels are found between 200 to 240 feet (61 to 73 m) above the present stream channels; and Qat_6 gravels are found between 260 to 280 feet (79 to 86 m) above the present stream channels. Qat_5 and Qat_6 clasts are distinguishable from those of lower terraces by a well-developed rind of desert varnish. Pleistocene. Deposits are as much as 60 feet (20 m) thick.

Qabf **Basin-Fill Deposits** - Mostly alluvial deposits that fill Moab Valley; gravel, sand, silt, and minor amounts of clay; no surface exposures but intercepted in drill holes and covered by Holocene surficial deposits. Pleistocene. Deposits may be as much as 450 feet (137 m) thick.

Qafy **Younger Alluvial-Fan Deposits** - Poorly sorted, generally unstratified, muddy to sandy cobble gravel, clasts locally derived and range from angular to subrounded; found along northeast and southwest sides of Moab and Spanish Valleys; fans have dendritic drainage patterns and typical fan shape; form gentle to moderate apron-like slope at the base of cliffs or head in gullies of older fan deposits (Qafo). Holocene to Late Pleistocene. Deposits as much as 20 feet (6 m) thick.

Qafo **Older Alluvial-Fan Deposits** - Poorly sorted, generally unstratified, muddy to sandy cobble gravel, boulders present near cliffs; clasts are locally derived and range fron angular to subrounded; commonly covered by a veneer of sand (Qes); fans are dissected and have limited fan morphology; form gentle to moderate apron-like slopes at the base of cliffs, found on southwest side of Moab and Spanish Valleys. Late and middle Pleistocene. Deposits as much as 40 feet (12 m) thick.

Qmt **Talus** - Angular boulders, cobbles, and smaller fragments commonly in a fine-grained matrix; derived from rockfalls and form relatively thick veneers on slopes below cliffs; commonly grade downward into alluvial-fan deposits. Holocene to Pleistocene. Deposits as much as 20 feet (6 m) thick.

Qms **Landslide** - Large mass of the Moab Member of the Entrada Sandstone that slid along a bedding plane parting of muddy sandstone at its contact with the underlying Slick Rock Member; located in Moab Canyon along Utah Highway 191 Probably Pleistocene. About 60 feet (20 m) thick.

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

Qes **Eolian Sand Deposits** - Fine- to medium-grained, quartzose sand, typically form thin, discontinuous sand sheets and small dunes Holocene. Locally as much as 30 feet (10 m) thick.

Qea **Eolian-Alluvial Deposits** - Mainly moderately to well sorted quartzose sand deposited and reworked by eolian and alluvial processes; generally thin and restricted to ephemeral washes and hollows on mesas and benches capped by Glen Canyon Group sandstone. Holocene. Deposits as much as 10 feet (3 m) thick.

Qeao **Older Eolian-Alluvial Deposits** - Mainly sand, but contain sparse lenses of rounded granules and pebbles, sheet-like and locally preserved on mesas and benches; deposit on Poison Spider Mesa is capped by an eroded Stage VI-V pedogenic carbonate soil. Early to middle Pleistocene. Deposits are as much as 15 feet (5 m) thick.

Qer **Mixed Eolian and Residual Deposits** - Mostly mix of reddish fine-grained sand and angular limestone rubble derived from carbonate units in the Navajo Sandstone on top of which they are deposited. Holocene to late Pleistocene. Mostly less than 3 feet (1 m) thick.

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

Qfd **Fill and Disturbed Deposits** - Clay- to boulder-size material used as railroad and road fill; sand-size mine tailings at the Atlas Minerals site; sand and gravel pits, and larger areas disturbed by development. Latest Holocene. Variable thicknesses as much as 70 feet (21 m).

Jurassic Rocks

Morrison Formation

Jms **Salt Wash Member** - Blocky ledges of pale-yellow-gray, cross-bedded sandstone interbedded with slope-forming, red and gray mudstone and siltstone; only a small remnant is present in the northwest corner of the quadrangle. Late Jurassic. Preserved thickness is 30 feet (10 m).

Jmt **Tidwell Member** - Red to brown, thin bedded, silty sandstone, muddy limy sandstone, siltstone, and shale containing thin to nodular beds of gray limestone; large white siliceous concretions are associated with the limestone; forms gentle slope littered with limestone and chert fragments; lower 6 to 12 feet (2 to 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 the lower steep slope and remainder of Tidwell may be the J-5 unconformity. Late to Middle Jurassic. Total thickness is 40 to 50 feet (12-15 m).

