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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SUBSURFACE GEOLOGY OF A POTENTIAL WASTE EMPLACEMENT SITE, SALT VALLEY ANTICLINE, GRAND COUNTY, UTAH

By

Robert J. Hite

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ABSTRACT

The Salt Valley anticline, which is located about 32 km northeast of Moab, Utah, is perhaps one of the most favorable waste emplacement sites in the Paradox basin. The site, which includes about 7.8 km^2, is highly accessible and is adjacent to a railroad.

The anticline is one of a series of northwest-trending salt anticlines lying along the northeast edge of the Paradox basin. These anticlines are cored by evaporites of the Paradox Member of the Hermosa Formation of Middle Pennsylvanian age.

The central core of the Salt Valley anticline forms a ridgelike mass of evaporites that has an estimated amplitude of 3,600 m. The evaporite core consists of about 87 percent halite rock, which includes some potash deposits; the remainder is black shale, silty dolomite, and anhydrite. The latter three lithologies are referred to as "marker beds." Using geophysical logs from drill holes on the anticline, it is possible to demonstrate that the marker beds are complexly folded and faulted.

Available data concerning the geothermal gradient and heatflow at the site indicate that heat from emplaced wastes should be rapidly dissipated.

Potentially exploitable resources of potash and petroleum are present at Salt Valley. Development of these resources may conflict with use of the site for waste emplacement.

INTRODUCTION

In 1973, a report was prepared (Hite and Lohman, 1973) that made a preliminary survey of the extensive salt deposits of Pennsylvanian age in the Paradox basin of southeast Utah and southwest Colorado. Its purpose was to determine if potential sites for waste emplacement might exist in these deposits. As the result of that work, which described the geology of 11 potential site areas, it was decided that one, the Salt Valley anticline in Grand County, Utah, was best suited for this purpose. As a second phase of the investigation, the geology of the Salt Valley anticline was investigated in as much detail as possible, resulting in the present report plus the work of Gard (1976), which described the surface geology of the site.

The present report is concerned primarily with the subsurface geology of the Salt Valley anticline. Its main purpose is to summarize what was learned from all drill holes penetrating the evaporite core of the anticline in regard to composition, structure, and geometry of the evaporite mass and its overlying caprock. In addition, ground water in the caprock, hydrocarbons in the evaporites, and the economic geology of the area are discussed.

LOCATION

The potential emplacement site on the Salt Valley anticline lies along the northeast flank of the Paradox basin (fig. 1). The site is in Grand County, Utah, about 32 km northeast of the town of Moab. A spur of the Denver & Rio Grande Western Railroad crosses the axis of Salt Valley anticline about 5.0 km from the northwest boundary of the site area (fig. 2). Easy access to the site from the railroad spur is possible along the floor of Salt Valley, where the average slope is about 4.3 m/km. The railroad spur, which services the Texas Gulf, Inc., Cane Creek potash mine, connects with the main east-west line about 11.3 km north of the site at the small village of Crescent Junction, Utah. The site can be easily reached by an unimproved dirt road that connects with U.S. Highway 160 about 8.9 km from the northwestern boundary of the site area.

All of the site area is on Federal or State lands. At present, the site is uninhabited and there is no mining or drilling activity in the area.

The site area covers about 7.8 km^2. Site boundaries were determined by using a cutoff depth of about 500 m to the top of the first halite bed, and by the common boundary on the southeast with the Arches National Park. The boundary could be expanded to the northwest if greater depths are considered.

GEOLOGY

This report is primarily concerned with the geology of the evaporite core and caprock of the Salt Valley anticline. The complementary report by Hite and Lohman (1973) should be used for more explicit details of the regional geologic setting. In brief, the Salt Valley anticline is the northernmost of a continuous chain of diapiric salt anticlines that lie along the deep northeastern border of the Paradox basin. This anticlinal chain, beginning with Salt Valley on the north, includes, in order, Cache Valley, Fisher Valley, and Sinbad Valley anticlines (fig. 1). The northeast edge of the Paradox basin is about 19.4 km northeast of the northeast flank of the anticline. This edge of the basin is bounded by a huge horst block known as the Uncompahgre uplift (fig. 1). The edge of the salt along this side of the basin is covered by nearly 3,700 m of Paleozoic and Mesozoic rocks. The Salt Valley anticline is diapiric along most of its length. At the northern end of the structure, the anticline plunges steeply to the northwest and is deeply buried by the Mancos Shale of Cretaceous age.

THE EVAPORITE CORE

The central or evaporite core of the Salt Valley anticline consists of halite, some of which has associated potash minerals, and thin interbeds of black shale, dolomite, and anhydrite. The latter are commonly referred to as "marker beds" because they are very useful for stratigraphic correlation (Hite, 1960). The evaporitic sequence makes up the Paradox Member of the Hermosa Formation of Middle Pennsylvanian age.

The central core of the anticline forms a huge ridgelike mass of evaporites that has an estimated amplitude of about 3,600 m. Maximum penetration of this mass was in drill hole no. 8 (table 1), which at a total depth of 4,030 m was still drilling in halite-bearing

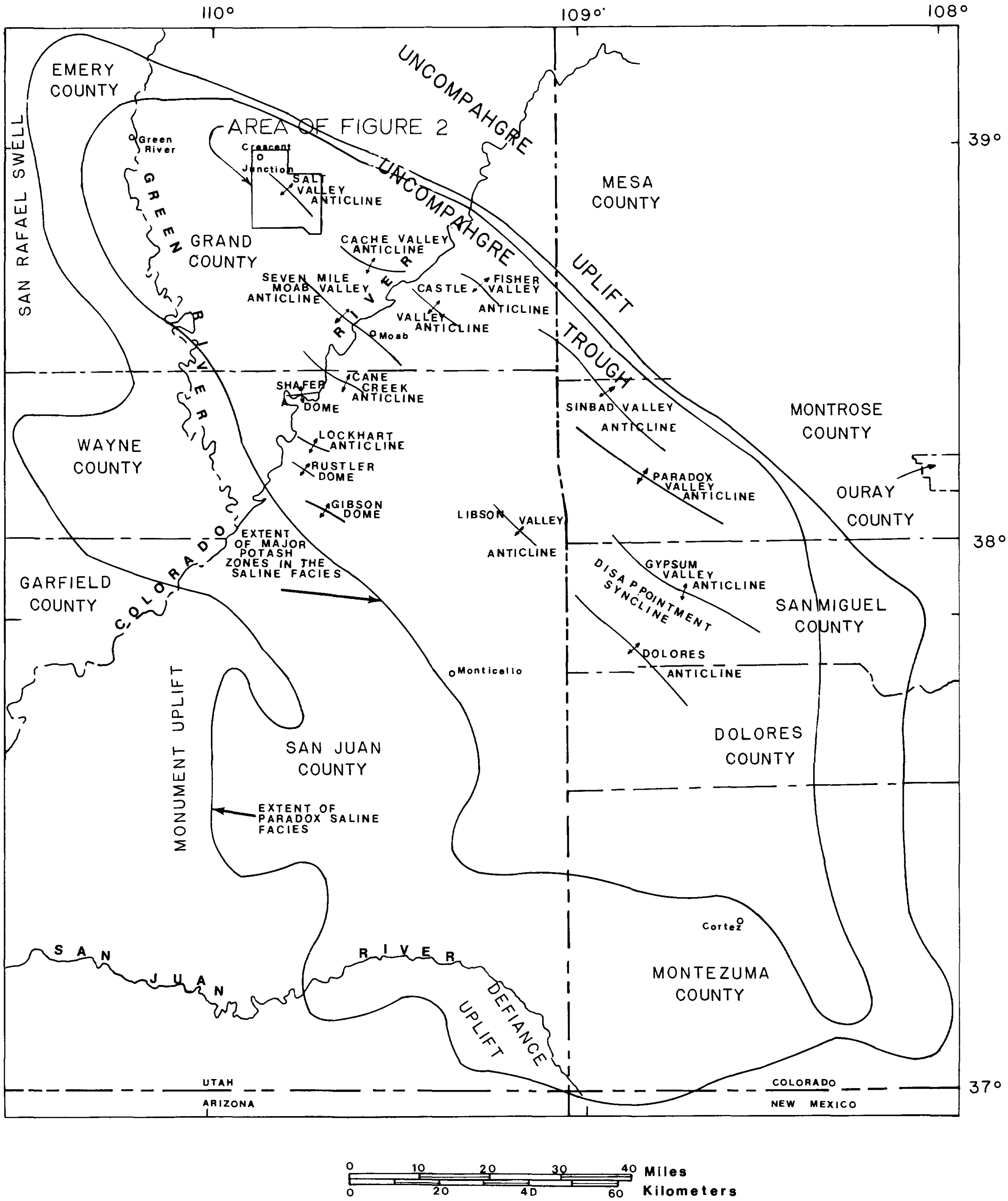

Figure 1.--Index map of Paradox basin showing salt anticlines and limits of saline facies and potash in the Paradox Member of the Hermosa Formation (from Hite, 1961).

