SALT DEFORMATION IN THE PARADOX REGION

by
Hellmut H. Doelling, Charles G. Oviatt, Peter W. Huntoon

UTAH GEOLOGICAL AND MINERAL SURVEY
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UTAH GEOLOGICAL AND MINERAL SURVEY

606 Black Hawk Way
Salt Lake City, Utah 84108-1280

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SALT DEFORMATION IN THE PARADOX REGION, UTAH

Preface:

Bedded salt deposits were identified by the U.S. Department of Energy (DOE) as places suitable to store or dispose of nuclear fuel and high-level radioactive waste. The Paradox Basin, with its thick salt beds, was a likely place for study and consideration. The DOE and its subcontractors began their study of the region in the mid-1970s and by 1983 had chosen two sites in the Utah portion of the Paradox Basin as potentially acceptable for the repository. Bedded salt deposits were chosen along with salt domes, basalt (solidified lava), tuff (compacted volcanic ash), and crystalline rock (certain varieties of igneous or metamorphic rocks) as suitable to be able to safely contain the dangerous materials and to prevent them from leaking into the natural environment. Salt "heals" itself when fractured, is an aquiclude, has a low thermal conductivity, and is relatively easy to mine.

Geologic studies were performed to insure that other natural activities in nature would not negate or diminish the advantages of the salt beds. Some important areas for study included the natural ground-water systems, the normal tectonic activity of the area, and man's activities in the area. unsaturated ground waters could dissolve the salt containing the dangerous materials, earthquakes and stresses on the salt might make it mobile and disrupt the containment of the nuclear wastes, blasting in mines and quarries would also place stresses on the salt. The half-lives of many of the radioactive isotopes are enormous; therefore it was necessary to insure that such a repository be safe for tens of thousands of years.

The Utah Geological and Mineral Survey along with other governmental agencies conducted studies simultaneously with those of the DOE and its subcontractors to make sure that any sites chosen in the Paradox Basin would be safe and in the best interests of the citizens of Utah and of the United States of America. Three of these studies appear in this bulletin.

"The geology of Salt Valley anticline and Arches National Park, Grand County, Utah," by Hellmut H. Doelling, is a study of one of the salt anticlinal structures in the Paradox Basin. Included in the study is a discussion of the stratigraphy and structure, with examples of how salt has been involved in the shaping of the landscape. Folded and faulted rocks, dissolution features, landsliding, arch and fin formation, and perhaps diapiric structures are all related to the presence of salt in the region. This paper is a technical companion to "the geologic map of Arches National Park and vicinity, Grand County, Utah," published as Map 74 of the UGMS.

"Evidence for Quaternary salt deformation in the Salt Valley anticline, southeastern Utah," by Charles G. Oviatt presents evidence that Quaternary deposits have been folded and faulted and otherwise deformed. He identifies datable volcanic ash beds involved in the deformation and indicates that dissolution and diapirism may still be active in the Salt Valley region.

"Late Cenozoic gravity tectonic deformation related to the Paradox salts in the Canyonlands area of Utah," by Peter W. Huntoon, discusses deformation observed in the rocks overlying the salt and relates them to three active mechanisms: (1) salt flowage, (2) salt dissolution, and (3) gliding of the rocks above the salt. He believes these processes became active due to the erosion of the Colorado River and its tributaries. He presents evidence that these processes continue to be active and are destabilizing the salt.

All three studies indicate that the salt is still active in various parts of the Paradox Basin and that radioactive waste disposal in the region should be viewed with extreme caution. The Paradox Basin of Utah and Colorado is truly a unique area of the world where active processes constantly create and destroy some rather unusual landforms in rather concentrated settings: deep canyons, salt valleys, stone arches, fins, dissolution features, diapirs, buttes, mesas, monuments, monoclines, joints, steep escarpments, cuestas, and hogbacks. These are well displayed by the colorful and varied formations of the region. These papers answer many questions that visitors ask about the region, such as why we don't see salt at the surface, how thick are the salt beds, how old are the rocks, the salt, and the structures, why are some rocks green and others red and lavender? Studies continue by the UGMS and other agencies to unravel many unanswered questions about this very interesting part of the world.

GEOLOGY OF SALT VALLEY ANTICLINE AND ARCHES NATIONAL PARK, GRAND COUNTY, UTAH

by
Hellmut H. Doelling
Senior Mapping Geologist, UGMS

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ABSTRACT

The Salt Valley anticline, Moab Valley, and Arches National Park are located in east-central Utah in the Paradox Basin fold and fault belt. Sedimentary rock thicknesses above the Precambrian basement include an average of 800 feet of Cambrian, 350 feet of Devonian, 500 feet of Mississippian, 7150 feet of Pennsylvanian, 2500 feet of Permian, 800 feet of Triassic, 2220 feet of Jurassic, and 1140+ feet of Cretaceous rocks. Thick cyclical salt beds (Paradox Formation) were deposited during Pennsylvanian time during the most rapid development of the Paradox Basin. The basin sank along northwest-trending faults which were active during salt deposition and at least into Late Triassic time. The salt was unstable and thickened by plastic movement over the fault lines to form salt anticlines at the expense of salt thickness in adjacent areas. This period of most active salt movement lasted from 300 to 225 million years ago. Parts of the salt anticline areas probably were "islands" from time to time and either received no sediments or had them removed by erosion. Peripheral areas where the salt was being thinned received greater than normal thicknesses of overlying sediments.

The Late Triassic Chinle Formation was the first to cover the salt-bearing Paradox Formation and ushered in the period of localized salt movement, which lasted from 225 to 100 million years ago. Salt movement was restricted to local places along the Salt Valley anticline and other salt anticlines. Finally, the Cretaceous sea covered the entire region, depositing the Mancos Shale. The salt remained covered from 100 to less than 10 million years ago. During Tertiary time, however, the region was gently folded into anticlines and synclines and long northwest-trending faults, which paralleled the older basin-producing faults, and ruptured salt and rocks alike.

Epeirogenic uplift elevated the region beginning about 10 million years ago and subjected it to widespread erosion. Salt Valley anticline and Moab anticline were exhumed and fresh water reached the salt via joints and faults opened during the folding and faulting of Tertiary time. The ensuing dissolution of salt caused local collapse of overlying strata, especially in the cores of the salt anticlines. The collapsed areas were occasionally covered by thick alluvium which locally collapsed after additional dissolution of salt.

The presence of salt is responsible for creating most of the unique landforms of the region, including arches, fins, and salt valleys. These landforms, the canyon cutting of the Colorado River and its tributaries, and the colorful bedrock formations have made the region a world-renowned scenic area.

The area also contains economic mineral deposits including uranium, vanadium, potash, petroleum, and sand and gravel. Other potential items include copper, gold, manganese, calcite, rockhound materials, magnesium, rock salt, gypsum, building stone, and limestone.

INTRODUCTION

Eastern Utah is a unique area where many colorful rock formations lie open to view. The dry climate coupled with the canyon cutting of the Colorado River and its tributaries make the region an easy place to read the geologic history as recorded in the rocks. The part of Utah described here lies within the Paradox Basin which straddles the Utah-Colorado state line (figure 1) and is an area in which thick beds of salt were deposited in mid-Pennsylvanian time.

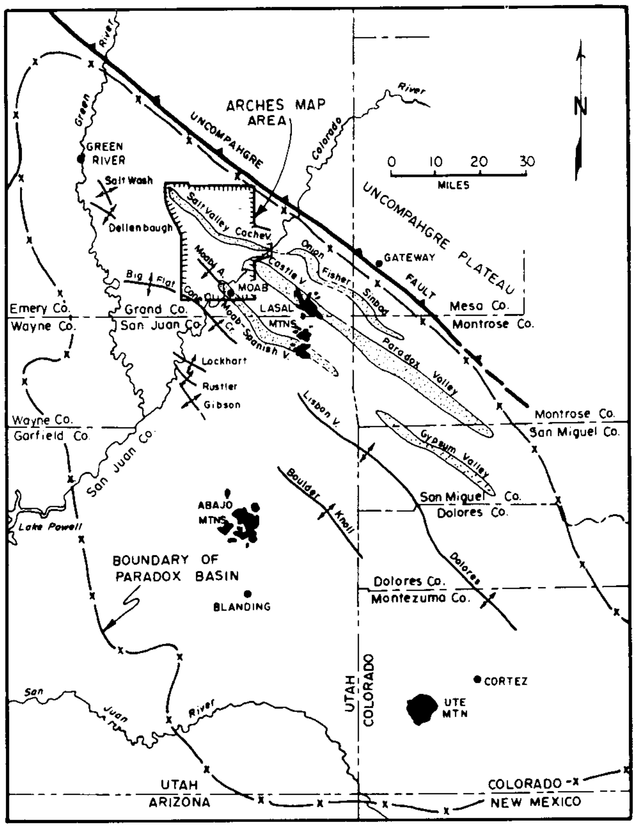


Figure 1. Index map to the Paradox Basin, southeastern Utah and southwestern Colorado, showing the principal structures. Salt anticline valleys are stippled and the area of Map 74 (Doelling, 1985) of Arches National Park is indicated.

Salt has many unique properties when compared to other sediments, among which are its plasticity, solubility, and light weight. These properties greatly influenced the subsequent depositional and structural histories of the area, especially where salt is thickest in the deep part of the Paradox Basin. This area is characterized by northwest-trending salt anticlines and intervening synclines and is known as the Paradox Basin fold and fault belt. Landforms here are mostly reflections of the effects salt movement and dissolution have had on the rocks; these are most effectively displayed in the vicinity of Arches National Park and the Salt Valley anticline. Arches National Park has the greatest concentration of natural rock arches in the world (Lohman, 1975, p. 40), but they would not have developed without the presence of the salt.

In the park and surrounding areas one can examine a host of collapse features, attendant folds and faults, highly contorted gypsum caprock exposures, and other related landforms. Geologists have been studying these features ever since the presence of salt became known in the region, but many aspects remain elusive and unclear.

PHYSIOGRAPHIC AND GEOGRAPHIC DESCRIPTION

Arches National Park and the Salt Valley anticline are in east-central Utah, entirely in Grand County, and in the northwestern part of the Paradox Basin (figure 1). A geologic map of the region was prepared as Utah Geological and Mineral Survey Map 74 which covers the U. S. Geological Survey Arches National Park, Utah special topographic map plus additions to cover the northwest end of Salt Valley and the eastern end of Cache Valley. Arches National Park covers about 113 square miles and Map 74 covers an area of a little over 390 square miles.

The area is accessible by U. S. Highway 191 which extends south from Interstate Highway 70 from Crescent Junction and is shown along the southwest part of Map 74. The town of Moab is located on the map's southern edge and the Colorado River is shown across the southeastern part. Several paved, graded, or unimproved roads provide connecting access to Arches National Park and the surrounding countryside.

The climate of Arches National Park is characterized by hot summers, pleasant autumns and springs and by cool to cold winters. The afternoon summer temperatures usually reach 95-105° F., while the winter lows usually range from 20-35° F. Precipitation is generally sparse all year round. In the winter the passage of frontal storms is often marked by high winds and occasional showers or snow flurries. Snow, should it fall, rarely remains on the ground more than a week or two. In summer, convectional thunderstorms occasionally bring torrential rains to local areas, creating flash floods.

PHYSIOGRAPHIC SECTIONS

Mancos Shale Lowland

The altitude of the area ranges from 3940 to 5650 feet above mean sea level and the topography is best described by dividing the area into physiographic sections (figure 2). The Mancos Shale lowland section is found along the north and northwest edges of the study area and Map 74. The section is typified by somber gray lands of low relief supporting little vegetation. Greater topographic relief occurs where sporadic, more resistant sandy beds of the Mancos Shale form low cuestas; the most obvious ones are in the Ferron Sandstone Member. To the north of Map 74, buttes of Mancos Shale rise above the lowland surface in places where they have been capped by more resistant pediment gravels.

Outer Anticlinal Flank

The outer anticlinal flank section is developed in the younger consolidated rocks (Morrison, Cedar Mountain, and Dakota Formations), which erode into alternating ledges and slopes. The physiographic section is characterized by cuestas or hogbacks between which elongate alluvium- or sand-filled valleys have developed.

Inner Anticlinal Flank

The inner anticlinal flank section is characterized by large areas of jointed bare-rock dip slopes and ledges. The strata involved (Kayenta, Navajo, and Entrada Formations) are mostly hard and soft sandstone units. Many of these, such as the Slickrock and Dewey Bridge Members of the Entrada Sandstone, are loosely cemented and are readily weathered into sand. Outcrops of these units are commonly covered by large irregular patches of unconsolidated sand.

Plateau Surfaces

The plateau surfaces physiographic section involves the same rock formations as those in the inner flanks section and is similar in appearance and characteristics. Because the section is generally located where strata dip more gently, sand accumulations are ubiquitous. The upper surfaces of the harder strata form prominent benches.

Escarpments and Canyonlands

The escarpments and canyonlands areas are those of greatest cliff formation and relief, commonly exceeding 1000 feet. These areas are generally located along the Colorado River and its more important tributaries. Permian to Jurassic units are most commonly exposed in the cliffs, especially the Jurassic Wingate Sandstone, which forms sheer vertical cliffs. The Jurassic Entrada Formation, where capped by the Moab Tongue, also forms escarpments and canyonlands. Other escarpments stand adjacent to faults and other structural discontinuities.

Alluvium-Filled Valleys

A section of low relief, but scattered mid-valley hills of consolidated rocks or gypsum caprock are not uncommon. It is generally found where the salt anticlines are wide and well developed and in valleys which have formed above structural discontinuities (such as faults) or hard sequences of rock.

Gypsiferous Outcrops

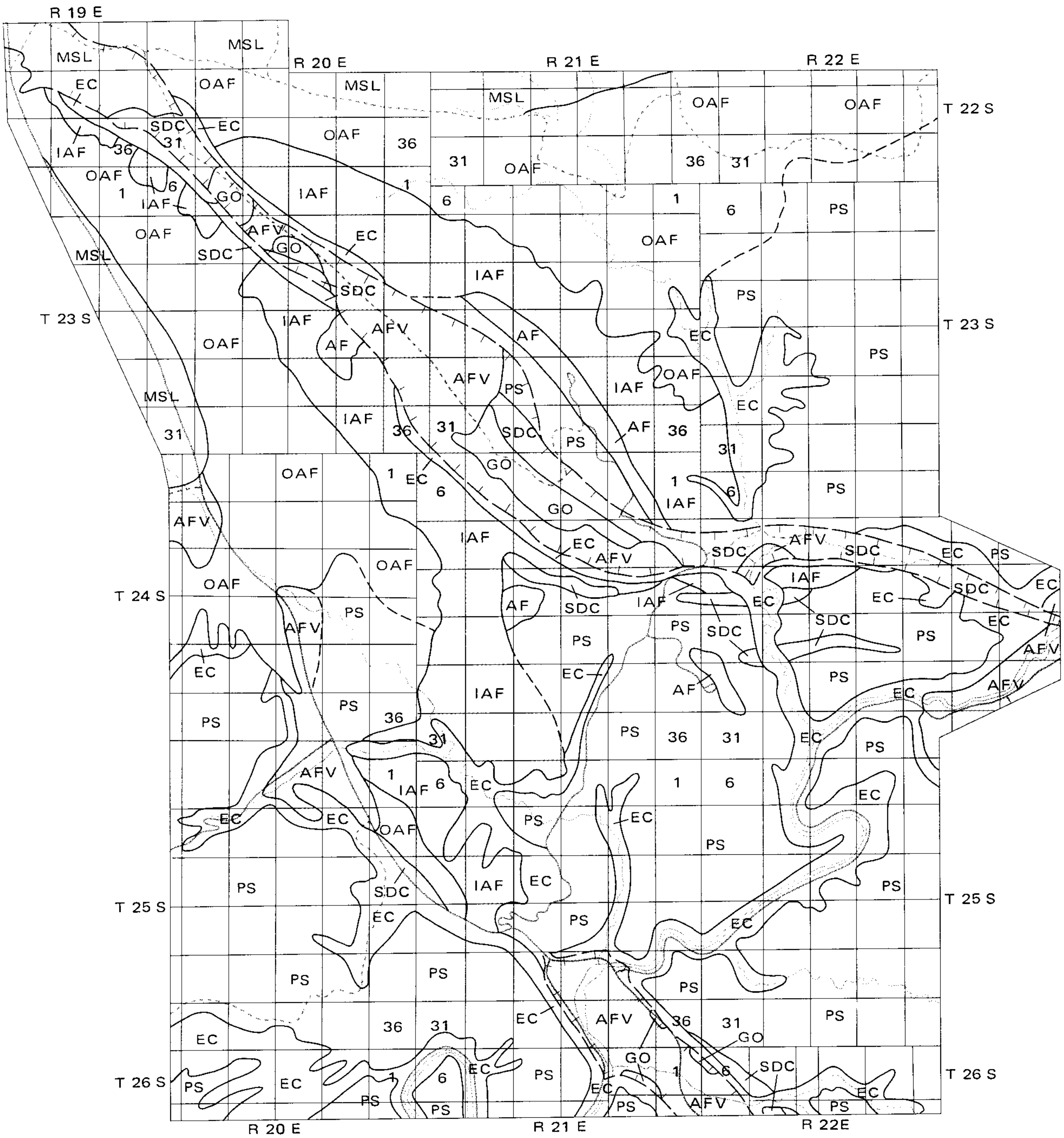
Larger areas of exposed gypsum caprock or deformed Paleozoic rocks form the gypsiferous outcrops section. These rounded dome-like hills of contorted gypsum and shale are often overlain by deformed thin limestone and sandstone beds.

Salt Dissolution and Collapse

This section encompasses areas where the strata have collapsed, either by tilting or folding, into a void created by the dissolution of salt by ground water. The best examples are located in Cache Valley and to a lesser extent in Salt Valley. Smaller areas of this type are also found on the south flank of Salt Valley anticline, on Dry Mesa, along the Moab fault, and on the northeast flank of Moab Valley.

Arches and Fins

The arches and fins physiographic section is well developed where the Slickrock Member of the Entrada Formation has been arched over an anticlinal axis. At Klondike Bluffs, Herdina Park, and Devils Garden-Fiery Furnace areas a "secon-



MSL Mancos Shale lowland section
OAF Outer anticlinal flank section
IAF Inner anticlinal flank section
PS Plateau surfaces section
EC Escarpments and canyonlands section
AFV Alluvium-filled valleys section
GO Gypsiferous outcrop section
SDC Salt dissolution and collapse section
AF Arches and fins section

Figure 2. Physiographic sections of Salt Valley anticline and Arches National Park.

Table 1.
Generalized section of bedrock formations in the Arches National Park or Salt Valley-Moab Valley area, Grand County, Utah.

System	Formations and Members	Character	Thickness (feet)
CRETACEOUS	Mancos Shale		
	Upper Member	Light to dark gray marine shale.	500+
	Ferron Member	Thinbedded sandstone, sandy shale, marine shale, carbonaceous shale, forms a double cuesta.	60-120
	Lower Member	Light to dark gray marine shale, slope-forming.	300-500
	Dakota Ss	Sandstone, conglomeratic sandstone, conglomerate, with subordinate gray sandy shale, and marl beds.	0-110
Unconformity			
	Cedar Mountain Fm	Silty variously colored non-resistant mudstones interbedded with ledge-forming quartzite, conglomerate, and gritstone.	100-200
JURASSIC	Morrison Fm		
	Brushy Basin Member	Variously colored slope-forming mudstone with thin ledges of conglomeratic sandstone, conglomerate, nodular limestone, limestone, and gritstone; overall maroon to north, green to south.	300-450
	Salt Wash Member	Light yellow gray crossbedded lenticular sandstone interbedded with red and gray mudstone and siltstone. Locally contains uranium, vanadium, and copper.	130-300
	Tidwell Member	Red silty shale with large white siliceous concretionary bodies.	40-100
Unconformity			
	Entrada Ss		
	Moab Tongue	Light yellow gray, fine- to medium- grained resistant and massive sandstone, usually jointed.	60-120
	Slickrock Member	Orange-red, fine-grained massive cliff-forming sandstone.	
	Dewey Bridge Member	Dark reddish fine-grained silty sandstone, with occasional white beds, contorted bedding, forms weak zone at base of arches.40-235	
Unconformity			
	Navajo Ss	Massive light-hued eolian crossbedded sandstone, forming cliffs, rounded knolls, and domes.	250-550
	Kayenta Fm	Lavender gray sandstone with local white and dark brown beds, forming thick step-like ledges.	200-300
	Wingate Ss	Massive fine-grained, well-sorted sandstone, forms the most prominent cliff in canyon areas.	250-450
Unconformity			
TRIASSIC	Chinle Fm	Reddish-brown silty fine-grained slope-forming sandstone, interbedded with mudstone and gritstone, locally contains uranium and copper in basal part.	200-900
Unconformity			
	Moenkopi Fm	Brown, evenly bedded sandy shale and micaceous silty sandstone, often ripple-marked.	0-1300
Unconformity			
PERMIAN	Cutler Fm	Red and marroon crossbedded sandstone and conglomerate with subordinate sandy shales.	0-1500
Unconformity			
PENNSYLVANIAN	Honaker Trail Formation	Limestone, shale, sandstone, arkosic sandstone, locally fossiliferous, forms cliff.	327+
	Non-gypsiferous rocks	Sandstone, limestone, conglomerate, shale, and sandy limestone.	300+
	Gypsiferous rocks (Paradox Fm)	Contorted gypsum with interbeds of black shale, thin chippy limestone and sandstone.	500+

dary" or "derivative" anticlinal axis has developed due to salt dissolution and collapse. The narrowly spaced and paralleling joints which opened during arching to form the fins are exceptional candidates for the formation of arches. In the case of The Windows, a thin remnant of Entrada Formation remains on the crest of a presumed non-salt-induced anticline. The Delicate Arch area is too small to be portrayed on figure 2. It occurs along closely spaced faults induced by salt-dissolution on the north flank of Cache Valley.

STRATIGRAPHY

Strata exposed in the Arches National Park region range in age from mid-Pennsylvanian to Late Cretaceous (300 to 90 million years ago). Table 1 presents a generalized section of the bedrock formations exposed in the Arches National Park area. Studies of boreholes in the area indicate that sediments have accumulated in Cambrian, Devonian, Mississippian and earlier Pennsylvanian time as well. Since the Late Cretaceous, unconsolidated and semi-consolidated Quaternary units are the only known rocks that were deposited and not subsequently eroded. In the Uinta Basin to the north, deposition of strata continued well into Eocene time, but the youngest consolidated rocks preserved in the collapsed tops of anticlinal salt cores are of the upper Mancos Shale (Late Cretaceous). Additionally deposited strata has been removed by erosion prior to later salt dissolution. The younger Uinta Basin units are exposed in the Book Cliffs only 6 miles to the north, and it is reasonable to assume that they were once present at least over the northern half of the study region.

The formations were deposited with considerable thickness variation over the area. There are places where the rocks are thicker than usual and other areas where they are thin or missing. The average thickness of the deposited formations totals 15,500 feet. The Paleozoic increment is more than 11,000 feet thick and was mainly deposited in marine environments. The Mesozoic deposition was primarily terrestrial, except for the Mancos Shale, although several formations were deposited marginally to a sea. At present about 6000 feet of Mesozoic strata are exposed at the surface. Average stratal thicknesses for the geologic periods are as follows: Cretaceous — 1140+ feet, Jurassic — 2220 feet, Triassic — 800 feet, Permian — 2500 feet, Pennsylvanian — 7150 feet with the salt beds, Mississippian — 500 feet, Devonian — 350 feet, and Cambrian — 800 feet.

SUBSURFACE ROCKS

Precambrian

Knowledge about the Precambrian basement rocks that underlie the Salt Valley anticline comes from surrounding areas; no boreholes have reached it in the area mapped and the nearest exposures are about 20 to 25 miles to the east in the Uncompahgre Plateau. There they consist of gneiss, schist, quartzite, intrusive granite, and minor dikes of pegmatite, aplite, and lamprophyre (Dane, 1935; Shoemaker, 1956; and Cater, 1970). Hedge and others (1968) have dated these rocks at 1700 to 1400 Ma.

Pre-Paradox Formation Paleozoic formations.

These deeply buried rocks have been subdivided into seven formations (ascending order): Ignacio Formation, Lynch Dolomite, Elbert Formation, Ouray Limestone, Leadville Formation, Molas Formation, and Pinkerton Trail Formation.

The Ignacio and Lynch units are latest Cambrian in age. As with the Precambrian rocks, they have not been penetrated in boreholes in the Salt Valley area and information is drawn from surrounding areas. The basal Cambrian Ignacio Formation is a hard sandstone or quartzite which locally becomes conglomeratic. It is time-transgressive and was deposited unconformably on the Precambrian surface by an eastward-transgressing sea. In the Grand Canyon it is known as the Tapeats Sandstone; in central Utah it is Tintic Quartzite. Although older to the west, in the Salt Valley area it is probably Late Cambrian in age, containing siltstone, shale, and local thin beds of dense unfossiliferous dolomite. The upper part probably correlates lithologically with the Bright Angel Shale and Ophir Shale of western sections (Baars, 1966, p. 2085). The unit varies considerably in thickness in the eastern Paradox Basin. The Ignacio is gradationally overlain by the dark-gray, commonly glauconitic and oolitic Lynch Dolomite. The Lynch is presumed to have a relatively constant thickness of 400 feet over the eastern Paradox Basin.

Ordovician and Silurian rocks were probably never deposited in the Paradox Basin. Three Devonian units are generally recognized: Aneth Dolomite, Elbert Formation, and Ouray Limestone. The Aneth is believed to be present only to the south in the Four Corners area where it consists of up to 200 feet of dark shale and argillaceous dolomite. Of two members in the Elbert Formation, the lower is the McCracken Sandstone, mostly composed of white to light gray and red, medium- to fine-grained, glauconitic, poorly sorted sandstone, with subordinate interbeds of sandy dolomite. The McCracken averages 50 feet in thickness in the area, but oil test wells nearby have penetrated from 42 to 119 feet. The upper Elbert is dense, silty, thin-bedded dolomite and dolomitic limestone with random interbeds of gray-green and red shales. The upper member is presumed to reach 200 feet in thickness, but information from local oil-test wells indicates thinner sections in the Salt Valley anticline area. The Ouray Limestone, of Late Devonian to Early Mississippian age, ranges between 50 and 200 feet in thickness across the basin, but is sporadically missing over old fault blocks (Hite and Lohman, 1973, p. 13) in the Paradox fold and fault belt.

The Leadville Formation gradationally overlies the Ouray Limestone. It is mostly thin-bedded to massive cherty dolomite, with limestone beds becoming more prominent in the upper half. Considered as Early to Late Misissippian in age, after deposition it was uplifted and a karst topography developed on its surface (Armstrong and Mamet, 1976). The Leadville usually ranges from 400 to 600 feet in thickness in the Paradox fold and fault belt, but wells in the Salt Valley area show that it ranges from 191 to 536 feet. Regionally the unit thickens westward. It may have been eroded from some of the uplifted fault blocks on which Devonian rocks were previously thinned by erosion.

The Early Pennsylvanian Molas Formation is the ancient soil that developed on the Leadville karst surface and is mostly red mudstone, claystone, and sandstone, with scattered lenses of fossil-bearing limestone (Wengerd and Matheny, 1958). The upper part of the unit is considered to be marine by Peterson and Ohlen (1962). It is variable in thickness and ranges from 8 to 128 feet in five penetrating wells.

The remaining Pennsylvanian strata are considered to be one formation by Elston, Shoemaker, and Landis (1962), Parr (1965), Hite and Lohmann (1973), Gard (1976), and Hite (1977) and to be a group of formations by Wengerd (1958), Wengerd and Matheny (1958), Wengerd and Strickland (1954), Baars, Parker, and Chronic (1967), Bechtel National Inc. (1978), Woodward-Clyde Consultants (1980, 1983), and Young (1983). The former assign the strata to the Hermosa Formation and divide it into three members: an upper and lower member and a middle Paradox Member. The latter assign three formations to the Hermosa Group (ascending order): Pinkerton Trail Formation, Paradox Formation, and Honaker Trail Formation. I will follow the latter practice.

The Pinkerton Trail Formation marks a transition from normal marine to restricted marine deposition which cyclically deposited salt in the Paradox Formation. The Pinkerton Trail consists of thin beds of limestone, siltstone, dolomite, black shale, and anhydrite. It is thin in the Paradox fold and fault-belt and thickens to the south and southwest. Under the Salt Valley area the unit is 100 to 150 feet thick.

Paradox Formation

The most important and thickest formation deposited in the region is the salt-bearing Paradox Formation. It is mostly a subsurface unit, with parts exposed as caprock in the salt anticline region making it the oldest unit exposed in the Arches National Park area (figure 3). It was deposited under a unique set of conditions; (1) the sea receiving the sediments was intermittently restricted from the open ocean, (2) a fault-controlled basin sank beneath this sea to collect the sediments, and (3) a mountain range was elevated to the northeast which contributed sediments to the adjoining part of the basin. During restricted periods the sea water evaporated and precipitated halite, gypsum, and other salts in great quantities.

In the deeper part of the Paradox Basin, 29 cycles of halite (salt) precipitation have been identified (Hite, 1960). About 12,000 square miles of salt deposits extended across southeast Utah and southwest Colorado (figure 1), however, the actual thickness deposited at any one locality is difficult to estimate because of subsequent salt movement. In addition, some salt movement began before the Paradox Formation was completely deposited. After deposition of the unit ceased the thickness is estimated to have been 5000 to 6000 feet in the Salt Valley anticline area while present salt anticlines contain a maximum thickness of nearly 14,000 feet (Hite and Lohman, 1973, p. 15, or figure 4, this paper). Because the faults that formed the Paradox Basin continued to move during deposition, several of the salt cycles are not complete or everywhere present.

The Paradox Formation consists mostly of salt, anhydrite, and dolomite, with a subordinate amount of incorporated detrital and organic material. The cycles in the Paradox Formation are described by Hite and Lohman, 1973, p. 18 as follows (with notations in parentheses by the present author):

> ...the upper contact of the halite unit (cycle below) is sharp. This sharp contact, at the top of the halite unit, is a dissolution surface or disconformity along which several feet of halite has been removed. These disconformities, which interrupt the chemical cycle (start new cycles), result from major incursions of sea water that reduce salinity in the evaporite basin. Using the disconformities as cycle boundaries the order of units would be (anhydrite, dolomite, black shale, dolomite, anhydrite, and halite). The change from transgressive (sea-water freshening) to regressive (increase in salinity) conditions occurs somewhere from the mid-point of the cycle (the black shale unit).

The regressive part of the cycle took a longer period of time and made the thicker part of the deposit. The Paradox Formation, in a salt anticline such as Salt Valley, contains 75 to 90 percent salt (averages 87 percent of the total mass). The remainder of rocks (13 percent of the mass), because they are cyclical, occur grouped together and are known as "marker beds" (Hite, 1977, p. 6). In the areas between the salt anticlines, the amount of salt is far less and the marker beds make up a greater percentage of the unit. In the Salt Valley anticline the thickest individual salt beds, as cut by the boreholes, have exceeded 1000 feet. In eight boreholes examined by Hite (1977, table 1), the thickest salt bed in each ranged from 190 to 1310 feet (average of 600 feet), and the thickest marker bed ranged from 42 to 670 feet (average of 175 feet). The salt beds and marker beds in the anticlines are badly deformed or faulted, and boreholes intercept beds that are steeply inclined or in vertical position, or are repeated by folding or faulting.

Salt, having been removed by near-surface solution processes, is nowhere exposed at the surface of Salt Valley and Moab Valley, but marker beds or caprock are (figure 5). Caprock is formed through the dissolution of the upper part of the Paradox Formation and is a thick residue of insoluble material. Hite (1977, p. 12) estimated an average caprock thickness of about 1000 feet for Salt Valley which may have encased as much as 5000 feet of salt. He believed that caprock first began to form in Late Pennsylvanian time and that the process continues each time the Paradox Formation is exposed at the surface. Therefore it still forms today.

PENNSYLVANIAN ROCKS

Honaker Trail Formation

The Honaker Trail Formation was deposited as normal (mostly unrestricted) marine conditions were restored across the region after the deposition of the last salt cycle. Its thickness varies considerably from one locality to another in the Salt Valley area because of early salt flowage in the underlying Paradox Formation; it is missing over much of Salt Valley and Moab Valley, but boreholes show a range from 1000 to 2000 feet thick across much of the intervening area. Composed of fossiliferous limestone, cherty limestone, siltstone, and sandstone, it has interbeds of arkosic sandstone, purple siltstone, and shale becoming more numerous in the formation in the northeast part of the Paradox Basin near the Uncompahgre source. Melton (1972) has made a detailed study of the paleoecology and paleoenvironment of the Honaker Trail Formation exposed across from Arches National Park Visitor Center.

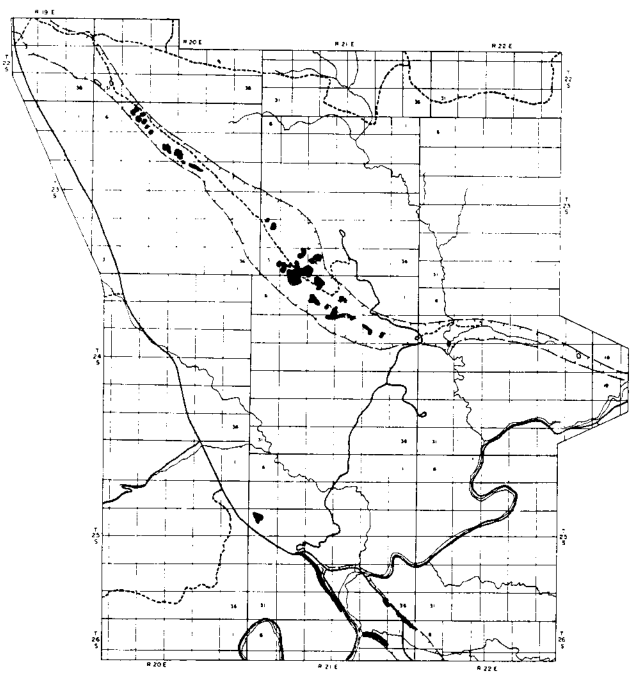


Figure 3. Pennsylvanian exposures in the Arches National Park area and Salt Valley (the black areas show the approximate distribution and locations, but smaller areas have been exaggerated in size and clusters of small outcrops have been combined).

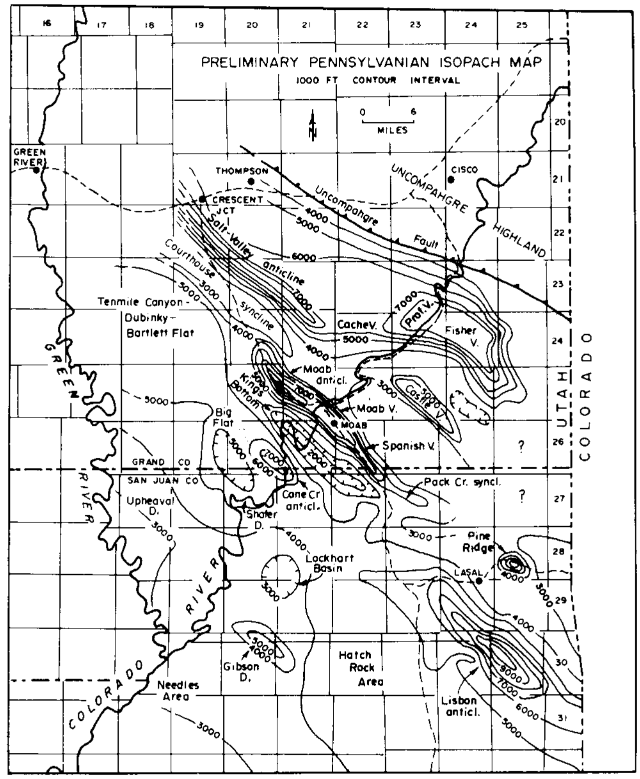


Figure 4. Pennsylvanian System isopach map for the Paradox Basin fold and fault belt, based and interpreted from limited borehole information.

Gypsiferous and Non-Gypsiferous Outcrops

Outcrop locations of exposed Pennsylvanian rocks are shown on the geologic map (Map 74) and figure 3. All are located in the breached cores of two anticlines or along their margins, and Map 74 depicts the outcrops as gypsiferous or non-gypsiferous rocks. In Salt Valley both varieties are present and the non-gypsiferous rocks appear to overlie the gypsiferous exposures, cropping out mostly in low, rounded hills, having a maximum relief of 150 feet, and projecting from a relatively flat-floored, alluvium-filled valley. The gypsiferous exposures are part of the caprock of the Paradox Formation and non-gypsiferous rocks may either be marker beds or part of the overlying Honaker Trail Formation. Gypsiferous outcrops are mostly highly contorted, white to dark gray, granular or porous to solid rock gypsum (alabaster) and produce a peculiar honeycombed surface on exposure. They commonly contain interbeds of dark shale and chippy limestone or sandstone fragments.

The few fossils found (crinoid stems) in non-gypsiferous rocks are poorly preserved. Most previous investigators (Elston, Shoemaker, and Landis, 1962, fig. 4; Gard, 1976, p. 15) have preferred to include all the rocks as "marker bed" material or part of the Paradox Formation. Dyer (1983) referred to these rocks as "tentative" Honaker Trail Formation. Gard (1976, p. 14-15) concluded that the non-gypsiferous strata are so complexly folded and faulted that a reliable stratigraphic sequence could not be worked out, and that each of the isolated hills exposes strata that differ from those in other hills.

The non-gypsiferous strata in Salt Valley are described as chippy weathering sandstone, limestone or dolomite, shaly siltstone, and conglomerate. The sandstones are most abundant, occasionally crossbedded, gray tan yellow or light brown, and calcareous. They are usually fine to medium grained but in a few places become gritty and pebbly. The sandstone chips appear to have come from shaly to thin-bedded units, but individual beds to four feet thick are present. The limestones are gray, thin-bedded to shaly, silty to sandy, and contain rare poorly preserved crinoidal material. The shales and siltstones are well-indurated, siliceous or calcareous, commonly distorted, and light-gray to dark-brown or black in color.

Near the west margin of Sec. 10, T 23 S, R 20 E is an exposure of conglomerate composed of sandy limestone and limestone or dolomite cobbles, most of which are rounded. The matrix is calcareous coarse-grained arkosic sandstone. Individual cobbles weather quite hackly and most are 3-4 inches in diameter, a few are up to 1.5 feet in diameter, and cobbles can be found which contain poorly preserved crinoidal and brachiopodal material. Dane (1935, p. 24) described this outcrop and found fossils which were identified as being of Mississippian age. He thought the conglomerate to be of Early Pennsylvanian age. Elston, Shoemaker, and Landis (1962, fig. 4), carefully mapped this outcrop and tentatively assigned it to the Cutler Formation of Permian age. A similar conglomerate, intercepted in the Pure Oil #1 Salt Valley well in SWSENW Sec. 2, T 23 S, R 20 E about two miles to the northeast, was interpreted to lie directly above the Paradox Formation and was only 20 feet thick. Elston, Shoemaker, and

Landis believed the source area for the conglomerate to be the ancestral Uncompahgre uplift, from which Mississippian rocks were being eroded in Permian time. The cobbles were thought to have been deposited under fluvial conditions and that the ancestral salt structure locally impeded the stream flow at the beginning of Cutler deposition.

Gard (1976, p. 16) studied the same outcrops and recognized flute casts, striations, and convolute bedding which he thought were indicative of a turbidite. He thought the conglomerate was deposited in a normal stratigraphic succession within the Middle Pennsylvanian Paradox strata. The exposed thicknesses of non-gypsiferous strata in northwestern Salt Valley amount to at least 200 or 300 feet. The conglomerate appears to be conformable with the deformed sandstones and shales above and below, which favors it being part of a Paradox Formation marker bed. The great quantity of sandstone in the section does not fit well with Hite's (1977) description of the cycles, even though 200-300 feet of marker bed fall in the range of the thickest marker bed interceptions in wells.

The largest domes of gypsiferous rocks are exposed in central Salt Valley, in Secs. 32 and 33, T 23 S, R 21 E and in Secs. 4 and 5, T 24 S, R 21 E. In most cases these domes emerge from beneath a semi-consolidated to unconsolidated Quaternary gravel but quite often are overlain by non-gypsiferous, chippy, thin-bedded sandstone and limestone, or by the Triassic Chinle Formation. The non-gypsiferous rock outcrops surround the domes, dip away from their centers only slightly more steeply than the overlying Chinle strata, and are usually not contorted like the gypsiferous material.

Only one small outcrop of gypsiferous Pennsylvanian rocks has been noted in Cache Valley, near its eastern end in Sec. 13, T 24 S, R 22 E, where it is directly overlain by the Chinle Formation. A fault bounds one side of the exposure and brings it adjacent to outcrops of the Moenkopi Formation. Pennsylvanian rocks are also exposed along both flanks of northern Moab Valley where, south of the Colorado River, thin highly contorted non-gypsiferous rocks rest on small or elongate domes of gypsum. Their upper surface has considerable relief which has been filled in by the overlying Chinle Formation. The description of these non-gypsiferous rocks is similar to that of corresponding strata in northwestern Salt Valley. On the southwest flank of Moab Valley about a mile northwest of The Portal of the Colorado River, thin wedges of Honaker Trail, Cutler, and Moenkopi Formations make their appearance and thicken northwestward along a branch of the Moab fault. Northwest of the Arches National Park Visitor Center, in Sec. 20, T 25 S, R 21 E, the Cutler Formation covers the Honaker Trail Formation along the drainage. To the northwest, another small window of Honaker Trail Formation emerges under the Cutler along the Moab fault, in Sec. 18 of the same township. Fusulinids collected from this locality (Baars, 1962, p., 159) properly identify the age of the Honaker Trail as Virgilian. The maximum exposed thickness does not exceed 400 feet here, and the base is not exposed. The Honaker Trail Formation opposite the Arches National Park Visitor Center (figure 6) is described below.

Figure 5. Paradox Formation (gypsiferous rocks) caprock as exposed on the southwest flank of Moab Valley, south of The Portal of the Colorado River. Paradox Formation salt is never found at the surface, having been removed by near-surface solution processes, but is encountered at depths greater than 500 feet.

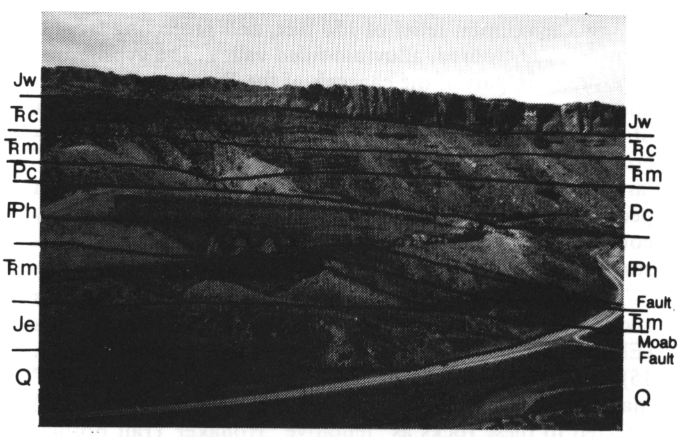


Figure 6. View southwesterly from above the Arches National Park Visitor Center. The Honaker Trail Formation (Member) is exposed in the middle. Two branches of the Moab fault drop strata in the foreground exposing the Moenkopi Formaiton between the branches and the Jurassic Entrada Sandstone just southwest of the highway. The Permian Cutler Formation, Triassic Moenkopi and Chinle Formations, and the Jurassic Wingate Sandstone overlie the Honaker Trail Formation. IPh=Honaker Trail Formation, Pc=Cutler Formation, TRm=Moenkopi Formation, TRc=Chinle Formation, Jw=Wingate Sandstone, Jc=Entrada Sandstone, and Q=larger patches of quaternary unconsolidated sand.

Section of the upper part of the Honaker Trail Formation exposed south of the Arches National Park Visitor Center, NWSW Sec. 21, T 25 S, R 21 E. Cutler Formation, about 300 feet thick, overlies the Honaker Trail Formation conformably.

Honaker Trail Formation:		*feet*
1.	*Limestone, gray, thin to medium bedded, sandy, quartz-filled vugs, smooth to nodular weathering, unfossiliferous.*	*25.0*
2.	*Sandstone, white to yellow gray with reddish streaks, fine to medium grained, thick bedded to massive, like sandstone in the Cutler Formation*	*38.0*
3.	*Limestone, gray, thin to medium bedded, contains brown chert, hackly weathering, ledge former, fossiliferous with horn corals, bryozoa and brachiopods*	*12.0*
4.	*Sandstone, brown weathering, fine grained, calcareous, massive, thin horizons infrequently grade to sandy limestone, calcite fracture and vug fillings, fossiliferous with brachiopods, crinoids, and bryozoa*	*22.0*
5.	*Limestone, weathers light green gray and lavender, thin bedded and nodular weathering, forms slopes, contains silt and fine-grained sand, quartz and calcite-filled vugs, crinoid fragment horizons*	*15.0*
6.	*Sandstone, mostly reddish or maroon, infrequently light tan, slightly micaceous, fine to medium grained, friable and massive, mostly produces a Cutler-like covered slope*	*40.0*
7.	*Sandstone, light reddish brown, slightly micaceous, medium to thick bedded, ledge former*	*6.0*
8.	*Interbedded tan and lavender fine-grained sandstone, nodular gray thin-bedded sandy limestone, and lavender-weathering shaly sandstone. forms steep slope and is mostly thin bedded; scattered brachiopods are found in the limy units, becomes sandy and thick bedded toward top*	*38.0*
9.	*Sandstone, gray and lavendar, fine grained, slightly micaceous, calcareous, thick-bedded to massive, forms cliff with unit below*	*16.0*
10.	*Limestone, gray on fresh surfaces, thin to medium bedded, somewhat nodular weathering, forms hard block cliff*	*19.0*
11.	*Sandstone, like unit 6, more thick bedded with minor shaly partings, some thin- medium- and coarse-grained sandstone horizons; in uppermost foot the sandstone weathers platy and is micaceous.*	*25.0*
12.	*Interbedded shale, brown and fissile; siltstone, slightly micaceous; thin bands of fine-grained silty sandstone; and purplish-brown, platy weathering, fine-grained and micaceous sandstone. Slope former, mostly thin to medium bedded*	*38.0*
13.	*Limestone, gray and tan weathering, thin to medium bedded, quartz-filled vugs, resistant ledge former*	*4.0*
14.	*Sandstone, like unit 16, but more friable, makes cliff undercut under thick, resistant limestone of unit 13*	*4.0*
15.	*Sandstone, weathers dark purplish and tan, mostly fine grained, some horizons silty, others calcareous, thin to medium bedded, calcareous, usually weathers into a platy slope*	*6.0*
16.	*Sandstone, white to lavender on fresh surfaces, weathers tan or light brown, fine grained and silty, less well sorted than unit 17, massive, slightly crossbedded, weathers irregular to smooth*	*6.0*
17.	*Sandstone, brown to maroon, fine grained, well sorted with infrequent bleached horizons (less than 1 inch thick), thick bedded to massive, platy weathering, ledge and slopeformers*	*6.0*
18.	*Limestone, gray, lavender gray, with irregular reddish streaks, sandy, fine grained, medium bedded, blocky, forms ledges, some beds with siliceous (quartz-filled) vugs, others with what appear to be fusulinid impressions, the interiors of which appear to be crystallized even on fresh exposures*	*7.0*
	Covered slope: Total exposed	*327.0*

For regional reference, the Paradox Basin terminates against the buried Uncompahgre fault to the northeast. The deep part of the basin lies between Moab and the buried fault and contains the Salt Valley, Castle Valley, and Fisher Valley salt anticlines. Pennsylvanian, Permian, and some Triassic rocks are completely missing on much of the northeast side of the fault. Even with limited borehole data, thickness variations of Pennsylvanian rocks are readily apparent (figure 4).