Entrada Sandstone

Jem **Moab Member** - Pale-gray-orange, pale-yellow-brown, and light-gray, fine- to medium-grained, quartzose, eolian sandstone; calcareous; forms massive cliff commonly with conspicuous joints. Middle Jurassic. Thickness is 60 to 100 feet (20 to 30 m).

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

Jed **Dewey Bridge Member** - Red-brown, muddy to silty, fine- to medium-grained sandstone; iron oxide or calcareous cemented; medium to thick bedded, weathers to distinct irregular and contorted rounded ledges; basal contact is the J-2 unconformity. Middle Jurassic. Thickness is 90 to 110 feet (27 to 33 m).

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

Jk **Kayenta Formation** - Red-brown, pale-red, gray-red, and pale-red-purple sandstone, interbedded with dark-red-brown to gray-red intraformational conglomerate, siltstone, mudstone, and silty limestone; mainly of fluvial and lacustrine origin; pale-gray-orange eolian sandstone beds are conspicuous in upper part, litharenites; calcareous; forms thick-bedded, step-like, resistant ledges and steep slopes. Lower Jurassic. Thickness is 250-400 feet (76 to 122 m).

Jw **Wingate Sandstone** - Gray-orange-pink, gray-orange, and light-brown, fine-grained, quartzose, eolian sandstone; calcareous or siliceous cement; commonly forms massive cliffs along canyon walls or blocky cliffys where fractured; cliff surfaces commonly streaked with dark-brown desert varnish. Lower Jurassic Thickness is 250–400 feet (76 to 122 m).

Triassic Rocks

Trc **Chinle Formation** - Red-brown to gray-red, interbedded sandstone, conglomeratic sandstone, siltstone and mudstone, with subordinate gray, sandy limestone; lenticular and sheet-like sandstone and conglomeratic sandstone are calcareous to quartzose; fine to coarse grained; bentonitic and calcareous mudstones form steep slopes separated by ledges and cliffs of sandstone and conglomeratic sandstone; indistinctly bedded, locally contains a discontinuous lower member of light-gray quartzose sandstone and mottled siltstone; upper member is divisible into a (ascending) slope-former, a ledge-former, another slope-former, and sheet-like flat beds of possible eolian origin. Upper Triassic. Thickness ranges from 100 to 700 feet (30 to 192 m).

Trm **Moenkopi Formation** - 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; local lenses of Hoskinnini Member (?) at base. Lower Triassic. Outcrop thickness ranges from 0 to 750 feet (0 to 229 m).