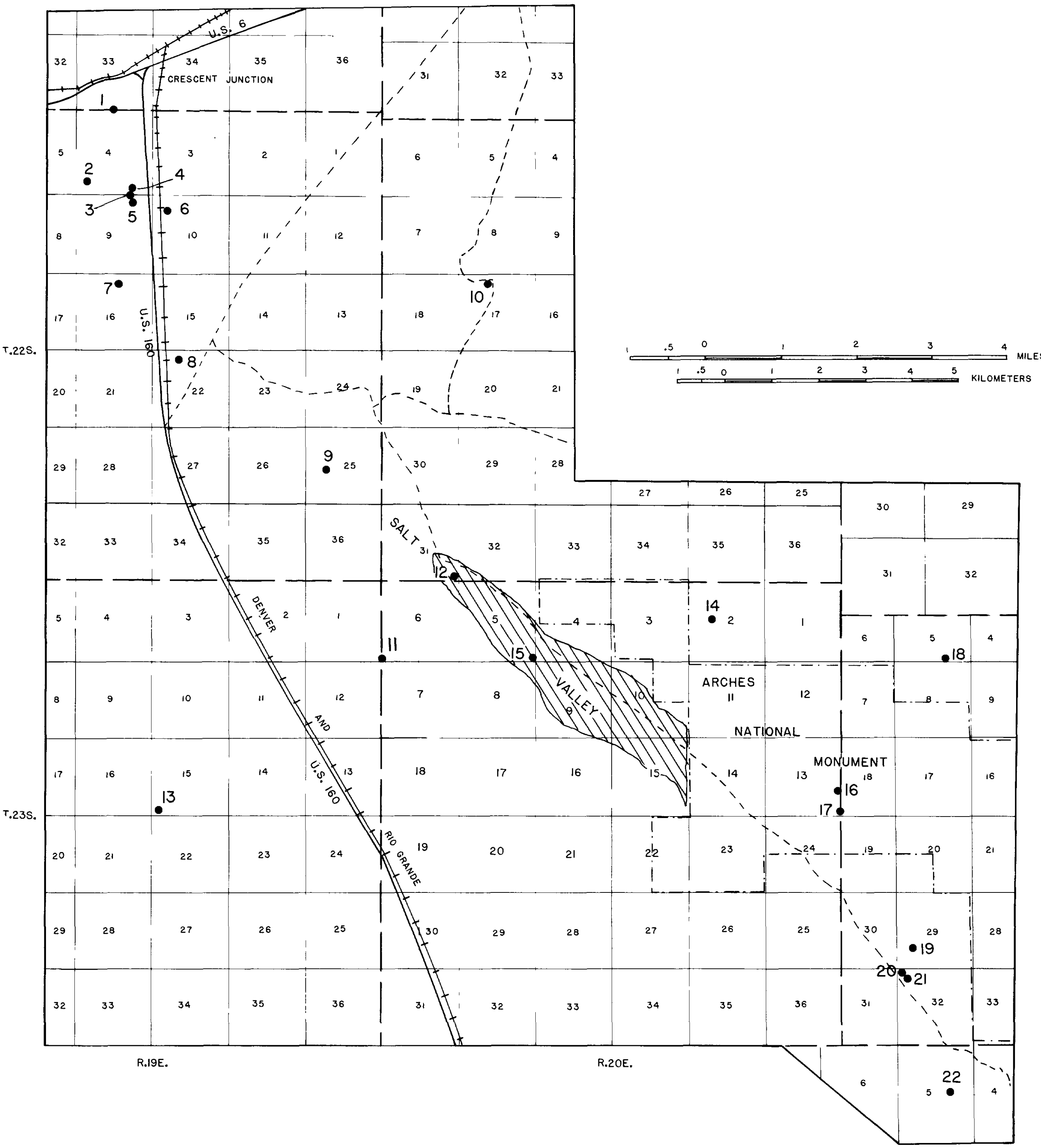

Figure 2.--Map showing Salt Valley anticline drill holes that penetrate halite and the potential emplacement site area (shaded).

Table 1.--*Thickness and other data for drill holes that penetrate halite in the Paradox Member, Hermosa Formation, Salt Valley anticline.*

[Short dashes indicate no data are available, queried where data not reliable]

Drill hole	Company name	Location Sec.	T.	R.	Total depth	Top of salt	Penetration thickness of halite-bearing rocks	Percent of halite in section	Thickest halite intersection	Thickest marker bed intersection	Caprock thickness	Ground level	Date of completion or abandonment	Comments
1	Potash Co. of America, Wright No. 2	33	21S	19E	1,528 m (5,012 ft)	1,328 m (4,357 ft)	200 m (655 ft)	89	--	--	--	1,483 m (4,865 ft)	1943	Potash test; no geophysical logs run. Paradox stratigraphy unknown.
2	Potash Co. of America, Wright No. 1	4	22S	19E	1,524 m (5,000 ft)	834 m (2,737 ft)	690 m (2,263 ft)	85	--	--	--	1,463 m (4,800 ft)	1943	Potash test; no geophysical logs run. Paradox stratigraphy unknown.
3	Crescent Eagle Oil Co., No. 1	4	22S	19E	1,222 m (4,009 ft)	628 m (2,060 ft)	594 m (1,949 ft)	--	--	--	--	1,457 m (4,780 ft)	1920?	Oil and gas test; no geophysical logs. Paradox stratigraphy unknown.
4	Defense Plant Corp., Reeder No. 1	4	22S	19E	3,155 m (10,350 ft)	638 m (2,091 ft)	2,518 m (8,259 ft)	74 (2,091-6,140 ft)	183 m (600 ft)	72 m (235 ft)	--	1,457 m (4,780 ft)	1949	Drilled as potash and magnesium test to 1,283 m. Hole later deepened to 3,155 m as an oil and gas test. Radioactivity log available to 1,850 m.
5	Brendel Oil and Gas Co., No. 1	9	22S	19E	1,258 m (4,125 ft)	565 m (1,854 ft)	692 m (2,271 ft)	--	--	--	--	1,454 m (4,770 ft)	1932	Oil and gas test; no geophysical logs run.
6	Potash Co. of America, Woods No. 1	10	22S	19E	1,528 m (5,013 ft)	864 m (2,833 ft)	665 m (2,180 ft)	84	--	--	--	1,454 m (4,769 ft)	1943	Potash test; no geophysical logs run.
7	Potash Co. of America, McCarthy State No. 1	16	22S	19E	1,601 m (5,250 ft)	1,212 m (3,975 ft)	389 m (1,275 ft)	88	--	--	--	1,439 m (4,720 ft)	1943	Potash test; no geophysical logs run.
8	Continental Oil Co., Unit No. 1	22	22S	19E	4,030 m (13,223 ft)	928 m (3,045 ft)	3,102 m (10,173 ft)	87 (3,045-9,640 ft)	162 m (530 ft)	204 m (670 ft)	--	1,424 m (4,670 ft)	1962	Oil and gas test did not reach base of salt; geophysical logs to 9,640 ft; upper salt section cored for potash.
9	San Jacinto Petroleum Corp., Salt Valley No. 3	25	22S	19E	1,238 m (4,060 ft)	813 m (2,665 ft)	425 m (1,395 ft)	77	58 m (190 ft)	20 m (65 ft)	--	1,436 m (4,710 ft)	1961	Potash test, cored continuously through salt.
10	Continental Oil Co., well No. 1	17	22S	20E	4,568 m (14,984 ft)	3,869 m (12,690 ft)	432 m (1,418 ft)	77	232 m (760 ft)	37 m (120 ft)	--	1,450 m (4,757 ft)	1973	Oil and gas test, completely penetrated thin section of Paradox Member on anticlinal flank.
11	Continental Oil Co., Hall No. 1	6	23S	20E	925 m (3,036 ft)	838 m (2,750 ft)	87 m (286 ft)	--	--	--	--	1,598 m (5,242 ft)	1957	Oil and gas test, still in salt at total depth.
12	Oil Securities and Uranium Corp., Peterson No. 1	31	22S	20E	820 m (2,690 ft)	241 m? (790 ft)?	579 m? (1,900 ft)?	89	193 m (634 ft)	13 m (42 ft)	155 m? (510 ft)?	1,457 m (4,780 ft)	1956	Potash test, cored continuously through Paradox Member. Top of salt could be at 220 m; hydrocarbon blowouts in all marker beds.
13	Texaco Inc., No. 1 Government McKinnon	15	23S	19E	3,684 m (12,083 ft)	2,816 m (9,235 ft)	606 m (1,987 ft)	?	--	--	--	1,395 m (4,574 ft)	1967	Oil and gas test, completely penetrated thin Paradox Member on southwest flank of anticline; no geophysical logs available through Paradox Member.
14	Pure Oil Co. NE Salt Valley Unit No. 1	2	23S	20E	926 m (3,036 ft)	848 m (2,780 ft)	78 m (256 ft)	?	--	--	--	1,596 m (5,235 ft)	1949	Oil and gas test; no radioactivity log.
15	K. Levi, Western Allies No. 1	5	23S	20E	384 m (1,258 ft)	236 m (755 ft)	147 m (483 ft)	?	--	--	--	1,474 m (4,835 ft)	1931	Oil and gas test to 252 m; later deepened to 384-m potash test; no cores taken.
16	Utah Southern Oil Co., King No. 1	13	23S	20E	1,167 m (3,829 ft)	504 m (1,652 ft)	689 m (2,259 ft)	78?	--	--	--	1,579 m (5,180 ft)	1932	Oil and gas test; only drillers' log available.
17	U.S. Government Potash test well 24	13	23S	20E	528 m (1,731 ft)	354 m (1,160 ft)	174 m (571 ft)	98.5	--	--	--	1,527 m (5,010 ft)	1931	Potash tests, cored continuously through salt; no potash present.
18	Union Oil Co., Devils Garden USA No. 1	5	23S	21E	2,824 m (9,262 ft)	2,255 m (7,396 ft)	569 m (1,866 ft)	69	111 m (364 ft)	36 m (118 ft)	--	1,439 m (4,720 ft)	1967	Oil and gas test, still in salt at total depth.
19	San Jacinto Petroleum Corp., Salt Valley No. 2	29	23S	21E	1,220 m (4,002 ft)	367 m (1,203 ft)	853 m (2,799 ft)	91	399 m (1,310 ft)	26 m (85 ft)	--	1,472 m (4,827 ft)	1961	Potash test, cored continuously through salt; no potash present.
20	King Oil Co., Well No. 1	32	23S	21E	1,082 m (3,550 ft)	?	?	--	--	--	--	1,488 m (4,882 ft)	1953	Oil and gas test; no stratigraphic data available.
21	Utah Southern Oil Co., Balsley No. 1	32	23S	21E	1,866 m (6,120 ft)	269 m (883 ft)	1,597 m (5,237 ft)	--	--	--	--	1,488 m (4,880 ft)	1949	Oil and gas test; no geophysical logs available.
22	San Jacinto Petroleum Corp., Salt Valley No. 1	5	24S	21E	1,220 m (4,003 ft)	255 m (835 ft)	966 m (3,168 ft)	82	109 m (356 ft)	24 m (78 ft)	165 m (540 ft)	1,476 m (4,840 ft)	1961	Potash test, cored continuously through salt; potash present.

rocks. The total volume of the evaporite mass within the boundaries of the site area is about 27.5 km^3. The surface of the evaporite mass dips away from the crestal area at about 380 m/km. The crest of the mass is probably almost flat, except for a gentle plunge to the northwest. Drill-hole density is still too sparse to verify this planar surface; however, the development of such a surface has been demonstrated on similar salt structures in other parts of the world. These surfaces, which are commonly referred to as salt tables or salt mirrors (Bloch, 1974), develop as the result of dissolution of halite by ground water. There is no reason to believe that such a surface has not developed at Salt Valley. It is possible, however, that some irregularities on this surface may be present where the water-insoluble marker beds protect halite from contact with ground water (fig. 3).