PERMIAN ROCKS
Cutler Formation

The Permian System is represented by a single unit, the Cutler Formation. The source area for these rocks, the Uncompahgre Highland, rose to the northeast as the Paradox Basin sank and then eroded until the Precambrian basement was exposed. The Cutler Formation reflects this, containing sediments of Uncompahgre Precambrian origin. The sediments consist of fluvially deposited arkosic sandstone, gritstone, conglomeratic sandstone, and subordinate amounts of conglomerate, siltstone, and shale. Most of the lithologies are micaceous and many of the coarser horizons reveal bits of granite in their makeup. Reddish brown, brick red, and purple-red dominate, other colors include grayish red, moderate reddish orange, moderate reddish brown, and pale red. These colors are generally brighter, with stronger red and purple shades than in the chocolate and reddish browns of the overlying Triassic Moenkopi Formation.

The unit was deposited as a large coalescing alluvial fan complex which extended from the highland front (Uncompahgre fault area) southwestward to Moab. Farther southwest the Cutler Formation intertongues with other lithologies, even marine units. In ascending order these units include the marine Elephant Canyon Formation (interbedded gray limestone, sandstone, and shale), the Cedar Mesa Sandstone (white, fine-grained, calcareous, crossbedded near-shore shallow-water marine sandstone), Organ Rock Shale (fine-grained southwestern extension of the Cutler Formation deposited on flood plains and tidal flats), and the White Rim Sandstone, which is similar to the Cedar Mesa Sandstone. None of these units, deposited southwest of Moab, are exposed in the Salt Valley-northern Moab Valley area but are sporadically recognized in well logs.

Locally, the Cutler Formation was more thinly deposited or is absent in areas where the salt thickens, notably over the salt anticlines (figure 7), which were active in their growth and complicated the Cutler deposition. It probably was not deposited over the Salt Valley anticline or over the Moab anticline south of the Colorado River. The most important outcrop of the Cutler Formation in the area of Map 74 extends northward from the Colorado River, on the southwest flank of the Moab anticline southwest of the Moab fault, to a point two miles north of Sevenmile Canyon where the outcrop is terminated by the Moab fault (figure 8). In Sec. 18, T 25 S, R 21 E, it is fully exposed and is 1100 feet thick. To the southeast the unit thins, and opposite Arches National Park Visitor Center the unit is less than 400 feet thick. There it loses much of its reddish color and becomes very pale orange, yellowish gray, or white. It becomes finer grained, but a few medium- and coarse-grained horizons persist. The mica particles become very fine and are not readily noticeable. Most grains are of quartz and the lighter colored sandstone has calcareous cement. Still farther southeastward the Cutler Formation feathers out (Sec. 34, T 25 S, R 21 E). Typical "red" Cutler outcrops are described in the following stratigraphic section.

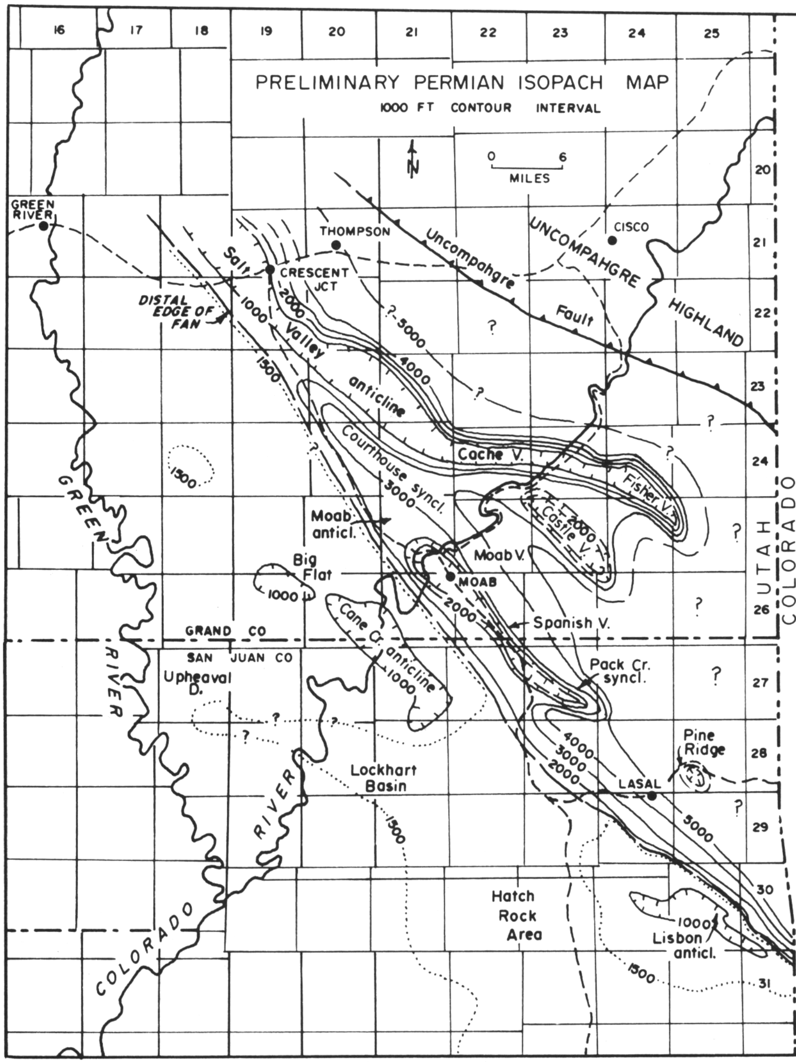


Figure 7. Permian System isopach map for the Paradox Basin fold and fault belt, based and interpreted from limited borehole information. The Permian System is represented by a single formation in the Arches National Park area, the Cutler Formation. The hachured contours indicate where the unit is thin or missing. The unit thins southwesterly from the Uncompahgre Highland until it reaches a line southwest of Moab Valley, southwest of which it is normally about 1,500 feet thick.

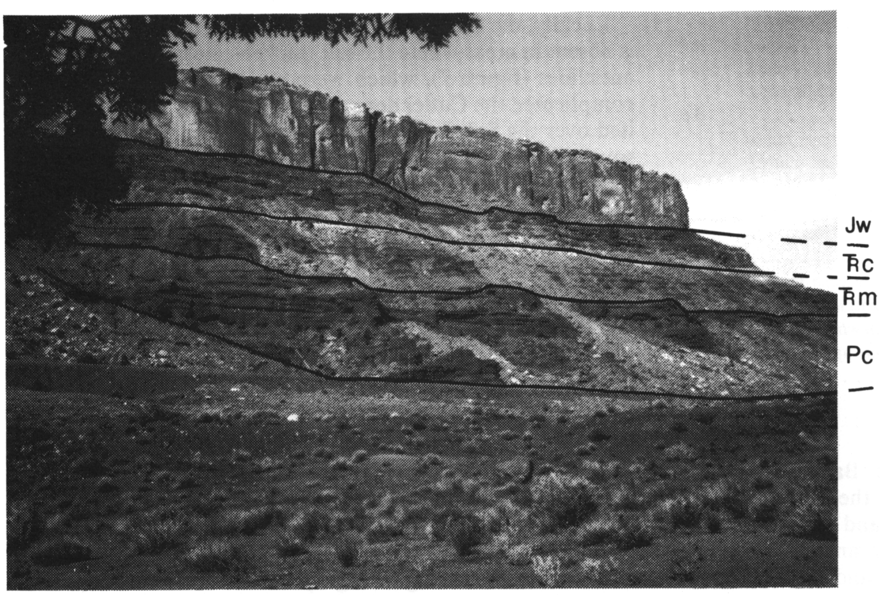


Figure 8. Cutler, Moenkopi, Chinle, and Wingate formations as exposed along U.S. Highway 191 between the Arches National Park Visitor Center and Sevenmile Canyon. The contact between the Cutler (Pc) and Moenkopi (Ꞧm) formations is marked along a nearly flat horizon where the bright reddish brown and thicker bedded rock changes to "chocolate" brown and thinner beds. The contact between the Moenkopi Formation and the overlying Chinle Formation (Ꞧc) is placed beneath a thin white horizon of pebble conglomerate or gritstone. The Wingate Sandstone forms a vertical cliff above the Chinle Formation.

Section of Cutler Formation exposed along U. S. Highway 191, two miles north of Arches National Park Visitor Center in SE Sec. 13, T 25 S, R 20 E, and SW Sec. 18, T 25 S, R 21 E.

Moenkopi Formation—Moderate reddish brown and pale reddish brown (10R 6/6 and 10R 5/4), fine-grained, silty, micaceous sandstone, mostly thin bedded to medium bedded and shaly, slope forming with irregular medium to thick beds near the middle. Lowermost foot is poorly sorted medium-to coarse-grained sandstone, very pale orange, with granite-derived sand, mica, quartz, feldspar, and black minerals. Overlies Cutler Formation unconformably.

	Cutler Formation:	*feet*
1.	Sandstone, arkosic and micaceous, moderate reddish orange (10R 6/6), fine grained with many medium grains, slightly calcareous and friable, rounded thick beds, horizontal and large-scale planar crossbedding, forms ledges, ripple marked in part, contains many dark minerals, some 1-2 inch bleached streaks, upper 2 to 3 inches are bleached to a very pale orange (10YR 6/2), medium grained, poorly sorted and reworked, with much mica and dark minerals	12.0
2.	Sandstone, micaceous, muddy, moderate reddish brown (10R 4/6) to moderate reddish orange (10R 6/6), fine to medium grained, poorly cemented, slope or indent former	1.4
3.	Sandstone, arkosic, grayish red (5R 4/2), looks purplish, medium to coarse grained, massive, some trough crossbedding, slope former	12.3
4.	Sandstone, micaceous, moderate reddish-orange (10R 6/6), fine to medium grained but mostly fine grained, moderately sorted, slightly calcareous, thick bedded to massive, planar crossbedding	85.1
5.	Sandstone, arkosic, pale red (5R 6/2) to grayish red (5R 4/2)(lavender), medium to coarse grained with granite pebbles, contains, mica, friable, thick bedded with trough crossbeds, slope former or cliff undercut	31.2
6.	Sandstone, micaceous, moderate reddish orange (10R 6/6) or red, fine grained, slightly calcareous, medium bedded to massive with a few thin-bedded partings, upper 10 feet slope forming, remainder is cliff forming	99.6
7.	Shaly mudstone, siltstone, and sandstone, grayish red(5R 4/2), but sands are moderate reddish brown (10R 4/6), fine grained with sporadic coarse-grained horizons, including some grit and pebblestone, forms slopes or indents	79.2
8.	Sandstone, micaceous, moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6), fine to medium grained, slightly calcareous, thin bedded to massive, upper and lower beds are thick or massive, middle part is thin bedded and darker and more resistant, weathers shaly and chippy	44.6
9.	Sandstone, arkosic, grayish red (5R 4/2), coarse grained, gritty and pebbly with granite pebbles, some conglomeratic sandstone, sporadic ledges of coarser material, calcareous and friable, massive, crossbedded, slope former	44.2
10.	Intraformational conglomerate, angular fragments from unit 11 and channelled into it	2.2
11.	Sandstone, micaceous, moderate reddish orange (10R 6/6), irregularly bleached in thin irregular horizons, fine grained, thick bedded to massive, resistant ledge former	9.1
12.	Sandstone, grayish red (5R 4/2), some streaky bleachings, medium grained, friable, massive, shaly or platy weathering, forms indent, not as resistant as units above and below	22.5
13.	Sandstone, like unit 11	28.8
14.	Sandstone, micaceous, muddy alternating with clean thicker ledges, moderate reddish orange (10R 6/6), fine grained, rather platy to shaly weathering, forms slopes and ledges	28.7
15.	Sandstone, very micaceous, grayish red (5R 4/2) or pale gray red, medium grained, some horizons coarse grained and conglomeratic with pebbles, friable, massive, fine trough crossbedding, slope former, coarser horizons more resistant	48.8
16.	Sandstone, micaceous, shaly, muddy, upper half moderate reddish brown (10R 4/6), fine grained and silty, lower half moderate reddish-orange (10R 6/6), medium bedded, unit forms indent or earthy slope	12.0
17.	Sandstone, micaceous and arkosic, grayish red (5R 4/2), fine to coarse grained and pebbly, some gritstone, poorly sorted, friable, massive, slope former, lower half very poorly exposed	43.2
18.	Sandstone, micaceous moderate reddish brown (10R 4/6), fine grained, earthy weathering	6.0
19.	Sandstone, like unit 17, very conglomeratic in lower 10 inches	8.3
20.	Sandstone, slightly micaceous and silty, moderate reddish orange (10R 6/6), fine grained, slope former	19.3
21.	Sandstone, micaceous, moderate reddish-orange (10R 6/6), fine grained, weathers chippy, shaly, and platy, but more resistant than unit above	9.8
22.	Covered, typical Cutler units already described appear through the cover from place to place	104.3
23.	Sandstone, micaceous, moderate reddish orange (10R 6/6), fine grained, thin bedded to shaly, forms slight ledge	7.7
24.	Covered and highway fill	113.8
25.	Gritstone, pale red (5R 6/2), contains granite grit, massive, forms ledge	20.5
26.	Sandstone, micaceous, grayish red (5R 4/2) and grayish green (5G 5/2), mostly fine grained, poorly cemented, earthy weathering, forms indent along creek bed	5.4
27.	Sandstone, micaceous, mottled moderate reddish orange (10R 6/6) and yellowish gray (5Y 7/2), fine grained, weathers lumpy	15.3
28.	Limestone, medium gray (N6), thin beds, nodular weathering	1.3
29.	Sandstone, like unit 27	5.6
30.	Sandstone, micaceous, moderate reddish orange (10R 6/6), fine grained, calcareous, massive, crossbedded, resistant ledge former	12.2
31.	Sandstone, micaceous, moderate reddish brown (10R 4/6), mostly fine grained, massive, earthy weathering, slope former	37.5
32.	Poorly exposed sandstone, probably like unit 31, some limestone gravel on the surface	24.8
33.	Cacarenite, very fine to medium grained	0.9
34.	Sandstone, like unit 31	8.8
35.	Sandstone, pale red (5R 6/2), coarse grained and gritty, massive	3.1
36.	Sandstone, pale reddish-brown (10R 5/4) with very pale orange (10YR 8/2) blotches, fine grained, massive and resistant to erosion	20.1
37.	Sandstone, like unit 36, but shaly to medium bedded and not quite as resistant	6.5
38.	Sandstone, pale red (5R 6/2), gritty and coarse grained, pebbly, massive, earthy weathering	35.0
39.	Limestone, light brownish gray (5YR 6/1), blocky thin bed	0.4
40.	Sandstone, like unit 38	29.0
41.	Sandstone, like unit 36	4.5
42.	Sandstone, like unit 31	4.2
43.	Sandstone, pale red (5R 6/2), medium grained, massive	7.1
	Total Cutler Formation	1,116.3

Honaker Trail Formation—Limestone, sandy, medium gray (N6), sand is fine grained, thin to medium bedded, nodular weathering, resistant, fossiliferous with pelecypods, brachiopods, gastropods, crinoidal and bryozoan fragments, and trilobites.

The Cutler Formation north of Moab has two principal interbedded lithologies. The first consists of finer grained (silt to medium-grained sandstone), generally more resistant, moderate reddish-orange or moderate reddish-brown beds, and the second consists of grayish-red, coarser grained to gritty arkosic sandstone (light and purplish beds of Parr [1965, p. 31]). In the finer grained moderate reddish-orange sandstone the grains are mostly quartz with some mica. The sorting is good to poor and the beds are usually cross stratified. Parr (1965, p. 33) believed these beds to be the eastward extensions of the Cedar Mesa Sandstone within the Cutler fan. If so, the moderate reddish-orange units probably represent offshore marine current deposits, beach deposits, and back-beach eolian deposits. The grayish-purple units are coarse arkosic sandstones deposited by streams from the ancestral Uncompahgre uplift, with grains consisting of quartz, gneiss, granite, feldspar, biotite, and muscovite, which are usually loosely cemented. Small-scale festoons are common (5-20 feet long by 3-8 feet wide) and beds are commonly contorted into wavy convolute laminae. The contorted wavy laminae may have formed by movement down or around the flanks of a rising salt anticline (Parr, 1965, p. 36).

The second outcrop area for the Cutler Formation is in Professor Valley on the north side of the Colorado River at the east end of Cache Valley, mostly in SW Sec. 17, T 24 S, R 23 E. Only the upper part of the formation is exposed. It has nearly the same description as the main part of the outcrop on the southwest flank of the Moab anticline, except that the grayish-red coarser units dominate. An additional outcrop is the questionable limestone and dolomite conglomerate already discussed with the Pennsylvanian outcrops in SW Sec. 10, T 23 S, R 20 E. Elston, Shoemaker, and Landis (1962, p. 1869) believed that this conglomerate may have been part of the Cutler Formation:

> ...the conglomeratic Cutler(?) Formation unconformably overlies the Paradox Member [Formation] of the Hermosa Formation (Group) in discontinuous exposures along the central part of the valley (Salt Valley). The conglomerate is composed largely of pebbles, cobbles, and boulders of limestone and dolomite by a matrix of fine- to coarse-grained quartz and fine- to coarse-grained calcite crystals. The sandy matrix contains sparse feldspar and scattered granules of chert. Most of the limestone pebbles are well rounded and ellipsoidal, but some small pebbles are subrounded to angular... Bedding characteristics indicate that the conglomerate and sandstone were, at least in part, deposited under fluviatile conditions. The coarsest material is exposed near the axis of the major salt anticline, north of a prominent local anticlinal fold in the Paradox. Finer grained material is present on the south side of the fold — on the side of the Salt Valley anticline that is away from the Uncompahgre front. This distribution suggests that here the salt structure locally impeded stream flow at the beginning of Cutler deposition. Many of the limestone pebbles and boulders in the conglomerate contain fossils of Mississippian age (Dane, 1935, p. 24). These pebbles and boulders probably came from beds of Mississippian age that were exposed in a belt around the plunging northwest end of the ancestral Uncompahgre uplift at the beginning of Cutler deposition. Nonfossiliferous, angular to subangular fragments of carbonate rock that also are present in the conglomerate are similar to carbonate rock of the upper member of the Hermosa Formation [Honaker Trail Formation]. This detritus may have been derived from carbonate beds of post-Paradox age along the northeast margin of the growing salt structure.

TRIASSIC ROCKS

From zero to more than 3000 feet of Triassic rocks were deposited over the Salt Valley area and these rocks have been divided into (in ascending order) Moenkopi Formation and Chinle Formation. Until recently it was thought that the Glen Canyon Group of formations (Wingate Sandstone, Kayenta Formation, and Navajo Sandstone) were mostly Triassic in age. Map 74 was published in 1985 and reflects this. The explanation for the new age assignment is found in Pipiringos and O'Sullivan (1978, p. A18), and in Imlay (1980).

Moenkopi Formation

The oldest Mesozoic unit is the Moenkopi Formation which normally ranges from 350 to 450 feet thick in east-central Utah. It is missing over the Uncompahgre Plateau to the east and thickens regionally westward. Locally, it thins or is missing over the crests of the salt anticlines while thickening on the peripheries (figure 9). It is generally described as a chocolate brown, thin-bedded and evenly bedded unit of siltstone and fine-grained sandstone with subordinate amounts of conglomerate, gypsum, and claystone. Many of the beds are ripple marked and mud cracked. In the Paradox fold and fault belt the Moenkopi siltstones and sandstones are commonly arkosic and micaceous. The unit overlies the Cutler Formation unconformably, but with an angular discordance of less than 5 degrees across the area portrayed by Map 74.

The environments of deposition of the Moenkopi are generally described as both marine and terrestrial. The thin, even beds suggest deposition in shallow near-shore waters, such as tidal flats and possibly in the flood plains of rivers or deltas. Shoemaker and Newman (1959) investigated the Moenkopi Formation in the salt anticline region and subdivided the unit into four members (ascending order): Tenderfoot, Ali Baba, Sewemup, and Pariott. These members are discernible only in the eastern part of Map 74 along the Colorado River.

Large areas of Moenkopi exposures occur at Professor Valley (Richardson amphitheater) and at the Big Bend of the Colorado River (figure 10) where thicker than normal sections of the formation are visible. The unit gradually thickens from the east into these areas. Along the Dolores River, Sec. 6, T 24 S, R 26 E, Dane (1935) indicated that 287 feet of the Moenkopi rest on the Cutler Formation. The Moenkopi is 400 to 500 feet thick where the Colorado River flows into Professor Valley and where the angular discordance between the underlying Cutler and the lower Tenderfoot Member is readily apparent. Stewart (1959) correlated the Tenderfoot with the Hoskinnini Member of the Moenkopi exposed to the west of the Map 74 area. The Hoskinnini is dated as Triassic(?) and it and the Tenderfoot may be Permian in age. The Tenderfoot consists of reworked Cutler and poorly sorted sandy mudstone or silty sandstone that commonly crops out as a vertical or very steep smooth cliff.

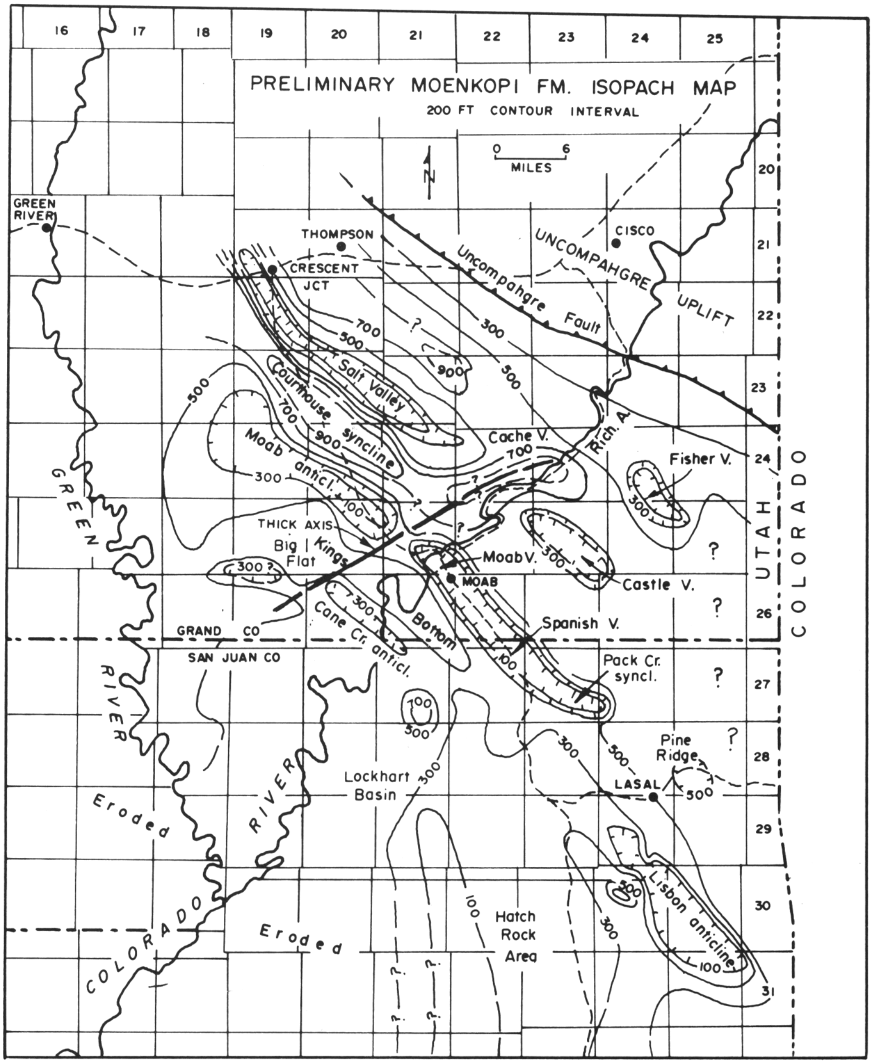


Figure 9. Moenkopi Formation thickness map for the Paradox Basin fold and fault belt, based and interpreted from limited borehole information. The Moenkopi Formation was influenced by early salt movement which greatly affected its thickness. Sections less than 300 feet are considered thin and areas within the hachured contours indicate the Moenkopi Formation to be thin or missing. Sections more than 700 feet thick are considered abnormally thick.

Figure 10. Composite photograph in Professor Valley looking north across the Colorado River. A faint white line of gritstone in the slope below the Wingate Sandstone cliff marks the base of the Chinle Formation. A very thick Moenkopi Formation is exposed beneath.

The next member, the Ali Baba, is usually separated from the Tenderfoot by a scoured surface, which is not readily apparent in Professor Valley. It consists mainly of brown to lavender ledge-forming conglomeratic arkosic sandstone with thin interbeds of reddish-brown and chocolate-brown silty shale and fine- to coarse-grained sandstone. The Ali Baba grades upward into the Sewemup Member which consists of a smooth slope of chocolate-brown or reddish-brown fissile siltstone or shale with a subordinate amount of light-brown fine-grained silty sandstone. Gypsum is common in veinlets or as thin beds.

The Sewemup Member is overlain by the Pariott Member, the lowest unit of which is a sandstone that fills shallow scours. It consists of ledges and slopes of interbedded reddish-brown to purple sandstone and chocolate-brown to red mudstone, siltstone, and shale. Regionally an unconformity has been recognized at the top of the Moenkopi but, along the Colorado River in Professor Valley and at Big Bend, the contact between it and the overlying Chinle Formation appears conformable and is difficult to place.

To the south of the east end of Cache Valley the Moenkopi Formation is more than 900 feet thick; the Pariott Member is 210 feet thick, the Sewemup Member is 441 feet thick, the Ali Baba is 190 feet thick, and the Tenderfoot is 90 feet thick. At Big Bend only the upper two members are exposed and the total Moenkopi Formation may be as much as 1300 feet thick (Shoemaker and Newman, 1959, p. 1847). A description of the Moenkopi Formation in Professor Valley south of the east end of Cache Valley is given below:

Section of Moenkopi Formation taken on the north side of the Colorado River south of the east end of Cache Valley, SW Sec. 19, T 24 S, R 23 E.

Chinle Formation (lowermost unit)—*Gritty sandstone, pale reddish brown (10R 5/4), very pale orange (10YR 8/2), light brown (5YR 6/4); very fine to very coarse grained (vfU-vcU), subangular, poorly sorted, mostly equant grains; contains scattered pebbles to 2cm in diameter; calcareous cement, poorly indurated and porous; cross-stratified in sets 1 foot high; lenticular bed, cliff forming; unconformable contact with Moenkopi Formation below.*

Moenkopi Formation, Parriott Member:	*feet*
1. Sandstone, pale reddish brown (10R 5/4), very fine to fine grained (vfU-fL), subangular to well-sorted equant grains; silty, calcareous cement, poorly indurated; indistinctly bedded; forms earthy slope, weathers to same color as fresh; in the upper part the sandstone becomes better exposed and appears massive and exhibits bleached spots	*40.5*
2. Sandstone, pale reddish brown (10R 5/4); fine to medium grained (fL-mU), subangular, moderately sorted equant grains; micaceous, calcareous cement, poor to fair induration; medium to thick bedded, low-angle crossbed sets 1 foot thick; weathers to same color as fresh, forms ledge	*31.7*
3. Siltstone, pale reddish brown (10R 5/4); calcareous, moderately indurated; bedding indistinct; has thin intercalated very fine-grained sandstone beds; slope former, weathers to same color as fresh	*48.3*
4. Sandstone, pale red brown (10R 5/4), sporadic mottling with pale red (10R 6/2); very fine grained (vfL), subangular, well-sorted equant grains; silty, calcareous cement, moderately to well indurated; fissile to medium bedded, ripple-marked on bedding planes, dessication cracks; forms rubbly slope	*10.8*
5. Siltstone, like unit 3, without intercalated sandstone	*14.3*
6. Sandstone, pale red (10R 6/2), speckled very pale orange (10YR 8/4), very fine to fine grained (vfU-fU), subangular, well-sorted, equant grains, calcareous, well-indurated; single medium bed; upper foot makes a significant ledge	*2.3*
7. Sandstone, moderate reddish brown (10R 5/4), very fine grained (vfL-vfU), subangular well-sorted equant grains; slightly calcareous, well indurated; platy to thin bedded; micaceous, forms rough steps	*20.5*
8. Sandstone, pale reddish brown (10R 5/4), very fine to fine grained (vfL-fL), subangular to subrounded, well-sorted, equant grains; silty, medium to massive bedding, platy in places; forms rounded cliffs to earthy slopes	*32.3*
9. Sandstone, pale reddish brown (10R 5/4) with one or two bleached streaks; very fine grained (vfL-vfU), subangular, well-sorted equant grains; calcareous, moderately indurated; massive beds; forms ledges and cliffs, the upper 1 foot is bleached pale greenish yellow (10Y 8/2)	*9.1*
Total Pariott Member	*209.8*
Sewemup Member:	
10. Interbedded siltstone and very fine-grained sandstone (50-50), pale reddish brown (10R 5/4); very fine grained (vfL-vfU), well-sorted equant subangular grains; calcareous cement, poorly indurated; platy to thin bedded; forms earthy slope	*16.2*
11. Sandstone, pale red brown (10R 5/4), very fine grained (vfL-vfU), subangular well-sorted equant grains; calcareous cement, moderately indurated; platy to thin bedded; forms slight ledge, thin silty interbeds, mostly a smooth slope	*7.5*
12. Siltstone interbedded with sandstone (60-40), pale reddish brown (10R 5/4), very fine grained (vfL-vfU), well-sorted subangular equant grains; micaceous, calcareous, poor to moderate induration; platy to thin bedded; forms earthy slope; siltstone is grayish-red (10R 4/2)	*90.4*
13. Covered slope, underlain with interbedded sandstone and siltstone	*17.8*
14. Interbedded siltstone and sandstone, like unit 12, but 80-20, becomes 50-50 25 feet below the top and is mostly siltstone 25 to 75 feet below the top; sandstone is very fine grained and silty; sporadic thin gypsum layers	*135.6*
15. Covered slope, rubble from overlying units covers the Moenkopi; adjacent ridge indicates a continued interbedded siltstone and sandstone regimen	*45.0*
16. Sandstone, pale reddish brown (10R 5/4), very fine grained (vfL-vfU), angular to subangular, well-sorted equant grains; micaceous, calcareous cement, moderately well indurated; platy to thin bedded; weathers to earthy slope, exhibits sporadic bleached zones, pale greenish yellow (10Y 8/2) and very pale green (10GY 8/2)	*5.0*
17. Siltstone, pale reddish brown (10R 5/4), with irregular thin sandstone interbeds; sandstone is very fine grained (vfL), calcareous and poorly indurated; platy to thin bedded; forms slope, is poorly exposed, weathers to same color as fresh or slightly lighter	*11.8*
18. Sandstone, pale reddish brown (10R 5/4), very fine grained (vfL), subangular to angular, well-sorted equant grains; calcareous cement, medium induration; single thick bed; weathers laty, forms a rise on an otherwise smooth earthy slope.	*4.3*
19. Siltstone, like unit 17	*25.9*
20. Sandstone, like unit 18	*5.6*
21. Siltstone, like unit 17	*10.1*
22. Sandstone, like unit 18	*7.1*
23. Siltstone, like unit 17	*10.6*
24. Sandstone, like unit 18	*4.6*
25. Siltstone, like unit 17, except for the presence of selenite beds in the upper 34 feet of the unit	*43.9*
Total Sewemup Member	*441.4*
Ali Baba Member:	
26. Sandstone, pale reddish brown (10R 5/4), with scattered bleached light green gray (5GY 8/1) rock; very fine grained	

(vfL-vfU), subangular well-sorted equant grains; calcareous cement; platy bedding, weathers into steep slope 17.2

27. *Sandstone, pale reddish brown (10R 5/4), fine grained (fL-fU), angular to subangular, well-sorted equant grains; slightly calcareous, well indurated; massive, forms rounded ledge with rough surface bordering on earthy, sporadic gypsum bands .* 10.5

28. *Siltstone interbedded with sandstone, pale reddish brown (10R 5/4); siltstone, calcareous, poorly indurated, earthy weathering; sandstone, very fine grained (vfL), fissile to platy; entire unit is slope forming, weathers to same color as fresh, upper 30 feet is gypsiferous, siltstone contains 3 percent in thin selenite beds and veins; sandstone is chippy . . . .* 97.0

29. *Interbedded siltstone and sandstone (80-20), moderate reddish orange (10R 6/6); very fine to fine grained, subangular equant sand grains, minor mica, calcareous and moderately indurated; fissile to thin bedded; sandstone exhibits oscillation ripple marks; weathers to same color as fresh, speckled bleachings, forms earthy slope with slight ledges where the sandstone beds are grouped, moderately well exposed; at 26 feet above the base the unit becomes 90-10 and forms a smoother slope . . . . .* 59.8

30. *Sandstone, moderate reddish orange (10R 6/6); very fine grained (vfL), subround to subangular, well sorted, equant grains; micaceous; non-calcareous, moderately to well indurated; fissile to thin bedded; interference and oscillation ripples; interbedded approximately each 2 feet with a thin sandstone bed 2 inches thick, light gray (N7) to light brown (5YR 6/4), fine grained (fU), subround to subangular, well-sorted equant grains; calcareous and well indurated; entire unit is slope former with sporadic ledges where the calcareous sandstone beds are present . . . .* 5.0

Total Ali Baba Member 189.5

Tenderfoot Member (break in measurement to Sec. 18):

31. *Sandstone, moderate reddish brown (10R 4/6), very fine grained (vfL) with bands of coarser grains to coarse (cL), subrounded, moderately sorted, equant grains; micaceous, calcite cement, well indurated; thick to massive bedding, no sedimentary structure, bleached zones of very pale green (10G 8/2) which decrease in number upwards, weathers pale reddish-brown (10R 5/4), faint manganese oxide stain, forms a rough cliff, well exposed, lower contact is sharp due to abrupt color changes; 25.3 feet from the base and upward the fresh color changes to pale reddish brown (10R 5/4) and the weathered color is moderate reddish orange (10R 6/6) . . . .* 90.0

Total Tenderfoot Member 90.0

Total thickness of Moenkopi Formation 930.7

Moenkopi outcrops on the southwest flank of the Moab anticline are thinner and the members described in Professor Valley cannot be recognized. The outcrop band extends from 2 miles north of Sevenmile Canyon southward to 1 mile south of the Atlas Uranium Mill tailings pond. At each end of the outcrop band the Moenkopi appears to feather out. The upper and lower contacts are unconformities, but angularity is not easily detectable. From northwest to southeast the unit gradually increases in thickness and reaches its maximum of 460 feet opposite the Arches National Park Visitor Center. At the southernmost measurable point it is only 135 feet thick. The extended outcrop is buried by talus, and south of The Portal of the Colorado River the Moenkopi is missing in the section. Between the Hermosa Formation road gap on U. S. Highway 191 and the Atlas tailings pond, part of the formation is repeated by branches of the Moab fault. There it consists of interbedded brown, mostly thin-bedded and evenly bedded siltstones and silty very fine-grained sandstones that form a steep slope (figure 11). The slope is somewhat more rough than that of the Sewemup in Professor Valley owing to thin ledges appearing at regular intervals.

The Moenkopi Formation is exposed in western Cache Valley and southern Salt Valley; the description for both locations is the same. The unit consists of mostly light-brown to moderate reddish-orange, silty, fine-grained sandstone. At the Salt Valley location (NW Sec. 14, T 24 S, R 21 E) the outcrops are stratigraphically below mottled siltstone or silty sandstone of the Chinle formation with no structural complications present. The Cache Valley location (Sec. 8, T 24 S, R 22 E) is an isolated small mid-valley outcrop. These outcrops are not exactly typical of the Moenkopi Formation in neighboring areas (nor of the Chinle Formation). Since they are located in the crestal parts of a salt anticline, some modification of the normal depositional environment may have been in effect in Triassic time. In eastern Cache Valley typical Moenkopi Formation crops out along the north flank as far west as Secs. 12 and 13, T 24 S, R 22 E.

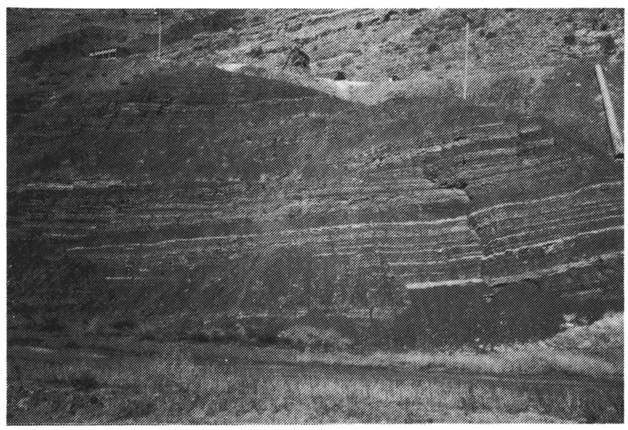


Figure 11. Exposure of thin, evenly bedded Moenkopi Formation at the north end of Moab Valley. This particular exposure is found at highway level lodged between branches of the Moab fault on the "Potash" road (State Route 279).

Shoemaker and Newman (1959, p. 1849) noted that fossils were collected from isolated outcrops of the Moenkopi Formation in the northwest part of Salt Valley (R 19 and 20 E). These were described as an "abundance of juvenile ammonites and gastropods." J. B. Reeside, Jr. (in Shoemaker and Newman, 1959), of the U. S. Geological Survey, identified the fossils as possibly belonging to the *Meekoceras* zone, although they were too small for certain determination. He thought the collection was Lower Triassic in age. I could not find these reported outcrops, but the exposures had been described as poor. The material containing the fossils was not described except to say that nearly all the beds were altered to a light yellowish-brown color. To complicate the issue, J. H. Hanley, U. S. Geological Survey, identified fossils collected from isolated hills in the same area which he described as an early Tertiary (Eocene) gastropod fauna in an irregularly silicified block (Dyer, 1983, p. 20). The Salt Valley hills are commonly veneered with a light yellowish-brown

Quaternary(?) gravel that contains clasts of many older units. The fossiliferous siliceous material, as identified by Hanley, is reasonably abundant in the gravel, and it is possible that the fossils identified by Reeside could also have been found in it. It is therefore assumed that no Moenkopi was present over the crestal part of the salt anticline when deposition of the Chinle Formation began. The oldest unit covering Pennsylvanian rocks in the northwest end of Salt Valley is the Chinle Formation. This same relationship exists in Moab Valley south of the Colorado River. Another small area of Moenkopi Formation in Dry Fork of Bull Canyon in the southwest corner of Map 74 has only the upper part exposed.

Map area boreholes indicate that the thickness varies greatly in the subsurface. Northeast of Salt Valley most wells indicate a thickness ranging from 400 to 600 feet. At the Ladd Petroleum well, NENENW Sec. 16, T 24 S, R 20 E, the Moenkopi has been reported as over 900 feet thick. On the southwest flank of the Salt Valley anticline two wells logged over 2000 feet of tentative Moenkopi strata. This indicates that the thickest sections are peripheral to the salt structures, as suggested by Shoemaker and Newman (1959, p. 1848), rather than directly under the synclinal axes.

Chinle Formation

The Chinle formation is primarily a floodplain deposit and is generally exposed directly underneath the Wingate Sandstone cliffs in the Escarpments and Canyonlands physiographic subdivisions. Exposures are present along the Colorado River, along the inner escarpment edges of Moab Valley and Salt Valley, and in the bottoms of Day and Bull Canyons to the southwest. Appearing as a reddish slope with a few prominent sandstone ledges, the Chinle Formation consists of siltstone, sandstone, conglomerate, and shale. The thickness ranges from 0 to 1000 feet across the area of Map 74, outcrop exposures range from less than 100 to almost 700 feet. Variations in thickness are largely due to salt movement in Triassic time. Normal thickness is presumed to have been 300 to 500 feet, regionally thickening to the south (Stewart, Poole, and Wilson, 1972a, pl. 3), but the isopach map for the Paradox fold and fault belt shows the complexity (figure 12).

Divisions of the Chinle Formation that are useful in the Salt Valley area have been established by Stewart, Poole, and Wilson (1972a) and include (ascending order) mottled strata, basal sandstone, Petrified Forest Member, "Black Ledge,"

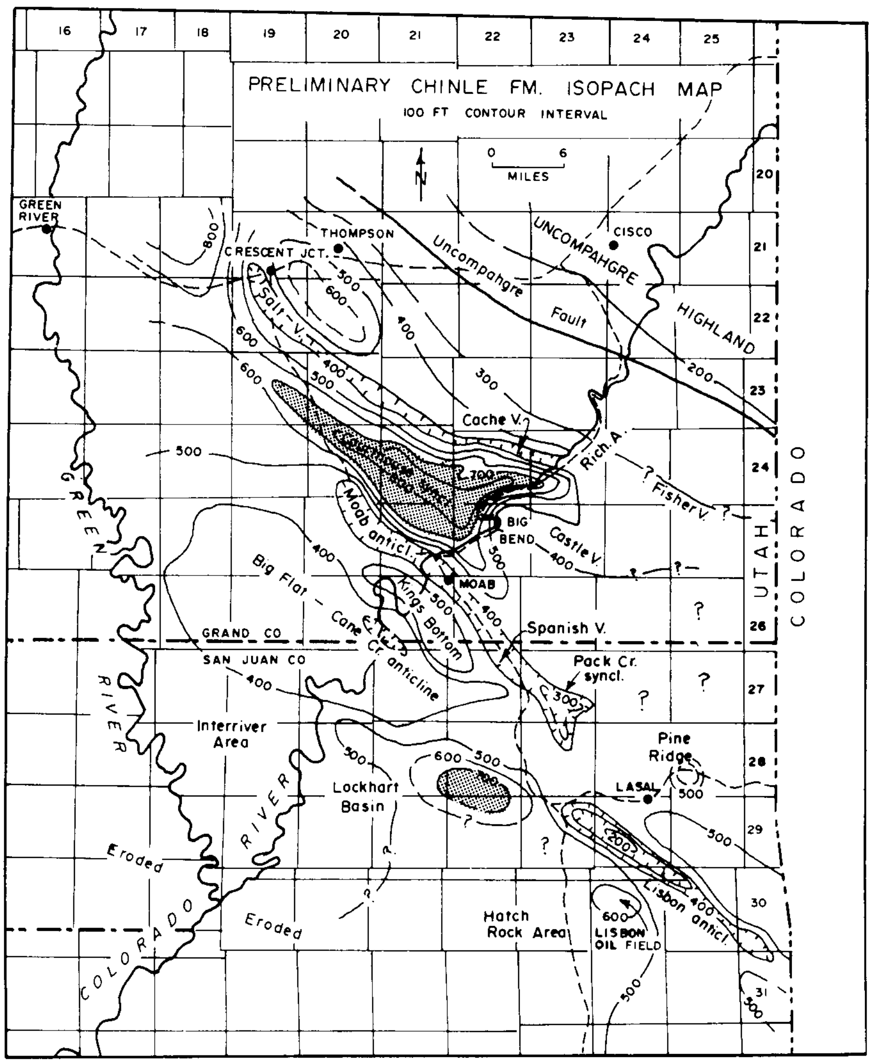


Figure 12. Chinle Formation thickness map for the Paradox Basin fold and fault belt, based and interpreted from limited borehole information. The Chinle Formation was also influenced by salt movement but eventually covered salt anticlines and lapped onto the Uncompahgre Highland. Thin Chinle is indicated within the hachured contours. Exceptionally thick Chinle Formation is indicated over 700 feet.

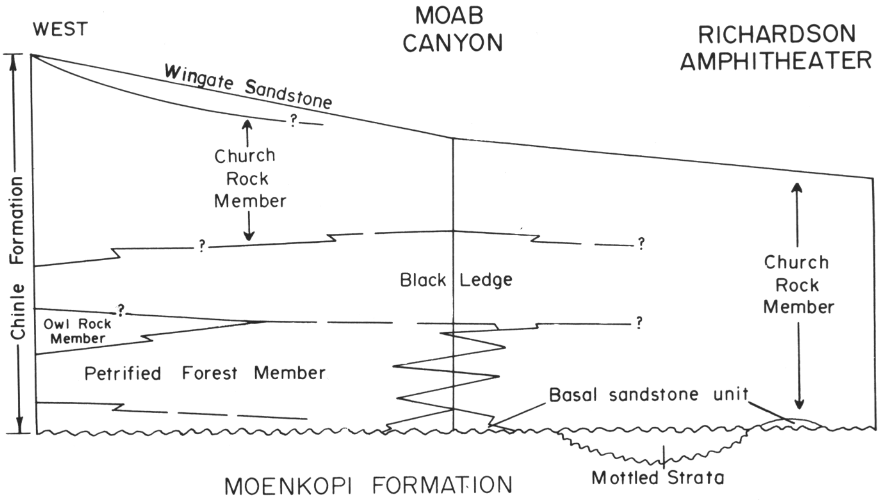


Figure 13. Divisions of the Chinle Formation as established by Stewart, Poole, and Wilson, 1972. The mottled siltstone strata are only in thick sections of the Chinle Formation beneath an unconformity. The mottled siltstone may grade laterally into the "white" basal sandstone or gritstone, indicating that there may also be an unconformity above those rocks.

