Salt Anticlines of the Paradox Basin, Colorado and Utah

by

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ABSTRACT

Five elongate northwest-trending salt structures occur within a deep trough in the northeastern part of a depositional basin of evaporites of Middle Pennsylvanian age known as the Paradox basin. In Pennsylvanian time the deep trough part of this basin was bordered on the northeast by the ancestral Uncompahgre uplift, and on the southwest by a broad depositional shelf. The individual salt structures are from 30 to 70 miles long, and they have cores of evaporites that range from about 4,100 to more than 14,000 feet in thickness. Structural relief at the top of salt ranges from about 1,000 to about 9,000 feet. At the end of time of salt deposition in the Middle Pennsylvanian, an irregular blanket of salt-bearing strata, ranging from about 3,000 feet or less to about 5,000 or possibly 7,000 feet in thickness, covered an irregular pre-salt surface in the basin. On the northeast, the salt-bearing beds pass abruptly into arkosic sandstone and shale containing material derived from crystalline rocks exposed on the ancestral Uncompahgre uplift. About 2,500 to more than 5,000 feet of abrupt structural relief is present under the salt beneath the southwest flanks of several of the salt structures. The salt section is thin or absent at places above structurally high pre-salt rocks. Information from deep drill holes suggests that some of the structurally high pre-salt rocks were uplifted and subjected to erosion prior to deposition of the salt, and also, that structural displacement of the pre-salt rocks probably also occurred during deposition of the salt.

Deformation of the pre-salt rocks in the basin presumably occurred in conjunction with Middle Pennsylvanian uplift of the ancestral Uncompahgre. These structural adjustments are believed to have initiated folding and rise of the salt structures at sites adjacent to the buried pre-salt highs. Evidence exposed at the surface indicates that the salt structures then evolved largely by means of gradual growth as post-salt beds were deposited around them rather than by diapiric piercement of the overlying deposits.

Salt deposition may have been terminated by regional tilting accompanying uplift of the Uncompahgre. Fresh arkosic debris derived from the ancestral Uncompahgre was transported into the marine basin, and, by the end of Pennsylvanian time, a thickness of as much as a few thousand feet of interbedded carbonate and clastic rocks was deposited around and between the growing salt structures. Some of the salt cores were fairly deeply buried by Upper Pennsylvanian beds. Elsewhere a few tens of feet of these beds at places unconformably overlapped the evaporite cores.

Uplift of the ancestral Uncompahgre culminated in Permian time. A flood of arkosic debris covered the site of the former marine basin, and in the trough area of the basin several thousand feet of continental red beds were deposited around the growing salt structures. Parts of the cores of evaporites are locally overlapped by only a few hundred feet of Permian beds. These beds repesent not only the lowermost Permian deposits but also probably contain thin representatives of much of the Permian section. Growth of the salt structures during most of Permian time was probably caused mainly by loading of sediments on the salt beds around the structures.

In the interval from latest Permian through Middle (?) Triassic time, minor uplifts of the ancestral Uncompahgre resulted in renewed transportation of arkosic debris into the basin, and these uplifts are correlated with pulses of growth in the salt structures. Above and on the flanks of some of the salt structures, beds of Early to Middle (?) Triassic age rest with marked unconformity on older beds. By the end of Middle (?) Triassic time, the period of great displacement between the Uncompahgre uplift and the basin ended. About 16,000 feet of Pennsylvanian, Permian, and Lower and Middle (?) Triassic beds filled the basin and wedge out against the uplift. The site of the old highland was subsequently covered by a veneer of younger Mesozoic beds.

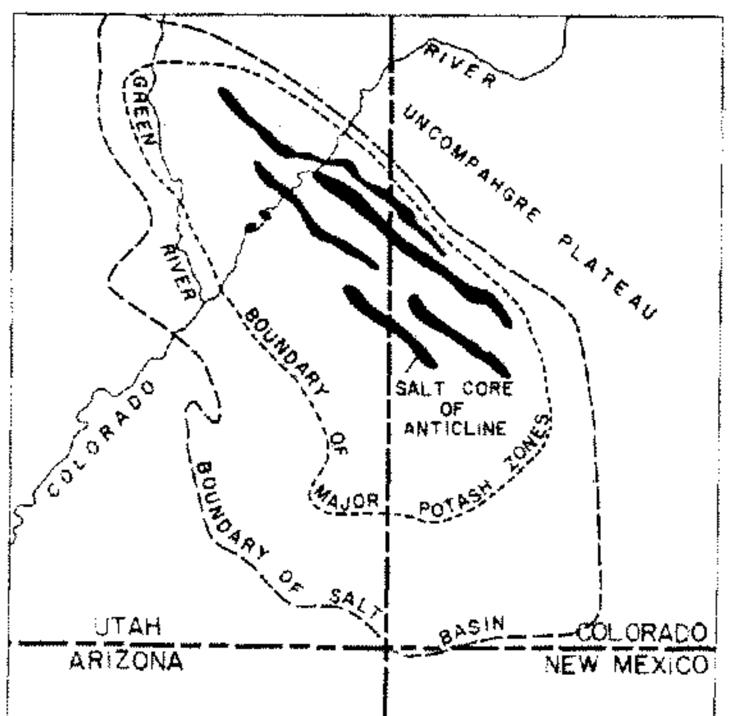
Some of the salt structures were covered in Late Triassic time, but several continued their growth into Late Jurassic time, when most of them finally were buried. Even after burial, slight structural adjustments in the cores continued to occur. Such adjustments are recorded locally by as much as a few hundred feet of thinning of beds of Late Jurassic and Early Cretaceous age above the salt structures. On part of one of the salt structures, the evaporite core apparently was not completely covered until Late Cretaceous time.

In latest Cretaceous or early Tertiary time, broad folds were developed in the rocks overlying the salt structures, probably in response to regional deformation that produced renewed uplift of the Uncompahgre. After regional uplift of the Colorado Plateau in middle Tertiary time, the cores of the salt anticlines were breached during entrenchment of the major streams.

INTRODUCTION

This paper summarizes briefly the structural history of the Paradox basin salt anticlines. Evidence is presented bearing on the early history of the Paradox basin salt anticlines in Pennsylvanian time, shortly after deposition of the salt. The fieldwork leading to this report was done by the U.S. Geological Survey, and was largely supported by the Division of Research and the Division of Raw Materials of the U.S. Atomic Energy Commission.

The salt structures of the Paradox basin (Figure 1; Baker and others, 1933) have been the subject of continuing geologic investigations since the pioneer work of Prommel (1923) and the



Salt and potash boundaries after R. J. Hite (1961)

0 20 40 60 80 MILES

Figure 1. - Index map of salt anticline region

early exploration for oil in the 1920's. As early as 1927 the general nature and broad outlines of structural history of the salt anticlines were correctly inferred by Prommel and Crum (1927), and the mechanics and causes of salt movement had been discussed by Harrison (1927) and by Powers (1926). Many of the details of the history of the region have gradually been revealed during the course of intensive geological mapping in the Paradox basin by the U.S. Geological Survey, beginning with the work of Baker (1933), Dane (1935), and McKnight (1940). Some of the more recent work of the Geological Survey has been summarized in a series of geologic quadrangle maps (see for example, Cater, 1954), and in guidebooks and other publications (Stokes, 1948; Shoemaker, 1954; Cater, 1955; Shoemaker and others, 1958; Joesting and Byerly, 1958; Byerly and Joesting, 1959; Hite, 1960; Elston and Landis, 1960; Elston and Shoemaker, 1960; and Joesting and Case, 1960). Additional data have also been published recently by Wengerd and Strickland (1954); Wengerd and Matheny (1958); Herman and Sharps (1956); and Fetzner (1960).

