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UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Federal Center, Denver, Colorado 80225

# GEOLOGIC APPRAISAL OF PARADOX BASIN SALT DEPOSITS FOR WASTE EMPLACEMENT

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## ABSTRACT

Thick salt deposits of Middle Pennsylvanian age are present in an area of 12,000 square miles in the Paradox basin of southeast Utah and southwest Colorado. The deposits are in the Paradox Member of the Hermosa Formation. The greatest thickness of this evaporite sequence is in a troughlike depression adjacent to the Uncompahgre uplift on the northeast side of the basin.

The salt deposits consist of a cyclical sequence of thick halite units separated by thin units of black shale, dolomite, and anhydrite. Many halite units are several hundred feet thick and locally contain economically valuable potash deposits.

Over much of the Paradox basin the salt deposits occur at depths of more than 5,000 feet. Only in a series of salt anticlines located along the northeastern side of the basin do the salt deposits rise to relatively shallow depths. The salt anticlines can be divided geographically and structurally into five major systems. Each system consists of a long undulating welt of thickened salt over which younger rocks are arched in

anticlinal form. Locally there are areas along the axes of the anticlines where the Paradox Member was never covered by younger sediments. This allowed large-scale migration of Paradox strata toward and up through these holes in the sediment cover forming diapiric anticlines.

The central or salt-bearing cores of the anticlines range in thickness from about 2,500 to 14,000 feet. Structure in the central core of the salt anticlines is the result of both regional compression and flowage of the Paradox Member into the anticlines from adjacent synclines. Structure in the central cores of the salt anticlines ranges from relatively undeformed beds to complexly folded and faulted masses in which stratigraphic continuity is undemonstrable.

The presence of thick cap rock over many of the salt anticlines is evidence of removal of large volumes of halite by groundwater. Available geologic and hydrologic information suggests that this is a relatively slow process and that any waste-storage or disposal sites in these structures should remain dry for hundreds of thousands of years.

Trace to commercial quantities of oil and gas are found in all of the black shale - dolomite - anhydrite interbeds of the Paradox Member. These hydrocarbons constitute a definite hazard in the construction and operation of underground waste-storage or disposal facilities. However, many individual halite beds are of sufficient thickness that a protective seal of halite can be left between the openings and the gassy beds.

A total of 12 different localities were considered to be potential waste-storage or disposal sites in the Paradox basin. Two of these sites, Shafer dome and Salt Valley anticline, were considered to have the most favorable characteristics.

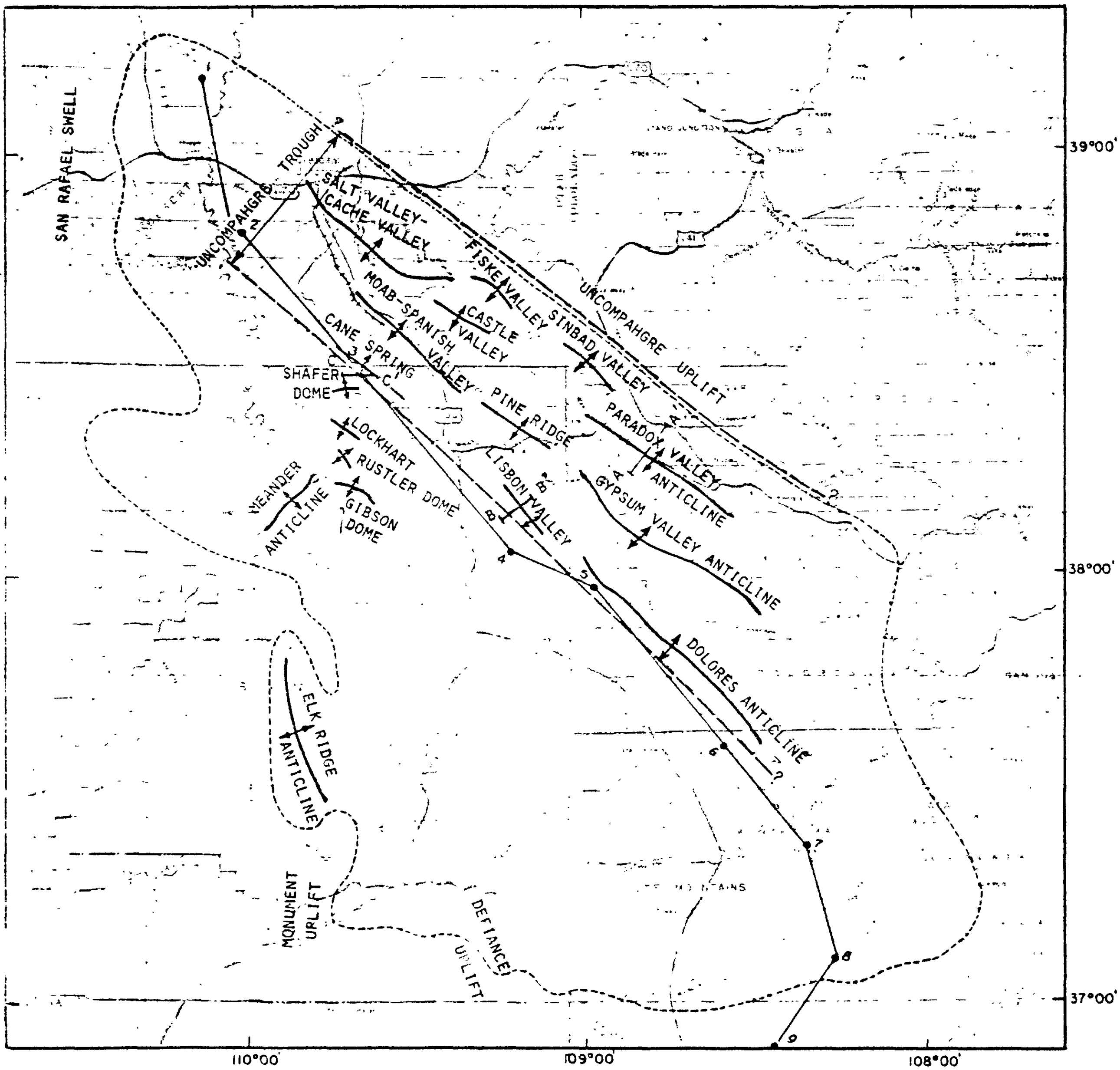
## INTRODUCTION

This report is one of a series prepared by the U.S. Geological Survey summarizing available geologic and hydrologic knowledge of certain salt deposits to help determine their suitability for waste emplacement. The report was prepared for the U.S. Atomic Energy Commission and the Defense Advanced Research Projects Agency.

The preparation of this series of reports has been expedited by the fact that two governmental agencies approached the U.S. Geological Survey with similar requests. In 1971 the Advanced Research Projects Agency, anticipating the difficulties Department of Defense agencies and their contractors might eventually face in finding safe underground sites for disposal of nonradioactive but chemically noxious wastes, asked the Geological Survey to evaluate potential subsurface sites in impermeable rocks, particularly salt deposits, in terms of their geologic and hydrologic suitability for emplacement of noxious wastes. Early in 1972 the U.S. Atomic Energy Commission asked the USGS to summarize the available geologic and hydrologic knowledge of selected areas and rock types, particularly salt, in regard to their suitability for the emplacement of radioactive wastes. Because the geologic and hydrologic factors involved in selecting sites for storage or disposal of wastes in subsurface salt deposits are much the same whether the wastes are highly radioactive or nonradioactive but highly toxic, the results of the Geological Survey's investigations for the Atomic Energy Commission are of parallel interest to the Advanced Research Projects Agency (now the Defense Advanced Research Projects Agency). This report is one of those that provide data needed by both agencies and is therefore being submitted to both.

The Paradox basin is in southwestern Colorado and southeastern Utah (fig. 1). The principal communities and their populations in the Utah part of the basin include Blanding (1,805), Moab (5,600), and Monticello (1,845). On the Colorado side, Cortez (6,764) and Durango (10,600) are the most important towns. Outside the urban areas the countryside is sparsely populated. Industrial development in the region consists of uranium mines and mills, some copper mines, one potash mine near Moab, and several oil and gas fields. Most of the area is suitable only for livestock grazing; farming is practiced only at a few localities where irrigation water is available. The northern end of the basin is crossed by the Denver and Rio Grande Western Railroad, and a spur from this line extends 36 miles south from Crescent Junction, Utah to the Texas Gulf Co., Inc. potash mine near Moab, Utah. Several good paved roads traverse the area; however, many of the features described in this report can be reached only by dirt or gravel roads.

The Paradox basin, which is not a definable physiographic feature, lies well within the much larger Colorado Plateaus province. Basin boundaries are usually determined by the extent of a thick sequence of Pennsylvanian evaporites for which the basin is named. The spectacular geography of the region is the result of rapid downcutting by the Colorado




EXPLANATION

- Approximate limit of Paradox basin
- Approximate limit of Uncompahgre trough
- Anticline or elongated dome
- 2 — 3 Trace of section, Figure 3
- A — A' Trace of section, Figure 5
- B — B' Trace of section, Figure 6
- C — C' Trace of section, Figure 7

0 15 30 MILES

Figure 1.--Index map of Paradox Basin showing major structures and traces of sections from figures 3, 5, 6, and 7.

River and its tributaries through relatively flat-lying resistant sandstones. Many of the massive resistant sandstones form sheer walls in canyons that are as much as 2,000 feet deep, creating formidable barriers to access. Within the basin three prominent isolated mountain masses rise above the general level of the land. The largest are the La Sal Mountains about 15 miles east of Moab; they reach an altitude of 13,089 feet. The other two masses are the Abajo Mountains near Monticello, Utah, and the Ute Mountains a few miles west of Cortez, Colo. Southeastward the basin is bordered by the high peaks of the San Miguel, San Juan, and La Plata Mountains. Each of these mountain groups consists of an intrusive igneous complex. Part of the basin is bordered by more gently rising uplifts including the Uncompahgre, Defiance, Monument and San Rafael. Locally, the famous salt anticlines of the region interrupt the continuity of the general land surface forming linear flat-floored valleys bounded by steep escarpments. Fracture patterns and joint systems on the flanks of the anticlines have provided planes of weakness leading to the development of natural arches, spires, fins and other spectacular erosional features.

Most of the area has a semiarid climate, but the precipitation varies with the altitude, and ranges from less than 10 inches in the low deserts bordering the Colorado River to more than 30 inches in the highest parts of the mountain masses. Much of the precipitation occurs as scattered thundershowers during the summer--particularly at the lower altitudes. Winter snows seldom remain on the ground longer than a few days or weeks except on the mountains and the Uncompahgre Plateau. The temperature ranges from about -20°F to about 100°F. Most of the area is covered by piñon and juniper or by sagebrush, and the streams are bordered by cottonwood, willow, and salt cedar (tamarisk). Ponderosa pine, spruce, fir, and aspen occur at the higher altitudes.

## DRAINAGE AND WATER SUPPLY

The Colorado River is the master stream of the area cutting diagonally across the northwestern half of the basin (fig. 1). Major tributary streams include the Green, San Juan, and Dolores Rivers (fig. 1). Most of the salt-anticline region is drained by the Dolores River, which heads higher in the San Juan and San Miguel Mountains, flows southward to the town of Dolores, then turns and flows northward and northwestward through the area. The fact that the Dolores cuts directly across the middle of Paradox Valley rather than flowing longitudinally through it is responsible for the name Paradox. A small eastern part of the area is drained by the San Miguel River, which also heads in the San Juan and San Miguel Mountains, and which joins the Dolores below Uravan, Colo.

Most of the small tributaries are ephemeral, as might be expected, but a few streams are perennial, particularly those emanating from the La Sal and Abajo Mountains, and the Uncompahgre Plateau. Except along the flanks of these high areas, springs are relatively few, small, and are mainly in the synclinal valleys. Exceptions are the several large springs that issue from the northeast wall of Paradox Valley and supply water for irrigation. Fred Cater (oral commun., July 17, 1972) recalls that these springs flow about 3 cubic feet per second (about 1,300 gallons per minute), and believes that the water issues from faults that border the northeast wall of the valley. Water may be conducted along these faults and fault zones from the flanks of the La Sal Mountains northwest of the valley.

The principal aquifers or potential aquifers are noted in the right hand column on table 1. These aquifers plus Quaternary alluvium supply many stock and domestic wells and a few wells used for irrigation, municipal, or industrial supplies. Some of these wells favorably situated on the flanks or troughs of synclines supply water under artesian conditions, and some of these wells flow small amounts. For example, the Dakota Sandstone supplied several flowing wells in the Nucla syncline near the town of Nucla (northeast of Paradox Valley anticline, fig. 1) when visited by Lohman in the late forties, but it is not known whether these wells still flow.

## STRATIGRAPHY AND HYDROLOGY

### General statement

In the Paradox basin a wedge-shaped sequence of sedimentary rocks overlies a basement complex of Precambrian crystalline rocks. Beginning with the Cambrian, every geologic period except the Ordovician and Silurian is represented by these sedimentary strata (fig. 2). From Cambrian through Mississippian time the area was covered by marine waters. A brief period of emergence during Early Pennsylvanian time allowed the development of karst topography overlain by a thin regolith. The basin then subsided rapidly at the same time that marginal areas

Table 1.--Paleozoic and Mesozoic formations exposed in salt-anticline region of Paradox basin

| System | Series | Rock unit | Thickness (feet) | Character | Water supply |
|---|---|---|---|---|---|
| Cretaceous | Upper Cretaceous | Mancos Shale | 2,000± | Dark-gray fissile marine shale | Not water-bearing |
| | | Dakota Sandstone | 20-200 | Interbedded sandstone and conglomerate, carbonaceous shale, and impure coal | Sandstones yield small supplies, water locally brackish |
| | | | | — Unconformity — | |
| | Lower Cretaceous | Burro Canyon Formation | 0-300· | Sandstone and conglomerate, green and reddish-purple shale | |
| Jurassic | Upper Jurassic | Morrison Formation: Brushy Basin Member | 300-750 | Variegated bentonitic mudstone, siltstone, red sandstone, and conglomerate, thin limestone beds | Not water-bearing |
| | | Morrison Formation: Salt Wash Member | 240-440 | Lenticular sandstones, mudstone, few thin limestones | Sandstones yield small supplies locally |
| | | San Rafael Group: Summerville Formation | 0-100 | Thin-bedded sandstone, sandy shale, and mudstone | Not water-bearing |
| | | San Rafael Group: Entrada Sandstone: Moab Member | 0-300 | White cross-bedded fine-grained sandstone | Yield small supplies of water where structure is favorable |
| | | San Rafael Group: Entrada Sandstone: Slick Rock Member | | Cross-bedded buff, orange, and white fine-grained sandstone | |
| | | San Rafael Group: Entrada Sandstone: Dewey Bridge Member | 0-150 | Red earthy sandstone and siltstone. Contorted bedding. Called Carmel in old reports | Yields little or no water |
| | | | | — Unconformity — | |
| | | Glen Canyon Group: Navajo Sandstone | 0-500 | Buff and gray cross-bedded fine-grained sandstone | Yields small to moderate supplies where structure is favorable |
| Triassic(?) | Upper Triassic(?) | Glen Canyon Group: Kayenta Formation | 0-300 | Lenticular channel sandstone, siltstone and mudstone | Yields little or no water |
| Triassic | Upper Triassic | Glen Canyon Group: Wingate Sandstone | 0-500 | Fine-grained reddish-brown, thick-bedded, massive and cross-bedded cliff forming sandstone | Yields small supplies where structure is favorable |
| | | Chinle Formation | 0-750 | Reddish siltstone, sandstone, and mudstone; some conglomerate | Not water-bearing |
| | | | | — Unconformity — | |
| | Middle(?) and Lower Triassic | Moenkopi Formation | 0-1,100 | Brown shale, mudstone, arkosic sandstone and conglomerate. Thin beds of gypsum locally near base | Water-bearing character not known, but sandstones and conglomerates probably would yield some water where structure is favorable. Yield of limestones not known, but probably small |
| | | | | — Unconformity — | |
| Permian | | Cutler Formation | 0-9,000 | Red arkosic sandstone and conglomerate, some red sandy siltstone and mudstone | |
| | Upper and Middle Pennsylvanian | Rico Formation | 0-575 | Similar to Cutler but contains few beds of marine limestone | |
| | | | | — Local unconformity — | |
| Pennsylvanian | Middle Pennsylvanian | Hermosa Formation: Upper member | 0-2,200 | Fossiliferous gray limestone, some shale and lenticular sandstones | |
| | | Hermosa Formation: Paradox Member | 0-14,000± | Dolomite, salt, gypsum, carbonaceous shale, and sandstone | Contains brine locally. Leached caprock yields brackish or salty water |

