UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Box 25046, Denver Federal Center, Mail Stop 954,
Denver, Colorado 80225

GEOLOGY OF THE NORTH END OF THE SALT VALLEY ANTICLINE, GRAND COUNTY, UTAH

by

Leonard M. Gard, Jr.

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ABSTRACT

This report describes the geology and hydrology of a portion of the Salt Valley anticline lying north of Moab, Utah, that is being studied as a potential site for underground storage of nuclear waste in salt. Selection of this area was based on recommendations made in an earlier appraisal of the potential of Paradox basin salt deposits for such use.

Part of sec. 5, T. 23 S., R. 20 E. has been selected as a site for subsurface investigation as a potential repository for radioactive waste. This site has easy access to transportation, is on public land, is isolated from human habitation, is not visible from Arches National Park, and the salt body lies within about 800 feet (244 m) of the surface. Further exploration should include investigation of possible ground water in the caprock and physical exploration of the salt body to identify a thick bed of salt for use as a storage zone that can be isolated from the shaly interbeds that possibly contain quantities of hydrocarbons.

Salt Valley anticline, a northwest-trending diapiric structure, consists of Mesozoic sedimentary rocks arched over a thick core of salt of the Paradox Member of the Middle Pennsylvanian Hermosa

Formation. Salt began to migrate to form and/or develop this structure shortly after it was deposited, probably in response to faulting. This migration caused upwelling of the salt creating a linear positive area. This positive area, in turn, caused increased deposition of sediments in adjacent areas which further enhanced salt migration. Not until late Jurassic time had flowage of the salt slowed sufficiently to allow sediments of the Morrison and younger formations to be deposited across the salt welt. A thick cap of insoluble residue was formed on top of the salt diapir as a result of salt dissolution through time.

The crest of the anticline is breached; it collapsed in two stages during the Tertiary Period. The first stage was graben collapse during the early Tertiary; the second stage occurred after Miocene regional uplift had caused downcutting streams to breach the salt core resulting in further collapse. The axis of the anticline is a narrow generally flat-floored valley containing a few hills composed of downdropped Mesozoic rocks foundered in the caprock. The caprock, which underlies thin alluvium in the valley, is composed of contorted gypsum, shale, sandstone, and limestone--the insoluble residue of the Paradox salt.

PREFACE

Because this report is aimed at a diverse audience of laymen as well as geologists, it is organized in a different manner than is the usual geologic report. The gist of the findings of this investigation are included in Section I (Introduction and Summary) at the beginning of the report. For those who wish to know more about the geology of the area, this information is included in Section II starting on page 14.

SECTION I

INTRODUCTION

Salt anticlines of the Paradox basin were recently appraised by Hite and Lohman (1973) as potential sites for waste emplacement. They reviewed the suitability of several areas and concluded that the Salt Valley anticline was one of two structures within the basin potentially having the most favorable characteristics for a waste storage site. On the basis of that appraisal, the area discussed in this report was selected for further study. This report describes the surface geology, hydrology, accessibility, and potential engineering problems of the northern end of the Salt Valley anticline, Utah. A smaller area in sec. 5, T. 23 S., R. 20 E. is recommended for further consideration as a potential emplacement site.

The area described in this report includes parts of T. 22 and 23 S., R. 19 and 20 E., and lies about 32 miles (51 km) northwest of Moab, in Grand County, Utah (fig. 1). All lands in this area are under State or Federal control (fig. 2). The geologic map (fig. 3, in pocket) includes 24 mi^2 (38.6 km^2) in these townships and shows the axis and both flanks of this portion of the Salt Valley anticline. The geology shown on figure 3 was modified from a 1:24,000-scale photogeologic map by J. S. Detterman (1955) and from an unpublished 1:62,500-scale photogeologic map by R. J. Hackman. These maps are on planimetric bases, and the geology was adjusted to fit the 1:24,000-scale topographic base enlarged from the Crescent Junction and Thompson 15-minute quadrangles.

Several small hills within the breached axis of the Salt Valley anticline were mapped in detail. The hills were numbered in the field for convenience; that numbering system is shown on figure 4. Figures 5 and 6 (in pocket), whose locations appear on figure 4, show details of the geology of those hills. Figure 5 shows the structure of blocks of Mesozoic rocks downdropped along the axis