GENERAL GEOLOGIC SETTING

The Paradox basin is an asymmetric depression filled chiefly with late Paleozoic and early Mesozoic rocks, about 70 to 100 miles across. In the northeastern part of the basin is a deep trough about 25 to 30 miles wide. The principal salt structures are located in this trough. On the northeast, the Paradox basin is bounded by the Uncompahgre front, which marks the edge of the ancient Uncompahgre uplift. The Uncompahgre front coincides approximately with the southwest margin of the present Uncompahgre Plateau, but it extends farther to the northwest and southeast.

The region containing the salt structures comprises about 7,000 square miles of rugged terrain in the Canyon Lands subdividion of the Colorado Plateau province. The region is characterized by broad plateaus, sheer-walled canyons, isolated mesas, and laccolithic mountains. Long, narrow, steepsided, flat-floored valleys, called "salt valleys," are eroded along parts of the crests of the salt structures (Figure 2). The salt valleys disrupt the characteristic

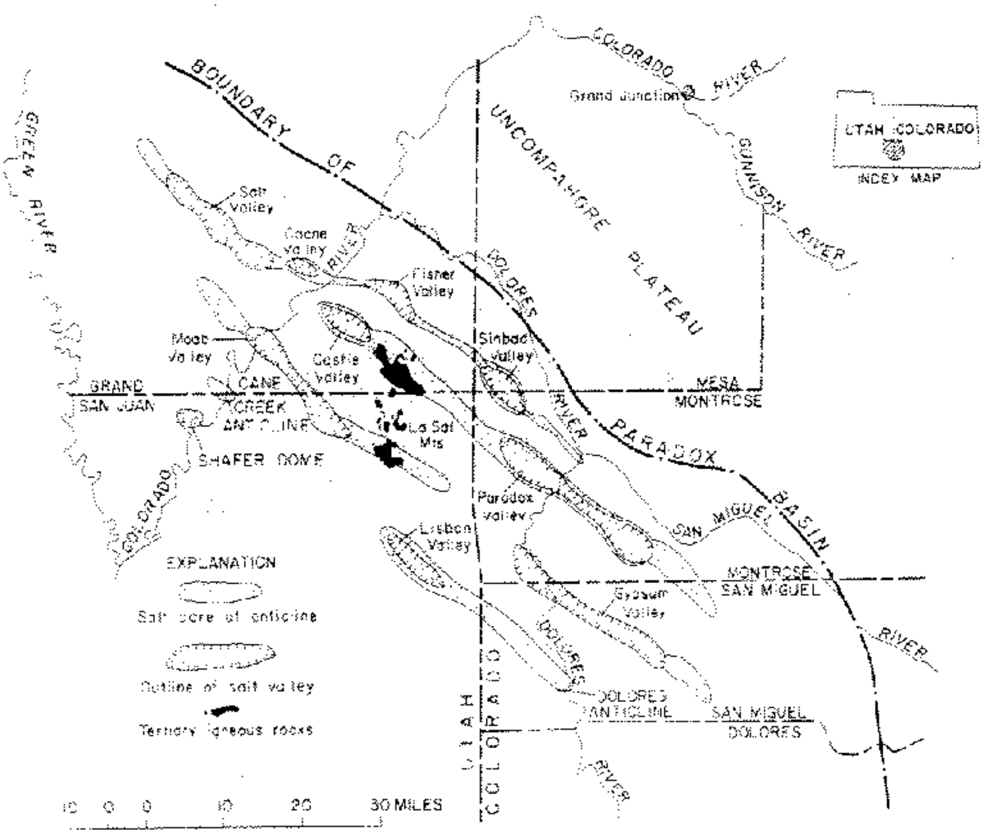


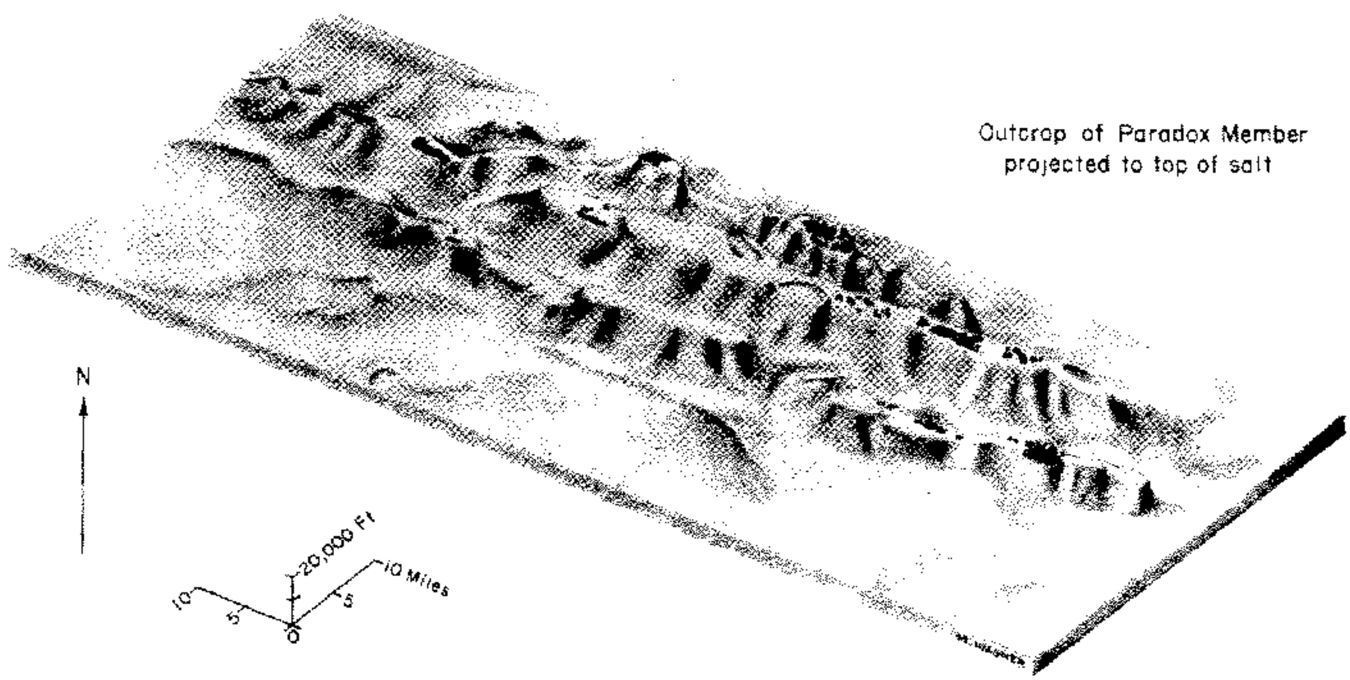
Figure 2.-- Location map of salt anticlines and salt valleys

canyon-land topography, and several are transected by the principal streams of the region. Salt does not crop out anywhere in the region, but crenulated gypsiferous caprock, a part of which formerly contained salt, locally crops out in the valley floors. The structure of the post-salt strata exposed in the valley walls is highly complex, but the exposed beds commonly dip away from the evaporite cores; it is this anticlinal aspect of the structures that has given rise to the term "salt anticline."