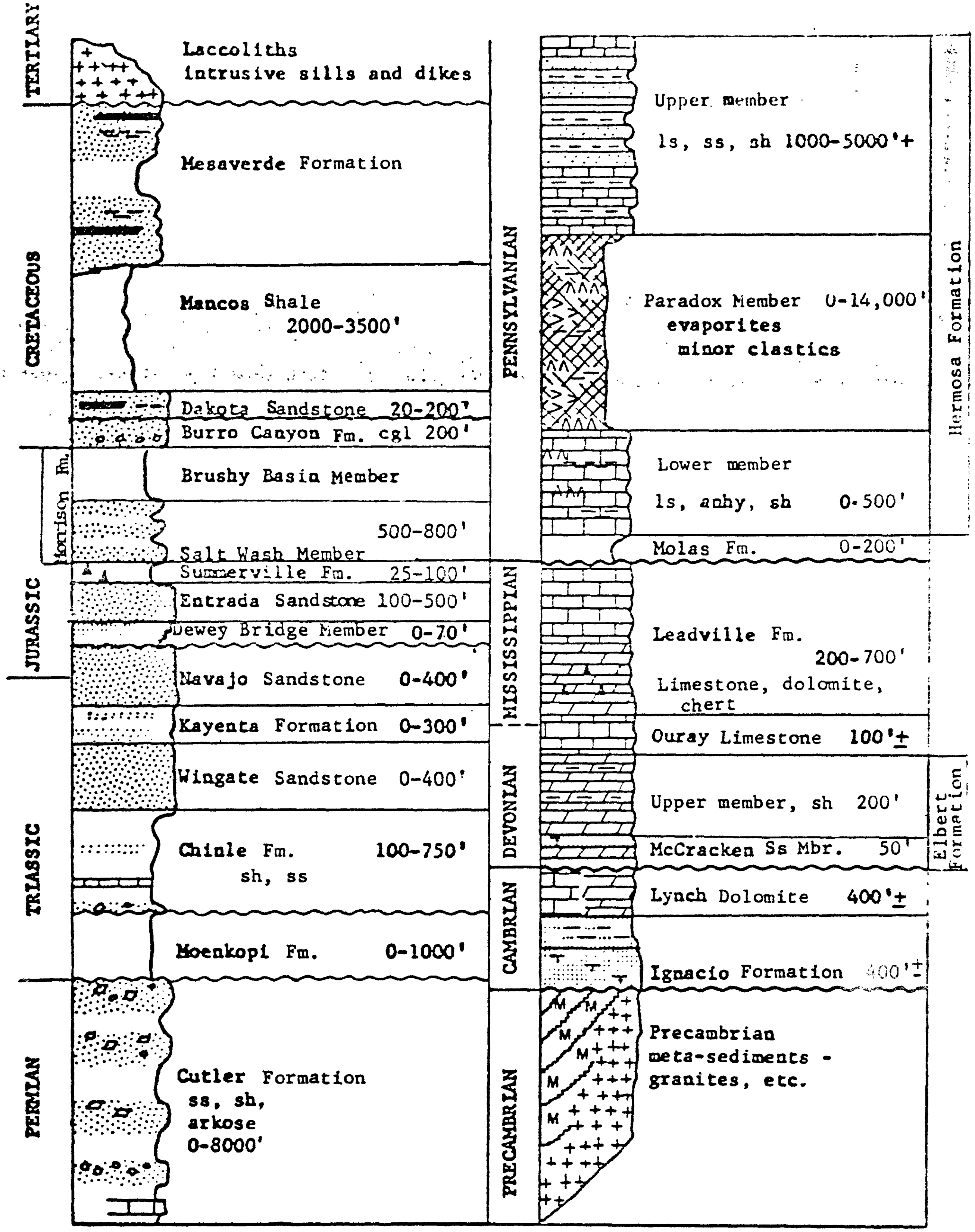



FIGURE 2.—GENERALIZED STRATIGRAPHIC CHART OF NORTHEASTERN PARADOX BASIN.

rose, particularly the Uncompahgre uplift to the northeast. Invasion by the sea began a new cycle of marine sedimentation during which the basin was nearly filled with evaporites. By Late Pennsylvanian time only a shallow basin remained, and the continued, slow retreat of the sea eventually left the entire area above water. The retreat of the sea was accompanied by strong positive movements of the bordering uplifts. Erosion of the exposed crystalline cores of these uplifts then covered the former marine basin with a flood of arkosic debris. Continental sedimentation continued until Late Cretaceous time, when a new invasion by the sea deposited a thick layer of shale. Regional uplift drove out the sea at the close of the Cretaceous and the area has remained high and dry since. Quaternary erosion has left a basin-filling wedge of sedimentary rock that is about 18,000 feet thick along the northeastern edge of the basin but thins to about 6,000 feet southwestward.

Rocks older than the Middle Pennsylvanian Paradox Member of the Hermosa Formation are not exposed within the Paradox basin but have been penetrated by numerous drill holes within the basin and are exposed near Durango along the southeastern margin of the basin. For convenience, the detailed descriptions of stratigraphic units are divided into three sections. The first section describes the subsurface stratigraphy and hydrology of pre-Paradox rocks. The second describes the stratigraphy and hydrology of the Paradox Member, including both subsurface relationships and surface exposures (cap rock). The third section describes the stratigraphy and hydrology of post-Paradox rocks around certain salt anticlines.

## Pre-Paradox rocks

Rocks of Precambrian age are not exposed in the Paradox basin but have been penetrated in a few deep drill holes and are exposed in deep canyons dissecting the Uncompahgre Plateau, which borders the basin on the northeast. In these exposures the Precambrian consists of gneiss, quartzite, schist, younger intrusive granites and minor dikes of aplite, pegmatite, and lamprophyre (Dane, 1935; Case, 1966; Cater, 1970).

Lowermost strata of Cambrian age in the Paradox basin belong to the Ignacio Formation (fig. 2). The formation consists of well-indurated sandstone, siltstone, shale, and local thin beds of dense unfossiliferous dolomite (Baars, 1966, p. 2085). Only a few wells in the Paradox basin were drilled deep enough to penetrate this unit. The Ignacio is overlain by dark-gray glauconitic and oolitic dolomite of the Lynch Dolomite. The combined thickness of the Ignacio and Lynch ranges from about 100 feet on the northeast side of the basin to more than 1,000 feet on the southwestern margin. Little is known about the hydrology of these Cambrian strata but it would seem that porosities and permeability are very low.

Rocks of Devonian age are separated from Cambrian strata by a hiatus. The oldest unit is the Aneth Formation of Knight and Cooper (1955, p. 56) consisting of dark shale and argillaceous dolomite. This unit is not shown in figure 2 for it is found only in the subsurface in the Four Corners area where it attains a maximum thickness of 200 feet. It is overlain by the Elbert Formation, which has basinwide distribution. The Elbert is primarily a clastic formation consisting of a sandstone unit at the base and an upper unit of dense silty dolomite, and dolomitic limestone. The basal sandstone unit is the McCracken Sandstone Member of Knight and Cooper (1955, p. 56). The McCracken is porous and permeable in Lisbon Valley where it yields petroleum to several wells. Elsewhere the unit is tightly cemented and has poor reservoir characteristics (Baars, 1966, p. 2089). In the Paradox basin the Elbert Formation ranges in thickness from about 100 to 300 feet. The Ouray Limestone, consisting of limestone and minor interbeds of green waxy shale, overlies the Elbert Formation. There is some question about the age of the Ouray but Baars (1966, p. 2089) feels it ranges from Late Devonian into Early Mississippian. The general range in thickness for the formation is 50 to 200 feet but in the salt-anticline area it is missing over some old fault blocks.

The Leadville Formation of Early and Late Mississippian age overlies and is transitional with the Ouray Limestone. The formation consists mostly of cherty dolomite although some limestone is present, particularly in the upper half. The sequence ranges in thickness from 200 to 700 feet but has been completely eroded from some of the uplifted fault blocks on which Devonian rocks have been thinned by erosion. According to Baars (1966, p. 2099) the upper part of the formation is highly porous and permeable as a result of dolomitization and solution of the original limestone. Several oil and gas fields in the Paradox basin produce from these zones. The Leadville Formation is probably the only significant aquifer of all the pre-Paradox rocks. It is usually water bearing, although the water is of poor quality (20,000 to 200,000 ppm dissolved solids). Recharge probably is taking place at outcrops near the southeastern and western limits of the Paradox basin.

The Molas Formation of Early Pennsylvanian age rests on a karst surface developed on the Leadville Formation. The unit is a thin (0-200 feet) sequence of red and variegated shale with interbedded thin limestone and sandstone. The Molas represents a residual and reworked soil mantle. Overlying the Molas is the lower member of the Hermosa Formation of Middle Pennsylvanian age. The lower member consists of thin beds of limestone, dolomite, black shale and anhydrite. Wengerd and Strickland (1954) have proposed the name Pinkerton Trail for this unit. In the deepest part of the Paradox basin the lower member is only about 150 feet thick. Near the southwest shelf of the basin it is as thick as 500 feet and is predominantly limestone. Over most of the basin the rocks in this unit are very dense and relatively impervious. They form an effective seal preventing solution of the overlying halite of the Paradox Member by the undersaturated waters in the underlying Leadville Formation.

## Paradox Member

The Paradox basin's extensive salt deposits of Middle Pennsylvanian age form the Paradox Member of the Hermosa Formation (Bass, 1944). Where the evaporite or halite facies is present, the Hermosa Formation can be divided into an upper member above the halite and a lower member below, both members being predominantly carbonate facies (fig. 3). The Paradox Member exhibits a remarkable cyclic pattern of chemical and clastic sedimentation. The member can be subdivided into 29 evaporite cycles in the deeper part of the basin and for convenience of correlation each cycle has been given a numerical designation (Hite, 1960; Hite and Liming, 1972).

The evaporite facies, predominantly halite, extends over an area of about 12,000 square miles in southeastern Utah and southwestern Colorado. The greatest thickness of evaporites is found in a troughlike depression bordering the ancestral Uncompahgre uplift along the northeastern margin of the basin (fig. 1). The original thickness of evaporites deposited in the trough area is difficult to estimate because of the widespread effects of salt flowage in the numerous diapiric salt anticlines of the region. Where the salt is not so severely disturbed the original thickness of the evaporites is estimated to have been between 5,000 and 6,000 feet. In the salt anticlines the maximum known thickness of evaporites now is nearly 14,000 feet. Isopach maps of the evaporite facies show thickness variations which are the result of both differential deposition across ancestral structural features and flowage into salt anticlines. The greatest thickness variations occur in the Uncompahgre trough (fig. 1) where thicknesses may vary from zero to more than 10,000 feet in a horizontal distance of 3 miles or less.

## Evaporite cycles

A typical Paradox Member evaporite cycle of deposition consists primarily of chemical precipitates; however, a small amount of detrital and organic material forms an integral part of the cycle. The lithofacies of the cycle include halite with or without potash salts, anhydrite, silty dolomite and black shale (fig. 4). The halite and anhydrite units of each cycle are entirely a chemical facies; however, the dolomite and black shale are both chemical and clastic, and contain organic material.

The sequential order of chemical precipitates in a typical Paradox cycle is determined by the degree of solubility of the rock-forming mineral in seawater. If a cycle is defined on the basis of the chemical sequence of rocks deposited, as seawater undergoes a gradual increase and then a decrease in salinity, the sequence is (A) silty calcareous dolomitic argillaceous organic-rich black shale, (B) silty dolomite, (C) nodular and laminated anhydrite, (D) halite with or without potash salts, (C) anhydrite as before, (B) dolomite as before, and (A) black shale as before. In this sense the cycle can be termed a chemical cycle and the lithologic sequence of units shows mirror-image symmetry as A, B, C, D, C, B, A. In detail, however, the Paradox chemical cycle is not symmetrical. At the base of the cycle, units A, B, C, and D are deposited as the result of gradually increasing salinity and each unit shows a gradual transition with the overlying unit. The halite unit (D), however, neither shows a gradual decrease in salinity nor grades into the overlying anhydrite unit (C). Studies by Raup (1966, p. 245) of the bromine content of halite in the Paradox Member have shown that salinities gradually increased all the way to the top, or near the top, of each salt bed. Further evidence of asymmetry can be seen in those cycles that are potash bearing. The potash deposits, which represent

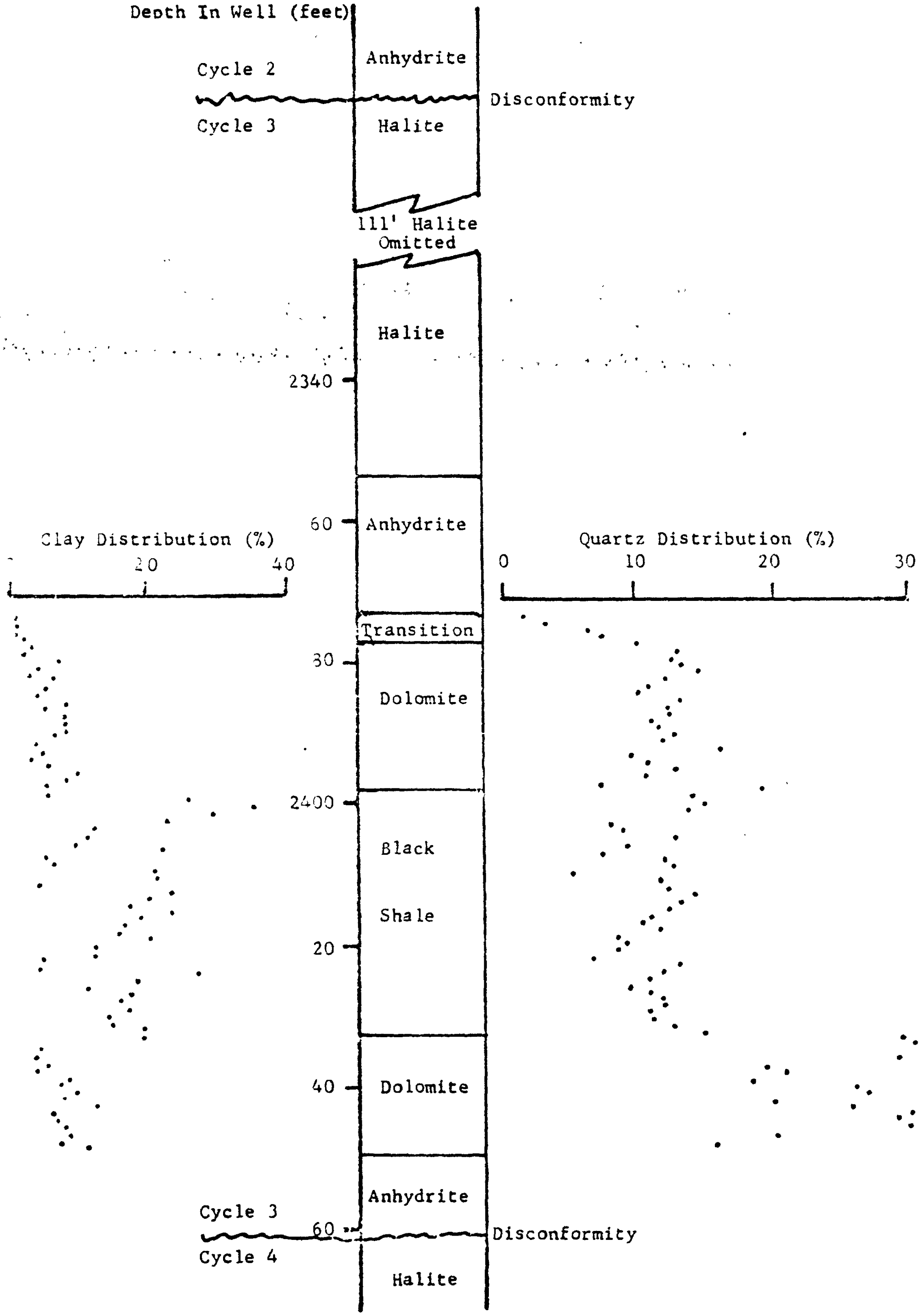



FIGURE 4.--TYPICAL EVAPORITE CYCLE OF PARADOX MEMBER (MODIFIED FROM HITE, 1969).

the period of highest salinity in the cycle, usually occur at the top of the halite instead of the middle (Hite, 1968, p. 323). A strongly asymmetrical distribution of detrital quartz through the cycle can also be noted (fig. 4). The lower dolomite unit (transgressive phase) contains nearly twice as much quartz as the upper dolomite unit (regressive phase).

Boundaries of Paradox cycles were at first defined on the basis of rock units, generally the black shales, but recently it was recognized that a more workable system of cycle boundaries can be outlined if disconformities are used (Peterson and Hite, 1969). In the evaporite cycle the basal contact of each halite unit is transitional with the underlying anhydrite, but the upper contact of the halite unit is sharp. This sharp contact, at the top of the halite unit, is a dissolution surface or disconformity along which several feet of halite has been removed. These disconformities, which interrupt the chemical cycle, result from major incursions of sea water that reduce salinity in the evaporite basin. Using the disconformities as cycle boundaries, the order of units would be C, B, A, B, C, D. The change from transgressive to regressive conditions occurs somewhere near the mid-point of unit A so that the transgressive hemicycle is C, B, A, and the regressive hemicycle is A, B, C, D. Comparison of the transgressive and regressive hemicycles shows considerable condensation of the sedimentary sequence in the transgressive phase. Transgression appears to have been more rapid than regression.

The evaporite cycles of the Paradox Member show a lateral change of facies, similar to the vertical change, from halite through anhydrite to dolomite rock. The lateral change is particularly well demonstrated from northeast (halite) to southwest (dolomite) in the basin (Fig. 3, wells 8 and 9).

### Anhydrite rock

The anhydrite rock of a Paradox evaporite cycle consists of material that is finely laminated or nodular in appearance. Fine-grained dolomitic mud is present as intervening laminae or as the matrix between anhydrite nodules. The rock is very dense and impermeable except where fractured. Quantitatively, anhydrite is the least abundant constituent of the cycles.

### Dolomite rock

Dolomite in the Paradox cycle is typically fine grained and may contain as much as 50 percent by weight of well-sorted quartz silt. The rock appears relatively impermeable but brine may be seen oozing from newly drilled cores in dolomite units. The rock is tough and dense and where encountered in underground mine workings it generally stands without support. Some flows of brine and/or oil and gas have been encountered in these rocks where they are intensely fractured.

### Halite rock

The halite rock of the Paradox Member is essentially the same as the halite of other marine evaporite deposits. The rock is composed of an intergrowth of halite crystals that range from 2 mm to 50 mm in diameter. Average crystal size is about 5 mm. The rock is generally a smoky gray color except where trace amounts of potash minerals, which generally contain trace amounts of hematite, color the rock shades of tan or red. Halite rock in the Paradox basin generally contains no more than 2 or 3 percent of minerals insoluble in water. Nearly all this insoluble fraction consists of anhydrite, although there may be trace amounts of dolomite, quartz, clay, and talc. The anhydrite occurs in thin discrete laminae, darker colored bands with indefinite boundaries, and as small euhedra scattered through the halite matrix. More than half of the halite units in the evaporite cycles contain potash deposits. The potash minerals include sylvite (KCl) and carnallite ($KMgCl_3 \cdot 6H_2O$). The economics of these deposits as related to waste disposal sites is treated in a later part of this report. Paradox halite contains some moisture in the form of tiny brine inclusions. A small number of measurements show a range of 0.144 to 0.093 percent $H_2O$ by weight. In addition to brine, inclusions of hydrocarbons have also been noted. These, however, have been seen only in the coarsely crystalline halite of cycle no. 10.

## Black shale

The black shale has the most complex lithology of the cycles. About 20 to 30 percent by weight is carbonate, divided about equally between dolomite and calcite. The remainder of the black shale is clay-size detritus consisting of quartz, feldspar, various clay minerals, and locally as much as 15 percent organic matter. These shales, like many other black organic-rich rocks, contain sufficient uranium to create radioactivity anomalies on gamma ray logs. By using these logs, a precise basinwide correlation of these units can be made. The rock is characterized by high porosity and low permeability except where fractured. Fracturing is widespread and can be observed in all cores of these units. In the Cane Creek potash mine, it was necessary to set steel arch supports in all workings where these rocks were encountered. Fractures and joints are nearly always filled with halite and less commonly with potash minerals. The role these fracture systems play in regard to accumulation of hydrocarbons or brine will be discussed in greater detail in a different section of this report.