Composition of the Evaporite Core

The evaporite core of the Salt Valley anticline consists of four major rock types; in order of greatest abundance, they are (1) halite with or without potash minerals, (2) silty dolomite, (3) organic-rich black shale, and (4) anhydrite. The latter three rock types rarely occur alone but are grouped together in units referred to as "marker beds." The marker beds, together with the adjacent halite beds, form a series of evaporite cycles which have been described in great detail in previous reports (Hite, 1960, 1961, 1969; and Hite and Lohman, 1973). Data regarding the composition of the evaporite mass were derived from drill cores, sample logs, and geophysical logs from 22 drill holes that penetrated all or part of the mass (table 1). These holes were drilled by companies exploring for petroleum or potash deposits.

The evaporite core of the anticline consists of 87 percent halite rock, and the remainder of the core is marker beds. This figure was obtained from 12 drill holes along the crest of the anticline, which penetrated a total of 8,616 m of halite-bearing rocks in the Paradox Member. Wells drilled downdip on the flanks of the anticline, such as wells 10 and 18 (table 1), were not included because they are probably not representative of the evaporite mass in the site area. These two holes have a smaller halite content because of differential rates of flow between halite and the marker beds. In other words, the halite simply flowed more freely from the flanking synclines into the anticline than did the marker beds. The figure of 87 percent halite is considerably higher than the 73.8 percent arrived at by Shoemaker, Case, and Elston (1958, table 2). The thickest continuous interval of halite penetrated by the drill was 399.3 m in a potash test (well 19, table 1) at the southeast end of Salt Valley. This great thickness is not depositional and can be explained as a steeply dipping bed, dilation of an originally thinner bed by plastic flow, repetition by faulting or folding, or a combination of any or all of these factors.

Halite Rock

In general, the halite rock in drill cores from the Salt Valley anticline is relatively free of water-insoluble impurities. The average insoluble content of samples studied by the writer is about 2.5 weight percent and consists primarily of anhydrite with trace amounts of dolomite, quartz, and talc. Sporadically erratic angular fragments, ranging from a few tens

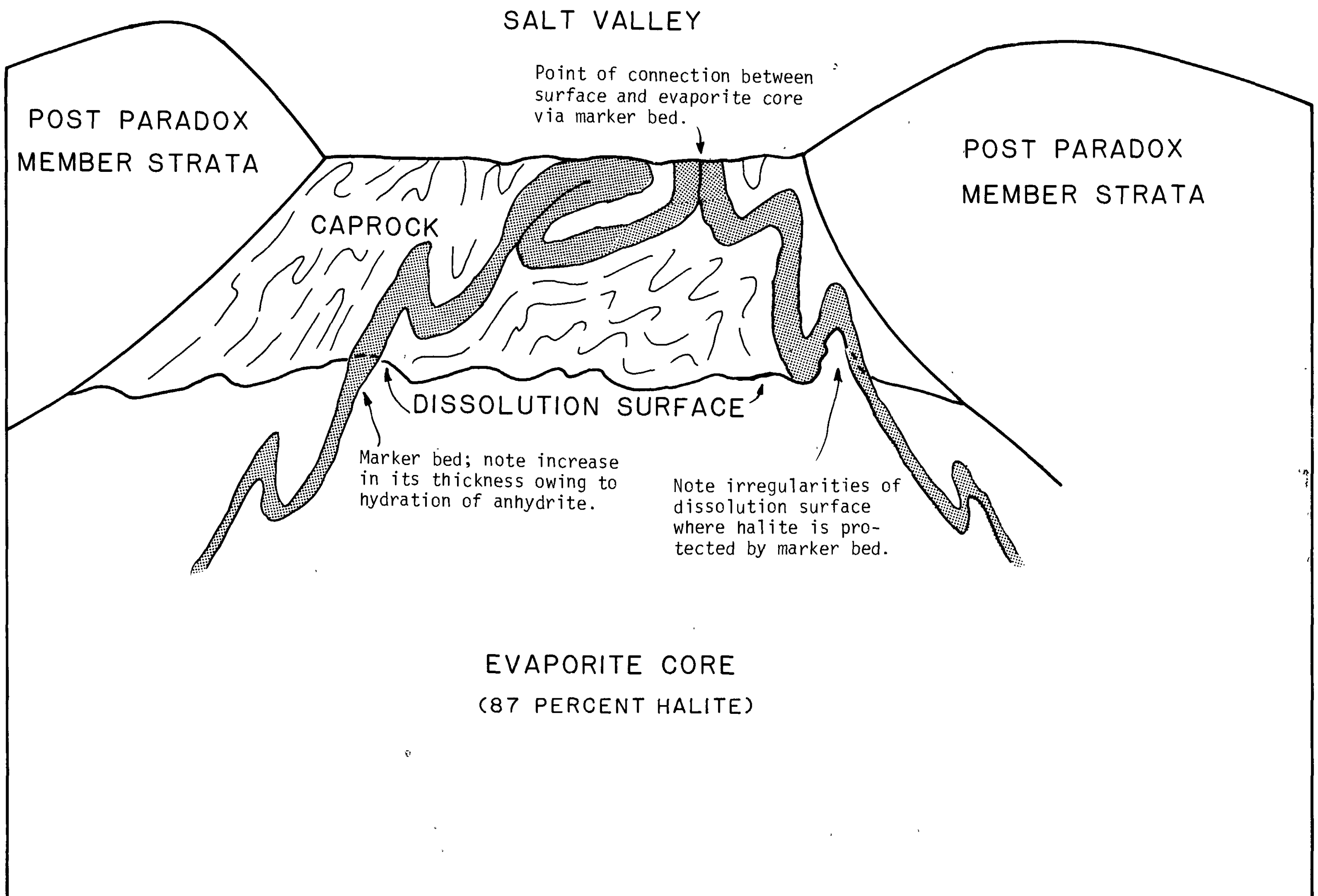

Figure 3.--Diagrammatic cross section through Salt Valley anticline showing interpretive relationships between caprock, evaporite core, and marker beds.

of millimeters to as much as 15 cm in their longest dimension, of dolomite, anhydrite, or black shale are present in the halite. These fragments have only been observed near the upper or lower contact of halite units and are probably derived from shear zones that dragged breccia into the halite unit from the underlying and overlying marker beds. The central part of thick halite units seems to be free of this material. Potash minerals such as carnallite and sylvite are present in some of the halite rock. The normal position of potash deposits is in the upper 4 or 5 m of a halite bed. Small (0.5-3 mm) inclusions of hydrocarbons are present in some halite units. This material occurs in both a liquid and gas phase. Pressures in these inclusions have not been measured but they are probably quite high. Freshly drilled cores from halite rock containing these inclusions frequently "snap, crackle, and pop" as the inclusions rupture, owing to release of lithostatic pressure.

Very little is known about the distribution of hydrocarbons in the halite rock of the Paradox Member. From visual inspection it would appear that hydrocarbons are most common near the top of halite beds. This suggests early vertical migration while the halite bed was still porous and permeable. The only analytical data concerning hydrocarbon concentration in salt of the Paradox Member is from the Texas Gulf, Inc., potash mine on the Cane Creek anticline southwest of Moab, Utah. A sample of sylvite ore from this mine contained 0.30 weight percent extractable petroleum (Peterson and Hite, 1969). Quantitatively more important are brine inclusions that are ubiquitous in the Paradox halite, just as they are in all other salt deposits. Halite samples from several localities in the Paradox basin were analyzed by the writer and found to contain brine inclusions ranging from 0.093 to 0.259 weight percent of the sample. This range of values is quite similar to that of the halite of other deposits for which these kinds of data are available.

Marker Beds

The evaporite core of the Salt Valley anticline also includes marker beds that average about 13 percent of the mass. Marker-bed lithologies observed in drill cores from Salt Valley are identical to those observed in drill cores from other salt anticlines. Details of these lithologies were adequately described by Hite and Lohman (1973) and therefore will not be repeated here.

In relatively undisturbed sections of the Paradox Member west of the Salt Valley area, depositional thicknesses of the marker beds range from about 5 m-60 m. In Salt Valley the greatest penetrated thickness, 204.2 m, of a marker bed was in drill hole 8 (table 1) at the northwest end of the anticline. This marker bed, which is probably the "Cane Creek Marker" (Hite, 1960), would probably have a normal depositional thickness of about 65 m in this area. The abnormal thickness of this unit in drill hole 8 is probably due to a steep dip (about 75°, assuming the drill hole is vertical). When such steep dips are encountered in the marker beds, coring may be difficult because the black shales and dolomites have a tendency to break along bedding planes. Such a break forms a wedgelike core segment that frequently jams in the core barrel.

The marker beds are extremely important to any contemplated emplacement project of Salt Valley because (1) they contain pockets of oil, gas, and brine under high pressures; and (2) they have certain identifiable characteristics on geophysical logs and in drill core and, therefore, can be used as key (or marker) beds to interpret structural geology in the evaporite mass. The first feature is discussed in detail under the heading of "Economic Geology" (p. 19) and the second under "Stratigraphy and Structure of the Evaporite Core" (p. 9).

Stratigraphy and Structure of the Evaporite Core

The regional stratigraphy of the Paradox Member is well defined over much of the Paradox basin. However, in salt anticlines such as Salt Valley, stratigraphic correlation becomes extremely difficult because of the complex structure affecting the marker beds. At the northern end of Salt Valley near Crescent Junction, structure in the evaporite core is less complex than it is within the boundaries of the site area. Two deep drill holes at the northern end (well nos. 4 and 8, fig. 2) penetrated evaporite cycles that can be identified on geophysical logs run in the drill holes. The Cane Creek Marker, C Marker, and Salt 19 (Hite, 1960) have been positively identified in both drill holes. Marker beds penetrated by other drill holes at Salt Valley have not been identified; however, the character of some of these beds on geophysical logs (gamma ray-neutron) is so different in detail that structural repetition can be easily demonstrated (figs. 4 and 5).

In addition to using marker-bed signatures on geophysical logs as a means of structural interpretation, it is also possible to use lithologic variations in the marker beds to determine whether they are in normal stratigraphic position or overturned. For example, the base of a marker bed should form a sharp contact with the underlying halite bed. In contrast, the upper contact of the marker bed with the overlying halite bed will be transitional through a vertical distance of as much as 1 m.