There are five principal salt anticlines which lie in a northwest trending belt that crosses the Colorado-Utah state line (Figure 2). They are, from northeast to southwest, the Salt Valley-Fisher Valley-Sinbad Valley anticline, the Castle Valley-Paradox Valley anticline, the Moab Valley anticline, the Gypsum Valley anticline, and the Lisbon Valley-Dolores anticline.

The individual salt structures are northwest-trending faulted folds that range from about 30 to 70 miles long, have structurally complex central parts 2 to 6 miles broad, and have salt cores that range from about 4,100 to 13,700 feet in thickness. The shape of the salt cores changes progressively from the southwest to the northeast (Figure 3). On the southwest, the subsurface form of the core is that of a low ridge with gently sloping sides; northeastward, the buried ridges have greater relief and steeper sides, and, in part, are more irregular; the northeasternmost salt anticlinal system consists partly of a series of steepsided columns or plugs, probably connected by a low ridge.

Sedimentary strata of Middle Pennsylvanian to Quaternary age are exposed in the salt anticline region, and Precambrian and lower and middle Paleozoic rocks have been encountered in the subsurface. The lower part of the sedimentary section is outlined in Table 1. Crystalline rocks of Precambrian age crop out in the Uncompahgre Plateau. Thick sedimentary deposits filling the basin are largely marine evaporite, carbonate, and fine-grained clastic rocks of Pennsylvanian age, and continental arkosic deposits of Permian and Early and Middle (?) Triassic age derived principally from the ancestral Uncompahgre highland. Sandstone and mudstone of Late Triassic, Jurassic, and Early Cretaceous age, also of continental origin occur in the basin and overlap the ancestral Uncompahgre as well. These beds are succeeded by Late Cretaceous deposits of marine shale and littoral sandstone. Igneous rocks of probable early Tertiary age occur in the laccolithic



Adapted from diagram by Esther T. McDermott
Structure after Elston and Shoemaker, 1961

Figure 3 - Isometric block diagram showing form of salt anticlines, constructed on top of salt in Paradox Member of Hermosa Formation

TABLE 1. Late Paleozoic and early Mesozoic rock units in and near the salt anticline region

System	Series	Formation and member	Thickness (feet)
Triassic	Upper	Chinle Formation	0- 850
Triassic	Middle(?) and Lower	Unnamed sandstone	0- 800 (?)
		Moenkopi Formation	0- 1,300 (?)
		Pariott Member	0- 200+
		Sewemup Member	0- 500
		Ali Baba Member	0- 290
Triassic(?)		Tenderfoot Member	0- 290
?	?		
Permian		Cutler Formation	0- 8,000
?	?		
Pennsylvanian	Upper	Rico Formation	0- 940
	Middle	Hermosa Formation: Upper member	0- 2,900(?)
		Paradox Member	0-14,500(?)
		Lower member	0- 195
	Lower	Molas Formation of Merrill and Winar (1958)	0- 135
?			
Mississippian	Upper		
	Lower		
Devonian		Pre-Pennsylvanian Paleozoic rocks	0- 2,000±
Cambrian			

La Sal Mountains. Two of the laccolithic complexes are intruded at the top of salt structures (Figure 2).

The deep trough part of the Paradox basin and the ancestral Uncompahgre uplift both were in existence during salt deposition in Middle Pennsylvanian time. Structural displacements within the basin and in the ancestral Uncompahgre apparently led to the development of the salt anticlines.

PRE-SALT ROCKS

Geophysical evidence (Joesting and Byerly, 1958) suggests the salt anticline region may be localized over a Precambrian structural depression, possibly an ancient sedimentary basin. The Uncompahgre uplift is underlain by granites, gneisses, and schists of Precambrian age, about 1,300 million years old and older (Shoemaker, 1956; Aldrich and others, 1958, p. 1130). Granite, overlain by early Paleozoic sedimentary rocks, was also penetrated in a drill hole in the deep trough part of the Paradox basin, south of Paradox Valley (Figure 4). The crystalline rock penetrated by the drill and the crystalline rocks exposed in the Uncompahgre Plateau may not be representative of all the Precambrian rocks under parts of the deep trough, however. On the basis of the geophysical data, H.R. Joesting and J.E. Case of the Geological Survey (oral communication, 1961) suggest that the northeastern part of the deep trough locally may be underlain by Precambrian sedimentary rocks. If late Precambrian sedimentary rocks are present, they might be broadly correlative with the Precambrian sedimentary rocks of the Uinta Mountains or of the Grand Canyon.

Pre-salt Paleozoic rocks in the salt anticline region are almost entirely marine. The sequence of pre-salt Paleozoic rocks consists of carbonate rocks and fine-grained clastic rocks of Cambrian, Devonian, Mississippian, and Early to Middle Pennsylvanian age (Table 1). These rocks are about 2,000 feet thick southwest of the salt anticline region, and perhaps 1,500 feet thick beneath the salt anticlines. Some of these rocks have been encountered by drilling along the