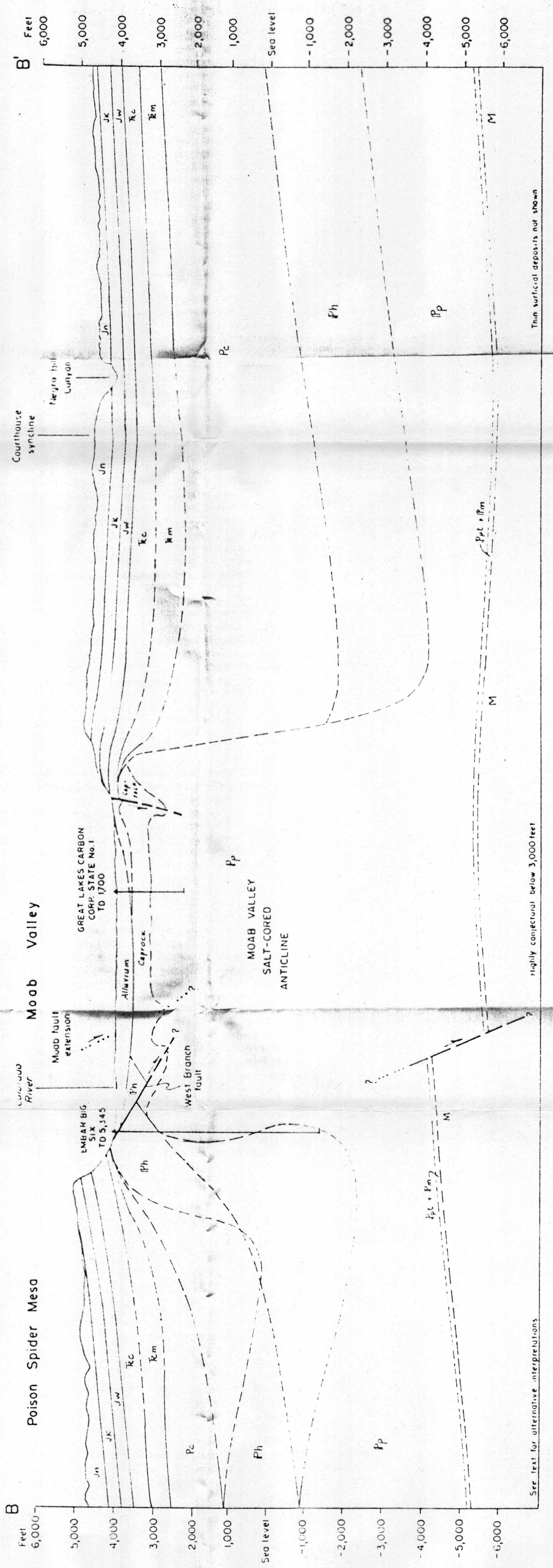
Permian Rocks

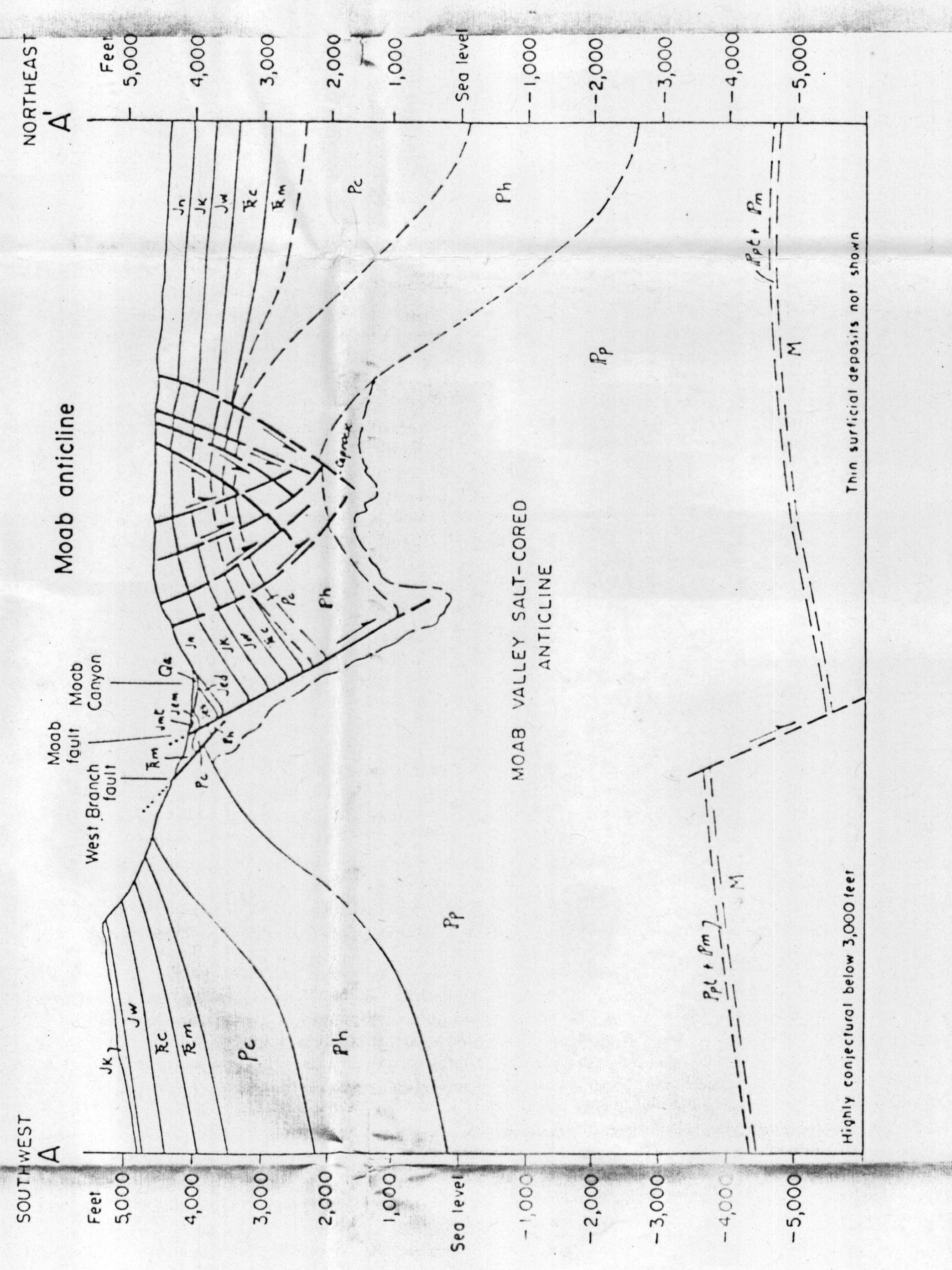
Pc **Cutler Formation** - Red-brown and red-purple, subarkosic to arkosic fluvial sandstone and conglomeratic sandstone interbedded with red-orange eolian sandstone; medium to thick bedded, thin beds of red-purple muddy siltstone and light-gray fossiliferous limestone in lower part; forms steep slopes,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