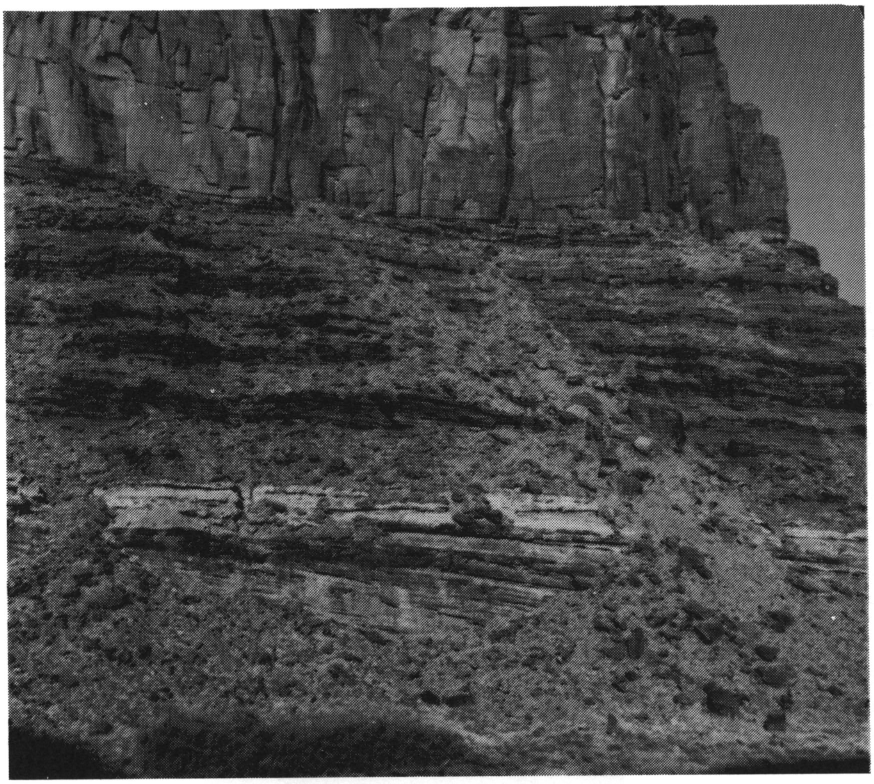


Figure 14. Exposure of the Church Rock Member of the Chinle Formation beneath the Wingate Sandstone cliff. The mottled siltstone is exposed below the angular unconformity. View to the west side of the Colorado River opposite Mat Martin Point.

and Church Rock Member (figure 13). To the east and over the Uncompahgre uplift the Church Rock comprises the entire formation; the veneer of Chinle Formation over the Uncompahgre is 100 to 200 feet thick. It thickens gradually southwestward and is about 260 feet thick in outcrop where the Colorado River flows into the Richardson Amphitheater (Professor Valley). The Chinle is a little over 300 feet thick on the west side of Fisher Valley and is 400 to 500 feet thick around Castle Valley. At the eastern end of Cache Valley two measurements, one on each side of the collapsed rocks, indicated 369 and 670 feet respectively. The thinner measurement was taken on the north side and contained 22 feet of mottled strata at the base. On the south side 220 feet of mottled strata are overlain by 50 feet of cliffy conglomerate and sandstone, followed by typical Church Rock Member. The Chinle-Moenkopi contact is obscure in Professor Valley, marked only by a relatively thin light-colored band of gritstone (basal Chinle). In a few places it is marked by a line of seeps.

Farther downstream around Mat Martin Point, the Colorado River has exposed a thick lens of mottled strata lying unconformably below the Church Rock Member (figure 14). In a measurement made in the NWNW Sec. 4, T 25 S, R 22 E, the Church Rock Member is 421 feet thick and the exposed mottled beds are 275+ feet thick. Shoemaker and Newman (1959, p. 1848) have commented on the mottled lens:

The lateral equivalent of the white grit bed also truncates the bedding of the mottled gray sandstone lens, which lies between the Pariott Member [of the Moenkopi Formation] and the white grit bed northwest of Castle Valley. Major bedding planes in the gray sandstone dip generally northwestward toward the apparent center of the lens, and at the large bend in the Colorado River, are truncated at angles greater than 10 degrees. The inclination of the gray sandstone strata was interpreted by Baker (1933, p 37-38) and by Dane (1935, p. 56) to be mainly an initial feature of the sediment, and the bedding, to be foreset bedding. Foreset-or cross-stratification can be seen within major bedding units, but the major bedding planes are interpreted by the present writers to have been initially horizontal, and the truncation of the beds to be a true angular unconformity as originally believed by Cross (1907, p 654-655 and fig. 8).

Another measurement of the Chinle Formation was taken only 1 ½ miles to the southeast, along the north line of Sec. 10, T 25 S, R 22 E, where the entire Chinle Formation is only 330 feet thick and consists entirely of the Church Rock Member.

Variations in the thickness of the Chinle Formation are also observable on the southwest flank of the Moab anticline northwest of The Portal of the Colorado River. Here the formation is divisible into four parts (figure 13 and 15): a thin basal coarse sandstone, gritstone, or conglomerate; a lower slope-forming unit where Petrified Forest Member strata interfinger with those of the Church Rock Member; a cliff-forming sandstone unit informally labelled the "Black Ledge;" and an upper Church Rock slope-forming unit. Parr (1965, p. 59) reports the Chinle to be almost 600 feet thick just north of The Portal. Opposite the Arches National Park Visitor Center the Chinle is about 235 feet thick. Parr indicated that it may be as thin as 170 feet here. It thickens northwestward, and above the narrow curve ("Hermosa Formation gap") along U. S. Highway 191 north of the visitor center it is 322 feet thick. From this point northwestward the thickness is consistently between 290 and 360 feet. The basal unit varies from 0 to 35 feet and is missing where the Chinle is less than 290 feet thick, notably in NE Sec. 29 and NW Sec. 28, T 25 S, R 21 E. The lower slope-former may exceed 300 feet to the southeast, thins to 55 feet opposite the visitor center, then thickens to 150 to 300 feet north of the "Hermosa Formation gap." The "Black Ledge" generally thins to the northwest along the entire length of outcrop, from 125 to 35 feet. The upper slope thins gradually from 150 feet to the "Hermosa Formation gap," then remains relatively constant at 70 to 90 feet. Parr (p. 57-58, fig. 29) discovered a Triassic landslide block incorporated in the Chinle Formation of this area.

South of the Colorado River, on both sides of Moab Valley, the Chinle rests unconformably on Pennsylvanian rocks. The Pennsylvanian rocks are highly deformed and the Chinle was probably deposited on a surface of relief. The amount of Chinle deposited varies from place to place. South of The Portal, on the southwest flank, about 340 feet of Chinle rest on deformed Pennsylvanian strata. The lower part of the Chinle is draped over the Pennsylvanian rocks, the result of recent salt dissolution. Both the upper slope-former and the "Black Ledge" are recognizable, but several horizons of the upper slope-forming member have been bleached, a common occurrence in the Chinle around Moab Valley.

On the northeast side of Moab Valley the Chinle is generally thinner and often there is less than 100 feet between the overlying Wingate Sandstone and the Pennsylvanian rocks. The character of the Chinle is modified as well, near the mouth of Mill Creek there are many limestone beds (Owl Rock Member?). Baker (1933, p. 40) thought these Chinle beds belonged to the upper member [Honaker Trail Formation] of the Hermosa Formation. He noted that the Wingate rests on these beds with angular unconformity. To the northwest of Mill Creek, the reddish beds immediately below the Wingate Sandstone are typical of the Chinle Formation, but the lower boundary with the Pennsylvanian rocks is not sharp and even appears transitional. Salt dissolution and diapirism were both active while the Chinle was being deposited, and the Pennsylvanian rocks were undoubtedly reworked into the Chinle Formation.

The Chinle Formation is also exposed along the flanks of the Salt Valley anticline and in several places laps onto domes of Pennsylvanian rocks. In NW Sec. 14, T 24 S, R 21 E, on the south flank, the Chinle is about 334 feet thick and consists of: a lower 54-foot slope-forming unit having 15 feet of mottled siltstone and fine-grained sandstone (figure 16) overlain by 6 feet of ledge-forming coarse sandstone and gritstone, and 33 feet of lavender, mostly slope-forming partly mottled siltstone which contains petrified wood and hematite nodules; 50 feet of "Black Ledge," a reddish thin-to medium-bedded and ledgy fine-grained sandstone; 220 feet of the upper slope-forming unit of mostly fine-grained reddish-brown sandstone; and 20 feet of a medium to thick-bedded conglomerate or conglomeratic sandstone.

Exposures of the Chinle Formation are also found in some of the mid-valley hills of Salt Valley. It is difficult to divide the formation into its members as lithologies vary from place to place. "Typical" lithologies were modified as normal depositional environments were changed in areas where the salt moved. Normal Chinle Formation outcrops are exposed in the Bull Canyon-Day Canyon area south of Arths Pasture in the southwest part of the mapped area (Map 74). The thickness ranges from 340 to 370 feet at these locations.

Figure 15. View of the Moenkopi-Chinle contact on the southwest side of Moab Valley about a mile south of the Atlas Uranium Co. tailings pond. A white gritstone at the base of the Chinle overlies the "chocolate" brown evenly bedded Moenkopi Formation. An angular unconformity is found a short distance above the contact and beneath the "Black Ledge."

Figure 16. Mottled siltstone beds of the Chinle Formation on the south side of Salt Valley. These beds appear to thicken southward.

JURASSIC ROCKS
Wingate Sandstone

The Wingate Sandstone, the lower formation of the Glen Canyon Group, is a prominent cliff former exposed along the flanks of Salt Valley, Cache Valley, and Moab Valley and along the course of the Colorado River and other major drainages (figures 6, 8, 10, and 14). The Wingate normally forms a reddish-brown, nearly vertical cliff, streaked and stained with desert varnish, which erodes as large slabs separate from the main mass along fractures that extend through its entire thickness. As support below is removed, these large slabs break up on the Chinle-Moenkopi slope below. Dry washes on the plateau above form unimpressive shallow swales in the Wingate. During flooding the dry washes fill with water which flows down the shallow swales and drops in magnificent waterfalls from the edge of the cliff into deep gulleys in the Chinle below. Contrastingly, along the flanks of the salt structures, the Wingate is shattered. Instead of the usual vertical cliff, a very ledgy and blocky orange-brown cliff has formed.

Uniform from top to bottom, the lithology of the Wingate Sandstone is commonly described in a single unit. It overlies the Chinle sharply, and O'Sullivan and MacLachlan (1975) believed the contact to be a disconformity. In several places, such as at the mouth of Mill Creek or near the junction of Day Canyon and the Colorado River, truncated edges of Chinle Formation channel sandstones can be observed at the contact. The Wingate consists mostly of light orange brown, moderate orange pink, moderate reddish-orange, pinkish-gray, or pale reddish-brown fine-grained, well-sorted, crossbedded sandstone. The Wingate is an eolian deposit with a source area to the northwest. A cap of somewhat lighter sandstone usually marks the top of the unit.

Section of Wingate Sandstone in Little Canyon, 3 miles northwest of Arches National Park Visitor Center and about 1½ miles southwest of U.S. Highway 191 in SE Sec. 23, T 25 S, R 20 E.

Kayenta Formation—*Sandstone, pale reddish-brown (10R 5/4), medium grained (mL), subangular to subrounded, well-sorted, equant grains; micaceous, calcite cement, medium to well cemented; platy to massive, some crossbed sets to 18 inches in thickness; weathers moderate orange pink (10R 7/4), some manganese staining, forms grooved to smooth ledgy step, contact with Wingate Sandstone below is sharp.*

Wingate Sandstone		*Feet*
1.	*Sandstone, pinkish gray (5YR 8/1), fine-grained (fL-fU), rounded to well-rounded, well sorted, equant grains; contains a few black accessory grains; silica cement, very porous but well indurated; massive; weathers grayish-orange pink (5YR 7/2), local heavy black stains, forms smooth rounded cliff. The top 5 to 10 feet is whitish in color*	*34.9*
2.	*Sandstone, moderate reddish orange (10R 6/6); very fine to fine grained (vfL-fL), subrounded, well-sorted, equant grains; mostly siliceous cement, some calcareous, well indurated, massive, crossbed sets to 2 feet (moderate angle cross-stratification); weathers same color as fresh, local black staining, scattered "Swiss cheese" style holes, forms smooth cliff, sharp lower contact; 141 feet above base and extending to the top is color banding with gray orange pink (5YR 7/2), bands, 2 feet or more thick, also sporadic thick (6-foot) low-angle cross-stratified sets*	*277.2*
	Total Thickness of Wingate Sandstone	*312.1*

Chinle Formation—*Interbedded sandstone and siltstone; sandstone light red (5R 6/6), very fine grained (vfL-vfU), subrounded to rounded, well-sorted equant grains; calcareous, moderately indurated; medium bedded, cross-stratified, asymmetrical ripple marks; forms hackly rough surfaces and ledges, locally stained black; siltstone, moderate red (5R 5/4) and pale green (5G 7/2); poorly cemented; platy to very thin bedded; cross-laminated, forms smooth to rough recesses and locally stained orange red.*

Boreholes and stratigraphic measurements show the thickness of the Wingate Sandstone to be less affected by salt movement than the underlying or older units. The normal thickness of the unit in the Salt Valley area ranges from 250 to almost 450 feet and averages a little over 300 feet. The Wingate was probably deposited over the whole region, burying even the cores of the salt structures except in a few local areas. In fact, a few boreholes in the northern part of the Salt Valley anticline pass directly into the Paradox Formation from formations above the Wingate (Doelling, 1981, p. 61). However, the Wingate was probably deposited slightly thinner over the crests of the salt structures and slightly thicker over peripheral areas (Doelling, 1981, p. 64).

Kayenta Formation

The Kayenta Formation is mostly stream-deposited sandstone with subordinate intraformational conglomerate, siltstone, and shale. The unit appearance is primarily reddish, but individual units vary considerably with respect to color; some beds are purple, lavender, red, tan, orange, or white. Most of the sandstones tend to be moderate orange pink with dark reddish brown to grayish red silty mudstones (figure 17). The variability in color is more prominent in the Salt Valley area and to the east. In outcrop the Kayenta Formation is ledgy or step-like, its individual units being thick bedded between the more massive and cliffy Wingate and Navajo Sandstones. Its sandstone units are lenticular and crossbedded, and display channeling, current ripple marks, and some slump features. The grain size is more variable than in its overlying and underlying neighbors, generally from fine to medium grained. The units are mostly calcareous and there is considerable mica. The formation intertongues with the Navajo Sandstone above.

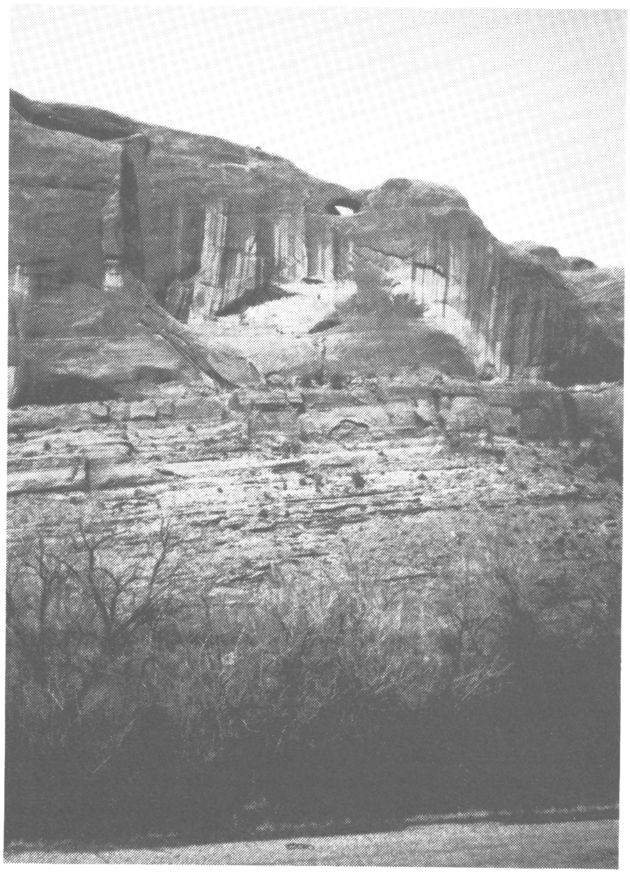


Figure 17. Kayenta Formation (ledgy) overlain by Navajo Sandstone (massive) at The Portal of the Colorado River. The Kayenta forms a ledgy slope between the massive and cliff-forming Navajo and Wingate Sandstones. Note the small arch near the skyline in the Navajo Sandstone.

Section of Kayenta Formation along Courthouse Wash, ½ mile north of the Colorado River Bridge north of Moab, Utah in SE Sec. 22, T 25 S, R 21 E.

Navajo Sandstone—*Sandstone, very pale orange (10YR 8/2), medium grained (mU), rounded to well rounded, well-sorted equant grains; calcareous cement, moderately indurated, thin bedded, bimodal crossbed sets, weathers to moderate orange pink (10R 7/4), smooth surfaces, forms a blocky slope, massive cliff former above, wavy uneven contact with underlying Kayenta Formation.*

Kayenta Formation:	*feet*
1. Sandstone, pale red (10R 6/2), medium grained, (mL), subrounded well-sorted equant grains; calcareous cement, moderately indurated, platy to thin bedded; horizontal laminae; weathers to same color as fresh, weathers earthy, overhanging ledge former, well exposed, thin dark lenses of mudstone intercalated in the sandstone	*10.1*
2. Sandstone, pale reddish brown (10R 5/4), fine grained (fL), subangular well-sorted equant grains; calcareous, poor to moderate induration; platy bedding, weathers slightly darker, forms shaly slope, hackly surface	*6.2*
3. Sandstone, similar to unit 1; 29 feet from top the crossbed sets are less well defined and unit becomes more blocky and massive and weathers to a smooth surface; at 26 feet from top are low-angle crossbed sets; 29 feet above the base are scattered iron concretions; from 29 feet below the top to 29 feet above the base the unit forms a slope	*84.5*
4. Micaceous sandstone, pale reddish brown (10R 5/4), fine to medium grained (fU-mL), subrounded, well-sorted equant grains; thick bedded to massive; low-angle cross stratification, weathers to moderate reddish brown (10R 4/6), some manganese oxide staining, weathers to smooth surfaces, cliff forming, well exposed, sharp contact with underlying unit; 14 feet above the base is a 3 foot channel of thinbedded sandstone; 39 feet below the top the weathered color is grayish orange pink	*124.0*
5. Sandstone, moderate reddish orange (10R 6/6), medium grained (mL), subrounded well-sorted equant grains; slightly calcareous, medium induration, platy and thin bedded; weathers to same color as fresh, weathers to earthy surface; ledge former, well exposed, sharp contact with underlying unit	*32.0*
6. Sandstone, pale reddish brown (10R 4/6) with white spots; fine grained, subrounded well-sorted equant grains; slightly calcareous, poorly indurated; thick bedded, weathers to same color as fresh, weathers to smooth surfaces, ledge forming, well exposed	*10.0*
Total thickness Kayenta Formation	*266.8*

Wingate Sandstone—Sandstone, grayish orange (10YR 7/4), fine to medium grained, subangular to subrounded well-sorted equant grains; siliceous cement, medium induration; massive, low-angle cross stratification, weathers to grayish orange pink (5YR 7/2), some manganese oxide staining, smooth surfaces, cliff former, well exposed, sharp contact with overlying unit.

Most measurements in the Salt Valley area show the Kayenta to be 150 to 300 feet thick. It was deposited relatively evenly across the area except at the northwest end of Salt Valley where boreholes pass directly from the Navajo Sandstone into the Paradox Formation. Salt movement was locally active during Kayenta time, but there is no evidence that a general thinning occurred over the crests of the anticlines. Some key borehole Glen Canyon thicknesses are tabulated in table 2.

Table 2.
Thicknesses (in feet) of Glen Canyon Group formations as recorded in boreholes in the Salt Valley area, (Petroleum Information Services)

Location	**Name of borehole**	**Wingate**	**Kayenta**	**Navajo**	**Total**
NENW 22-22S-19E	Conoco #1 Salt Valley	0	0	178	178
NESE 36-23S-19E	Equity #1 State	362	164	684	1210
SWSW 6-23S-20E	Conoco #1 Hall	380	260	285	925
SESE 2-23S-21E	Union #1 P-2 State	408	557	?	?
SWSE 5-23S-21E	Union #1 Devils Garden	445	188	529	1162
SWNE 12-24S-20E	Shell #1 Legget Courthouse	400	230	500	1130
SWSE 36-24S-20E	Union #1 State	250	434	?	?

Navajo Sandstone

The Navajo Sandstone is the classic example of an eolian-deposited unit and is the uppermost formation of the Glen Canyon Group. The massive crossbedded unit has been described as fossilized sand dunes and the tangential cross-laminae lie as much as 30 degrees from the true attitude of the unit. It is mostly orange to light gray, fine grained, and forms vertical cliffs in its lower parts, and domes and rounded bare slopes in its upper parts (figure 18). Sporadic thin hard lenticular limestones (lacustrine) are also found in the unit. These are most noticeable on the flanks of the Salt Valley anticline, especially the southeast flank. Limestone is present elsewhere, but the lenses are not as extensive or as continuous as on the flanks of the salt anticlines.

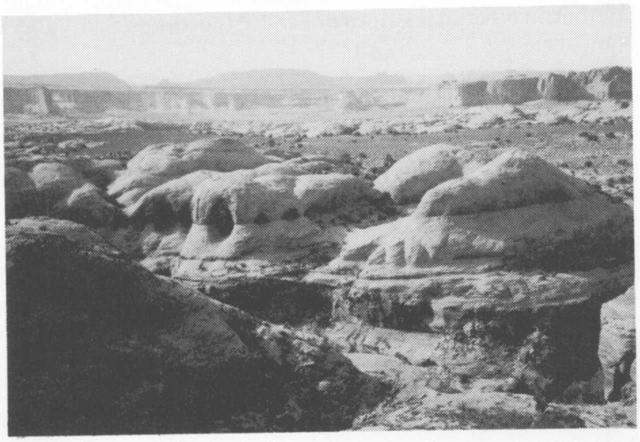


Figure 18. The Navajo Sandstone weathers into rounded knolls, bare rock outcrops and "frozen sand dunes." High-angle crossbeds which attest to an eolian origin are its trademark.

According to Wright, Shawe, and Lohman (1962, p. 2059), the upper contact with the Dewey Bridge Member of the Entrada Formation is a sharp truncation plain on which detrital chert granules and pebbles are widespread (J-1 unconformity of Pipiringos and O'Sullivan, 1978). The Navajo participates in producing the upper surfaces of the Plateau Surfaces physiographic section but also crops out in the Escarpments and Canyonlands section of the Salt Valley anticline area.

Regionally, the Navajo Sandstone thins from west to east across the Salt Valley anticline area but was locally modified in thickness by salt movement. The normal thickness, where not influenced by salt movement, is 300 to 450 feet. Thicknesses of the unit measured along the crestal parts of the Salt Valley anticline range from 250 to 360 feet, however, surface measurements can vary as much as 100 feet because of irregular choices by geologists in picking the base of the formation. The lower contact is an intertonguing relationship. Borehole measurements, although few, indicate the Navajo Sandstone to be 500 to 550 feet thick in peripheral locations to the Salt Valley anticline. One borehole, the Union #1 State, reports a questionable 890 feet about 1 mile southwest of the Courthouse syncline but peripheral to the Moab anticline.

The Navajo Sandstone was deposited across the region and covered the crestal portions of the anticlines. Locally a salt diapir or dome may have stood in relief along the crest of the Salt Valley anticline, which was not covered by the Navajo Sandstone. At the northwest end of the Salt Valley anticline, the Conoco #1 Salt Valley well is reported to intercept only 178 feet of Navajo before reaching the Paradox Formation. All of the intervening units are missing.

Entrada Sandstone

The Entrada Sandstone is significant as the unit in which most of the arches in Arches National Park have formed. It has been divided into three members: Dewey Bridge, Slickrock, and the Moab Tongue (figure 19). The middle Slickrock Member has also been termed the "main body," or "Slickrim" Member in other reports. Arches form in all three members, even at their contacts. The lithology for all three is principally sandstone, and all thicken regionally to the west.

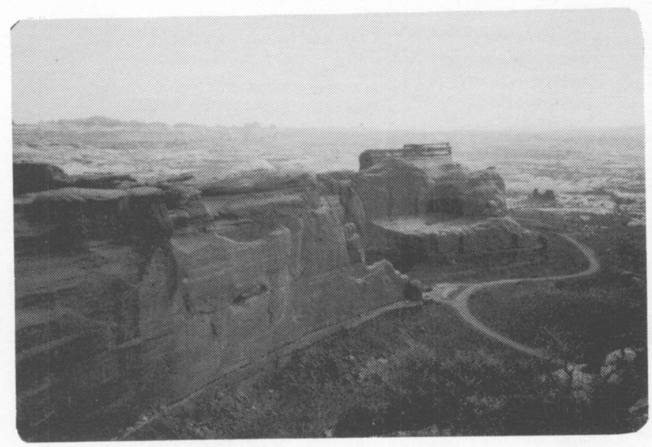


Figure 19. Entrada Sandstone exposures along the Courthouse Towers road. The reddish silty sandstone at the base with contorted bedding is the Dewey Bridge Member of the Entrada Sandstone. The smooth cliff-former is known as the Slickrock Member or main body of the Entrada Sandstone. The caprock is the Moab Sandstone Tongue of the Entrada Sandstone. Its contact with the Slickrock is often indicated by siltstone at its base or a line of seeps and springs.

Dewey Bridge Member The Dewey Bridge Member was formerly known as the Carmel Formation (Dane, 1935) in the Arches National Park area, but Wright, Shawe, and Lohman (1962, p. 2059) proposed a change consistent with lithological criteria. The red earthy siltstone at the base of the Entrada Sandstone at the San Rafael River, in Emery County, is clearly continuous laterally with red earthy siltstone in the top part of the Dewey Bridge Member farther east. Lower beds correlate with part of the Carmel, but a facies change occurs near the Green River. In many of the sections measured by Wright, Shawe, and Lohman, the unit was siltstone, but in most places across the Salt Valley anticline area it is mostly fine-grained sandstone with some siltstone interbeds.

The member is a soft, red, muddy sandstone with irregular contorted bedding. This bed deformation affects the lower parts of the Slickrock Member as well, with which it is conformable. The deformation is most pronounced in eastern exposures. The Dewey Bridge Member was probably deposited on broad tidal flats marginal to a sea located to the west.

Section of the Dewey Bridge Member of the Entrada Sandstone, on the northeast flank of Salt Valley anticline, 8 miles SSW of Thompson, SW Sec. 32, T 22 S, R 20 E.

Entrada Sandstone, Slickrock Member—*Sandstone, very pale orange (10YR 8/2); very fine grained (vfL-vfU), subrounded to rounded, well-sorted equant grains; orange and black accessory grains sprinkled throughout; calcareous, well indurated; massive; weathers pale red (10R 6/2), manganese oxide staining, weathers smooth, cliff forming, well exposed, lower contact sharp.*

Dewey Bridge Member:		*feet*
1.	*Siltstone, grayish red (10R4/2); calcareous, poorly indurated; thin to medium bedded; weathers to same color, weathers to smooth spheroidal surfaces, recess forming, poorly exposed, upper contact sharp*	*4.0*
2.	*Sandstone, moderate red (5R 5/4) and very light gray (N8); very fine to fine grained (vfL-fU), subrounded to rounded well-sorted equant grains; orange and black accessory grains sprinkled throughout; calcareous, medium indurated; platy to medium bedded; weathers to same color, weathers to rough surfaces, step forming, well exposed*	*6.4*
3.	*Sandstone, grayish orange pink (5YR 7/2); very fine to fine grained (vfU-fU), rounded, well-sorted equant grains; some black accessory grains; calcareous, well indurated; massive bedding; weathers grayish orange pink (5YR 7/2) and pale red (5R 6/2), weathers to a smooth rounded surface, cliff forming, well exposed*	*53.0*
4.	*Interbedded sandstone and siltstone: sandstone, moderate reddish orange (10R 6/6) and very light gray (N8); very fine grained (vfL-vfU), subrounded to rounded, well-sorted equant grains; orange and black accessory grains sprinkled throughout; calcareous, well indurated; medium to massively bedded; weathers and stains to a pale red (5R 6/2), weathers smooth, ledge forming: siltstone, graysh red (10R 4/2); possibly cemented with hematite, poorly indurated; thin bedded; weathers to same color as fresh, weathers to smooth surfaces, recess forming, poorly exposed*	*22.8*
5.	*Sandstone, very light gray (N8); very fine to fine grained (vfL-fU), subrounded to rounded, well-sorted equant grains; black and orange accessory grains sprinkled throughout; calcareous, medium to well indurated and thick bedded; color of rock obscured by pale red (10R 6/2) staining, weathers to smooth blocky surfaces, step forming*	*12.6*
6.	*Interbedded sandstone and siltstone: sandstone, pale reddish brown (10R 5/4); very fine to fine grained (vfU-fL), subrounded to rounded, well-sorted equant grains; calcareous, poorly indurated; medium bedded with thin horizontal laminations; weathers to an earthy surface, slope forming, poorly exposed; light gray banding (N7); siltstone, like in unit 4*	*10.5*
7.	*Sandstone, very pale orange (10Yr 8/2); fine grained (fL-fU), rounded, well-sorted equant grains; orange and black accessory grains scattered throughout; calcareous, well indurated, thick bedded, some cross stratification; weathers, grayish orange (10YR 7/4), some manganese oxide staining, weathers blocky, ledge forming, well exposed, the ledge holds up a bench*	*4.5*
8.	*Interbedded sandstone and siltstone like unit 6, upper 10 feet are platy bedded*	*19.3*
9.	*Sandstone, like unit 7 with small black accessory grains*	*1.9*
10.	*Interbedded sandstone and siltstone, like unit 6, except it forms recesses; lower contact is covered with Navajo Sandstone*	*7.8*
	Total Dewey Bridge Member	*142.8*

Navajo Sandstone—*Sandstone, very light gray (N8), very fine to fine grained (vfL-fL), subrounded to rounded, well-sorted equant grains; calcareous, medium induration; massive, cross stratified; weathers to same color, some manganese oxide staining, weathers to smooth rounded surfaces, ledgy cliff former, well exposed.*

The Dewey Bridge Member is more than 100 feet thick (100-235 feet) in exposures in the western half of Map 74, and less than 100 feet thick (40-100 feet) in eastern exposures. It was probably little affected by salt movement during its deposition.

Slickrock Member This member is a massive, well-indurated, reddish-orange or brown, very fine- to fine-grained sandstone with sparse medium to coarse sand grains. It often weathers to smooth cliffs and bare-rock slopes. This member forms the pronounced fins of the Arches and Fins section of the area (figure 20) and, with the Dewey Bridge Member, it forms monuments, arches, and windows. Parts of the unit are distinctly cross stratified (eolian deposition), other parts are planar bedded. The unit was probably deposited marginally to a sea located to the west and at least part is sandy beach deposits. In places the unit is uniform in color from top to bottom, in others it is striped or banded (northwest Salt Valley anticline).

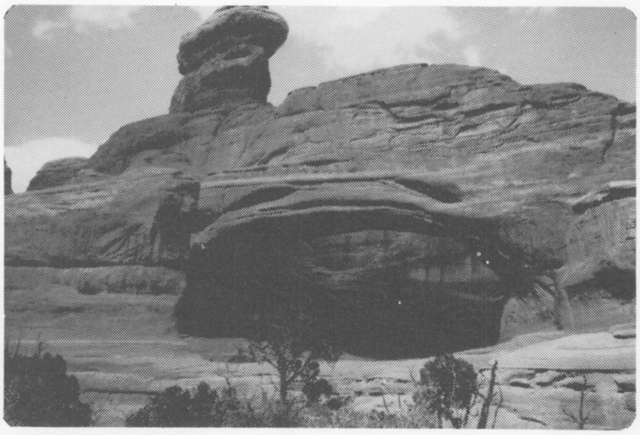


Figure 20. Tower Arch in the Klondike area of Arches National Park is cut entirely in the Slickrock Member. The uppermost bed of the tower is Moab Tongue.

Generally, where the Entrada outcrop is not exposed as a cliff or as fins, the outcrop band is covered or partly covered by large irregular fields of self-derived windblown sand. Cementation is generally calcareous and easily dissolved by meteoric water. The thickness of the Slickrock Member in the Salt Valley area ranges from 0-400 feet, but normally is found 200-350 feet thick in outcrop. It was deposited over the entire map area and may be a little thinner over the crestal parts of the anticlines. One borehole northwest of the map area indicates a local spot where the Entrada Sandstone may be completely missing over the crestal portion of the Salt Valley anticline, and similar buried areas along the crest may yet be found.

Moab Member or Tongue The uppermost member of the Entrada Sandstone is the Moab Member or Tongue. It is a very pale orange, grayish orange, pale yellowish brown, or light gray, fine- to medium-grained, calcareous, massive, cliff-forming sandstone. It is well indurated, exhibits low-angle cross stratification, and when not exposed in a cliff face is found as a bare-rock, highly jointed dip slope. This dip slope is quite wide in most places where the softer, overlying Tidwell Member of the Morrison Formation has been eroded from it. It is somewhat like the Navajo Sandstone, but thinner, with less Quaternary sand on its surface, and with joints and "biscuits" rather than "frozen sand dunes" as its obvious trademark (figure 21). The bare-rock dip slope, lighter color, and lack of sand accumulation are characteristics that make it easy to differentiate it from the underlying Slickrock Member.

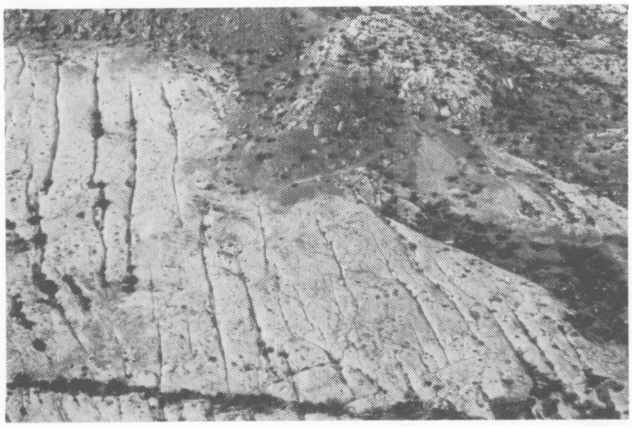


Figure 21. The upper surface of the Moab Member of the Entrada Sandstone displays much jointing and large bare-rock outcrops.

In most places it is separated from the Slickrock Member by a prominent bedding plane or a few inches of reddish sandy siltstone, which is sometimes lined with springs and seeps. At the north end of Salt Valley anticline as much as 26 feet of interbedded slope- and ledge-forming, thin- to medium-bedded reddish sandstones separate the two members. These mostly fine-grained and silty beds are mapped with the Moab Tongue and were correlated by O'Sullivan (1981) with part of the Curtis Formation in the San Rafael Swell.

Section of Entrada Sandstone, NE flank of Salt Valley anticline near the northwest end, about 8 miles SSW of Thompson, Utah, in NW Sec. 32, T 22 S, R 20 E, Grand County, Utah.

Tidwell Member of the Morrison Formation—*Interbedded sandstone and siltstone: sandstone very light gray (N8) and grayish orange (10YR 7/4); very fine to medium grained (vfU-mL), subrounded medium sorted, equant grains; calcareous, well-indurated; thick-bedded, some laminae of alternating fine and coarse grains; stained orange pink (10YR 8/4) and with manganese oxide (black), weathers to a ribbed surface and makes step-like exposures: siltstone is grayish red (10R 4/2), contains some quartz grains; calcareous, poorly indurated; platy to fissile, weathers to same color as fresh, weathers to earthy surface and forms recess; entire unit is mostly poorly exposed with the sandstones somewhat more obvious; contact with Entrada Sandstone below is an abrupt change in color and lithology.*

Entrada Sandstone, Moab Member or Tongue:	*feet*
1. Sandstone very pale orange (10YR 8/2); fine to medium grained (fL-mL), subrounded, well-sorted equant grains; contains small black accessory grains, calcareous and well indurated; massive with low-angle cross sratification; jointed; weathers grayish orange (10YR 7/4) and light gray (n7) with orange blotchy areas, some manganese oxide staining, weathers to smooth rounded surfaces, cliff former, well exposed, sharp lower contact	*65.9*
2. Interbedded sandstone and sandy mudstone: sandstone mottled light red (5R 6/6) and pale yellowish orange (10YR 8/6); fine grained (fU-fL), subrounded, well-sorted equant grains; calcareous, poorly indurated; thin bedded; weathers to same color as fresh and stains moderate orange pink (10R 7/4), weathers to rough blocky surfaces, forms recess, poorly exposed; sandy mudstone is moderate greenish yellow (10Y 7/4) and pale green (5G 7/2); non-calcareous, poorly indurated; fissile to thin bedded; contains some secondary gypsum veins; weathers to same colors and to earthy surfaces, poorly exposed recess former	*7.1*
3. Sandstone, light red (5R 6/6), fine grained (fU), rounded to subrounded, well-sorted equant grains; calcareous, poor to medium induration; thin to medium bedded; weathers moderate red (5R 5/4), weathers to a grooved surface, forms recess or poorly exposed	*12.7*
Total Moab Member or Tongue	*85.7*
Slickrock Member:	
4. Sandstone, very pale orange (10YR 8/2); fine grained (fU), subrounded to rounded, well-sorted equant grains; calcareous, well indurated; massive, has low-angle cross stratification; stained moderate reddish orange (10R 6/6), weathers to smooth surface, well-exposed cliff former; contact with Dewey Bridge Member below is sharp; 62 to 67 feet above the base 1-inch ironstone concretions are present; broad color banding occurs at various intervals	*216.3*
Total upper two members of Entrada Sandstone	*302.0*

The Moab Member or Tongue, combined with the possible Curtis Formation beds at the base, is 60 to 120 feet thick in the Salt Valley anticline area. In most outcrop measurements it is 80 to 100 feet thick; the thinnest measurements are found where the outcrop is located adjacent to the crest of the anticline. In the Shell Oil #1 Leggett Courthouse Wash borehole, SWNE Sec. 12, T 24 S, R 20 E, on the periphery of the anticline, the thickest known section of 120 feet was intercepted.

Morrison Formation

The three members of the Morrison Formation are extensively exposed in the Outer Anticlinal Flank and the Salt Dissolution and Collapse physiographic sections of the area, and they are the Tidwell Member, Salt Wash Member, and Brushy Basin Member. I have treated the Morrison Formation as entirely Jurassic in age. Kowallis and Heaton (in press, 1988), however, dating bentonites and bentonitic mudstones in the Morrison Formation by fission track methods, indicate that the upper part of the Brushy Basin Member may be Early Cretaceous in age. Peterson and Turner-Peterson (1987) have recently reported on the regional aspects of the Morrison Formation. Their report involves recent advances in sedimentology, stratigraphy, and paleotectonics associated with the formation and clearly discusses the source areas of the clasts.

Tidwell Member In the Salt Valley area the Tidwell Member is a very useful and easily recognized marker bed (figure 22). In previous reports the Tidwell Member horizon has been mapped as the Summerville Formation (Baker, 1933; Dane, 1935; and McKnight, 1940). The work of O'Sullivan (1980a, 1980b, 1981) showed that an unconformity is present at the top of the Moab Member of the Entrada Sandstone in the Salt

Valley anticline area. He reported that this same unconformity is at the top of the Summerville Formation in the San Rafael Swell and has shown that the Moab Member of the Entrada Sandstone correlates with the Curtis and Summerville units to the west.

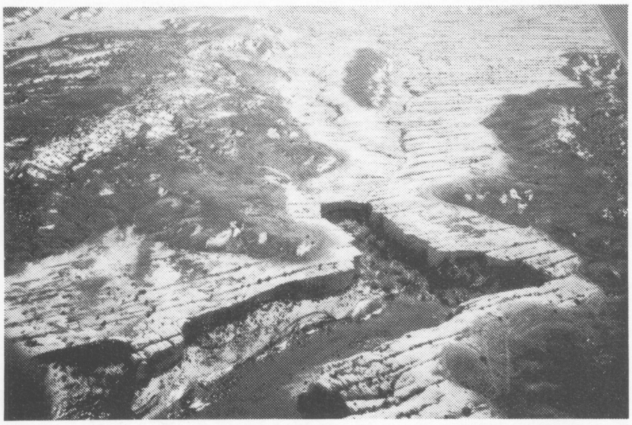


Figure 22. The Tidwell Member of the Morrison Formation rests as dark reddish "scabs" on the jointed light Moab Member of the Entrada Sandstone on the northeast flank of the Salt Valley anticline.

Peterson (1980, p. 306-308), studying the Morrison Formation in the Henry Mountains region, found some "lower beds" above the Summerville Formation and below the Salt Wash Member of the Morrison Formation and stated:

> The Tidwell unit, considered as a separate entity at the base of the Morrison Formation in the Henry Basin, lies disconformably on the Middle Jurassic Summerville Formation and equivalent beds. In recent years, several uranium companies have resurrected the name "Tidwell Member" for these beds because that name appeared on unpublished and unauthored maps in the files of the U. S. Department of Energy [formerly the U.S. Atomic Energy Commission]. Because this important unit needs to be recognized it is informally referred to as the Tidwell unit of the Morrison in this report, in keeping with use of the informal name already applied to it.

In the Salt Valley anticline the unit is thin-bedded red sandstone and shale, much ripple marked, with some gray limestone locally studded with large chert concretions (Dane, 1935, p. 19). It weathers to a short, steep, earthy slope so that little bedding is displayed. In the Yellow Cat area and in some local areas (west of Herdina Park, northeast of the highway junction along Sevenmile Wash, and Cache Valley), there are broad, nearly level tracts exposing the upper surface of the unit. The harder strata, the limestones and large chert concretions, are exposed or are scattered on the surfaces or slopes. On fresh surfaces the strata are thin bedded to shaly and consist of sandy mudstone, muddy sandstone, silty sandstone, silty shale, with lesser percentages of nodular limestone, large chert concretions, and shale.

On the Moab anticline there is a reworked layer of sandstone, about a foot thick at the base, on top of the Moab Member of the Entrada Sandstone. The large chert concretions appear one-third of the way up and a 6 to 12 inch bed of nodular-weathering, light-gray limestone appears two-thirds of the way up on the Tidwell slope (figure 23). On the northeast flank of Salt Valley anticline the reworked basal sandstone is medium grained, loosely cemented, and 2 feet thick. This is followed by 8 ½ feet of reddish muddy siltstone and a 1 foot white, friable, medium-grained sandstone ledge, followed in turn by 10 feet of more reddish muddy siltstone, then by 14 feet of interbedded thin- to medium-bedded muddy sandstone and red siltstone. The final unit is reddish muddy siltstone, 31 feet thick, in the middle of which is a 2 foot bed of blocky gray limestone. The large chert concretions are generally missing in exposures to the northwest.

The Tidwell-Salt Wash contact appears gradational, conformable, and probably interfingering. The contact is placed where the reddish shaly or earthy exposures of the Tidwell give way upward to gray, greenish-gray, or brown muddy siltstones or distinctly crossbedded and lenticular sandstones. In some places the slope continues and the change from red to greenish-gray marks the contact. In other places the contact is placed at the base of a well-defined, brownish channel sandstone lying directly over the reddish siltstones.

The Tidwell Member varies in thickness from 44 to 96 feet, averaging about 65 feet throughout the Salt Valley area. There appear to be no regional trends or response to local salt movements. In the Conoco #1 Salt Valley well, NENW Sec. 22, T 22 S, R 19 E, in the northwest and crestal part of the Salt Valley anticline, the thickness is 145 feet. Dane (1935, p. 106) indicated that the Tidwell Member was deposited in rather quiet shallow waters on a gently sloping flood plain. These conditions may have persisted locally for a longer period of time in the crestal portions of the salt anticline.

Figure 23. The Tidwell Member of the Morrison Formation overlies the Moab Tongue of the Entrada Sandstone on the crest of the Moab anticline. The Tidwell Member contains large white chert concretions, especially in the southern half of the mapped area.

Salt Wash Member This unit consists of fluvially deposited sandstone, mudstone, siltstone, shale, conglomerate, quartzite, and limestone, along with gradations between these types (figure 24). It crops out as benches, dip slopes, or in shallow ravines; the sandstone, quartzite, and conglomerate are generally more resistant and lenticular than the remaining lithologic units. The sandstones represent old river channels, and individual channels can often be traced for considerable distances.

Sedimentary features associated with the channels are often readily identifiable: meanders, bars, trough cross stratifications, cut and fill, and others. The sandstones are mostly calcareously cemented and the grain sizes vary within the lenses as well as from lens to lens. The sandstone lenses commonly contain a great deal of carbonaceous debris along the sides and bottoms of the channels: leaves, twigs, and wood, along with silicified bone and wood and clay clasts. Thicker and coarser grained channels are mostly near the top of the Salt Wash Member. The colors include very light gray, grayish yellow, light greenish gray, and very pale orange. In the Yellow Cat area, northwest of the arches of the national park, these sandstones are mineralized with vanadium and uranium. At the northwest end of the Salt Valley anticline, on the southwest flank, these sandstones are mineralized with copper. Stokes (1952) discussed the geology and minerals of the Thompson district (Yellow Cat area) and prepared an excellent review of the fluvial features and ore deposits in the Salt Wash Member.

The softer, finer grained sediments usually weather into earthy slopes. In better exposures they are found in the recesses between the sandstone lenses in colors of reddish-brown, reddish-gray, or light greenish-gray. Gray limestones are not common but more prevalent in the lower part of the member while finer grained units are typical of flood-plain deposits.

Most available measurements indicate that the Salt Wash Member is 200 to 300 feet thick in the area of Map 74. The average thickness for the Salt Wash Member is 230 feet. The thinnest measurement of 132 feet occurs in SE Sec. 26, T 22 S, R 19 E, on the southwest flank of the northwest end of Salt Valley anticline. Measurements within the crestal area, either in boreholes or in dissolution-collapsed ridges, show the unit to be on the thick side of the thickness range.

Figure 24. Outcrops of the Salt Wash Member of the Morrison Formation on the southwest flank of the Salt Valley anticline. The lenticular channel sandstones of the member break apart on the mudstone interbeds

Brushy Basin Member The uppermost member of the Morrison Formation is the Brushy Basin Member in the Salt Valley area (figure 25). It consists of variegated muddy siltstone and claystone, for the most part, with lesser amounts of sandstone, conglomeratic sandstone, and limestone. Sandstone and conglomerate can be found anywhere in the section but are usually more prevalent in the lower half. All units are lenticular, lensing out and in, but the overall appearance remains constant. Outcrops of collapsed Brushy Basin Member in Secs. 15 and 19, T 23 S, R 20 E, in northwest Salt Valley, have a significant amount of light-gray aphanitic limestone containing blebs of red jasperized chert.