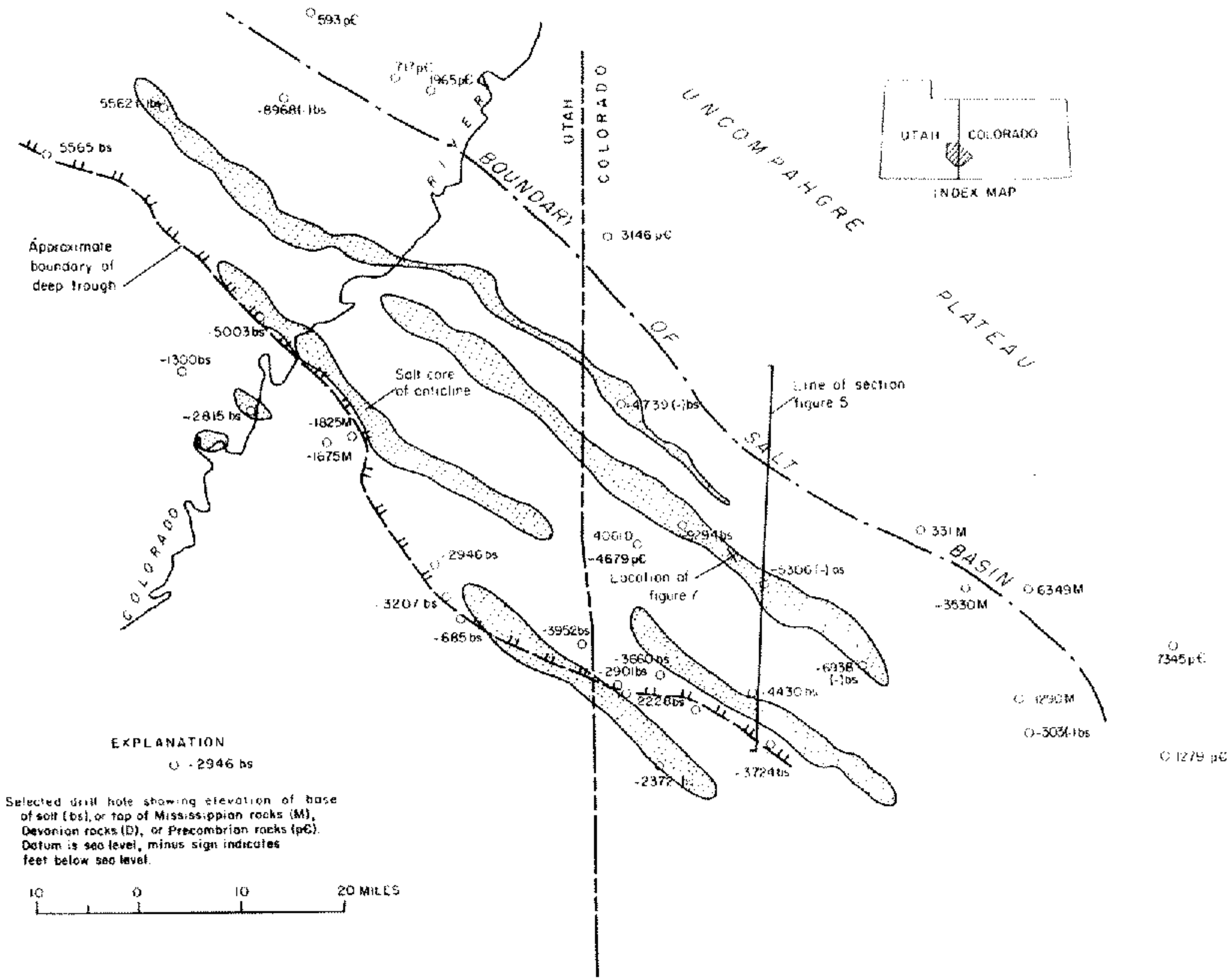


Figure 4 -- Structural relief on pre-salt rocks in and near the salt anticline region

southeastern part of the Uncompahgre front, and, although they are absent from the Uncompahgre highland, they may have covered it prior to Pennsylvanian time.

Rocks of Mississippian age on the margin of the Uncompahgre uplift are about 16,000 feet higher structurally than Mississippian rocks in the deep trough part of the basin (Figure 4). About 16,000 feet of Pennsylvanian, Permian, and Lower and Middle (?) Triassic strata fill the trough, and pinch out abruptly against the Uncompahgre front.

Deeply buried Mississippian rocks within the basin also exhibit structural relief. From the top of Mississippian rocks near Lisbon Valley to the top of Mississippian rocks underlying Paradox Valley, the relief is nearly 9,000 feet (Figure 4). The southwestern part of the Paradox basin is an irregular shelf bordering the deep trough. Strata of Pennsylvanian and Permian age are roughly about twice as thick in the trough as they are on the shelf.

The surface on which salt was deposited evidently was irregular. Deep drilling in and near the trough has revealed not only the existence of abrupt structural relief in pre-salt Paleozoic rocks, but also has shown that some of the pre-salt rocks on local buried structurally high areas probably were eroded prior to deposition of the salt. South of Paradox Valley, evaporite-bearing beds rest directly on rocks of Devonian age and the pre-salt Paleozoic section here is only about 600 feet thick[1]. The base of the salt is here about 5,000 feet higher than in a nearby part of Paradox Valley (see Figure 4). Northeast of the Lisbon Valley-Dolores anticline, salt directly overlies a thin section of Mississippian rocks. As shown by Neff (1960, p. 61 and Figure 9), the missing section of rocks, probably aggregating about 300 feet in thickness, includes rocks of Early Mississippian, and Early and Middle Pennsylvanian age. At this place the overlying section of salt is only 760 feet thick, but it contains thin representatives of salt beds that range from the lower through the upper part of the salt sequence (R. J. Hite, oral communication, 1961). These relations suggest the contact of the salt with older rocks is depositional rather than the result of post-salt faulting in the basement. The inferred history of development of the relief on the pre-salt rocks is illustrated in Figure 5.

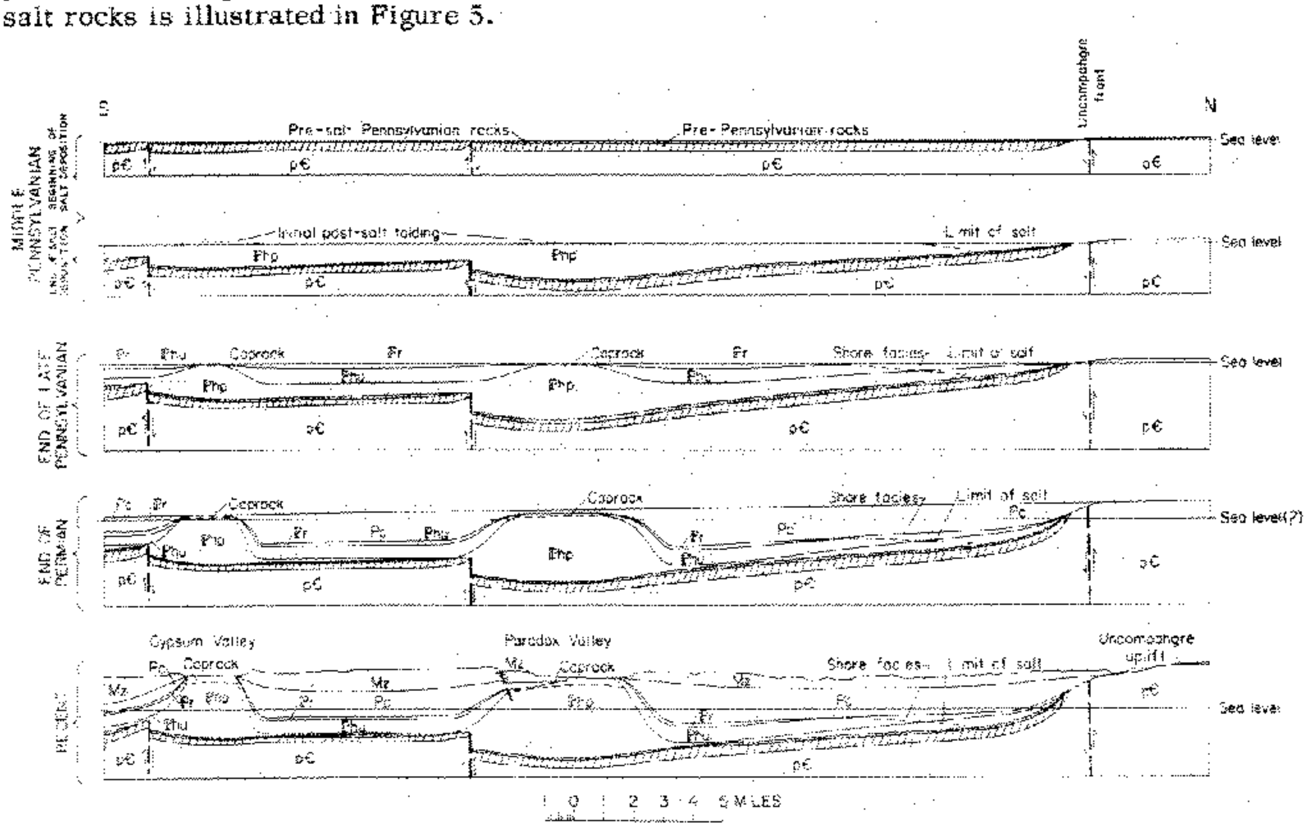


Figure 5.--Sections diagramming inferred structure and development of salt anticlines and Uncompahgre front.
Mz-Mesozoic rocks; Pc-Cutler Formation (Permian); Pr-Rico Formation (Middle and Late Pennsylvanian); Phu-upper member of Hermosa Formation (Middle Pennsylvanian); Php-Paradox Member of Hermosa Formation (Middle Pennsylvanian), p€-Precambrian rocks.