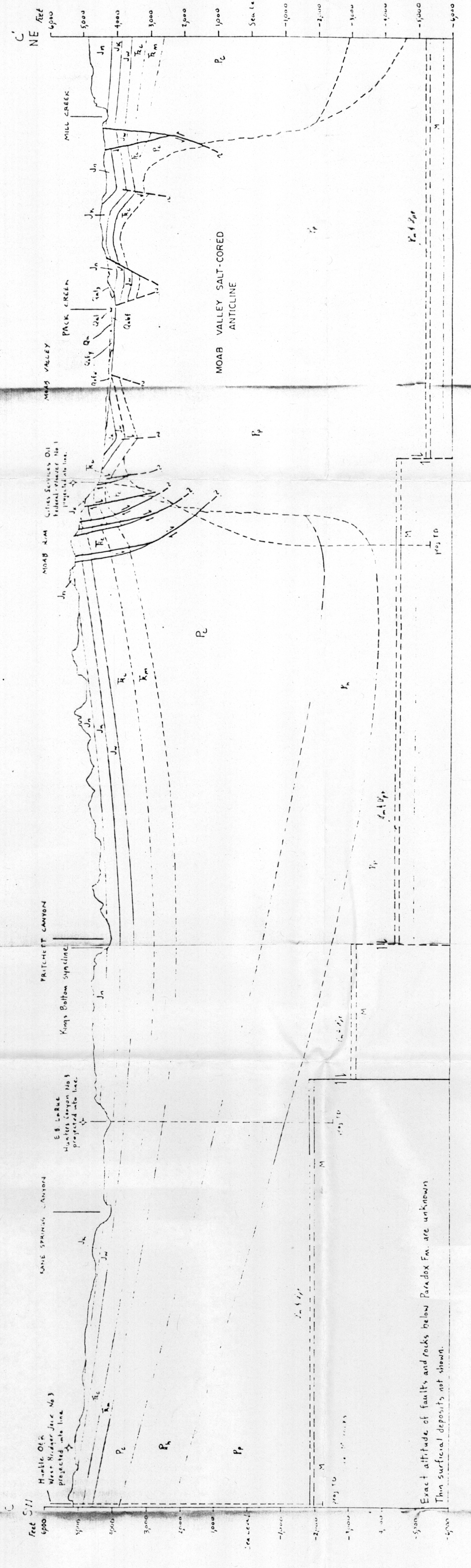
Pennsylvanian Rocks

IPh **Honaker Trail Formation** - Light-gray, pink-gray, 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 cliffs, ledges and steep slopes. Upper Pennsylvanian (Missouri-Virgil). Outcrop thickness may be as much as 700 feet (213 m), but may be as much as 2,700 feet (823 m) thick in subsurface due to movement of salt diapirs.

IPp **Paradox Formation** - Gray, sucrosic gypsum, gypsiferous claystone, gray to black silty shale, with subordinate gray, fine-grained sandstone and carbonates, mostly gypsiferous claystone is infolded and contorted with resistant and pitted sucrosic gypsum as caprock; contains thick salt beds in the subsurface. Middle Pennsylvanian (Desmoines). Estimated caprock thickness is as much as 700 feet (213 m); estimated height of Moab salt diapir may be as much as 10,000 feet (3,048 m).