## Post-Paradox rocks

The normal sequence of undisturbed post-Paradox rocks is shown in table 1, but in many parts of the Paradox basin the normal sequence has been changed locally during the development of salt anticlines. Normally, the Paradox Member of the Hermosa Formation is overlain by an unnamed upper member of fossiliferous limestone that is of Middle Pennsylvanian age. In many places, however, even in the type locality of Paradox Valley, outcrops of the Paradox Member include cap rock material that may have developed as late as Quaternary time. The distribution and the sequence of post-Paradox rocks varies considerably from one salt anticline to another.

Most of the post-Paradox formations wedge out locally (table 1). This results from the fact that many of the salt anticlines were uplifted in a series of pulses, so that some formations either were not deposited over the rising structures or were removed by erosion before deposition of the next younger unit. In southwestern Colorado, the Morrison is the oldest formation to have completely or almost completely blanketed the salt anticlines (Cater, 1970, p. 35). In eastern Utah, the Morrison again is the oldest formation to have covered the Salt Valley anticline.

Aside from alluvium, the chief post-Paradox strata that overlie the Paradox Member in the salt anticlines are the upper member of the Hermosa Formation, and the Rico and Cutler Formations--all of Paleozoic age. None of these units is an actual or potential aquifer for many miles in any direction.

The only ground-water investigations made in the salt-anticline area to date have been of the Spanish Valley by Sumsion (1971), and of a part of Canyonlands National Park by C. T. Sumsion and E. L. Bolke (U.S. Geol. Survey, Open-file report, May 15, 1972). Accordingly, the information on water supply in table 1 was obtained in part from these reports and reports on surrounding areas, such as the Grand Junction area by Lohman (1965) and the Navajo Country by Harshbarger, Repenning, and Callahan (1953), and in part by appraising the probable water-bearing character from the nature of the rocks comprising the different formations.

The principal aquifers in and near the salt-anticline area are the Moab and Slick Rock Members of the Entrada Sandstone and the Navajo and Wingate Sandstones. Because these sandstones generally are firmly cemented by calcium carbonate, however, they have relatively low permeability and hence yield only small to moderate supplies of water. Some of the sandstones and conglomerates in other formations probably would yield some water, as noted in table 1, but little or no data are available.

## STRUCTURE

The depth of the salt varies considerably throughout the Paradox basin. Along the southwestern and western edges of the basin the combination of the structural rise over the Monument upwarp and deep dissection by the Colorado and San Juan Rivers exposes gypsum beds of the Paradox Member. Halite is present in the subsurface a few miles downdip from these outcrops. In this same general area drill holes on the axis of the Elk Ridge anticline have penetrated salt at depths of 2,500 to 3,000 feet. The only other outcrop of the Paradox Member around the edge of the basin is along the southeastern edge about 10 miles north of Durango, Colorado. Here again only gypsum beds are exposed, but halite-bearing rocks are present in the subsurface about 15 miles southwest of this locality. Halite-bearing rocks may be present downdip a short distance from the outcrop, but less than 2 miles from the outcrop the Paradox Member is deeply buried beneath towering cliffs of Mesozoic sedimentary and Tertiary volcanic rocks. Along the northeastern margin of the basin, bordering the Uncompahgre uplift, the salt-bearing rocks of the Paradox Member are faulted down against the Precambrian core of the uplift and covered by a thick wedge of coarse Permian clastics. The top of the salt in this area is from 14,000 to 15,000 feet below the surface. In the rest of the basin, depths to the salt average about 6,000 feet, except in the salt anticlines where locally it is brought within 500 feet of the surface. Generally speaking, the salt will be at favorable mining depths only within those areas where the Paradox Member or the upper limestone member of the Hermosa Formation is exposed.

## Salt anticlines

The dominating structural features in the Paradox basin are the salt anticlines which occupy a rectangular shaped area about 50 miles wide and 120 miles long on the northeastern side of the basin. This area coincides with the Uncompahgre trough (fig. 1) which is also the area of the thickest salt accumulation. The salt anticlines can be divided geographically and structurally into five major systems. Each system consists of a long undulating welt of thickened salt over which the younger rocks are arched in anticlinal form. Surface structural expression is more pronounced along certain segments of each anticlinal system, and these have been given individual names. The anticlines are commonly breached along these segments, forming prominent flat-floored valleys. The major salt anticline systems are (1) Lisbon Valley-Dolores Valley, (2) Moab Valley-Spanish Valley-Pine Ridge, (3) Gypsum Valley, (4) Castle Valley-Paradox Valley, and (5) Salt Valley-Cache Valley-Fisher Valley-Sinbad Valley (fig. 1). Several smaller anticlines not included in the five major chains lie southwest of Moab along the Colorado River: Cane Creek anticline, Shafer dome, Lockhart anticline, Rustler dome, Gibson dome, and Meander anticline.

As the result of geophysical studies, detailed surface mapping, and study of data from numerous drill holes, the gross form of the Paradox salt anticlines is fairly well known. A typical anticline can be broken into three structural components: the floor of nonevaporitic rocks beneath the anticline, the central core of halite and its associated cap rock, and the overlying or flanking beds of nonevaporitic rocks.

These components show considerable difference in structural form. These differences are due to rheological contrasts and also to the influence of one component on another. The floor component, influenced by the underlying rigid basement complex, was deformed primarily by block faulting and strike-slip faulting. The central core, which is plastic, was deformed almost independently of the floor or the overlying component. The floor and overlying or flanking strata, although similar rheologically, bear little structural resemblance because they are separated by the thick plastic central core, which absorbs most of the stress transmitted from the crystalline basement.

The floor of a Paradox salt anticline consists of a relatively thin skin (1,500 to 2,500 feet) of alternating units of limestone, dolomite, shale, sandstone, and quartzite resting on the crystalline Precambrian basement. The sedimentary rocks range in age from early Pennsylvanian to Cambrian. Pre-Paradox strata dip to the northeast under the salt anticline area at about 250 feet per mile. Through much of the area the beds are relatively undisturbed except for gentle flexing. Locally, however, deep drilling has shown that pre-Paradox strata are cut by normal faults beneath some of the salt anticlines. The maximum known relief on one of these faults is 5,615 feet (Baars, 1966, p. 2107) on the southwest flank of the Paradox Valley anticline (figs. 1 and 5). As diagrammed in figure 5, the pre-Paradox strata were thinned by erosion before the deposition of salt. Fault-block structures played an important role in the origin of the salt anticlines.

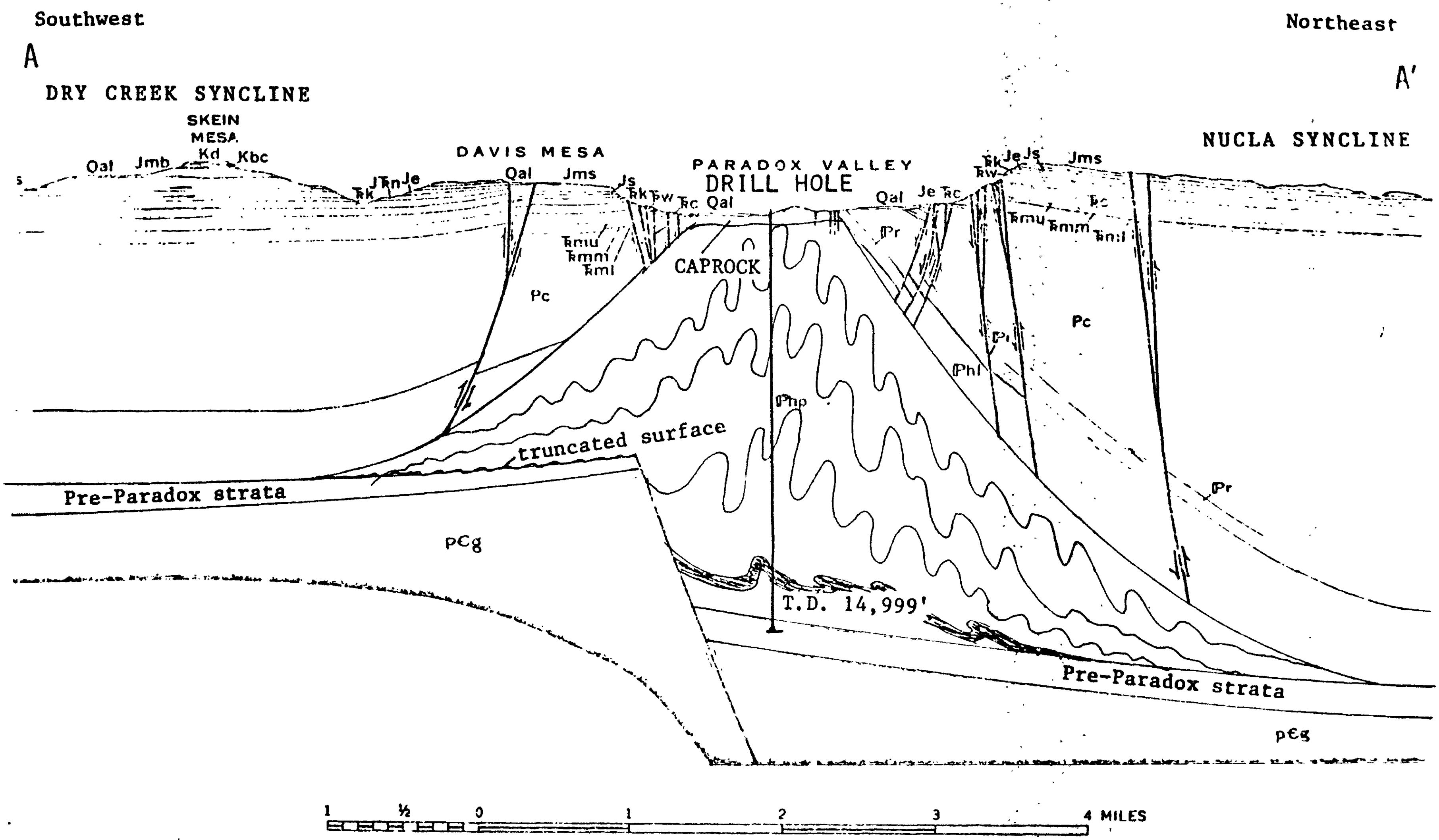



FIGURE 5.--CROSS SECTION THROUGH PARADOX VALLEY ANTICLINE, TRACE OF SECTION SHOWN ON FIGURE 1

(ADAPTED FROM CATER, 1970)

## EXPLANATION FOR FIGURES 5 AND 13

Qal--Alluvium

Km--Mancos Shale

Kd--Dakota Sandstone

Kbc--Burro Canyon Formation

Jmb--Morrison Formation, Brushy Basin Member

Jms--Morrison Formation, Salt Wash Member

Js--Summerville Formation

Je--Entrada Formation

JTRn--Navajo Sandstone

TRk--Kayenta Formation

TRw--Wingate Sandstone

TRc--Chinle Formation

TRm--Moenkopi Formation

- TRmu--upper member
- TRmm--middle member
- TRml--lower member

Pc--Cutler Formation

Pr--Rico Formation

IPhl--Hermosa Formation, limestone member

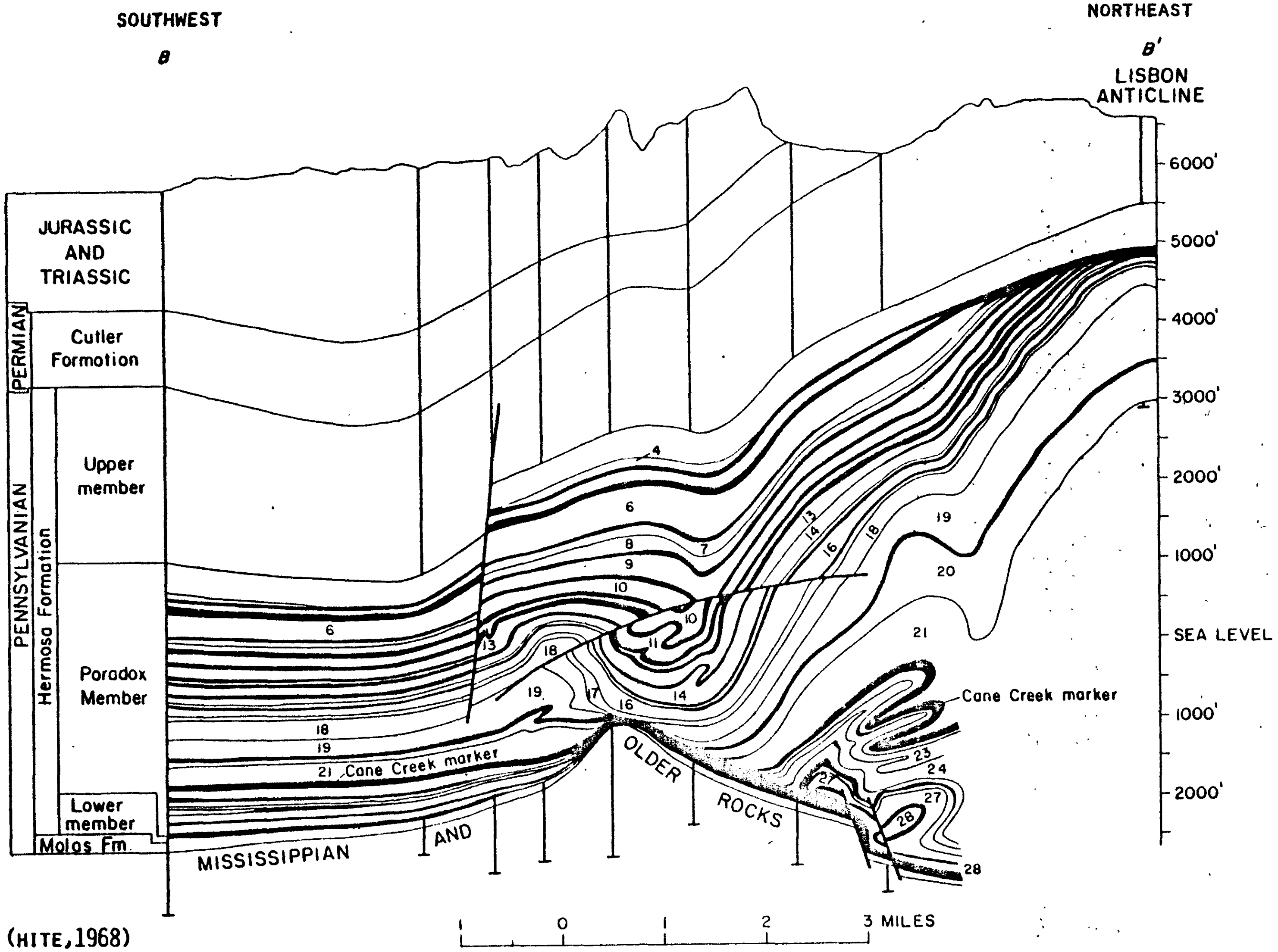
IPhp--Hermosa Formation, Paradox Member

p€g--Gneiss, schist, granite, and pegmatite

Locally they may form important traps for petroleum, as they do in the Lisbon Valley anticline (figs. 1 and 6).

The central cores of the salt anticlines range in thickness from about 2,500 to 14,000 feet (table 2). They consist of 70 to 80 percent halite rock with associated potash minerals; the remainder is made up of marker beds of anhydrite, dolomite, and black shale. These marker beds, which may be up to 200 feet thick, impart a confining strength to the halite layers so that the structural behavior of these central cores was different from the behavior expected of an unconfined homogeneous mass of halite. In addition, the marker beds make it possible to map the structural detail of the central core, if drill hole records are available.

The structure in the central core of a salt anticline contrasts sharply with the structure of the underlying and overlying nonevaporitic rocks. The core structure is the result of both regional compression and flowage of the Paradox Member into the anticlines. The amount of flowage in an anticline is a function of three factors--(1) thickness of the original salt layer, (2) degree of differential loading on the flanks of the anticline, and (3) whether or not the salt core was confined throughout its history by younger rock layers. Of these three factors the last was probably the most important. Locally there were areas along the axes of anticlines nearest the Uncompahgre uplift where confining younger strata were missing. This allowed large-scale migration of Paradox strata toward and up through these holes in the sediment cover to form diapiric anticlines.