[1]Petroleum Information, Denver, Colorado.

SALT-BEARING BEDS

The salt deposits are part of the Hermosa Formation of Middle Pennsylvanian age (Bass, 1944; Wengerd and Strickland, 1954). The Hermosa Formation comprises two members of strongly contrasting lithology: the Paradox Member, composed mainly of salt, and an upper member, composed mainly of limestone and clastic rocks. In the deep subsurface the major part of the Paradox Member includes about 30 beds of halite rock separated by anhydrite, dolomite, limestone, and black carbonaceous shale. Rocks similar to those between the halite beds enclose the halite-bearing section and form the basal and uppermost parts of the Paradox Member.

Deposition of the salt and associated rocks followed a repeated, fairly uniform cycle. R. J. Hite, of the Geological Survey (Hite, 1960) has identified 29 separate evaporite cycles, each cycle displaying a complete or incomplete vertical gradation from limestone to dolomite to anhydrite to halite rock (with or without potash salts), and thence inversely to anhydrite, dolomite, and limestone. In addition to halite, potash salts were precipitated in 18 of the evaporite cycles, the potash deposits occurring with the halite beds. One potash deposit has been traced in the subsurface for a distance of about 110 miles (from the Salt Valley anticline in the northwestern part of the region into northern Montezuma County, Colorado, south of the Lisbon Valley-Dolores anticline (Hite, 1961, p. D-135). Though the thicknesses of the beds vary, the conditions of sedimentation were relatively uniform across most of the basin through each depositional cycle, reflecting the broad scale of the tectonic adjustments in the sinking salt basin.

The salt-bearing part of the Paradox Member, as estimated from data from 84 drill holes in and near the deep part of the basin, contains an average of 71 percent halite rock. The proportion of salt cut in individual drill holes ranges from about 40 percent to more than 90 percent. The proportion of salt is highest in a belt roughly parallel to and about 10 to 20 miles southwest of the Uncompahgre front (Figure 6). Lines of equal salt content locally transect the salt anticlines. As the distribution of salt is at least partly independent of the trend of the anticlines, the pattern suggests that the original depositional pattern of the salt has not been greatly modified by transfer of salt and associated rocks into the cores of the anticlines.

On outcrop, the Paradox Member consists of beds of laminated gypsum interbedded with subordinate clastic and carbonate rocks, and with internally disrupted clayey gypsiferous units. The clayey gypsiferous units are interpreted to be the residue of leached salt beds. These rocks make up an ablated or leached caprock above the salt cores that ranges in thickness from about 400 to 1,300 feet. The gypsum content of the caprock, as estimated from detailed mapping, is about 25 to 50 percent in Sinbad Valley, about 55 percent in central Paradox Valley, and as much as 80 percent in southeast Gypsum Valley. This apparent increase in the proportion of evaporite rock in the caprock correlates with the subsurface increase in the proportion of salt away from the Uncompahgre.

The proportion of shale and sandstone in the Paradox Member increases abruptly toward the northeast near the Uncompahgre front. Near the Colorado-Utah state line, beds of the salt-bearing part of the Paradox Member containing a high proportion of clastic rocks extend somewhat farther from the Uncompahgre front than in areas to the northwest and southeast. Arkosic material derived from the ancestral Uncompahgre was shed into this margin of the Paradox basin.

Sinbad and Fisher Valleys are close to the Uncompahgre front and are within the area that has a high content of clastic rocks in the Paradox Member. At these places, about 50 to 75 percent of the exposed beds of the Paradox are claystone, siltstone, and sandstone, most of which appear to have been deposited in a shallow water, near-shore environment. These beds are referred to as the near-shore facies. Although the fine-grained rocks are predominantly light gray some beds of shale are red. Macerated plant debris, fusain, and small pockets of coal are locally common. The sandstone is fine to coarse grained and generally arkosic. Rarely, cobbles and boulders of granite are present. In places, the sandstone contains salt casts and small-scale sedimentary structures such as desiccation cracks and ripple marks, which are features that are commonly associated with intermittently exposed shallow-water deposits.

In the shelf part of the Paradox basin, southwest of the salt anticline region, the salt-bearing section ranges from a featheredge along the margin of the basin to about 3,000 feet in thickness. Although the original thickness of the Paradox Member in the vicinity of the salt anticlines is not

