DISTRIBUTION AND THICKNESS OF SALT IN THE PARADOX BASIN OF SOUTHWESTERN COLORADO AND SOUTHEASTERN UTAH, A PRELIMINARY REPORT

By Elmer H. Baltz

Trace Elements Investigations Report 706

UNITED STATES DEPARTMENT OF THE INTERIOR

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DISTRIBUTION AND THICKNESS OF SALT IN THE PARADOX BASIN OF SOUTHWESTERN COLORADO AND SOUTHEASTERN UTAH

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ABSTRACT

Thick deposits of salt and other evaporite rocks occur in the Paradox member of the Hermosa formation of Pennsylvanian age in an area of nearly 12,000 square miles of southwestern Colorado and southeastern Utah. Interpretation of well logs and surface and subsurface structure as portrayed in published literature indicates that the salt-bearing part of the Hermosa formation may be 8,000 to 10,000 feet thick in the northeastern part of the Paradox salt basin. In this part of the basin as much as 80 percent of the Paradox member may be composed of salt.

Salt is thickest in the large, northwest-trending anticlines in the northern half of the Paradox fold and fault belt. Salt seems to have flowed into the anticlines from adjacent synclines as a result of regional compressive forces which formed the anticlines, and as the result of later isostatic readjustments. The anticlines were formed in early Permian time and the intrusive evaporite bodies may have pierced overlying rocks and stood at the surface during parts of Permian, Triassic, and Jurassic time. Jurassic and Cretaceous rocks which were deposited across the anticlines

were downfaulted along the axial part of the larger anticlines and subsided to form narrow grabens many miles long. Presumably this occurred in latest Cretaceous or early Tertiary time at about the same time that the older anticlines were rejuvenated and enlarged by Laramide compressive forces. Deflation of the salt bodies by ground water in middle and late Tertiary time may have continued the process of graben formation.

Folds associated with expanded thicknesses of salt in the Paradox salt basin are classed as salt anticlines and salt domes. Nearly all of the larger anticlines are classified as salt anticlines, inasmuch as their great length and orientation with regional structures indicate that they were formed as a result of regional stresses. The salt behaved passively and was deformed with the enclosing beds. Small piercement plugs of salt found on most of the large anticlines are superficial to the salt core of the anticlines. Several smaller structures located in the west-central part of the Paradox salt basin are similar to the Gulf Coast salt domes and probably have plug-like cores which have risen and pierced overlying rocks in response to a change in isostatic conditions.

INTRODUCTION

Thick deposits of salt occur in the Paradox member of the Hermosa formation of Pennsylvanian age in an area of nearly 12,000 square miles of southwestern Colorado and southeastern Utah. The Paradox member is exposed in the collapsed axial portions of several large anticlines, but in most of the region knowledge of the member must be obtained from deep oil tests which have penetrated these rocks.

General distribution of salt is known from widely scattered drill holes, but spacing of these drill holes is far too wide to give reliable quantitative data of a detailed nature. In the present study the writer has attempted to derive a semiquantitative picture of salt distribution by interpretation of sample and electrical logs of the wells and by interpretation of surface and subsurface structure of the rocks as portrayed in published geologic literature of the region.

Certain basic premises were necessary concerning stratigraphy, structure, and age of deformation of the rocks. Some of these premises are supported by evidence presented in the literature of the region considered; others are applications of principles of structure and evaporite stratigraphy which seem to be generally applicable to the Paradox salt basin, although developed in other regions.

The writer believes that thickness and distribution of salt portrayed in this paper are reasonably accurate in a general or regional sense, and that in some local areas as in the Paradox fold and fault belt of Colorado the portrayal may be semiquantitative. However, in some areas data are lacking or so sparse that the interpretations are open to question.

The writer was greatly assisted in compilation and plotting of well data by J. F. Fallis.

This work is part of a program that the U. S. Geological Survey is conducting in connection with its Investigations of Geologic Processes project on behalf of the Division of Research, U. S. Atomic Energy Commission.

STRATIGRAPHY

Hermosa formation

The Hermosa formation of Pennsylvanian age is composed of varying proportions of limestone, dolomite, sandstone, shale, gypsum, anhydrite, and salt; all are predominantly of marine origin. The Hermose formation consists of three members: an unnamed lower member, the medial Paradox member, and an unnamed upper member (Bass, 1944, p. 8). The lower member is composed of dense, gray limestone and interbedded black shale. In many places sandstone beds also are intercalated. The Paradox member is composed of interbedded black shale, dolomite, limestone, gypsum, and anhydrite, and thin to thick beds of salt. Thin sandstone beds are present at places. The upper member is composed mostly of thick gray limestone with interbeds of dark shale and sandstone. In places much of the upper member is composed of sandstone.

In most of the region the Hermosa formation is underlain by thin beds of limestone, reddish shale, and sandstone of the Molas formation. The Hermosa formation is overlain by the Rico formation which is composed of limestone, red shale, and arkosic sandstone. The Rico formation is a transitional phase between marine beds of the Hermosa formation and continental sandstone and shale beds of the Cutler formation which overlies the Rico.

The Molas, Hermosa, and Rico formations represent most of the Pennsylvanian system. Locally the uppermost part of the Rico formation may be earliest Permian in age. The Cutler formation is mostly of Permian age, although the lowest part of this formation in places may be as old as latest Pennsylvanian.

Wengerd and Strickland (1954, p. 2166) have redefined the Pennsylvanian rocks of southwestern Colorado and southeastern Utah as shown below.

<table>
<tr><th colspan="2">Wengerd and Strickland</th><th colspan="2">U. S. Geological Survey</th></tr>
<tr><td rowspan="2">Hermosa forma-tion</td><td>Clastic facies</td><td colspan="2">Rico formation</td></tr>
<tr><td>Carbonate facies</td><td rowspan="5">Hermosa formation</td><td>Upper member</td></tr>
<tr><td rowspan="3">Paradox formation</td><td>Upper member</td><td rowspan="3">Paradox member</td></tr>
<tr><td>Middle member</td></tr>
<tr><td>Lower member</td></tr>
<tr><td colspan="2">Pinkerton Trail limestone</td><td>Lower member</td></tr>
<tr><td colspan="2">Molas formation</td><td colspan="2">Molas formation</td></tr>
</table>

The terminology of Wengerd and Strickland is in current usage by some geologists but has not been adopted by the U. S. Geological Survey. The older, more simple terminology is used in the present paper.