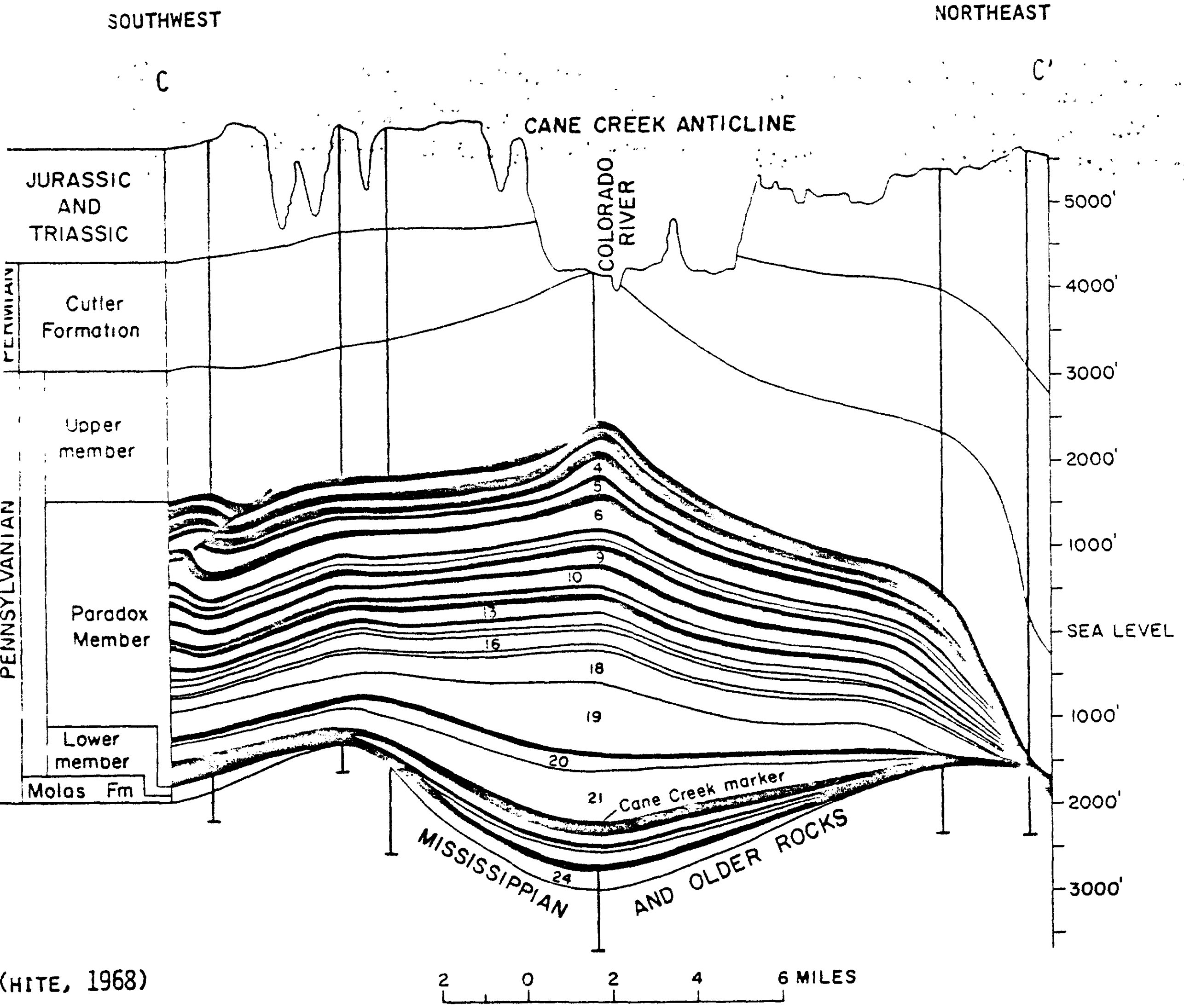



(HITE, 1968)

FIGURE 6.--CROSS SECTION THROUGH PART OF LISBON VALLEY ANTICLINE, UTAH. DARK ZONES IN PARADOX MEMBER REPRESENT CLASTIC-PENESALINE MARKER BEDS. INTERVENING UNITS, SEVERAL OF WHICH ARE NUMBERED, ARE SALT BEDS.

The migration of Paradox strata from flanking synclinal areas to the salt anticlines involved movement of both halite layers and the intervening marker beds as a single mass. This contrasts with the Gulf Coast salt domes in which nonchloride beds are generally absent except for an occasional erratic block.

Contrasting degrees of structural complexity are evident between the diapiric and nondiapiric anticlines. Nondiapiric anticlines, such as Cane Creek (figs. 1 and 7), Shafer dome, and Gibson dome, are characterized by relatively simple disharmonic folding and minor faulting. Some of the nondiapiric anticlines such as the Lisbon Valley anticline (fig. 6) are considerably more complex, but the stratigraphic identity of the evaporite cycles is still preserved. Recumbent folds and low-angle reverse faults are typical structures in the salt core of the Lisbon Valley anticline. In one drill hole near the crest of this structure the same bed was repeated seven times by recumbent folding. Detailed studies of folding in the Paradox Member have been made by Evans and Linn (1969) in mine exposures in the Cane Creek anticline. These authors classified the orders of folding in this structure on the basis of periodicity (p. 290). The anticline itself was considered a first-order fold. Folds in the marker beds were considered as second order, and the folds involving thin anhydrite laminae in the halite and potash units were given third, fourth, and fifth order ranking. As shown on their mine maps, the second order folds have wave lengths of as much as 400 feet, although the average is about 200 feet. Amplitudes of up to 75 feet were noted on some of these folds. The third, fourth,




(HITE, 1968)

FIGURE 7.--CROSS SECTION THROUGH CANE CREEK ANTICLINE, UTAH. DARK ZONES IN THE PARADOX MEMBER REPRESENT CLASTIC-PENESALINE MARKER BEDS. INTERVENING UNITS, SEVERAL OF WHICH ARE NUMBERED, ARE SALT BEDS.

and fifth order folds have wave lengths and amplitudes of a few feet or inches. The second-order folds are most significant to any type of underground mining operation where it is necessary to avoid penetration into the marker beds above or below a particular salt bed.

As might be expected, the structure in the central core is most complex in the diapiric salt anticlines. Although all these anticlines have been drilled, structural interpretation in the central cores of the anticlines is somewhat hypothetical because it is impossible to recognize stratigraphic units of the Paradox Member with any degree of certainty. The problem of identification is the result of a combination of drill penetration of marker beds at very low angles and the rapid thickening of these beds as they approach the ancestral Uncompahgre uplift.

The marker beds in the cores of the anticlines are believed to be deformed into a series of nearly vertical isoclinal folds whose axes parallel the northwest trend of the salt anticlines. Accurate knowledge of the geometry of these folds will come only through extensive drilling, but some reasonable interpretations can be made on the basis of available information. For example, it is known from drilling that complete removal of salt by flowage has occurred in the Dry Creek syncline on the southwest flank of the Paradox Valley salt anticline (fig. 5). The salt flowed into the Paradox Valley anticline and also into the Gypsum Valley anticline, the next anticlinal system to the southwest. When flowage from the synclines into the anticlines began, it is likely that a nearly equal volume was transferred to each of the adjacent anticlines. If so, then each marker bed might be expected to pull apart somewhere near the midpoint of the syncline. With a complete transfer of salt, the associated marker beds would be subjected to a high degree of crustal shortening. In figure 8, a marker bed is shown in the position it might occupy in the Paradox Valley anticline after flowage from the adjacent Dry Creek basin syncline. The original length of the bed, measured from the midpoint of the syncline, would have been about 5.7 miles. After flowage the same bed might have been shortened by folding so it would occupy a horizontal distance of only 2 miles. The depicted bed has a thickness of about 100 feet, which is about average for the area. According to Currie et al. (1962), the wave length of folds in a multi-layer sandwich of competent and incompetent layers is dependent on the thickness of the competent layers. Using that concept, a 100-foot-thick marker bed should fold with a wave length of about 3,700 feet. This means that a 100-foot-thick marker bed should fold eight times in the distance A-A' (fig. 8). Continued flowage of salt and marker beds into the anticline would eventually shorten the bed to the distance B-B', and decrease the wave length of the folding to about 1,300 feet. With this wave length and degree of shortening, the folds could have amplitudes of 1,000 feet or more. Structures observed in caprock and in drill holes on some of the salt anticlines suggest that the fold geometry described above may closely resemble the actual structures.

Dissolution of halite from the upper surface of the central core has locally developed a cap rock of insoluble material along the crestal

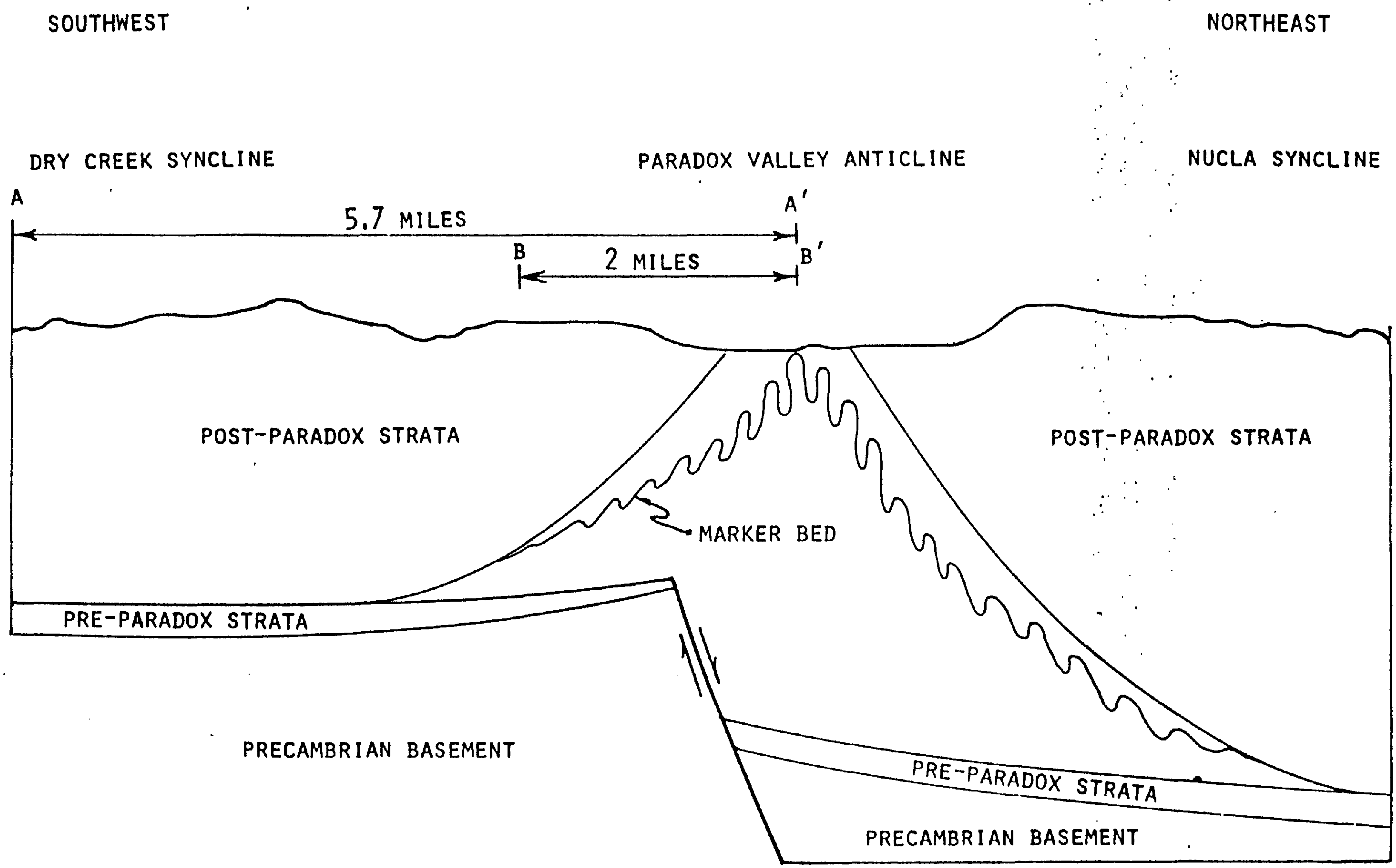



FIGURE 8.—DIAGRAMMATIC CROSS SECTION THROUGH PARADOX VALLEY ANTICLINE SHOWING THE SHORTENING OF MARKER BED IN PARADOX MEMBER CAUSED BY FLOWAGE FROM ADJACENT SYNCLINE. A TO A′ REPRESENTS ORIGINAL LENGTH OF MARKER BED, ABOUT 5.7 MILES. B TO B′ REPRESENTS HORIZONTAL DISTANCE, ABOUT 2 MILES, OCCUPIED BY THE BED AFTER TRANSFER BY FLOWAGE FROM DRY CREEK BASIN SYNCLINE. REDUCTION OF ORIGINAL LENGTH BY 65 PERCENT IS ACCOMPLISHED BY SERIES OF VERTICAL TO NEAR VERTICAL FOLDS WITH AMPLITUDES OF 1,000 FEET OR MORE.

parts of the salt anticlines. This cap rock differs somewhat from the Gulf Coast variety. Both originated as the result of solution of halite; however, the Gulf Coast cap rock was formed entirely from anhydrite occurring in the halite as thin laminae and small disseminated crystals. The Paradox cap rock includes this type of material and also the marker beds whose lithologies were previously described. All the anhydrite in this residuum has been converted to gypsum. In contrast to the Gulf Coast there has been no microbial reduction of sulfate and development of a limestone layer.

Cap rock in anticlines such as Cane Creek or Lisbon Valley results from the solution of only a few hundred feet of salt. This took place prior to deposition of overlying shales, limestones, and thin anhydrite units of the upper member of the Hermosa Formation. These beds of the upper member are essentially impervious and have prevented further solution of halite over these structures for nearly 250 million years. The protective beds of the upper member were not deposited across such diapiric structures as the Paradox Valley and Gypsum Valley anticlines, and as a result those structures have experienced a long history of salt solution that may have removed as much as several thousand feet of halite. In both types of anticlines the maximum development of cap rock occurred at the point of greatest uplift of the central core.

In areas where cap rock crops out, and weathering has not been too severe, it is possible to map certain lithologic units, particularly black shales. Continuity of individual units in the cap rock may sometimes exceed a half mile or more. Structures in the cap rock are probably not too dissimilar from the original form when these rocks were still interbedded with halite. A slight modification probably took place as the result of volume change following the conversion of anhydrite to gypsum. These cap rocks are porous and locally, in anticlines such as Paradox Valley, they are saturated with brine.

The strata overlying the halite cores of the salt anticlines have a structural expression which differs greatly from the other two components of the anticlines. The difference is due to rheological contrasts and a set of forces not involved in the deformation of the other two components.

The rocks in this uppermost component consist of massive sandstone units, siltstones, shales, and locally, limestones. These units have a combined strength greatly exceeding that of the underlying plastic-like evaporite core. This component ranges in thickness from 5,000 to 15,000 feet. Extreme variations in thickness are due primarily to differential rates of sedimentation in the Cutler Formation of Permian-Pennsylvanian age. The form of folding in this component consists of a gentle arching across the axis of each salt anticline. Dips in beds exposed along the flanks of nondiapiric structures seldom exceed 10 degrees. In the diapiric anticlines, particularly in the Paleozoic rocks, dips may exceed 30 degrees. The arching of these strata over the salt anticlines is the result of an initial horizontal compressional force that later gave way to a vertical force stemming from the upward movement of the central core of evaporites. These structural arches are now broken by high-angle normal faults across which some blocks of

Mesozoic strata have been dropped as much as 2,000 feet. This faulting is due to collapse caused by dissolution of the underlying evaporites. Various authors have shown many of these faults extending into the Paradox Member. It is true that some may extend into Paradox cap rock, but because they are the result of solution of halite at the cap rock-halite interface they cannot extend into the salt itself. The effects of the salt removal and subsequent collapse are particularly evident near the ends of salt anticlines such as Moab Valley and Paradox Valley (fig. 1). There, Mesozoic strata, although highly faulted and fractured, are continuous across the evaporite core and form a conspicuous downsag. Locally, in some of the diapiric anticlines, isolated blocks of younger rocks appear to have sunk into the Paradox Member. Cater (1970, p. 66) suggests that this foundering may be due to isostatic adjustments between the heavier downsagged blocks and the lighter evaporite core.

## GEOLOGIC PERSISTENCE OF PARADOX SALT DEPOSITS

During preliminary planning for the type of information that should be included in this report it was pointed out that, for safe waste disposal, an underground depository should remain essentially intact for a long period of time, perhaps on the order of two hundred fifty thousand years. In spite of their highly soluble nature, rock salt deposits show great geologic persistence, as indicated by the survival of extensive salt deposits from every geologic period since the Cambrian. The nature of most salt deposits is such that, unless disturbed by drilling or mining, solution takes place only along the upper surface. Generally this surface is protected from ground water by an impervious layer of clay or anhydrite. Good examples are the salt deposits of Cretaceous age in northeastern Thailand. Despite the fact that rainfall in this region commonly exceeds 60 inches per year, the salt deposits have survived even though they locally occur at depths of less than 200 feet (Jacobson and others, 1969). Even where ground water is in direct contact with salt, dissolution is effective only where hydrologic conditions permit the escape of saturated brine.

The permanence of the Paradox salt deposits can be estimated by calculating present dissolution rates from the salt load carried by surface drainage in the basin, and by calculating the average dissolution rate since the salt was deposited, based on the volume of present-day cap rocks. It is known that the only areas of salt removal, past and present, are along the western and southeastern edges of the salt basin and the crestal parts of the salt anticlines. At most, downdip dissolution of salt along basin edges has probably advanced no more than 2 or 3 miles since the close of the Pennsylvanian period (280 million years). Dissolution from the edges of the salt basin should, therefore, pose no threat to sites well within the basin margins.

Some idea of the rate of dissolution of salt from the crests of salt anticlines may be obtained from measurements of the discharge rate and chloride content of the Dolores River, the Colorado River, and several tributaries of the Colorado that drain structures in which salt bodies are exposed. Five of the larger salt anticlines of the Paradox basin--Gypsum, Lisbon, Paradox, and Sinbad Valleys and the Dolores anticline--are drained by the Dolores River (fig. 1). At a gaging and sampling station 9 miles above the mouth, the Dolores carried an average of 528 tons per day of sodium chloride during the 16-year period of record--1954 through 1969.

The remaining salt anticlines of the Paradox basin are drained by the Colorado River, but the determination of the additional salt load picked up by the Colorado below the mouth of the Dolores is hampered by lack of records. For only 1 year, 1952, is it feasible to determine both the load carried by the Dolores River (measured at Gateway, Colorado), and the net load added to the Colorado below the Dolores (between Dewey Bridge and Hite, Utah):

| Tons per day of NaCl | | |
|---|---|---|
| | 3,450 | Carried by Colorado River at Hite (below Paradox basin) |
| 984 | | Carried by tributaries of Colorado River between junction with Dolores River and Hite |
| +2,340 | | Carried by Colorado River above junction with Dolores River |
| 3,324 | -3,324 | Tonnage of NaCl not from Paradox basin |
| | 126 | Tonnage from Paradox basin exclusive of Dolores River |
| | +544 | Carried by Dolores River near junction with Colorado River |
| | 670 | Average tonnage of NaCl carried daily (in 1952) from Paradox basin by Colorado River |

The 670 tons per day would include all the common salt for 1952 from all salt anticlines including the Meander anticline in Cataract Canyon. Note that the value for the Dolores River at Gateway, 544 tons, is comparable to the average value of 528 tons 9 miles above the mouth, as mentioned earlier, so the total value should be the right order of magnitude.

The chloride content of the Dolores River is derived in part from dissolution of halite from the Gypsum Valley, Paradox Valley, and Sinbad Valley anticlines. Two other anticlines, the Dolores and Lisbon Valley, are also drained by the river but the Paradox Member is not exposed in these structures and there is no evidence of recent salt removal taking place. Solution of halite is probably taking place from the first three anticlines over a combined surface area of about 130 square miles. This area of active salt removal is obtained by measuring the prominent collapsed parts of each anticline. The average yearly load of nearly 200 thousand tons of sodium chloride carried by the Dolores River represents removal of halite from an area of 130 square miles at a rate of about 0.0009 foot per year. If this rate of removal continued over a period of 1 million years, 900 feet of halite rock would be stripped from each of the three anticlines. This calculated rate of removal is probably excessive because: (1) it does not take into consideration that a considerable percentage of the sodium chloride carried by the Dolores River may be derived from rocks younger than the Paradox Member; and (2) salt is probably being removed from a much wider area than that on which surface collapse has become conspicuous.