Another useful tool for structural interpretation is distribution of trace amounts of the element bromine throughout individual halite beds. This bromine substitutes for chlorine in the halite crystal lattice. The amount of bromine in a halite crystal is always proportional to the amount of bromine in the brine from which the crystal grew, unless the halite is the product of a much later period of solution and recrystallization. Because most bromine stays in solution in the brine and does not form bromine minerals, the amount of bromine in the brine will increase with brine concentration. Thus, trace bromine in halite beds is an indicator of paleosalinities in the evaporite basin. The first halite crystals deposited on the bottom of an evaporite basin will have relatively low bromine values. As more and more halite is deposited, the salt concentration of the brine increases along with a corresponding increase in bromine in the brine. Thus each new crop of halite crystals will have a slightly higher bromine content. Plots or profiles of bromine distribution throughout several halite beds in the Paradox Member (Raup, 1966) show an increase in bromine from base to top of all the halite beds (fig. 6). The shape of bromine profiles in each halite bed is slightly different and could provide a geochemical signature that might be used to identify the halite bed. An example of using a bromine

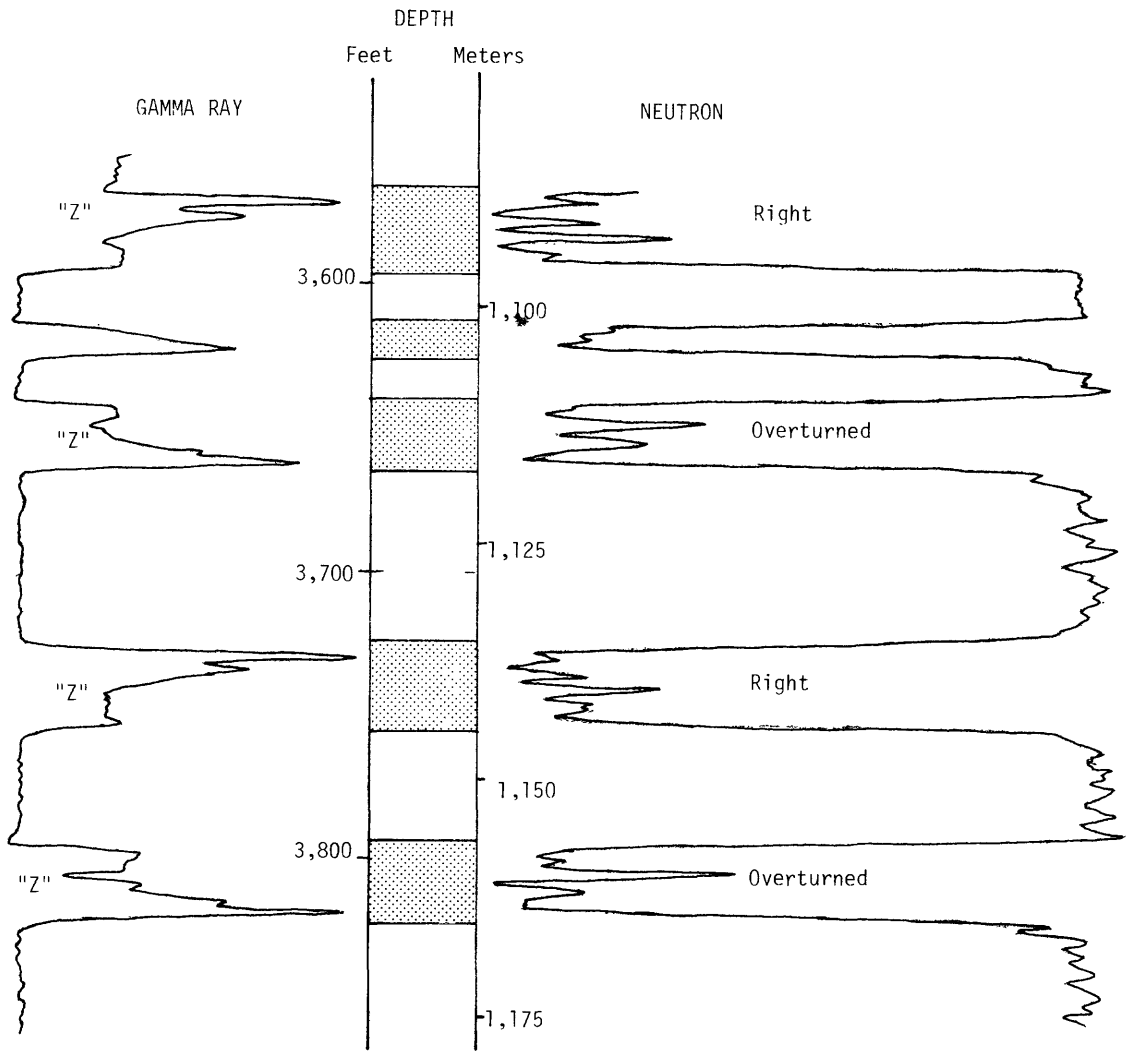

Figure 4.--Gamma ray-neutron log in San Jacinto Petroleum Corp., Salt Valley No. 3 (drill hole no. 9, table 1), located in sec. 25, T. 22 S., R. 19 E., showing folded marker bed "Z."

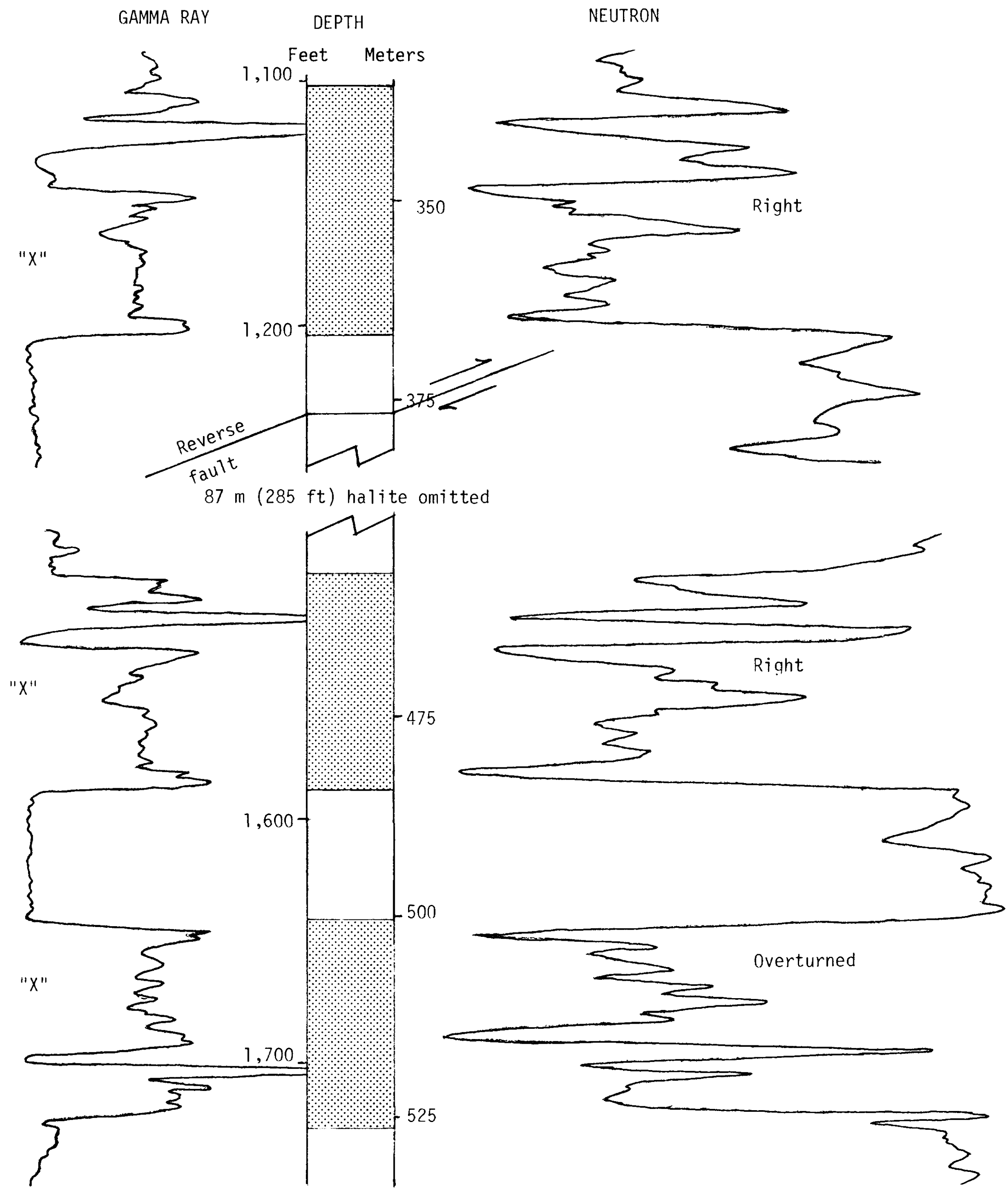

Figure 5.--Gamma ray-neutron log in San Jacinto Petroleum Corp., Salt Valley No. 2 (drill hole no. 19, table 1) in sec. 29, T. 23 S., R. 21 E., showing folded and faulted marker bed "X."