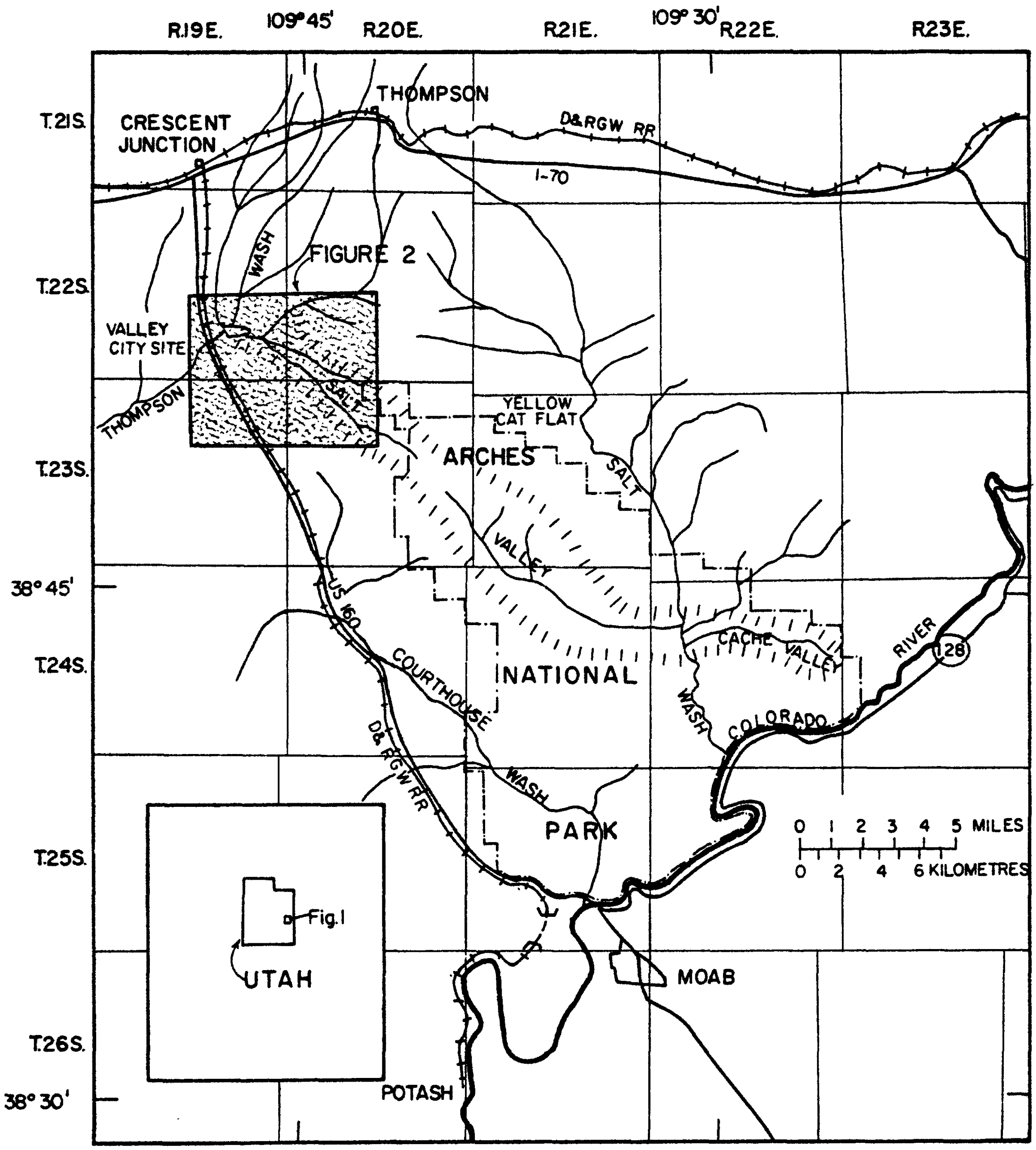
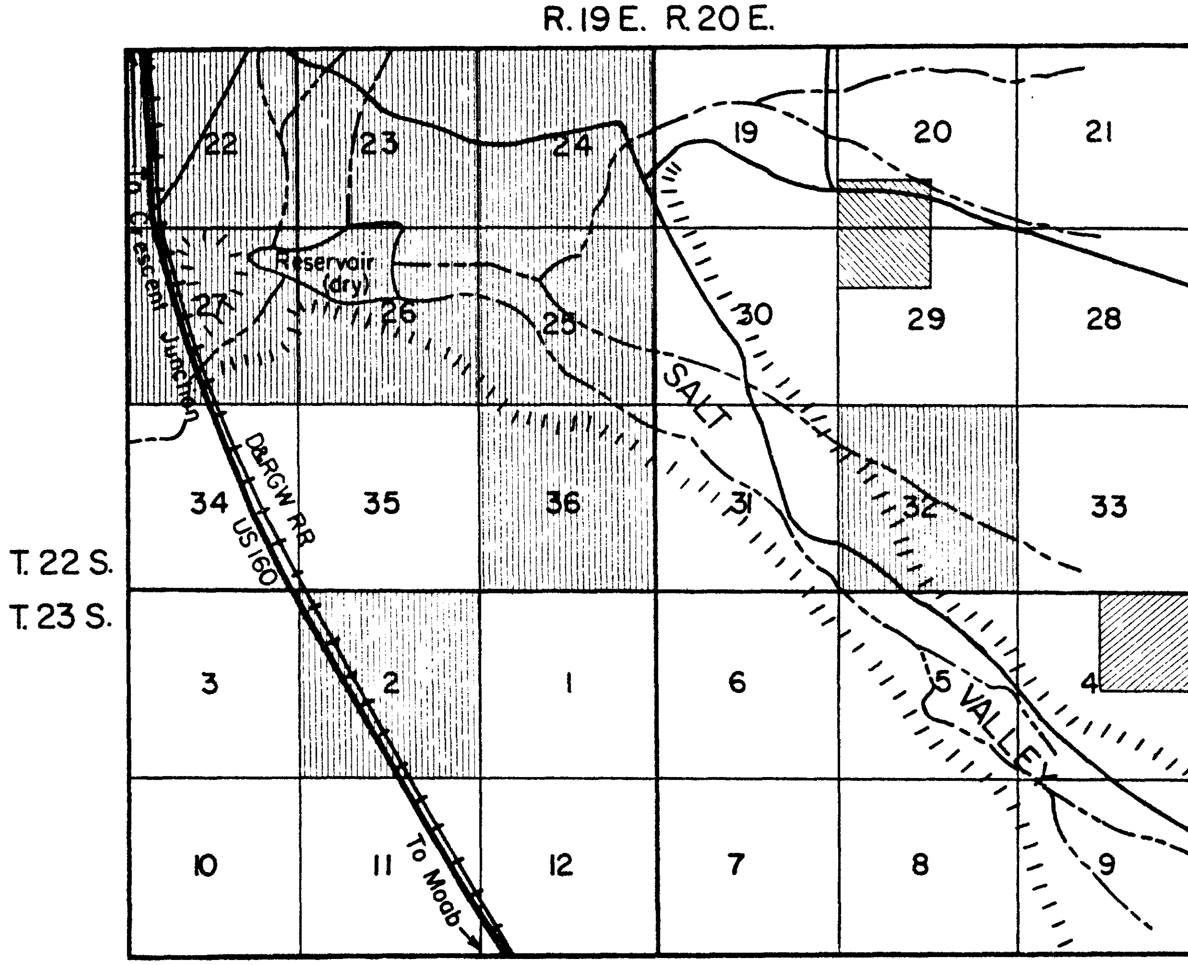


Figure 1.--Index map of part of Grand County, Utah, showing Arches National Park and location of Salt Valley area (figure 3).



EXPLANATION

State of Utah

National Park Service

Federal Use Permit

National Resource Land (BLM)

Intermittent streams

Unimproved or secondary roads

Figure 2.—Map showing land ownership, drainage, and roads at north end of Salt Valley anticline. Hashers indicate extent of valley.

Table 1.--Mesozoic and Cenozoic sedimentary rock formations exposed at the north end of the Salt Valley anticline

System	Series	Stratigraphic unit		Thickness feet (metres)	Character
Quaternary	Holocene	Alluvium		0-40(?) (0-12)	Reddish-brown gypsiferous sand with scattered pebbles; partly aeolian
	Pleistocene(?)	Older alluvium		0-5(?) (0-1.5)	Reddish-brown, gravelly to bouldery sand
Cretaceous	Upper Cretaceous	Mancos Shale	Upper member	1,600+ (488)	Dark-gray fissile shale
			Farron Sandstone Member	45± (14)	Two thin yellowish-brown fossiliferous calcarenites separated by dark-gray fissile shale
			Lower member	350± (107)	Dark-gray fissile shale
		Dakota Sandstone		43 (13)	Yellowish-brown conglomeratic sandstone
					------Unconformity--------------
	Lower Cretaceous	Burro Canyon Formation		163 (50)	Yellowish-gray cliff-forming sandstone and conglomerate, greenish-gray claystone, lenses of limestone
Jurassic	Upper Jurassic	Morrison Formation	Brushy Basin Member	379 (116)	Varigated claystone and mudstone, bentonitic; lensing sandstone, conglomerate, and limestone
			Salt Wash Member	235 (72)	Dark-reddish-brown to yellowish-gray or white claystone, mudstone, and sandstone. Sparce thin limestone lenses

System	Series	Stratigraphic unit			Thickness feet (metres)	Character
Jurassic	Upper Jurassic	San Rafael Group	Summerville Formation		24 (7)	Dark-reddish-brown to yellowish-orange claystone and friable sandstone
Jurassic	Upper Jurassic	San Rafael Group	Entrada Sandstone	Moab Member	85 (30)	White to gray cliff-forming crossbedded sandstone
Jurassic	Upper Jurassic	San Rafael Group	Entrada Sandstone	Slick Rock Member	270 (82)	Light-buff to light-reddish-brown, massive to crossbedded fine-grained sandstone
Jurassic	Upper Jurassic	San Rafael Group	Entrada Sandstone	Dewey Bridge Member	140 (43)	Dark-reddish-brown to pale-orange, horizontally bedded mudstone, siltstone, and sandstone ----------Unconformity----------
Jurassic and Triassic(?)	Upper Triassic(?)	Glen Canyon Group	Navajo Sandstone		227 (69)	White to pale-orange, tangentially crossbedded sandstone
Triassic(?)	Upper Triassic(?)	Glen Canyon Group	Kayenta Formation		211 (64)	Dark-reddish-brown, irregularly crossbedded sandstone and shale
Triassic	Upper Triassic	Glen Canyon Group	Wingate Sandstone		196 (60)	White to moderate-reddish-orange thick-bedded and crossbedded cliff-forming sandstone ---------Intrusive contact------
Pennsylvanian	Middle	Hermosa Formation	Paradox Member		800-10,000+ (244-3050)	Sandstone, limestone, gypsum, carbonaceous shale, salt