The cap rock of the salt anticlines provides another means of estimating rates of salt removal. The average thickness of cap rock over these structures is about 1,000 feet. Allowing for the increase in volume that results when anhydrite is converted to gypsum, the present 1,000 feet of cap rock would represent about 750 feet of residual nonchloride material after the dissolution of salt from the anticlinal core. Because the original core of these anticlines averages about 25 percent nonchloride material, 750 feet of residual nonchloride material would remain after the dissolution of salt from about 3,000 feet of halite-bearing rock. At the rate of 900 feet per million years, it would take 3.3 million years to remove this much halite, suggesting that the cap rock started developing in the early Pliocene. The age of the cap rock is unknown. Cater (1970, p. 65) has stated "Collapse of the crests of the salt anticlines occurred in two stages apparently widely separated in time. The first stage followed perhaps rather closely the Late Cretaceous folding. The second stage followed epeirogenic uplift of the entire Colorado Plateau in the middle and late Tertiary, and this stage is still continuing." If the cap rocks as we see them now began forming at the close of the Cretaceous, about 65 million years ago, then the removal rate of halite would have been about 46 feet per million years. If accretion of the cap rocks did not begin until the epeirogenic uplift of the Colorado Plateau, which according to Hunt (1956, p. 27) began during the Miocene, about 20 million years ago, then removal of salt proceeded at the rate of 150 feet per million years. The question of cap rock age is further complicated by data from drill holes on the crests but outside the collapsed parts of the anticlines. One drill hole on the southern end of the Paradox Valley anticline (Petroleum Production Broad Government 1 in sec. 19, T. 45 N., R. 15 W., Colo.) penetrated the Cutler Formation underlain by 290 feet of Paradox cap rock. Another drill hole on the northern end of the Salt Valley anticline (Defense Plant Corp., Reader 1, in sec. 4, T. 22 S., R. 19 E., Utah) penetrated the Morrison Formation underlain by 650 feet of Paradox cap rock. At Lisbon Valley anticline a thin cap rock is overlain by the upper member of the Hermosa Formation, about 250 million years old. These and other relationships between cap rock and overlying strata of Mesozoic and Paleozoic age suggest that at least part of the cap rock over the Gypsum Valley, Paradox Valley, and Sinbad Valley anticlines may have developed during Permian time and has probably received continuous additions since that time. Considering then that a cap rock with a present-day thickness of 1,000 feet might be the result of dissolution of halite through a period of 250 million years, the rate of halite removal might be as slow as 3 feet per million years.

In summary, the exact rate of halite removal from the Paradox salt anticlines is difficult to determine but a range of 3 to 900 feet per million years is suggested. The preponderance of available evidence suggests that the actual rate lies within the lower half of that range.

## GAS IN THE PARADOX MEMBER

Oil and petroleum gases, primarily methane, are found in the Paradox Member by almost every well drilled in the Paradox basin.

These occurrences constitute a hazard to any underground mining operation. They range from trace amounts to high pressure-high volume flows which have on occasion resulted in spectacular blowouts during drilling. Generally these flows dissipate in a matter of a few hours or days. A few wells, however, have been completed for commercial production from these zones. One well on the west flank of the Cane Creek anticline has produced nearly one million barrels of oil over a period of 10 years. The oil and gas is generally limited to marker beds, although small inclusions of liquid hydrocarbons are occasionally noted in drill cores of halite. The marker beds in the Paradox Member have very low permeabilities and as a result significant accumulation of hydrocarbon is found only where the beds are intensely fractured.

In the Cane Creek potash mine of Texas Gulf, Inc. near Moab, the potash ore lies only a few feet beneath a marker bed. Roof bolts extending up into the bed were commonly sites of hydrocarbon leakage. To safeguard against entry of high-pressure flows into the advancing mine workings the company routinely drilled holes into the marker bed, allowing any large accumulation of oil and gas to bleed off before mining operations proceeded. Unfortunately the proximity of potash ore and marker bed combined with folding of these beds brought about an occasional intersection of mine workings and marker bed necessitating all the precautions required in the operation of a gassy mine.

Regardless of location, any plan to use the salt deposits of the Paradox basin as a waste disposal site should provide for the problem of gas in the Paradox Member. Any shaft sunk into the Paradox Member is bound to encounter some gas, although most would probably be bled off by drilling a pilot hole. Gassy conditions could probably be avoided during mine development by keeping an adequate thickness of halite as a seal between the workings and the marker beds.

## GEOLOGY OF SPECIFIC SITES

### General statement

If waste storage or disposal requires a shaft and conventional underground mine development at depths of 2,500 feet or less, then only certain salt anticlines can qualify. Even some of these anticlines are so remote and inaccessible that further consideration may be impractical. Some anticlines or parts of anticlines were excluded on the basis of conflicts with industrial development, population centers, or national parks. The remaining areas are included in table 2 and discussed in detail in the following section.

### Castle Valley anticline

Castle Valley is about 15 miles by highway up the Colorado River from Moab, Utah (fig. 1). The road is paved and in excellent condition. The site is about 21 miles by paved road from the Denver and Rio Grande Western Railroad siding at Seven Mile Canyon. There are about 3 small ranches in the area and part of the flat valley floor is irrigated farmland. The anticline has been drilled unsuccessfully at two locations for oil and gas. One of the drill holes confirmed the presence of potash deposits of questionable economic value. The anticline is diapiric and the cap rock of the Paradox Member crops out around a

Table 2.--Potential waste emplacement sites in the Paradox basin

| Site name | Minimum[1/] depth to salt (feet) | Thickness[2/] of salt (feet) | Thickness[3/] of target bed (feet) | Areal extent[4/] (square miles) | Non-chloride[5/] beds (percent) | Complexity of[6/] internal structure | Accessibility | Economic development |
|---|---|---|---|---|---|---|---|---|
| Castle Valley anticline | 1,855 (drilled) | 12,000 ± (estimated) 4,647 (drilled) | unknown | 15 | -- | very complex small igneous plug | Paved road | Two drill holes penetrated salt. Potash deposits, questionable value. Three groups of range dwellings. Potash deposits present. |
| Fisher Valley anticline | No drill holes 1,000 (estimated) | 12,000 (estimated) | unknown | 6 | unknown | very complex | Poor roads Very remote | Structure has never been drilled. Several small ranches in area. |
| Gibson Dome | 1,950 (drilled) 1,700 (estimated) | 3,137 (drilled) | 265 | 15-20 | 31 | less complex | 3 miles dirt Poor roads Very remote | Five drill holes, two which penetrated salt. Minor low-grade potash. No ranch dwellings. Just east of Canyonlands National Park. |
| Gypsum Valley anticline | 780 (drilled) | 7,835 (drilled) | 600 ± | 44 | 19 | very complex | Good paved roads | Four drill holes penetrated salt. Andy's Mesa gas field on NE flank. No ranch dwellings. Potash deposits. Crossed by Dolores River. |
| Lisbon Valley anticline | 1,620 (drilled) | 8,000 ± (estimated) 5,989 (drilled) | 500 ± | 4-5 | 22 | moderately complex | Good roads | Large number of drill holes penetrated salt. Adjacent oil and gas production, uranium and copper mines. No ranch dwellings. |
| Lockhart Anticline and Rustler Dome | 2,255 (drilled) 1,900 (estimated) | 2,273 (drilled) | 250 | 10 | 23 | less complex | Poor roads Very remote | Four drill holes penetrated salt. Potash deposits. No ranch dwellings. Just east of Canyonlands National Park. Crossed by Colorado River. |
| Moab-Spanish Valley-Pine Ridge | 804 (drilled) | 10,000 (estimated) | 450 ± | 10 | 24 | very complex | Good paved roads. Short distance from railroad. | An estimated 15-20 drill holes penetrated salt. LPG storage cavern and two brine wells in salt. Potash deposits. Town of Moab (5,000 pop.) at northwest end. Crossed by Colorado River. |
| Paradox Valley anticline | 510 (drilled) | 13,705 (drilled) | 600 ± | 66 | 29 | very complex | Good paved roads. | About 20 drill holes totaling about 50,000 feet of drilling that penetrated salt. Brine well with minor production. Potash deposits. Uranium mines on flanks of structure. Several farms nearby. Crossed by Dolores River. |
| Salt Valley anticline | 775 (drilled) | 10,173 (drilled) 11,000 (estimated) | 400 ± | 21 | 31 | very complex | Good paved road up to edge of area. Railroad crosses structure. | About 18 drill holes which penetrate salt. Potash deposits. Small town, Crescent Junction, at northwest end of structure. No farms or ranches. Bordered on south by Arches National Park. |
| Shafer Dome | 1,610 (drilled) | 3,905 (drilled) | 205 | 8 | 20 | less complex | About 5 miles from railroad spur and paved road at T.G.S. potash mine. | Four drill holes penetrated salt. Nearest oil and gas production at Big Flat field a few miles west. Minor potash deposits. Cane Creek potash mine 3 miles northeast. Dead Horse Point and Canyonlands parks on west border of area. Crossed by Colorado River. |
| Sinbad Valley anticline | 405 (drilled) | 9,911 (drilled) 12,000 (estimated) | 1,900 ± | 18 | 27 | very complex | Five miles from paved highway. Very remote. | Two drill holes penetrated salt. Potash deposits. No ranch or farm dwellings. |

1/ Shallowest depth to salt in any drill hole or estimated depth if undrilled area of lesser depth is present.
2/ If salt sequence has not been completely penetrated by drill, maximum penetration is given as well as estimated total salt thickness.
3/ Maximum penetrated thickness of any salt bed at favorable depth. Some beds are dipping steeply so the figure represents only an apparent thickness.
4/ Area beneath which top of salt is no deeper than 2,500 feet excluding areas of possible conflict with surface development.
5/ Discrete beds of anhydrite, black shale and dolomite which are more than 10 feet thick in the salt-bearing Paradox Member.
6/ Very complex: large scale isoclinal folds, faulting, poor stratigraphic continuity, cap rock present.
Moderately complex: some folding and faulting, cap rock present over some structures.
Less complex: a few minor folds and faults. Excellent stratigraphic continuity, no cap rock.

small igneous plug near the center of the structure (Baker, 1933; Williams, 1964). A well drilled in sec. 16, T. 25 S., R. 23 E. penetrated halite in the Paradox Member at the depth of 1,855 feet and was still in the Paradox at a total depth of 6,502 feet. This well was on the crest of the anticline and the depth to salt at that point probably represents the minimum for the entire structure. Structure in the salt core of the anticline is probably much the same as in the other diapiric anticlines.

## Fisher Valley anticline

The Fisher Valley anticline can be reached by continuing on state highway 128 past the Castle Valley turnoff for about 4.5 miles and then turning southeast on a dirt road which follows Onion Creek. The road is in the stream bed for nearly 8 miles before reaching the floor of Fisher Valley, and during rainy periods it is impassable to all but four-wheel drive vehicles. The site is about 30 miles by road from the railroad siding at Seven Mile Canyon. There are a few ranch dwellings in the valley and some of the valley floor is irrigated. The anticline has never been drilled so the depth to salt is unknown; however, it is probably similar to Castle Valley. Thickness of the salt is also unknown but is probably more than 10,000 feet. Complexly folded cap rock of the Paradox Member is exposed and deeply dissected at the northwest end of the anticline where cap rock is in intrusive contact with the Cutler Formation.

## Gibson dome

Gibson dome is one of a series of gently folded anticlines southwest of Moab along the Colorado River (fig. 1). Recent road improvements in the area have provided relatively easy access via state highway 211, which leaves highway 163 about 18 miles north of Monticello, Utah. From this junction the structure can be reached by about 29 miles of paved and 3 miles of dirt road. The total distance by road from Gibson dome to the Seven Mile railroad siding is about 76 miles. The area is uninhabited, the nearest ranch being about 12 miles distant. Sparse vegetation supports only very limited stock grazing. Five petroleum tests have been drilled on this structure with negative results. Three potash deposits are present in the Paradox Member. These deposits occur below a depth of 3,000 feet and have limited economic value. Only two of the drill holes in the structure were deep enough to penetrate salt. The top of the salt in one hole was at a depth of 1,950 feet (fig. 9). This same well penetrated all of the Paradox Member (3,137 feet) and was abandoned while drilling in the Leadville Limestone. Red beds and thin limestones of the Rico Formation are the oldest rocks exposed over the anticline. Surface closure is about 200 feet and maximum dips are about 4 degrees (Baker, 1933, p. 70). The Paradox Member is conformable with the overlying upper member of the Hermosa Formation. Structure on top of the Paradox Member is probably much the same as the surface. Geophysical logs are available from the one drill hole which penetrated all of the Paradox Member and they show that stratigraphic continuity of the halite and

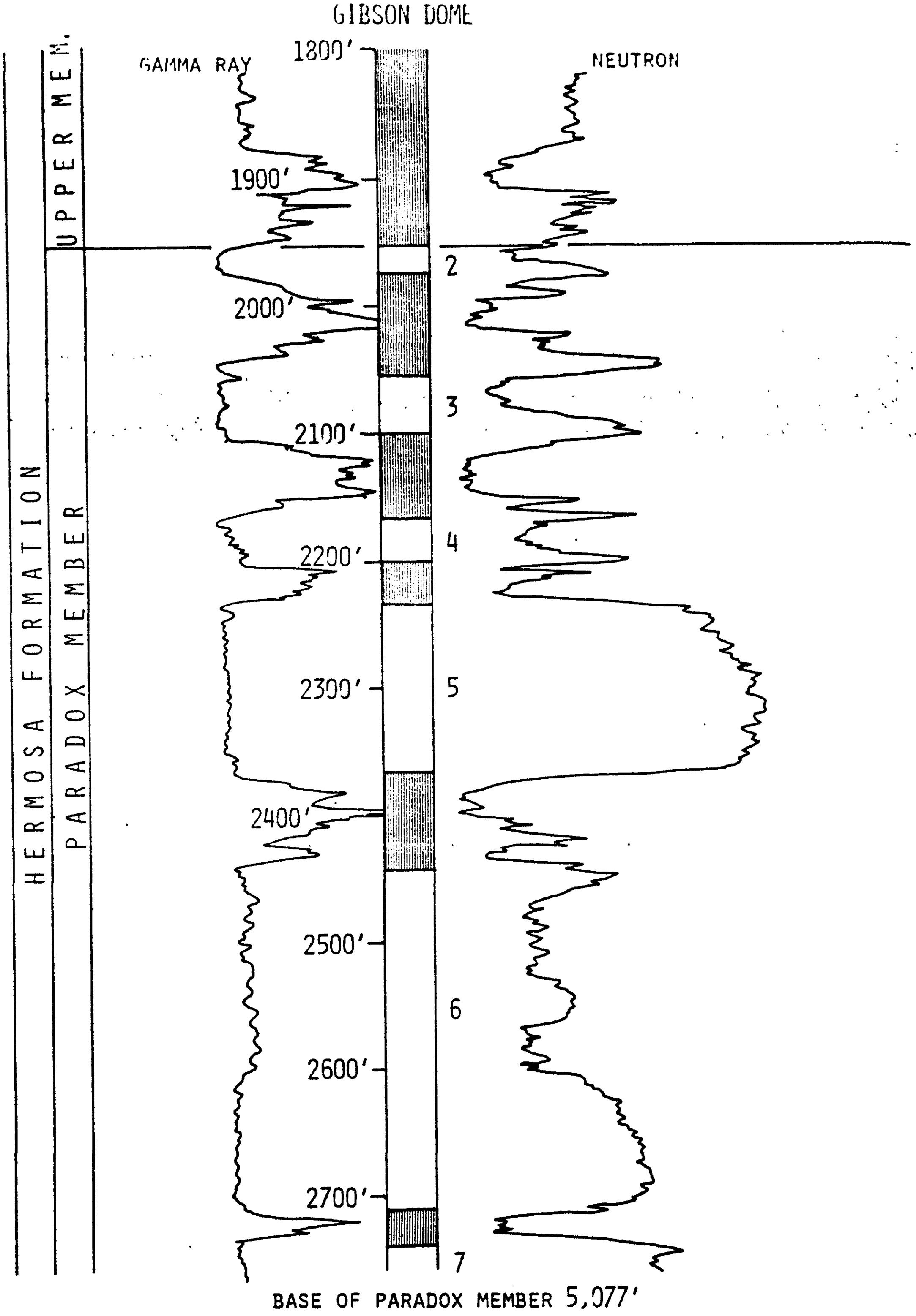



FIGURE 9.--RADIOACTIVITY LOG OF REYNOLDS MINING CORPORATION GIBSON DOME 1, IN SEC. 35, T. 29½ S., R. 20 E., SAN JUAN COUNTY, UTAH. DARK UNITS IN COLUMN ARE MARKER BEDS OF BLACK SHALE, DOLOMITE AND ANHYDRITE. UNSHADED UNITS WITH LARGE NUMBERS ADJACENT TO THE COLUMN ARE HALITE BEDS AND THEIR NUMERICAL NOMENCLATURE.

marker beds is excellent (fig. 9). The uppermost halite unit in this structure belongs to evaporite cycle 2 (figs. 4 and 9). In this area, halite units in cycles 2, 3, and 4 are thin (less than 50 feet thick) and therefore some of the older beds seem better suited for waste disposal. Salt 5 and salt 6 are 133 feet and 265 feet thick, respectively, and from the standpoint of thickness and depth they may be suitable horizons for disposal. Without additional drill holes, an accurate analysis of structure at the level of these two beds cannot be made; however, the one well (fig. 9) and regional data suggest that these beds would be relatively undisturbed.

## Gypsum Valley anticline

Gypsum Valley salt anticline is about 30 miles northeast of Monticello, Utah. All of the anticlinal structure is in Colorado, although the northwest end comes within 3 miles of the Utah State line. The structure is about 25 miles long and no more than 2 miles wide at any point. State highway 141, which is paved, cuts through the south end of the anticline. By paved road the structure is about 58 miles from Monticello, 113 miles from Moab, and 123 miles from the Seven Mile railroad siding. There are no farms or ranches in the area, but there are many uranium mines and camps, some of which are still operating, on the flanks of the anticline. The Andy's Mesa gas field, with six producing wells, is on the northeast flank of the anticline. This field produces gas from the Cutler Formation and the upper member of the Hermosa Formation.