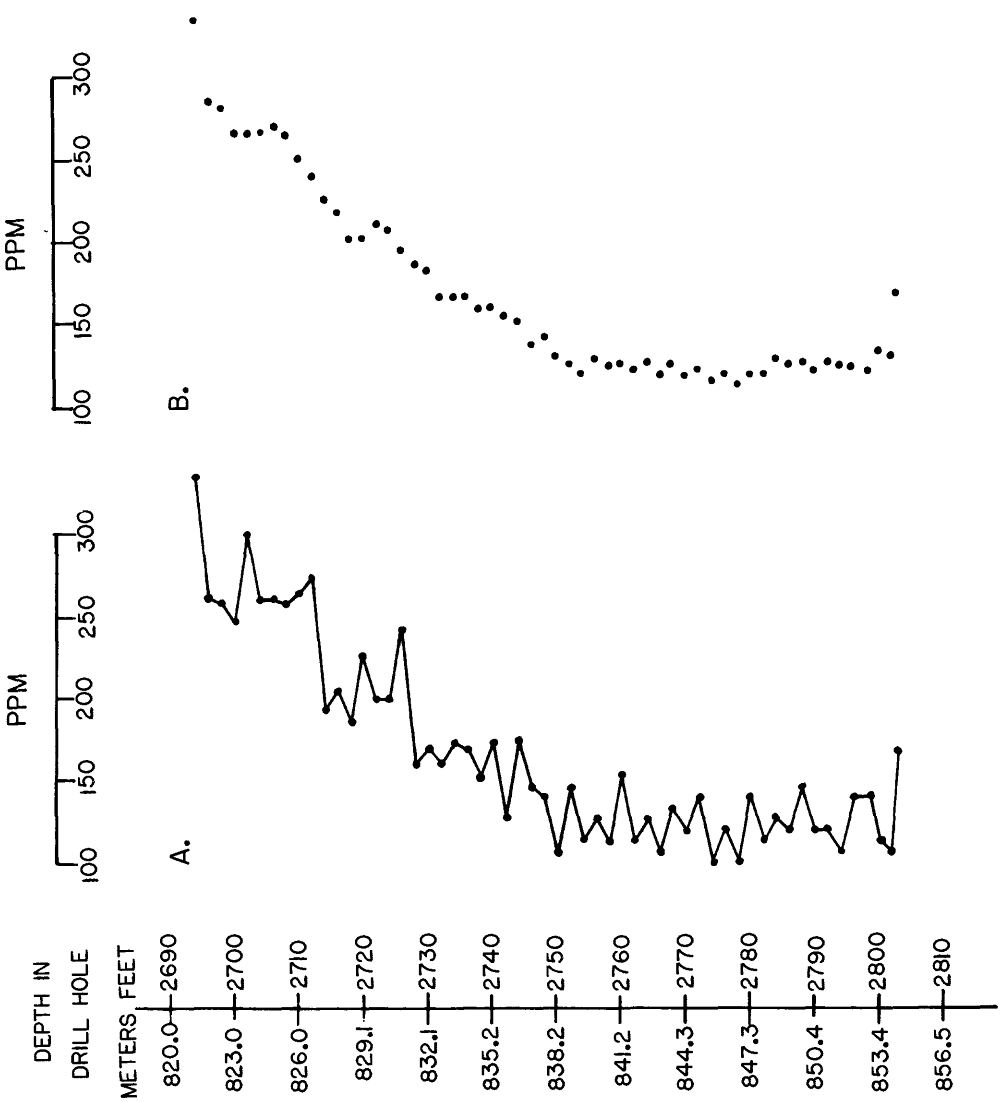

Figure 6.--Bromine distribution in halite in "evaporite cycle 5," Paradox Member (from Raup, 1966). A, plot of raw data; B, arithmetically smoothed profile.

profile to determine the stratigraphic position (normal or overturned) of a halite bed is shown on figure 7. This profile was prepared from chemical analyses of drill core of a halite bed that was suspected of being overturned because a potash deposit was present at the base of the bed instead of in the normal top-of-the-bed position. The profile shows a decrease in bromine concentration from lower to upper part of the halite bed, verifying that the bed is overturned.

At present, there are no bromine data from halite in drill core from Salt Valley. Such data would be extremely useful for structural interpretation should drill cores become available from future drilling at the site area.

CAPROCK

Locally, the crest of the evaporite core of the Salt Valley anticline is capped by a thick residue of insoluble material (fig. 8). This caprock formed as the result of dissolution of halite from a great thickness of Paradox Member. For example, at Salt Valley a caprock thickness of 300 m would represent about 1,562 m of the original halite-bearing Paradox Member. This figure is calculated on the basis of a 16-percent insoluble content for the evaporite core (including marker beds, plus 2 or 3 percent insolubles in the halite rock) and allows for the volume increase following conversion of anhydrite to gypsum.

In the Salt Valley anticline, the caprock crops out along the axis of the anticline through most of the recommended site area. This caprock probably began to form in Late Pennsylvanian time, when the halite-bearing rocks were subjected to attack first by unsaturated seawater and later by ground water. Since that time, the caprock has accumulated slowly and intermittently, reaching a thickness of perhaps as much as 300 m. Caprock is probably still forming today; however, the rate of growth must be quite slow.

The caprock consists of a jumbled mass of marker beds, plus insoluble material from the halite beds. All of the anhydrite has been hydrated and converted to gypsum. The caprock differs considerably from typical Gulf Coast-type caprock in that there was no development of limestone and sulfur deposits. Although traces of native sulfur and hydrogen sulfide have been reported in drill holes that penetrate Paradox basin caprocks, the process of sulfate reduction apparently never occurred on a large scale.

The caprock is somewhat cavernous, probably owing to dissolution of some gypsum and also to voids created along axial planes in folded marker beds when the original halite was leached out. Drill-hole data indicate that part of this porous material is water or brine saturated. In some drill holes the drilling mud became quite salty as much as 15 m above the actual contact with the halite of the evaporite core. Neutron logs, run in drill holes that penetrate the caprock, also suggest that locally as much as 75 m of caprock is water saturated (fig. 8). The neutron log is used to detect formation hydrogen, which can be present in the form of hydrocarbons, free water, or bound water. In this case, hydrogen response on the log indicates either the presence of water of brines in voids in the caprock or water of crystallization in the mineral gypsum.

The only source of recharge for the caprock aquifer is from the meager amount of precipitation, probably no more than 25 cm a year, which falls on an area of about 20 km^2.

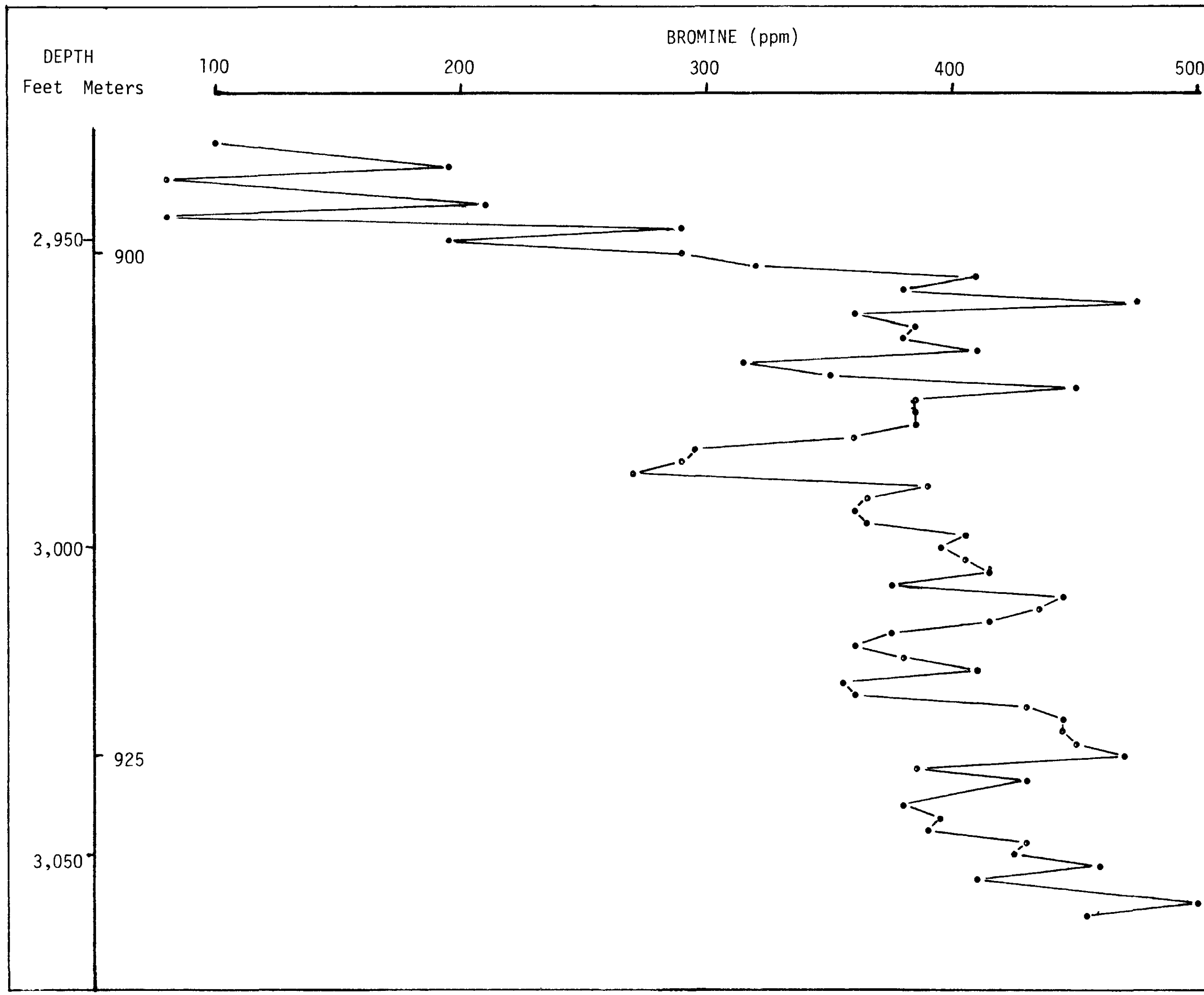

Figure 7.--Bromine distribution in overturned halite bed in unknown evaporite cycle of Paradox Member in Tenneco Oil Co., Redd Ranch No. 1, in sec. 28, T. 28 S. R. 25 E. (H. L. Groves, U.S. Geological Survey, Denver, Colo., analyst).