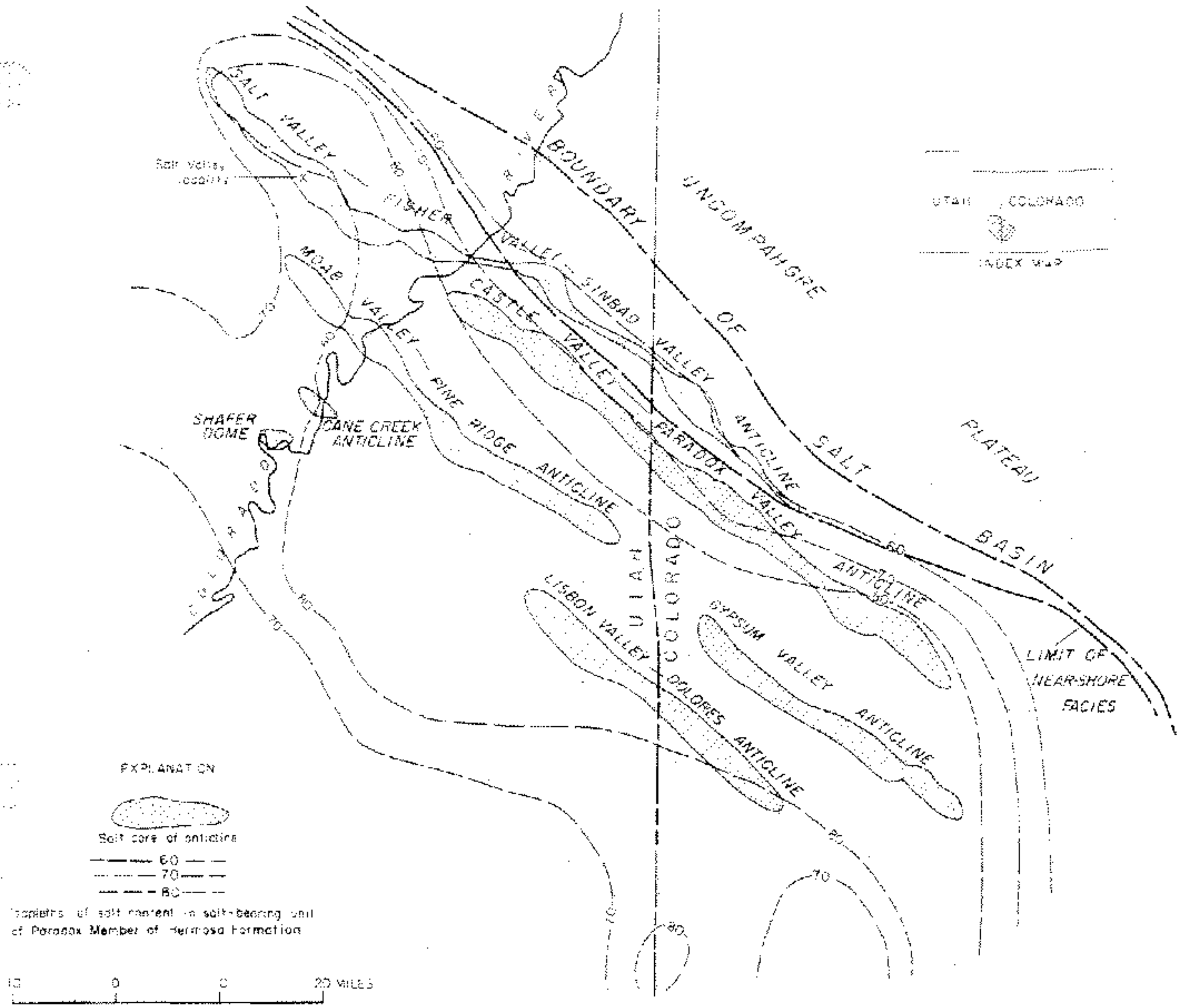


Figure 6.--Distribution of salt content and near-shore facies in Paradox Member of Hermosa Formation in salt anticline region

known because it has been modified greatly by flowage of the salt, the thickness along the sites of the major salt structures probably was at least 5,000 feet, and may have been as much as 7,000 feet (Figure 5).

On the shelf area of the basin near the salt anticline region, individual salt beds undisturbed by flowage range from about 100 to 500 feet in thickness, and non-salt-bearing intervals between the salt beds commonly are about ten to a few tens of feet thick. In the core of the Paradox Valley salt structure, the greatest uninterrupted interval of salt is about 1,300 feet thick; most of the non-salt-bearing intervals penetrated beneath Paradox Valley range from about 100 to 400 feet thick. The thickness of individual salt beds in the cores of salt anticlines tends to be roughly twice the thickness of undisturbed beds on the shelf area of deposition, which suggests that the increased thickness of the salt cores of the anticlines, due to salt flowage, is about double the thickness of the original salt section.

Several types of evidence indicate that at the end of the time of deposition of the salt an irregular pre-salt surface was overlain by a body of salt of varying thickness, a part of which probably had already been folded. On deeply buried structurally high areas of pre-salt rocks, the Paradox Member is greatly thinned, and at places salt is absent (Figure 5). Nearby in cores of the salt anticlines, the Paradox Member locally forms great masses with thicknesses on the order of 10,000 feet or more. Several thousand feet of abrupt structural relief occurs at the top of salt and also at the base of the salt (Figures 4 and 5), as shown by deep holes recently drilled in and near the Paradox Valley, Gypsum Valley, Lisbon Valley, and Moab Valley salt anticlines. In each case, these salt structures appear to be localized in structurally low areas that are bordered on their south sides by high ridges of pre-salt rocks. The subsurface data from Paradox Valley illustrate this relation especially well. In the Continental Oil Co. No. 1 Scorup and others well, in the core of the salt structure, the salt-bearing mass is more than 14,000 feet thick and the base of salt is more than 9,000 feet below sea level. About 3 miles southwest of the margin of the salt core, the Paradox Member, apparently lacking salt, is reported to be less than 300 feet thick[2]. At this place, the base of the Paradox Member lies about 4,000 feet below sea level or more than 5,000 feet higher than the base of the Paradox Member beneath the salt core. The known structural relief at the base of salt across the Gypsum Valley salt structure is about 2,600 feet (Figures 4 and 5). Near the southwest flank of the Lisbon Valley anticline about 2,500 feet of structural relief occurs at the base of salt. Near the Moab Valley anticline the known structural relief on the base of salt is about 3,700 feet (Figure 4).

Information from one deep hole -- the Delhi Taylor No. 2 Utah -- drilled in the northwest part of the Moab Valley salt structure (Figure 4) suggests deformation of pre-salt rocks occurred during the time of deposition of the salt. The top of the salt core at the northwest end of the Moab Valley salt structure is a normal sedimentary contact. The core is about 7,000 feet thick, and the base of salt is about 5,000 feet below sea level. Individual salt beds in the upper half of the core are about the same thickness as salt beds away from the salt structure. In the lower half of the core, however, several of the salt beds are much thicker than their equivalents in the adjacent shelf area on the southwest. One of the lowest salt beds apparently is duplicated by folding in the anticlinal core (R.J. Hite, 1960, Figure 2). These relationships may be explained by subsidence of pre-salt rocks along the site of the salt structure during the early to middle part of the period of salt deposition. Such subsidence might result not only in the deposition of locally thicker sections of salt, but might also have initiated folding of previously deposited salt beds. This structure presumably was then masked by younger deposits of salt.

GROWTH OF THE SALT CORES AFTER SALT DEPOSITION

Initial growth of the salt cores occurred in Middle Pennsylvanian time, under marine conditions, and with no significant cover of post-salt sediments overlying the salt structures (Elston and Landis, 1960; Landis and others, 1961; see Figure 5). Continued rapid growth of the salt cores occurred during Late Pennsylvanian and Permian time. Pennsylvanian and Permian beds lie with successive unconformable onlap on the evaporite cores. The crests of the evaporite cores were maintained at or near local base level for a long period of time during which thick sections of post-salt rocks were deposited on their flanks. Thus the salt cores are not basically piercement or diapiric structures. Thin wedges of Pennsylvanian, Permian, and early Mesozoic strata at places overlie the evaporite cores. Although these wedges have been locally disrupted by subsequent pulses of growth, the salt structures evolved largely by means of gradual growth as the beds, deposited on the flanks of cores, subsided.

An example of the field evidence demonstrating early growth of the salt cores is illustrated in a geological map of a small area in central Paradox Valley (Figure 7). Here, as is common at other places, beds of the Paradox Member of the Hermosa Formation are folded and crenulated. The beds include gypsum, gypsiferous breccia that probably once contained salt, and black shale and subordinate carbonate rock and sandstone. As shown by the map, beds of the Paradox are unconformably overlain by a very thin wedge of the upper member of the Hermosa Formation, which consists of carbonate rock and greenish shale. The carbonate beds of the upper member

[2] Shell Oil Co. No. 1 Wray Mesa unit, Petroleum Information, Denver, Colorado.