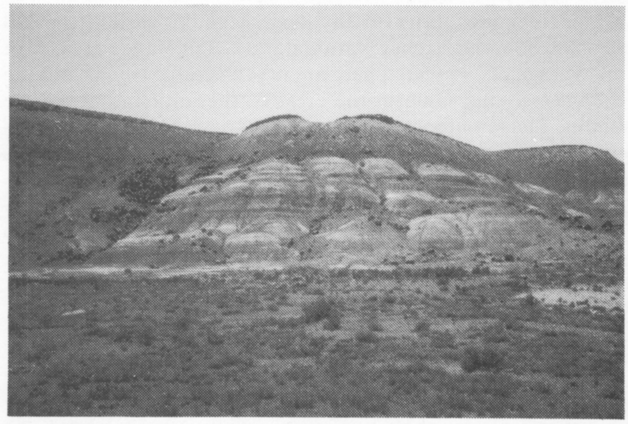


Figure 25. The Brushy Basin Member of the Morrison Formation forms varicolored slopes, such as shown above, over most of its outcrop area. To the north, maroon colors dominate, to the south the outcrops are generally bright green or blue-green. Replete with altered volcanic ashes, the Brushy Basin shale obtains its coloration from iron oxide minerals, not from copper or chromium.

Clay present in the mudstones of the member swells and shrinks in the presence of moisture and provides typical "popcorn" texture outcrops. The swelling clay was apparently derived from the hydrolysis and devitrification of volcanic ashes (Stokes, 1952, p. 13).

Outcrops of the Brushy Basin are generally steep, smooth slopes extending upward in concave fashion from the step-like, ledgy Salt Wash to the first coarse clastic unit of the Cedar Mountain Formation. Alluvial strike valleys have developed over the lower part of the Brushy Basin Member and along the contact with the Salt Wash Member on the salt anticline flanks. The Salt Wash-Brushy Basin contact appears to be sharp and conformable, but it is an interfingering relationship. Stokes (1952, p. 13) stated that it is not a definite stratigraphic plane or erosion surface. Its position is governed arbitrarily by the local position of the uppermost sandstone or conglomerate lens in the Salt Wash Member and probably ranges through an interval of 50 to 100 feet. Where sandstone and conglomerate are well developed near the bottom of the Brushy Basin, the outcrop pattern is commonly similar to that of the Salt Wash Member.

The depositional environment of the Brushy Basin Member is principally that of a flood plain, with streams having lower gradients than those of the Salt Wash Member. The Salt Wash environment appears to be dominated by river channels; the Brushy Basin by interfluve sediments. The lenticular units of the Brushy Basin have a wider irregular distribution and are much thinner, as would be produced by an overbank deposit during a flood of a major river.

Colors associated with the Brushy Basin Member range from dominantly maroon to dominantly green. To the north, along the east-west band of outcrops extending from Poison

Strip to the northwest end of the Salt Valley anticline, the overall color is maroon. The maroon also persists on the southwest flank southward to T 24 S, but there the outcrop begins to show the lensing in of bright green mudstone. Collapsed outcrops in southeastern Salt Valley and Cache Valley are an almost uniform bright green. Close examination reveals that the unit is variegated and individual colors include gray, brown, purple, white, yellow, green, lavender, pink, and red.

The thickness of the Brushy Basin Member varies from 300 to 450 feet in the Arches National Park-Salt Valley area, with an average of 375 feet. There are no detectable trends and the thickness is the same in the crest of the anticline as on the flanks. The apparent variation in thickness is probably attributable to the placing of the Brushy Basin-Salt Wash boundary.

Section of Morrison Formation, 6 miles south of Crescent Junction, east side of U. S. Highway 191, at the northwest end of Salt Valley, SE Sec. 26, T 22 S, R 19 E, Grand County, Utah.

Cedar Mountain Formation—*Conglomeratic sandstone, very pale orange (10YR 8/2), fine-grained to pebbly (fL to 2 cm), subrounded to rounded, poor to fair sorting, equant grains; contains some limonitic accessory grains; calcareous and well indurated; massive; cross stratified with fining upward sequences, lenses of conglomerate at base and less common higher in the section; forms a rough block cliff; mud clasts present; weathers light brown (5YR 6/4).*

Morrison Formation, Brushy Basin Member: feet

1. Siltstone, very pale orange (10YR 8/2), calcareous, moderately indurated; thick bedded, weathers dark yellow orange (10YR 6/6), weathers to rough surface, recess forming, lenticular, concave lower contact, wavy upper contact 4.0
2. Mudstone, grayish red purple (5RP 4/2), calcite cement, very poorly cemented; fissile; weathers light red (5R 6/6) and very pale green (10G 8/2), weathers to earthy convex slopes; has small scattered sandstone lenses, weathers to "popcorn" textures 26.8
3. Limestone, yellowish-gray (5Y 7/2), aphanitic, contains black accessory grains; hard; thin to medium bedded; weathers grayish orange pink (5YR 7/2), some light brown (5YR 5/6) staining; forms a blocky step, poorly exposed 2.6
4. Mudstone, same as unit 2, also grayish red (10R 4/2) and pale green (10G 6/2) . 17.2
5. Dolomite, yellowish-gray (5Y 7/2), aphanitic, some black accessory grains, hard; thin to medium bedded; weathers grayish orange pink (5YR 7/2), some light-brown (5YR 5/6) staining, forms a blocky step, poorly exposed 1.7
6. Mudstone, like unit 4 . . . . 17.3
7. Boulder-covered slope, probably underlain by sandstone, slope is moderate reddish brown (10R 4/6) 58.0
8. Mudstone, like unit 2, a resistant step occurs 2.9 feet above base, also pale green (10G 6/2) and grayish red purple (5RP 4/2) . 23.4
9. Siltstone, dusky red (5R 3/4) 1.0
10. Sandstone, grayish-red (5R 4/2), mottled with very pale green (10G 8/2) and very light gray (N8), very fine grained (vfL), subangular to subrounded, well-sorted equant grains; siliceous, well indurated; medium bedded, laminated; weathers yellowish-gray (5Y 7/2), forms a rounded to blocky step, poorly exposed. 3.8
11. Mudstone, like unit 2, except fresh color is grayish red (10R 4/2) and pale green (10G 6/2) 15.3
12. Sandstone, like unit 10, except fresh color is very light gray (N8), and the weathered colors are grayish yellow green (5GY 7/2) and dark yellowish orange (10YR 6/6) 5.7
13. Covered slope grading into alluvium, laterally mudstone, like unit 11; 37.3 feet below the top are darker bands and bouldery cover; at 32.7 feet above base and continuing up the colors change to grayish purple (5P 4/2) and light gray (N7); color bands are 2 to 10 feet thick 139.3
14. Alluvium; covers contact between the Brushy Basin Member and the Salt Wash Member 16.4

Total Brushy Basin Member 332.5

Salt Wash Member:

15. Sandstone, pinkish gray (5YR 8/1), very fine to fine grained (vfL-fL), subangular to subrounded, well-sorted equant grains; black accessory grains; calcite cement, well cemented; cross stratified with horizontal laminations; weathers pale red (5R 6/2), stained moderate orange pink (10R 7/4) and manganese oxide staining; weathers to rough surfaces, step forming, poorly exposed; lenticular, thickens to 12 feet laterally 1.0
16. Boulder-covered slope, probably underlain with mudstone, moderate red (5R 5/4) and very pale green (10G 8/2); calcareous, poorly cemented; fissile to medium bedded; horizontal laminations; weathers same color as fresh, earthy slope former, contains some thin sandstone lenses such as unit 15; poorly exposed, lower contact covered 28.3
17. Sandstone, like unit 15 . . . . 4.5
18. Covered slope 7.2
19. Sandstone, grayish orange pink (5YR 7/2), very fine grained (vfL-vfU), subangular to subrounded, well-sorted equant grains; black accessory grains; calcareous, moderately cemented, horizonal laminations; weathers yellowish gray (5Y 8/1), stained moderate orange pink (10R 7/4), forms rough surface and steps, poorly exposed 1.9
20. Covered slope 3.4
21. Sandstone, white (N9), fine to medium grained (fU-mL), subrounded, moderately sorted equant grains; calcareous and well cemented; platy to massive; worm burrows abundant at top of unit, mud clasts at base, laminated, low-angle crossbed sets, calcite vein fillings; weathers grayish orange pink (5YR 7/2), manganese oxide staining; forms a blocky ledge, basal contact is sharp and concave 9.2
22. Covered slope, mudstone underneath, light red (5R 6/6), 6 feet below top color changes to very light gray (N8) 13.8
23. Sandstone, like unit 21, except grain size is very fine (vfL-vfU) and there are fewer limonitic grains; forms a low step, light red staining, no cross stratification is evident 0.9
24. Covered slope, like unit 22, light red (5R 6/6) 3.7
25. Sandstone, like unit 21; in top 11 feet grains are fine to medium (fL-mL); limonitic grains exceed 7 percent, graded cross stratification; in lower 2.7 feet grains are fine (fL to fU) and limonitic grains make up 7 percent of the rock 13.7
26. Interbedded sandstone and mudstone: sandstone, yellowish gray (5Y 8/1), very fine grained (vfL), subrounded to rounded, well-sorted, equant grains; accessory fine (fU) black grains; calcareous, poorly cemented; thin to medium bedded; weathers grayish orange pink (5YR 7/2), weathers to rough surfaces and is recess forming; there is an upper sandstone lens that weathers pale yellowish orange (10YR 8/6): mudstone is moderate red (5R 5/4) and grayish yellow green (5GY 7/2); calcareous, poorly cemented; fissile to very thin bedded; weathers same color as fresh, forms an earthy recess with the sandstone . . 0.7
27. Boulder-covered slope, sandstone talus boulders exhibit abundant vertical burrows 12.7
28. Limestone, light olive gray (5Y 5/2), aphanitic, minor dark green lithic fragments; moderately indurated; thin bedded; weathers yellowish gray (5Y 8/1), stained light brown (5YR 5/6), weathers smooth, resistant slope former, poorly exposed 11.6
29. Sandstone, yellowish gray (5Y 8/1), very fine to fine grained (vfU-fU), subangular to subrounded, moderately sorted equant grains; large orange accessory grains; calcareous, moderately indurated; thin to medium bedded; weathers dark yellowish brown (10YR 4/2), forms a rough surface, forms a step or slope 2.7
30. Limestone, dusky yellow green (5GY 5/2), aphanitic, well indurated; medium bedded; secondary calcite present in veins and

vugs; weathers pale yellowish brown (10YR 6/2) and moderate yellowish brown (10YR 5/4); weathers to pitted surfaces, slope former with slight steps or ledges; poorly exposed 16.6

Total Salt Wash Member 131.9

Tidwell Member:

31. Sandy siltstone, grayish red (10R 4/2), calcareous, well cemented, thin to medium bedded, bands of secondary calcite; weathers same color as fresh, forms a rough surface, step-like and well exposed; higher exposures contain no sand or calcite 18.4
32. Limestone, grayish green (10GY 5/2), aphanitic, well indurated; platy to thin bedded, calcite vein fillings; weathers very light gray (N8) and light brown (5YR 5/6), smooth and pitted surfaces, forms a more resistant slope, poorly exposed with a sharp lower contact 0.9
33. Sandy siltstone, like unit 31, except fresh color is pale red (10R 6/2) and the sandy and secondary calcite bands are present throughout the whole unit 1.8
34. Covered slope, dark reddish brown 4.0
35. Sandstone, very pale orange (10YR 8/2), very fine to fine grained (vfL-fL), subrounded to rounded, well-sorted equant grains; less than 1 percent black accessory grains; calcareous, well indurated; medium bedded; ripple marked on bedding surfaces, weathers same color as fresh; stained pale red (10R 6/2), forms blocky surface, step-like, locally well exposed, but commonly buried 7.4
36. Interbedded silty sandstone and mudstone: silty sandstone, very pale green (10G 8/2) with grayish red (10R 4/2); very fine to fine grained (vfL-fU), subrounded, poor to moderately sorted dark laminae, weathers same color as fresh, forms rough surface with a tendency to spheroidal weathering, recess and slope-forming, locally well exposed; mudstone, dark reddish brown (10R 3/4) and very pale green (10G 8/2); poorly cemented and calcareous; fissile to thin bedded, laminated thinly, weathers same color as fresh; not stained, forms earthy recesses 2.7
37. Sandstone, like unit 35 .... 1.8
38. Interbedded silty sandstone and mudstone, like unit 36, except silty sandstone is grayish red (10R 4/2) with splotches and bands of very pale green (10G 8/2) and mudstone is dark reddish brown (10R 3/4) 11.6

Total Tidwell Member 48.6
Total Morrison Formation 513.0

Entrada Sandstone—*Sandstone, very light gray (N8), fine grained (fU), rounded, well sorted equant grains; contains sporadic black accessory grains; silica cement, well cemented; massive, weathers same as fresh color, forms smooth rounded cliff or prominent bench; there is a thin cap on the Entrada, about 8 inches thick, of sandstone, grayish orange (10YR 7/4), medium grained (mL), subrounded, well-sorted, equant grains; contains sporadic black accessory grains; mostly calcareous cement, some ferruginous, moderately cemented; medium bedded, contains some parallel lineations of ironstone; weathers same color as fresh, forms rough step, contact with Tidwell Member above is sharp.*

CRETACEOUS ROCKS

Five Cretaceous units are recognizable in the Arches National Park area. The lower two, the Cedar Mountain Formation and Dakota Sandstone are continental deposits; the upper three, all members of the Mancos Shale, are marine. They represent at least 1000 feet of sediment, perhaps as much as 1800 feet, and are best exposed at the north end of the Map 74 area. The Cedar Mountain Formation is considered Early Cretaceous in age and correlates with the Burro Canyon Formation southeast of the Colorado River (Stokes, 1952). It has recently been suggested that the upper part of the Morrison Formation may also be Lower Cretaceous in age based on fission track dating (Kowallis and Heaton, 1988 in press), but pending further studies I have left the entire Morrison Formation with a Jurassic age assignment.

Cedar Mountain Formation

This formation is similar in description to that of the Brushy Basin Member of the Morrison Formation (figure 25). The lowermost part is generally cliff-forming sandstone, gritstone, conglomerate, limestone, or a combination of them. These lenticular beds vary considerably in thickness and fill channels scoured into the Brushy Basin Member. The limestones usually contain abundant jasperized chert and form a litter on the Brushy Basin slope below. In a few places this cliff-forming lower unit is missing and it is difficult to identify the contact. Above the cliff-forming unit is a slope of silty or shaly mudstone. This slope is sporadically interrupted by thin ledges of sandstone, quartzite, or nodular-weathering brown muddy limestone. The mudstones are variegated and bentonitic like those of the Brushy Basin Member, but the colors are more subdued. In areas where the Brushy Basin is a bright green overall, the shales or mudstones of the Cedar Mountain are light green. Where the Brushy Basin is dominated by maroon coloration, the Cedar Mountain is a light lavender, probably indicating a common source.

Along the north flank of the Salt Valley anticline and north of the Yellow Cat area the overlying Dakota Sandstone fills scours in the slope-forming unit of the Cedar Mountain. On the west flank of the anticline a third Cedar Mountain unit overlies this slope, a ledge of sandstone or gray quartzite commonly exceeding 20 feet in thickness and sometimes overlain by another slope-forming mudstone. On the west flank this second slope former is overlain by shaly rocks of the Dakota Formation.

Thickness of the Cedar Mountain Formation varies from 100 to 250 feet but is usually 100 to 150 feet thick at surface sections. Fossils are rare, but occasional ostracodes, protistids, and snails can be found. White petrified wood, especially in the lower cliff former, is locally relatively abundant.

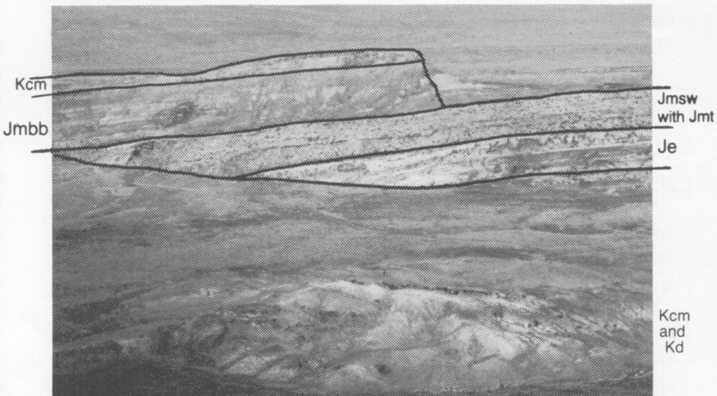


Figure 26. Upper Jurrasic and Lower Cretaceous strata on the northeast flank at the northwest end of Salt Valley anticline. The hill in the foreground exposed Cedar Mountain Formation (Kcm) and Dakota Sandstone (Kd). Weak ridges between this hill and the northeast flank indicate that the Mancos Shale is shallowly buried under the valley alluvium.

Dakota Sandstone

The Dakota Sandstone, in the northern part of the area, is mostly yellow-gray to brown sandstone, conglomeratic sandstone, and conglomerate. The conglomerates, mostly cobble and pebble size, are interlensed with the sandstones of medium to coarse grain, sometimes gritty, and yellow-gray color. Most of the cobbles are of quartzite, but black chert is locally common. The unit forms a hard capping ledge on top of the Cedar Mountain Formation and usually caps the last hogback or cuesta below the Mancos Shale (figure 27). The Mancos Shale is usually eroded from the top of the formation on the hogbacks down to valley level. Other than occasional plant fossils, there is little to identify its age. Stokes (1952, p. 21) notes that a silicified *Tempskya* trunk was found in place in the lower stratum of the Dakota in Sec. 28, T 22 S, R 22 E.

Figure 27. The Dakota Sandstone, center and right, overlies the shale and gray quartzite and "metaconglomerate" of the Cedar Mountain Formation, left, on the north flank of the Salt Valley anticline. The Cedar Mountain Formation differs from the Brushy Basin Member of the Morrison Formation (which it resembles) in having shales with paler hues and containing several ledge-forming quartzites or conglomerates. The Dakota Sandstone contains yellow-gray sandstone, gray shales, some coaly beds, and a caprock of conglomerate. A complete suite of these lithologies is not always present and the unit is discontinuous on the southwest flank of the anticline.

To the west and along the southwest flank of Salt Valley the Dakota is less continuous and changes character. Soft gray mudstone, carbonaceous shale, and white limy marl appear under the sandstone and conglomeratic sandstone. These rest on the Cedar Mountain Formation so that the line dividing the two units becomes difficult to recognize; therefore the two units were mapped as one on Map 74. McKnight (1940, p. 111-112) noted that east of U.S. Highway 191 there are two sandstone ledges separated by 27 feet of shale. He also noted that the general thinness and discontinuity of the sandstone, the intermediate Mancos-like shale unit, and the presence of *Halymenites* favor a marine origin for the unit. Nevertheless, the lenticular conglomerates and sandstones, fossil wood and sporadic fossil leaves all indicate a fluvial depositional environment. The intertonguing of marine and continental units is the explanation. The Dakota was continentally deposited on a broad coastal plain in front of an advancing Mancos Sea which inundated the area thereafter.

In the northwest end of Salt Valley the Dakota Sandstone has collapsed because of salt dissolution. Exposures of Dakota are mostly cobble conglomerate. In Cache Valley and the eastern end of Salt Valley it consists mostly of yellow-gray sandstone, but conglomerate, gritstone, and even some gray and carbonaceous shale are to be found. The known thickness ranges from 0 to 110 feet. Places where the Dakota is missing or where it is thick are rare and questionable (due to the difficulty of locating precise and consistent upper and lower boundaries). In the Salt Valley area thickness ranges from 20 to 80 feet with no apparent change of thickness that can be ascribed to salt movement. Thicknesses in the crests of the salt anticlines are comparably variable as they are elsewhere.

Mancos Shale

The Mancos Shale is the youngest consolidated unit in the area of Map 74. The formation crops out west of U.S. Highway 191 and along the north map margin. The unit also crops out at the northwest and southeast end of Salt Valley and in Cache Valley in collapsed blocks. Three members exposed are the lower and upper shale members and a middle Ferron Sandstone Member.

Lower shale member The lower shale member is a shaly, fissile unit, commonly silty or sandy along certain horizons; the silt or sand lightens the otherwise somber gray outcrops. Locally, these platy-weathering, marine, fine-grained silty sandstone ledges interrupt the monotonous gray outcrops. There is little difference between the lower shale member and the upper shale member, except that the lower has a greater carbonaceous content, making it darker. The color has been described as slate-gray, lead-gray, and steel-gray. It is a soft unit and forms lowlands upon which little vegetation grows. The lower shale member is 300 to 500 feet thick, averaging 400 feet. It lies conformably on the Dakota Sandstone and grades into the overlying Ferron Sandstone Member. Megafossils are rare in this lower shale member.

Ferron Sandstone Member This member forms a double cuesta and a long dip slope on the upper cuesta (figure 28). The two resistant units upon which the cuestas are developed are similar in description. The lower shale member becomes sandy toward the top and the contact is placed where the color changes to tan or light brown and the outcrop shows platy or thin-bedded brown-gray, very fine-grained sandstone as the principal lithology. This lower unit forms the first cuesta with its shorter dip slope littered with platy and chippy fragments of calcareous sandstone. These sandstones are sporadically fossiliferous, but are not as fossiliferous as those of the upper cuesta. The lower unit of the Ferron Sandstone averages 35 feet thickness

The middle of the Ferron Sandstone Member forms slopes and a strike valley and consists of about 25 feet of gray shale, carbonaceous shale, and some coaly material. Its slope appears banded, the darker horizons indicating a greater carbon content. The upper sandstone unit is like the lower and is 35 to 45 feet thick. It grades upward into the upper shale member which is usually stripped from the dip slope of the upper Ferron sandstone to valley level. Abundant fossils occur in the upper sandstone, especially as fragments, with oysters, gastropods, cephalopods, and shark teeth. Molenaar (1975, p. 191) reported collecting *Prionocyclus macombi, Inoceramus dimidius, Baculites* sp. and *Scaphites* sp. from the part near the Moab airport and *Prionocyclus wyomingensis, Inoceramus dimidius, Baculites* sp., and *Scaphites* sp. from the upper resistant cuesta-former near Woodside, 40 miles to the northwest of the area of Map 74. He correlated these beds to the Juana Lopez Member of the Mancos Shale of the San Juan Basin and indicated that they are equivalent. He also indicated that the depositional environment during Juana Lopez time is one of a widespread, shallow, shoaling sea at a time of little clastic influx. The entire Ferron Sandstone Member varies from 60 to 120 feet thick in the Salt Valley area and averages 90 to 100 feet.

Figure 28. Aerial view of the Ferron Sandstone on the north flank of the Salt Valley anticline. It forms a double cuesta rising above the Mancos Lowland.

Upper shale member This unit is similar to the lower shale member, but usually exhibits a lighter or more tan color in outcrop (figure 29). Like in the lower member, there are scattered sandy layers which are more tan and slightly more resistant than the encasing gray marine shale. They often form slight ridges. One such ridge is exposed in the northwest end of Salt Valley, where it is folded around an oval, doubly plunging anticline 1 ½ miles long and a half mile wide. The sandy beds are similar to those in the Ferron Member, but the double cuesta, intermediate carbonaceous shales and abundant fossil fragments are missing. The top of the upper shale is not exposed in the map area but is found north of Interstate Highway 70 in the Book Cliffs. McKnight (1940, p. 113) has estimated the presence of 3450 to 4120 feet of Mancos Shale. The total of the three members exposed (upper shale member incomplete) in the area of Map 74 may be 1800 feet.

Figure 29. Badlands of weathering and eroding Mancos Shale accentuated by snow north of Salt Valley anticline. The Mancos Shale is the youngest bedrock formation of the area.

The same amount of Mancos Shale has been preserved in the collapsed blocks in the northwest and east ends of Salt Valley and in Cache Valley (figure 30). All three members are recognizable and of normal thickness. The lower shale member is 371 feet thick in Sec. 8, T 24 S, R 22 E in Cache Valley, and the Ferron Sandstone is 90 feet thick in the same location. The Mancos members are the youngest consolidated units preserved in the crest of the salt structures of the Paradox Basin. In the Uinta Basin to the north (Book Cliffs area), additional Cretaceous and Tertiary units are known to have been deposited,but some may have pinched out southward against a high area.

Figure 30. Collapsed Mancos Shale along Salt Wash near Delicate Arch. The Mancos is the youngest bedrock unit preserved in the Salt Valley anticline and in Cache Valley.

QUATERNARY ROCKS

Unconsolidated rocks found in the Salt Valley-Arches National Park area have been divided into eight units. Parts of some units mapped as Quaternary may be latest Tertiary in age. Quaternary units are divisible into three groups based on origin: alluvial, eolian, and gravity. All units are gradational with each other. Maximum thickness of these materials rarely exceeds 100 feet at any location; at most places they are quite thin (less than 30 feet). The thickest accumulations undoubtedly occur in Salt Valley and Moab Valley where they rest on salt caprock. By far, the most abundant constituent in all the Quaternary units is sand derived from the bedrock in the area.

Figure 31. Thick alluvium, mostly sand, fills valleys and is found along the more active stream and wash courses. This view is of Salt Wash valley north of Salt Valley and Cache Valley.

Alluvium

Alluvium is sediment deposited by rivers, streams, and washes and includes particles of all sizes; clay, silt, sand, gravel, and large boulders (figure 31). Alluvium was mapped in two categories: Qa_1 and Qa_2. Qa_1 is found along the more active drainages and shows little mixing with sediments of eolian, lacustrine, and gravity origin. The alluvium along the Colorado River is of this type. The Colorado River, being a through-going stream, has introduced much sediment from outside the area, including many granitic and metamorphic cobbles and pebbles from the Uncompahgre Plateau. Along streams draining the Mancos lowland physiographic section (Salt Wash, Courthouse Wash, Thompson Wash), some of the alluvium is gray and dominated by mud, similar in appearance to the Mancos Shale. Alluvium along streams which drain the Mesozoic sandstone units (Sevenmile Wash, lower Salt Wash, etc.) is principally sandy. In other areas the washes (Salt Valley Wash) derive and rework sediment from older alluvium and reflect the composition and textures of the older unit.

Qa_2 differs from Qa_1 through two criteria and includes two categories of alluvial materials. The first criterion is based on the degree of mixing with other sediments. Many minor drainages in the area carry water only when local summer storms are of torrential proportions. Between storms several years may pass so that a considerable but subordinate percentage of eolian and other materials may interfinger or admix with the alluvial materials. The involved sediments usually lack the coarser cobbles and boulders and are dominated by sand. The deposits, generally thin, form veneers over any consolidated sediments but favor certain formations or horizons. A belt of Qa_2 of this type has developed along the Salt Wash-Brushy Basin contact in the Morrison Formation on both sides of the Salt Valley anticline.

The second type of Qa_2 is obviously older than that being deposited along the more active drainages (Qa_1) or along the more intermittent washes. Again, as in the intermittent drainage alluvium, there is considerable mixing with sediments of other than fluvial origin. Many of these deposits are being actively eroded and marked by deep gullying (Salt Valley Wash) or they stand vertically as a terrace above the more recent alluvium of the active stream (Salt Wash). Still others have developed a thick soil profile or layer of caliche at the top of the deposit. These are generally thicker alluvial deposits and are thickest in Salt Valley and Moab Valley (figure 32). In Salt Valley, gypsum from caprock has been eroded and locally incorporated into the alluvium as a prominent layer. The best exposures of older alluvium are located at the southeast end of Salt Valley where the Arches National Park roadway crosses the valley. The section essentially consists of sand alternating with consolidated or nearly consolidated white calcareous sandy horizons with a thick pebble to cobble gravel at the base. Two volcanic ashes have been found in the section, the Bishop and the Lava Creek B (Oviatt, this publication). The former was not found or identified in the following measured section but occurred less than 100 yards away. The Bishop Ash has been dated as having been deposited 740,000 years ago, whereas the Lava Creek B ash was deposited about 620,000 years ago (Colman and others, 1986, and Oviatt, this publication).

Figure 32. Older alluvium (Qa_2) exposed in Salt Valley. A similar alluvium underlies younger alluvium (Qa_1) in Moab Valley.

Incomplete section of Qa_2 alluvium in the east end of Salt Valley, SW Sec. 7, T 24 S, R 22 E and SE Sec. 12, T 24 S, R 21 E. Section starts at the top of the exposure with no overlying beds.

	Qa_2 Alluvium:	feet
1.	Sandstone, white, fine to coarse grained, calcareous and mostly consolidated, weathers irregularly	8.5
2.	Sand, moderate reddish brown, fine grained	0.9
3.	Sandstone, white, fine to coarse grained, calcareous and mostly consolidated, weathers irregularly	0.4
4.	Sand, moderate reddish brown, fine grained	4.6
5.	Sand, grayish pink (5R 8/2), fine grained, calcareous and nearly consolidated, contains root and rootlet impressions and molds	0.4
6.	Sand, moderate reddish brown, fine grained	1.9
7.	Lava Creek B ash bed, sandy and crossbedded in part	0.5
8.	Marl, sandy	0.5
9.	Sand, moderate reddish brown, fine grained	4.7
10.	Sandstone, white, calcareous, like units 1 and 3	1.2
11.	Sand, moderate reddish brown, fine grained	1.8
12.	Sand, white, calcareous	1.3
13.	Sand, moderate reddish brown, fine grained	3.3
14.	Sand, nearly white, contains small pebbles and grit, somewhat cemented calcareously, weathers nodular and hackly, makes hard layer, has calcified root tubes and animal burrows	0.7
15.	Sand, moderate reddish brown, fine grained, clayey in places	14.1
16.	Sandstone, nearly white, calcareous, with clay clasts and carbonate nodules	0.5
17.	Clay, moderate reddish brown (10R 4/6), sandy	3.0
18.	Sand, streaky bright orange or limonitic, mostly fine grained, fairly well sorted, argillaceous and slightly calcareous, indistinct bedding, contains sporadic coarse clasts	12.5
19.	Clay, moderate brown (5YR 3/4) and light olive gray (5Y 5/2), sandy, indeterminate bedding, contains thin lenses of limonitic sandstone	2.5
	(Section moved laterally at this point to describe a better exposed section of the basal gravel about 100 feet to the south.)	
20.	Sand or sandstone, gritty and pebbly with sporadic cobbles	8.0
21.	Gravel or conglomerate, grit to cobbles, mostly sandstone cobbles, but much chert, some clay clasts, cobbles angular to subrounded, better sorted than in unit below	3.5
22.	Gravel or conglomerate, pebbles to boulders in sand matrix, angular to subrounded, mostly sandstone clasts, some rounded black chert, identifiable clasts indicate Glen Canyon Group sandstones and Morrison and Cedar Mountain derivatives, largest clasts are Glen Canyon sandstones; unit overlies the Chinle Formation with angular unconformity and overlies the Paradox Formation 100 yards distant	4.5
	Total alluvium	79.3
	Angular unconformity	

Dyer (1983, p. 19) described this alluvium as Tertiary(?) giving it the name, "Formation of Salt Valley." He noted that the basal conglomerate or gravel unconformably overlies the Pennsylvanian Hermosa Group, the Triassic Chinle Formation and the Cretaceous Mancos Shale. In addition to the clasts identified in the measured section he found clasts of silicified limestone containing a fresh-water gastropod fauna identified by J. H. Hanley of the U.S. Geological Survey to be of Eocene age. Dyer indicates that such fossils are available only from high in the Book Cliffs and had to be transported to the site by an ancestral drainage. The transformation to the present drainage systems and gradients would be expected to have taken considerable time and for this reason Dyer gave it the Tertiary(?) designation. The presence of the fossils in the gravel was reaffirmed by Oviatt (this publication), but he also discovered the Quaternary Bishop and Lava Creek ashes in the sandy layers that conformably overlie it. Similar Quaternary deposits containing these ashes have been reported by Colman (1983) in Fisher Valley and so a Quaternary age is favored for the whole deposit.

Gravel Deposits

Gravel deposits of alluvial origin (Qag) are scattered around Arches National Park area. Larger areas were separately indicated on Map 74, including larger patches associated with the Qa_1 and Qa_2 deposits. Included are the larger areas of gravel associated with the thicker older alluvium to which Dyer (1983, p. 13) attributed a possible Tertiary age. These include most of the gravel patches found in Salt Valley. Another area in which such gravels are found are those collected at the foot of the Dakota dip slopes. The deposits vary considerably in grain and in the degree of sorting and clast roundness.

Terrace Gravel Deposits

Gravels of exotic origin forming many levels of terraces (Qat) are found along the major through-going streams and have been differentiated from the gravel deposits described above (figure 33). These are mostly confined to locations adjacent to the Colorado River and Mill Creek. The poorly sorted, crudely stratified pebbles, cobbles, and boulders are mostly derived from outside the mapped area and include igneous and metamorphic clasts, with sources on the Uncompahgre Plateau and La Sal Mountains. The gravels are locally auriferous and contain flour, flakes, and small nuggets of free gold along with much magnetite and titaniferous sand.

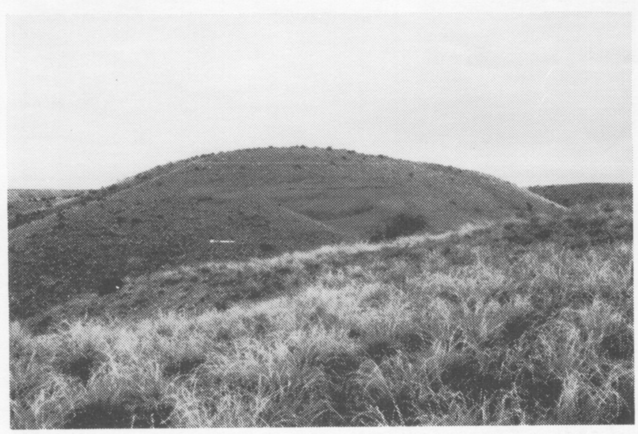


Figure 33. Gravelly alluvium is sparsely scattered in the Arches National Park area. Terrace gravels, containing exotic pebbles and cobbles, are found along the larger active stream courses.

Sand Deposits

Accumulations of eolian sand have developed over considerable areas in Arches National Park with the many consolidated sandstone deposits in the area as a source. Most of the deposits are of eolian origin but have been modified to some extent by alluvial processes, hence the Qeas designation. Thin accumulations of alluvially derived sandstone and pebble gravels are interbedded with these units in some places. Some sandstone units are especially favorable to the formation of sand deposits. One of these is the Slickrock Member of the Entrada Formation. Even though the fields of sand are irregular in shape, they form a crude belt along the Slickrock outcrop wherever it does not form a cliff. To a lesser extent, fields of sand are also developed on the Navajo Sandstone outcrops and on the downdip side of the Salt Wash Member of the Morrison Formation.

Eolian Sand Deposits

Larger dune or sheet accumulations of sand (Qes) which are strictly of eolian origin are locally present. The dunes and sheets are generally aligned along the direction of the prevailing wind, northeast-southwest. They accumulate mostly on the northeast-facing slopes of escarpments (figure 34). Origin of the sand is the same as for the Qeas deposits, the local sandstone bedrock. Such sand commonly fills narrow canyons and interfin areas. Accumulation of eolian sand are found opposite the Arches National Park Visitor Center, across U.S. Highway 191 and along Winter Cabin Wash northeast of Delicate Arch. Many sand sheets cover the older alluvium in Salt Valley from Sec. 6 to Sec. 13, T 24 S, R 21 E.

Figure 34. Eolian sand deposits are common in the Arches National Park area, the sand derived from the many sandstone formations exposed. Many sand deposits blow over cliffs and fall on the lee side (northeast-facing slopes). View is to the southwest of the Arches National Park Visitor Center.

Landslide Deposits

Landslide deposits (Qms) are not common in the Arches National Park area. Here they are mostly coherent to partly broken masses of consolidated units that have moved downslope a considerable distance without having disintegrated into scattered unrecognizable debris. The movement is along a plane of slippage, usually in the clayey units of the participating consolidated formations along oversteepened cliffs and slopes. Practically all the landslides involve the members of the Morrison Formation, Cedar Mountain Formation and the Dakota Sandstone. Slippage is enhanced in saturated units and the paucity of slides reflects the dry climate.

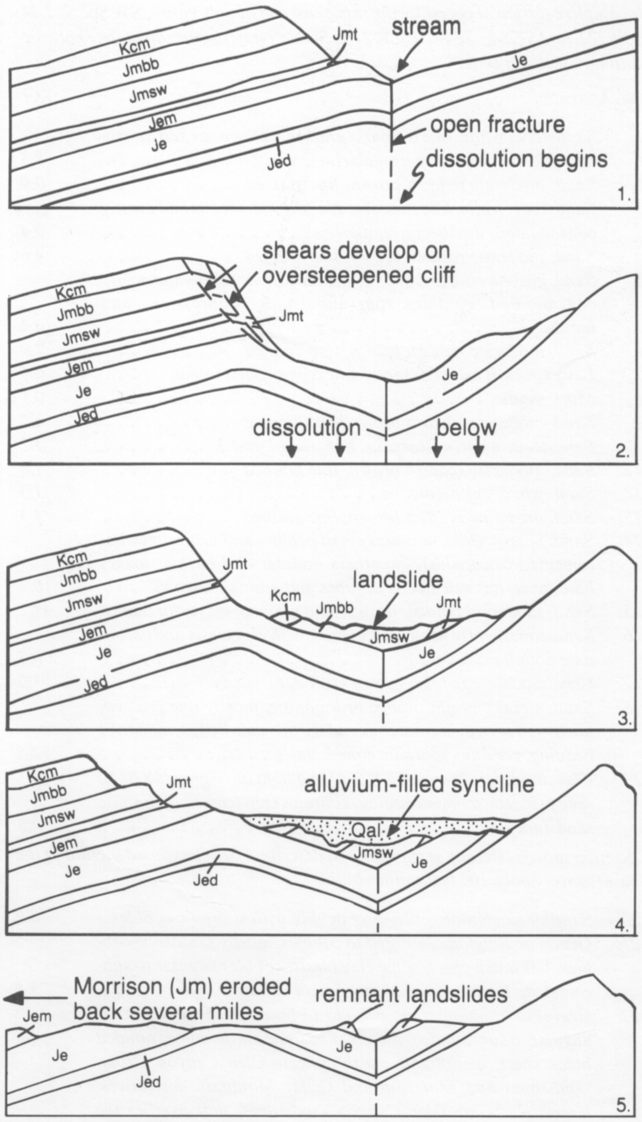


Figure 35. Development of the Elephant Butte folds landslides. The preservation of these ancient landslides is explained in the text.

Unusual landslide deposits (figure 35) are found in a belt on the southwest flank of Salt Valley anticline, extending from Sec. 6 to Sec. 13, in T 24 S, R 21 E, in the syncline of the Elephant Butte folds. Landslides are generally short-lived in geologic time and are relatively quickly removed by erosion. The nearest outcrops of the parent material are located 1-6 miles to the west; the source of the debris having retreated erosionally that distance. Other possible sources include collapsed outcrops now occurring at lower altitudes than those of the landslides. In all exposures where more than one formation or member can be identified, the older unit is on the northeast end whereas the younger unit is on the southwest end (diagram 4, figure 35). This is especially evident in the larger slides, especially those in Secs. 13 and 14, T 24 S, R 21 E. The most abundant material found in the landslides was derived from the Salt Wash Member of the Morrison Formation. These slides were formed during a wetter climatic period, perhaps during the Pleistocene, and were subsequently buried

Figure 36. View of old landslide preserved in an area of collapsed rocks. These slides stand as mounds, being more resistant than the surounding alluvium, and in many cases, are more resistant than the bedrock upon which they rest.

by sandy alluvium. The oversteepening of the contributing cliff was probably aggravated by simultaneous downwarping of the syncline due to salt dissolution, a process also thought more active during the wet climate. Downwarping changed the base level and the syncline was filled with alluvial sand. More recently, long after the parent cliffs had been eroded far back from their former positions, the alluvium began to be eroded and the landslides were exhumed. These landslides now stand as mounds, being more resistant than the surrounding alluvium and, in some cases, more resistant than the bedrock units upon which they rest. The units are mostly the Slickrock and Dewey Bridge Members of the Entrada Sandstone and the Navajo Sandstone (figure 36). Dyer (1983, p. 27) hypothesized that the rubble or blocks moved slowly down the anticlinal flank and accumulated near the line at which the limb dip abruptly shallowed. He felt that these were not catastrophic landslide types.

One large landslide block, not involved in the Elephant Butte Folds syncline, is of interest. It is located in NE Sec. 19, T 25 S, R 21 E, along the Moab fault, where an almost coherent block of Salt Wash Member has slipped over an exposure of the Permian Cutler Formation. The contact, as from the southeast, appears as if the Salt Wash rests on the Cutler formation in angular unconformity (figure 37).

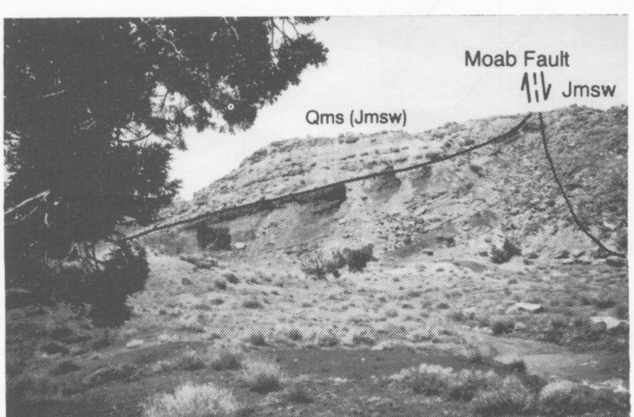


Figure 37. Landslide on the southwest flank of the Moab anticline. A prism of Salt Wash Member of the Morrison Formation (Qms[Jmsw]) has slipped over a Permian Cutler Formation (Pc) slope, overriding the trace of the Moab fault.

Talus Deposits

These deposits (Qmt) consist of rockfall blocks, boulders, and smaller angular fragments which have fallen by gravity from the cliffy units above. They collect on slopes immediately below their parent outcrop and are therefore nearly always restricted to the Escarpments and Canyonlands physiographic subdivision. Most commonly they are mappable (where large enough and where they mask the underlying units) beneath the Wingate Sandstone cliffs, resting on the Chinle and Moenkopi Formations.

Man-Made Fill

The only area mapped as man-made fill on Map 74 is the tailings pond of Atlas Minerals Co., located at the north end of Moab Valley. Smaller areas along the railroad or highways were not considered large enough to map

STRUCTURAL GEOLOGY

Structures of the Arches National Park area were formed by regional tectonic and salt-induced events. Regional tectonism created the basin to receive the original salt deposition and subsequent regional tectonic activities were influenced by the presence of the salt. It is difficult to separate structures not influenced by salt from those that have been affected by it.

Arches National Park is located in the Paradox fold and fault belt of the Paradox Basin (figure 1). The dominant structural features are the diapiric salt anticlines, two of which are exposed in the Map 74 area: Salt Valley and Moab Valley. The surface expression of these includes a valley up to 2 ½ miles wide, which follows the trend of the anticline, bordered by cliffs or escarpments with relief of as much as 1000 feet or more but averaging 200 to 500 feet.

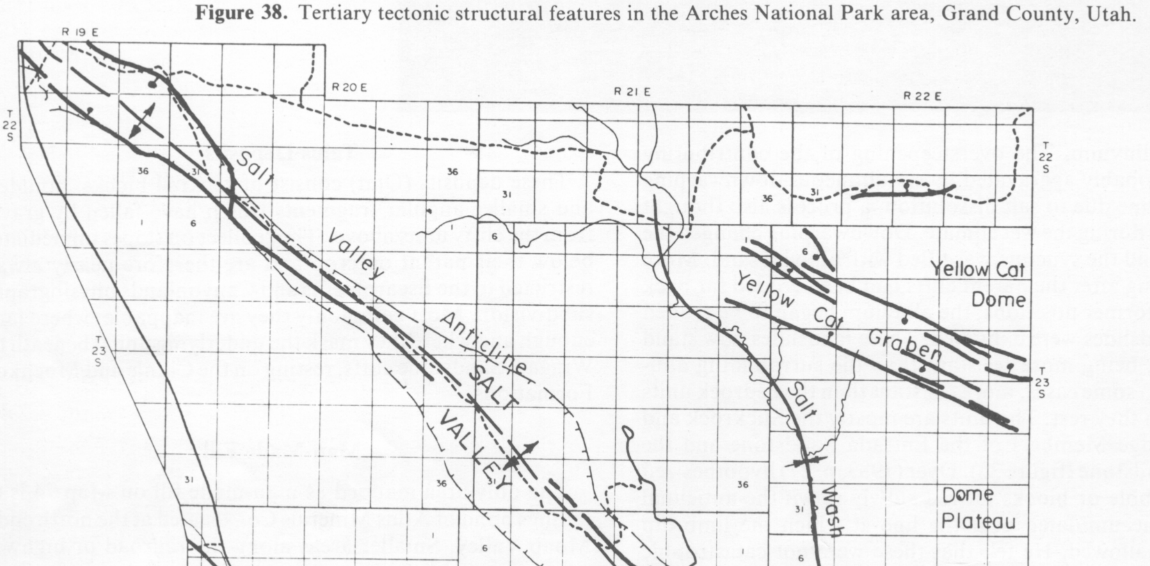
Many closely spaced faults parallel these diapiric salt anticlinal structures. The rocks are tilted from gentle to vertical angles and strike mostly parallel to the major structures. Most of these faults are of small displacements, but a few, such as the Moab fault, are of relatively large displacement (as much as 2600 feet). Between the diapiric salt anticlines the structure is relatively simple; the rocks are gently warped into synclines and are in some places cut by short faults of small displacement.

REGIONAL TECTONIC FEATURES

Faults

The most important faults in the region are the series of northwest-trending faults or flexures that lowered surfaces to form the Paradox Basin (Szabo and Wengerd, 1975). These are presently buried by post-Pennsylvanian sedimentary rocks. They were intermittently active from Mississippian to Triassic time and were probably reactivated in Tertiary time. In addition, northeast-trending lineaments were simultaneously developed across the region related to basement wrench faulting (Hite, 1975). Most of the northwest-trending sub-salt faults have their downthrown blocks to the northeast (at least those with greater displacements), so that the deeper part of the Paradox Basin is on the northeast side. Seismic data indicate that they die out upward in the Paradox salt beds. Most investigators show these faults as high-angle normal faults. The northeasternmost fault (Uncompahgre fault) has opposite and much greater displacement than the others. Drill-hole investigations of the Uncompahgre fault show it to be a high-angle reverse fault with many branches (White and

Figure 38. Tertiary tectonic structural features in the Arches National Park area, Grand County, Utah.



Jacobson, 1983). Subsurface fault movements probably provided the energy to move, thicken, and localize the salt in the rising anticlinal structures during Pennsylvanian to Triassic time.