The salt with which the present paper is concerned occurs in the Paradox member of the Hermosa formation. The areal occurrence of salt is limited to the Paradox salt basin. As defined by Wengerd and Strickland (1954, p. 2158-2159) the Paradox salt basin is an elongate northwest-trending sedimentation basin of Pennsylvanian age in southeastern Utah and southwestern Colorado (fig. 1). The basin is approximately 200 miles long and 100 miles wide. The structural axis is

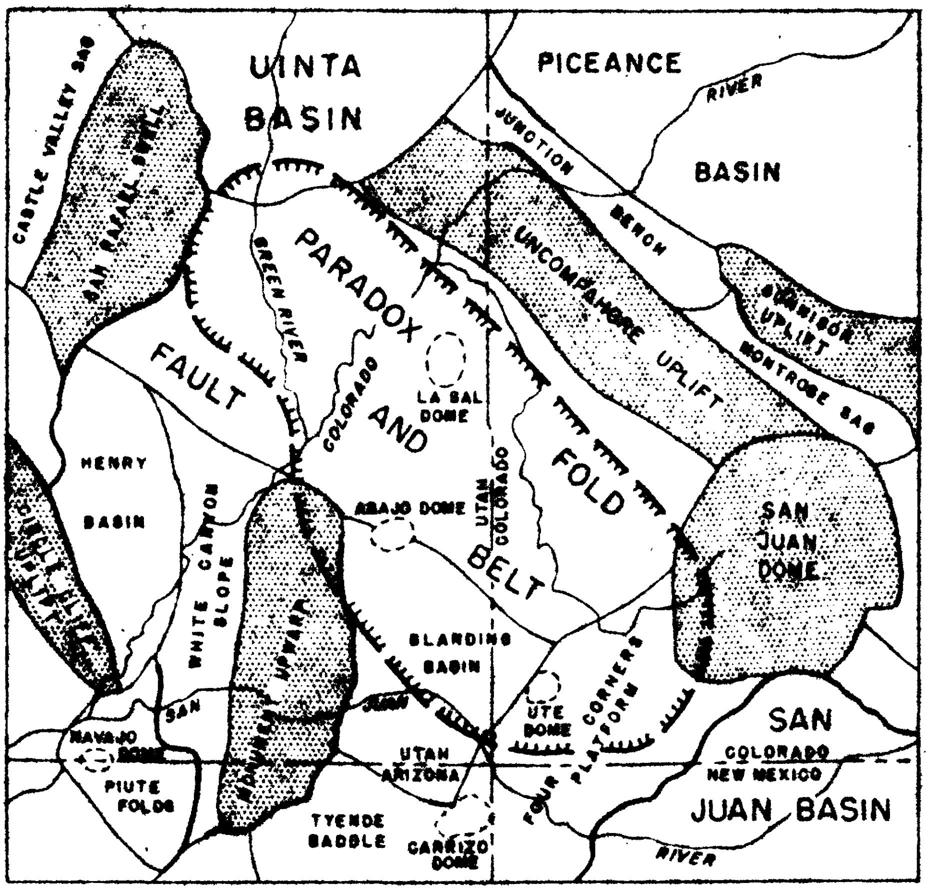

Figure 1._Tectonic divisions of part of the Colorado Plateau (After Kelley, 1955, p. 23). Broken hachured line indicates limits of Paradox salt basin.

parallel to the southwest edge of the Uncompahgre uplift, and the deepest part of the basin lies only a few tens of miles southwest of the uplift causing a strong assymmetry of the basin in northeast-southwest cross-section. The Paradox salt basin is regionally high at the present time, but its deep basinal character in late Paleozoic time is indicated by thickening into the basin of the Hermosa formation from all sides. Wengerd and Strickland (1954, fig. 11, p. 2178-2179) estimate that Pennsylvanian rocks were originally as much as 8,000 feet thick in the deep northeastern part of the basin. On the adjacent Uncompahgre uplift Pennsylvanian and older sedimentary rocks have been completely removed by erosion, and Permian and Triassic rocks rest on the Pre-cambrian basement. On the west, south, and east sides of the Paradox salt basin Pennsylvanian rocks range in thickness from about 2,500 feet to less than 1,000 feet.

Studies of logs of wells located in the basin and published stratigraphic sections of rocks cropping out in adjacent mountainous regions indicate that the Hermosa formation thickens into the Paradox salt basin mainly as the result of thickening of the black shale and evaporite sequence of the Paradox member. The Paradox member may have been originally as much as 4,000 to 5,000 feet thick in the deeper part of the basin (fig. 2). The lower member shows minor irregular basinward thickening. The upper member is as much as 1,500 to 2,000 feet thick in the northeastern part of the basin.