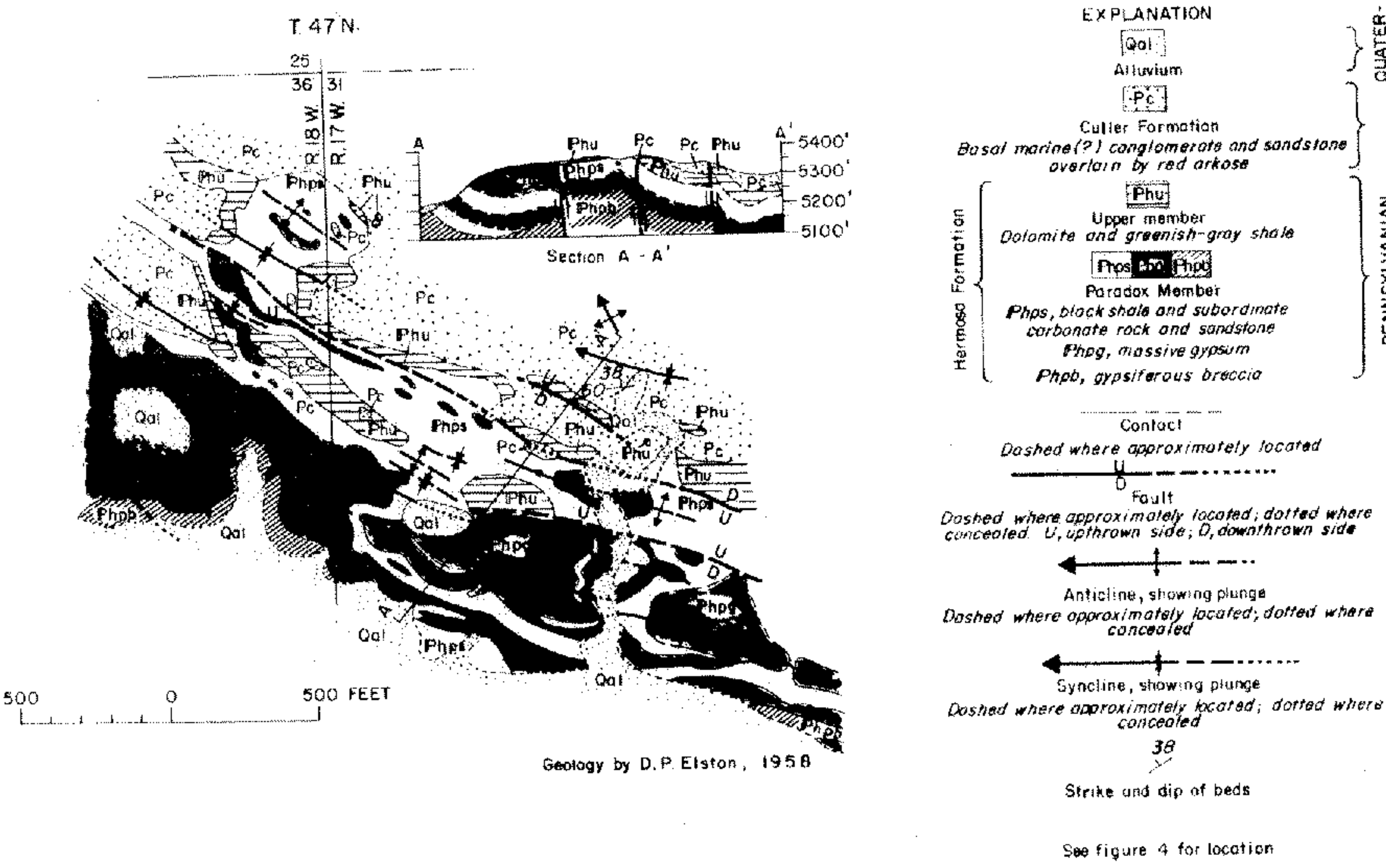


Figure 7. — Geology of part of floor of Paradox Valley, Montrose County, Colorado

are, in turn, unconformably overlain by a basal conglomerate and sandstone sequence of probable marine origin, which is transitional upward into characteristic red beds of the Cutler Formation of Permian age. At this place, the marine Rico Formation, which in most places lies between the Hermosa and Cutler Formations, is absent. The Rico Formation is present, however, in northwest Paradox Valley, where it is unconformably overlain by a thin wedge of the Cutler Formation.

Along the north wall of northwest Paradox Valley the exposed part of the Cutler Formation is locally more than 2,000 feet thick. It is only a few tens of feet thick, however, in nearby outcrops in the center of the valley. There is no marked angular discordance at the top of the Cutler (Shoemaker and others, 1958), and the thinning of section is subtle. Here the thinning of the Cutler takes place within the formation, which indicates the core of the salt structure was growing during Cutler time.

In exposures on the north side of Gypsum Valley, near the Dolores River (Figure 2), unconformities separate the Paradox Member from the upper member of the Hermosa Formation, the Hermosa Formation from the Rico formation, and the Rico Formation from the Cutler Formation (Elston and Landis, 1960). At one place an internal unconformity has been observed within the upper member of the Hermosa Formation. The aggregate thickness of these exposed post-Paradox beds is less than 250 feet, yet they are the correlatives of beds distributed through a stratigraphic thickness of more than 5,000 feet beneath the adjacent north flank of the Gypsum Valley salt structure[3] (as shown on Figure 5). Essentially contemporaneous growth occurred on both the Gypsum Valley and Paradox Valley salt structures in Middle and Late Pennsylvanian, and in Permian time.

In Salt Valley, Utah (Figure 8), a conglomerate containing boulders of Mississippian limestone unconformably overlies the Paradox Member (Elston and Shoemaker, 1960). The conglomerate is interpreted to be the basal member of the Cutler Formation. A part of the limestone detritus contained in the conglomerate probably was derived from Mississippian beds upturned on the flank of the ancestral Uncompahgre, about a dozen miles to the northeast. Here again the principal growth of the salt structure occurred before the end of Cutler deposition.

Growth of the salt structures in late Paleozoic time was concomitant with uplift on the ancestral Uncompahgre. From the time of deposition of the Paradox Member through deposition of the Cutler Formation arkose was spread progressively greater distances across the Paradox basin (Figure 8). The first major pulse of uplift of the Uncompahgre source area apparently occurred in Middle Pennsylvanian time and was possibly accompanied by deformation of the pre-salt rocks in the basin. Possible southwest tilting of the basin during this uplift may have caused the cessation of salt deposition. Initial folding of the salt section may have taken place during this regional deformation. Arkosic debris, which had been transported only into the margin of the basin during salt deposition, was spread farther from the Uncompahgre after the cessation of salt deposition (Figure 8, arkosic facies of upper member of Hermosa Formation), but the detritus was still deposited in a marine basin. The culmination of major uplift on the Uncompahgre resulted in a flood of coarse arkose across the salt anticline region (the Cutler Formation), and in the exclusion of the sea from the area of the salt anticlines.

In the deep trough part of the Paradox basin, thick deposits of the Cutler were laid down in the synclinal areas between the growing salt anticlines. Much thinner deposits of the Cutler were laid down southwest of the deep trough. The growth of the salt cores largely kept pace with deposition on their flanks, but by the end of Permian time a few hundred feet of beds of the Cutler locally overlapped the evaporite cores. The lack of Paradox detritus in Paleozoic beds that lap on or are adjacent to the salt structures is suggestive that the plastic evaporite cores did not form topographically high ridges. Growth of the salt structures during much of Permian time probably was caused mainly by loading of sediments on the flanks of the structures.