During Tertiary time lengthy faults of relatively large displacements were formed. McKnight (1940) thought that this faulting was the result of tensional stress that developed after regional compressional stress had gently folded the rocks. The tensional stress was the result of a relaxation at the end of a compressional tectonic phase and was undoubtedly relieved along the old buried "basement" faults. The tectonic fault ruptures were influenced by the salt; some rupturing proceeded directly through the thick salt bodies and other fractures were deflected to the margins. These Tertiary faults can be differentiated from the salt tectonic or dissolution faults by their greater displacement. Faulting induced solely by salt is principally due to collapse of strata above areas where the salt has been dissolved away. Larger faults and folds thought to have formed by tectonism during Tertiary time are shown on figure 38. Tectonically induced stress that developed in the strata above the salt was relieved by faulting which mostly developed along the flanks of the thick salt accumulations (where the rocks would be weaker). These faults are presently intercalated with others created by salt dissolution.

The most prominent of the Tertiary tectonic faults, as shown on Map 74, is the Moab fault. It extends N 40-50° W from the Colorado River (southwest side of Moab Valley) for about 29 miles, forming several curving branches to the northwest (figure 39). Dipping from 50 to 75 degrees to the northeast, it reaches a maximum displacement of about 2600 feet between the Arches National Park Visitor Center and Sevenmile Canyon.

Figure 39. Branch of the Moab fault located just west of the area of Map 74. The Entrada Sandstone (left) abuts against the Brushy Basin Member of the Morrison Formation and the Cedar Mountain Formation (right).

Similar faults occur along the escarpment margins of the Salt Valley anticline. Escarpment faults along both margins of Salt Valley at its northwest end place Mancos Shale or Upper Jurassic units against the Navajo Sandstone. From Sec. 5, T 23 S, R 20 E southeastward, only one prominent fault is present. On the north end it is found along the southeast side of the valley, but as the valley widens southeastward opposite Klondike Bluffs, it migrates to the center of the valley where it is buried under the alluvium. It reappears in Sec. 33, on the northeast side. This fault dies out where the Salt Valley trend turns to become east-west. At that point a new fault appears on the south side, crosses Salt Wash, and extends along more than half the length of Cache Valley. Then it also dies out and another fault, favoring the north side, appears and extends almost to the Colorado River. These faults place Mancos Shale against Chinle Formation or against gypsiferous Paradox Formation. The true displacement is complicated by the positions of collapsing units in the valley floor. Cross sections indicate that the maximum displacement along the Salt Valley Tertiary tectonic faults may be as high as 1000 feet.

Most of the faults in the synclines between the salt anticlines are short in length and have small normal displacements. In most cases it is impossible to ascertain if they are adjustments over salt or if they were formed during McKnight's (1940) Tertiary tensional episode. The shallow, complex, Yellow Cat graben in the northwest corner of the map area consists of a set of normal faults trending N 65 to 75° W. In association with the principal graben-forming faults, others have dropped the intervening strata so that two relatively deeper grabens are found on each side. The block between the two deeper grabens is horst-like but down-dropped with respect to the boundary faults. The displacements of the Yellow Cat graben faults do not appear to exceed a maximum of 80 feet.

Displacements reach only a few tens of feet in a swarm of normal faults which occur in the Big Bend area in the southeastern part of Map 74. They are 1 to 5 miles in length and trend N 35 to 70° W. Because they cluster around the Big Bend of the Colorado River at the distal end of the Windows anticline, they may have formed fairly recently in response to stresses created by deep canyon cutting.

A series of northwest-trending faults cuts the steep southwest flank of the Moab anticline, north of Moab Valley. These are probably adjustment faults that relieved stresses related to folding of the involved brittle sandstone units. The cross-sectional exposure of Glen Canyon Group rocks at the south end of the Moab anticline shows the dips of these faults to range from 35 degrees to vertical, usually to the northeast, and downdropped on the northeast toward the anticlinal axis. Part of the faulting may be due to local salt dissolution and such faults are mostly found adjacent to the Moab fault.

Folds

A regional compressional tectonic event folded rocks in the region in early to mid-Tertiary time. It formed synclines between the salt anticlines and accentuated the diapiric salt anticlines. The Kings Bottom syncline trends N 55-60° W between Moab Valley (Moab anticline) and the Cane Creek anticline (figure 9). The axis of the Cane Creek anticline is present to the southeast just beyond the southwest corner of Map 74. The axis of the syncline plunges toward the Colorado River from both directions and crosses it near the north end of the Amasa Back meander. The distance between the Cane Creek anticlinal axis and Kings Bottom synclinal axis is about 5 miles. The dips of strata between the two axes range up to 11 degrees. The steepest part of the northeast flank of the syncline is closest to the Moab fault, where dips up to 16 degrees have been observed. This flank is only 2 to 2½ miles wide.

The Moab anticline, as opposed to the larger Moab salt anticline, clearly indicates participation in the compressional event. It trends N 45-50° W and extends from just north of the Colorado River for 6 miles to about a half mile north of Sevenmile Wash. It flattens out farther to the northwest. The southwest flank of the fold, extending down to the Moab fault, is very steep, in places reaching 37 degrees (McKnight, 1940, p. 117), and is only ¾ to 1 mile wide. Closely spaced paralleling faults have developed, especially along its southwest flank, on which only minor displacements have occurred. They represent minor movement on fractures initially formed as joints.

The Courthouse syncline trends N 45—50° W between the Moab fault, Moab anticline, and Moab Valley on the west side and Salt Valley, Windows anticline, Big Bend faults, and Castle Valley on the east side. The axis plunges northwest along its entire length and is followed by the Courthouse Wash drainage, which was localized by it. The axis continues southeasterly across the Colorado River near the mouth of Negro Bill Canyon. The syncline apparently localized the lowermost mile of Negro Bill Canyon and a bend in the Colorado River. The width of the southwest flank is 1 to 3 miles and dips are less than 10 degrees. The northeast flank is 4 to 5 miles wide and dips of strata average 5 to 10 degrees. South of the Colorado River, the northeast flank of the Courthouse syncline rises 3 to 7 degrees to the Castle Valley salt anticline. Most areas of locally steeper dips, especially near the Salt Valley anticline, are probably due to later salt dissolution.

The northwest-trending part of the Salt Valley anticline was accentuated by the Tertiary folding, but folding features have been masked or obliterated by subsequent salt dissolution, erosion, and burial by alluvium along the crestal zone. Dips along the northeast flank of the anticline range to 15 degrees, steepening to the northwest. The northeast flank of Salt Valley anticline is bounded by a northwest-trending syncline, the axis of which is north of the map area, and which is termed the Whipsaw Flat syncline by Woodward-Clyde Consultants (1983, p. 56). The axis of this syncline appears to flatten out before reaching the Salt Wash syncline, which shares its western flank with the Salt Valley anticline. In Salt Valley near the Fiery Furnace, there is a bend which formed in response to the trend of the thicker salt, but the anticlinal axis continues southeasterly as the Windows anticline. The famous Windows Section of Arches National Park has formed along this anticline. Its axis dies out at the Big Bend of the Colorado River. Dips on the southwest flank are gentle and in common with the northeast flank of the Courthouse syncline. The northeast flank of the Windows anticline is only a mile wide, extending to the Salt Wash drainage. The dips vary to 10 degrees but have been influenced to some degree by salt dissolution in the vicinity of Salt Wash.

The Salt Wash synclinal axis trends more northerly than northwesterly, ranging from N 10 to 40° W. It is a shallow feature which has localized the Salt Wash drainage and caused it to erode perpendicular to the east-west-trending part of Salt Valley and Cache Valley, which were not accentuated by compressional folding. The axis plunges to the north and flattens out near the north edge of Map 74. North of Salt Valley-Cache Valley, dips on the 2 to 3-mile-wide west flank rarely exceed 7 or 8 degrees. The east flank is more gentle, averaging 2 to 4 degrees. The east flank rises to the Yellow Cat dome and Dome Plateau (figure 38) on the north half of the eastern map margin.

The Yellow Cat dome is located just south of the Yellow Cat (Thompson district) uranium mines and is a local closure (Stokes, 1952, p. 21) on a broad high developed between the Salt Wash syncline and the prominent Sagers Wash syncline to the northeast. The broad and gentle high plunges northwesterly and is in line with the "salt anticline" of Fisher Valley. The high is topographically known as the Dome Plateau.

Joints

Prominent joints have formed as a result of the folding and are most pronounced in the brittle sandstone units (figure 40). A little movement has occurred on some, such as over the Moab anticline. These parallel the northwest trends of the folding and do not bend with the salt anticlines where they deviate from this trend. At the Fiery Furnace, joints in the Entrada Sandstone are terminated by the graben-producing dissolution faults of the salt anticline. The maximum development of joints occurs in the Entrada Sandstone, especially in the upper two members, giving rise to the fins and arches at favorable sites. Gard (1976, p. 26) noted the joint development in the Moab Member as:

> ... a truly amazing pattern of joints where large dipset-slope areas are exposed. On the southwest flank a single joint set predominates. This set is parallel to subparallel to the anticlinal axis, trends N 25-50° W and is spaced about 100 feet apart. On the northeast flank, however, the large area of the Moab outcrop is densely cross-hatched, with two joint sets closely spaced about 20-60 feet apart producing a grid pattern. These joint sets trend N 80° E and N 20° W.

Dyer (1983) described the jointing in the sandstones of Arches National Park in detail. Some of the joints may be due to "arching" during dissolution collapse.

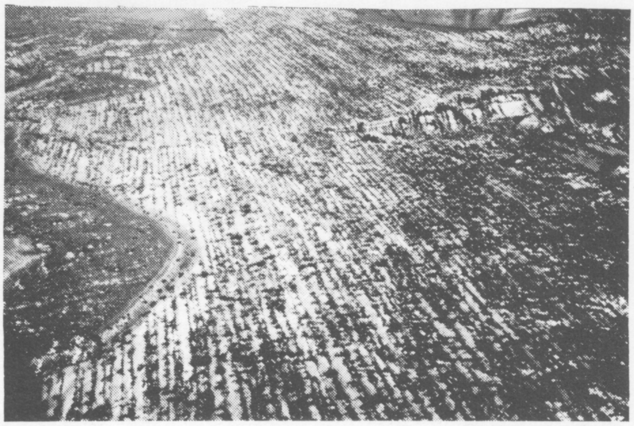


Figure 40. Prominent joints have formed in the brittle rocks (Moab Member of Entrada Sandstone) because of Tertiary folding. View is along northeast flank of Salt Valley anticline.

SALT TECTONIC STRUCTURES

Salt tectonic structures as discussed here are features formed by salt movement or salt dissolution. Salt activity commenced shortly after the deposition of the first salt bed in Pennsylvanian time. The features developed can generally be ascribed to four periods: (1) the period of most active salt movement, (2) the period of localized salt movement, (3) the period of deep cover, and (4) the period of dissolution (figure 41).

Structures formed in the first period include the thick salt anticlines, the local angular unconformities on the flanks of the thick salt (either at the tops or within the formations), radical thickening or thinning of post-salt rock units in the peripheral or crestal regions of the thick salt, and facies changes at the margins of the thick salt. Seismic data obtained by Woodward-Clyde Consultants (1983, fig. 5-6) for the northwest end of Salt Valley anticline show a deep trough of post-salt rock formations that were deposited peripherally along the southwest flank (figure 42). Exposures of rock units in deep canyons, high escarpments, and wells drilled into this peripheral zone verify this, moreso here than under the present surface alignment of the Courthouse syncline. Salt was pushed from under the trough and moved to form the salt anticline. Angular unconformities along the margins of the salt anticlines indicate that rocks were pushed up above the levels of deposition and that erosion occurred at intervals during this period (figure 43). Dissolution of salt probably occurred during this period, if rocks were elevated. Evidence for attendant faulting or folding due to early salt dissolution was largely obscured by later events. The period of most active salt movement lasted about 75 million years.

The localized salt movement period, lasting about 125 million years, had activity limited to areas over thick salt. Diapirism was locally active, and although the area was gradually subsiding and receiving sediments, caprock features projected in relief so that overlying sediments are locally missing. Deep salt activity decreased so that thicker and thinner deposition over the peripheral and crestal zones of the salt anticlines is far less noticeable. Salt dissolution activity undoubtedly occurred at intervals, but time has destroyed most of such features. Most active at the beginning, salt movement had probably ceased at the end of this period.

Thereafter the salt and salt structures were deeply buried and confined by overlying sediments. Some salt activity may have occurred during the time of Tertiary regional tectonic

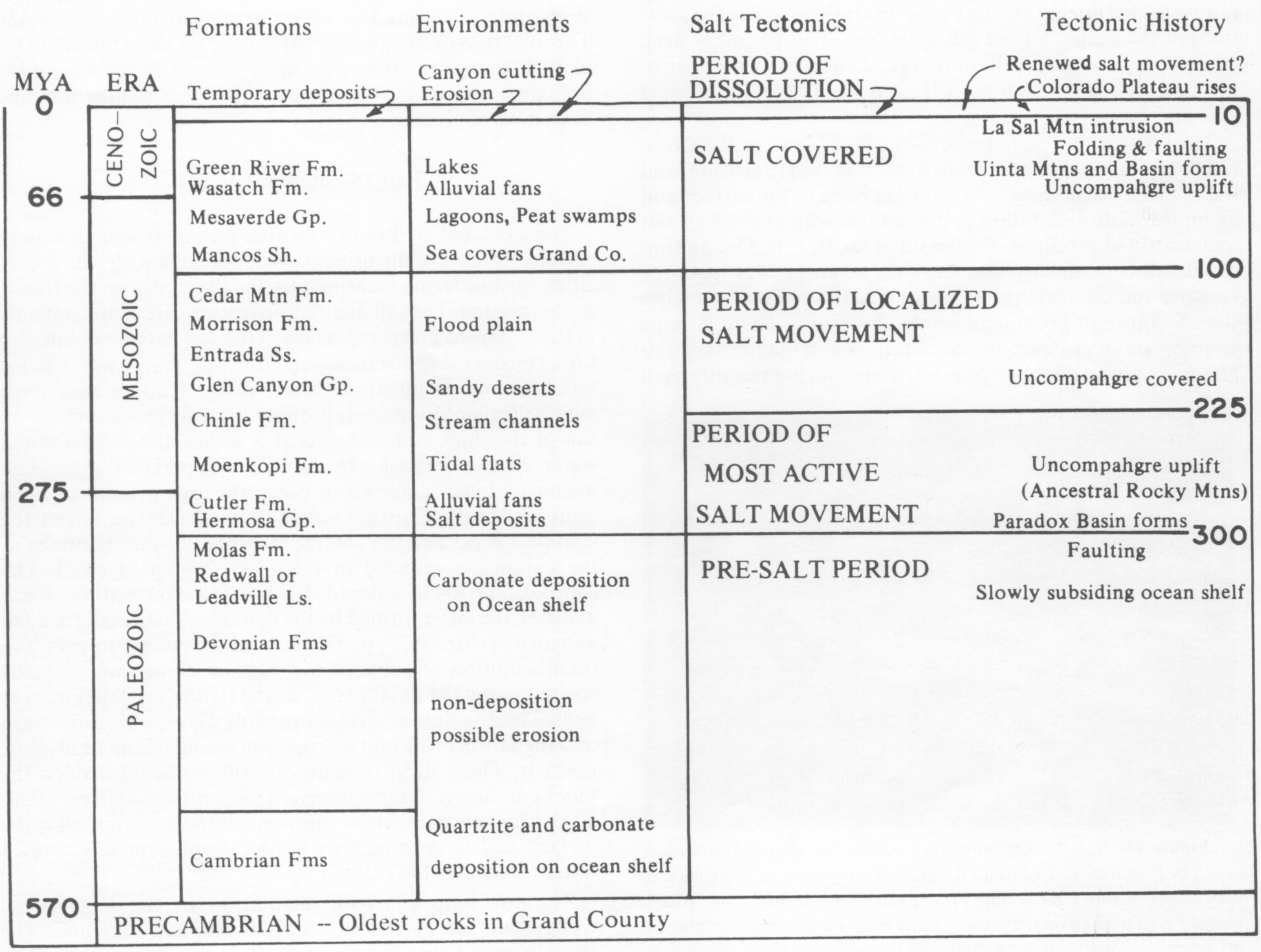


Figure 41. Periods of tectonic history for the Arches National Park and Salt Valley area.

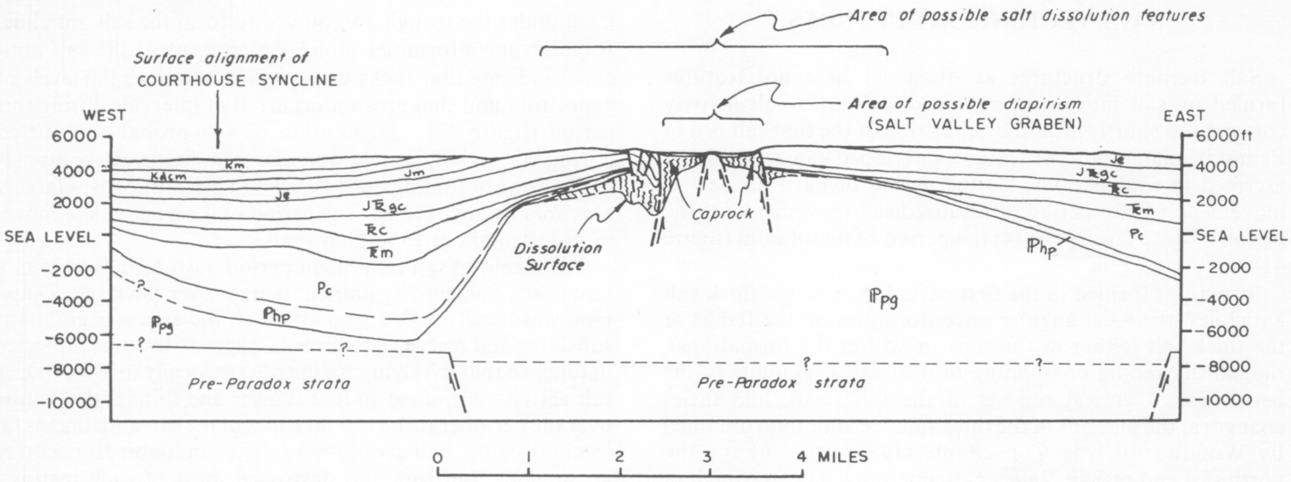


Figure 42. Cross section across northwest part of Salt Valley anticline, reinterpreted from Hite and Lohman (1973, p. 10), as modified by seismic data from Woodward-Clyde Consultants (1983, fig. 5-6).

activity that folded and faulted the rocks of the area, but evidence is lacking. Certainly, the positioning of fold axes and faults formed during Tertiary time was influenced by the locations of the deeply buried salt anticlines. This period of deep cover lasted about 90 million years and ended with the epeirogenic uplift of the Colorado Plateaus about 10 million years ago.

The last period (period of dissolution) began as the Colorado Plateaus and eastern Utah were subjected to erosion, and the thick salt structures were brought close to the surface and exhumed. Salt dissolution is the natural way of eroding salt anticlines and produces its own set of landforms. Dissolution of the salt core under remaining rock layers creates space for collapse and occurs when a flow of unsaturated water reaches the salt through prominent joints and faults. There is some circumstantial evidence for late Tertiary and Quaternary diapirism, but it is difficult to prove. If diapirism has recently been active it would be caused by unequal loading on the salt beds, which are believed to continue thickly in their lateral extensions under the flanks for a considerable distance (figure 42). The thickness or weight of the Mesozoic rocks on the flanks far exceeds that of the load carried by the salt in the core of the anticline, which consists of 500 to 600 feet of alluvium and cavernous caprock.

Figure 43. Angular unconformity within the Chinle Formation near The Portal of the Colorado River. Salt movement (diapirism) was very active during Chinle time prior to the deposition of the "Black Ledge." Salt pushed up the lower Chinle beds which were then planed off by erosion before the remainder of the formation was deposited. This angular unconformity is evident around Salt Valley and Moab Valley.

Salt Dissolution Features

The axes and strikes of salt dissolution structures closely parallel the axis of the principal salt anticline with which they along the bordering escarpments and down-dip on the flanks are associated. The salt dissolution features are found not only in the collapsed crests or valleys of the salt anticlines, but also for a considerable distance, sometimes down-dip as far as 1½ miles. Figure 42 illustrates many of the features associated with salt dissolution. A salt dissolution surface develops on top of the thick salt wherever it is attacked by unsaturated water. The water reaches the salt either by percolation through unconsolidated materials or down through prominent open joints and faults. Caprock is formed as the salt is removed; the insoluble rocks and less soluble horizons become deformed as the column is reduced in thickness (collapsed core). The caprock consists of a jumbled mass of marker bed rocks and gypsum, the latter formed by the hydration of the interbedded anhydrite (Hite, 1977, p. 13). It is partly cavernous owing to the dissolution of some of the gypsum or because of voids created along the axial planes of the tightly distorted marker beds. The dissolution surface probably dips steeply downward into the salt-bearing unit where the prominent faults and joints reach it. These deep trenches are the voids into which the blocks of the overlying competent units tilt and collapse. Usually a drainage parallels or subparallels the joint or fault at the surface and is presumed to be the supplier of unsaturated water (Doelling, 1982, 1983).

The down-dip limits for dissolution are the depositional troughs of the peripheral zone of the salt anticline. The Woodward-Clyde Consultants (1983, fig. 5-6) seismic data revealed the presence of a trough on the northeast flank of Salt Valley with a decrease in salt thickness that is more gradual in that direction than to the southwest. Northeast of the northeast escarpment of Salt Valley, salt dissolution structures quickly decrease and soon disappear as the overlying units thicken and impose an impermeable barrier to the passage of water.

The collapsing cores of the salt anticlines develop erosionally into valleys or grabens with bordering escarpments. The geomorphic development of a salt anticlinal valley is diagrammatically indicated in figure 44 and for simplicity the younger post-Paradox formations are treated as a single brittle unit. The sequence starts as the overlying rocks have been folded, fractured, and faulted over the axial part of a salt anticline as shown in diagram A. Diagram B shows erosion followed by salt dissolution. The drainages that appear follow the fracture traces because the shattered rock is easier to erode. These subsequent streams parallel the joint or fault traces to form their valleys and supply water to the salt and dissolve it. The overlying rocks collapse as linear ridges and form v-shaped dissolution synclines and dissolution anticlines in brittle rocks (figure 45). Dissolution anticlines and synclines are not as angular when formed in incompetent units. Some of the valleys begin to fill with alluvium in this youthful stage of salt valley development.

As the process continues the valley widens both because of the surface erosion of escarpments and ridges and continued subsurface dissolution. Diagrams C and D indicate a salt valley in the mature stages of development. Old age is reached when valley widening has reached the edges of the thick salt. The ridges of caprock projecting through the alluvium may be diapirs or anticlinal ridges over which all younger rocks have been eroded. Typically, along the length of any salt anticline, all geomorphic stages of development can be observed. Cache Valley, for example, is in a youthful stage of development while parts of Salt Valley are in early, middle, and late maturity.

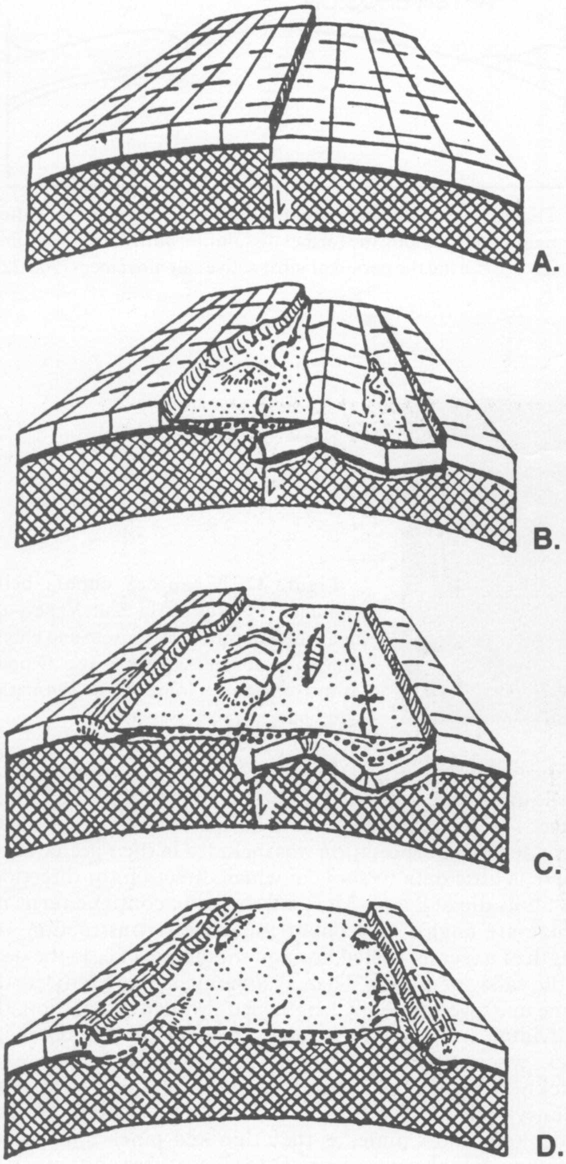


Figure 44. Valley development along a salt anticline, due partly to erosion and partly to dissolution collapse. Mid-valley domes, hills or ridges are due either to diapirism, as at x, or are anticlinal ridges projecting through the alluvium from buried, collapsed and tilted strata. In stage 3 dissolution valley diapirs often appear along the valley edges (block D). See text for explanations.

Figure 45. V-shaped dissolution syncline just east of the Moab fault and along old U.S. Highway 191. The collapsed rocks are the Salt Wash Member of the Morrison Formation; each flank of the syncline dips toward the road.

Diapirism and Pseudo-Diapirism

The presence of dome-shaped and ridge-like exposures of caprock along the margins and in the middle of mature salt anticlines suggests that salt movement may be an active process. There are other explanations for these features as well. Diapirism indicates that the weight of high flanking cliffs irregularly pushes up salt (and overlying caprock) from under the edges of collapsed strata (figure 44D). The movement would be imperceptible to human observation but significant in geologic time — consider the millions of years that passed during the period of most active salt movement. For this reason modern diapirism is difficult to prove. The amount of cover over the salt and caprock must be minimal so as not to impede the growth of the diapir. Diapirs forcing their way up through the formations outside of the salt valleys cannot be found in the Paradox fold and fault belt.

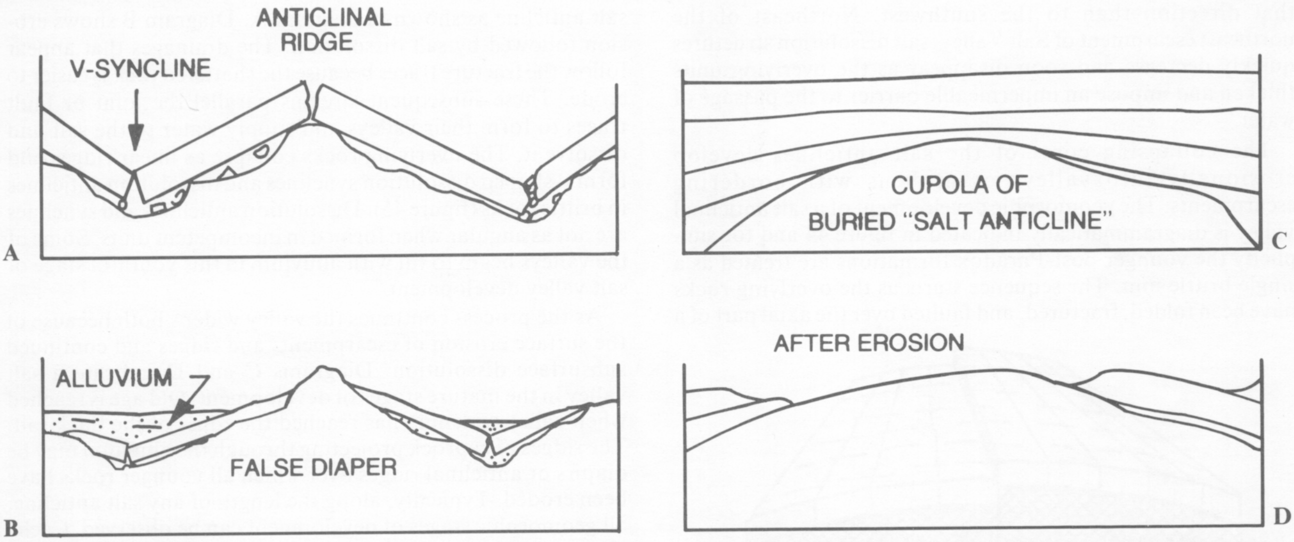


Figure 46. Two alternate explanations for possible modern diapir features. Diagrams A and B are sequential drawings to indicate that after the collapsed rocks are stripped away by erosion, the caprock beneath would remain as ridges along the former dissolution anticlines. Diagrams C and D indicate that some so-called diapirs may be cupolas of the salt anticline formed during the period of most active salt movement (300-225 mya).

Figure 47. A caprock cupola being exhumed by erosion in Salt Valley, the light colored rocks are gypsum and chippy limestone of Pennsylvanian age. Dipping away from the dome are Chinle Formation and younger rocks.

Additional ways to explain the caprock domes and ridges are shown in figure 46. Diagrams A and B show v-shaped dissolution synclines and anticlines. Should the dissolution anticlines be stripped of their cover by erosion, a ridge-line of caprock would remain. These might be construed to be diapirs, especially if all traces of former overlying rocks had been removed over the crest. Some of the broader "diapirs" might actually be exhumed cupolas of the original thick salt anticline formed during earlier periods of salt movement as shown by diagrams C and D. An excellent example of such a cupola is present in central Salt Valley, in the N ½ Sec. 33, T 23 S, R 21 E (figure 47).

Salt Valley, Cache Valley, and Moab Valley Dissolution Features

A series of 18 cross sections were prepared at intervals across the salt anticlines portrayed on Map 74 (figures 48 to 50). These show a variety of stages of geomorphic development. The cross sections are exaggerated vertically so as to accentuate offsets on faults and the topographic relief. Areas influenced by salt tectonics commonly do not allow reconstruction to original volumes and lengths, because many of the units were deposited as early diapiric events were taking place. The cross sections should be accepted with caution as a great deal of interpretation was included in their preparation. There is little data to show in which direction (or directions) the faults dip at depth. Most are shown to continue vertically, others are angled to account for some reconstruction—the length of a reconstructed horizon should not exceed the width of the valley or graben. There is some evidence to indicate that some units were actually lengthened through dissolution, that individual strata slid past each other like playing cards in a deck when tilted. It is impossible to predict the exact thicknesses of the deeper formations, especially the Pennsylvanian Honaker Trail, Permian Cutler, Triassic Moenkopi and Chinle, as they thin and pinch out over the anticline. It is also guesswork as to where these units pinch out on the flanks. Salt dissolution was possible in earlier geologic times and units may locally have been removed then.

Cross sections A-A', B-B', C-C', and D-D' are all sections across youthful development, including the Elephant Butte folds where a valley or graben is just beginning to be formed. Cross section A-A' shows a single block that has collapsed into

Figure 48. Locations of cross-sections shown on figures 49 and 50.

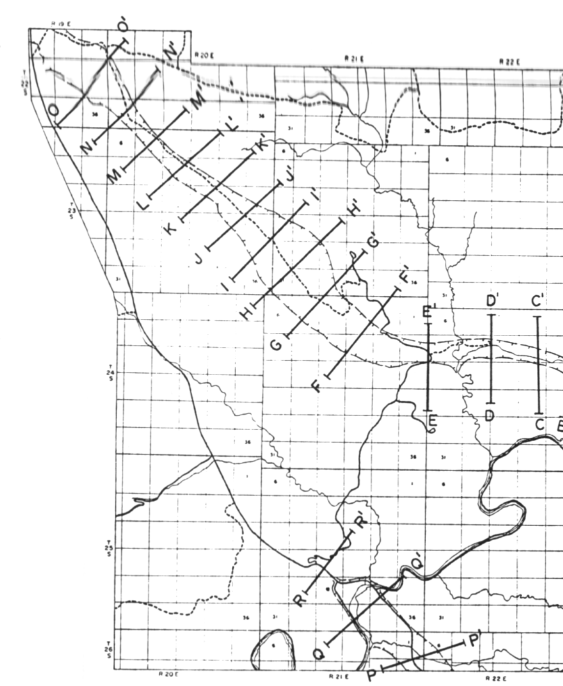
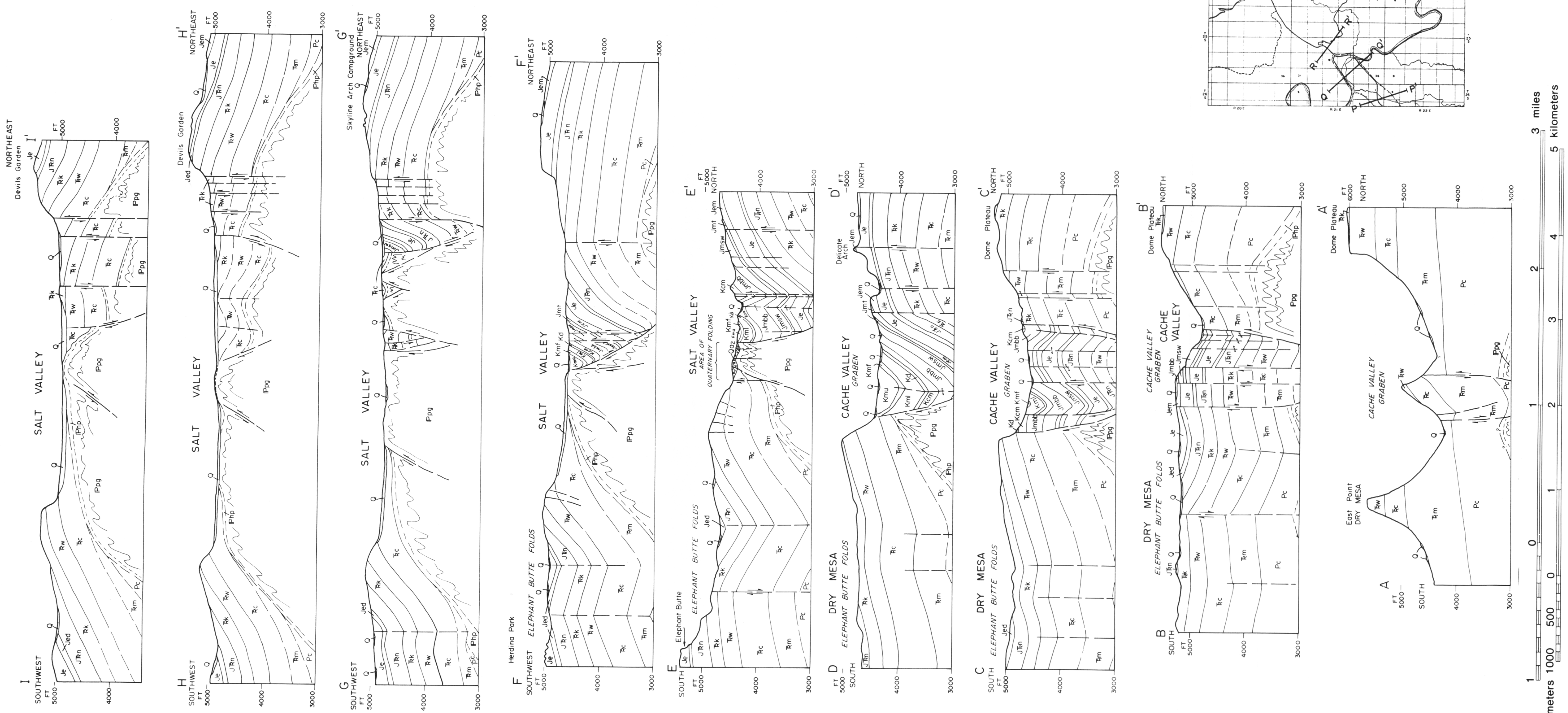


Figure 49. Cross-section across Salt Valley and Cache Valley salt anticlines. See text for explanations. The locations of cross-sections are shown on figure 48.



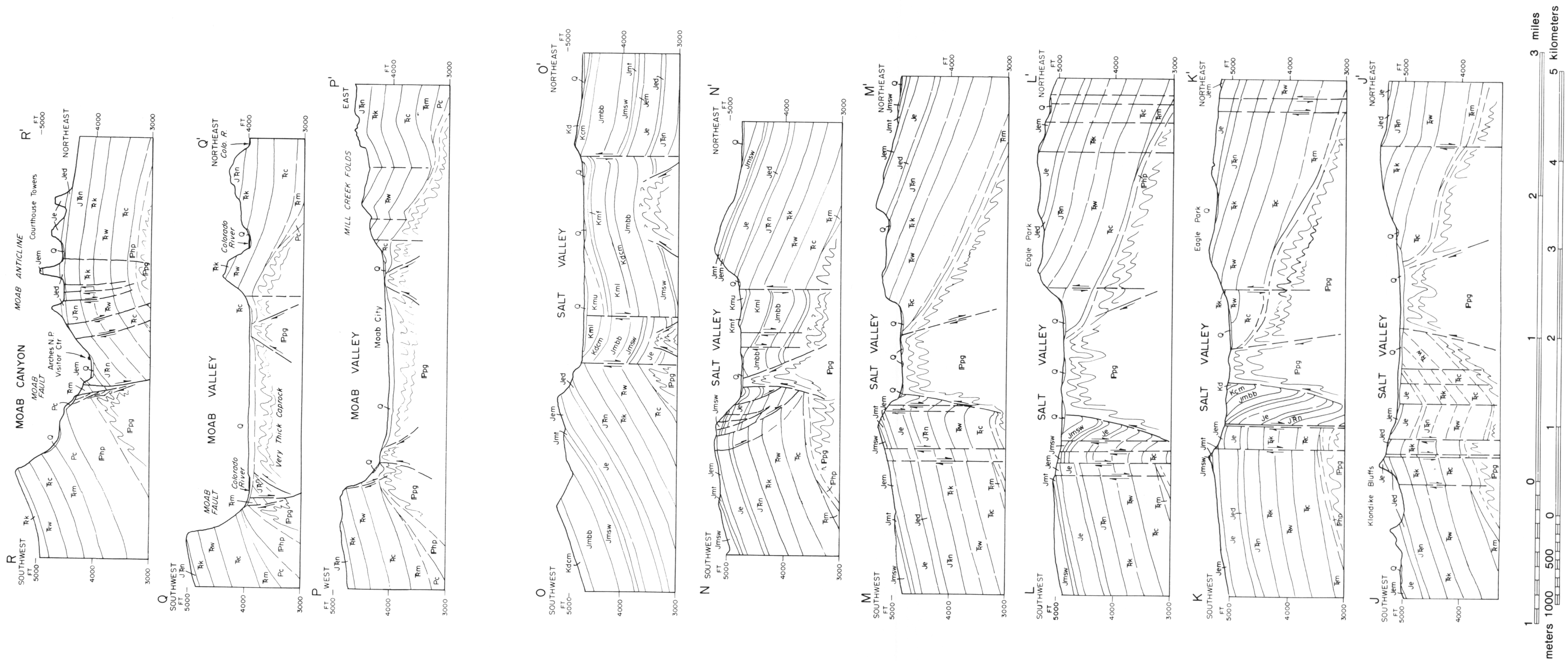


Figure 50. Cross sections across Salt Valley and Moab salt anticlines. See text for explanations. Locations of cross sections are shown on figure 48. Vertical scale is twice the horizontal scale of approximately 1:50,000.

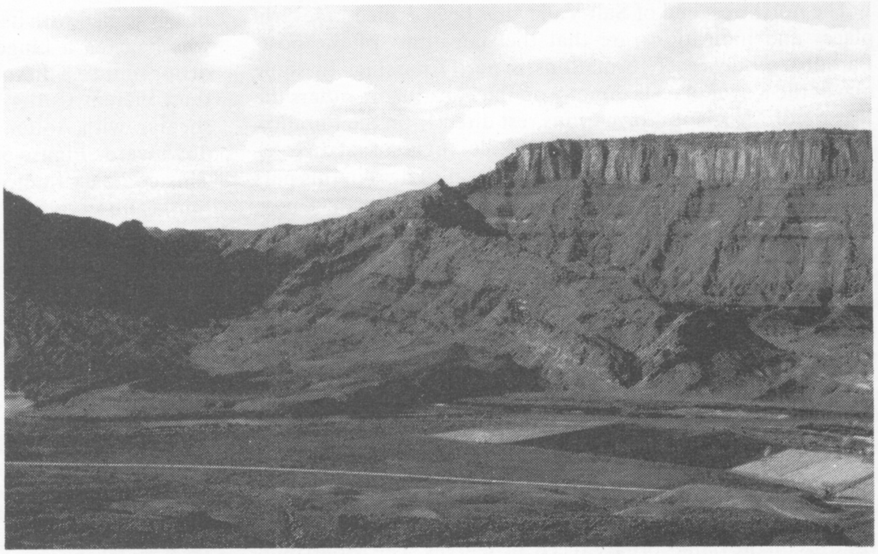


Figure 51. View northerly across the Colorado River at the place where the dissolution deformation of Cache Valley is present. See A-A', figure 49.

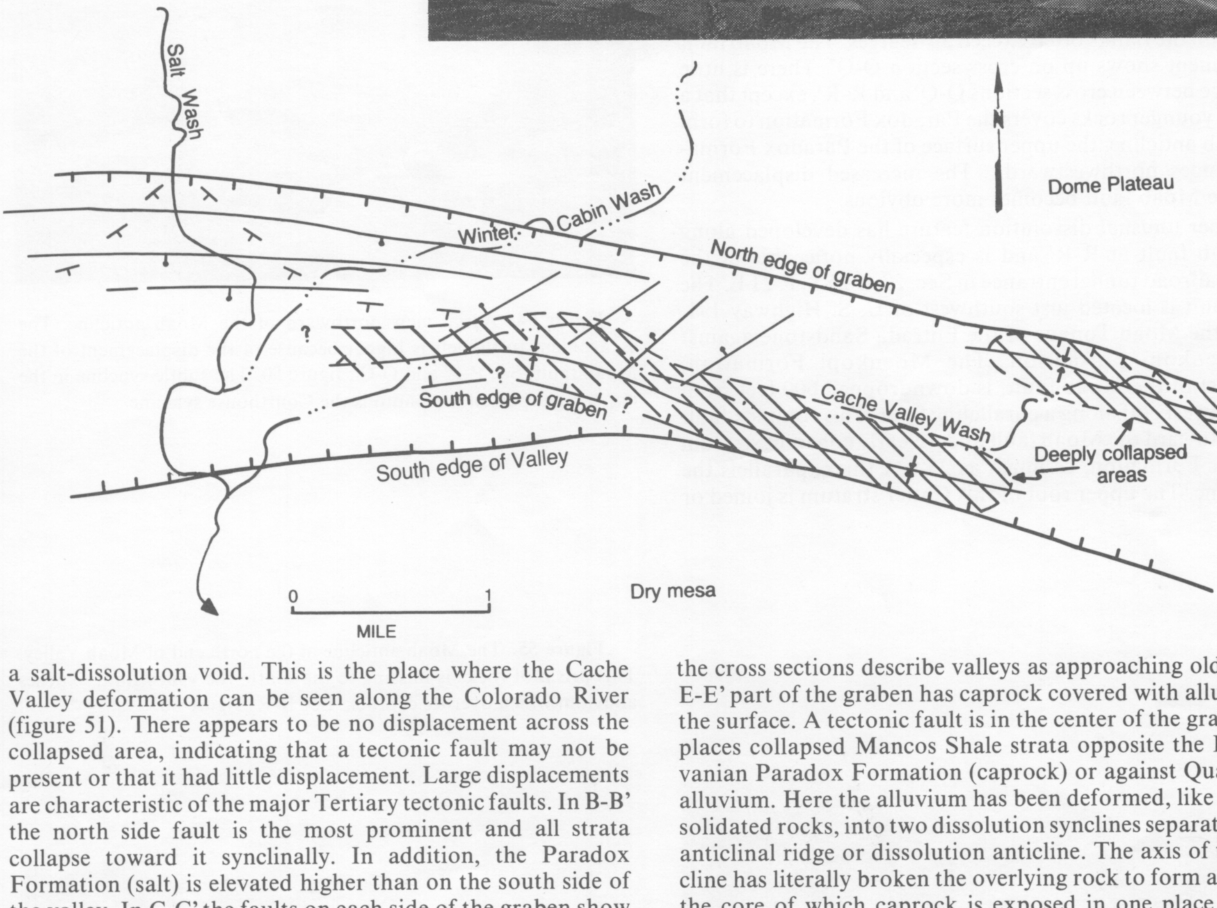


Figure 52. Simplified structural features of a part of Cache Valley. The areas of deepest bedrock collapse subparallel the course of Cache Valley Wash.

a salt-dissolution void. This is the place where the Cache Valley deformation can be seen along the Colorado River (figure 51). There appears to be no displacement across the collapsed area, indicating that a tectonic fault may not be present or that it had little displacement. Large displacements are characteristic of the major Tertiary tectonic faults. In B-B' the north side fault is the most prominent and all strata collapse toward it synclinally. In addition, the Paradox Formation (salt) is elevated higher than on the south side of the valley. In C-C' the faults on each side of the graben show equal prominence, the strata collapse synclinally into these faulted areas and there is a mid-graben anticline (see also figure 52). In D-D' the prominent fault is clearly on the south side, the Paradox Formation of the south flank is elevated above that of the north flank and the north fault(s) indicate(s) little or no displacement.

Cross sections E-E' to M-M' are all through grabens or valleys in maturity because the Paradox Formation is at the surface or is covered by valley alluvium. In some of these areas the cross sections describe valleys as approaching old age. In E-E' part of the graben has caprock covered with alluvium at the surface. A tectonic fault is in the center of the graben and places collapsed Mancos Shale strata opposite the Pennsylvanian Paradox Formation (caprock) or against Quaternary alluvium. Here the alluvium has been deformed, like the consolidated rocks, into two dissolution synclines separated by an anticlinal ridge or dissolution anticline. The axis of the anticline has literally broken the overlying rock to form a fault, in the core of which caprock is exposed in one place and the Chinle Formation in another. The contact between the alluvium and the older units is an angular unconformity. In the next two cross sections the salt rises sequentially higher and the valley widens. From cross section H-H' to M-M' the salt irregularly lowers and the valley decreases in width. In M-M' the valley is not very wide and is mostly floored with caprock. Between this cross section and N-N' much of the valley floor is filled with Cretaceous rocks. An important fault, downthrown to the northwest, crosses the valley obliquely between the two sections (figure 53).