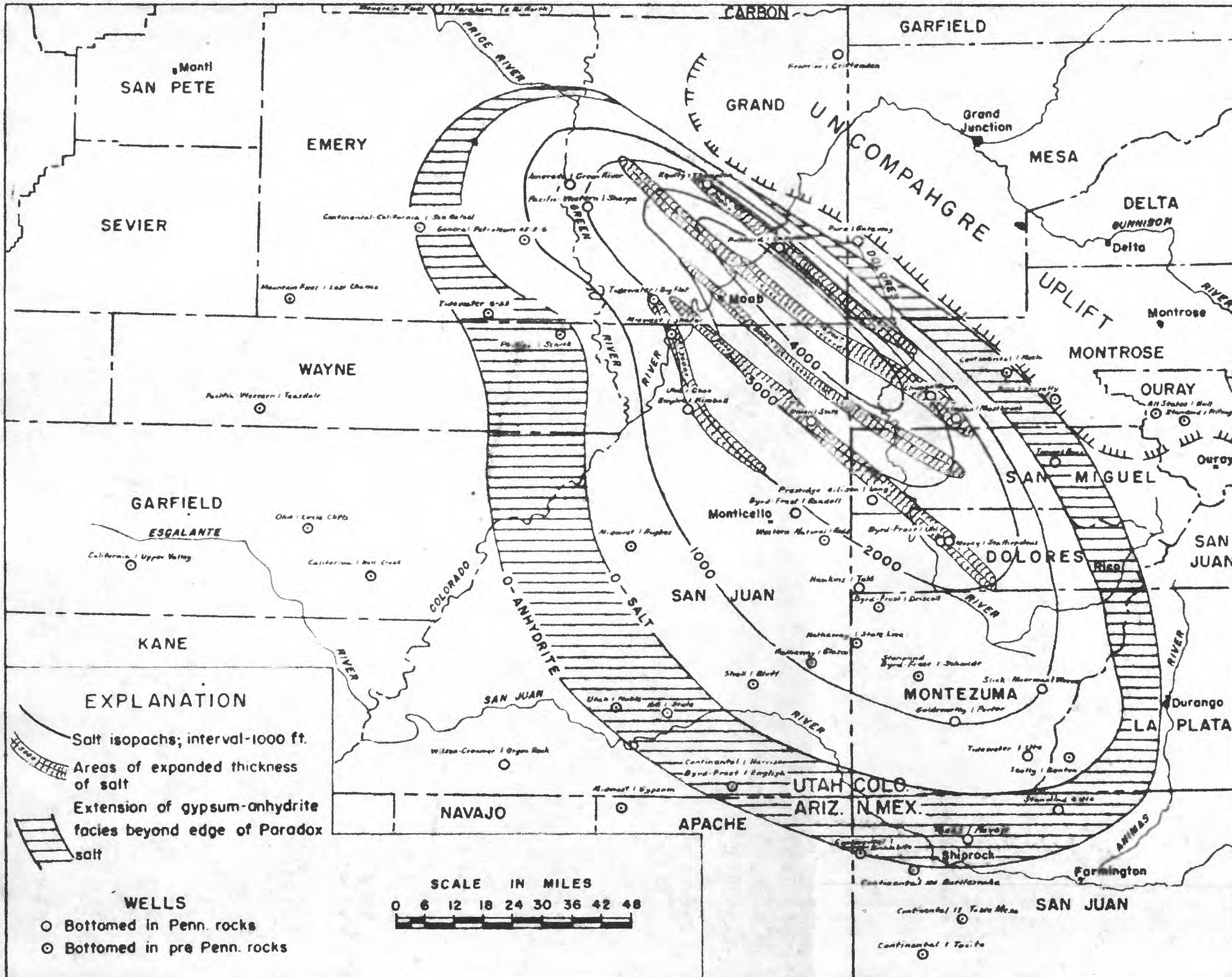

Figure 2_ Estimated original thickness of evaporite rocks in the Paradox salt basin. (After Wengerd and Strickland, 1954, p.2180-2181).

Basinward thickening of the Hermosa formation is accompanied by changes in facies of the rocks. A large proportion of the formation is composed of sandstone and sandy limestone on the east, south, and southwest sides of the basin. This facies changes basinward to the predominantly limestone facies of the upper member and the evaporite facies of the Paradox member. Anhydrite and gypsum of the Paradox member are present over a wider area than the salt (fig. 2). In the deeper part of the basin most of the Paradox member is composed of salt which may represent as much as 80 percent of the total thickness of the member; the remainder is composed of thin interbeds of anhydrite, dolomite, and black organic shale.

Estimates of original thickness of salt-bearing parts of the Paradox member are difficult to make for the northeastern part of the basin not only because of insufficient data, but because of the system of large northwest-trending folds along which much plastic flowage of evaporites has occurred during parts of several geologic periods. From the present great thickness of salt in these folds (more than 10,000 feet) it is apparent that the salt was originally of considerable thickness in this area.

Present thickness and distribution of the salt-bearing part of the Paradox member are indicated by isopachous lines on figure 3. This stratigraphic interval does not represent the entire Paradox member but only that part between the top of the highest bed of salt and the base of the lowest bed of salt.

This is approximately equivalent to the middle member of the Paradox formation as defined by Wengerd and Strickland. The isopached interval is composed of varying proportions of interbedded shale, limestone, and salt and other evaporites and the actual thickness of salt at any given place is not represented by the isopachous lines. Near the zero line salt beds may represent no more than 10 percent of the thickness. In the deeper part of the basin salt may comprise as much as 60 to 80 percent of the isopached interval. Table 1 lists percentage of salt to other rocks in drill holes where records of rocks penetrated were sufficiently good. Electric logs in most cases were good for this purpose, especially if they include micrologs. Inasmuch as the rocks immediately adjacent to the hole are usually permeated to some extent by the drilling fluids, the resistivity curve gives some indication of the permeability of the rocks, or, in the case of salt, the solubility. Salt dissolved in the drilling fluid gives a flat, characterless, low resistivity curve, which contrasts sharply with the high resistivity "kicks" of limestone, anhydrite, and organic shale, thus greatly facilitating the accurate plotting of rocks of these lithologies. Drill holes shown on figure 3 are listed in table 2.

Table 1.--Calculated percentages of salt in the Paradox member of the Hermosa formation

Colorado

County	Section, township, and range	Company and farm	Thickness of salt-bearing rocks (feet)	Total thickness of salt beds (feet)	Percent salt	Remarks
Montezuma	3-38N-19W	Byrd Frost West. Nat. #1 Driscoll	1,820	800	44	One 400 ft + bed and three 100 ft ± beds of salt.
Montezuma	11-37N-20W	Hathaway #1 USC (Lyon-Fed)	1,362	964	70	One 575 ft bed, one 120 ft bed, and five 60 ft beds of salt.
Montezuma	24-36N-18W	Stanolind #1 Schmidt	1,545	530	34	No thick beds of salt. Occurs in five 100 ft ± zones.
Montezuma	27-37N-17W	Gulf #1 Fulks	1,148	810	70	One thick salt zone with numerous shale and anhydrite breaks.
Montezuma	7-32N-19W	Continental #1 Ute Mtn.	150?	150?		150 ft of no sample.
Dolores	26-41N-17W	Continental #1 Lone Dome	3,215	2,565	79	One thick salt section with numerous shale and anhydrite breaks.
Dolores	26-41N-17W	Byrd Frost West. Nat. #1-A Uhl	1,510	640	42	One 400 ft bed, rest interbedded salt, shale and anhydrite.