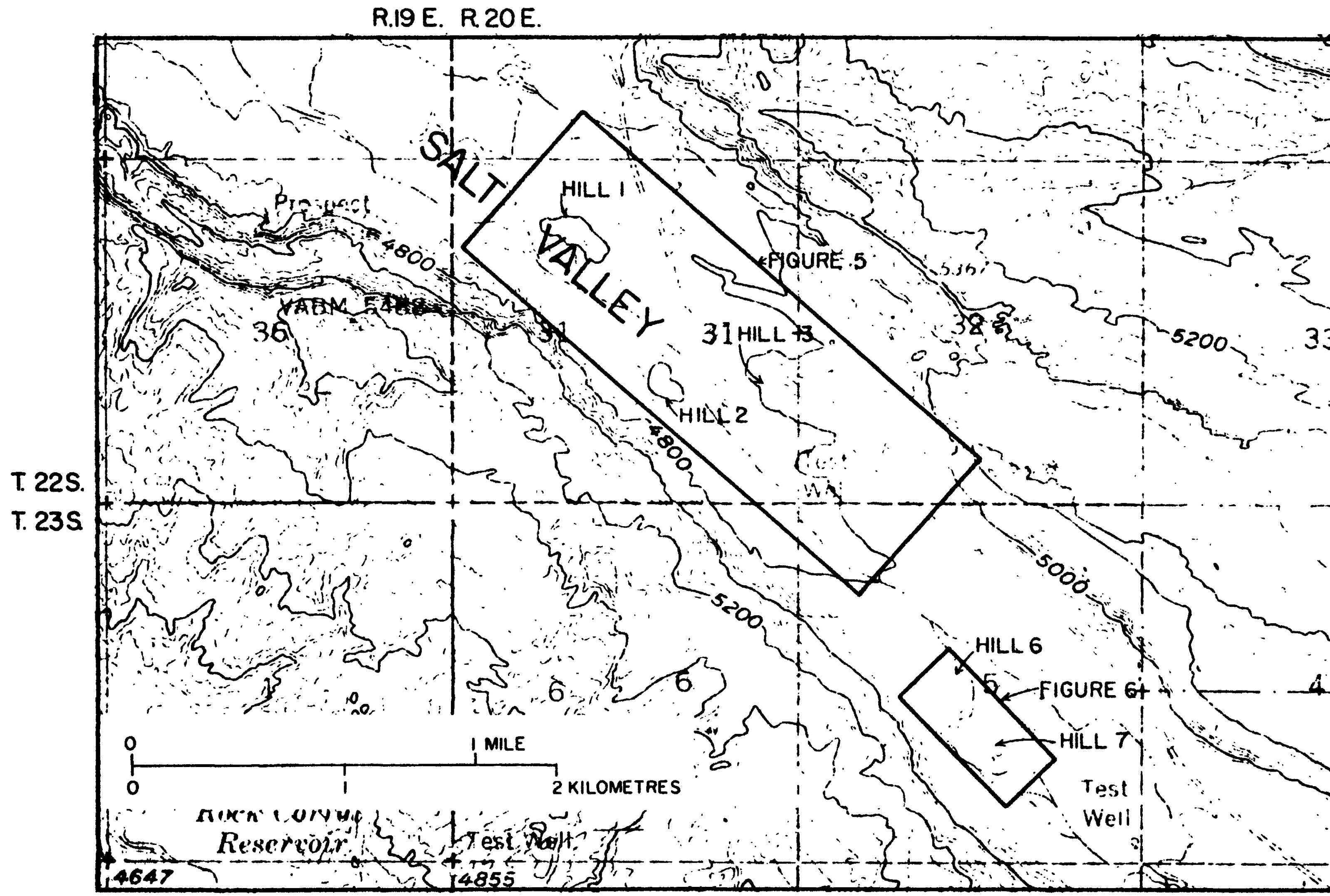


Figure 4.--Map of parts of T. 22 and 23 S., R. 19 and 20 E., showing area of figures 5 and 6 and location of hills 1-3, 6 and 7.

of the anticline, and figure 6 shows the structural complexity of the Paradox Member of the Hermosa Formation of Pennsylvanian age forming the caprock in the anticlinal core. Figures 5 and 6 are sketch maps made without planimetric control directly from 1:2,400-scale low-altitude color aerial photographs flown in October 1974; thus the scale on these maps is only approximate.

This detailed mapping was done to determine if the structure seen at the surface, either in the downdropped blocks of Mesozoic rocks or in the caprock could be used to determine the structure in the salt at depth. After mapping the hills it was concluded that the structure in the blocks of Mesozoic rocks (fig. 5) is totally unrelated to structure presumed to be in the salt. Further, it seems unlikely that the structure in the caprock (fig. 6) bears any relation to the presumed structure in the underlying salt. The rocks in the caprock not only have been squeezed laterally and upward along the salt welt that forms the core of the Salt Valley anticline but they also probably have moved downward in response to leaching of the enclosing salt and hydration of anhydrite to gypsum.

Salt Valley anticline trends northwest. Its axis has been breached and eroded to a valley that varies in width 0.5-2 miles (0.81-3.2 km). In the map area, the axis consists of a flat-floored valley (Salt Valley) broken by a few low hills. An intermittent stream drains the valley northwest to Thompson Wash and thence to the Green River. The walls of the valley rise as much as 400 feet (122 m) above the valley floor and are formed by strata in the limbs of Salt Valley anticline. Rocks ranging from Triassic to Cretaceous age crop out as slopes and cliffs of the valley walls and dip away from the axis at about 10°. Certain of these strata form the magnificent landscapes to be seen in Arches National Park only a few miles to the southeast (Lohman, 1975).

An unimproved dirt road traverses Salt Valley from the national park to the old highway leading from Thompson to the Valley City site. A recently built construction road also connects the study area with Thompson which lies to the northeast. Just north of the area these roads traverse the Mancos Shale and during and after a heavy rainstorm become impassable quagmires. Flash floods can turn Thompson Wash and its tributaries into dangerous raging muddy torrents, impossible to cross.

A visitor to the area would do well to closely watch rainstorms even though they may not be in the immediate vicinity. Because there are only two ways to egress the area, to the northwest across Thompson Wash and to the southeast through the streambed tributary to Salt Wash in the national park, one can easily be trapped in the area and spend many unpleasant hours waiting for streams to subside. Thompson Wash can remain impassable for days after the water has subsided because of the presence of the Mancos Shale. During dry weather (and dry Mancos Shale) the area is traversable in a sedan; during and after rains, even a four-wheel-drive vehicle is marginal transportation.

The geology of this region was first described by Dane (1935). The present report describes only that portion of the geologic section that crops out at the surface (table 1); the subsurface geology will be discussed elsewhere (R. J. Hite, written commun., 1976) and consequently no cross sections accompany the geologic maps. Descriptions and thicknesses of rocks younger than the Paradox Member of the Hermosa Formation are summarized from a composite stratigraphic section measured nearby on the northeast flank of the anticline (Craig, 1959), and from Dane (1935) and Cater (1970). Discussion of the Paradox exposed in the core of the anticline is based on brief field studies conducted in 1974 and 1975 by the author and R. P. Snyder. Discussions on stratigraphic and structural problems of the Paradox basin with L. C. Craig and F. W. Cater have been of immeasurable assistance.