Potash is known to be present in the Paradox Member and at least three holes were drilled on the structure by Tenneco Oil Co. to test these deposits. The complex structure in the core of the anticline greatly diminishes the economic value of these deposits even though they might be of adequate thickness and grade. Only one drill hole, on the crest of the anticline, penetrated the entire Paradox Member which at that location was 7,835 feet thick. The minimum depth to halite in the four wells on the crest of the anticline is 780 feet. The thickest interval of halite penetrated in any of these wells was 545 feet at the depth of 1,680 feet. The Gypsum Valley anticline is a diapiric structure and a leached cap rock of the Paradox Member is exposed over large areas of the valley floor. As in other diapiric anticlines, its salt core is so complexly folded that recognition of stratigraphic units in the Paradox Member has not been possible.

## Lisbon Valley anticline

The Lisbon Valley anticline is an asymmetrical structure in Utah near the Utah-Colorado border about 31 miles southeast of Moab. It is about 54 miles by highway from the Seven Mile railroad siding north of Moab. All but 5 miles of this road are paved. The southwest flank of this structure is the site of Charles Steen's famous Mi Vida uranium mine. There are several other uranium mines and one copper mine in the area. The Lisbon oil field is also on the southwest flank of the anticline. This field produces from a buried fault block of Mississippian and Devonian strata (fig. 6). The Paradox Member contains several potash deposits in this part of the basin and the Lisbon Valley structure was extensively explored for this commodity in the early 1960's. Complex folding of the deposits apparently discouraged further development. There is some grazing but no farming in the immediate area.

The anticline is nondiapiric and the oldest rocks exposed over the structure are limestones and shales of the upper member of the Hermosa Formation. The northeast limb of the anticline is downdropped by a northwest-trending normal fault of regional extent. This fault brings the upper member of the Hermosa into fault contact with the Dakota Sandstone. Structural closure against the fault is about 2,500 feet. The fault is a collapse structure caused by removal of salt from the adjacent syncline on the northeast, either by flowage or by solution or both. The fault does not extend into the Paradox Member and is not related to the older fault block shown on figure 6. Drill holes across the crest of the anticline show that as much as 2,700 feet of upper Paradox beds are missing (Hite, 1968, p. 327). These beds were either removed by solution and erosion before deposition of upper Hermosa beds or the early salt structure was emergent before the cessation of evaporite deposition. As a result, some of the older and thicker salt beds of the Paradox Member are brought relatively near the surface. Salt 19, which is one of the thickest salt beds in the evaporite sequence, was penetrated in a potash test hole near the crest of the anticline at a depth of 2,155 feet. The penetration thickness of the bed was 955 feet. The minimum depth to salt in the anticline is 1,620 feet, and the maximum thickness of the evaporite core probably exceeds 8,000 feet.

## Lockhart anticline and Rustler dome

Lockhart anticline and Rustler dome are two small folds on the east side of the Colorado River about 18 miles southwest of Moab. The northwest plunging axes of the folds are crossed by the river and the boundary of Canyonlands National Park. Only a shallow structural saddle separates the two folds; therefore, they are treated here as a single structural unit. The southern edge of the area is about 7 miles north of Gibson dome and can be reached by the same road system that provides access to the latter structure. The area is uninhabited and has only limited value as grazing land. The structures have been drilled at five locations for oil and gas with no success. A potash deposit of commercial grade and thickness is present in salt 18 in this area. This deposit is somewhat deep (3,500 to 4,000 feet) and as yet has not been the target of any exploration program.

The anticlines are nondiapiric and the Rico Formation is the oldest unit exposed over the structures. Structural closure, using the top of the Rico Formation as a datum, is about 100 feet for the Lockhart anticline and 50 feet for the Rustler dome (Baker, 1933, p. 69). A northeast-trending normal fault terminates the southeast end of Lockhart anticline and separates it from the Lockhart syncline. The latter structure is an unusual circular structural basin and, according to Baker (1933, p. 70), there is a difference of 1,400 feet in altitude on the same datum between the deepest part of the syncline and the east end of the anticline. A deep well, drilled near the center of the structural basin to test the Leadville Formation, shows that halite of the Paradox Member is missing. If, as suggested by Baker (1933, p. 71), the missing salt was transferred by flowage into the adjacent anticline, then beds of the Paradox Member should be highly deformed in the anticline. Geophysical logs of wells drilled on the anticline show little evidence of this. In addition, the average thickness of salt-bearing rocks in this area is about equal to the structural relief between the basin and the anticline. Complete transfer of salt by flowage should have created structural relief of much greater proportions; if, however, the salt was removed by solution, the structural relief should be equal to the original thickness of the salt layer. Minimum depths to halite of the Paradox Member are 2,305 feet in a well drilled by Humble Oil Co. near the crest of Rustler dome (fig. 10) and 2,255 feet in a well on Lockhart anticline. The maximum drilled thickness of the Paradox Member is 2,273 feet in the Gulf Oil Co. Aztec Lockhart 1, located in sec. 22, T. 28 S., R. 20 E., on Lockhart anticline. The uppermost salt in this area is salt bed 5. Salt bed 6, which locally is 150 feet thick, and salt bed 9 are probably the most favorable horizons for waste disposal in this area.

## Moab-Spanish Valley-Pine Ridge anticline

The Moab-Spanish Valley-Pine Ridge salt anticline extends nearly 40 miles southeast from a point near the Seven Mile railroad siding to the Colorado State line. The salt anticline has a variety of surface expressions, the most conspicuous being the broad flat-floored valley which surrounds the town of Moab. Moab is a city of about 5,000 people

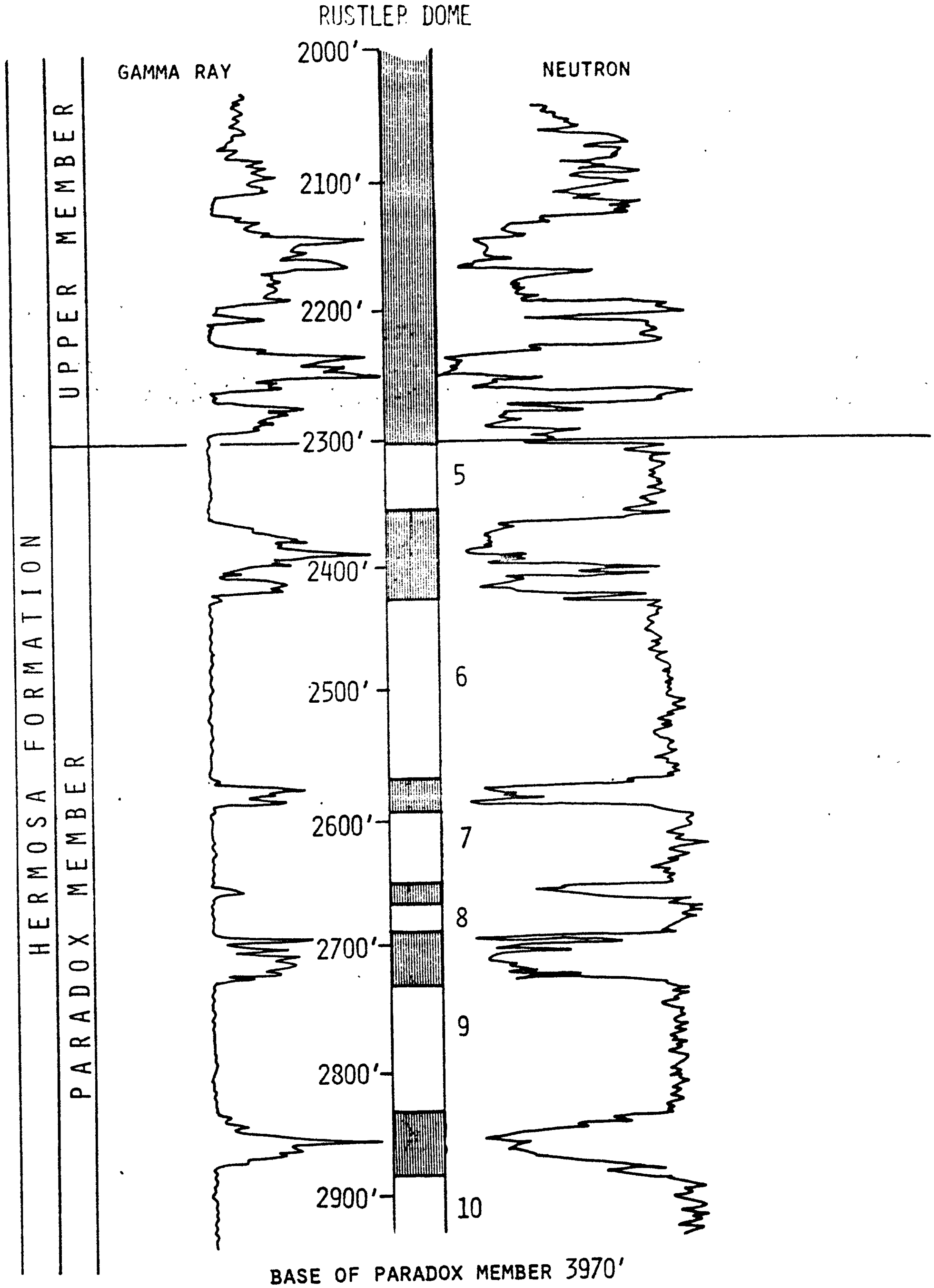



FIGURE 10.--RADIOACTIVITY LOG OF HUMBLE OIL COMPANY RUSTLER DOME 1, SEC. 4, T. 29 S., R. 20 E., SAN JUAN COUNTY, UTAH. DARK UNITS IN COLUMN ARE MARKER BEDS OF BLACK SHALE, DOLOMITE, AND ANHYDRITE. UNSHADED UNITS WITH LARGE NUMBERS ADJACENT TO COLUMN ARE HALITE BEDS AND THEIR NUMERICAL NOMENCLATURE.

and has an economy based largely on tourism, agriculture, uranium mining and milling, and potash mining. There is some industrial use of the halite deposits of the Paradox Member in the Moab area. The Suburban National Gas Co. created a solution cavern in the halite and uses it to store liquefied petroleum gases. Sodium chloride brine, produced by wells that inject fresh water into the salt, is used by the Atlas Corp. uranium mill in the processing of uranium ores. The northern end of the anticline has been extensively drilled for potash deposits and at one time was being considered for commercial development. Potash leases are still held in this area by the Texas Gulf Co., Inc. Good access to most of the anticline is afforded by U.S. Highway 163, and the railroad spur leading to the potash mine at Cane Creek crosses the north end of the structure. The Colorado River flows across the anticline at Moab and several smaller streams heading in the La Sal Mountains pass through part of the valley.

The Moab-Spanish Valley-Pine Ridge salt anticline can be divided into three structural segments. The northernmost, about 8 miles long, consists of a faulted anticline that is sometimes referred to as the Seven Mile structure (Hite, 1960, p. 86). In this segment the Paradox Member is conformably overlain by the upper member of the Hermosa Formation. Limestones of that member are the oldest rocks exposed on the crest of the anticline. The northeast flank of the anticline is downdropped by the Moab fault, which brings the upper member of the Hermosa in contact with the Morrison Formation. Closure against the fault is about 1,500 feet. The Moab fault is a collapse structure and does not extend into the Paradox Member. The minimum depth to halite on this part of the anticline is about 2,300 feet and a deep well in sec. 18, T. 25 S., R. 21 E., showed that the evaporite core at this point is 7,000 feet thick. All the stratigraphic units in the Paradox Member are readily identifiable in wells in this area, but there is evidence of some folding and faulting.

The middle segment of the anticline, about 16 miles long, forms the Moab and Spanish Valleys. The southern end of this segment is abruptly terminated by a northeast-trending fault system. Apparently a more intense upward movement of the salt occurred in this middle part of the anticline and drill holes have penetrated salt at depths of 800 feet. Large-scale salt solution combined with collapse and erosion have breached the anticline, exposing residual beds of the Paradox Member. The thickness of the salt core of this segment of the anticline probably exceeds 10,000 feet. Structure in the salt core is very complex as indicated by several drill holes.

The southernmost segment of this anticlinal trend is called the Pine Ridge anticline. This structure, about 12 miles long, is occupied at its northern end by one of the intrusive masses of the La Sal Mountain igneous complex. The anticline is covered by strata of Cretaceous age and drill holes in the structure show that locally rocks as young as the Chinle Formation rest on the Paradox Member. Over the anticlinal crest halite is within 2,900 feet of the ground surface, and one deep well penetrated the entire salt core which was about 9,200 feet thick. The Pine Ridge anticline has been extensively explored for potash deposits. Several high-grade deposits were found but complex structure and lack of stratigraphic correlation have hindered further development.

## Paradox Valley anticline

The Paradox Valley anticline, which is 30 miles southeast of Moab (fig. 1), is the largest and one of the most spectacular of the salt anticlines. The valley, developed on the crest of the anticline, is about 25 miles long and up to 4 miles wide. Colorado State Highway 90, which is a good paved road, runs almost the full length of the valley. The valley is about 57 miles by paved road from the Seven Mile railroad siding. The Dolores River cuts across the northwestern part of the valley. Northwest of the river are numerous farms and part of the valley floor is irrigated. The valley floor southeast of the river comprises about two-thirds of the valley proper and is undeveloped except for uranium mines and camps along the cliffs bordering the valley. Vanadium Corp. of America operates a small brining facility on the south bank of the Dolores River on the northeast side of the valley. A nearly saturated sodium chloride brine is produced from a shallow well in Paradox cap rock. About 15 gallons per minute of brine is pumped through a pipeline to the Company's uranium mill at Uravan, Colo., where it is used in processing uranium ore. Several deep petroleum tests have been drilled on the structure without success. Although the presence of potash has been established by drilling, the complex structure in the evaporite core of the anticline has discouraged further development.

The Paradox Valley anticline is a diapiric structure and has a cap rock of leached beds of the Paradox Member. The structure is a part of a continuous thick trend of salt which includes the Castle Valley anticline. The cap rock of leached Paradox Member is well exposed at many points on the valley floor. The thickness of the cap rock is variable, ranging from 510 to 1,500 feet. The enormous dimensions of the evaporite core of this anticline are exemplified by one well that penetrated 14,345 feet of cap rock plus halite-bearing rocks before reaching pre-Paradox strata (fig. 11). Considering only the area of the valley, the underlying evaporite mass amounts to 195 cubic miles. Although geophysical logs are available from many of the drill holes that penetrated the evaporite core of this structure, none of the stratigraphic units of the Paradox Member have been identified in these drill holes. Because of this, structure of the core can only be shown schematically (fig. 5).

## Salt Valley anticline

One of the most accessible salt structures in the Paradox basin is the Salt Valley anticline. The axis of this structure is crossed by the Denver and Rio Grande Western Railroad near Crescent Junction, Utah, about 32 miles northwest of Moab (figs. 1 and 12). U.S. Highway 163 parallels the west flank of the anticline. A dirt road runs through the

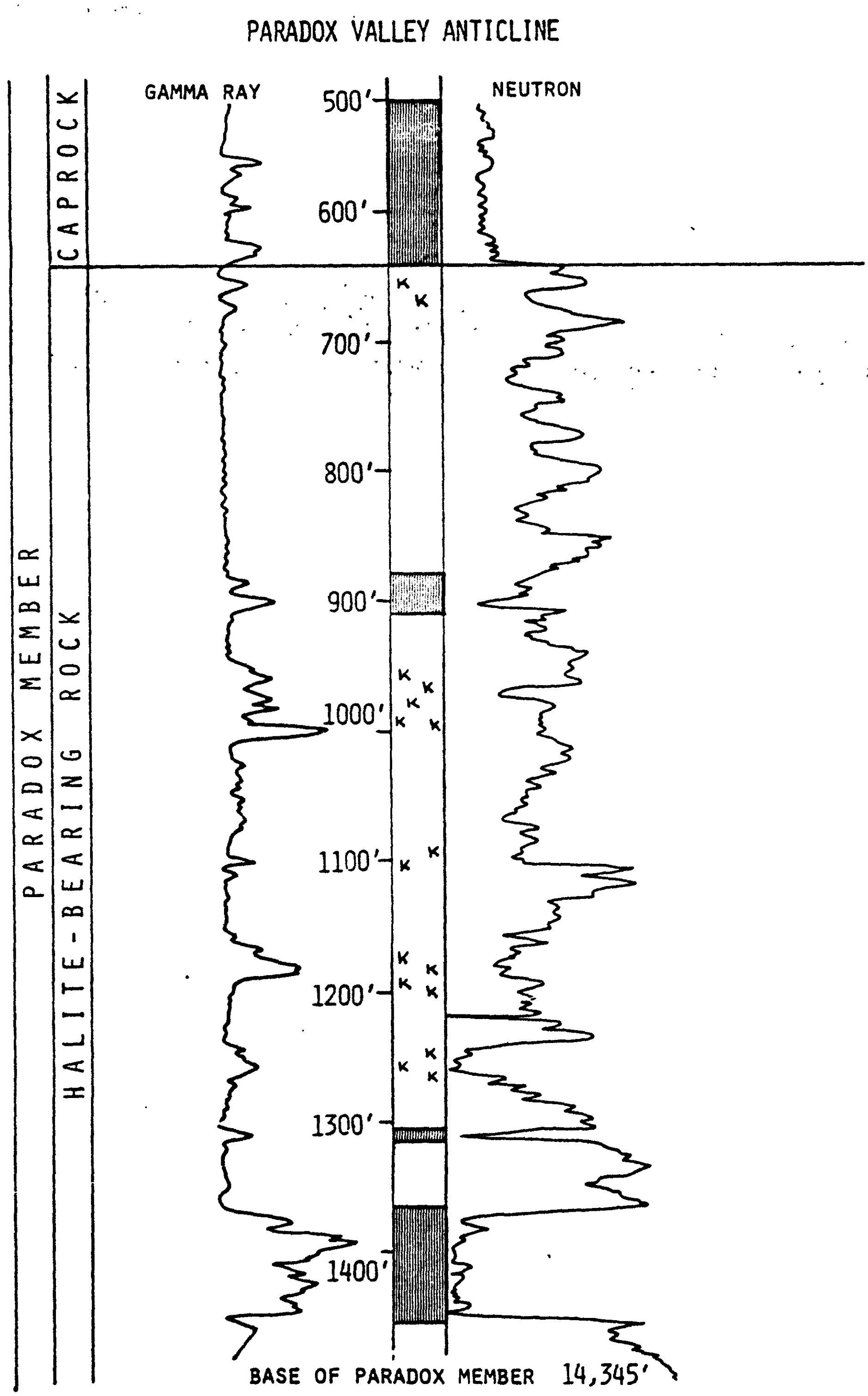



FIGURE 11.--RADIOACTIVITY LOG OF CONTINENTAL OIL CO. SCORUP 1, IN SEC. 8, T. 47 N., R. 18 W., MONTROSE COUNTY, COLORADO. DARK UNITS IN COLUMN ARE MARKER BEDS OF BLACK SHALE, DOLOMITE, AND ANHYDRITE. UNCOLORED UNITS ARE HALITE BEDS. THE LETTER K INDICATES HALITE ROCK CONTAINING POTASH MINERALS.