Table 1.--Calculated percentages of salt in the Paradox member of the Hermosa formation.--Continued

County	Section, township, and range	Company and farm	Thickness of salt-bearing rocks (feet)	Total thickness of salt beds (feet)	Percent salt	Remarks
			Colorado			
La Plata	3-34N-11W	Great Western #1 Ft. Lewis	800			No salt beds. Salt casts in anhydrite.
La Plata	15-33N-13W	Skelly #1 Lloyd Benton	165?	165?	?	165 ft of no sample--may indicate salt dissolved in drilling fluid.
San Miguel	14-43N-19W	Reynolds #1 Egnar	4,200	3,290	78	One thick salt section with numerous shale and anhydrite breaks.
Mesa	16-49N-19W	Huber #1 Sinbad	9,196	5,125+	56	Residual gypsum, dolomite, shale, and sandstone 1,100 ft thick above salt. Hole does not penetrate total Paradox.
			Utah			
Emery	28-22S-15E	Equity #1 Government	1,450	700	48	Occurs in six 100 ft ± beds.
Emery	5-24S-15E	General Pet. 45-5-G	969	345	36	One 150 ft ± bed; five 45 ft ± beds.

Table 1.--Calculated percentages of salt in the Paradox member of the Hermosa formation.--Continued.

Utah

County	Section, township, and range	Company and farm	Thickness of salt bearing rocks (feet)	Total thickness of salt beds (feet)	Percent salt	Remarks
Grand	11-26S-19E	Tidewater #74-11 Big Flat	3,455	2,900	84	Very thick salt section with numerous shale, anhydrite, and limestone beds.
San Juan	16-27S-20E	Midwest #1 J. H. Shafer	3,880	2,520	65	Very thick salt section with numerous breaks.
San Juan	30-34S-19E	Midwest #1 Hughes	380	100	26	Three thin beds.
San Juan	23-34S-25E	Western Nat'l Gas #1 Redd	1,690	?		No salt recovered, only salt casts in anhydrite. Salt probably dissolved in drilling fluid.
San Juan	35-38S-22E	Glasco Shell #1 Govt.	1,225	670	55	No pure salt beds. All have anhydrite and pyrite. 180 ft of no samples.
San Juan	29-39S-22E	Carter #1 Bluff Bench	770	370	48	Occurs as four impure salt zones.
San Juan	32-39S-23E	Shell #1 Bluff Unit	725	390	43	Generally impure salt.
San Juan	4-39S-24E	Reynolds #1 Hatch	1,100	685	62	Good salt section. Some shale and anhydrite breaks.

Table 1.--Calculated percentages of salt in the Paradox member of the Hermosa formation.--Continued.

Utah

County	Section, township, and range	Company and farm	Thickness of salt-bearing rocks (feet)	Total thickness of salt beds (feet)	Percent salt	Remarks
San Juan	5-39S-25E	Hathaway 1-B Glasco-Fed.	1,120	530	47	One thick salt bed with three thin shale breaks.
San Juan	5-40S-26E	Shell #1 Hovenweep	923	325	35	One thick bed with some impurities.

It is apparent that the thickest salt-bearing rocks are in the area of large collapsed anticlines in the northeastern part of the basin. Wells drilled in the Gypsum Valley and Sinbad Valley anticlines in western Montrose and southwestern Mesa Counties, Colorado indicate that at least 10,000 feet of evaporite rocks, mainly salt, are present in parts of these anticlinal areas. Comparison of gravity anomaly maps (Joesting and Byerly, in preparation) of Sinbad Valley, Paradox Valley, and Gypsum Valley anticlines indicates that possibly as much as 10,000 feet of evaporite rocks are present also in the Gypsum Valley anticline. Estimates of maximum evaporite thickness in parts of Salt Valley anticline and Moab Valley anticline in Utah are 6,000 to 8,000 feet, and 7,000 feet, respectively. Evaporite rocks in Castle Valley anticline may be as much as 8,000 feet thick. The great thickness of salt in the anticlines is attributed to considerable original thickness of the Paradox member in this region and also to flowage of evaporites into the anticlines during their formation.

Table 2.--List of wells shown on isopachous map (fig. 3)

Colorado

County	Section, township, and range	Company and farm	Depth to top Paradox member (feet)	Depth to top of salt-bearing rocks (feet)	Depth to base of salt-bearing rocks (feet)	Total depth and bottom formation
Dolores	26-41N-17W	Continental #1 Lone Dome	5,923	6,170	9,385	9,950 Leadville
Dolores	30-41N-16W	Moody #1 Stathopulous	5,920	6,240		6,747 Paradox
Dolores	26-41N-17W	Byrd Frost #1-A Uhl	6,000	6,070		7,680 Paradox
La Plata	3-32N-14W	Delhi #2 Barker	8,800	No salt		7,550 Paradox
La Plata	15-33N-13W	Skelly #1 Lloyd Benton	8,495	8,855?	9,020?	10,388 Elbert
La Plata	3-34N-11W	Gr. Western #1 Ft. Lewis	8,330	8,600	9,400	10,214 Elbert
Mesa	16-49N-19W	Huber #1 Sinbad Valley	At surface	1,120		10,316 Paradox
Mesa	15-15S-104W	Pure #1 Gateway		Cutler fm on granite		7,939 Precambrian
Montezuma	7-32N-19W	Continental #1 Ute Mountain	5,850	6,050?	6,200	7,227 Precambrian (?)
Montezuma	8-33N-14W	Tidewater #1 Ute	8,702	8,920		9,502 Paradox
Montezuma	1-35N-14W	Slick Moorman #1 Weaver	6,074	6,322?		6,701 Paradox
Montezuma	24-36N-18W	Stanolind #1 Schmidt	4,395	4,850	6,395	7,099 Elbert
Montezuma	25-36N-18W	Byrd Frost #1 McIntosh	4,510			4,965 Paradox (?)

Table 2.--List of wells shown on isopachous map (fig. 3).--Continued.