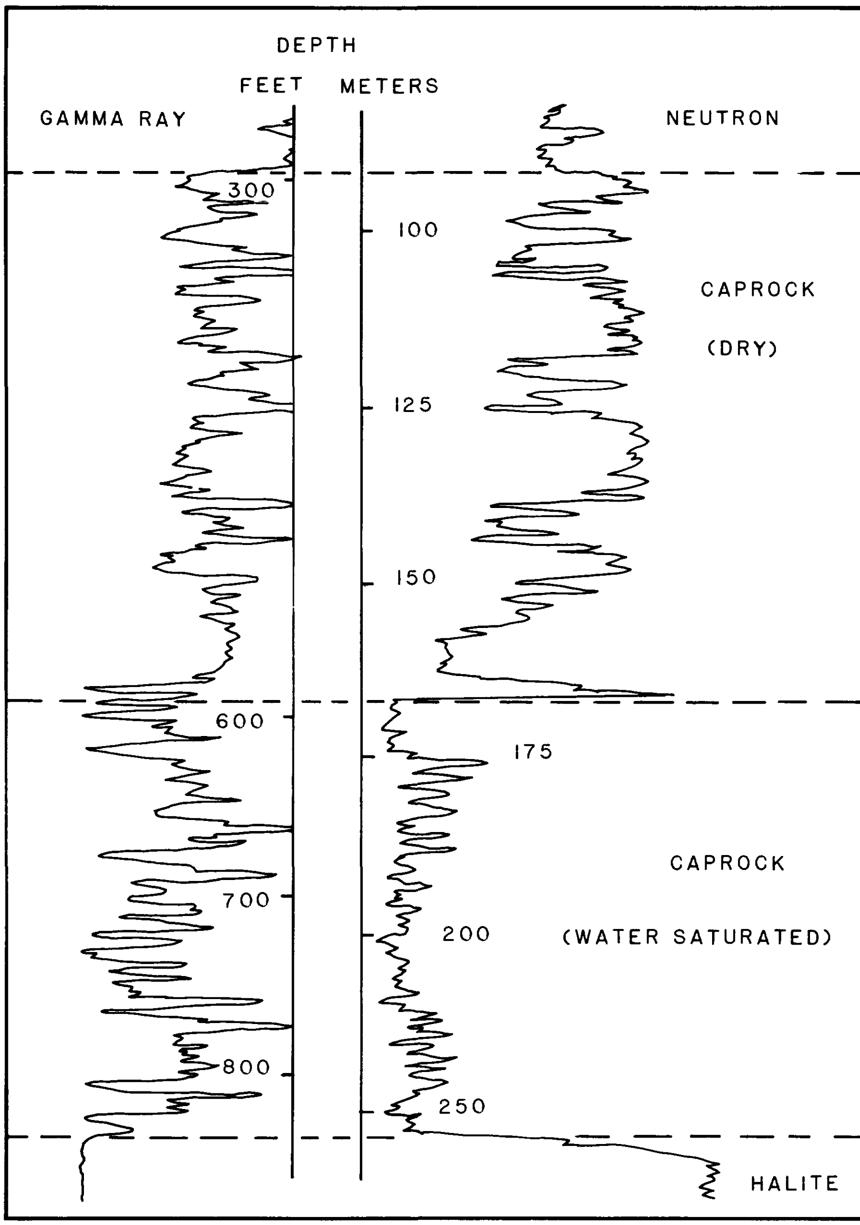

Figure 8.--Gamma ray-neutron log in San Jacinto Petroleum Corp., Salt Valley No. 1 (drill hole no. 22, table 1), located in sec. 5, T. 24 S., R. 21 E. Dashed lines show boundaries between caprock and evaporite core and limit of water-saturated caprock.

The small amount of fresh water that finds its way into the caprock slowly diffuses with saturated sodium chloride brine that is in contact with the underlying halite.

For caprock to form, there must be a means by which brine escapes from the aquifer; otherwise the aquifer would eventually become full of saturated chloride brine and no further solution of halite could take place. Although there is a low surface-drainage divide near the southeast end of the site area (sec. 14, T. 23 S., R. 20 E.), it seems likely that most of the water in the caprock aquifer would have to move southeast along the axis of the Salt Valley anticline. The anticline is intersected by the canyon of Salt Wash 18 km southeast of the site boundary. A small perennial stream flows through the canyon and joins the Colorado River about 6.4 km downstream from the stream's intersection with Salt Valley. The point of intersection with Salt Valley is about 244 m lower in elevation than the drainage divide previously mentioned. Thus, it would be quite possible that the caprock is drained by Salt Wash. About 4.8 km downstream from the Salt Valley intersection with Salt Wash, a salt spring issues from the floor of Salt Wash. Unfortunately, no data are available on the rate of flow or the salt content of this spring. It seems quite likely, however, that the high salt content of the spring is related to brine discharge from Salt Valley caprock.

Most caprock marker beds pass without interruption into the underlying evaporite core (fig. 3). The effect of this lithic connection between surface, caprock, and evaporite core is unknown. No evidence suggests that ground water might move downward into the evaporite core along a marker bed. Nor is there any evidence of hydrocarbons or brine moving up into the caprock through a marker bed. This relationship might pose a problem to an emplacement facility, but further study is needed before this is proved.

GEOTHERMAL GRADIENT AND HEATFLOW

Fortuitously, the Salt Valley anticline is the one location in the Paradox basin where a study of the geothermal gradient and heatflow has been made. Using thermal measurements made in several abandoned petroleum test holes located on the anticline, Spicer (1964) reported a geothermal gradient in the Paradox Member of 15.7°C/km for the northwest end of the anticline and 12.3°C/km for the southeast end. Heatflow to the surface at the northwest end was reported to be 1.32 microcalories/cm^2 per second and at the southeast end, 1.11 microcalories/cm^2 per second. These measurements represent thermal conditions that had returned to normal after being upset by drilling operations.

At Salt Valley, temperature profiles in two drill holes that penetrated the Paradox Member show a marked change in geothermal gradient at the contact of the halite-bearing rocks (figs. 9 and 10). This break in the gradient illustrates the high thermal conductivity of halite.

Applying Spicer's gradient values of 37.4°C/km for rocks overlying the Paradox Member and 15.7°C/km for the Paradox Member, a calculation was made for the expected bottom hole temperature at the depth of 3,133 m in drill hole no. 8 (fig. 1). In this drill hole the rocks overlying the Paradox Member are 928 m thick; therefore, the temperature at the top of the Paradox would be 34.7°C above ambient air temperature. From 928 m to 3,133 m the

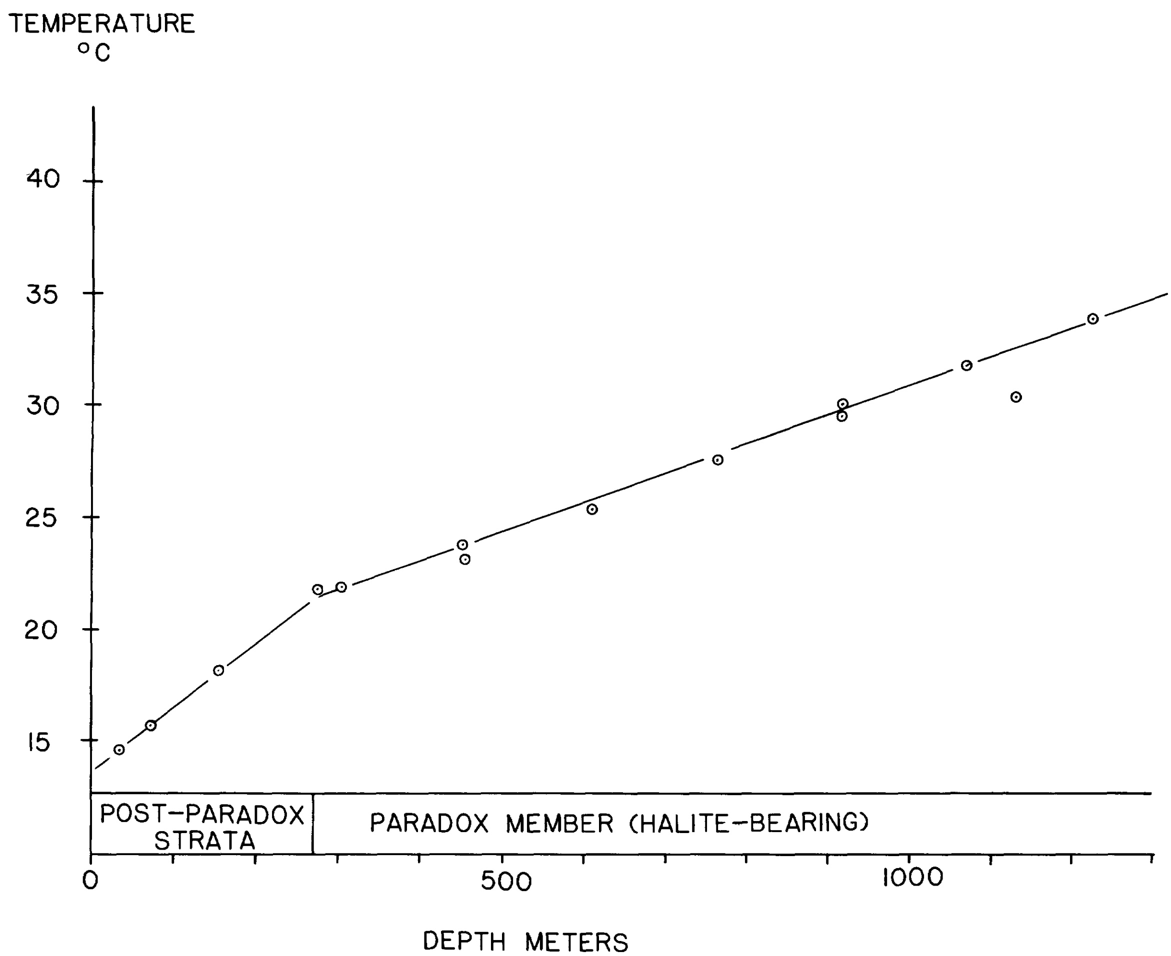

Figure 9.--Temperature profile in Balsley No. 1-C (drill hole no. 21, table 1) in sec. 32, T. 23 S., R. 21 E. (from Spicer, 1964).