SUMMARY

Site selection

Field examination of the area outlined in this report indicates that the part of Salt Valley lying in part of sec. 5, T. 23 S., R. 20 E. (see figs. 2 and 3), represents the best area for further exploration for the following reasons:

1. The salt body lies within about 800 feet (244 m) of the surface, allowing a proportionately greater amount of salt to be explored by drilling. To the northwest along the axis of the anticline, the top of the salt increases in depth.

2. In section 5 the caprock lies at the surface or under thin alluvium. Insofar as can be determined from surface examination, a site can be chosen here that will avoid drilling through any downdropped blocks of Mesozoic rocks, which might create drilling or shaft construction problems.

3. This area has easy access to a major highway and rail line (about 7 miles (11.3 km) away). Construction of an access road and railroad should have only minor engineering problems, thus access development costs would be minimal (see Engineering considerations). Doubtless there are other salt anticlines of the Paradox basin that have salt characteristics similar to or possibly even better than this area is believed to have (Hite and Lohman, 1973), but their remoteness from major transportation lines would substantially increase the cost of their development as a waste storage facility.

4. This area is remote from permanent human population. The nearest habitation is at Crescent Junction (about 8 miles (13 km) away).

5. The site area lies on public land controlled by the BLM (U.S. Bureau of Land Management). The surrounding lands are also controlled by BLM or other State and Federal agencies (fig. 5). This situation permits the exercise of some sort of control over drilling

or other activities that might jeopardize the integrity of a storage facility. It also eliminates the problem of purchase of private land.

6. The area lies about 1 mile (1.61 km) from the nearest national park boundary which is now and likely will always be inaccessible to vehicular traffic. That part of the park is not likely to be frequented by many hikers as it has little or no spectacular scenery comparable to other parts of Arches National Park.

7. The area lies about 3.5 miles (5.6 km) from the nearest accessible national park boundary which crosses the unimproved road to the southeast of the site in Salt Valley. This part of the park is presently undeveloped. Any facility built in section 5 should be far enough from the park to be visually inoffensive.

8. At this time a specific site location within section 5 has deliberately not been designated. This would allow for possible shifting of the site if it becomes necessary after further subsurface investigation. The site could be shifted as much as 0.5 mile (0.8 km) northwest or 1.5 miles (2.4 km) southeast. The site could also be moved more than 0.5 mile (0.8 km) northwest (pending subsurface exploration) if item 1 can be compromised, but any shift to the southeast might jeopardize item 7.

Engineering considerations

One of the physical advantages of this area as a repository for nuclear waste is its easy access and relative isolation from human activity, as noted by Hite and Lohman (1973, p. 58). Only about 7 miles each (11.3 km) of railroad and paved road from U.S. Highway 160 and a spur of the Denver and Rio Grande Western Railway would need to be constructed. Interstate Highway 70 lies about 8 miles (13 km) away at Crescent Junction, the closest human habitation. Most access right-of-way will cross the Mancos Shale and encounter its inherent construction problems related to swelling clays.

Further, any roadbeds constructed would need to be adequately elevated across the many branches of Thompson Wash because of the common occurrence of flash floods in this region.

Access shafts and facilities should be located well above the dry stream bed in Salt Valley to avoid possible flash floods although flooding does not appear to be a major problem here. The potential for large floods is minimal as the catchment basin above sec. 5 has an area of only about 5 mi^2 (13 km^2), whereas Thompson Wash drains an area of about 60 mi^2 (156 km^2). Further, the soil here is sandy and thus has a greater potential for absorbing moisture than the Thompson Wash watershed which is underlain almost exclusively by Mancos Shale.

Underground construction problems may include brine inflow from the caprock during shaft sinking. The potential hazard of gaseous hydrocarbons leaking into underground openings in the salt has been discussed by Hite and Lohman (1973, p. 42).

Conclusions

The results of this investigation suggest that there is little or no relationship between structure believed to exist in the salt diapir (Hite and Lohman, 1973, p. 32; Hite, unpubl. data, 1976) with that mapped at the surface. The investigation has shown however, that on the surface this area is, in many ways, attractive as a potential site for waste storage.

Because of the lack of accurate knowledge of the internal structure of the salt diapir at suitable depths for construction of a waste storage facility, further extensive exploration of the subsurface by drilling and by geophysical methods is required. It will also be necessary to acquire detailed knowledge of the presence and movement of ground water in the caprock.

SECTION II

STRATIGRAPHY

Sedimentary rocks ranging in age from Pennsylvanian through Cretaceous crop out in the map area. The oldest exposed rocks, which are the insoluble residue of saliferous deposits of Pennsylvanian age, crop out in the core of the anticline. The next younger exposed rocks are of the Upper Triassic Glen Canyon Group. Rocks of Permian and Triassic age stratigraphically below the Glen Canyon Group are not exposed at the surface here but are present at depth on the flanks of the anticline. After Pennsylvanian time the area lay above sea level for about 200 m.y. (million years), during which time thousands of feet on nonmarine sediments were deposited. A large portion of these sediments was emplaced by the wind. Not until Late Cretaceous time did the sea again cover the area and deposit the Mancos Shale. After Mancos time the area emerged and has remained above sea level.

PENNSYLVANIAN ROCKS

Paradox Member of the Hermosa Formation

The oldest rock that crops out in the area is the Paradox Member of the Hermosa Formation. This rock consists of marine-deposited gypsum, sandstone, limestone, and shale which are the insoluble residue of the saliferous Paradox that forms the core of the Salt Valley anticline. In several places more resistant beds form low rounded hills in the generally flat-floored valley. Outcrops on these hills are poor and the strata are so completely folded and faulted (fig. 6) that it generally is not possible to work out a reliable stratigraphic sequence. Each of the isolated hills in the area appears to be composed of strata different from those in other hills.

Strata exposed in these hills are sandstone, shale, and limestone. Gypsum forms part of the flat valley floor and also occurs on the lower flanks of some of the hills. Several small hills next to the valley wall west of hill 1 (fig. 3 and 4) are composed of highly contorted dark-gray honeycombed gypsum, that contains small isolated sandstone and limestone fragments.

The shale is dark colored, finely laminated, extremely well indurated, commonly crumpled and distorted, and gives off a fetid petroliferous odor when broken. Although this rock crops out poorly, the amount of shale float present suggests the shale ranks next to gypsum as the most common rock type.

Sandstone beds as much as 4 feet (1.2 m) thick crop out on hill 6 and to a lesser extent on hill 7 (fig. 4). These beds have been strongly folded and faulted (fig. 5). Apparently they were lithified prior to folding, as they commonly display recemented fractures. At least two sandstone beds, 3-4 feet (0.9-1.2 m) thick separated by thin-bedded black shale, crop out extensively on hill 6. The upper sandstone contains some dark-gray chert pebbles and displays convolute bedding commonly associated with penecontemporaneous deformation. The lower sandstone is evenbedded to slightly crossbedded and is readily differentiated from the upper one. The intervening shale is strongly crumpled and deformed and the separation of the two sandstones varies from less than 20 feet (6 m) to more than 100 feet (30 m) in a lateral distance of perhaps 100 feet (30 m). Obviously, the true stratigraphic separation of the sandstone beds cannot be determined. These sandstones are the most continuous beds to be seen here in the Paradox Member and can be traced over much of hill 6 but not elsewhere.