Colorado

County	Section, township, and range	Company and farm	Depth to top Paradox member (feet)	Depth to top of salt-bearing rocks (feet)	Depth to base of salt bearing rocks (feet)	Total depth and bottom formation
Montezuma	11-37N-20W	Hathaway #1 USC (Lyon-Fed.)	5,298	5,543	6,905	7,628 Leadville
Montezuma	27-37N-17W	Gulf #1 Fulks	5,760	5,982	7,130	8,787 Precambrian
Montezuma	9-38N-19W	Byrd Frost West. Nat. #1 White	6,010			6,202 Paradox
Montezuma	3-38N-19W	Byrd Frost #1 Driscoll	5,590	6,000	7,820	8,286 Leadville
Montezuma	1-38N-19W	H.E.R. #1 Eva Marr	5,865			6,158 Paradox
Montezuma	34-39N-18W	H.E.R. #1-A Lane-Coffee	5,705	6,016		6,031 Paradox
Montezuma	33-39N-19W	Colo. 3 States #2 White	5,885			6,202 Paradox
Montrose	18-45N-10W	Penrose Tatum #1 Orme				1,753 Tertiary (?) igneous
Montrose	4-45N-16W	Indian #1 Mastbrook	5,060?			5,185 Paradox ?
Montrose	14-46N-13W	Pure #1 Horsefly	No Pennsylvanian present			5,035 Sawatch ?
Montrose	24-46N-14W	Pure #1 San Miguel	7,201			7,480 Paradox
Montrose	10-46N-17W	Amer. Liberty #1 Federal	At surface	4,590		10,544 Paradox
Montrose	18-47N-14W	Continental #1 Nucla	5,105	No salt in Paradox		7,618 Devonian (?)
Montrose	31-47N-18W	Chicago #1 Ayers				6,860 Upper Hermosa

Table 2.--List of wells shown on isopachous map (fig. 3).--Continued.

County	Section, township, and range	Company and farm	Depth to top Paradox member (feet)	Depth to top of salt-bearing rocks (feet)	Depth to base of salt-bearing rocks (feet)	Total depth and bottom formation
			Colorado			
San Miguel	9-42N-19W	Prestidge-Ailison #1 Long	5,820	6,137		6,211 Paradox
San Miguel	14-43N-19W	Reynolds #1 Egnar	4,955	5,440	9,640	10,220 Leadville
San Miguel	26-44N-13W	Turner #1 Buss	6,793	No salt in Paradox		8,790 Tertiary(?) igneous
San Miguel	13-45N-12W	Penrose Tatum #1 Marie Scott				2,561 Hermosa
			Utah			
Emery	9-19S-12E	Hancock Utah #1 Cedar Mountain	No Paradox present			4,940 Leadville
Emery	5-22S-12E	3 States Nat. Gas #1 Sinbad	No Paradox present			4,183 Precambrian
Emery	28-22S-15E	Equity #1 Govt.	No top	6,040	7,490	8,130 Leadville
Emery	27-23S-11E	Std. of Calif. #2 San Rafael	No Paradox present			4,900 Precambrian
Emery	28-24S-10E	Blackwood & Nichols #1-28 San Rafael	No Paradox present			4,182 Cambrian
Emery	34-25S-12E	Delhi #1 U. N. Russell	No Paradox present			6,008 Leadville
Emery	25-26S-13E	Tidewater #6-25	4,700	No salt		5,472 Molas
Emery	5-24S-15E	General Pet. 45-5-G	3,981	5,386	6,355	7,161 Leadville

Table 2.--List of wells shown on isopachous map (fig. 3).--Continued.

Utah

County	Section, township, and range	Company and farm	Depth to top Paradox member (feet)	Depth to top of salt-bearing rocks (feet)	Depth to base of salt-bearing rocks (feet)	Total depth and bottom formation
Garfield	24-34S- 7E	N. B. Hunt #1 Circle Cliffs	No Paradox present			5,628 Cambrian
Garfield	18-36S-10E	California #1 Muley Creek	No top	No salt		8,360 Devonian
Grand	23-20S-21E	Cont'l Un., Mtn. Fuel #1, Cisco Dome	No Pennsylvanian rocks			4,743 Precambrian
Grand	33-21S-21E	Pacif. West, Equity #1 Thompson	12,135	12,200		13,766 Paradox
Grand	20-21S-23E	Equity #1 Govt.	No Pennsylvanian rocks			3,810 Precambrian
Grand	2-22S-16E	Amerada #1 Green River	4,815	5,125		5,645 Paradox
Grand	2-22S-16E	Amerada #2 Green River	4,797	5,054		5,896 Paradox
Grand	32-22S-17E	Pacif. West. #1 Sharp St.	4,680	4,990		5,046 Paradox
Grand	4-22S-19E	Crescent Eagle	1,981?	2,155		4,009 Paradox
Grand	20-23S-18E	Equity #1 Donahue		5,516	5,962	6,618 Penn.-Miss.?
Grand	36-23S-19E	Equity #1 State	5,390	5,450	5,840	6,140 Hermosa ?
Grand	2-23S-20E	Pure #1 Salt Valley	2,480	2,750		3,036 Paradox
Grand	13-23S-20E	Utah South. #1 Southern King	1,015	1,570		3,829 Paradox

Table 2.--List of wells shown on isopachous map (fig. 3).--Continued.

Utah

County	Section, township, and range	Company and farm	Depth to top Paradox member (feet)	Depth to top of salt-bearing rocks (feet)	Depth to base of salt-bearing rocks (feet)	Total depth and bottom formation
Grand	31-23S-21E	Utah So. #1 Balsley	At surface			6,120 Paradox
Grand	12-24S-23E	Harry Hubbard #1 Federal	No Paradox			7,955 Hermosa
Grand	11-26S-19E	Tidewater #74-11 Big Flat	4,220	4,270	7,725?	8,408 Leadville ?
Grand	36-26S-20E	Midwest #1-A Shafer	2,048	2,130		3,095 Paradox
San Juan	16-27S-20E	Midwest #1 J. H. Shafer	1,580	1,610	5,490	5,863 Leadville
San Juan	35-29½S-20E	Reynolds #1 Gibson Dome		1,953	4,496	6,036 Miss.-Dev. ?
San Juan	16-30S-25E	Union #1 Utah St.	1,155	1,615		4,960 Paradox
San Juan	23-33S-24E	Byrd-Frost #1 Randall	5,654			6,265 Paradox
San Juan	17-33S-25E	Byrd-Frost #1 Sitton	5,661			5,828 Paradox
San Juan	30-34S-19E	Midwest #1 Hughes	1,260	1,570	1,950	4,422 Precambrian
San Juan	23-34S-25E	West. Natl. Gas #1 Redd	5,575	5,910	7,600	8,678 Elbert
San Juan	15-35S-25E	Gulf #1 Coalbed Canyon	5,568	5,875		5,912 Paradox
San Juan	22-38S-20E	Gr. West. Drlg. #1 Fish Creek	No tops			4,840 Cambrian
San Juan	13-38S-21E	Woodward Hawkings #1 Butler Wash	6,410			6,548 Paradox

Table 2.--List of wells shown on isopachous map (fig. 3).--Continued.