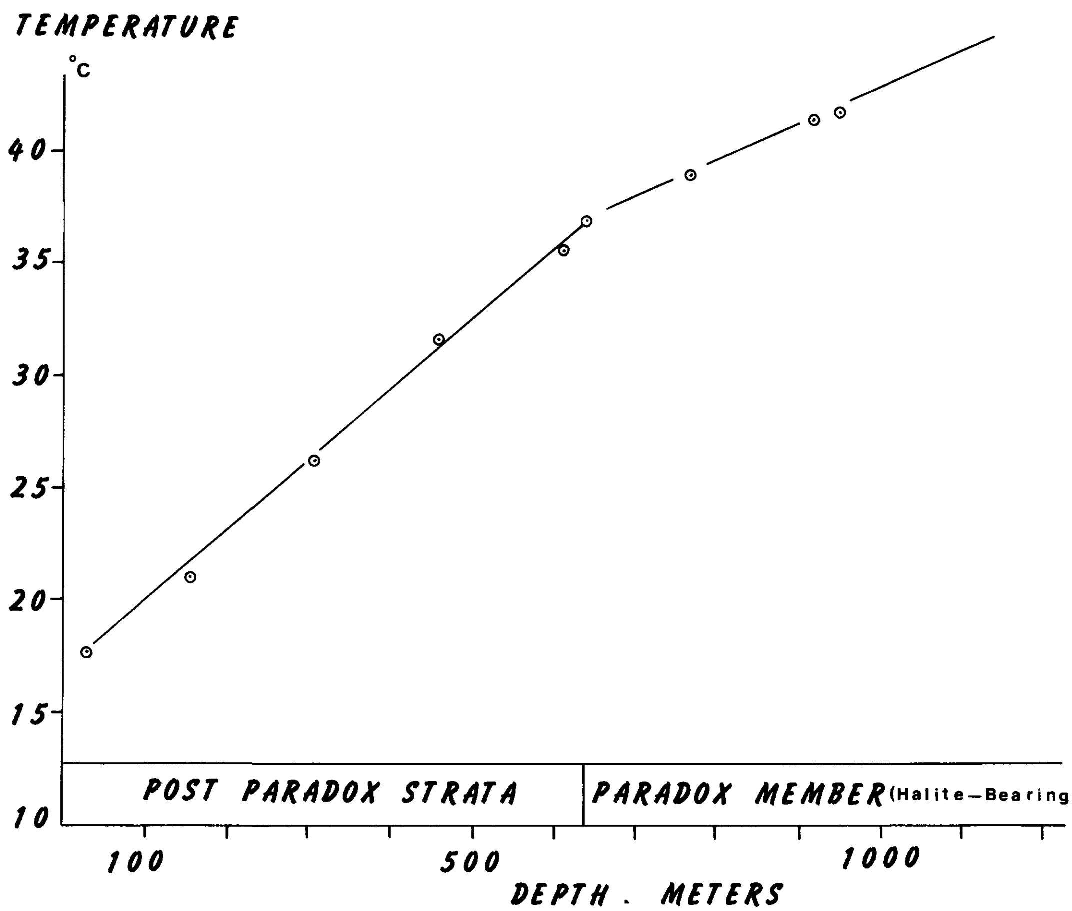

Figure 10.--Temperature profile in Defense Plant Corp., Reeder No. 1 (drill hole no. 4, table 1), in sec. 4, T. 22 S., R. 19 E. (from Spicer, 1964).

temperature would increase another 34.6°C. Using 12.2°C as ambient air temperature, the bottom hole temperature in this well at 3,133 m should be 81.5°C. This agrees surprisingly well with a temperature of 80°C measured during drilling operations.

Assuming the presence of 244 m of caprock in the site area, the calculated temperature at a depth of 500 m would be about 25.6°C. The caprock gradient was assumed to be equal to that measured by Spicer (1964) for Mesozoic sandstones and shales overlying the Paradox Member. It is possible that the caprock gradient may be considerably less.

In summary, the Salt Valley waste emplacement site should have a relatively low initial temperature. In addition, the site is unique in that the Paradox Member crops out and thus is not insulated by younger rocks which have lower heat conductivity. Heat loss from emplaced wastes should be highly efficient.

ECONOMIC GEOLOGY

Mineral resources in the Salt Valley area include uranium, copper, gypsum, rock salt, potash, magnesium, and petroleum. Exploration for these mineral commodities has been characterized by short flurries of activity and longer periods of inactivity, and dates back nearly 60 years. Although mineral resource discoveries have been made in the area, none has ever resulted in commercial operation. Despite this, a potential for mineral resource development in the area still exists.

Small deposits of uranium and copper in Mesozoic sandstones flanking the Salt Valley anticline have been prospected by shallow drilling, shafts, and pits without tangible results. The only productive district (uranium) in the general area is at Yellow Cat Dome, which is nearly 9 km east of the southeast boundary of the site area.

The caprock on the crest of Salt Valley anticline contains gypsum deposits. This gypsum is the product of hydration of anhydrite in marker beds of the Paradox Member; there is also a small amount of anhydrite residue from dissolved halite beds. Because the deposits are relatively thin and impure and are complexly folded and faulted, it is doubtful that they will ever have economic value.

Resources of rock salt (halite) in this area are virtually unlimited and of high quality. However, for rock salt deposits to have economic value they must be close to a market and, as yet, none exists in this area. As an example, for lack of a market there are several million tons of rock salt stockpiled at the Texas Gulf, Inc., potash mine near Moab. Should a market for rock salt develop in this area, many other localities could supply the demand.

Potash was first discovered in the Paradox basin in 1924 at Salt Valley (Dyer, 1945). The discovery was made after some unusual-appearing salts recovered from a petroleum test hole (drill hole no. 3, table 1) proved to be sylvite (KCl) and carnallite ($KMgCl_3 \cdot 6H_2O$). Although the discovery stimulated some shallow drilling in the area, no further knowledge concerning the potash occurrence was obtained. In 1932, another petroleum test (drill hole no. 5, table 1) was drilled 127 m southeast of the potash discovery hole. Samples from this hole were carefully collected and analyzed by the U.S. Geological Survey. "These analyses indicated the presence of carnallite and sylvite horizons extending from 3,369 to 3,919 ft." (Dyer, 1945).

In 1942, critical war needs for magnesium and potash led the Defense Plant Corp. to drill another test (drill hole no. 4, table 1) 183 m northwest of this second potash occurrence. This hole was cored continuously from the first halite in the Paradox Member (637 m) to total depth (1,282 m). Analyses of drill cores from this hole verified the presence of an unusually thick potash deposit extending from 1,012 to 1,078 m (Severy and others, 1949). The deposit consisted of both carnallite and sylvite. The following year (1943), four holes (drill hole nos. 1, 2, 6, and 7, table 1) were drilled by Potash Co. of America to establish the extent of the potash deposit. Unfortunately none of these holes intersected the deposit. The disappointing results of this drilling discouraged further exploration efforts, because it was assumed that the potash deposit had an abnormal thickness and very limited extent.

In the 1950's, the discovery of petroleum in the southern part of the Paradox basin prompted much drilling throughout the basin. During this period the radioactivity log came into use, and it became accepted practice to run this type of log in drill holes that penetrated the Paradox Member. Using these logs, the first stratigraphic framework for the evaporite cycles of the Paradox Member was finally established (Hite, 1960). It was also shown that many of the evaporite cycles contained potash deposits that could be correlated over much of the basin. Finally, the correlation of the thick potash deposit at Salt Valley with an extensive and very thick deposit in "evaporite cycle 19" was established (Hite, 1961). This brought about another wave of exploration at Salt Valley, which resulted in three core holes being drilled along the axis of the anticline by San Jacinto Petroleum Corp. in 1961. Some potash was discovered by this drilling, but the thick deposit in "cycle 19" was not intersected. The last exploration effort was in 1961 by Continental Oil Co., which drilled a deep test (4,031 m) on the northwest end of Salt Valley anticline. This hole was drilled primarily as a petroleum test, the Leadville Limestone of Mississippian age being its primary objective. The company also cored a potash-bearing interval of the Paradox Member. Later studies of the geophysical logs in this drill hole by the writer revealed that it had intersected the "cycle 19" potash deposit between the depths of 2,810 m and 2,871 m.

Although there has been no drilling for potash at Salt Valley since 1961, potash leases and prospecting permits have been filed on much of the State and Federal lands in the area.

The potash resources at Salt Valley are probably quite large. This has been verified in part by drilling and also by construction of an isopleth map of the Paradox basin showing regional distribution of potash in the Paradox Member (fig. 11). The theory behind the use of the isopleth map is discussed in the following paragraphs.

It is a well-known fact, based on observations of present-day evaporite basins, that large standing bodies of brine do not have a homogeneous composition. Invariably these brines are density stratified, the heaviest brine being located at the base of the brine layer. The heaviest brine also contains the highest concentration of potassium and magnesium salts. Thus, in an evaporite basin, the deepest depressions will be the first

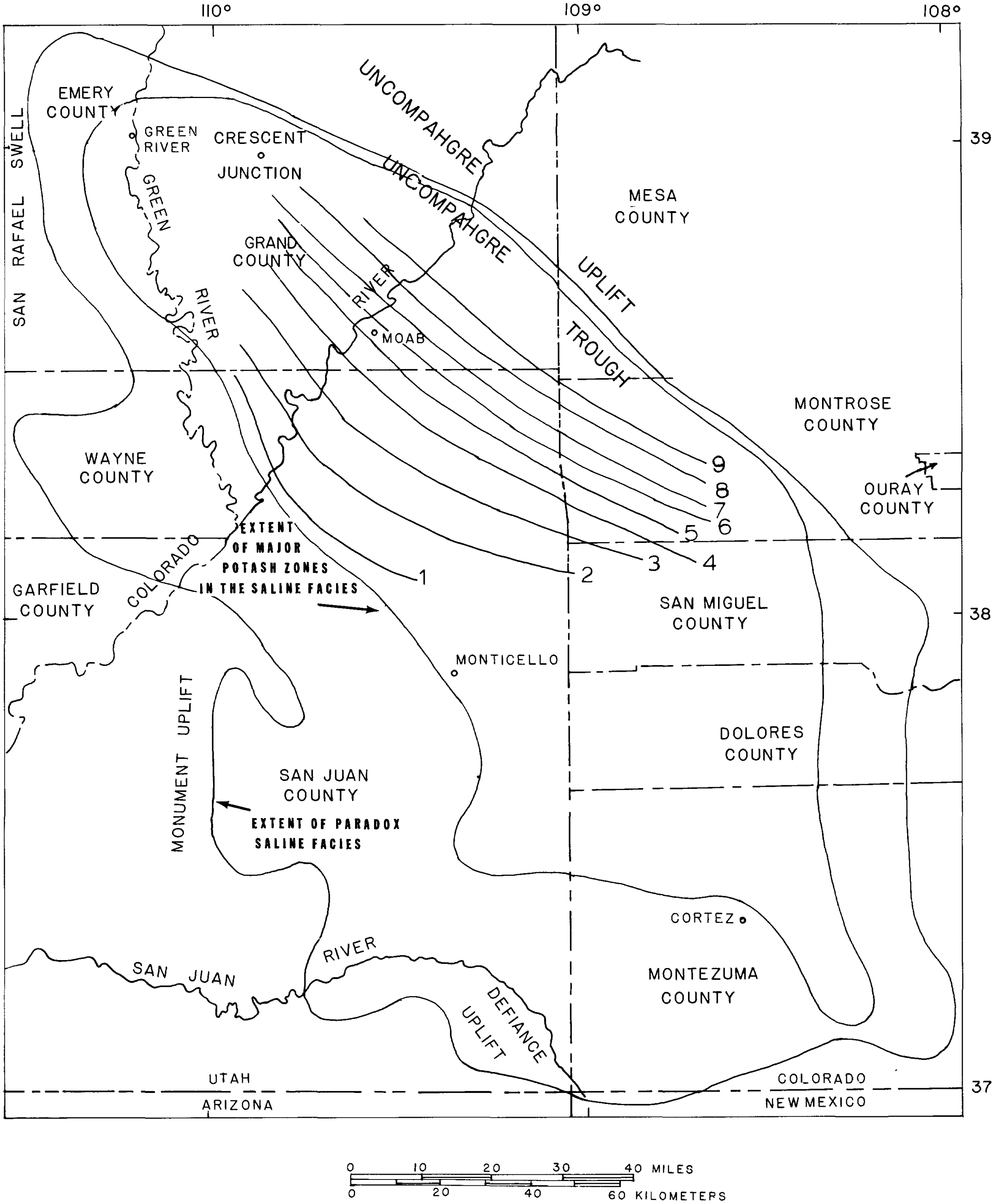

Figure 11.--Potash isopleth map, Paradox basin. Contours show regional distribution of potash deposits in the Paradox Member. Contour values represent the part (in percent) of the total evaporite sequence that consists of potash deposits containing >15 percent K_2O. Halite and potash boundaries from Hite (1961). Contour interval is 1 percent.

site of evaporite deposition and will continue to receive these chemical sediments at a greater rate than shallower parts of the basin. In addition, the lowest depression will receive a correspondingly higher percentage of the very soluble potassium and magnesium salts.