The strata described are part of an insoluble residue lying on salt of the Paradox Member in the core of the anticline. Drill-hole information indicates that the thickness of the caprock is 800 feet (244 m) or more in the map area. As the salt rose along the crest of the anticline the upper surface was subjected to solution. The insoluble beds, which constitute about 26 percent of the Paradox Member in the Salt Valley anticline (Shoemaker and others, 1958), thus accumulated at the top of the salt, forming a cap that probably eventually retarded solution. Presumably then, the minimum amount of salt that has been dissolved here is about 2,300 feet (702 m). This figure is doubtlessly too low because an unknown amount of caprock has been removed by erosion.

Because the cores of the salt anticlines were exposed at the surface from Permian to Late Jurassic time, or more than 100 m.y., according to Cater and Craig (in Cater, 1970, p. 9), it may be assumed that the caprock began to form in Permian time.

No fossils were found in any of these strata although Dane (1935, p. 24) described small poorly exposed outcrops of a conglomerate in Salt Valley to the southeast of the map area that contain fossiliferous limestone boulders. The fossils were identified as being of Mississippian age, which suggested to Dane a possible Early Pennsylvanian age for the conglomerate. R. P. Snyder and the author examined one of these outcrops and recognized many features such as flute casts, striations, and convolute bedding, which suggest that the conglomerate is a turbidite. The rock may have acquired its content of older somewhat angular limestone boulders from somewhere on the periphery of the Paradox Basin of deposition. The turbidity-current mode of origin for such deposits was not recognized until at least a decade after Dane mapped the area. The newly recognized features suggest that the anomalous conglomerate probably was deposited in a normal stratigraphic succession within the Middle Pennsylvanian Paradox Member of the Hermosa Formation, and does not have to be as old as Early Pennsylvanian.

No rocks were found in this area that could be ascribed to the upper member of the Hermosa Formation, although Dane (1935, p. 34) described 855 feet of sandstone and fossiliferous limestone of the upper member that is exposed in Fisher Valley 27 miles (43 km) southeast of the study area.

TRIASSIC AND JURASSIC ROCKS

Glen Canyon Group

The Glen Canyon Group is composed of three conformable nonmarine formations in this area. In ascending order these are the Wingate Sandstone of Late Triassic age, the Kayenta Formation of Late Triassic(?) age, and the Navajo Sandstone of Triassic(?) and Jurassic age. Erosion of this group of massive colorful cliff-forming sandstones has produced much of the spectacular scenery throughout the Colorado Plateau. These rocks comprise the base of the cliffs that form the walls of Salt Valley. All three formations are exposed on the northeast valley wall but only the Navajo Sandstone is exposed on the southwest valley wall in the map area.

Wingate Sandstone

The Wingate Sandstone, widespread throughout the Colorado Plateau, crops out at the base of the cliff on the northeast flank of the anticline in the area. The Wingate is composed of several cross-stratified sandstone units ranging from less than 2 to nearly 80 feet (0.6-24 m) thick. These units are separated by horizontal bedding planes that are traceable laterally for more than one-quarter of a mile (0.4 km). The Wingate forms a nearly vertical reddish-brown wall, streaked and stained with desert varnish, and is broken by widely spaced vertical joints.

In this area the Wingate is 196 feet (60 m) thick (Craig, 1959), 50-100 feet (15-30.5 m) thinner than reported elsewhere by Dane (1935, p. 72). This thinning is probably due to non-deposition across the rising salt diapir (see Structure).

Kayenta Formation

The Kayenta Formation lies conformably on the Wingate Sandstone; the contact between the two formations is transitional and cannot be determined with certainty. According to Dane (1935, p. 81) the

Kayenta varies considerably in thickness, ranging from 200 to 300 feet (61-98 m). In the map area Craig and V. L. Freeman (Craig, 1959) measured and described 211 feet (64 m) of Kayenta. The Kayenta is generally more distinctly bedded than the Wingate, containing lensing sandstone units that display crosslaminations, channeling, current ripple marks, and slump features typical of fluvial deposition. The finer grained beds generally are dark reddish brown and erode to form slopes, whereas the thicker pale-orange sandstones form ledges.

Navajo Sandstone

The Navajo Sandstone, which crops out on both valley walls, is 227 feet (69 m) thick in this area (Craig, 1959). According to Dane (1935, p. 86) it varies in thickness in this region from 160 to 300 feet (49-91 m). The Navajo is a classic example of fossilized sand dunes, characterized by great sweeping tangential crosslaminae that lie as much as 30° from the true attitude of the formation. It conformably overlies the Kayenta and represents a change from fluvial to eolian deposition. In the map area the Navajo is a white to pale-orange ledge-former on both flanks of the anticline. The lower 140 feet (43 m) forms a prominent cliff; the upper part is softer and forms a smoothly rounded bare slope. Lack of diagnostic fossils and intertonguing relations with the Kayenta and the Jurassic Carmel Formations (Dane, 1935, p. 90) elsewhere have led geologists to assign a Triassic(?) and Jurassic age to the Navajo.

JURASSIC ROCKS

San Rafael Group

The San Rafael Group in this area consists of two formations of Late Jurassic age, the Entrada Sandstone and the overlying Summerville Formation.

Entrada Sandstone

The Entrada Sandstone, 495 feet (151 m) thick here, is divided into three members. In ascending order they are the Dewey Bridge Member, the Slick Rock Member, and the Moab Member.

Dewey Bridge Member

The Dewey Bridge Member in this area consists of 140 feet (43 m) of claystone and sandstone beds which commonly display contorted bedding. These strata vary in color from dark reddish brown to pale yellowish orange. The Dewey Bridge conformably overlies the Navajo Sandstone and contains some reworked Navajo in its basal part. Originally called the Carmel Formation in this area by Dane (1935), these rocks in the Salt Valley area have been redefined and renamed Dewey Bridge Member of the Entrada Formation by Wright, Shaw and Lohman (1962). The Dewey Bridge is well exposed throughout much of Arches National Park where it lies at the base of the cliffs formed by the overlying Slick Rock Member of the Entrada.

Slick Rock Member

The Slick Rock Member here includes 270 feet (82 m) of light-buff to light-reddish-brown sandstones. They display eolian crosslaminations but include thin units near the base and top that are parallel bedded. The Slick Rock includes those sandstone beds that originally were defined as Entrada Sandstone by Dane (1935) and from which the vertical cliffs and magnificent erosional features in Arches National Park are carved.

Moab Member

This member, sometimes referred to as the Moab tongue, has been included in the Entrada by Wright, Shaw, and Lohman (1962); in this area, however, it is separated from the Slick Rock Member by 24 feet (7.3 m) of sandstone assigned to the Curtis Formation, also in the San Rafael Group. This separation is absent in nearby areas to the east and southeast, and to simplify the geologic map (fig. 2) the Curtis has been combined with the Moab. The combined thickness of the Curtis and the Moab as measured by V. L. Freeman (in Craig, 1959) is 85 feet (26 m). This sandstone is characteristically marked by distinctive white cliffs and large-scale sweeping crossbeds. The Moab Member, a widespread lens of sandstone, was deposited under eolian conditions in its thicker central portion; the thinner distal edges of the lens were water laid.

Summerville Formation

The Summerville Formation conformably overlies the Moab Member of the Entrada Sandstone and forms a red slope above the cliff-forming Moab on the valley walls. In this area it is composed of 24 feet (7.3 m) of alternating 2- to 6-foot-thick (0.6-1.8 m) beds of claystone and friable platy sandstone (Craig, 1959). The claystones tend to be dark reddish brown, whereas the sandstones are pale yellowish orange. The Summerville was deposited in shallow quiet water, perhaps on the lower reaches of a delta.