Topographic relief on the ancestral Uncompahgre was evidently much reduced near the end of Permian time, and a deep regolith was developed on the crystalline surface (Figure 5). A pulse of uplift at the end of Permian resulted in the stripping of the regolith and renewed erosion of the crystalline core of the uplift. The deposition of this material in the basin produced the Tenderfoot

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[3]Shell Oil Co. No. 1 North Gypsum Valley unit, Petroleum Information, Denver, Colorado.

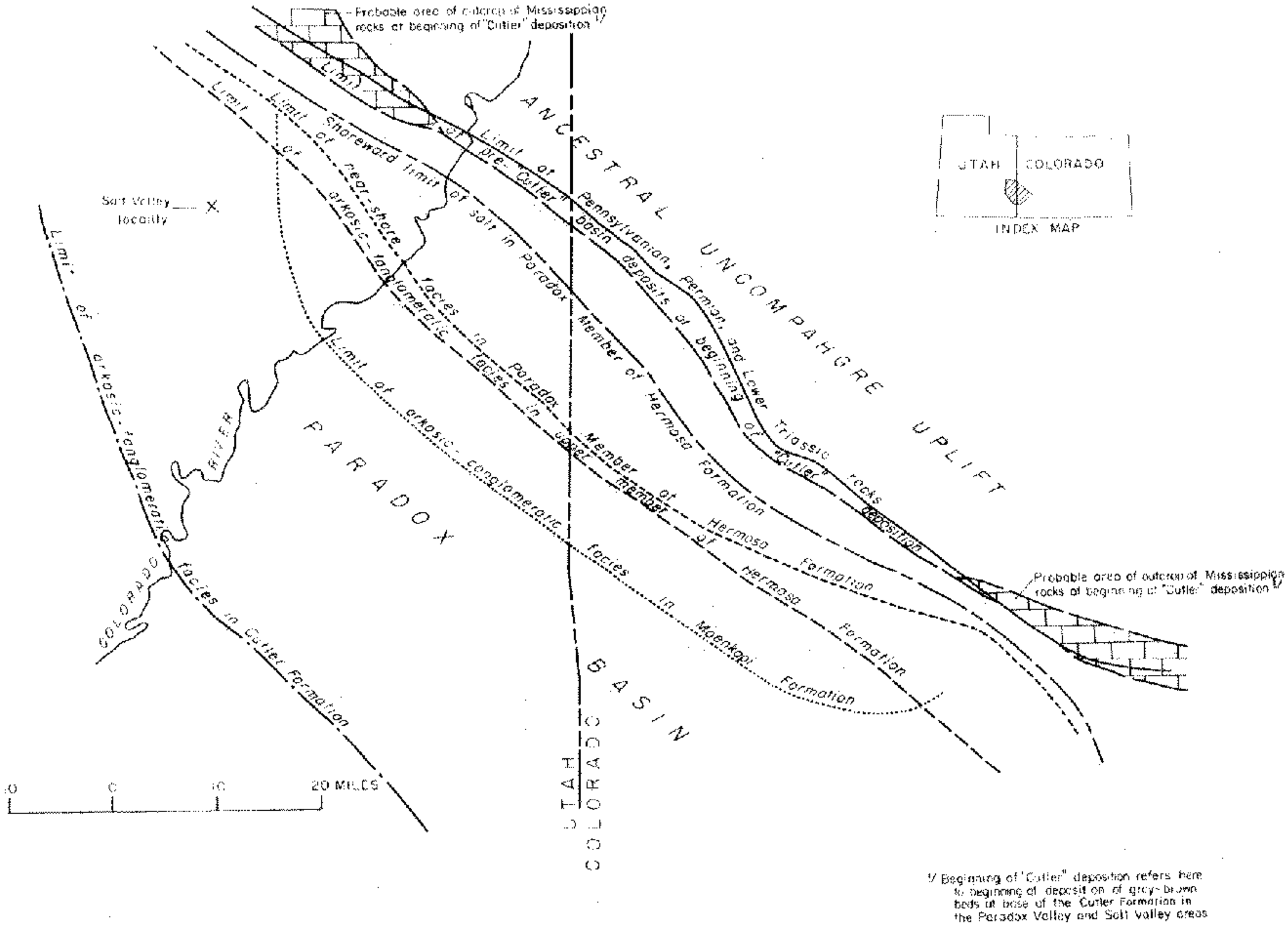

Figure 8 - - Facies map of Pennsylvanian, Permian, and Lower Triassic rocks in salt anticline region

Member of the Moenkopi Formation (Table 1), which overlies the Cutler Formation with gentle unconformity in exposures away from the salt structures (Shoemaker and Newman, 1959). Very locally over the salt structures the Tenderfoot Member lies with strong angular unconformity on the Cutler. A bed of gypsum locally present near the salt structures at or near the base of the Tenderfoot Member (Shoemaker and Newman, 1959, p. 1841) may have been derived from exposed Paradox. In places the Tenderfoot is overlain with angular unconformity by the conglomeratic Ali Baba Member of the Moenkopi. Surges of growth of the salt cores apparently accompanied the renewed uplift on the Uncompahgre.

A second, minor, pulse of uplift occurred on the Uncompahgre later in Early or Middle (?) Triassic time resulting in deposition in the basin of the conglomeratic uppermost (Pariott) member of the Moenkopi. This pulse of uplift also is correlated locally with renewed growth of the salt cores.

By the end of Middle (?) Triassic time the period of great displacement between the ancestral Uncompahgre and the deep trough of the Paradox Basin had ended. The core of the Uncompahgre was overlapped by a veneer of Late Triassic, Jurassic, and Cretaceous beds. The salt anticlines, however, continued their growth slowly. The exposed cores were overlapped to a progressively greater extent until, in Late Jurassic time, most of the salt structures were covered. A part of one of the salt structures, the southeast end of the Gypsum Valley anticline, probably was not buried until Late Cretaceous time (Landis and others, 1961).

During a period of regional deformation in the interval from latest Cretaceous to early Tertiary, in which there was renewed uplift on the Uncompahgre, broad folds were developed over the salt structures. Subsequent regional uplift of the Colorado Plateau during middle to late Tertiary time resulted in the entrenchment of the streams and the breaching of the salt anticlines.

The rate of growth of the salt anticlines was directly correlated with the rate of subsidence of the Paradox Basin and filling of the Basin with sediments. By the end of Middle Triassic time, when the local subsidence of the deep trough had ceased, the growth of the salt structures slowed greatly. If rapid subsidence of the Basin had continued throughout the Mesozoic and into the Tertiary, salt domes of the Gulf Coast type might have formed at places above several of the more active cells of growth on the salt structures. The ultimate cessation of growth of the salt cores in late Mesozoic time apparently was accompanied by local pinch-off and exhaustion of salt beneath the areas flanking the salt structures. Because the active period of growth of the salt structures ended in mid-Triassic time and the Colorado Plateau was later elevated and deeply dissected, evidence for the early growth of these salt structures has become accessible.

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