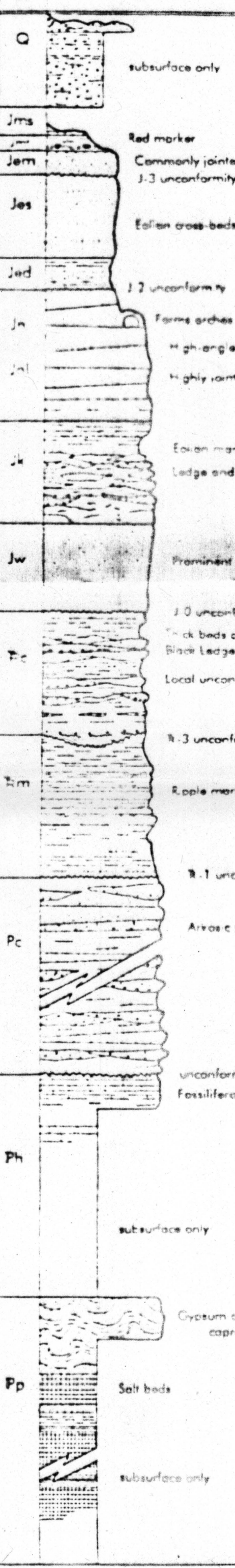






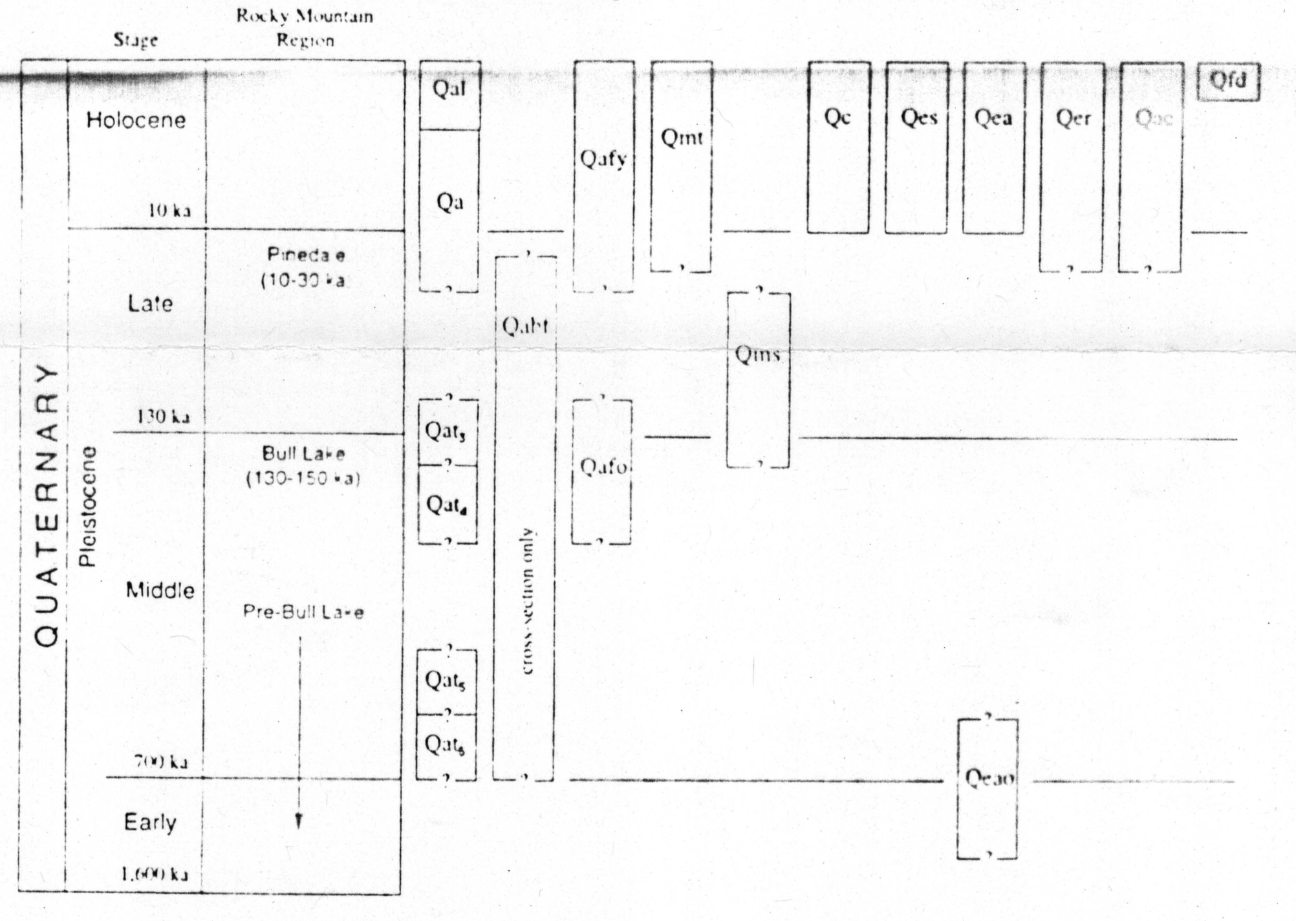
MAP SYMBOLS

Contact -- Dashed where inferred, dotted where covered
Fault -- Dashed where inferred, dotted where covered, bar and ball on downthrown block, arrow indicates dip of fault surface
Inferred trace of Moab fault prior to salt-dissolution collapse
Vertical fracture, minor brecciation
Trace of axial plane of anticline showing plunge; dotted where covered
Trace of axial plane of syncline showing plunge; dotted where covered
Minor anticline and syncline showing plunge
Strike and dip of beds
Strike of nearly vertical joints
Strike and dip of inclined joint
Adit
Dry hole, abandoned
Gas injection, disposal, or brine well
Gravel pits
Natural stone arch or bridge
Dinosaur footprints
Line of cross section
Brecciated rock (pattern over affected rock unit)



PERIOD	SERIES	FORMATION AND MEMBERS		THICKNESS feet (meters)	SYMBOLS	LITHOLOGY
QUATERNARY		SURFICIAL AND BASIN-FILL DEPOSITS		450+ (137+)	Q	subsurface only
JURASSIC	Upper	Morrison Fm	Salt Wash Mbr	30+ (9+)	Jms	
			Tidwell + Summerville	45-50 (14-15)	Jmt	Red marker
	Middle	ENTRADA SANDSTONE	Moab Mbr	60-100 (18-30)	Jem	Commonly jointed J-3 unconformity
			Slick Rock Mbr	250± (76±)	Jes	Eolian cross-beds
			Dewey Bridge Mbr	90-110 (27-33)	Jed	J-2 unconformity
	Lower	NAVAJO SANDSTONE		300-700± (91-213)	Jn Jnl	Forms arches High-angle crossbeds Highly jointed
		KAYENTA FORMATION		250-400 (76-122)	Jk	Eolian marker bed Ledge and bench forming