Morrison Formation

Outcrops of the nonmarine Morrison Formation of Jurassic age have the widest areal distribution of all the formations present in the map area because an overlying protective cap of Cretaceous Burro Canyon Formation has been largely removed from the flanks of the anticline by erosion. The Morrison is divided into two members, The Salt Wash Member, and the overlying Brushy Basin Member. The total measured thickness of the Morrison in this area is 614 feet (187 m) (Craig, 1959). According to Cater and Craig (in Cater, 1970, p. 35) the Morrison is the oldest formation to have completely or almost completely blanketed the salt and gypsum cores of the salt anticlines in southwestern Colorado. Within the map area, however, only the uppermost 20 feet (6 m) or so of the Brushy Basin are exposed in the core of the anticline (hill 2, fig. 5).

Salt Wash Member

The Salt Wash Member, 235 feet (72 m) thick nearby, consists of alternating sandstone, mudstone, and claystone beds, each less than 30 feet (9 m) thick. Thin freshwater limestone lenses occur uncommonly in this section. The mudstones and claystones generally are dark reddish brown, whereas the sandstones vary from white to yellowish gray. The overall topographic expression of these alternating beds is a steep irregular slope broken by low cliffs. The Salt Wash was deposited largely by streams in channels and on flood plains.

Brushy Basin Member

The Brushy Basin Member, 379 feet (116 m) thick in this area, is composed of varigated mudstone and claystone containing lesser amounts of sandstone, conglomeratic sandstone, and limestone, all of which are commonly lensing. Only about 18 percent of the total thickness of the section measured by Craig (1959) is sandstone or conglomerate. The dominant clay in the mudstone and claystone is montmorillonite, a swelling clay apparently derived from the hydrolysis and devitrification of volcanic ash (Cater and Craig, _in_ Cater, 1970, p. 41). The Brushy Basin generally crops out as steep, easily eroded slopes brightly colored in hues of red, green, purple, and gray. There was little change in the depositional environment from Salt Wash time except that the streams appear to have had generally lower gradients, and showers of volcanic ash were common. Common throughout the areal distribution of the Brushy Basin are pebbles of red and green chert and quartzite as well as silicified bone fragments and wood. Secondary masses of brightly colored jasper are common and litter the surface of the Brushy Basin. The large amount of silica required to provide this material is thought to have been derived from the alteration of volcanic ash to montmorillonite.

CRETACEOUS ROCKS

Burro Canyon Formation

The Burro Canyon Formation of Cretaceous age conformably overlies the Brushy Basin Member of the Morrison Formation; although much of it has been removed by erosion, it forms resistant hogbacks on either flank of the Salt Valley anticline in the map area. The Burro Canyon and the overlying Cretaceous Dakota Sandstone also form three resistant hills in the core of the anticline (fig. 5). In this area the Burro Canyon consists of 163 feet (50 m) of alternating sandstone, claystone, and lensing limestone (Craig, 1959). The yellowish-gray cliff-forming sandstones are lensing, sporadically conglomeratic, and in places, quartzitic. The claystones vary from gray to green, are soft, and weather readily. However, one distinctive hard, green calcareous bed is found on hills 1 and 3 (fig. 5) and also on the northeast limb of the anticline. Light-gray freshwater limestone as much as 3 feet (0.9 m) thick crops out on hill 3. Although these fossils have not yet been identified, fossil plants and freshwater invertebrates, elsewhere in the Burro Canyon, are of Early Cretaceous age, according to Cater and Craig (in Cater, 1970, p. 44).

Dakota Sandstone

The Dakota Sandstone of Cretaceous age crops out on both flanks of the anticline (fig. 3) as well as on hills 1 and 3 (fig. 5) within the core of the structure. The Dakota disconformably overlies the Burro Canyon Formation and is relatively thin in this area; an incomplete section measured by Craig and V. L. Freeman (in Craig, 1959) consists of 43 feet (13 m) of limonite-stained yellowish-brown conglomeratic sandstone. On hills 1 and 3 in the core of the anticline (fig. 5), the Dakota is about 40 feet (12 m) thick, it consists mainly of lensing cross-stratified pebbly conglomeratic sandstone with lesser amounts of sandstone that contains poorly preserved silicified wood fragments and leaf impressions. At one place on the northeast side of hill 3 it contains a lens of carbonaceous shale; elsewhere, discontinuous impure coal seams are present that have been mined locally (Cater, 1970, p. 44). The Dakota is a terrestrial deposit that Cater and Craig (in Cater, 1970, p. 46) believe was deposited on a broad coastal plain in front of an advancing Cretaceous sea, which deposited the overlying Mancos Shale.

Mancos Shale

The Cretaceous Mancos Shale, a thick soft gray marine deposit, skirts the flanks of the Salt Valley anticline as broad flat areas supporting little vegetation. It has been downdropped in the core of the anticline and underlies the area from hill 3 northwest to the Book Cliffs (not on fig. 1) north of Crescent Junction. It conformably overlies the Dakota Sandstone and is gradational into it. The Mancos is probably as much as 2,000 feet (610 m) thick but because of its soft nature is easily eroded and poorly exposed. About 350 feet (107 m) above the base of the formation in this area, the persistent thin-bedded Farron Sandstone Member of the Mancos Shale forms a low cuesta ridge throughout much of the area peripheral to the anticline. North of hills 1 and 3 (fig. 5) the Farron forms a low ridge consisting of two fossiliferous calcarenites each 15-20 feet (4.6-6 m) thick separated by about 15 feet (4.6 m) of dark-gray shale.

QUATERNARY DEPOSITS

Alluvium

The floor of Salt Valley is partly covered by reddish-brown gypsiferous sandy alluvial and eolian soil derived from erosion of the rocks that form the anticline. The alluvium is generally restricted to the present drainage and probably rather thin and of Holocene age (<10,000 years old). Southeast of the Salt Valley area a thick alluvial fill in the Fisher Valley anticline contains two volcanic-ash beds dated at 0.7 and 0.6 m.y. (Izett and others, 1970; Naeser and others, 1973). No such ash was observed in the alluvium either in or adjacent to the map area.

Certain of the low rounded knobs and hills rising 10-15 feet (3-5 m) above the general valley floor are composed of soft gypsiferous caprock material and appear to be capped by remnants of thin reddish-brown older alluvium (fig. 5). This alluvium contains distinctive pebbles and cobbles of brightly colored chert derived from the Brushy Basin Member of the Morrison Formation as well as shale and sandstone fragments from the Paradox. The Morrison was observed, as mentioned earlier, to crop out only at the base of hill 2 within the axis of the anticline. Presence of these chert pebbles suggests that the Brushy Basin was at one time more widely distributed in the collapsed center of the anticline but has since been removed by erosion. This alluvium was not recognized on the higher hills, such as 1, 2, 3, and 6.

STRUCTURE

The Paradox basin is characterized by a thick sequence of generally flat-lying sedimentary rocks that are folded into a striking series of northwest-trending salt-cored anticlines and intervening synclines (see Hite and Lohman, 1973, fig. 1). The area of interest lies near the northwest end of one of these structures, the Salt Valley anticline; it is part of a larger structural feature that extends sinuously more than 60 miles (97 km) southeast into Colorado. This large structure includes the Salt Valley, Cache Valley, and Fisher Valley anticlines in Utah, and the Sinbad Valley anticline in Colorado.