During deposition of the evaporites of the Paradox Member, the floor of the Paradox basin sloped from southwest to northeast, the deepest part of the basin being located in a linear depression called the Uncompahgre Trough (fig. 11). This depression was also tilted toward the northeast so that the deepest part was located along the northeast margin of the basin. This bathymetry controlled the depositional thicknesses of the evaporite layers and the concentration of potash within the layers.

With these relationships in mind, an isopleth map was constructed showing percent of potash in the evaporite sequence. Potash content (expressed as K_2O) and thickness were interpreted from gamma-ray logs of key drill holes. Potash deposits estimated to contain less than 15 percent K_2O were not included in the data. All the data points on the map apply to salt anticlines. The total evaporite sequence in all the anticlines except Paradox Valley, Salt Valley, and Sinbad Valley has been drilled and was evaluated for the percentage of potash in the evaporite column. In the three anticlines mentioned, drill holes have penetrated several thousand feet of evaporites, so that even though evaluation of the entire sequence was not possible the data obtained are still reasonably representative of the complete sequence.

The percent of the evaporite sequence that contains potash deposits having >15 percent K_2O ranged from 1.24 at Gibson Dome, on the southwest limit of the potash deposits, to 9.45 at Sinbad Valley, which is in the deepest part of the ancestral basin. The distribution of potash maintains a uniform regional pattern even in areas characterized by a high degree of salt tectonism. Even in diapiric salt anticlines, where the evaporite sequence is complexly deformed, the amount of potash present is still related to the original regional pattern of deposition. For example, in the evaporite core of Salt Valley the potash deposits intersected by drill holes are frequently steeply dipping or repeated by faulting or folding so that their true original thickness is unknown. However, the other layers of halite, anhydrite, dolomite, and black shale are affected to a similar degree by the same structures, and so the relative percentages of each lithology remains the same as in the original undeformed deposit regardless of where it is intersected by the drill.

The total potash resources at Salt Valley can be estimated by using the isopleth map. Assuming a thickness of 3,600 m for the evaporite sequence and using the isopleth value (7.7 percent), then about 277 m of potash (with a content of at least 15 percent K_2O) will be present in any complete vertical intersection of the evaporite core of the anticline. The potash resources in this anticline would then amount to about 555 million metric tons of potash ore per square kilometer.

Although potash resources in the Salt Valley anticline are large, they may be difficult to develop because they are complexly deformed. Future development will probably involve solution mining. The deposit in "evaporite cycle 19" might be ideally suited for this type of mining. This deposit is so thick that structural complexities might not be an insurmountable problem.

The history of petroleum exploration of Salt Valley reaches back nearly 60 years. The initial exploration began at the northwest end of the anticline, where a large number of shallow holes were drilled to test the Dakota Sandstone, Mancos Shale, and Morrison Formation. Although a small amount of oil was produced from these wells, no well was completed for commercial production.

The next phase of exploration at Salt Valley came during the 1920's and 1930's. During this period the evaporite core of the anticline was the primary drilling target. This was an extremely frustrating period of exploration, because almost every test hole encountered numerous and sometimes spectacular occurrences of oil and gas. Despite this, not a single well proved capable of sustained production.

In 1960, a significant petroleum discovery was made on the southwest flank of Lisbon Valley anticline in San Juan County, Utah (fig. 1). The production in this field is from Mississippian and Devonian Formations that underlie the Paradox Member. The petroleum accumulation is structurally controlled by a large fault block that is deeply buried by a thick evaporite cover and has no surface expression. This fault block was discovered by seismic reflection methods. During this same period it was discovered that older structurally controlled topography influenced depositional patterns in the Paradox Member evaporites. Thicker sequences of evaporites accumulated in structural depressions, and these thick sequences later became the site of salt anticlines (Hite, 1960, 1968). Thus, it became apparent that the favorable area for prospecting for structural highs was not directly beneath the salt anticline but on the flank or in the adjacent syncline. For these reasons the salt anticline area underwent intensive drilling and seismic search for buried fault blocks. Although several of these structures were found, only one--the Salt Wash field, located about 30 km west of Salt Valley--contained petroleum in commercial quantities. Two deep tests searching for this type of structure were drilled on the northern end of Salt Valley by Continental Oil Co. in 1962 and 1973 (drill hole nos. 8 and 10, table 1). The first test (no. 8) was abandoned before reaching the base of the Paradox Member. The second test (no. 10) reached older rocks beneath the evaporites, but no oil or gas was encountered.

The most recent phase of exploration in the salt anticline region has been for gas and has concentrated on the thick accumulations of Permian sediments in synclines adjacent to large salt anticlines. Several gas wells have been completed in sand in the Permian Cutler Formation. The Cutler Formation is 2,000-3,000 m thick in these synclines and may contain several potentially productive sandstone bodies. As yet there has been no exploration directed at this type of stratigraphic trap on the flanks of the Salt Valley anticline.

Of all the various types of petroleum accumulation mentioned in the preceding discussion, it is the hydrocarbon occurrences in the evaporites of the Paradox Member that would significantly affect the construction of a waste emplacement site at Salt Valley. The effect would be twofold: first, a potential conflict exists because these occurrences might someday prove to be of economic value; and, second, they constitute a hazard to underground facilities.

Hydrocarbons in the Paradox Member are most abundant in the marker beds, which consist, on the average, of about 25 percent black shale. These black shales commonly contain 7 to 10 percent organic carbon. In addition, the shale beds have had a history of deep burial, perhaps as deep as 5,000 m or more in the salt anticline region. Although no data concerning the maturation index of the organic matter in these shales were available to the writer, indirect information suggests that hydrocarbon conversion has been complete. Many of the shales have a graphitic appearance, and Fischer assays of several samples collected by the writer yielded only small amounts of petroleum. The original organic matter was probably composed largely of remains of marine algae, which would have had a high rate of conversion to hydrocarbons. Assuming a conversion rate of about 25 percent, which is probably ultraconservative, the black shales could have generated a large volume of hydrocarbons. The marker beds are sealed in above and below by impervious evaporites (halite and anhydrite), and so all hydrocarbons generated in the black shale are locked into the marker beds. All the lithologic units in the marker beds have very low permeabilities; thus, hydrocarbon migration and significant accumulation is related to fracture systems. Drill cores of marker beds all show considerable fracturing; however, those from areas where these beds have been complexly folded and faulted, such as Salt Valley, show even more fracturing. Commonly the fractures are filled with wide veins of halite or potash salts. The halite in these veins frequently consists of coarsely crystalline fibrous material that is quite permeable. These veins act as conduits for oil and gas and are commonly stained by hydrocarbons. The spectacular "blowouts" of oil and gas, which frequently take place as wells drill into the marker beds, are related to these fracture reservoirs. Usually the flow of oil and gas is short-lived; however, in some wells the flows have persisted for many days, and at least one well has been producing an average of 100 barrels of oil a day since 1962. As more is learned about these fracture reservoirs in the marker beds, a technology may be developed that will provide a means of unlocking these otherwise "tight" rocks and producing commercial quantities of oil. When this happens, the evaporite sequence at Salt Valley may become an important source of petroleum.

SUMMARY AND RECOMMENDATIONS

The potential waste emplacement site at Salt Valley has many favorable characteristics, but it also has some problems that must be given careful consideration.

A serious conflict between using the site for waste disposal and as a potentially exploitable resource of potash and oil and gas exists. As previously stated, the area is currently involved in an active potash lease play. The parties involved are reportedly considering a solution-mining operation. In addition, a large acreage of State land is involved, and potash leases have probably already been assigned on these lands. Viable petroleum prospects exist on both flanks and in the core of the anticline. Production could probably be developed on the anticlinal flanks without jeopardizing an emplacement facility, but production from the evaporite core would be out of the question. Eventually someone will have to decide which has the greater economic value to the nation and the State of Utah--the mineral resources or the emplacement site.

The marker beds in the evaporite core of the anticlinal pose a serious problem.

Because they contain high-pressure pockets of oil and gas and sometimes brine, it is assumed that they must be avoided. In addition, these beds are continuous from the evaporite core into the caprock and ground-water zone. It is possible that some communication between surface and the evaporite core might be present along a marker-bed conduit. This, however, is a problem that needs more study and perhaps is not important if underground facilities completely avoid these beds.

If the integrity of the site area is dependent on complete avoidance of marker beds, then close-spaced drilling will be required to map the complex structure in these beds. Although our knowledge of the geometry of the folds in the evaporite core of Salt Valley is severely limited, there is a strong suggestion that many large folds having nearly vertical limbs may be present. The axes of these folds probably parallel the major axis of the salt anticline. A further suggestion is that the dimensions of these folds are such that linear, but large-volume, space may be present in the halite along the axial planes of these folds. The only means of ascertaining the geometry of these folds is by close-spaced drilling. The first reconnaissance drilling should entail continuous coring through the evaporite sequence. Once the structural framework is established, the most favorable piece of space could be blocked out by air drilling small-diameter holes and by running suitable geophysical logs. Expensive, continuous coring would not be necessary during this phase of exploration.

One last recommendation is that a study of caprock ground-water conditions at Salt Valley should be made. It is possible that such a study would provide an accurate accounting of the present-day rate of salt removal from the site area.

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