The northwest end of Salt Valley has been drilled in several places and indications are that the older part of the post-Paradox sequence of formations is partly missing. In some places the Kayenta rests directly on the Paradox, in others the Navajo or Morrison Formations rest directly on the Paradox Formation. The differences, hole to hole, suggest that dissolution, erosion, or diapirism were active in past ages in this part of the Salt Valley salt anticline, and irregularly, but effectively, removed local sections of rock along the crest. A very narrow zone of exposed caprock persists on the southwest side of the valley. At O-O' the valley is a true graben. The downdropped Cretaceous units are gently folded in the center but dip steeply away from the escarpment faults, flattening out over a relatively short distance.

Cross sections P-P' to R-R' are of the Moab salt anticline (figures 54 and 55). P-P' shows a salt valley at old age or nearing old age, with younger strata completely removed above the caprock. However, the east flank exhibits the Mill Creek folds, which are similar to the Elephant Butte folds. These zigzag folds are doubly plunging toward Mill Creek and the dips on the flanks often exceed 30 degrees. The Moab fault displacement shows up on cross section Q-Q'. There is little difference between cross sections Q-Q' and R-R', except that a prism of younger rocks covers the Paradox Formation to form the Moab anticline; the upper surface of the Paradox Formation plunges northwestward. The increased displacement along the Moab fault becomes more obvious.

A rather unusual dissolution feature has developed along the Moab fault at R-R' and is especially noticeable at the Potash railroad tunnel entrance in Sec. 28, T 25 S, R 21 E. The Moab fault is located just southwest of U. S. Highway 191, placing the Moab Tongue of the Entrada Sandstone against the Moenkopi Formation. The Moenkopi Formation, southwest of the Moab fault, is downdropped 600 feet from the southwest cliff along a paralleling fault. This complex fault dips 35° toward the Moab fault and a clearly coherent stratum of Cutler Formation, as much as 25 feet thick, parallels the fault plane. The upper root of this Cutler stratum is joined or nearly joined with its counterpart in normal position, so that it was bent as a hinge when underlying rocks collapsed and dropped into a dissolution void below. The fault plane below the coherent Cutler stratum consists of a series of imbricate shears, with softer parts "smeared out" and lengthened downward. Figure 56 suggests how this may have occurred. This complex fault, complete with the coherent Cutler stratum, is observable along the Potash railroad tracks for more than a mile. This feature could be construed to be a landslide with the strata falling into a dissolution cavern. Additional information about this feature is given in Baars and Doelling (1987, p. 275-280).

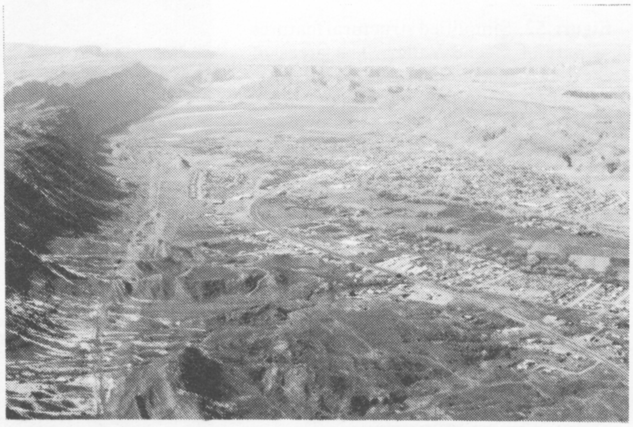


Figure 54. Aerial view northward of the Moab anticline. The escarpment to the left is higher because of the displacement of the Moab fault. See P-P' and Q-Q', figure 50. The subtle syncline in the upper right part of the photo is the Courthouse syncline.

Figure 53. Aerial view of the north end of the Salt Valley anticline. The projections in the valley consist of collapsed Cretaceous rocks or cupolas of caprock (Pennsylvanian rocks). See M-M' and O-O', figure 50.

Figure 55. The Moab anticline at the north end of Moab Valley. This prism of rocks is missing to the south; the valley floor exposes alluvium which overlies caprock. See R-R', figure 50.

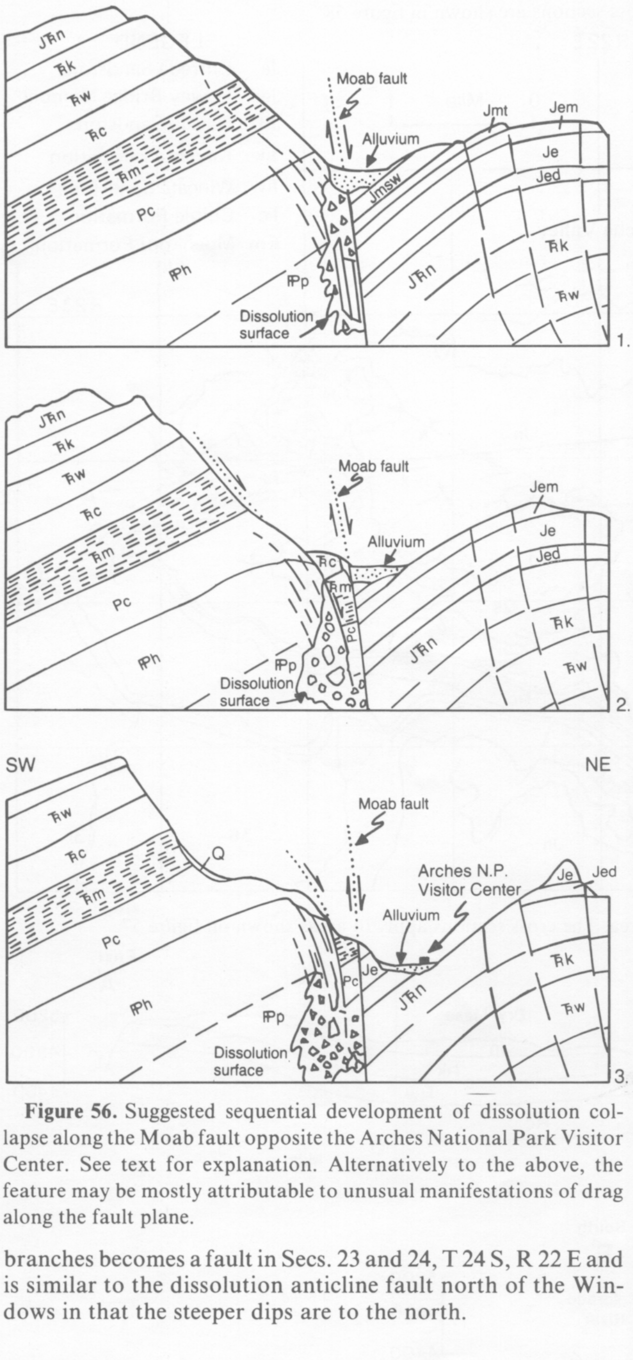


Figure 56. Suggested sequential development of dissolution collapse along the Moab fault opposite the Arches National Park Visitor Center. See text for explanation. Alternatively to the above, the feature may be mostly attributable to unusual manifestations of drag along the fault plane.

branches becomes a fault in Secs. 23 and 24, T 24 S, R 22 E and is similar to the dissolution anticline fault north of the Windows in that the steeper dips are to the north.

Elephant Butte Folds

The Elephant Butte folds are a fine example of salt dissolution features on the flanks of an anticline (figures 57 and 58). These folds extend for about 10 miles along the south flank of Salt Valley and Cache Valley from Sec. 6, T 24 S, R 21 E, eastward to Sec. 13, T 24 S, R 22 E. The northernmost dissolution syncline is best developed west of Salt Wash. A tributary drainage extends from the Arches National Park roadway to Salt Wash, and the dissolution syncline plunges toward the through-going Salt Wash. The syncline continues easterly on Dry Mesa for an additional mile before dying out, after reversing its plunge. The plunge angle increases dramatically within ½ mile of Salt Wash.

The synclinal axis continues west of the Arches roadway and plunges into a downwarped (collapsed) area where the drainage has cut a deep gorge into the escarpment wall and drains into Salt Valley. This drainage is through-going; the dissolution syncline plunges toward it from both directions. The Slickrock Member of the Entrada Sandstone is the youngest unit preserved in the downwarp; the oldest rock exposed on the flanks is the Kayenta Formation. The dip on the flanks ranges to as much as 30° and is usually steeper on the north flank.

A dissolution anticlinal axis parallels the synclinal axis about 2000 feet to the south. There is no prominent joint or fault along its extent except between Sec. 24, T 24 S, R 21 E to Sec. 19, T 24 S, R 22 E, just north of The Windows. The fault is downthrown slightly to the north and the south flank is more gentle than the north flank. Another dissolution syncline is present south of the anticline along the east half of the Elephant Butte fold belt. It extends from The Windows easterly across Salt Wash and across most of the length of Dry Mesa. It also doubly plunges toward Salt Wash and bifurcates on the east half of Dry Mesa. The northen branch changes its plunge in Sec. 14, T 24 S, R 22 E and preserves the Slickrock Member in its axial area. Dips on the flanks of the syncline(s) are mostly gentle, not exceeding 10 degrees. The dissolution anticline between the two eastern branches becomes a fault in Secs. 23 and 24, T 24 S, R 22 E and is similar to the dissolution anticline fault north of The Windows in that the steeper dips are to the north.

Arches and Fins

Arches and fins are unique and spectacular features to visitors of Arches National Park. Many of the arches are an indirect consequence of dissolution activity, but arches can form in several ways. The most important conditions controlling arch development in the park are: (1) the physical makeup of the Entrada Sandstone, (2) the erosional and weathering characteristics of the Entrada Sandstone, and (3) Tertiary folding of the Entrada Sandstone. Most arches or fins have formed where the Entrada Sandstone is arched over an anticline on which closely spaced parallel joints developed (figure 59). Dissolution-induced anticlines occur mostly along the escarpments bordering the valleys. The strata rise on the flanks, then arch over and collapse into the valley in response to the dissolution of salt there. Good examples are at Klondike Bluffs (J-J', figure 50), Devils Garden, Fiery Furnace (H-H', G-G', figure 49), and Herdina Park (F-F', figure 14). In The Windows Section a thin remnant of Entrada Sandstone stands as Elephant Butte, arched over a tectonic anticline. The Entrada Sandstone is also arched over the Moab anticline (R-R', figure 50) but is more completely covered by the Moab Member or Tongue. Faults and joints are not as closely spaced, nevertheless, a few arches, developed along the Courthouse Towers, are even more unusual in having developed along a set of joints that strike northeasterly, perpendicular to the axis of the anticline.

The Slickrock Member of the Entrada Sandstone is composed mostly of quartz grains largely cemented by calcium carbonate ($CaCO_3$). Rain water, charged with atmospheric carbon dioxide (CO_2), forms a weak carbonic acid which can

Figure 57. Geologic sketch map of Elephant Buttes-Dry Mesa Area. Cross sections are shown in figure 58.

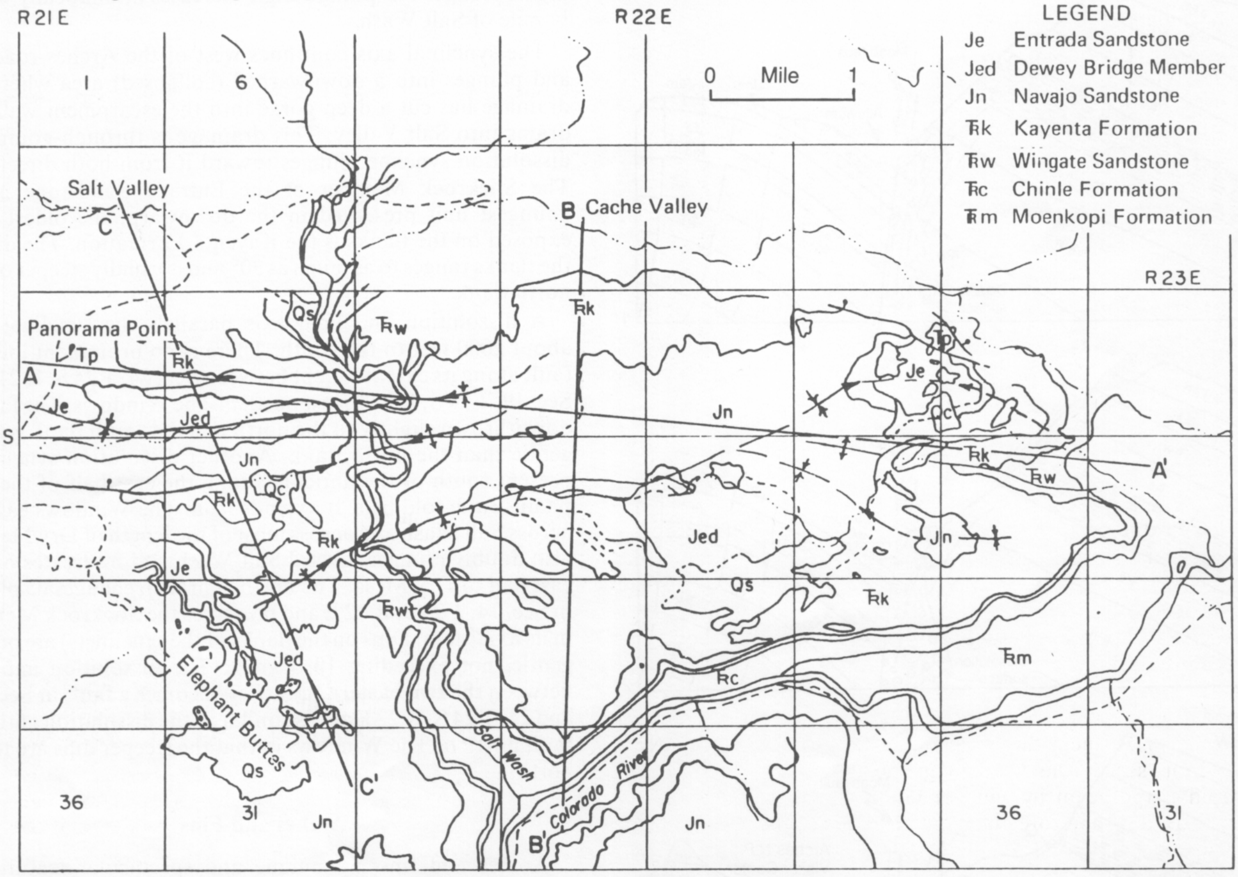


Figure 58. Structural cross sections of the Elephant Buttes-Dry Mesa Area. The cross sections apply to areas shown on figure 57.

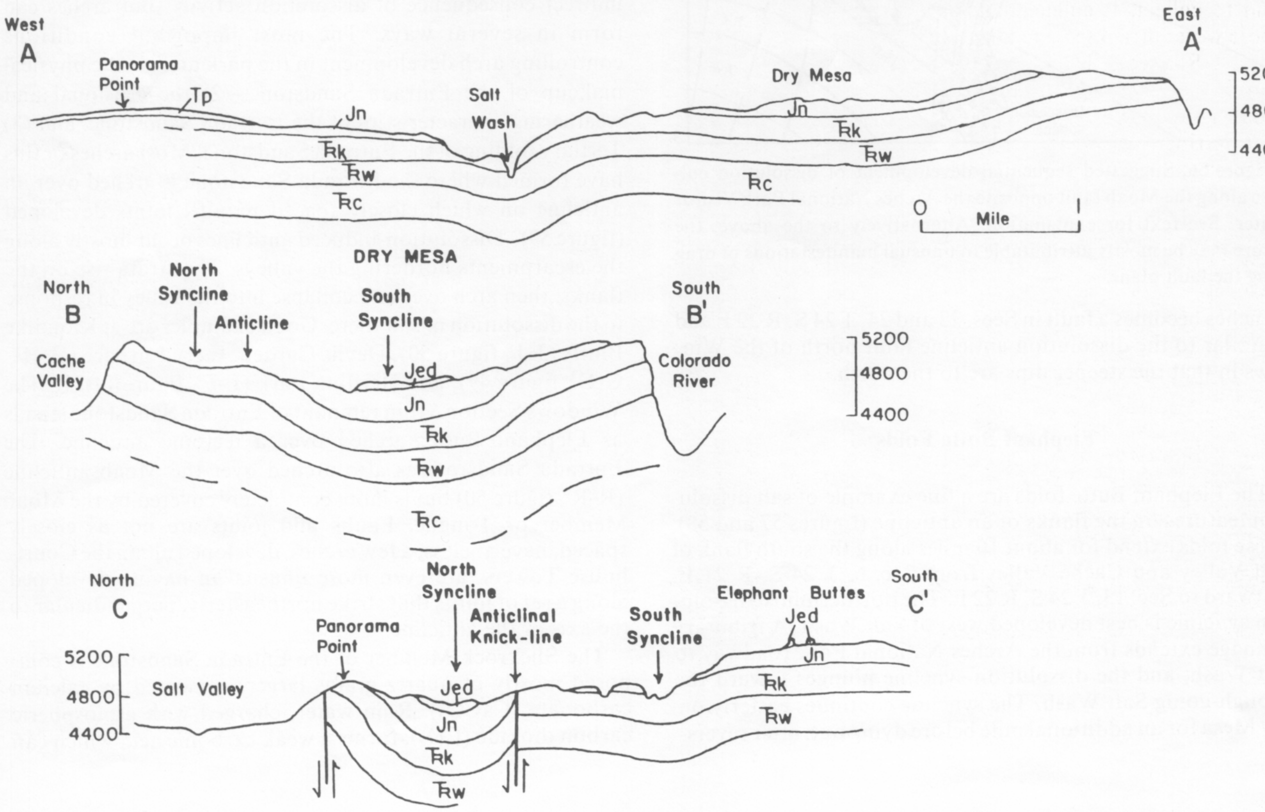


Figure 59. Closely spaced paralleling joints erode into fins which are particularly susceptible to sideward erosional attack to form arches.

dissolve the cement. Many other sandstone units are also cemented with calcium carbonate, but the individual Slickrock grains do not blow away from the parent rock as readily as from the other units. Large irregular patches of sand cover much of the outcrop area of the Slickrock Member. The reasons for this are not fully understood and may be related to grain size, angularity, or to the degree of frosting. Slightly acidic rain water percolates through this veneer of sand by gravity and attacks the still-cemented rock underneath, forming more sand. This meteoric ground water is protected from rapid evaporation by wind or hot sun as it would be at the surface. It is therefore given more time to do its work and the sandstone under the sandy fields is more quickly destroyed than the bare-surfaced rock.

Where thin fins are present there is little upper space for the sand to collect. It collects between the fins and the slightly acidic water attacks their sides. The partings in the otherwise massive Slickrock Member are especially prone to the sideward attack of the ground water. The contacts between the Moab Tongue and Dewey Bridge Member also act as prominent partings. The water seeps into the partings and dissolves the sand grains to create a thin opening along an interval of parting. Gravity then creates stresses in the overlying rock and upward-moving fractures develop. As in mines with unbolted poor roofs, the back collapses until it creates the typical arch form, which is a strong support, and collapse ceases. Delicate Arch has formed along the contact of the Moab Tongue and Slickrock Member. While Skyline Arch is formed along a parting entirely within the Slickrock Member (figure 60.), the Windows arches occur along the Dewey Bridge - Slickrock contact. The Dewey Bridge Member is much weaker than the Slickrock and erosion often enlarges the arch. Thick-walled fins are not as favorable for arch development as the thin ones, but alcoves and caves can form on their sides (figure 61).

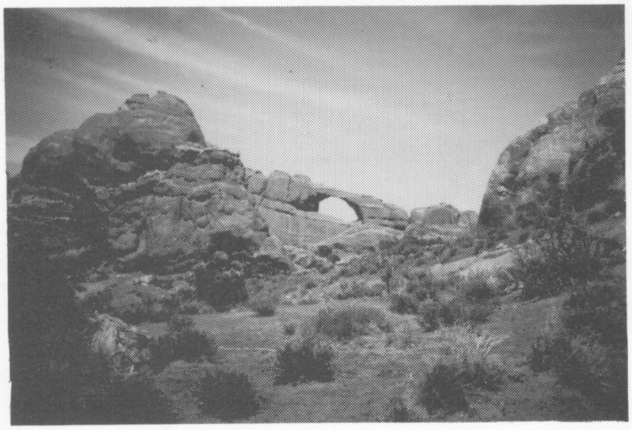


Figure 60. Skyline Arch on the northeast flank of the Salt Valley anticline. This arch formed entirely within the Slickrock Member of the Entrada Sandstone above a particularly well-developed parting.

Figure 61. Thick-walled fins or non-fin outcrops do not form arches but caves or alcoves. These are developed on Elephant Butte at the contact between the Dewey Bridge Member and Slickrock Member of the Entrada Sandstone.

ECONOMIC GEOLOGY

The Arches National Park area contains mineral resources in addition to its scenic resources, including uranium, vanadium, copper, gold, manganese, calcite, rockhound materials, potash, magnesium, rock salt, gypsum, and petroleum. Additionally there is potential for the development of construction materials such as sand and gravel, building stone, and limestone. These are, of course, not exploitable within the National Park boundaries, but those economic resources with the greatest potential were excluded from the park boundaries.

Occurrences of the principal minerals have been plotted on figure 62. Petroleum drill holes are scattered across the area because of abundant oil shows, especially in the Mississippian Leadville Formation, the Pennsylvanian Paradox Formation, and the Permian Cutler Formation. Anticlines have always been prime targets for petroleum exploration and Salt Valley and Moab anticlines have not been neglected. To date, a relatively small but important production of oil and natural gas has been achieved from the Paradox and Leadville Formations from wells in the southwest corner of Map 74 (Long Canyon oil and gas area).

Two principal uranium-producing areas are present within the confines of Map 74. To the northeast is the Yellow Cat area of the Thompson vanadium-uranium district, with such important mines as the Ringtail, Parco, Little Pittsburgh, Cactus Rat, Memphis, Black Ape, Blackstone, and Johns

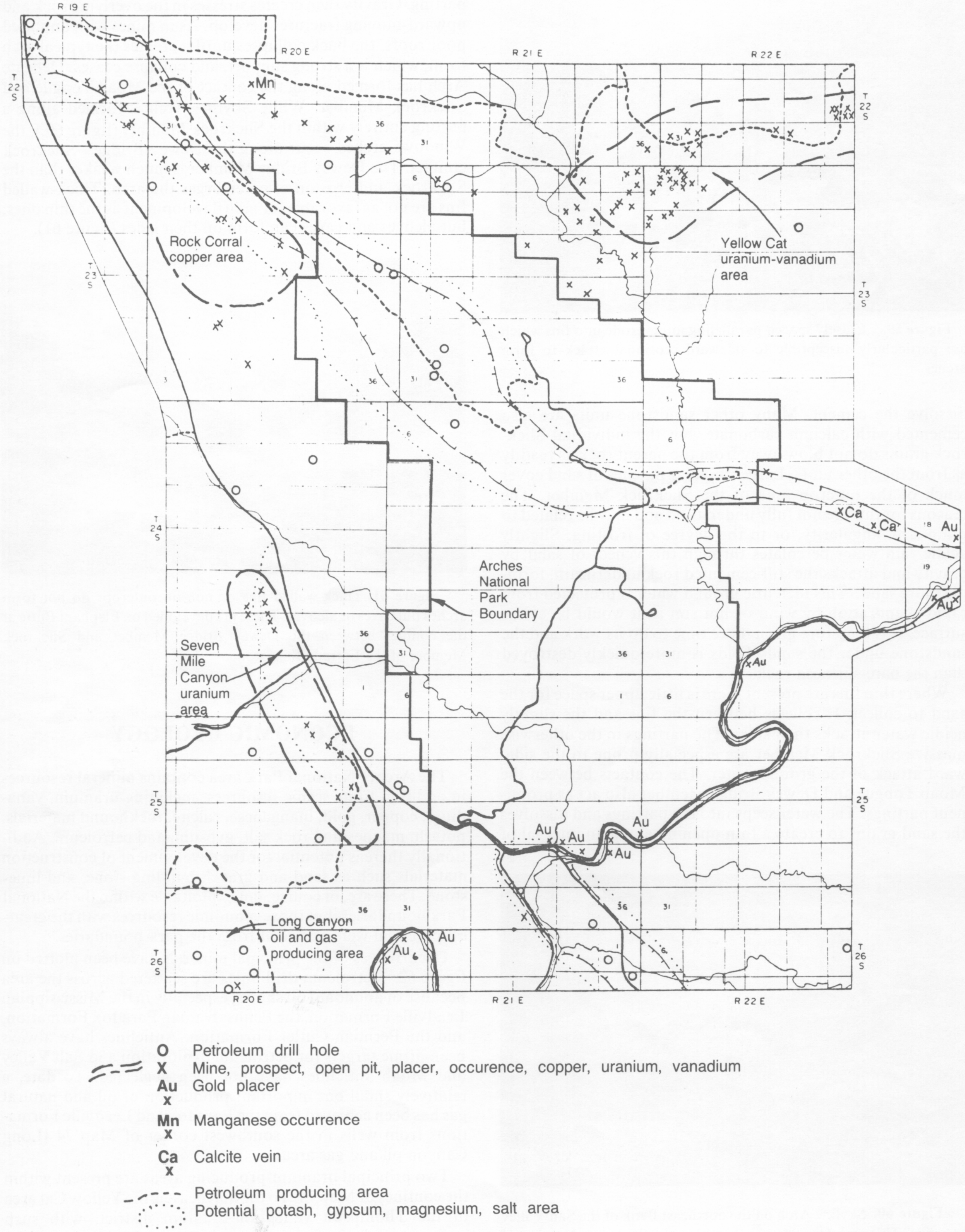


Figure 62. Principal mineral resources around Arches National Park.

Figure 63. Uranium mines (Parco mines) in the Salt Wash Member of the Morrison Formation to the north of Arches National Park in the Yellow Cat area of the Thompson district. Uranium in the Salt Wash Member is commonly found in the bottoms and sides of thick channel sandstones in the upper part of the member.

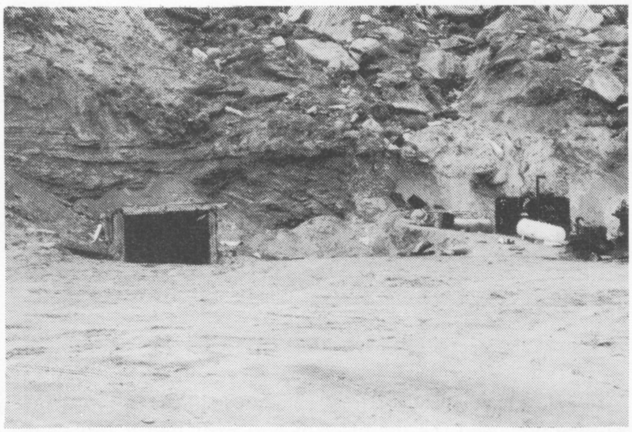


Figure 64. Uranium mine entrance in the Sevenmile Canyon area of the Green River district. The host is the basal gritstone of the Chinle Formation.

(figure 63). These have yielded at least one-half million pounds of uranium and significantly more vanadium. Most of the ore has been mined from the upper channel sandstones of the Salt Wash Member of the Morrison Formation, from ore bodies ranging to 5 feet across, 200 feet in length, with a thickness of 12 feet or more (Stokes, 1952, p. 25). The ore grade has ranged to 10 percent vanadium and 0.4 percent U_3O_8. Carnotite, tyuyamunite, corvusite, vanoxite, hewettite, pascoite, and rossite are the principal ore minerals associated with abundant organic matter in the sandstones. The ore deposits were highly exploited during the uranium boom of the 1950s but were originally discovered in 1899, being first mined for radium. Production from the area has virtually ceased because of the present low uranium demand, but exploration activity continues.

The Sevenmile Canyon uranium area is an important part of the larger Moab uranium district and includes the Shinarump and the Thornburg (Corral Canyon) mines. The mineralization is principally confined to the lower 25 feet of the Chinle Formation in which at least three ore horizons have been identified (Finch, 1954, p. 5). The ores carry only minor amounts of vanadium and copper, the principal mineral is uraninite or pitchblende. Small amounts of gummite, schroeckingerite, and becquerelite are also present. Orebody thickness averages 1-2 feet, but occasionally reaches a maximum of 5 feet. In contrast to the Yellow Cat area the ore deposits do not appear as channel fills but in flat-bedded (planar), discontinuous, sedimentary lenses deposited on an irregular surface, but carbonaceous material is present. The ore grade has ranged from 0.10 to 1 percent U_3O_8 in this area, active since 1949 (figure 64).

Several copper prospects and a few mines constitute the Rock Corral Copper area. These workings are concentrated in the northwest end of the southwest flank of the Salt Valley anticline. The principal host is the Salt Wash Member of the Morrison Formation, although mineralized Entrada Sandstone and Navajo Sandstone are also present. Mostly small specks of copper oxides (malachite, azurite, and tenorite) are disseminated in the upper thicker sandstone lenses or coat fractures in fault zones. Most of the mines have produced a little ore; a significant attempt was made to leach the copper in Sec. 6, T 23 S, R 20 E. Presently there is no activity in the copper area.

Flour, fine flakes, and small nuggets of gold have been extracted from the terrace gravels along the Colorado River. The total production has been small, but activity occurs intermittently, especially during economically depressed times. Some manganese nodules have been prospected in the Brushy Basin Member of the Morrison Formation in Sec. 28, T 22 S, R 20 E, and calcite veinlets occur along faults in the Entrada Sandstone in Cache Valley.

The potential for production of saline minerals and gypsum occurs wherever the Paradox Formation is relatively near the surface and might be economically mined. Possible favorable areas are along Salt Valley and Moab Valley and on the southwest upthrown side of the Moab fault, where it has the greatest displacement. Potash, as sylvite, is commercially solution-mined southwest of the map area at the Cane Creek anticline. Potash was first discovered in the Paradox Basin at Salt Valley in 1924 (Dyer, 1945). Sylvite (KCl) and carnallite ($KMgCl_3.6H_2O$) were identified and interest has continued to the present. The resources are large. Hite (1977, p. 22) has estimated the total potash resources of the Salt Valley area to amount to 1.5 billion tons per square mile. However, the potash resources may be difficult to exploit, inasmuch as the deposits are complexly deformed in the anticlinal areas. A great deal of magnesium is present in the carnallite, but the procedures to extract it and separate it are presently too expensive to compete with other sources. The potash area on the upthrown side of the Moab fault, under the Sevenmile Canyon uranium area, may not be as complexly deformed as under Salt Valley.

The unlimited rock salt resource is of high quality, but rock salt is a plentiful, low-cost item state-wide. The Arches National Park region is not in an important market area. The gypsum supply is also unlimited but has the same market constraints as the rock salt. In addition, the gypsum beds are much contorted, thin, and mixed with significant amounts of clastic impurities.

Rockhound materials are abundant in the region, mostly as jasperized chert, petrified wood, dinosaur bone, and other polishable siliceous materials that can be fashioned into gems, cabachons, and even bookends. Most materials are found in the Brushy Basin and Tidwell Members of the Morrison Formation, but interesting materials have also been found in the Cedar Mountain, Entrada, Navajo, and Chinle formations. Luckemeyer and Stewart (1956, p. 52-53) have listed some specific localities. Collecting of rockhound materials inside the boundaries of Arches National Park is prohibited.

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EVIDENCE FOR QUATERNARY DEFORMATION IN THE SALT VALLEY ANTICLINE, SOUTHEASTERN UTAH

by
Charles G. Oviatt
Faculty, Kansas State University

UTAH GEOLOGICAL AND MINERAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
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INTRODUCTION

This paper summarizes results of reconnaissance studies of Quaternary deposits and landforms at a number of localities in the Salt Valley area and of more detailed studies at several sites (figure 1). Because the region has been exposed to erosion in a semiarid climate for millions of years (Hunt, 1969), the Quaternary record is fragmentary and must be pieced together from relatively few isolated exposures. Thick Quaternary deposits in deformed depositional basins exist locally in Salt Valley only because of a long history of salt movement and dissolution in the Pennsylvanian Paradox Formation. Quaternary depositional sites controlled by salt deformation are rare but have been previously documented in the salt anticlines of the Paradox Basin (Cater, 1970; Colman, 1983), and they offer valuable opportunities to study Quaternary stratigraphy and salt tectonics in this region. Other deposits, soils, and structural and geomorphic features provide valuable clues to the Quaternary history of the Salt Valley area.

Previous work in Salt Valley has dealt primarily with pre-Quaternary stratigraphy and structures (see Doelling, this publication). Dane (1935) noted some Quaternary deposits and soils, and a few areas of recent deformation; Dyer (1983) discovered some enigmatic deposits that have a bearing on the Quaternary history of the Salt Valley anticline. Woodward-Clyde Consultants have conducted reconnaissance investigations in the area for the Office of Nuclear Waste Isolation and have discussed Quaternary geology with respect to the disposal of nuclear waste (Woodward-Clyde, 1983). Other important studies of Quaternary deposits and soils in the Salt Valley area include those of Richmond (1962), Biggar and others (1981), Harden and others (1985), and Colman (1983). Because of the general lack of good dating control on Quaternary deposits in the Salt Valley area, I refer to the ages of deposits or events simply as early, middle, or late Quaternary. The precise time boundaries for the three subdivisions of the Quaternary as used here are summarized in figure 2. Deposits, events, and geomorphic features discussed here are dated as precisely as possible based on relationships with dated volcanic ashes and on relative measures of geomorphic position, soil development, and degree of preservation on the landscape.

STRATIGRAPHY AND GEOMORPHOLOGY

EXOTIC GRAVELS

Isolated gravel deposits containing exotic clasts provide clues to the pre-collapse history of the Salt Valley anticline. Although the gravel deposits have not been dated, they have been found on both the rim and the floor of the valley and show that an integrated drainage system was superimposed across the Salt Valley anticline prior to the complete collapse of the anticline.

Dyer (1983) and Dyer and others (1983) reported exotic cobbles and boulders of silicified limestone or chert containing an Eocene molluscan fauna in Salt Valley (table 1). The fauna is similar to faunas studied by J. H. Hanley in rocks from marginal facies of the Green River Formation in Colorado and Wyoming, and it is indicative of lowland flood-plain pond or lake environments peripheral to the main Green River lakes (J. H. Hanley, personal communication, 1984).

Dyer (1983) and Dyer and others (1983) regarded all deposits containing clasts of the fossiliferous Eocene chert as belonging to the "Formation of Salt Valley" and of probable late Tertiary age. However, there are geomorphic, lithologic, and stratigraphic reasons, developed in this paper, to separate the deposits containing the Eocene chert into two distinct gravel assemblages. Assemblage A gravels occur as isolated remnants of probable late Tertiary age near the middle of Salt Valley and on the rim of the anticlinal valley (figures 1 and 3). Assemblage B comprises Quaternary channel gravels of Salt Valley Wash in the lower part of Salt Valley. In assemblage B gravels, the Eocene chert clasts are uncommon and are mixed with rock types that are derived from within Salt Valley. The Eocene chert clasts in assemblage B gravels were probably derived from assemblage A deposits. Gravels similar to assemblage B are also found northwest of the drainage divide in Salt Valley (figure 1). The basal channel gravels discussed under "Lower Salt Valley" in this report belong to assemblage B.

TABLE 1. EOCENE "MOLLUSK ROCK" FAUNA FROM SALT VALLEY

Locality	Deposit	[1]Taxa
SW¼ NE¼ sec. 30, T. 23 S., R. 21 E., E. of dirt road on floor of Salt Valley	assemblage A; abundant clasts in a gravel mound uplifted by a salt diapir	*Plesielliptio* sp. indet. Bivalvia indet. *Goniobasis* cf *G. tenera* (Hall) *Physa* sp. indet. *Biomphalaria* sp. indet. *Drepanotrema* (?) sp. indet. Planorbidae: genera and spp. indet.
NE¼ NW¼ SW¼ sec. 11, T. 24 S., R. 21 E., near abandoned road on floor of Salt Valley	assemblage B; uncommon clasts in Quaternary gravels and sands	Bivalvia indet. *Goniobasis tenera* (Hall) cf *Biomphalaria* sp. indet. Planorbidae; genera and spp. indet.

[1] All identifications by John H. Hanley, U.S. Geological Survey, Denver. According to Hanley, the mollusk fauna reported here is identical, except for the bivalves, to the fauna he has studied previously in collections from Salt Valley made by himself and J.R. Dyer (J.H. Hanley, personal communication, 1984; Dyer, 1983.

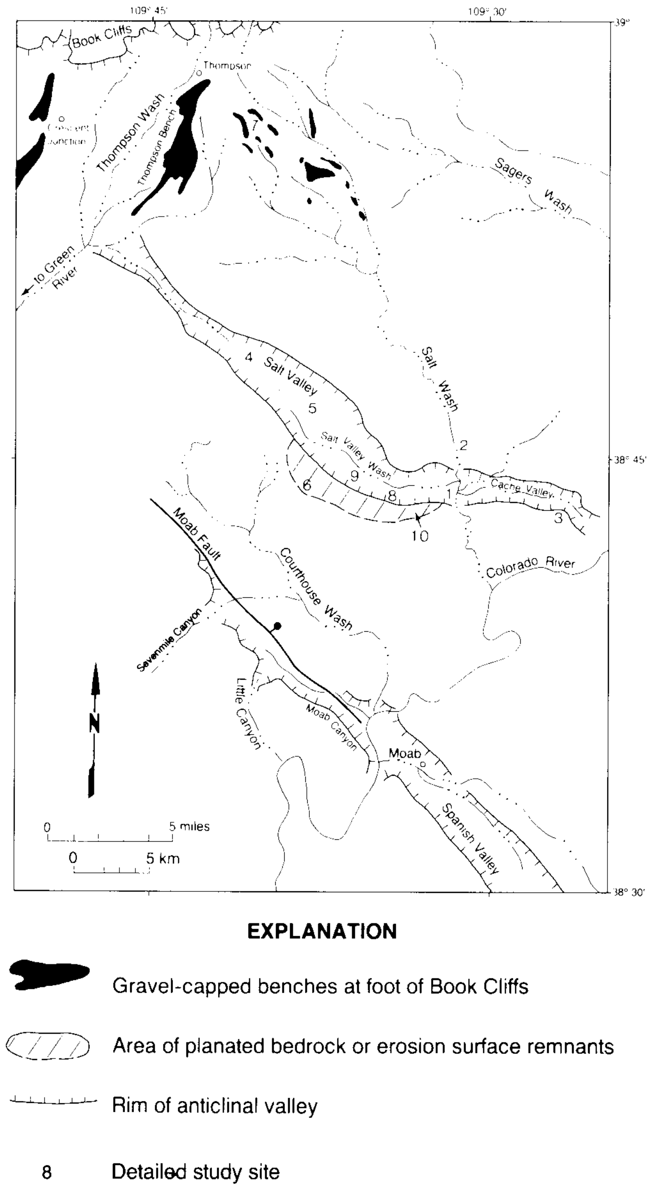


Figure 1. Map showing localities disussed in text. Numbered localities are: 1) location of figure 9; 2) Holocene alluvial terraces; 3) location of figure 5; 4) drainage divide; 5) gravel mound containing assemblage A exotic gravels on floor of valley; 6) gravel mound containing assemblange A exotic gravels on rim of valley; 7) alluvial benches or pediment remnants of ancestral Salt Wash; 8) deformed Quaternary beds and caprock outcrops shown in figure 14; 9) Bishop ash locality (Colman, personal communication, 1984); 10) Panorama Point petrocalcic soil (Colman, personal communication, 1984).

Abundant clasts of the Eocene chert, including large boulders, in association with other exotic rock types of assemblage A, are exposed both on the southwest rim of the anticlinal valley (Dyer, 1983) and in gravel mounds that appear to have been uplifted by small salt diapirs on the floor of Salt Valley (localities 5 and 6; figure 1). One of the associated exotic rock types is a resistant, fine-grained, orange-weathering (10 YR 6/4), but gray on fresh surfaces, slightly calcareous sandstone. Boulders and cobbles of this sandstone are identical in lithology to clasts in the gravel cap of Thompson Bench north of Salt Valley (figure 1). Thompson Bench is a Quaternary alluvial bench or pediment formed by Thompson Wash, which drains exposures of Cretaceous and Tertiary rocks in the Book Cliffs. The orange sandstone clasts, which include large boulders, were probably derived from one of the Cretaceous marine sandstones in the Book Cliffs and are abundant in Thompson Bench gravels.

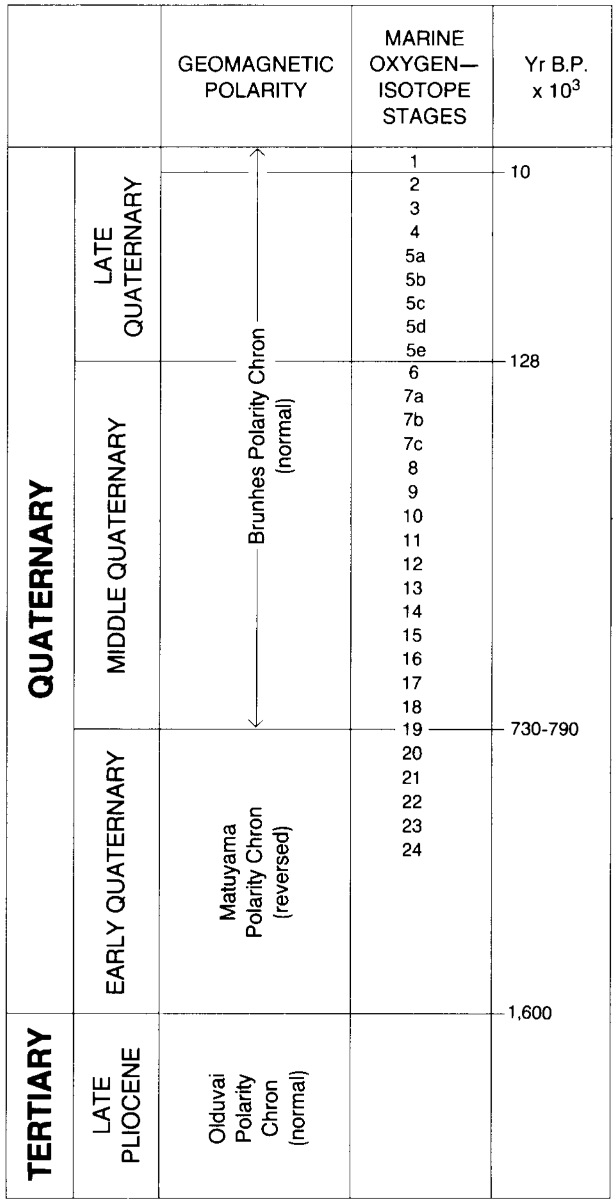


Figure 2. Diagram showing Quaternary chronostratigraphic classification as referred to in this paper. Even-numbered oxygen-isotope stages represent major glaciations; odd-numbered stages represent interglaciations. Note nonlinear time scale. The Holocene is the last 10,000 years. Modified from Bowen (1978, table 10-1).

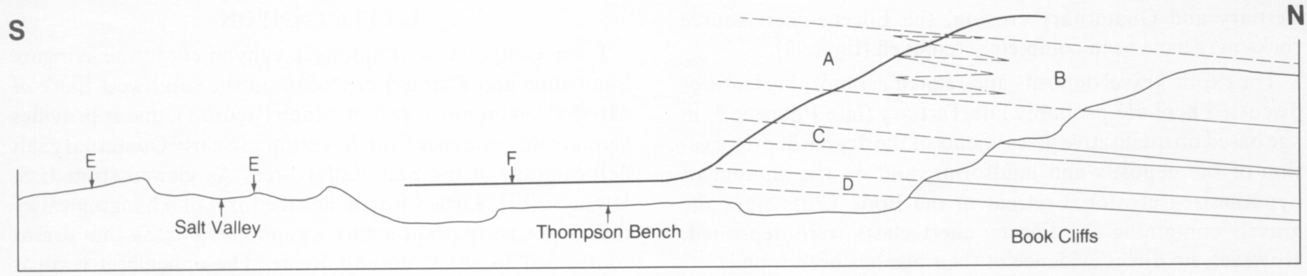


Figure 3. Schematic cross section showing stratigraphic relationships and source areas for exotic gravel in Salt Valley area, Utah. A. Hypothetical position of fossiliferous Eocene chert facies, now completely eroded away by the northward retreat of the Book Cliffs escarpment. B. Green River Formation. C. "Conglomerate beds at Dark Canyon." D. Cretaceous marine sandstone (possible source of orange-weathering sandstone clasts). E. Exotic gravel assemblage A. F. Inferred configuration of Book Cliffs escarpment during deposition of assemblage A gravels.

Also present in assemblage A gravels and in Thompson Bench gravels are abundant well-rounded pebbles of black chert and many other varieties of chert, quartzite, and igneous and metamorphic rocks. These pebbles were most likely derived from exposures of the "conglomerate beds at Dark Canyon" of Paleocene age in the Book Cliffs (Fouch and Cashion, 1979) and, therefore, are recycled pebbles, possibly originally derived from Precambrian and other rocks in the Uncompahgre Uplift (Willis, 1986). The presence of abundant large clasts of the Eocene chert in association with an assemblage of clasts having a probable source area in the Book Cliffs suggests that the Eocene chert may have had a similar source area (figure 3).

Another distinctive exotic rock type in assemblage A gravels is white to gray oolitic chert in varying degrees of silicification. It is similar to oolitic cherts from the Green River Formation in the Unita Basin and probably had a primary source similar to that of the fossiliferous Eocene chert.

The presence of deposits of assemblage A both on the rim and on the floor of the valley suggests that the stream that deposited the gravel flowed across the Salt Valley anticline prior to the collapse of the core of the anticline. In this hypothetical reconstruction, collapse of the core of the anticline disrupted the drainage system and separated the exotic gravel from the headwaters of the stream, which may have been diverted around the north end of the anticline to form ancestral Thompson Wash. Alternatively, the stream may have been an ancestral Salt Wash (Dyer, 1983), in which case it eroded laterally to the east and downward off the plunging Salt Valley anticline and became entrenched across the structure as an antecedent or superimposed stream.