A through discussion of the salt anticlines in Colorado and their origin was presented by Cater (1970). Northwest-trending normal faulting of the basement rocks underlying the Paradox basin occurred in Pennsylvanian time during and shortly after deposition of the salines of the Paradox Member of the Hermosa Formation. This faulting caused local uplift of the salt along these fault trends and corresponding subsidence in adjacent areas. Post-Paradox sediments accumulated at a greater rate in the subsided areas, providing more overburden weight there. Salt, being plastic, tended to migrate laterally from these areas of thicker and heavier overburden toward the areas of thinner, or no, cover. As salt was forced from the originally subsiding areas, they continued to sink and trap sediments. This self-generating process continued until most or all of the salt had been squeezed from the synclines into the anticlines. The linear welts of thickened salt received little or no sedimentation from Pennsylvanian well into Jurassic time; the adjacent areas were simultaneously receiving great thicknesses of sediment. Not until Morrison time were sediments deposited across these salt ridges, suggesting that migration of the salt from the synclines to the anticlines was slowing down or was nearly complete by Morrison time. During the time interval when the salt formed positive ridges, dissolutioning must have been occurring and a caprock consisting of insoluble residue of the saliferous Paradox must have been forming.

Collapse of the axes of the salt anticlines occurred in two stages widely separated in time, according to Cater (1970, p. 65). The first stage took place shortly after an episode of Late Cretaceous folding. This was simple graben faulting along the axes of the folds. The salt cores at that time were covered by as much as 5,000 feet (1525 m) of sediments of the Jurassic Morrison Formation through the Late Cretaceous Mesaverde Formation, which were downdropped into the grabens. The second stage of collapse occurred after the entire Colorado Plateau was involved in epeirogenic uplift during middle to late Tertiary time. "Uplift rejuvenated the streams and increased ground-water circulation. Deep canyons eventually breached the crests of the anticlines and exposed the underlying salt to rapid solution and removal. With the abstraction of salt, renewed collapse of the anticlinal crests began" (Cater, 1970, p. 66).

Salt Valley anticline

The northwestern end of the Salt Valley anticline plunges gently northwestward and appears to pass into a graben within the Late Cretaceous Mesaverde Formation in the Book Cliffs north of Crescent Junction. In the map area the anticline shows axial collapse topographically expressed by a narrow valley of low relief flanked by steep cliffs formed by the gently dipping (5°-10°) rocks of post-Pennsylvanian age. The collapsed axis varies from less than 0.5 mile to about 1.5 miles (0.8-2.4 km) wide in the study area. The northwest plunge of the anticline causes the resistant formations on the flanks to disappear beneath the weak Mancos Shale to the northwest.

Probably during the second stage of collapse in middle Tertiary time the complex series of normal faults on the southwest flank of the anticline were induced (fig. 3). These faults, which roughly parallel the axis of the anticline, stairstep Paleozoic and Mesozoic rocks down toward the axis.

Sandstone strata on both flanks of the Salt Valley anticline have been shattered by joints caused by flexing of the rocks (Lohman, 1975, fig. 12). Although all competent sandstones contain some joints, in the map area the Moab Member of the Entrada Sandstone displays a truly amazing pattern of joints where large dipset-slope areas are exposed. On the southwest flank a single joint predominates. This set is parallel to subparallel to the anticlinal axis, trends N. 25°-50° W. and is spaced about 100 feet (30 m) apart. On the northeast flank, however, the large area of the Moab outcrop is densely crosshatched, with two joint sets closely spaced about 20-60 feet (6-18 m) apart producing a grid pattern. These joint sets trend N. 80° E. and N. 10° W.

In secs. 30 and 31, T. 22 S., R. 20 E., several low hills and ridges in Salt Valley are formed by downdropped blocks of Jurassic and Cretaceous rocks foundered in the caprock. The oldest rock exposed is the upper 20 feet (6 m) of the Brushy Basin Member of the Morrison Formation which forms the base of hill 2 and underlies sandstone and quartzite of the basal part of the Burro Canyon Formation.

No distinct overall structural pattern emerges from these outcrops. The rocks of hill 2 are warped into two small faulted structural basins. Hills 1 and 3 are complexly faulted and distorted anticlines of Cretaceous Burro Canyon, rimmed by Dakota. These anticlines are asymmetrical with prominent northeast-dipping hogbacks that were downfaulted and drag-folded in transit.

North of hill 3, but separated from it by an irregular patch of gypsiferous caprock, is a long cuesta of foundered northeast-dipping Farron Sandstone Member of the Mancos Shale that lies about 350 feet (107 m) stratigraphically above the base of the Mancos. At its southeast end the Farron is in fault contact with Triassic Wingate Sandstone and at its northwest end it is in contact with Dakota Sandstone of hill 1.

Hills 1 and 3 are believed to be unconnected and separated by caprock material at depth. The thickness of the blocks can be estimated with reasonable accuracy if certain assumptions are made. Cater (1970, p. 35) believes that the Morrison Formation covered all or most all of the anticlines prior to collapse of their crests. If this premise holds true for this area (although the Salt Wash Member is not exposed within the collapsed center of the anticline here) then a complete, although possibly thinned, stratigraphic section from Salt Wash to Mancos crossed the anticline here and should be present in the downdropped blocks. Each block should then contain that part of the stratigraphic section underlying the highest exposed formation. If one were to drill on the south flanks of hills 1 and 3, the drill should penetrate Dakota, Burro Canyon, Brushy Basin, and Salt Wash, a stratigraphic thickness of about 820 feet (250 m), before entering either caprock or salt. Actual depth to caprock or salt would, of course, be more than this depending on the dip of the formations and unknown structural irregularities at depth.

An isolated block of copper-bearing Salt Wash Sandstone lies in the valley partly buried in alluvium. It is located about 500 feet (152 m) from the base of the south wall of the valley and about 600 feet (180 m) northwest of hill 6. Bedding in the block strikes north and dips 60° northwest. The block, about 60 feet (18 m) long and 20 feet (6 m) wide, was staked as a mining claim and a small shaft was sunk in it. The shaft, now choked with debris, probably was sunk until caprock was reached and then was abandoned. I speculate that the block tumbled from the valley wall rather than having been let down by solution and collapse of the anticline.

North of hill 1, in the southwest corner, SE 1/4, sec. 30, T. 22 S., R. 20 E., the Stellar Oil Co. Federal No. 1 well was drilled to a depth of 1,262 feet (385 m). The driller's log claims the hole penetrated the Triassic Chinle-Shinarump contact at 1,185-foot (361 m) depth; however, it seems more probable that the hole was drilled entirely in a downdropped block of Mancos Shale that is exposed to the north and south of the hole. Casing was hung in the hole to shut off a flow of water at 900 feet (274 m). It is possible that the water was coming from the Farron Sandstone Member of the Mancos Shale, which crops out 1,250 feet (381 m) south of the drill hole and dips toward it at 30°-60°. If the average dip of the Farron is about 36° and there are no intervening faults, the Farron would intersect the well at about the 900-foot (274 m) depth. Although the Farron is not noted as an aquifer, compared with the overlying and underlying upper and lower members of the Mancos Shale, it probably is fairly permeable. If the foregoing calculations are valid, the Stellar well would have had to drill to at least 2,650 feet (808 m) below ground level to reach the base of the Salt Wash Member of the Morrison Formation.