Utah

County	Section, township, and range	Company and farm	Depth to top Paradox member (feet)	Depth to top of salt-bearing rocks (feet)	Depth to base of salt-bearing rocks (feet)	Total depth and bottom formation
San Juan	35-38S-25E	Glasco, Shell #1 Govt.	5,341	5,650	6,875	8,054 Elbert
San Juan	15-39S-18E	Carter #1 Cedar Mesa	2,545	No salt		5,000 Cambrian
San Juan	29-39S-22E	Carter #1 Bluff Bench	5,810	6,040	6,810	7,811 Elbert
San Juan	32-39S-23E	Shell #1 Bluff Unit	5,942	6,135	6,860	8,762 Precambrian
San Juan	4-39S-24E	Reynolds #1 Hatch	5,764	6,050	7,150	8,815 Cambrian
San Juan	5-39S-25E	Hathaway #1-B Glasco-Fed.	5,415	5,800	6,920	7,621 Leadville
San Juan	5-40S-26E	Shell #1 Hovenweep	5,820	6,050	6,973	7,915 Elbert
San Juan	32-40S-20E	Al Hill #1 State	1,402	No salt		3,214 Elbert
San Juan	28-40S-18E	U.O.R. #1 U.S.O. Noble	1,180	No salt		3,630 Precambrian
San Juan	28-41S-26E	Superior #1 Navajo	5,917			6,152 Paradox
San Juan	10-43S-21E	Ohio #1 Navajo	5,110	No salt		6,944 Cambrian
Wayne	16-27S-16E	Phillips #1 Schick	4,093	No salt		5,191 Leadville

STRUCTURE

General description of region

The region underlain by salt of the Paradox member of the Hermosa formation lies within the Paradox fold and fault belt tectonic division of the Colorado Plateau as defined by Kelley (1955, p. 35-36). The division is bounded by the Uncompahgre uplift and Uintah Basin on the northeast and north; the San Rafael Swell on the northwest; the Henry basin, Monument upwarp, and Blanding basin on the southwest; and the Four Corners platform and San Juan dome on the southeast. Major structural features of the region are shown in figure 1 and smaller features in figure 3.

Most of the region is characterized by broad open folds having a northwesterly trend roughly parallel to the Uncompahgre uplift. In the southwestern part of the Paradox fold and fault belt the folds trend in a more northerly direction parallel to the Monument upwarp. Anticlinal folds in the southern and southwestern part of the tectonic division are widely spaced and of relatively low structural relief. In the central and northeastern parts the folds are crowded more closely together, are of greater length, and greater amplitude. In this region the axial portions of the larger anticlines have been downfaulted in a complex manner forming grabens many miles in length. Situated near the center of the band of faulted anticlines is the intrusive igneous complex of the La Sal Mountains. Structural features of the faulted anticlines are obscure in this area. Other areas of large-scale igneous intrusion in the Paradox fold and fault belt are the Abajo Mountains west of Monticello, Utah, and the Ute Mountains near the southwestern corner of Colorado.

The band of large faulted anticlines is located in the region which was formerly the deepest part of the Paradox salt basin and in which the greatest thickness of salt was deposited in Pennsylvanian time. The largest of the folds also are adjacent to the area of present maximum structural relief on the Uncompahgre uplift in western Montrose and San Miguel Counties, Colorado.

General structure and history of the salt anticlines

Most of the structural features depicted in figures 1 and 3 involve rocks of Late Cretaceous age; thus much of the deformation of these particular features occurred in latest Cretaceous or Tertiary time. However, it is known that some of the structures are superposed on much older features.

Erosion or downfaulting of Mesozoic rocks in most of the large anticlines in the northeastern part of the Paradox fold and fault belt has exposed cores of greatly contorted anhydrite, gypsum, black shale, and limestone of the Paradox member of the Hermosa formation in fault contact with younger rocks (fig. 4). At depth below the zone of leaching these rocks are composed mainly of salt. Detailed mapping of the faulted anticlinal structures by Baker (1933), Dane (1935), and McKnight (1940) in Utah, and by Stokes and

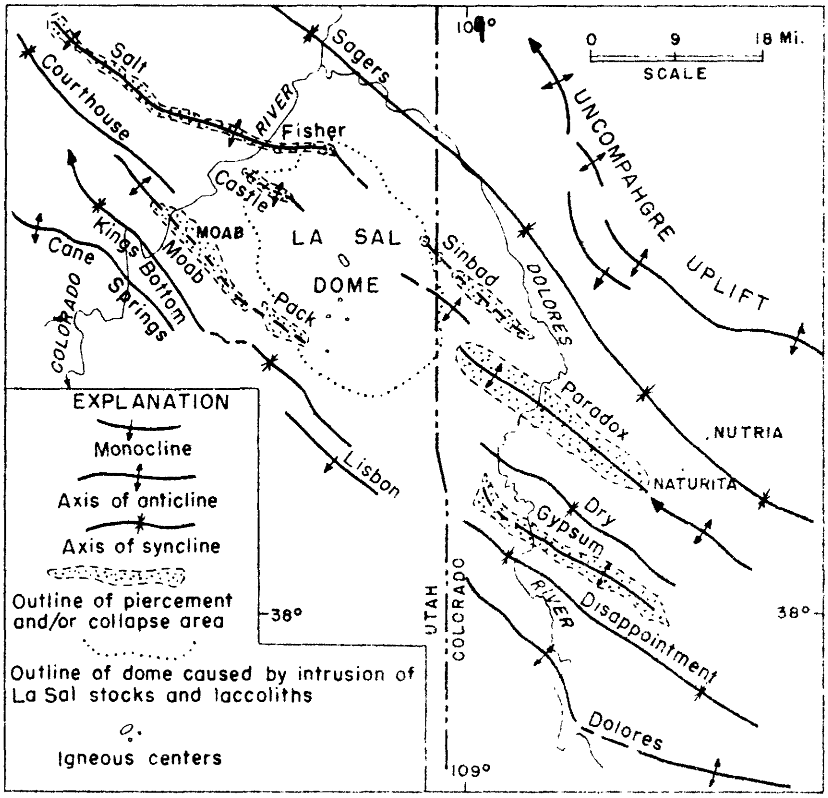

Figure 4.—Map of the principal folds and areas of piercement and collapse in the Paradox basin. (After Kelley, 1955, p.37)