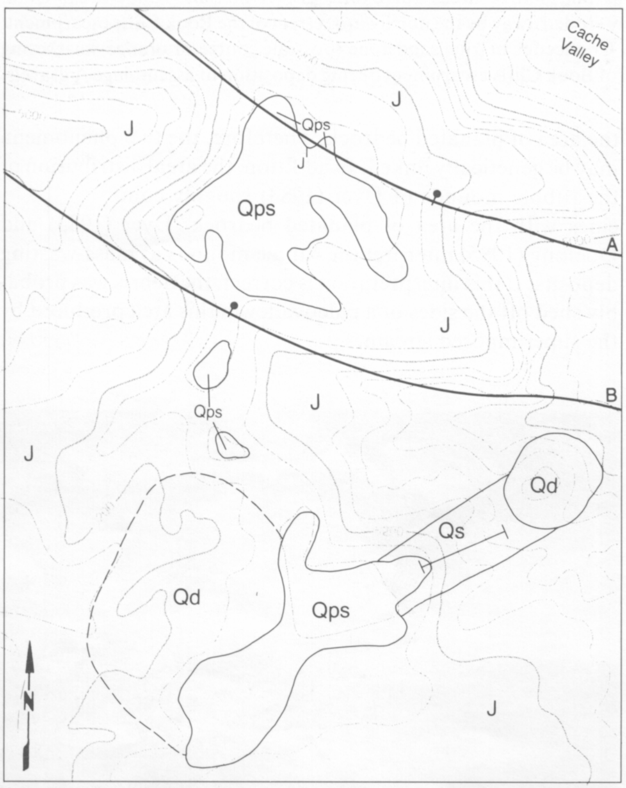
There is additional evidence on the southwest flank of the anticline for a stream that existed prior to the complete collapse of the core of the anticline. Here remnants of a tilted erosion surface that truncates folded beds of the Glen Canyon Group and the Entrada Sandstone are preserved (figures 1 and 4). The remnants of the surface, one of which is preserved at Panorama Point (locality 10, figure 1), are overlain by thin sand deposits that bear a strongly developed (stage IV to V) petrocalcic soil (S. M. Colman, personal communication, 1984; terminology after Gile and others, 1966; and Machette, 1985). The assemblage A exotic-gravel locality on the rim of the anticline (locality 6, figure 1) is on the northwestern end of the area of planated bedrock. Therefore, the two phenomena may be genetically linked. In addition, the areal distribution of the rubble mounds of Dyer (1983) roughly coincides with the area of planated bedrock. Dyer (1983) and Doelling (1985) interpret the rubble mounds as mass-wasting deposits. If this interpretation is correct, the debris was probably shed off the sides of a paleovalley in this area produced by the superimposed stream.

Figure 4. Tilted erosion-surface remnant on southwest flank of the Salt Valley Anticline, southeast of locality 6 (figure 1). The erosion surface truncates a syncline in the Dewey Bridge Member of the Entrada Sandstone. View is to the northwest.

Despite a determined search, clasts of the fossiliferous Eocene chert have not been found in Thompson Bench gravels, nor in other bench or pediment gravels east of Thompson Bench that are associated with Salt Wash (locality 7, figure 1), nor in modern channel gravels of Thompson Wash or Salt Wash. This indicates that the Eocene-chert source area has probably not been exposed in these drainage basins since middle Quaternary time, depending on the ages of Thompson Bench and the Salt Wash benches. Rocks of a marginal Green River facies containing the mollusk fauna may once have interfingered with the main lacustrine facies of the Green River Formation south of the present Book Cliffs area, but as the ancestral Book Cliffs retreated northward in response to late

Tertiary and Quaternary erosion, the Eocene-chert source rocks may have been completely removed (figure 3).

The exotic gravel deposits and related geomorphic features discussed here are probably late Tertiary (late Pliocene ?) in age based on qualitative assessments of the degree of preservation of the deposits and landforms, and on the amount of hypothesized erosional retreat of the Book Cliffs since the gravels containing the Eocene chert clasts were deposited. However, no direct evidence of their age has been found.



Map area is in parts of sections 13 and 14, T. 24 S., R. 22 E., Castle Valley 15′ quadrangle.

0 2000 ft

contour interval 40 feet

EXPLANATION

Location of measured section C (fig. 7)

Major bedrock faults

Qps — Sand containing petrocalcic soil

Qs — Horizontally bedded sand

Qd — Debris: jumbled boulders, cobbles, and finer material of Salt Wash and Tidwell Members of the Morrison Formation; bedrock surrounding debris deposits is Entrada Sandstone (Slickrock Member)

J — Jurassic bedrock; including Navajo Sandstone, Dewey Bridge Member of Carmel Formation, Entrada Sandstone, Morrison Formation

Figure 5. Generalized geologic map of locality 3 (figure 1) showing faulted petrocalcic soil, Cache Valley area, Utah. Fault A displaces Qps about 12 feet.

LITTLE CANYON

Little Canyon is a broad, deep canyon cut in the Wingate Sandstone and Chinle Formation on the southwest flank of Moab Canyon northwest of Moab (figure 1), and it provides geomorphic evidence for late Tertiary to early Quaternary salt deformation in the Salt Valley area. As viewed from U.S. Highway 191, Little Canyon has the form of a hanging valley that is presently occupied by an ephemeral wash that drains southward to the Colorado River. The ephemeral wash is underfit and the canyon is completely severed from a larger drainage system that must have produced the feature, although no trace of that drainage system is preserved northeast of Little Canyon. The stream that eroded the canyon was a consequent stream flowing off the southwest flank of the moab salt anticline, but apparently the stream was beheaded by movement on the Moab fault (figure 1).

The Moab fault formed during the collapse of the Spanish Valley salt anticline (Huntoon, 1982, p. 947). Judging from the excellent degree of preservation of Little Canyon as a geomorphic feature, it was undoubtedly isolated in late Tertiary to early Quaternary time. No deposits of the consequent stream that produced the canyon have been identified in Little

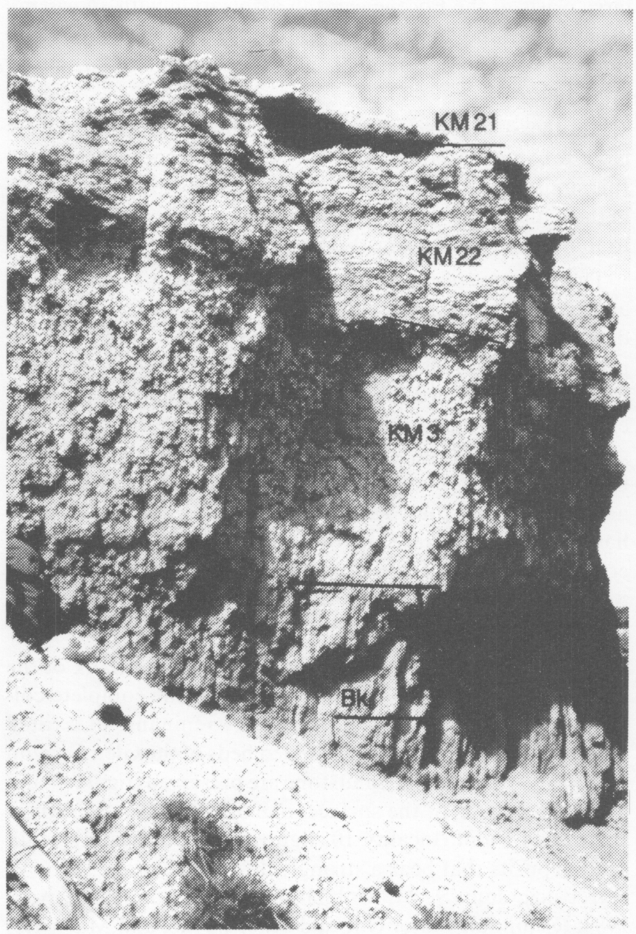


Figure 6. Petrocalcic soil profile exposed in Cache Valley at locality 3 (figure 1). Compare with figure 7 for scale and horizon descriptions.

Canyon; only thin and relatively young, locally derived Quaternary deposits are exposed on the floor of the canyon. Little Canyon is very similar to the beheaded drainages on the flanks of Fisher Valley anticline described by Colman (1983), all of which show that late Tertiary and Quaternary salt tectonics have had a profound effect on the development of landforms in this region.

CACHE VALLEY PETROCALCIC SOIL AND RELATED FEATURES

An area near the eastern end of Cache Valley on the southern flank of the anticline, where salt-related collapse has been less than in adjoining areas, contains evidence of Quaternary faulting and possible tilting. Tectonic events in this area are dated relative to a strongly developed petrocalcic soil that is preserved in deposits capping a number of small erosion-surface remnants (locality 3, figure 1; figure 5). The soil is

MORPHOLOGIC STAGE	HORIZON	DESCRIPTION
	B(?)	reddish-brown sand with fragments of underlying carbonate horizons; 1 ft
V	Km21	multiple thin laminar horizons separated by cemented breccia(?) or platy horizons; 2 ft
IV	Km22	tabular horizon, strongly cemented, tabulae ½ to 4 inches thick; 3 ft
III	Km3	nodular horizon, $CaCO_3$ nodules progressively better cemented, and coalescing, in upper part; 4 ft
I-II	Bk	calcic horizon, calcareous sand in lower part; $CaCO_3$ nodules in upper part; gradational with Km3; 2 ft
		horizontally bedded sand, thin interbedded clay; occasional lenses of angular gravel; 160 + ft

Figure 7. Cache Valley petrocalcic soil profile and measured section C, Salt Valley area, Utah. Location of profile shown on figure 5. Carbonate morphologic stages after Gile and others (1966) and Machette (1985). Horizon nomenclature after Gile and others (1965).

Figure 8. Tilted remnants of an erosion surface capped by the strongly developed petrocalcic soil in Cache Valley at locality 3 (figures 1 and 5). The surface is tilted approximately 8 degrees to the northeast. View is to the north.

developed in eolian and alluvial sand and reaches carbonate morphologic stage V in its Km21 horizon (figures 6 and 7; terminology after Gile and others, 1965, Gile and others, 1966, and Machette, 1985). Soils elsewhere on the Colorado Plateau having comparable carbonate morphology are formed in parent materials having reversed paleomagnetic polarity, and are early Quaternary in age and possibly older (Biggar, 1983). Some soils in the American southwest having stage V carbonate morphology may be late Pliocene or older in age (Machette, 1985).

The Cache Valley petrocalcic soil is formed on an eolian-mantled geomorphic surface that truncates gently dipping strata of Jurassic age, primarily the Entrada Sandstone. The surface itself is tilted approximately 8 degrees to the east or northeast (figure 8). The observed tilt may be the initial dip of the surface or may be the result of tectonic tilting. Dane (1935, p. 137-138) recognized the soil and noted that it was cut by a fault that also displaces the underlying bedrock (figure 5).

Deformation also occurred in this area prior to the development of the erosion surface and the petrocalcic soil. The area is along the trend of the Roberts rift (figures 2 and 7 of Hite, 1975), which in this area is expressed in cross section as a crack in the Slickrock Member about 500 feet wide, filled with over 160 feet of horizontally bedded sand, clay, minor gravel, and jumbled coarse rock debris (figure 5). The coarse debris is similar to that in the rubble mounds of Dyer (1983; see also Doelling, 1985) and consists of blocks of the Tidwell and Salt Wash Members of the Morrison Formation—rocks which are no longer preserved on the walls of the crack. Northeast of here, two small diapirs of the Paradox Formation on the floor of Cache Valley, and a northeast-trending graben on the north flank of the valley (Dane, 1935; Doelling, 1985), are in line with the Roberts rift.

The relationships exposed in the area of figure 5 indicate the following geologic history. During an early period of collapse along the axis of the Cache Valley anticline, during which the major bedrock faults A and B (figure 5) formed, the Roberts rift opened along a northeast-trending zone of weakness in the

Entrada Sandstone. The structural details of how the crack opened are not known, but after it had opened it was filled with debris that fell in from the sides. Undeformed fine-grained sediments fill the spaces between accumulations of coarse debris in the crack. No buried soils or unconformities have been detected in the fine-grained fill, showing that the sediments accumulated nearly continuously and possibly rapidly. During or after crack filling, the area was tectonically stable and most rocks younger than the Entrada Sandstone were eroded. The geomorphic surface thus formed was capped by thin eolian sands in which the petrocalcic soil developed. Parent material for the soil was in place, and the period of tectonic stability was underway, at least by early Quaternary time, and possibly by late Pliocene time. During or since the early Quaternary, fault displacement, totalling approximately 12 feet (Dane, 1935, p. 137-138), was renewed along fault A (figure 5), and the entire area is interpreted as having been tilted to the east or northeast. Along the Colorado River east of here, Quaternary terraces are slightly tilted upstream on the upstream side of the Cache Valley anticline, suggesting that salt continued to flow into the collapsed anticline in Quaternary time (Colman, 1983). The combination of salt flow into the anticline from adjacent areas and collapse along the axis of the anticline could cause the structures observed in eastern Cache Valley.

LOWER SALT VALLEY

At the lower (east) end of Salt Valley, within 1.5 miles of its juncture with Salt Wash (locality 1, figure 1), a thick sequence of Quaternary sediments is exposed (figures 9-13) and displays some of the best evidence of Quaternary salt deformation on the floor of Salt Valley. Dyer (1983) and Dyer and others (1983) considered these beds as part of the "Formation of Salt Valley," of probable late Tertiary age. The sediments include two volcanic ash beds, however, identified as Bishop ash (0.74 Ma) and Lava Creek B ash (0.62 Ma; G. A. Izett, personal communication, 1984; Izett, 1982; Izett and Wilcox, 1982), and therefore are Quaternary in age. The Bishop ash had been previously collected at this locality by S. M. Colman (personal communication, 1984).

For the purposes of this report, the Quaternary beds exposed in the area of figure 9 have been divided into five mappable lithologic units. These are: two basal gravels, two fine-grained lower basin-fill units, and an upper fine-grained basin-fill unit. The volcanic ash beds are found in the folded and faulted lower basin-fill units, which are separated from the upper basin-fill unit by an angular unconformity.

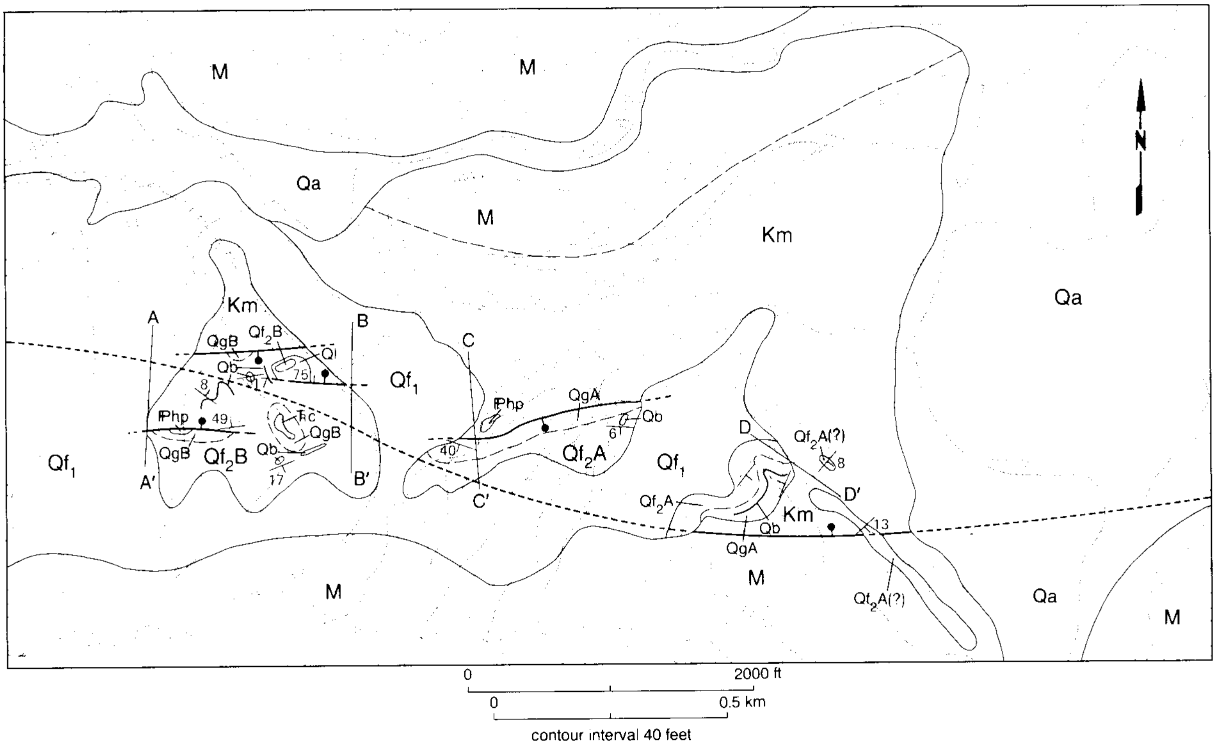
Gravels at the bases of the lower basin-fill units unconformably overlie dipping Mesozoic bedrock (figure 10). The gravels are loose to well cemented and contain pebbles of many varieties of chert and igneous and metamorphic rocks, as well as occasional clasts of the exotic Eocene chert, probably derived from exotic gravel assemblage A upstream in Salt Valley (see discussion under Exotic Gravels). Clasts of locally derived bedrock from the Glen Canyon Group, the Morrison Formation, the Cedar Mountain Formation, and the Mancos Shale are dominant in the basal gravels. The gravels were probably deposited in the channel of ancestral Salt Valley Wash. Similar gravels are exposed upstream in Salt Valley.

In the vicinity of section D-D′ (figure 10) Bishop ash is interbedded with a basal gravel that overlies the Mancos Shale, but near section B-B′ (figure 10) Bishop ash is interbedded with sandy basin-fill deposits approximately 60 feet above the basal gravel. This shows that there are two basal gravels in this small area, and that multiple unconformities and facies changes should be expected in the Quaternary deposits of Salt Valley. It is also the basis for separating the lower basin-fill sediments into two mapping units (figure 9). Based on the known ages of the Bishop and Lava Creek B ashes and their measured stratigraphic separation, the age of the basal gravel at section B (figure 13) is probably greater than 1 Ma.

The lower basin-fill sediments are generally sandy with marly beds containing diatoms (Dyer and others, 1983), ostracodes, poorly preserved plant-root structures, and other evidence of possible bioturbation. The boundaries of the basins are poorly defined, but the marly sands and local pond marls were deposited in closed basins or in areas of impeded drainage or standing water. The presence of sedimentary basins in this area suggests that during the period of deposition the base level of Salt Valley Wash was rising, or that the basins were subsiding due to salt dissolution. Either case would have been a sharp contrast to the modern erosional regimen of this stream.

The lower basin-fill sediments have been faulted and folded. Near the junction of the main Arches National Park paved road and the gravel road to Delicate Arch, a syncline and an adjacent anticline are well exposed (figures 9 and 10). At this locality the beds apparently thicken slightly toward the axis of the syncline and become thinner over the axis of the anticline. Bishop ash is exposed along the axis of the syncline and on the south flank of the anticline, but it is not present near the axis of the anticline although the marly bed that locally contains the ash can be traced across the structure. The slight thickening of beds and accumulation of ash in the syncline demonstrates that deformation was taking place during deposition, but the presence across the anticline of marly beds, which imply deposition in low areas of standing water, suggests that deformation continued after the sediments were deposited. A small fault that dips 75 degrees northward within the lower basin-fill sediments displaces Lava Creek B ash (figures 9 and 10), but apparently either dies out lower in the section or decreases in relative displacement to the west, or both.

The upper basin-fill sediments are generally sandy but intertongue laterally with sandy gravel containing a greater percentage of sandstone clasts derived from the walls of the Salt Valley anticline than do the lower gravels in this area. A basal gravel overlying bedrock is present in some sections. Locally the upper basin-fill sediments contain beds rich in gypsum that was probably derived from the caprock of the Paradox Formation (H. H. Doelling, personal communication, 1984), which occurs in isolated diapirs in the valley. An angular unconformity, produced during a period of stability and lateral planation, separates the upper basin-fill sediments from older units.



EXPLANATION

Qa	Holocene alluvium
Qf_1	Upper basin-fill deposits; includes Holocene sand dunes
Ql	Lava Creek B ash
Qf_2A	Lower basin-fill deposits; eastern basin
Qf_2B	Lower basin-fill deposits; western basin
Qb	Bishop ash
QgA	Basal gravel; eastern basin
QgB	Basal gravel; western basin
Km	Mancos Shale
TRc	Chinle Formation
M	Mesozoic rocks; undivided
ℙhp	Caprock of Paradox Formation
	Contact, dashed where approximately located
	Fault, dotted where concealed; bar and ball on downthrown side
16	Strike and dip of fault plane
	Apparent dip of beds
17	Strike and dip of beds

Figure 9. Geologic map of Quaternary deposits and related features in lower Salt Valley (locality 1, figure 1).

Upper basin-fill sediments thicken toward the valley, indicating a second period of rising base level in Salt Valley Wash or of basin subsidence, but the beds show little evidence of deformation other than slight valleyward tilting. Faults that offset the lower basin-fill sediments do not displace the upper basin-fill deposits (figure 10). Marly beds are uncommon and are thinner and less extensive than in the lower basin-fill unit, and the center of the basin was farther to the north than it had been earlier.

Based on a reconnaissance assessment of the degree of soil development (S. M. Colman, personal communication, 1984) and on stratigraphic position, the upper basin-fill deposits are considered middle Quaternary in age. They unconformably overlie the Lava Creek B ash (0.62 Ma) and bear a calcic soil having stage II to stage III carbonate morphology.

Caprock of the Paradox Formation is exposed at two localities in the area of figure 9. At the western locality (near cross section A-A′) it consists of highly deformed yellow sandstone,

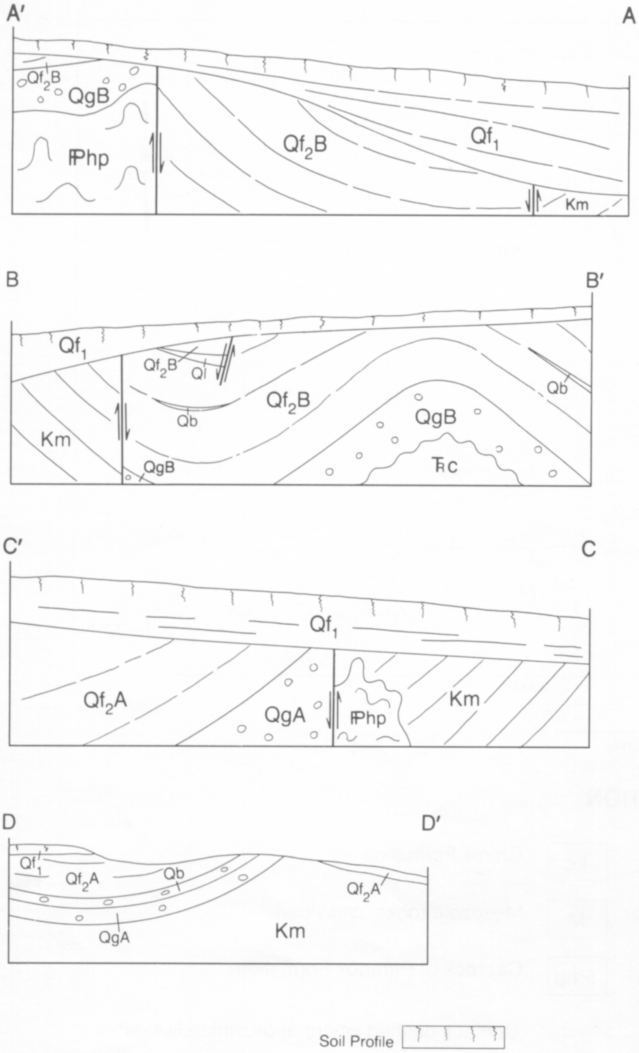


Figure 10. Diagrammatic geologic cross sections of figure 9, Salt Valley, Utah. Data for cross sections are projected from badland exposures onto cross section planes located approximately as shown in figure 9. Most faults are shown with vertical dips because their actual dips are unknown.

platy limestone, and black carbonaceous shale. Its upper contact with the basal Quaternary cemented gravel is irregular and the lowest beds of the conglomerate are fractured and slightly folded into the deformed caprock. The eastern outcrop of caprock (near cross section C-C′) consists of highly contorted gypsum and black carbonaceous shale that underlies the Mancos Shale, which likewise is complexly deformed and folded into the gypsum. In both localities the rocks of the Paradox Formation are found in the upthrown blocks of faults that cut the lower basin-fill sediments. The faults trend generally east-west, parallel to the major structures of the Salt Valley anticline. These patterns suggest that Quaternary deformation in this area was controlled by larger and older structures that continued to be active. In this area it is not possible to demonstrate whether the Quaternary deformation was caused by upward movement of salt or by collapse due to dissolution of salt at depth, or by both causes.

In summary, the Quaternary stratigraphy and structures within the small area of figure 9 indicate the following history. Deposition of basal fluvial gravel on the floor of Salt Valley began in early Quaternary time, probably before 1 Ma. Soon after gravel deposition had commenced, a small sedimentary basin began to form in the vicinity of profiles A-A′ and B-B′ in which sand, marly sand, and volcanic ash accumulated (Qf_2B, figure 9). While this basin was filling with fine-grained sediments, however, the channel of Salt Valley Wash was still active as shown by the occurrence of Bishop ash in channel sand and gravel near profile D-D′, but in basin-fill deposits in profile B-B′. This shows that the sedimentary basin at profiles A-A′ and B-B′ was separated from the main fluvial system of Salt Valley during much of its history. Following deposition of Bishop ash (0.74 Ma) a second sedimentary basin began forming in the vicinity of profiles D-D′ and C-C′ in which sands, marly sands, and marls accumulated (Qf_2A, figure 9). Sedimentation continued in the western basin until at least the time of deposition of Lava Creek B ash (0.62 Ma). The lower basin-fill sediments were folded and faulted both during and after their accumulation.

Figure 11. Deformed Quaternary sediments in Salt Valley at locality 1 (figures 1 and 9). View east of tilted Bishop ash (a) and Lava Creek B ash (b), directly west of the Delicate Arch road/main Arches highway intersection.

In middle to late Quaternary time, deformation ceased and the structures were planed off. The middle Quaternary basin-fill sediments were deposited across the truncated structures and have been deformed very little. They accumulated in an entirely separate basin slightly north of the older basins. Late Quaternary and modern erosion along Salt Valley Wash and its tributaries has exposed the older Quaternary deposits and structures. The accumulation of sediments in basins, and the folding and faulting of the sediments, were caused by dissolution of salt at depth or by upward movement of salt during Quaternary time.

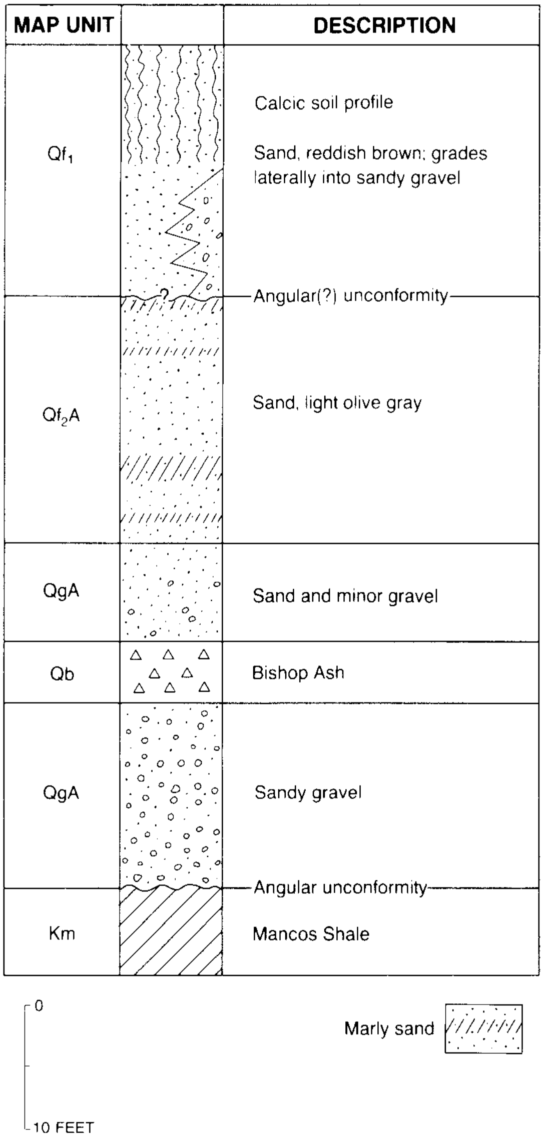


Figure 12. Measured section A; measured near cross section D-D′, figure 9; Salt Valley, Utah.

MIDDLE AND UPPER SALT VALLEY

Caprock of the Paradox Formation is exposed at a number of localities along the middle and lower reaches of Salt Valley where the Quaternary fill and underlying rocks are dissected. Figure 14 is a schematic cross section showing structures commonly associated with exposures of the Paradox Formation in the vicinity of locality 8 (figure 1). Structural relationships suggest that salt diapirs of the Paradox Formation have locally pushed up and deformed younger rocks. The deformation consists of both Mesozoic beds and Quaternary fluvial sediments that dip away from the outcrops of Paradox Formation on both the upstream and downstream sides of the outcrops, and of both high- and low-angle reverse faults in Quaternary sediments (figure 15). Local accumulations of Quaternary sediment over 100 feet thick suggest that subsidence occurred in areas adjacent to the salt diapirs. Upward movement of salt and subsidence of an adjacent sedimentary basin have been documented in the Onion Creek salt diapir in Fisher Valley (Colman, 1983).

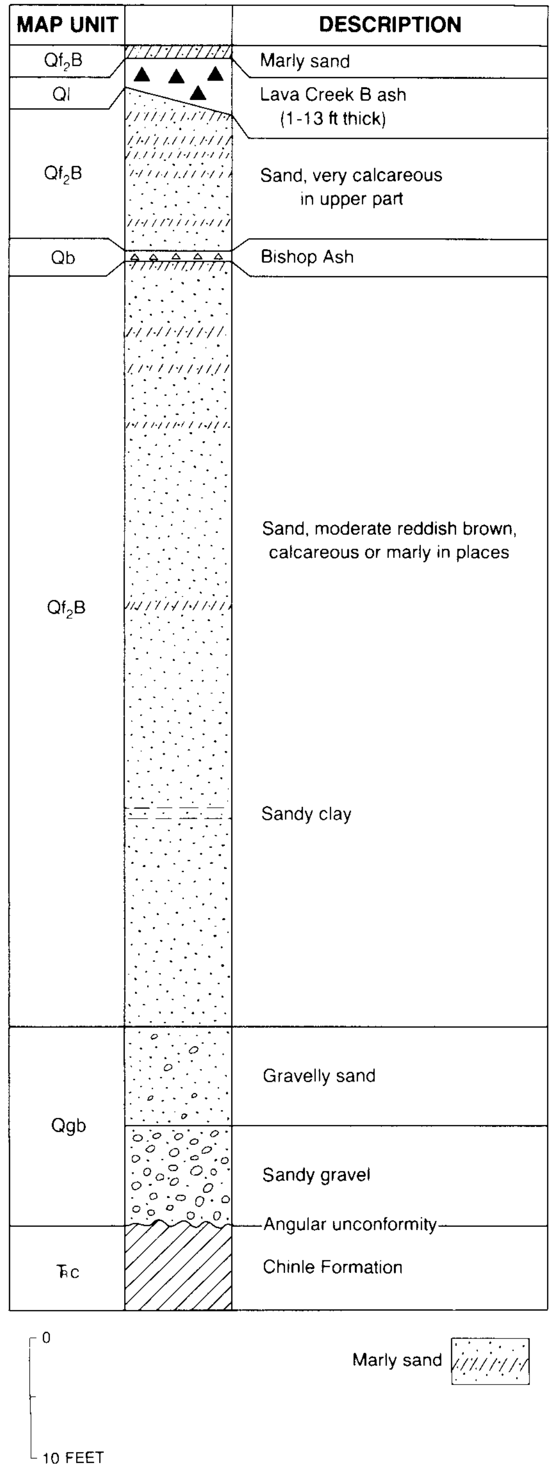


Figure 13. Measured section B; measured near cross section B-B′, figure 9; Salt Valley, Utah.

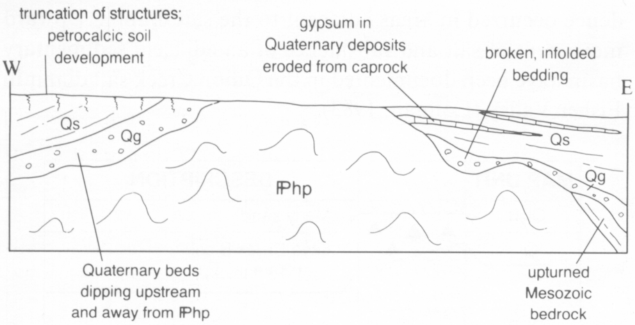


Figure 14. Diagrammatic cross section in Salt Valley in vicinity of locality 8 (figure 1) showing typical stratigraphic and structural relationships exposed in this part of the valley.

Bishop ash has been reported in valley fill at Salt Valley locality 9 (figure 1; NE¼ NE¼ NW¼ sec. 10, T. 24 S., R. 21 E.; S. M. Colman, personal communication, 1984), showing that a depositional basin existed here at the same time as the basins in lower Salt Valley. Therefore, the floor of Salt Valley during Bishop-ash time (0.74) Ma) was characterized by multiple small sedimentary basins localized by salt dissolution and collapse, and (or) by salt diapirism.

In Salt Valley where the Mancos Shale is underlain by the Paradox Formation, the shale is highly contorted and faulted, and Quaternary sediments are folded and faulted into the shale. The Mancos Shale is more ductile than the other local bedrock units, which consist predominantly of brittle sandstone.

Many of the salt diapirs in the upper part of the valley have not been dissected but are expressed topographically as low mounds on the floor of the valley. Caprock of the Paradox Formation is exposed in the cores of some of the mounds, and Mesozoic strata form dome structures surrounding the cores (Doelling, 1985). Some mounds of probable Tertiary-age alluvial gravel containing exotic clasts, which now stand topographically higher than the younger valley fill, are interpreted as having been forced upward by salt diapirism.

In the vicinity of the drainage divide in Salt Valley (locality 4, figure 1), and at a number of other localities northwest of the divide on the floor of the valley, surface runoff and sediment are trapped in mud flats or playas (figure 16). Salt dissolution at depth, which creates local subsidence, and (or) small salt diapirs, which have locally blocked the drainage system of Salt Valley, have caused the playas to form. Most of the playas overflow to external drainage, but runoff is impeded by low gradients on the playa surfaces and by constricted outlets.

One playa northwest of the drainage divide has an entrenched channel cut along the contact between the Paradox caprock and Quaternary gravels. The playa at this locality is in the initial stages of dissection by the stream that drains it. A low inset terrace 2 to 3 feet high in the entrenched channel of the draining stream suggests episodic cutting and filling of the channel, and therefore of the playa. The episodic cutting and filling could be caused by episodic salt deformation, by climatic change, or by normal intrinsic processes of sediment storage and flushing in the ephemeral stream.

The playas in the upper part of Salt Valley show that salt deformation is presently active in this area. The areas affected by salt deformation are small, probably less than 0.25 mile in diameter, but they are common. It is likely that the playas represent a depositional environment similar to the environment in which the lower basin-fill sediments, including the volcanic ash beds, were deposited in lower Salt Valley (locality 1, figure 1). The pond marls and marly sand beds exposed in lower Salt Valley represent periods of more effective moisture (e.g., cooler or wetter climate), or times when the basins were closed to external drainage due to increased salt deformation.

BRAIDED CHANNEL OF SALT WASH

Salt Wash flows southward from the Book Cliffs and crosses the axis of the Salt Valley anticline at a high angle

Figure 15. Low-angle (25°) reverse fault in Quaternary alluvial gravel in Salt Valley at locality 8 (figure 1). The nearly horizontal stress required to produce this fault was probably created by salt diapirism. Individual beds are offset 1.5 feet along the fault.

Figure 16. Two small playas in northern Salt Valley, northwest of the drainage divide at locality 4 (figure 1). In this area, the axial drainage in the valley has been impeded and sediments are accumulating due to damming by salt diapirism and/or to subsidence caused by salt dissolution. View is to the northwest.

(figure 1). The present erosional regimen of this stream in the reach above the anticline contrasts with the depositional regimen of the reach that crosses Salt Valley and suggests that the core of the anticline is presently subsiding.

In the entrenched reach above the anticline (locality 2, figure 1) the valley of Salt Wash is wide and contains at least two mappable alluvial terraces, as much as 20 feet above modern stream level, which are probably late Holocene in age based on the weak soil development at their surfaces and on their morphologic similarity to dated terraces in other drainages in the Colorado Plateau. No comparable terraces exist in the reach that crosses Salt Valley, and the braided channel and flood plain are essentially at the level of the valley floor. The depth of fill is unknown, but the stream appears to be actively aggrading in this reach.

Although it is possible for ephemeral streams to undergo simultaneous entrenchment and aggradation in different reaches independent of changes in extrinsic controls such as tectonism (Patton and Schumm, 1981), the boundary between the two distinct reaches of Salt Wash coincides with the northern flank of the Salt Valley anticline. It is likely, therefore, that the core of the Salt Valley anticline is subsiding and is thus inducing aggradation in the short reach of Salt Wash that crosses Salt Valley. Similar stream braiding and aggradation are occurring in the grabens of the Needles fault zone of Canyonlands National Park where ephemeral streams cross the downfaulted blocks (B. L. Everitt, personal communication, 1984). There is independent evidence that the faults of the Needles fault zone are presently active structures (Huntoon, 1982, p. 949; Biggar, 1983, p. 22-30).

QUATERNARY HISTORY AND CONCLUSIONS

The late Tertiary and Quaternary history of Salt Valley can be summarized as follows. By Miocene time the Colorado River drainage system was established and the entire Colorado Plateau was being eroded in response to regional uplift (Hunt, 1969). Tremendous volumes of Cretaceous and Tertiary rocks were eroded from the Salt Valley area in Miocene and Pliocene time. A late Pliocene to early Quaternary erosion surface documented by Biggar and others (1981) in the Green River area may correlate roughly with the erosion-surface remnants in the Salt Valley and Cache Valley areas that are capped by stage IV to stage V petrocalcic soil profiles. During the formation of this surface probably only the major rivers, such as the Green and Colorado, were incised (Biggar and others, 1981, p. 141), and Salt Valley anticline had not begun, or was in the early stages of, collapsing. In addition, consequent streams, such as the stream that carved Little Canyon, were flowing off the flanks of the salt anticlines which were probably partly exhumed structures but may also have been forming in response to erosional unloading. A stream that deposited exotic gravel assemblage A was flowing across the Salt Valley anticline prior to its complete collapse.

Salt Valley anticline had begun to collapse as a result of salt dissolution by at least late Pliocene time. The anticline had collapsed considerably by 0.74 Ma when the Bishop ash was deposited in local sedimentary basins on the floor of Salt Valley. Local subsidence and diapirism continued through the middle and late Quaternary and are still active today.

The effects of upward salt flowage or diapirism are difficult to distinguish from the effects of salt dissolution and collapse. Both processes induce vertical stresses that can create identical structures in the Quaternary sediments. Subsidence due to salt dissolution at depth is a more likely Quaternary deformational process than diapirism; however, certain relationships are strongly suggestive of upward salt movement. For instance, Quaternary sediments dipping away from outcrops of Paradox Formation caprock, in combination with the reversal of depositional dip in Quaternary fluvial sediments on the upstream sides of outcrops of the caprock, are best explained by upward movement of the caprock and underlying salt as a diapir, which blocks the through-flowing drainage in a valley (Colman, 1983). These conditions can be demonstrated on a small scale in the middle part of Salt Valley. In addition, if subsidence were the dominant deformational process in Salt Valley and other areas, the locus of the greatest amount of dissolution, and hence of subsidence and sediment accumulation, should be where the salt is closest to the surface (S. M. Colman, personal communication, 1984). Therefore, the Quaternary beds would be expected to dip toward the outcrops of Paradox caprock. However, the deformed Quaternary beds in Salt Valley invariably dip away from the caprock outcrops—a pattern that cannot be explained by subsidence and requires upward movement of salt. Therefore, the evidence suggests that in Salt Valley both salt diapirism and subsidence have been active in Quaternary time and are probably still active.

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LATE CENOZOIC GRAVITY TECTONIC DEFORMATION RELATED TO THE PARADOX SALTS IN THE CANYONLANDS AREA OF UTAH

by
Peter W. Huntoon
Faculty, University of Wyoming

UTAH GEOLOGICAL AND MINERAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
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ABSTRACT

The Pennsylvanian Paradox salts and overlying rocks in Canyonlands, Utah, are deforming in response to three mechanisms: (1) salt flowage, (2) salt dissolution, and (3) gliding of the rocks above the salts. The resulting faulting and folding of the rocks above the salt can be classified as gravity tectonic in origin because gravity-induced stress gradients drive the deformation.

Factors which have contributed to accelerated rates of salt-related deformation in post-Miocene time include: (1) erosion of the canyons of the Colorado River, and (2) erosional stripping of the Triassic and younger rocks from large parts of the area. Canyon cutting provided the topographic relief necessary to induce the differential stresses which facilitate salt flowage and overburden gliding. Erosion of the Triassic section removed confining layers above the Pennsylvanian-Permian section, thus enhancing ground-water circulation through the rocks above the salts to promote dissolution.

Both salt flowage and dissolution have taken place periodically in the region since the salts were deposited beginning in Pennsylvanian time. However the current cycle of rapid salt dissolution, gliding, and diapirism was triggered by erosion of the canyons of the Colorado River and concurrent stripping of the Permian surface. Incision of the canyons of the Colorado River is a Pliocene and later event so the present generation of structures is younger than 5 Ma (million years).

PURPOSE

The purpose of this paper is to classify and describe the post-Miocene salt-related structures that occur in the vicinity of Canyonlands National Park, Utah. Attention is focused on the physical processes that cause deformation of the overlying rocks and on evidence that these processes are still operating or have been active during Quaternary time.

CENOZOIC TECTONIC PROCESSES AND SALT DESTABILIZATION

As shown on figure 1, the area of concern lies on the southwestern margin of the Paradox Basin, defined as that region underlain by the salt facies of the Pennsylvanian Paradox Formation. The Paradox salt section is shown schematically on figure 2. Post-Pennsylvanian burial of the salt, variable externally imposed regional tectonic stresses, and erosion have produced changing states of stress within the salt body and overlying rocks ever since they were deposited. Changing stress gradients within the salt body have produced episodic deformation of the salt and younger rocks throughout most of post-Pennsylvanian time. The concerns of this paper are the salt-related gravity tectonic mechanisms that continue to cause deformation in the Canyonlands area.

Major uplift of the region containing the Paradox Basin has been taking place throughout Cenozoic time. This has resulted in substantial erosion of the rock sequence housing the Paradox salts. In the process the salt itself and the rocks overlying the salt have become destabilized. Consequently there has been continuing deformation and destruction of these rocks, in some cases at ever accelerating rates.

Three processes are now operating to deform or destroy the salt in the Canyonlands area: (1) salt flowage accompanied by folding and faulting of the overlying rocks, (2) salt dissolution accompanied by collapse of overburden strata, and (3) gliding and attendant disaggregation of the overburden rocks above the salt horizon. Many of the resulting structural features postdate erosion of the modern canyons of the Colorado River and hence are less than a few million years old.

The salt-related structural features initiated during late Cenozoic time in the Canyonlands vicinity owe their youthfulness to: (1) the cutting of Cataract Canyon and deep incision

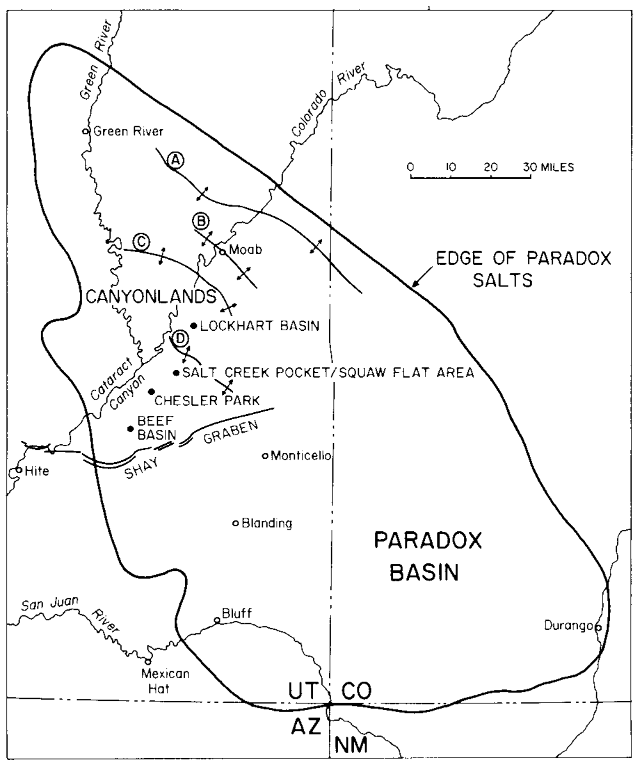

Figure 1. Location of the Paradox Basin, Utah and Colorado, and selected structural features discussed in this article. Salt anticlines: A -Sinbad-Fisher-Cache-Salt Valley, B - Spanish Valley, C - Cane, D - Gibson Dome. Data from Williams (1964), Huntoon and others (1982), and Woodward-Clyde Consultants (1983).

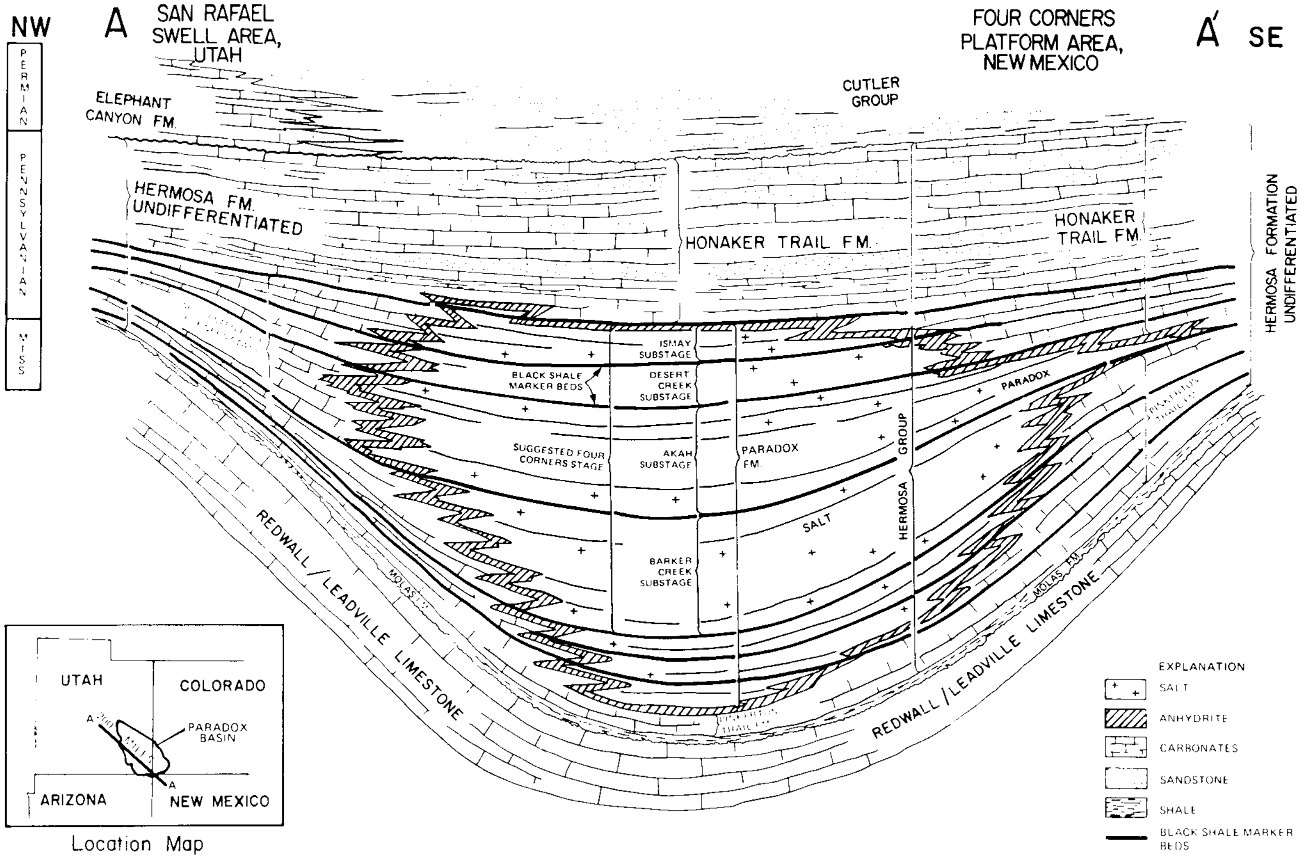

Figure 2. Schematic vertically exaggerated profile showing the Paradox salts within the Pennsylvanian section, Paradox Basin, Utah. The Triassic section rests directly above the Cutler Group. From Woodward-Clyde Consultants (1982) as redrawn from Baars and others (1967).

of its tributaries, and (2) erosional stripping of the Triassic and younger rocks from above the Permian section.