GEOMORPHOLOGY

By Miocene time this area probably had a surface of low relief and only the laccolithic intrusives such as the La Sal Mountains projected above it. Epeirogenic uplift began during the Miocene; rejuvenated streams began downcutting, and erosion was greatly accelerated. At that time, the present drainage pattern was imprinted on the area. Antecedent streams crossing the salt anticlines are not uncommon according to F. W. Cater (oral commun., 1975); the Dolores River crossing Paradox Valley in Colorado is a well-known example. Downcutting reached the salt cores of the anticlines, and accelerated dissolutioning of the salt enhanced the slumping of the anticlinal axes.

This part of Salt Valley is drained by a small unnamed dry wash that heads at Arches National Park boundary, about 1.5 miles (2.4 km) southeast of the map area. The wash drains northwest joining Thompson Wash, which flows southwest to the Green River. In the southeastern part of the map area the dry wash consists of two channels. The southerly of these channels is unusual in that it flows between hills 6 and 7 (figs. 3 and 6) following a zig-zag course. It is surprising that this ephemeral stream should have followed such a difficult course rather than flowing around these hills of resistant sandstone, shale, and limestone of the Paradox Member. Two explanations are possible. The stream could have been superimposed on the hills as the valley floor was lowered by erosion, or it could be an antecedent stream at this place and recent upward movement of the caprock could have caused the hills to rise beneath the previously established stream course. Conclusive evidence to support either superimposition or antecedence is lacking; however, the presence of the wash is consistent with Cater's antecedent stream interpretation. A broad flat area of alluvium upstream from hill 7 suggests that brief ponding caused by recent upward movement of these hills may have occurred.

As mentioned earlier the drainage divide in Salt Valley lies about 1.5 miles (2.4 km) southeast of the map area just inside the Arches National Park boundary. On the southeast side of the divide, Salt Valley is drained by an intermittent stream that is tributary to Salt Wash. Salt Wash, an antecedent stream, crosses the Salt Valley anticline flowing southeast and empties into the Colorado River northeast of Moab (fig. 1). North of the anticline it heads at the Book Cliffs 3 miles (5 km) northeast of Thompson and drains a large area that includes the Yellow Cat mining district (Yellow Cat Flat on fig. 1). As Salt Wash crosses the anticline it is joined by the subsequent streams that drain Salt Valley to the northwest and Cache Valley to the southeast. The Colorado River is presently degrading or has been degrading recently according to Dane (1935, p. 156) and downcutting of small tributaries such as Salt Wash have not kept pace.

The tributary to Thompson Wash that drains the map area falls 1,000 feet (305 m) in about 25 miles (40 km) to reach the Green River, whereas the tributary to Salt Wash draining to the southeast also falls 1,000 feet (305 m) but travels only 15 miles (24 km) to the Colorado River. Thus Salt Wash has a steeper gradient than Thompson Wash and should be eroding more rapidly. It seems likely then that the drainage divide in Salt Valley will migrate slowly northwestward into the map area as Salt Wash adjusts itself to the new base level of the Colorado River. However, because these are both ephemeral streams having small drainage areas in a semiarid climate, migration of the divide about 5 miles (8 km) northwest to where the target area lies could take millions of years barring the advent of a wetter climate.

HYDROLOGY

The area of interest in Salt Valley embraces a watershed of about 5 mi^2 (8 km^2), which is drained by the unnamed dry tributary to Thompson Wash. This unnamed tributary consists of several branches that are intermittently entrenched in the alluvium. These entrenched sections are as much as 4-8 feet (1.2-2.4 m) deep and extend for as much as half a mile (0.8 km). This type of arroyo cutting is common in the semiarid west and is caused by changes in stream gradient owing to slight steepening of the valley gradient (Shumm and Hadley, 1957).

Surface water

Precipitation is low; there are no permanent streams in or near the area. The average annual precipitation at Thompson, 8 miles (13 km) to the north, during a 15-year recording period was 7.81 inches (19.8 cm) (Dane, 1935, p. 12). At Moab, 20 miles (32 km) to the south, the average annual precipitation over a 68-year recording period was 8.18 inches (20.8 cm) (Sumsion, 1971, p. 8). Precipitation falling in the area is most likely to be in the form of thunderstorms and, although likely to be heavy locally, is also apt to be irregular in distribution. The greatest total annual precipitation recorded near Moab was 15.96 inches (40.5 cm) in 1918 and in 1927; the least total annual precipitation recorded there was only 3.02 inches (7.67 cm) in 1956 (Sumsion, 1971, p. 8). Precipitation near Moab is greatest in the fall and winter months and least during May, June, and July.

Ground water

To date, there have been no ground-water studies within or near the map area. Very little hydrologic information has been obtained from a few drill holes near the area of interest.

In 1936 a borehole was drilled for stock water in Salt Valley about 7 miles (11.3 km) southeast of the area. This well was in sec. 31, T. 23 S., R. 21 E., in the area now included in Arches National Park. This hole penetrated 858 feet (262 m) of caprock and saline water was found between 850 and 858 feet (260-262 m). The water rose 300 feet (91.5 m) in the drill hole and the yield was reported to be 12 gpm (gallons per minute) (45.4 litres per minute). Another hole drilled about 5 miles (8 km) to the southeast on the edge of Salt Valley was the Utah Southern Oil Co. King No. 1 well, which was drilled in 1929. This hole, 3,829 feet (1168 m) deep, is located in sec. 13, T. 23 S., R. 20 E. (Dane, 1935, p. 158). The well, lying on the northeast flank of the Salt Valley anticline, drilled through 1,060 feet (323 m) of Triassic and Permian formations before penetrating 580 feet (177 m) of caprock between the 1,060- and 1,640-foot (323-500 m) depth. Saltwater in unrecorded amounts was found in the caprock between 1,478 and 1,480 feet (451-451.4 m). Records of drill holes near Crescent Junction and on the flanks of the anticline indicate that large amounts of water, both fresh and saline, have been found in strata ranging from Permian through Cretaceous in age.

It is not known how deeply the bases of the foundered blocks of Jurassic and Cretaceous rocks lie in the caprock. The answer to this may be important if there is ground water moving through the caprock. These huge blocks may impede or restrict the ground-water flow which may result in an irregular piezometric surface.

No springs or seeps are known within this part of Salt Valley. On the northeast flank of the anticline a small spring issues from either the Burro Canyon or the Dakota Formation. Several small springs and seeps are known to issue from the Entrada Sandstone along Courthouse Wash on the west side of the national park about 10 miles (16 km) south of the study area.

MINERAL DEPOSITS

The occurrence of uranium and vanadium ores in Mesozoic sediments of the Colorado Plateau has been known since the late 19th century (Dane, 1935, p. 196). During the 1940's and 1950's this area was subject to intensive search for uranium. Although no uranium was found in the map area, the famous Yellow Cat uranium mining district lies on the northeast flank of the anticline about 10 miles (16 km) to the east (fig. 1). No mines are currently active there.

Copper, in the form of the carbonates azurite and malachite, occurs as disseminated splotches in the Salt Wash Member of the Morrison Formation on the southeast flank of the anticline; several small inactive prospects are located near the national park boundary to the southeast. In sec. 6, T. 22 S., R. 20 E., at the top of the cliff overlooking the site area, a small operation was being developed in the fall of 1974 to leach copper from the Salt Wash Member. When revisited in May 1975, however, the operation was inactive. Copper mineralization is thought to be related to emplacement of the middle Tertiary laccolithic intrusive rocks such as those that form the La Sal Mountains. Faulting on the southwest flank of the anticline postdates mineralization because copper is distributed throughout the faulted blocks of sandstone of the Salt Wash Member.

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