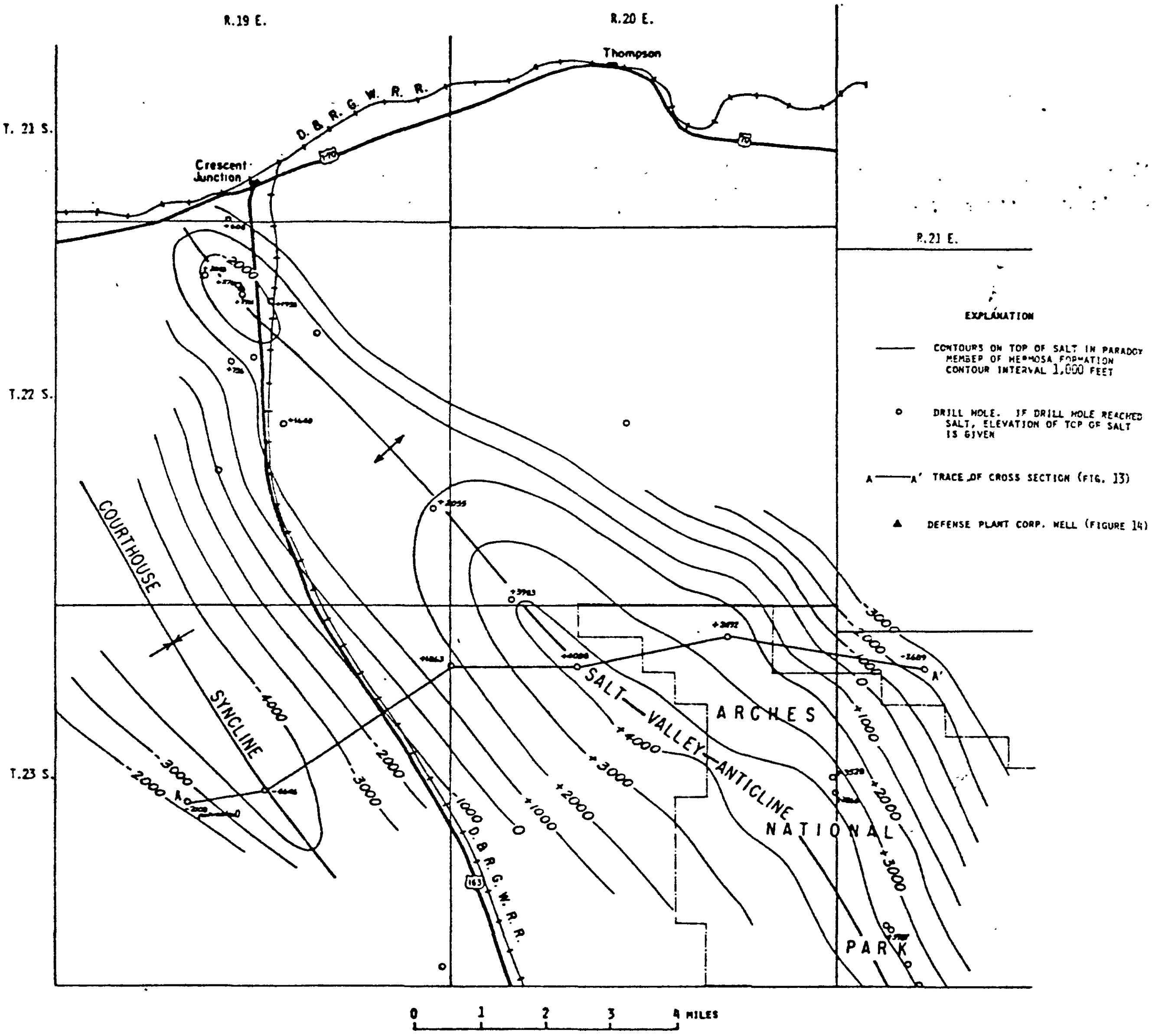



FIGURE 12.—STRUCTURE CONTOUR MAP ON TOP OF SALT IN PARADOX MEMBER OF HERMOSA FORMATION, SALT VALLEY ANTICLINE, GRAND COUNTY, UTAH.

central part of the anticline (fig. 12) from the northwest end to the southeast where it connects with pavement in the Arches National Park. The valley developed along the crest of the anticline is about 25 miles long. The southern half of the valley is inside the boundary of the Arches National Park. The area is uninhabited except for the small village of Crescent Junction at the extreme northwest end of the anticline.

Although prospecting has been extensive, the area contains no active mines. The flanks of the anticline have been extensively prospected for uranium and, in addition, a small amount of development work has been done on some small copper deposits. One of the first discoveries of potash in the United States was made at the northern end of this structure in 1924 (Dyer, 1945). Since that time thick high-grade deposits of sylvite and carnallite have been penetrated in several drill holes (Hite, 1964), but the complex structure of the deposits has discouraged further exploration. Numerous oil and gas tests have been drilled on the flanks of the structure with only minor success. At the time of this report a deep test was being drilled on the northeast flank of the structure. The drilling objective of this well is reported to be a pre-salt fault block.

The Salt Valley anticline is the northernmost segment of the Salt Valley-Cache Valley-Fisher Valley-Sinbad Valley system (fig. 1). It is a diapiric structure and residual beds of the Paradox Member are exposed in many places inside the collapsed and breached part of the anticline. Halite-bearing rocks rise to within 700-800 feet of the surface along the crest of the anticline near the boundary of the Arches National Park. About 4 miles northwest of where the boundary crosses the anticline, the salt surface plunges northwest at about 500 feet per mile (fig. 12). The northwest plunge of the structure is abruptly interrupted about 1 mile south of Crescent Junction by a small spirelike salt mass which rises to within about 1,800 feet of the ground surface. Total relief on the salt surface between the adjacent Courthouse Wash syncline on the southwest and the crest of the anticline is about 6,000 feet. The southwest flank of the anticline may be underlain by a pre-salt fault block as in other salt anticlines of the basin (fig. 13), although drilling has not yet verified it. The deepest, but still incomplete penetration of the salt core of the anticline was 10,173 feet in a well about 4 miles south of Crescent Junction (+1,640 on fig. 12). Salt-bearing rocks in the core of the anticline are probably more than 11,000 feet thick.

Drill-hole data indicate that the internal structure of the Salt Valley anticline is very complex. At the northwest end of the anticline the salt core is somewhat less disturbed and some stratigraphic markers in the Paradox Member can be recognized by study of the geophysical logs of some drill holes (fig. 14). The northwest end of the anticline plunges under a thick cover of Cretaceous rocks which confined the salt and apparently suppressed its deformation.

## Shafer dome

Shafer dome is a small east-west trending dome about 13 miles southwest of Moab. A bend in the Colorado River crosses the structure, but most of the fold lies west of the river. The end of the Denver

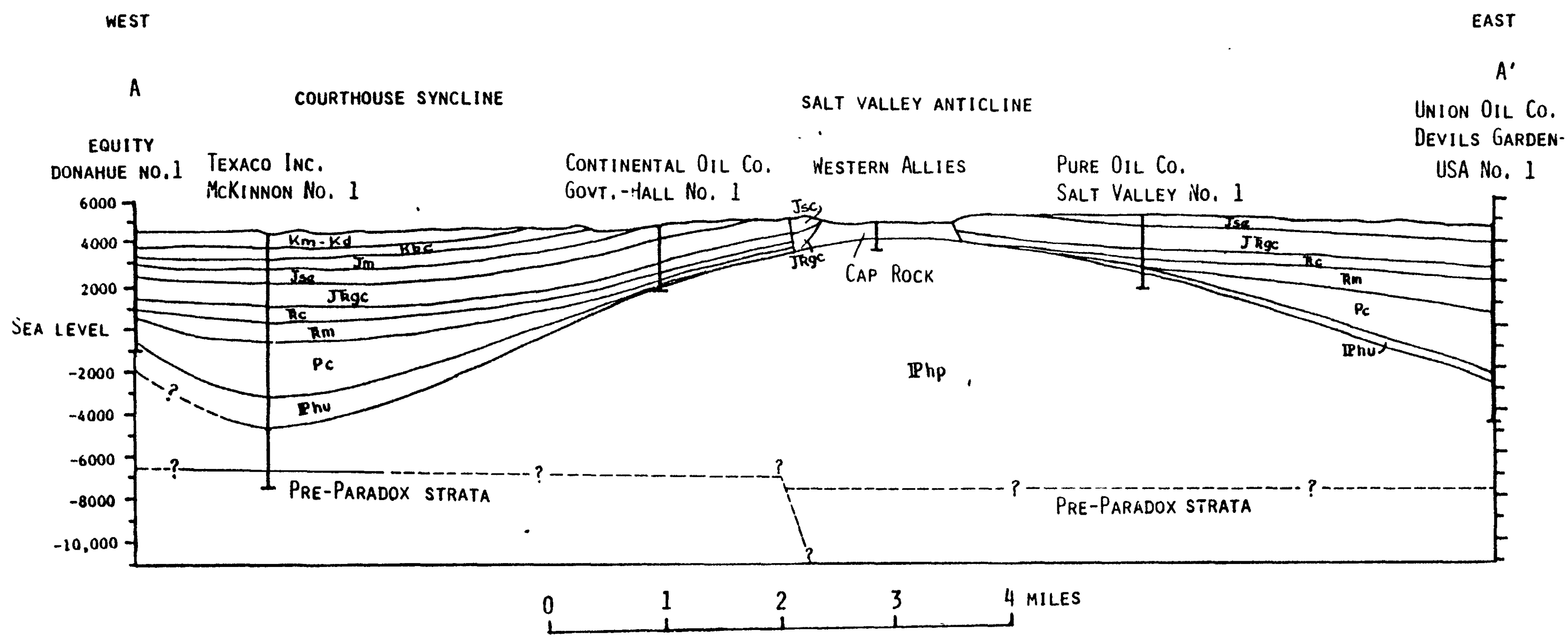



FIGURE 13.--CROSS SECTION THROUGH COURTHOUSE SYNCLINE AND SALT VALLEY ANTICLINE, GRAND COUNTY, UTAH. TRACE OF SECTION ON FIGURE 12.

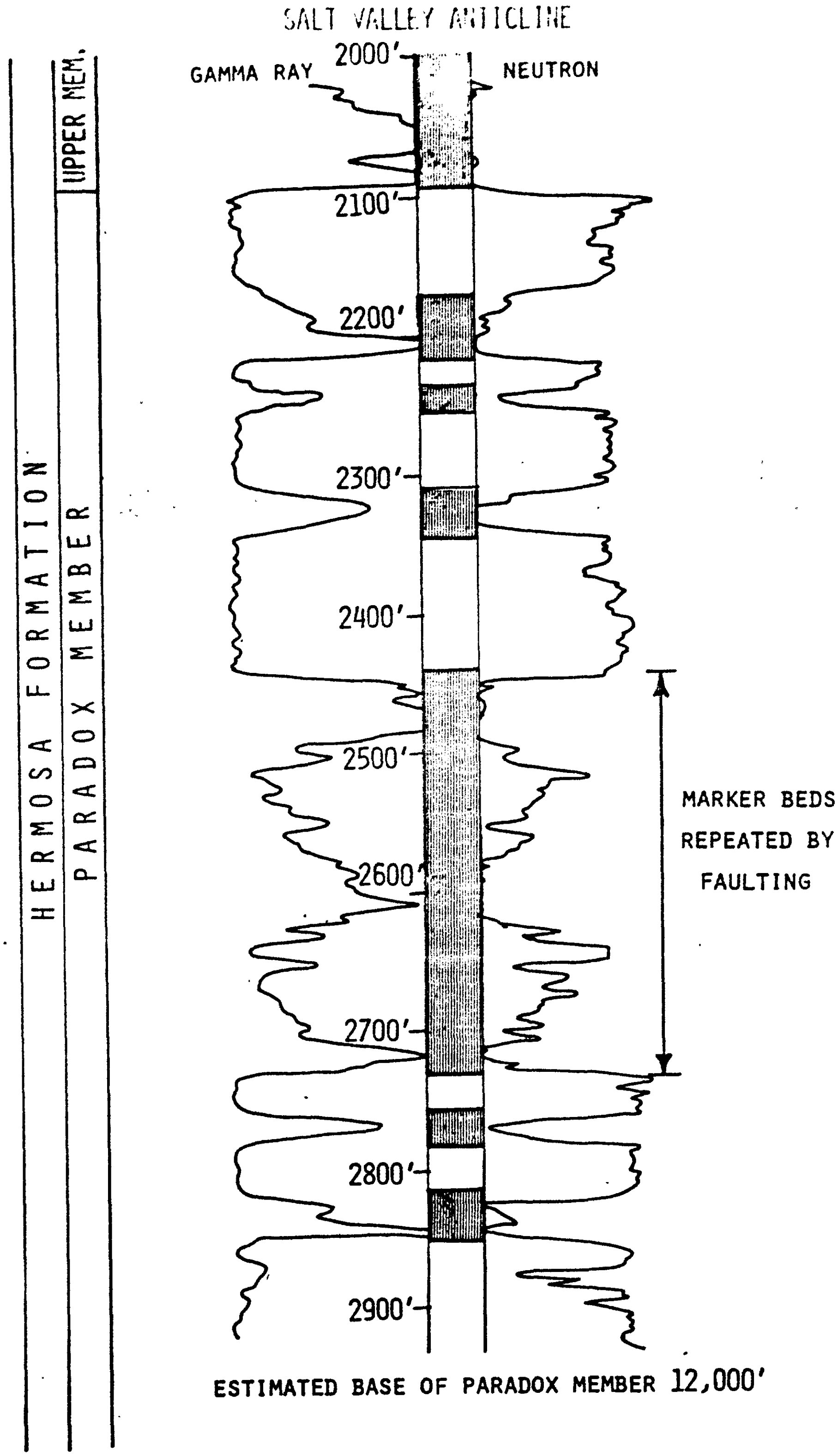



FIGURE 14.—RADIOACTIVITY LOG OF DEFENSE PLANT CORPORATION REEDER 1, SEC. 4, T. 22 S., R. 19 E. GRAND COUNTY UTAH (SEE FIGURE 12). DARK UNITS IN COLUMN ARE MARKER BEDS OF BLACK SHALE, DOLOMITE AND ANHYDRITE. LIGHT UNITS ARE HALITE BEDS. UPPERMOST HALITE BED IS NOT SHOWN.

and Rio Grande Western Railroad spur to the potash mine at Cane Creek is about 5 miles up river from the axis of the dome. The Colorado River has cut a narrow 400-foot-deep canyon across the dome. Good access to the canyon rim on the northwest bank of the river is afforded by a dirt road which connects with pavement at the Cane Creek potash mine owned by Texas Gulf Co., Inc. The opposite bank of the river cannot be reached by road either at river level or along the canyon rim. Two miles northwest of the dome is the well-known Dead Horse Point overlook. From this feature, which is now a state park, one can look down on the structure 1,200 feet below.

The principal economic development in the area is the Cane Creek potash mine. The mine shaft and refining facilities are about 5 miles north of Shafer dome. Some of the evaporation ponds used by the company to concentrate their potash brines from the mine cover an area of about half a square mile northeast of the dome. Shafer dome has been explored for oil and gas and for potash without success. The potash deposit mined at Cane Creek is represented at Shafer dome by a weakly mineralized zone of subeconomic value. Other deposits with higher concentrations of potash are present but are too deep for conventional mining.

Structural closure on top of the Cutler Formation at Shafer dome is about 400-500 feet and surface dips range from 3 degrees to 6 degrees (Baker, 1933, p. 68). The oldest rocks exposed at river level are limestones of the upper member of the Hermosa Formation, which overlies the Paradox Member conformably. A well drilled at river level on the axis of the anticline penetrated 3,905 feet of halite-bearing rocks.

The top of the salt in this well was at 1,610 feet. The internal structure in the salt core of this anticline is relatively simple. None of the drill holes located on or near the dome show any evidence of folding or faulting. Several salt beds in this area have thicknesses of 100 feet or more. Salt beds 2 and 5 (fig. 15) are 120 and 205 feet thick, respectively, and could be reached by a mine shaft at depths of less than 2,500 feet.

## Sinbad Valley anticline

Sinbad Valley just east of the Utah-Colorado State line is one of the more remote salt anticlines in the Paradox basin (fig. 1). The structure is about 15 miles northwest of the village of Uravan (population 750). The only access to this structure is by paved State Highway 141, which passes near the northeast limb of the fold, and by dirt road for 5 miles up Salt Creek canyon. The floor of the valley is used for grazing and contains a few ranch dwellings.

The area has seen little economic development. The rimrock enclosing the structure has been prospected extensively for uranium, but no significant discoveries have been made in this district. Two wells were drilled on the crest of the structure--one for oil and gas (fig. 16) and the other for potash. Another petroleum test was drilled on the northeast flank of the anticline. Geophysical logs of the well shown on figure 16 indicate potash mineralization in many of the halite intervals. The potash test unfortunately encountered a marker bed in vertical position, so no conclusions could be drawn about either the halite stratigraphy or the distribution of potash mineralization.