The erosion of the deep canyons has destabilized the geologic environment by enhancing gravity tectonic processes. Included are landslide features such as the Needles fault zone and the accompanying Meander anticline, and salt flowage features such as rejuvenated deformation along existing salt anticlines and emplacement of salt diapirs along the Colorado River in Cataract Canyon.

The removal of the Triassic and younger strata from the region has produced a more subtle, but no less important, impact by enhancing ground-water circulation through the post-salt Pennsylvanian-Permian section. The upper boundary for this ground-water system consists of the Triassic Moenkopi and Chinle Formations, both of which contain regionally extensive thick shale confining layers. With erosion of these units, direct hydraulic connection is made possible between surface waters and the permeable zones within the Pennsylvanian-Permian section, particularly faults. The consequent enhancement of ground-water circulation rates has significantly increased rates of dissolution of the underlying Paradox salts. The result has been development of collapse features such as Lockhart and Beef Basins.

TIMING OF LATE CENOZOIC DEFORMATION

The topographic position of erosion surfaces and late Cenozoic deposits summarized in Hunt (1969), Biggar and others (1981, p. 140-141), and Woodward-Clyde Consultants (1983) reveals that the Permian surface in the vicinity of Canyonlands was largely stripped of its Triassic cover by the end of Miocene or beginning of Pliocene time. Incision of the Permian section by the Colorado River appears to have been a Pliocene event so that most of the present depth of Cataract Canyon and many of its tributaries was accomplished before the beginning of Quaternary time. The significance of the timing of these events is that most of the structural features to be discussed here date from Pliocene or later time. Therefore, they are younger than 5 million years old.

For example, remnants of shallow Miocene(?)-Pliocene(?) channels that were eroded on the Permian surfaces in the vicinity of Cataract Canyon are preserved on the surface of horst blocks within the Needles fault zone. These channels occur as abandoned hanging valleys that trend perpendicular to the strikes of the faults, and they can be traced from horst to horst toward what is now Cataract Canyon. From these it is clear that the Needles fault zone postdates deep incision of Cataract Canyon.

As shown on figure 3, the tectonic evolution of the region has removed the bedded Paradox salts from their once reasonably stable, deep burial status to one of great instability.

SALT FLOWAGE

The Pennsylvanian Paradox salt facies is as thick as 5,000 feet under the Canyonlands of Utah. This unit consists of as much as 85 percent halite (sodium chloride) and 15 percent interbedded gypsum, limestone, dolomite, and shale. The salt section is best imagined as a viscous liquid that can flow in response to imposed stresses. It has been flowing at variable rates since it was originally deposited over 300 million years ago.

The most dramatic examples of this flowage are the great salt anticlines which trend northwestward throughout the Paradox Basin. These anticlines dominate the structural fabric of the Paradox Basin. Their evolution is summarized on figure 4. In places, accumulation of salt in the cores of the anticlines was well over 10,000 feet thick. The periodic influx of salt into the cores of the anticlines caused the overlying rocks to arch upward, even as many of the units were being deposited. The Spanish Valley salt anticline at Moab is one of the more prominent of these anticlines.

Figure 4 illustrates that the dominant process by which salt accumulated in the cores of the anticlines before the close of Mesozoic time was through lateral flowage of the Paradox salts from areas adjacent to the anticlines. Gradually the salt in the flanking regions was greatly attenuated or depleted.

Salt flowage within the anticlines has become more localized during Cenozoic time wherein diapiric cells of salt have risen off parts of the salt cores. The salts feeding the diapirs were, and continue to be, derived from adjacent sites along the axes of the anticlines. Consequently the rocks along the axes of the anticines are refolding into a series of domes and basins. As the domes grow in height, the basins subside.

A less dramatic example of salt flowage in the area has been the geologically young squeezing of salt into and through the overlying strata along the floor of Cataract Canyon. Piercements of the salt have extruded through the Honaker Trail Formation at few locations in Cataract Canyon.

QUATERNARY SALT FLOW INTO THE CORE OF THE GIBSON DOME ANTICLINE

Strong circumstantial evidence reveals that there is active salt flowage into the core of the Gibson Dome anticline which is causing its continued growth. Examination of figure 5 reveals that Quaternary alluvium has accumulated in large volumes in the entire Indian Creek drainage system upstream from the axis of the Gibson Dome anticline. In contrast, these same sediments have been almost entirely swept clean from the canyon downstream from the axis. The distribution of Quaternary sediments coupled with the extremely gentle upstream gradient of Indian Creek indicates that the axis of the anticline is rising to form a dam that is causing the sediments to deposit.

Verification of this hypothesis awaits core drilling and trenching of the Quaternary units upstream from the anticline in order to characterize the timing and geometries of the Quaternary deposits. However, the proposition that Gibson Dome anticline is still rising is not surprising. Recent work along the analagous Sinbad-Fisher-Cache-Salt Valley anticline northeast of Moab by Colman (1983) and Oviatt (this publication) confirms Pliocene and Quaternary deformation along the salt anticlines in the region. Colman (1983) describes a setting in which salt diapirs are rising in pulses from the salt mass that comprises the core of the anticline. The result is the development of localized domes along the axis of the anticline with intervening depositional basins.

Colman (1983, p. 242) states:

> "The Onion Creek diapir has moved upward at least 70 m, and the adjacent sedimentary basin has subsided a similar amount, for a total relative displacement of about 140 m. These movements occurred, apparently in pulses, between perhaps 2-3 and 0.25 m.y. ago. Younger movement of the diapir is possible but is difficult to demonstrate because younger basin-fill deposits are absent. The steep, unstable valley walls of Onion Creek where it cuts through the caprock suggests that the diapir may still be active."

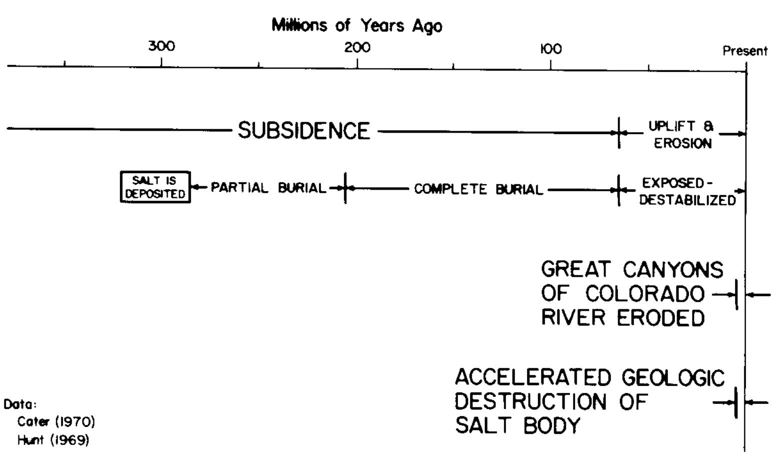

Figure 3. History of the Paradox salt deposits in the Canyonlands area, Utah.

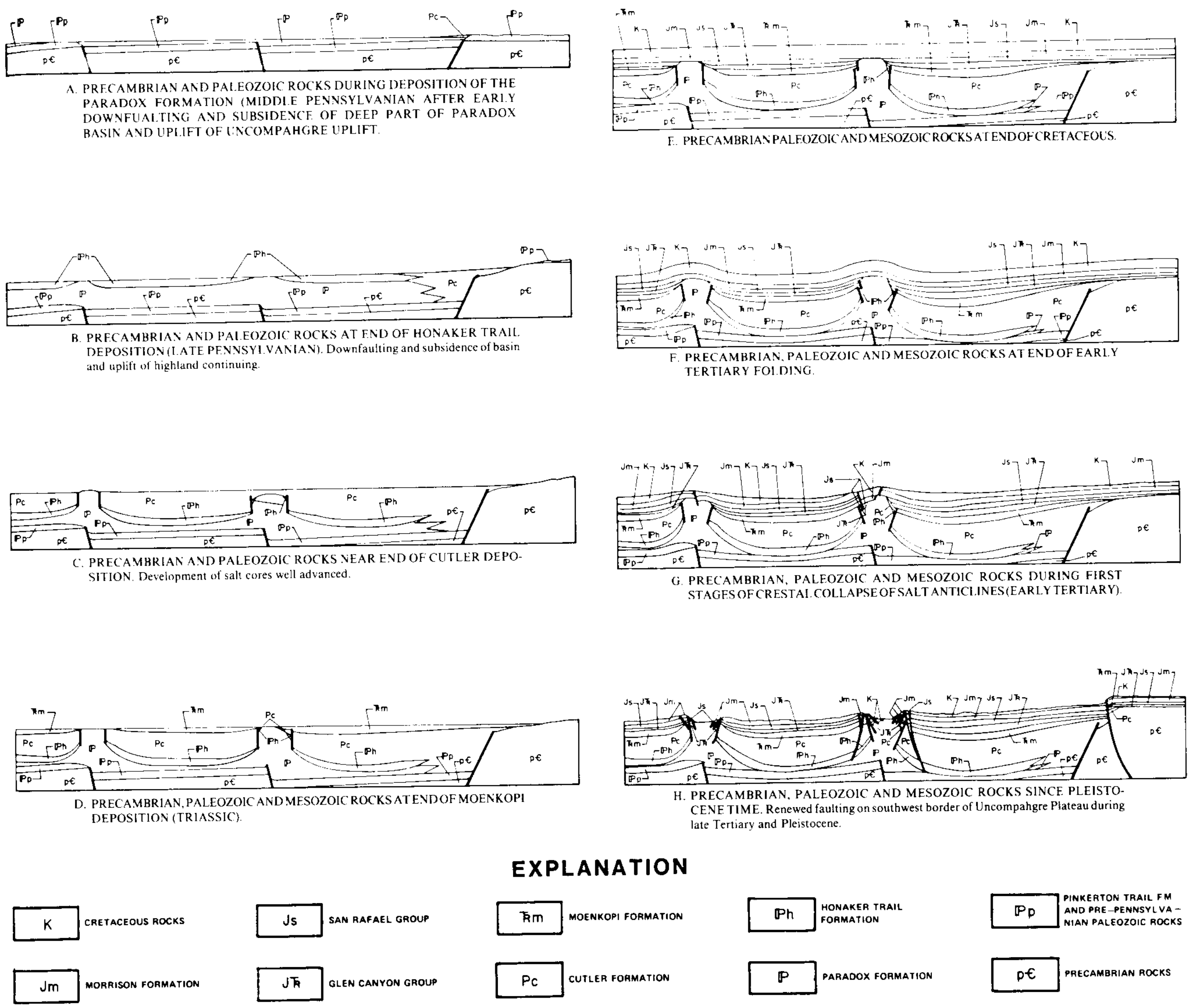

Figure 4. Structural evolution of the Gypsum Valley-Paradox Valley salt anticline, a typical salt anticline in the Paradox Basin of Utah and Colorado. Figure from Woodward-Clyde Consultants (1983, figure 6-8) as modified from Cater (1970, figure 13).

Oviatt (this publication) has discovered identical evidence for Quaternary deformation along the Cache Valley and Salt Valley segments of the same anticline to the north. In places the datable Bishop and Lava Creek B tuffs, respectively 0.73 Ma and 0.61 Ma old (Izett, 1981), are folded to 60 degrees or more as a result of the growth of the diapirs (see figure 6). Doelling (1984) has observed recent ponding of sediments in broad depressions developed along the northern part of the axis of the Salt Valley anticline. The implications of these ponded sediments are that diapirs are currently rising along the anticline and locally blocking drainages.

Biggar and others (1981, p. 133-134) thoroughly summarize observations made by numerous workers concerning folded and faulted Pliocene and Quaternary deposits along various salt anticlines in the region including Spanish Valley. Some of the reported deformation is the result of Quaternary salt flowage comparable to that described above for the Sinbad-Fisher-Cache-Salt Valley anticline. The accumulated evidence confirms that salt flowage and attendant anticlinal growth is a continuing Quaternary process. It is certainly reasonable to assume that the same salt flowage-anticlinal growth mechanisms are currently operating along the Gibson Dome anticline.

The rate of growth of the Gibson Dome anticline is undoubtedly less than that documented along the Sinbad-Fisher-Cache-Salt Valley anticline for the following reasons: (1) the available salt section in the vicinity of Gibson Dome is thinner; (2) the salt is not exposed or particularly close to the surface along the Gibson Dome anticline; (3) the topographic relief between the eroded crest of Gibson Dome anticline and adjacent loaded synclines is less than comparable load differentials along the Sinbad-Fisher-Cache-Salt Valley anticline.

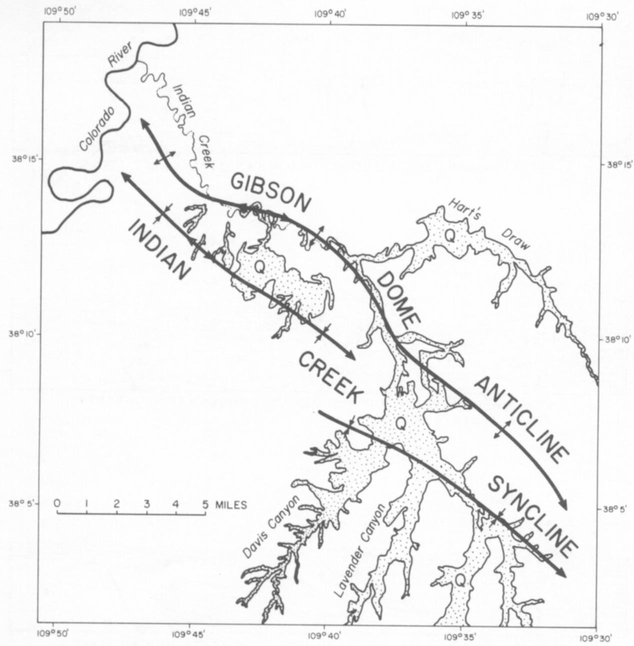

Figure 5. Map showing that Quaternary rocks (stippled) have deposited upstream from the rising axis of the Gibson Dome salt anticline in the main stem and all tributaries of Indian Creek. Adapted from Huntoon and others (1982).

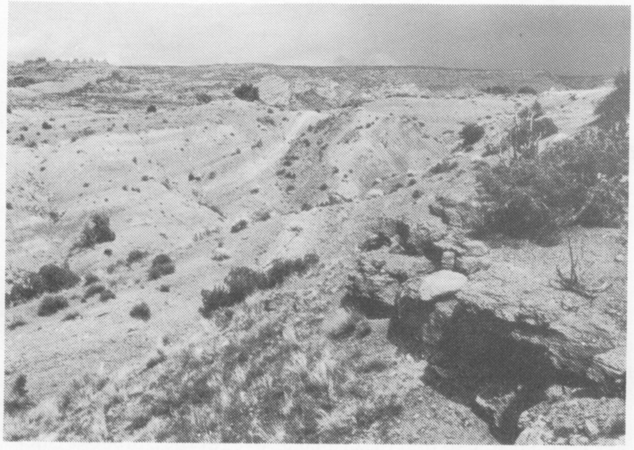

Figure 6. Steeply folded Quaternary sediments along the Salt Valley anticline, Utah. The deformation is the result of salt flowage into diapirs rising from the salt core of the anticline.

CATARACT CANYON DIAPIRS

Four small salt diapirs rising from the Paradox Formation have pierced through the Honaker Trail Formation in the floor of Cataract Canyon. These are respectively shown on figure 12 as the Harrison dome, Prommel dome, and the two Crum domes. Their positions are both structurally and topographically controlled.

Three of the diapirs are situated on the axes of valley anticlines, and all four are on the eastern flank of the Meander anticline. The locations appear to be controlled by (1) weaknesses associated with fracturing along the crests of the anticlines, and (2) the fact that the thickness of the bridging Honaker Trail Formation is minimized as a result of the doming of the unit and the topographic beveling of the domes by the floor of the canyon. As shown on figure 7, the salt plugs that are exposed stand as high as 200 feet above the floor of the canyon and are highly eroded with no sodium chloride remaining.

Because the plugs are in part topographically controlled, they postdate most of the cutting of Cataract Canyon. Initial flowage in them therefore dates from Pliocene or early Pleistocene time.

The Paradox Formation in the vicinity of the plugs consists of as much as 85 percent sodium chloride and 15 percent interbeds of gypsum, limestone, dolomite, and shale. Because the sodium chloride is dissolved away from the plugs, each cubic foot of rock now preserved in the plugs represents about 6 cubic feet of intruded Paradox lithologies.

SALT DISSOLUTION AND COLLAPSE STRUCTURES

The processes of salt dissolution and collapse of overlying strata have been taking place intermittently since the Paradox salts were deposited (Cater, 1970). Dissolution of the Paradox salts has been the most rapid denudation process operating in the Paradox Basin during late Cenozoic time. Proof that this statement is correct is the fact that the lowest topography in the region - sites where the thickest sections of rocks have been removed - corresponds to the solutional collapse of salt-cored anticlines. In the case of the Spanish Valley anticline at Moab, dissolution has removed a thickness of several thousands of feet of salt, much of which dissolved during the latter part of Cenozoic time. The overlying strata concurrently collapsed and largely eroded from the area, leaving a valley 18 miles long and 3 miles wide.

Figure 7. White rocks in the center of this photo are the Paradox salts in the Crum dome, a salt diapir which has pierced the floor of Cataract Canyon, Canyonlands area, Utah. The salt has dissolved so that each cubic foot of rock in the piercement represents six cubic feet of intruded Paradox lithologies. The diapir developed in response to the cutting of the canyon.

The principal mechanism for the collapse of salt anticlines in the region involves progressive downward dissolution of the upper surface of the salt section by ground water circulating through extensional fractures developed along the crests of the anticlines as shown on figure 8. The fractures developed as the overlying strata arched upward as a result of salt flowage into the cores of the anticlines (Cater, 1970, figure 13; Huntoon and Richter, 1979, p. 52; Doelling, 1983, figure 9). Thackston and others (1981, p. 219) proposed an alternative mechanism wherein the collapses of certain small salt anticlines resulted from the dissolution of the base of the salt section by Leadville waters.

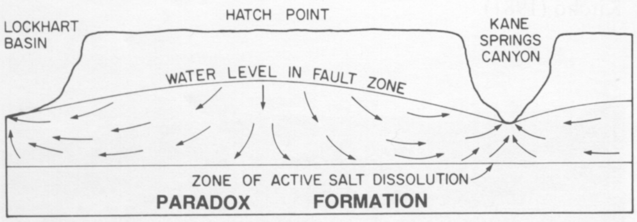

Figure 8. Ground-water circulation in the plane of a fault in the rocks above the Paradox Formation which causes dissolution of salt from the top of the Paradox Formation. Note that erosion of the canyons provides ample topographic relief to allow development of hydraulic gradients within the fault zone necessary to circulate the water. This model was used by Huntoon and Richter (1979) to explain the early stages of salt dissolution in Lockhart Basin.

Downward dissolution of the salt cores is facilitated by the presence of nearby deep canyons and erosional stripping of the Triassic confining layers from the region. Both conditions are currently met in the Canyonlands area.

The importance of deep canyons lies in the fact that topographic relief allows for the development of strong hydraulic gradients in the ground-water system in the adjacent rocks. The steep gradients accelerate the circulation of ground water in fractures above the salt and thus enhance solutional removal of the salt from the upper surface of the salt body (as shown on figure 8). Atwood and Doelling (1982, p. 6-7) point out that the most extensively developed salt anticlines are those transected by deep canyons.

Erosional removal of the Triassic and younger confining layers aids dissolution by improving the hydraulic connection between surface sources of water and the Pennsylvanian-Permian section which rests on the salt. This is particularly important in areas where the salt anticlines are weakly developed such as southwest of Spanish Valley. In these locations, extensional faults and fractures can become well developed in the brittle rocks comprising the post-salt Pennsylvanian-Permian section as the rocks are folded over the rising salt cores of the anticlines. However, these fractures attenuate as they propagate upward into the ductile units comprising the Triassic section. The result is that the presence of the Triassic rocks provides an hydraulic seal which greatly reduces the opportunity for downward circulation of meteoric waters into

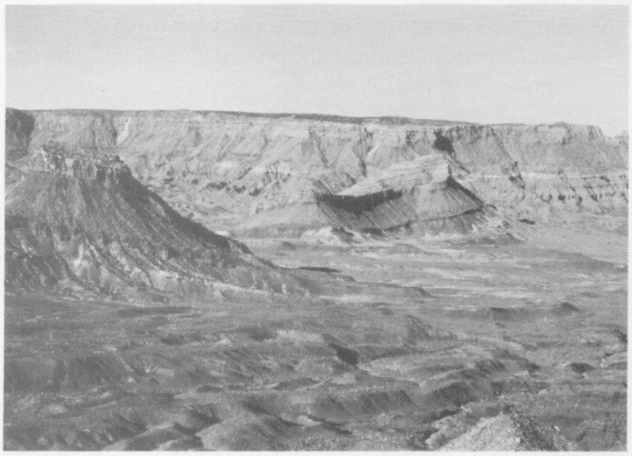

Figure 9. Infolding of strata at Lockhart Basin, Canyonlands area, Utah. Approximately 3,000 feet of salt have dissolved from the Paradox Formation under the center of the basin.

the fractured Pennsylvanian-Permian section. The upward attenuation of faults is well documented in exposures along the Colorado River in the Cane Creek anticline (Huntoon and others, 1982). Here fault densities diminish upward from the Permian rocks.

Two notable, but minor, collapsed salt anticlines occur in the Canyonlands area: Lockhart Basin and Beef Basin. Lockhart Basin is shown on figure 9 and the evolution of the basin is summarized on figure 10.

Subsurface gamma ray well log correlation of members within the Paradox salt section through the solution-collapsed Lockhart Basin (4 miles in diameter) reveals removal of as much as 3,000 feet of halite (Huntoon and Richter, 1979, p. 51-52). All the halite is missing from the Paradox section in the center of the basin. The salt section thickens toward the edges of the basin by the appearance of successively younger salt members beginning with the basal salt closest to the center of the basin. From this geometry it appears that the dissolution front in the basin advanced from the top downward and outward from the center of the basin. According to Huntoon and Richter (1979), the solvent was water circulating along extensional faults in the overlying rocks as shown on figure 8.

The Beef Basin collapse structure is larger than Lockhart Basin, measuring 9 by 3 miles in area. DOE (1984, p. 3-53) advises that salt is apparently absent in two drill holes in the basin.

Initial collapse of the strata overlying the dissolving salts involves infolding of the overlying strata with attendant increases in fracture density. As the process proceeds, faulting and drape folding become more pronounced (Cater, 1970, p. 65-67; Doelling, 1983, p. 87). In advanced stages, the overlying strata are shattered by fractures and faults, grabens at all scales are present, and differential subsidence occurs throughout the downdropping section. The highly fractured infolded and collapsed material readily erodes, leaving basins and linear valleys in locations once occupied by the crests of the anticlines.

The valley walls, comprised of less densely fractured strata, dip away from the downdropped and eroded strata, revealing the former presence of the salt anticline.

The hydrologic impact of the dissolution-collapse mechanism is to increase permeabilities in the overlying deformed strata. Faulting is dominantly extensional which greatly enhances vertical permeabilities. In cases where the halite section has been completely dissolved from the cores of the anticlines, such as in Lockhart and Beef Basins, there is even the potential for circulation of fluids between the pre- and post-salt stratigraphic units (Thackston and others, 1981, p. 219).

Lockhart and Beef Basins are characterized by infolding of the strata above the salt as shown on figure 9. A few faults and fault-cored folds are present in the infolding masses, but the rocks have not reached the shattered state exposed, for example, along large parts of the Spanish Valley anticline.

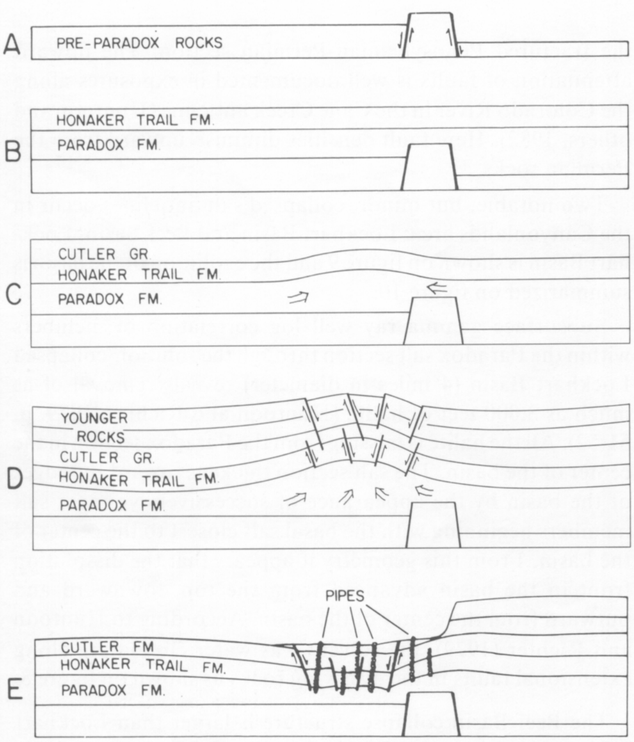

Figure 10. Evolution of Lockhart Basin and its breccia pipes, Canyonlands, Utah. A - Pre-Paradox surface. B - Deposition of the Paradox and Honaker Trail Formations without flowage of salt in the Paradox Formation. C - Deposition of the Cutler Group with depositional thinning as a result of flowage of salt in the Paradox Formation. D - Continued deposition and continued growth of the salt anticline, units thin and faults develop above the salt as a result of growth of the salt core in the anticline. E - The crest of the anticline has eroded and active ground-water circulation in the fault zones has dissolved salt from the core of the anticline. Anticline collapsed through a combination of infolding and faulting. Pipes stoped upward from space created by dissolution of the salt and extensional openings in the Honaker Trail Formation. Vertical scale is greatly exaggerated. Corrected from Huntoon and Richter (1979, figure 5).

BRECCIA PIPES

Breccia pipes are columns of brecciated country rocks which have been displaced downward relative to their surroundings. Commonly the wall rocks surrounding the breccia pipes are infolded toward the pipes and ring fractures circle the pipes in the country rock. The rubble fills within the pipes are altered or bleached, attesting to upward circulation of ground water through the pipes. Breccia pipes such as the one in Lockhart Basin shown on figure 11 commonly develop in association with the solutional collapse of salt anticlines. Literature citations for occurrences of these features in the Paradox Basin are found in Huntoon and Richter (1979) and Sugiura and Kitcho (1981).

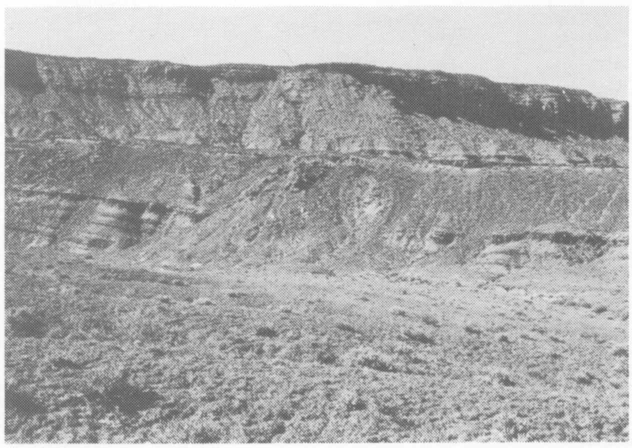

Figure 11. Breccia pipe in Lockhart Basin, Canyonlands area, Utah. The disaggregated mass in the center is the breccia fill which has been altered by upward circulation of ground water in the pipe.

The pipes have developed as a result of upward stoping from cavities at depth (Huntoon and Richter, 1979, p. 53). Siginificant upward propagation is possible if the breccia, wall rocks, or basal subsurface can continue to dissolve in circulating ground water in order to create additional space within the pipes. For example, the pipes in Lockhart Basin stoped upward from 2,000 foot depths.

Huntoon and Richter (1979) conclude that breccia pipes can readily form in collapsing salt anticlines because there are abundant opportunities for creating space or initial cavities at depth. Space allowing for collapse can directly accompany the dissolution of the Paradox salts. Alternatively, initial voids can be produced by the physical opening of extensional fractures as the overlying strata infold into the dissolving salt cores of the anticlines. Once the pipe nucleates, it can grow upward through dissolution of the breccia matrix, wall rocks,or basal substrate.

Approximately 30 breccia pipes, up to 500 feet in diameter have been found in Lockhart Basin (Huntoon and others, 1982; Sugiura and Kitcho, 1981, figure 4). The breccia fills provide a highly permeable vertical conduit through the country rock. Many breccia pipes in Lockhart Basin contain altered (bleached) fills, attesting to their historic role as vertical conduits for ground water. Ideal reducing solutions to account for the bleaching are salt brines from the lower part of the Pennsylvanian-Permian aquifer or even Leadville waters circulating upward through the window provided by the missing salt section under the basin.

Well-developed breccia pipes have not been found in Beef Basin, possibly because the floor of the basin is buried by Quaternary rocks which have obscured the pipes. A half-mile-diameter subsidence structure characterized by infolded strata, intense fracturing, and bleaching has been mapped by Huntoon and others (1982) in the headwaters reach of Gypsum Canyon along the western edge of Beef Basin. It is probably a developing breccia pipe.

INCIPIENT DISSOLUTION FEATURES

A number of sites with potential dissolution collapse features occur in the Canyonlands including: (1) the Chesler Canyon fault zone (Potter and McGill, 1978); (2) the Shay Graben fault zone (Hintze and Stokes, 1964); and (3) the Salt Creek Pocket/Squaw Flat area (figure 1). Chesler Canyon contains a gentle northwest-trending syncline-fault complex that probably represents insipient salt dissolution at depth. The Shay Graben complex is a suspect site because the faults in the zone cut through both the salt and underlying Leadville carbonate section, both of which can dissolve to yield collapse structures (DOE, 1984, p. 3-50). The Salt Creek Pocket/ Squaw Flat area is characterized by unusually gentle topographic gradients and local deposition of Quaternary rocks (Huntoon and others, 1982). It is possible that the land surface in this area is beginning to subside as a result of salt dissolution at depth.

Salt dissolution is taking place in the extensive Needles fault zone and is contributing to deformation in that complex. Although important because dissolution is removing large volumes of salt, dissolution is not the primary tectonic mechanism responsible for the development of the Needles fault zone as will be outlined in a later section.

AGE OF SALT DISSOLUTION FEATURES

Rates of dissolution in the Canyonlands vicinity have not been quantified. However, it is important to point out that dissolution processes are currently active, and all of the dissolution collapse features discussed above including Lockhart and Beef Basins are geologically young. Quaternary rocks are depositing or have recently been deposited on the floors of both Lockhart and Beef Basins, demonstrating Quaternary subsidence in those areas. It is likely that the Lockhart and Beef Basin structures developed largely in Pliocene and Quaternary time coincident with the erosion of Cataract Canyon and erosional stripping of the Triassic sediments from those areas. Consequently the bulk of the dissolution associated with those basins has taken place within the last 5 million years.

GRAVITY GLIDING ON THE PARADOX SALT

The Needles fault zone shown on figure 12 is a gravity slide feature wherein the strata above the Paradox salts are rifting apart as shown on figure 13 and gliding toward Cataract Canyon on the ductile salt surface. As such, the fault zone is not a deep-seated feature. The Needles fault zone encompasses approximately 90 square miles and is the youngest and most active fault zone in the Canyonlands area. Huntoon (1982) summarizes the theories proposed for its origin, describes the zone in detail, and cites the relevant literature concerned with the zone.

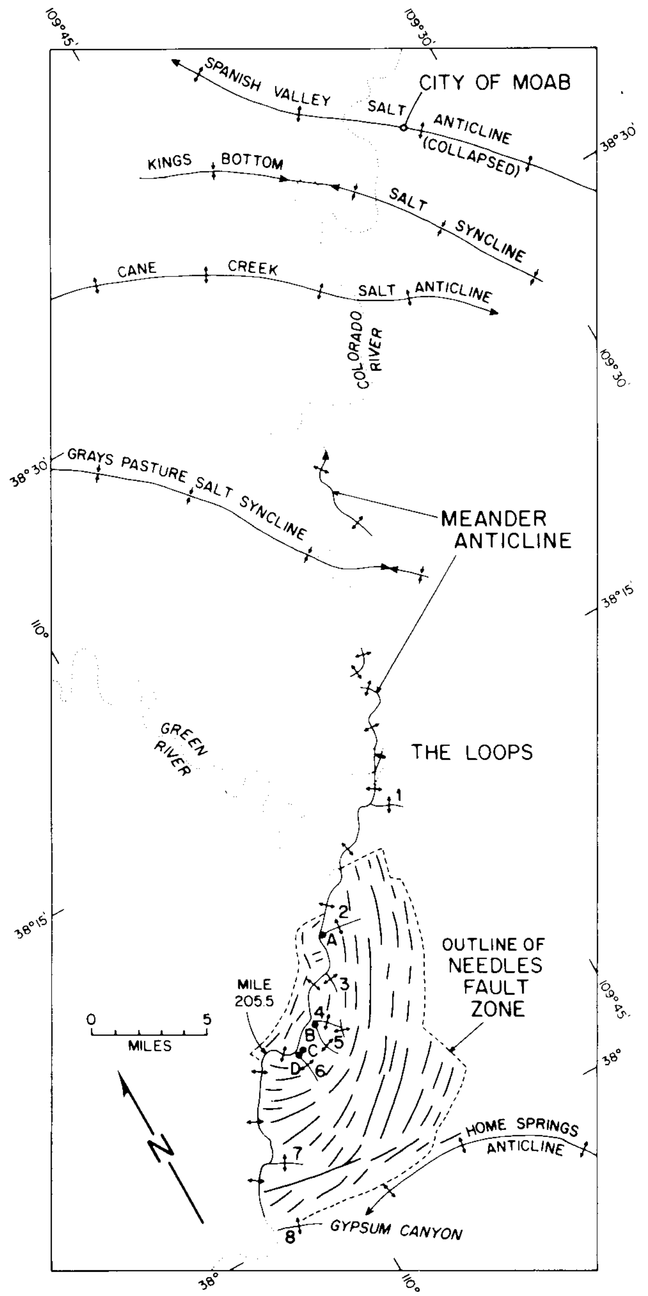

Figure 12. Locations of the Meander anticline, Needles fault zone, and other geologic structures, Canyonlands area, Utah. Valley anticlines in tributary canyons: 1 - Salt Creek, 2 - Red, 3 - unnamed, 4 - Y, 5 - Cross, 6 - unnamed, 7 - Imperial, 8 - Gypsum. Salt plugs: A - Harrison, B - Prommel, C and D - Crum.

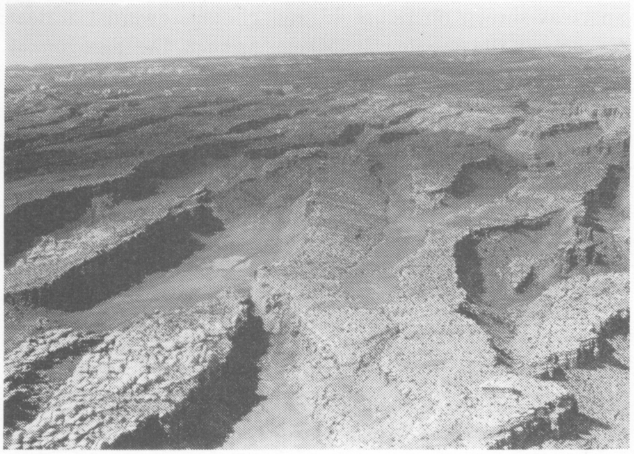

Figure 13. View looking south across the Needles fault zone, Canyonlands area, Utah. The faults were activated by the cutting of Cataract Canyon which lies to the right of the photo. The blocks of rock are sliding to the right on the Paradox salt. Notice the recent fissure that is swallowing sediments left of center.

Figure 14 summarizes the theories developed to explain the fault zone - the currently favored one being the brittle plate gliding on salt model. The observed deformation shown on figure 13 was initiated by the cutting of Cataract Canyon and is therefore Pliocene to Recent in age. Stromquist (1976, p. 94) documents evidence that the fault zone has progressively propagated southeastward up the gentle regional dipslope. Huntoon (1982, p. 946) concludes that north-westward translation of the fault blocks shown on figure 15 into Cataract Canyon horizontally compresses the rocks flooring the canyon and causes them to fold upward to form the Meander anticline (figure 16) which follows the trend of the river.

The Meander anticline is not a salt flowage feature. If salt has flowed into its core, the movement of the salt was largely a secondary response to the folding of the overlying rocks. Similar valley anticlines such as the one shown on figure 17 occur in the deep tributary canyons that extend into the fault zone. Each valley anticline owes its origin to compression across the floor of its canyon, a situation identical to that which creates the Meander anticline.

The fact that the gradient of the Colorado River increases to 8 feet/mile in Cataract Canyon as compared to less than 1 foot/mile above and below illustrates that the fault zone is still active. The river has had to steepen in this reach in order for erosion to keep pace with upward growth of the Meander anticline and sloughing of rocks off the walls of the canyon as they close vice-like on the river (see figure 18). Cox (1985) observed that the rate of spalling of rocks from the walls of Cataract Canyon is sufficiently rapid to prevent vegetation from reaching climax stages of ecological succession, a fact which is consistent with the instability associated with the oversteepened side slopes of the eroding canyon walls. Harrison (1927, p. 127) concluded that the Meander anticline was still growing on the basis of strain relationships he observed along the axis of the structure.

Faulting is an ongoing process in the Needles fault zone. There are numerous technical and popular reports of fissures opening within the zone such as those of Lewis and Campbell (1965, p. 31) and Salt Lake Tribune (April 4, 1984). A substantial record of Quaternary rocks are depositing in numerous closed basins within the fault zone, indicating that the graben blocks continue to drop. Deposition is not restricted to the surface depressions. Sediments wash in large volumes into holes along open fissures such as the one shown on figure 13 where the sediments deposit deeply in the subsurface in dike-like masses (Biggar and others, 1981, p. 132). A Miocene(?)-Pliocene(?) erosion surface is disrupted but still preserved on the surface of the horsts within the zone. This erosion surface predates significant incision of Cataract Canyon and thus provides an older limit for development of the fault zone.

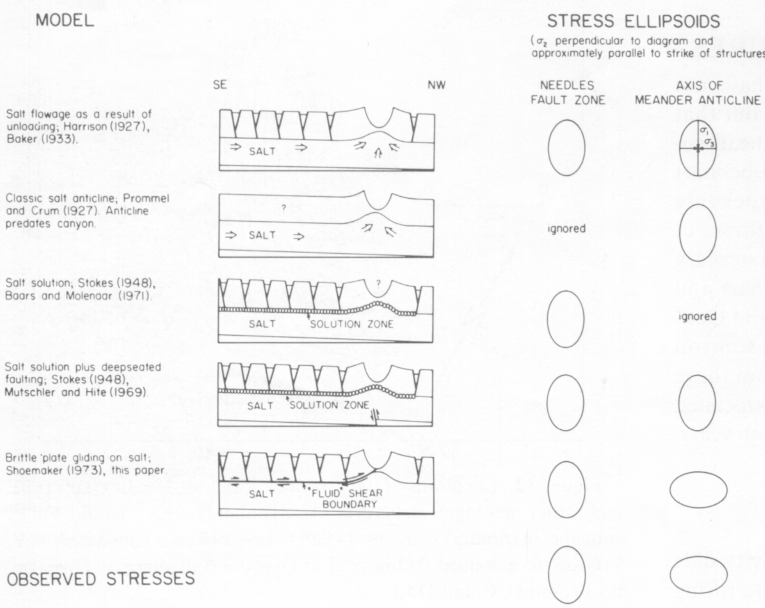

Figure 14. Summary of the various models proposed to explain the Needles fault zone and the Meander anticline, Canyonlands area, Utah. Only the brittle plate gliding on salt mechanism produces a stress field compatible to that recorded in the rocks. Salt Dissolution is taking place in the fault zone, however the process is secondary to the development of the zone, not a primary causative mechanism. From Huntoon (1982, figure 5).

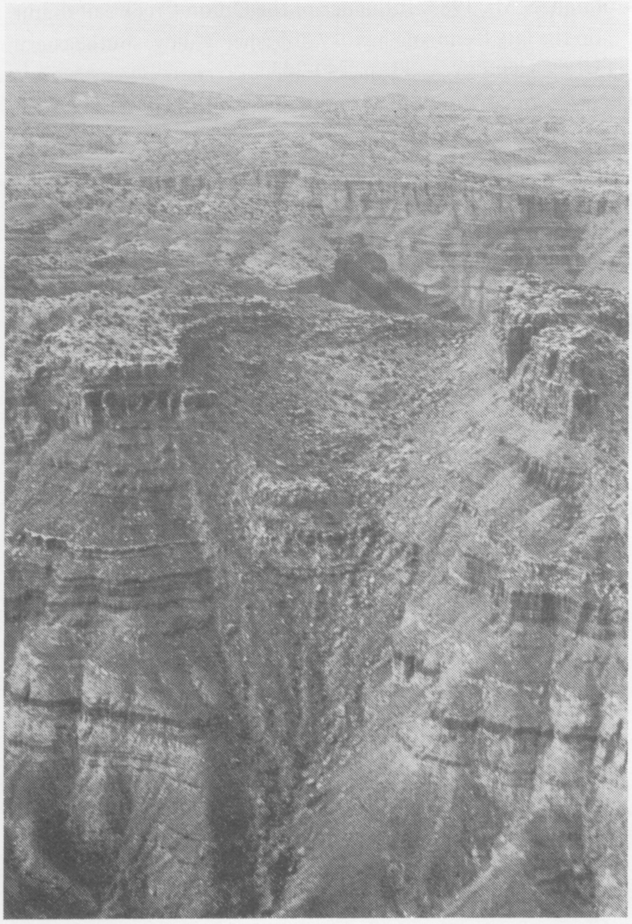

Figure 15. Profile through a graben in the Needles fault zone, Canyonlands area, Utah. The wedge-shaped block is moving downward as the block to the right moves toward Cataract Canyon which is off the photo to the right.

Figure 16. View southward along the axis of the Meander anticline, Canyonlands area, Utah. The anticline is being arched up as the canyon walls close vice-like on each other.

Figure 17. Typical valley anticline in a tributary to Cataract Canyon, Canyonlands area, Utah. Notice the dips of the rocks away from the center of the canyon. The anticline is being arched up as the canyon walls close vice-like on each other, a process that is still active.

Figure 18. Debris is sloughing into the Colorado River from the oversteepened walls of Cataract Canyon at the Big Drop Rapids as the canyon walls close on the river, Canyonlands area, Utah. Both the debris and upward arching of the canyon floor produce the rapids.

Future growth of the Needles fault zone will continue as long as the Colorado River continues to deepen its canyon. The fault zone will grow most rapidly toward the north and east away from the river as the canyon above the confluence of the Green and Colorado Rivers incises. Present canyon incision rates, estimated to be of the order of 200 meters per million years (Woodward-Clyde Consultants, 1982, p. 3-20), ensure continued activity in the Needles fault zone.

The Needles fault zone should be viewed as a highly water-transmissive rock sequence in both the vertical and lateral dimensions. The extensional fractures comprising the fault zone intercept all ground water flowing into the zone through the post-salt Pennsylvanian-Permian section and most surface water entering the area (Huntoon, 1979, p. 44). The large vertical permeabilities associated with the fractures allow these waters to circulate to the top of the Paradox salts where they can readily interact with and dissolve the salts. Huntoon (1979, p. 44) speculates that rates of deformation within the zone are increasing with time as water saturates the upper surface of the Paradox salts and lowers their viscosity.

DISCUSSION

Three mechanisms are currently operating to destroy or deform the salts and overburden, each of which can be classified as a gravity tectonic process: (1) salt flowage, (2) salt dissolution, and (3) gliding of the rocks above the salt on the viscous salt surface. These processes can be classified as unloading phenomenon as well because each relies on or is enhanced by erosion of canyons to produce topographic relief in the area.

Rates of deformation associated with the salt structures in the Paradox Basin have been highly variable through geologic time. The rates of deformation associated with the three classes of active structures described here appear to be accelerating, a tentative conclusion that is explained by the great topographic relief that now characterizes the region. Large relief produces (1) large stress gradients to drive rock deformation, be it salt flowage or gravity sliding, and (2) large hydraulic gradients which maximize rates of ground-water circulation and attendant salt dissolution.

Considerable additional study is required to quantify the present extent and rates at which late Cenozoic salt-related deformation is taking place in the Canyonlands area. This work will require sophisticated subdivision, correlation, and mapping of Quaternary rocks and erosion surfaces; dating of these rocks and surfaces; and determination of the tectonic timing styles, and severity of deformation of these Quaternary elements.

The Canyonlands area is being considered as a site for the disposal of high-level nuclear wastes. The Paradox salts are the proposed host rocks for the repository. High-level nuclear wastes require prolonged geologic isolation from the accessible environment, consequently the processes described herein require quantification to ensure the long-term integrity of such a repository.

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