Phoenix (1948), Cater (1954 and 1955, a, b, and c), and Shoemaker (1954 and 1956) in Colorado has disclosed abundant evidence that the gypsum and salt have risen in places as a semiplastic mass and pierced overlying sedimentary rocks. All of these writers agree that the flowage began in Early Permian time and continued intermittently during parts of Permian and Triassic time. Baker and Dane argue that, although folding occurred early, piercement did not occur prior to Late Cretaceous or early Tertiary time. Stokes and Phoenix, Cater, and Shoemaker believe that the intrusive evaporite bodies of the Colorado anticlines stood at the surface during parts of Permian, Triassic, and Jurassic time because of angular unconformities between the rocks on the flanks of the anticlines. The Morrison formation is said to be the oldest Mesozoic formation to overlap the salt bodies (Stokes and Phoenix, 1948). Apparently upward movement of the salt bodies halted for a period of time during which a thick sequence of Upper Cretaceous marine sediments was deposited. Cretaceous rocks are involved in the final phase of folding which seems to have been oriented along the pre-existing folds. The earlier-developed folds seem to have been much broader but shorter than the later folds.

The final phase of deformation appears to have been that in which the axial portions of the anticlines sagged or were downfaulted into the salt masses. This may have occurred as early as latest Cretaceous or early Tertiary time and continued in places until middle or late Tertiary time. Several mechanisms have been conceived to account for the collapse of the anticlines. Baker (1933, p. 65) has suggested that some of the faulting in the Moab anticline is of relatively recent date and resulted from uplift of overlying sediments accompanying the flowage of salt, and the later settling of strata due to solution and erosion of the salt.

Cater (1954) has suggested that the faulting began during relaxation of compressional forces following Late Cretaceous or early Tertiary folding. Further collapse is believed to have occurred in middle Tertiary time when erosion breached parts of the anticlines and removed large amounts of the salt. Lateral flowage of salt toward these areas of salt removal is believed to have caused the collapse in other parts of the fold. Kelley (1955, p. 41-42) has postulated that the collapse was partly due to loading of the folded area by a thick cover of Cretaceous rocks which upset isostatic load relations causing salt to flow backward causing collapse. In his view this early collapse was probably modified by Late Cretaceous and Tertiary deforming stresses, and later by ground-water action and erosion.

At any rate, evidence is at hand to indicate that the long, narrow grabens or structural troughs situated on anticlines over a large region are related to expanded thicknesses of salt. This concept was utilized in isopaching salt on other faulted structures for which data are sparse or lacking.

Smaller anticlinal structures in the central and southern parts of the Paradox salt basin also are believed to be areas where the salt has been thickened by flowage, but to a lesser degree than in the great anticlines to the northeast. Folding that involves competent rocks such as sandstone and limestone and interbedded incompetent rocks such as shale, gypsum, and salt, usually causes some flowage of incompetent rocks away from the flanks of the structures into the crests of anticlines and troughs of flanking synclines. In the case of the broad, low folds of the central and southern Paradox basin this effect probably would have been slight, but erosion of the crestal portions of these anticlines would cause a static imbalance between crest and flanks causing further flowage of salt into the anticlines. Thus it seems likely that some thickening has occurred on nearly all of the anticlines situated in the region of fairly thick evaporite deposits.

Classification and internal structure of salt folds

Folds associated with expanded thicknesses of salt in the Paradox basin may be considered as belonging to two groups which differ in general structure and origin. These may be classified following the definition of Levorsen (1954, p. 259-260) as salt domes and salt anticlines. A salt dome, as typified in the Gulf Coast region of the United States, is formed by doming and rupture of sedimentary rocks by an actively rising salt plug. The plug is forced upward presumably because of the plastic nature and lesser specific gravity of the salt, and because differential static pressures are exerted by rocks directly above the plug and those around the margin of the plug. In terms of rocks ruptured, intruded, and domed, the salt may be considered to play an active role. In the case of the salt anticline the salt is interbedded with the folded sediments and its role may be termed passive, being deformed with the enclosing sediments. Incompetence of the salt beds gives rise to anomalous folding different from that of more competent beds and the salt may be greatly deformed and even extruded at places.

Salt anticlines

Nearly all of the larger anticlines of the Paradox basin region seem to fit best the definition of salt anticlines. The great length of the anticlines and their alinement with other large structural features such as the Uncompahgre uplift indicates that their formation was due to tectonic forces active over the entire region, and not as the result of local upward movement of adjacent discrete salt plugs coincidentally or otherwise alined.

Distinct intrusive plugs or composite groups of plugs of evaporite rocks have been observed in all of the major anticlines of the northeastern part of the basin, and the plugs have been shown to be intruded into younger rocks in places. Shoemaker (1954, p. 51-55) has written a comprehensive summary of these features and has indicated distribution and shape of many of the plugs. The plugs are probably superficial to the larger buried salt cores and probably were formed as the result of internal readjustments in the salt bodies after regional folding produced the anticlines. Intrusive plugs may have been formed and modified during several periods.