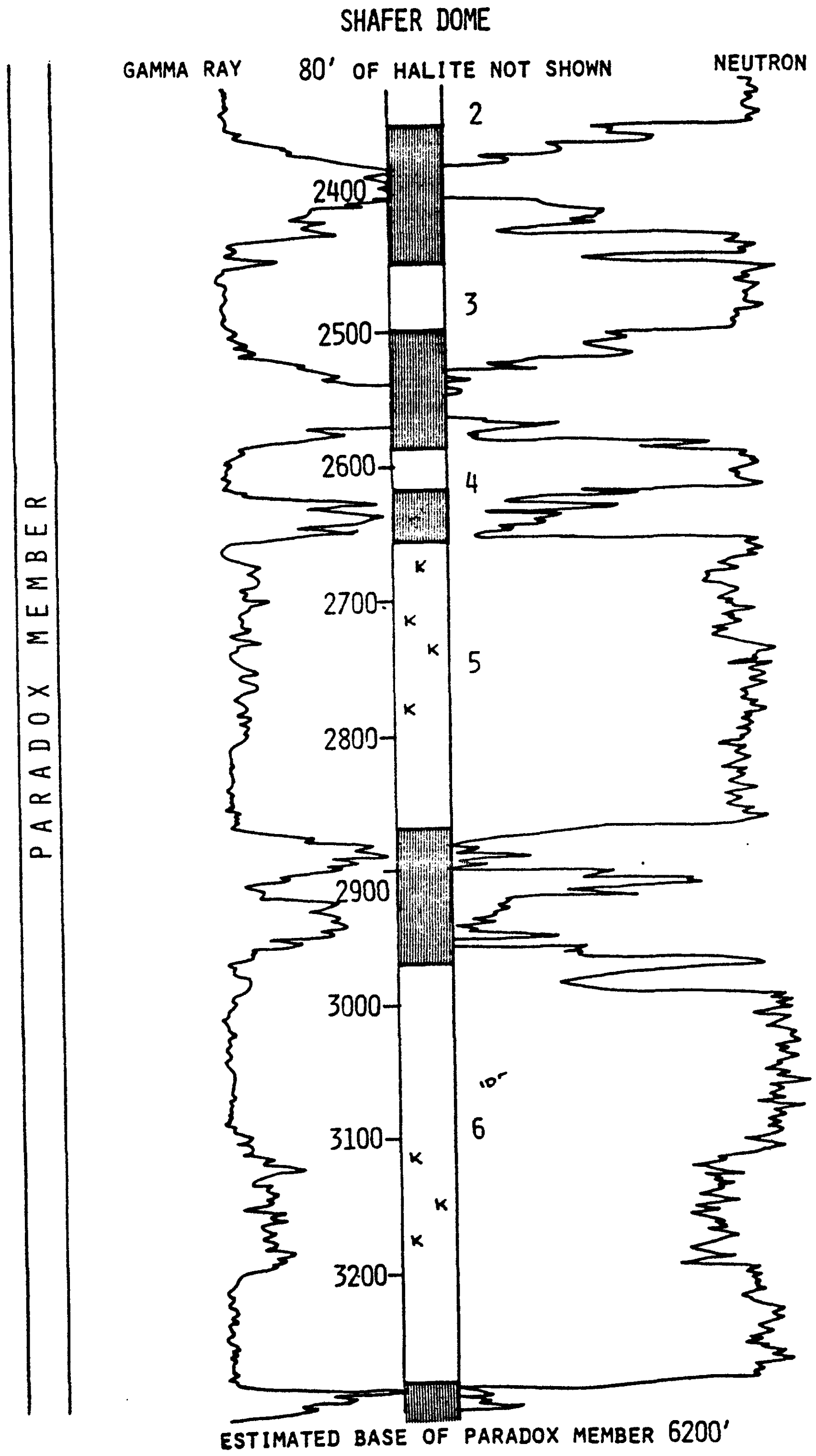



FIGURE 15.—RADIOACTIVITY LOG OF DELHI-TAYLOR OIL CORPORATION SHAFER DOME 1, SEC. 15, T. 27 S., R. 20 E., SAN JUAN COUNTY, UTAH. DARK UNITS IN COLUMN ARE MARKER BEDS OF BLACK SHALE, DOLOMITE, AND ANHYDRITE. LIGHT UNITS WITH LARGE NUMBERS ADJACENT TO COLUMN ARE HALITE BEDS AND THEIR NUMERICAL NOMENCLATURE. LETTER K INDICATES HALITE ROCK CONTAINING POTASH MINERALS. TOP OF UPPERMOST HALITE UNIT NOT SHOWN.

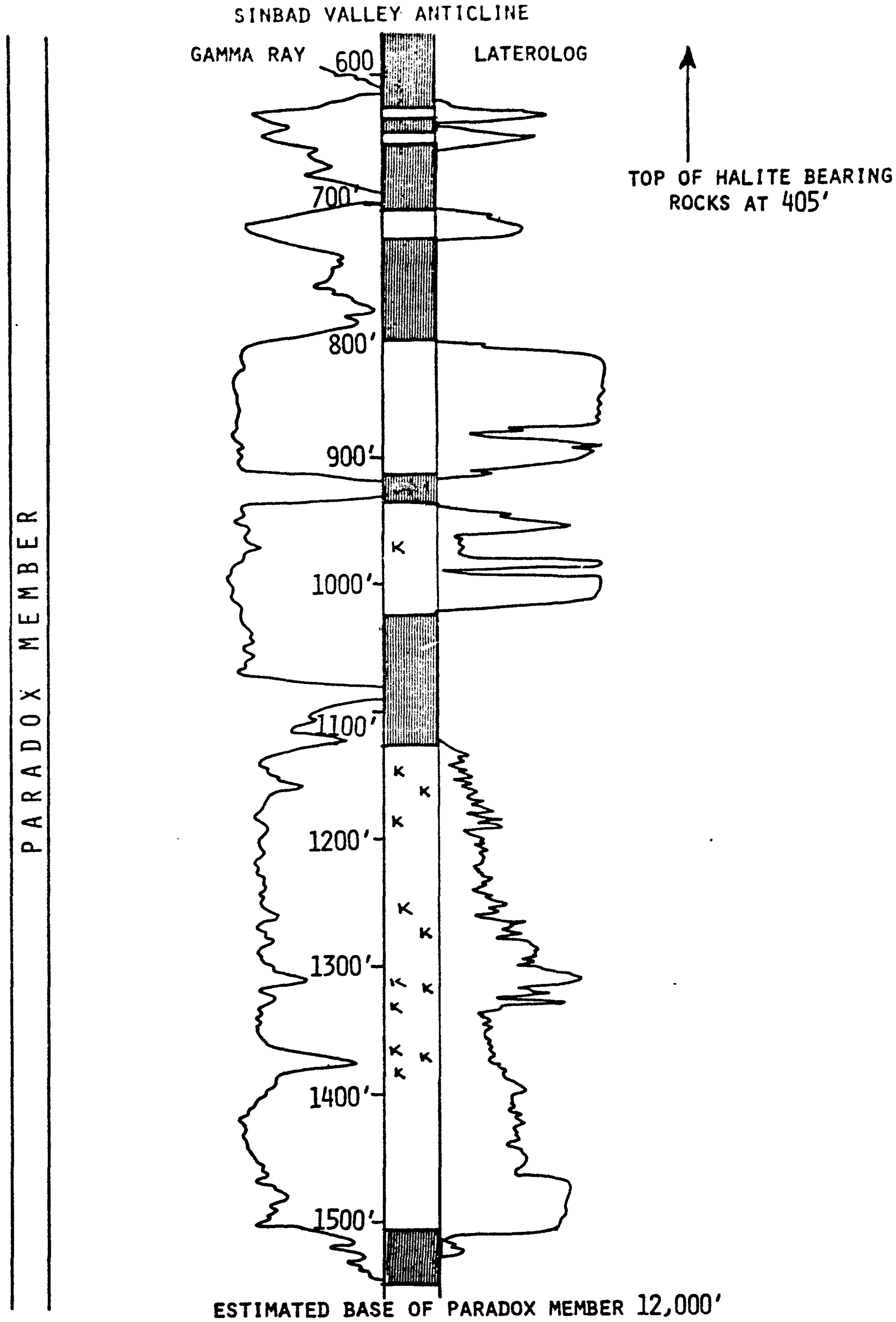



FIGURE 16.--RADIOACTIVITY LOG OF J. M. HUBER CORPORATION SINBAD VALLEY 1, SEC. 16, T. 49 N., R. 19 W., MESA COUNTY, COLORADO. DARK UNITS IN COLUMN ARE MARKER BEDS OF BLACK SHALE, DOLOMITE, AND ANHYDRITE. LETTER K INDICATES HALITE ROCK CONTAINING POTASH MINERALS. UPPERMOST HALITE UNIT NOT SHOWN.

Sinbad Valley is at the southeastern end of a chain of salt anticlines that includes Fisher Valley, Cache Valley, and Salt Valley. The structure has an ellipsoidal shape and the valley floor covers an area of about 18 square miles. The valley is completely surrounded by precipitous cliffs that rise as much as 3,500 feet above the valley floor and are broken only by the narrow canyon of Salt Creek. The anticline is diapiric and leached beds of the Paradox Member are exposed on the valley floor. One deep drill hole (fig. 16) on the crest of the structure penetrated the top of the salt at a depth of 405 feet and was still in halite-bearing rocks at a total depth of 10,316 feet. The total thickness of halite-bearing rocks in the core of the anticline is estimated to be about 12,000 feet. The walls of the salt mass are probably very steep. For example, a deep well only 1 mile northeast of the anticlinal crest was abandoned at a depth of 9,215 feet without reaching salt. Internal structure in the salt core of the anticline is probably complex with steeply dipping to vertical beds. Because of complex structure, and thickening of clastic units (the Uncompahgre source area is only 10 miles to the northeast), stratigraphic units of the Paradox Member are not identifiable in the two wells that penetrate the member. The deep petroleum test (fig. 16) penetrated several intervals of salt that might be considered potential horizons for waste disposal. The intervals between depths of 1,127 and 1,510 feet (fig. 16) and between depths of 1,636 and 3,555 feet (not shown on fig. 16) both contain some potash. The lower interval, apparently 1,919 feet thick, probably represents a nearly vertical salt bed.

## SUMMARY

The Paradox basin contains a widespread series of thick salt deposits. The low density of population and the minor economic development of the region are advantages for underground storage or disposal of noxious or radioactive wastes. The number of potential sites are limited, however, because only in the salt anticlines of the region do the tops of these salt deposits come within 2,500 feet of the surface. The salt cores of the Paradox basin anticlines differ from the typical Gulf Coast salt dome. Instead of a nearly pure mass of halite, the cores of the Paradox anticlines are made up of multiple layers of salt and intervening layers of black shale, dolomite, and anhydrite. These nonsalt layers are gas-bearing, but many individual halite beds are thick enough to provide a protective seal of halite between the gassy beds and the openings mined for underground storage or disposal. The salt layers are not flat in the salt anticlines, so a detailed knowledge of the geometry of individual salt layers is needed to avoid undesirable layers in mining. In most of the larger anticlines the geometry of the salt layers is strongly influenced by diapirism. In nondiapiric anticlines, mine openings can stay well within specific salt layers if grades are planned that will follow the general dip of the anticlinal limbs. In diapiric anticlines it may be necessary to plan mine openings that conform with the axial plane of vertical to near-vertical folds.

In choosing a site for waste storage or disposal in the Paradox basin, the potential future value of any potash deposits at that site

should be considered. At present the potash deposits have only marginal economic value, but a hundred years from now some of the Paradox potash might compete favorably with other potash sources in the world.

Of all the structures in the Paradox basin (table 2), Salt Valley anticline and Shafer dome are perhaps the best suited for further detailed investigation. Both have favorable, although somewhat different, geologic characteristics and are on or near a railroad. The proximity of both sites to cultural or industrial developments should not be a major disadvantage. The Salt Valley site is bordered on the south by the Arches National Park, but disposal facilities could be located out of view, and at least 5 miles from the boundary. The Shafer dome site presents a similar situation. The Dead Horse Point overlook, a Utah State park, is on the canyon rim above the Shafer dome site, but the topography of the area could be used to hide any surface facilities of an emplacement site. The area is already scarred by large evaporation ponds that are fully visible from the overlook. The Shafer dome site is not far from the Cane Creek potash property of Texas Gulf Co., Inc. The potash mine has been flooded and converted to a solution mining operation so there are no men working underground in the area. A site could be located that would be at least 4.5 miles from the nearest underground workings of this mine.

## REFERENCES


Baars, D. L., 1966, Pre-Pennsylvanian paleotectonics--key to basin evolution and petroleum occurrences in Paradox basin, Utah and Colorado: Am. Assoc. Petroleum Geologists Bull., v. 50, no. 10, p. 2082-2111.

Baker, A. A., 1933, Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U.S. Geol. Survey Bull. 841, 95 p.

Bass, N. W., 1944, Paleozoic stratigraphy as revealed by deep wells in parts of southwestern Colorado, northwestern New Mexico, northeastern Arizona, and southeastern Utah: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 7, with accompanying text.

Case, J. E., 1966, Geophysical anomalies over Precambrian rocks, northwestern Uncompahgre Plateau, Utah and Colorado: Am. Assoc. Petroleum Geologists Bull., v. 50, no. 7, p. 1423-1443.

Cater, F. W., 1970, Geology of the salt anticline region in southwestern Colorado: U.S. Geol. Survey Prof. Paper 637, 80 p.

Currie, J. B., Patnode, H. W., and Trump, R. P., 1962, Development of folds in sedimentary strata: Geol. Soc. America Bull., v. 73, p. 655-674.

Dane, C. H., 1935, Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U.S. Geol. Survey Bull. 863, 184 p. [1936].

Dyer, B. W., 1945, Discoveries of potash in eastern Utah: Am. Inst. Mining and Metall. Engineers Tech. Pub. 1755, v. 9, no. 1, p. 56-61.

Elston, D. P., Landis, E. M., and Shoemaker, E. M., 1962, Uncompahgre front and salt anticline region of Paradox basin, Colorado and Utah: Am. Assoc. Petroleum Geologists Bull., v. 46, no. 10, p. 1857-1878.

Elston, D. P., and Shoemaker, E. M., 1961, Preliminary structure contour map on top of salt in the Paradox Member of the Hermosa Formation in the salt anticline region, Colorado and Utah: U.S. Geol. Survey Oil and Gas Inv. Map OM 209.

Evans, R., and Linn, K. O., 1969, Fold relationships within evaporites of the Cane Creek anticline, Utah, in Third symposium on salt: Northern Ohio Geol. Soc., v. 1, p. 286-298.

Harshbarger, J. W., Repenning, C. A., and Callahan, J. T., 1953, The Navajo Country, Arizona-Utah-New Mexico; Chapter 7 in The physical and economic foundation of natural resources, pt. IV, Subsurface facilities of water management and patterns of supply--Type area studies: U.S. Congress, House of Representatives, Interior and Insular Affairs Committee, p. 105-129.

Haynes, D. D., Vogel, J. D., and Wyant, D. G., 1972, Geology, structure, and uranium deposits of the Cortez quadrangle, Colorado and Utah: U.S. Geol. Survey Misc. Geol. Inv. Map I-629.

Hite, R. J., 1960, Stratigraphy of the saline facies of the Paradox Member of the Hermosa Formation of southeastern Utah and southwestern Colorado, in Geology of the Paradox basin fold and fault belt: Four Corners Geol. Soc. Guidebook 3rd Field Conf., 1960, p. 86-89.

Hite, R. J., 1961, Potash-bearing evaporite cycles in the salt anticlines of the Paradox basin, Colorado and Utah, in Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424-D, p. D135-D138.

_________ 1964, Salines, in Mineral and water resources of Utah: U.S. Cong. 88th, 2d sess., Comm. Print, p. 206-215.

________ 1968, Salt deposits of the Paradox basin southeast Utah and southwest Colorado, in Saline deposits: Geol. Soc. America Spec. Paper 88, p. 319-330.

_________ 1969, Shelf carbonate sedimentation controlled by salinity in the Paradox basin, southeast Utah, in Third symposium on salt: Northern Ohio Geol. Soc., v. 1, p. 48-66.

Hite, R. J., and Liming, J. A., 1972, Stratigraphic section through the Pennsylvanian System in the Paradox basin, in Geologic atlas of the Rocky Mountain region: Rocky Mountain Assoc. Geologists, Denver, Colorado, 1972, p. 134-135.

Hunt, C. B., 1956, Cenozoic geology of the Colorado Plateau: U.S. Geol. Survey Prof. Paper 279, 99 p.

Jacobson, H. S., Pierson, C. T., Danusawad, Thawisak, Japakasetr, Inthuputi, Boonmai, Siriratanamongkol, Charlie, Prapassornkul, Saner, and Pholphan, Narin, 1969, Mineral investigations in northeastern Thailand: U.S. Geol. Survey Prof. Paper 618, 96 p.

Knight, R. L., and Cooper, J. C., 1955, Suggested changes in Devonian terminology of the Four Corners area: Four Corners Geol. Soc., 1st Ann. Field Conf. Guidebook, p. 56-58.

Lohman, S. W., 1965, Geology and artesian water supply of the Grand Junction area, Colorado: U.S. Geol. Survey Prof. Paper 451, 149 p.

Peterson, James A., and Hite, Robert J., 1969, Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrences, southern Rocky Mountains: Am. Assoc. Petroleum Geologists Bull., v. 53, no. 4, p. 884-908.

Raup, Omer B., 1966, Bromine distribution in some halite rocks of the Paradox Member, Hermosa Formation, in Utah, in Second symposium on salt: Northern Ohio Geol. Soc., v. 1, p. 236-247.

Shoemaker, E. M., Case, J. E., and Elston, D. P., 1958, Salt anticlines of the Paradox basin [Colorado-Utah], in Intermountain Assoc. Petroleum Geologists Guidebook, 9th Ann. Field Conf., Salt Lake City, Utah, 1958: p. 39-59.

Sumsion, C. T., 1971, Geology and water resources of the Spanish Valley area, Grand and San Juan Counties, Utah: Utah Dept. of Natural Resources, Technical Pub. No. 32, 45 p.

Wengerd, S. A., and Matheny, M. L., 1958, Pennsylvanian System of Four Corners region: Am. Assoc. Petroleum Geologists Bull., v. 42, no. 9, p. 2048-2106.

Wengerd, S. A., and Strickland, J. W., 1954, Pennsylvanian stratigraphy of Paradox salt basin, Four Corners region, Colorado and Utah: Am. Assoc. Petroleum Geologists Bull., v. 38, no. 10, p. 2157-2199.

Williams, P. L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S. Geol. Survey Misc. Geol. Inv. Map I-360.