		WINGATE SANDSTONE		250-400 (76-122)	Jw	Prominent cliff former
TRIASSIC	Upper	CHINLE FORMATION		100-700 (30-213)	Trc	J-0 unconformity Thick beds at top Black Ledge Local unconformities
	Lower	MOENKOPI FORMATION		0-750 (0-229)	Trm	Tr-3 unconformity Ripple marks
PERMIAN	Lower	CUTLER FORMATION		0-5,000+ (0-1,524+)	Pc	Tr-1 unconformity Arkosic sandstone
PENNSYLVANIAN	Upper (Missouri & Virgil)	HONAKER TRAIL FORMATION		0-2,700 (0-823)	IPh	unconformity Fossiliferous subsurface only
	Middle (Desmoines)	PARADOX FORMATION		500-10,000+ (152-3,048m)	IPp	Gypsum and shale caprock Salt beds subsurface only

CORRELATION OF QUATERNARY MAP UNITS



Correlation of Bedrock Map Units

JURASSIC	Upper	Morrison Formation Salt Wash Member	Jms
		Tidwell Member Summerville Formation	Jmt
	Middle	Entrada Sandstone Moab Member	Jem
			J-3 unconformity
		Slick Rock Member	Jes
		Dewey Bridge Member	Jed
			J-2 unconformity
	Lower	Navajo Sandstone	Jn
		Kayenta Formation	Jk
		Wingate Sandstone	Jw
			J-0 unconformity
TRIASSIC	Upper	Chinle Formation	Trc
			Tr-3 unconformity
	Lower	Moenkopi Formation	Trm
			Tr-1 unconformity
PERMIAN	Lower	Cutler Formation	Pc
			unconformity
PENNSYLVANIAN	Upper	Honaker Trail Formation	IPh
	Middle	Paradox Formation	IPp
		Pinkerton Trail (cross-section only)	IPpt
		Molas Formation (cross-section only)	IPm
			unconformity
MISSISSIPPIAN and OLDER ROCKS		Mississippian and older rocks (cross-section only)	M