Flowage of salt into the anticlinal areas from the flanking synclines during and after regional folding may have removed all or nearly all of the salt from the flanking areas at least in the case of the Dolores, Gypsum Valley, Paradox Valley, and Sinbad Valley anticlines in

Colorado. This conclusion is supported by several lines of evidence. Gravity surveys seem to indicate that little or no salt is present north of Paradox Valley anticline and between Paradox Valley and Gypsum Valley anticlines (Joesting and Byerly, in preparation). A strong positive anomaly is present also west and southwest of the Gypsum Valley anticline, and this may indicate complete withdrawal of salt from this area. The apparent cessation of upward movement on the anticlines in Late Jurassic time also may indicate at least partial exhaustion at this time of salt in the synclinal areas adjacent to the major anticlines.

If the upward movement of salt ceased temporarily in Late Jurassic time it is probable that hydrostatic equilibrium was reached between the salt in the flanks and central part of the anticlines. These equilibrium conditions would have been upset by deposition of Jurassic rocks and by a blanket of Upper Cretaceous shale and sandstone which was probably more than 6,000 feet thick. In the view of Kelley (1955, p. 41-42) this loading would have forced the salt back down and caused rupturing and subsidence of Jurassic and Cretaceous rocks across the crestal portions of the anticlines.

However, the present writer believes that loading of a thick blanket of sediments over the anticlines would have upset the equilibrium in such a way as to cause a renewal of upward movement of the salt. Whereas the crestal portions of the salt bodies were overlain by only the Morrison formation and Cretaceous rocks, the flanks of the salt bodies were overlain by Permian, Triassic, Jurassic, and Cretaceous rocks. Thus, the load on the flanks was greater than on the top of the salt bodies which should have caused the salt to move upward again. During and after deposition of the thick blanket of Cretaceous rocks isostatic conditions must have been similar to those pertaining in the Gulf Coast today, and some of the salt plugs of the Paradox fold and fault belt may have formed in Late Cretaceous time in response to these conditions.

Upward movement was probably accentuated in latest Cretaceous or early Tertiary time by regional compressive forces which rejuvenated and enlarged the older anticlines. Upward movement of the piercement bodies was undoubtedly facilitated by erosional unloading of rocks from the higher parts of the anticlines. Lateral flowage of salt from parts of the anticlines into the plugs may have caused part of the collapse of overlying rocks into areas from which salt was withdrawn. Later in Tertiary time deflation of the salt bodies by ground-water probably resulted in further collapse.

In the central and southern parts of the Paradox salt basin anticlinal folds exhibit much less structural relief, and no evidence has been found which would indicate that piercement of salt has occurred on these structures. Thickening of the salt appears to have occurred mainly as a response to slight normal flowage from the limbs of anticlines into the crests, perhaps aided in some measure by isostatic adjustments. It is unknown whether these anticlines are superposed on older structures or are entirely the result of Laramide deformation.

Salt domes

Several structures located in the west-central part of the Paradox salt basin southwest of Moab, Utah, seem to be more similar to salt domes of the Gulf Coast than do the plugs on the large salt anticlines.

The Upheaval dome is a nearly circular uplift surrounded by a rim syncline and has almost exactly the shape of an ideal theoretical salt dome. McKnight (1940, p. 126-128) has argued that this is, in fact, a salt dome, but others have argued that the features may be cryptovolcanic in origin. The question has not been resolved.

The Meander anticline is believed to have resulted from upward flowage of salt and slight piercement of overlying rocks caused by static imbalance resulting from unloading of sediments in an area which has been deeply dissected by the Colorado River (McKnight, 1940, p. 123-124). Although the Meander anticline is an elongate feature it seems to have been formed as the result of differential static pressures rather than as a result of tectonic activity. Downfaulting in the Needles fault zone east of the Meander anticline may have resulted from extraction of underlying salt which flowed into the anticline (Baker, 1933, p. 74).

The Lockhart anticline and Rustler dome are in an area of considerable erosion adjacent to the Colorado River and probably are underlain by a thickened salt section. Lockhart syncline is a roughly circular closed basin located about midway between and east of Lockhart anticline and Rustler dome. The origin of this basin is probably related to migration of salt from this area into the anticlines (Baker, 1933, p. 71).

Cane Creek anticline, Shafer dome, and Gibson dome also are located in deeply eroded areas adjacent to the Colorado and presumably are underlain by thickened salt bodies.

Igneous intrusive rocks

Three large groups of laccolithic intrusive bodies occur within the Paradox salt basin and others occur near the margins. The groups within the basin are the Abajo and La Sal Mountains in Utah and Ute Mountain in Colorado. Little is known of the effect of the intrusive igneous rocks on salt. Some evidence, however, indicates that in places near the La Sal Mountains and Ute Mountain sills and other bodies were injected in selective fashion into the salt-bearing part of the Paradox member of the Hermosa formation. Little or nothing is known of relation of igneous bodies of the Abajo Mountains to salt.

In the La Sal Mountains laccoliths have been intruded mainly near the top of the salt-gypsum bodies (Shoemaker, 1954, p. 56), and domes surrounding stocks of igneous rock are superimposed on the salt anticlines. What the total effect on the salt has been in this area is not known.

Thick sills have been intruded into the salt on the north flank of Ute Mountain. This is shown in logs of wells drilled in the area. Whether the intrusion of igneous rocks was accomplished by stoping and digestion of salt or whether the salt was forced out by the igneous rocks is not known. Increased mobility of the salt engendered by heat and pressure from the invading magma may have caused the salt to flow northward into the area of McElmo dome. On the other hand, this dome may be underlain by igneous rocks rather than by a thickened section of salt.

The Byrd-Frost No. 1 Uhl well on the Dolores anticline in Colorado bottomed at a depth of 7,680 feet in metamorphosed Paradox beds after penetrating approximately 1,515 feet of salt-bearing rocks. The metamorphosed rocks are believed to overlie Tertiary igneous rocks which have been intruded into the Paradox member.

The Continental No. 1 Lone Dome well drilled several miles east of the Dolores anticline penetrated the entire Paradox member and penetrated a sill of igneous rock enclosed in salt beds between 8,320 and 8,430 feet.

A large pluglike body of igneous rock is present in the central part of Castle Valley anticline west of the La Sal Mountains in Utah. This plug is intruded into the evaporite core of the anticline. Baker (1933, p. 62) has found no evidence indicating that Castle Creek anticline is underlain by a large body of igneous rock but indicates that some of the upward movement of the core was possibly the result of heat and pressure exerted during intrusion of the igneous rock.

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