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October 24, 1958

AEC-137/9

Dr. Joseph A. Lieberman
Chief, Section of Sanitary Engineering
Engineering Development Branch
Division of Reactor Development
U. S. Atomic Energy Commission
Washington 25, D. C.

Dear Joe:

Transmitted herewith are 50 copies of TEI-725, "Summary of rock salt deposits in the United States as possible disposal sites for radioactive waste," by W. G. Pierce and E. I. Rich, May 1958.

We plan eventually to revise this report for publication by the Geological Survey.

Sincerely yours,

V. T. Stringfield
V. T. Stringfield
Chief, Radiohydrology Section
Water Resources Division

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# SUMMARY OF ROCK SALT DEPOSITS IN THE UNITED STATES AS POSSIBLE DISPOSAL SITES FOR RADIOACTIVE WASTE*

By

W. G. Pierce and E. I. Rich

May 1958

Trace Elements Investigations Report 725

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It is not for public inspection or quotation.

*This report concerns work done on behalf of the Division of Reactor Development of the U. S. Atomic Energy Commission.

USGS - TEI-725

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# CONTENTS

ILLUSTRATIONS

TABLES

# SUMMARY OF ROCK SALT DEPOSITS IN THE UNITED STATES AS POSSIBLE DISPOSAL SITES FOR RADIOACTIVE WASTE

By W. G. Pierce and E. I. Rich

## ABSTRACT

This summary report on the rock salt deposits of the United States has been prepared as a part of the study of radioactive waste disposal. A thick salt bed, as a place for the storage or disposal of radioactive waste products, is viewed with favor because salt, being relatively plastic, seals itself and eliminates the likelihood of space within it coming in contact with ground water. Consequently, information on the geologic occurrence of salt, and the distribution, thickness and depth below the surface of all of the known rock salt deposits of the United States is assembled here so that the possibilities of radioactive waste disposal in salt beds may be considered in conjunction with plans for the geographic location of power reactors and fuel element processing plants.

Salt deposits are widely distributed over the United States, being known to occur in 23 of the 48 states. Not only is salt widely distributed, but some of the deposits have a lateral extent of several hundred miles. Bedded salt does not commonly occur at the surface, however, because it is readily soluble and has been removed by solution. Consequently, most of the information on the thickness and extent of the salt is interpreted from drilling records.

The Silurian salt deposits of the northeastern United States underlie parts of New York, Pennsylvania, West Virginia, Ohio, and Michigan. The salt is in the Salina formation of Late Silurian age and was deposited in two tectonic basins connected at times by the Chatham sag on the Cincinnati arch. The Salina formation ranges in thickness from a few feet up to 3,000 feet and consists of shale, dolomite, limestone, salt, anhydrite, and gypsum. The dominant structural elements are the Michigan basin, which is an elliptical-shaped structural basin with its center in the southern peninsula of Michigan, and the Appalachian basin, which in the area of the salt deposits slopes southeastward, with increasing structural complexity down the regional dip to the southeast. The greatest aggregate thickness of salt is in the Michigan basin. In the center of the basin the combined thickness of all the salt beds is about 1,800 feet. From this point it thins in all directions to about 500 feet at Lake Michigan on the west and Lake Huron on the east and north. In New York State a maximum combined thickness of 800 feet of salt beds is found south of the south end of Seneca Lake; these beds thin to less than 100 feet within a distance of 60 miles to the east, south, and west, and within 35 miles to the north. In eastern Ohio, the combined thickness of salt beds ranges from 0 feet on the western border of the basin of deposition to a maximum of 300 feet at the eastern edge of the State. A thickness of 100 to 200 feet prevails along the western border of Pennsylvania, thins eastward, and is absent to the southeast. In Michigan the depth to the top of the salt ranges from 500 feet or more on the borders of the basin to 6,000 feet in the center. In northern Ohio, northwestern Pennsylvania and southern New York it is about 1,000 feet to the salt, and the depth to salt increases southward.

In the Gulf Coast embayment, salt deposits underlie parts of southern Arkansas, eastern and southern Texas, Louisiana, Mississippi, and Alabama. The Louann salt in the Eagle Mills formation of Jurassic or Permian age underlies southern Arkansas, and is presumed to continue southward beneath the Gulf of Mexico. Along the Gulf Coast the salt bed lies at a depth of 20,000 to 30,000 or more feet, but salt domes, in which the salt has migrated upward, are found at various depths, some within a few feet of the surface. More than 200 salt domes are now known, either from drilling or geophysical evidence. They are roughly circular and range in diameter from less than a mile to more than four miles. The height of salt domes above their base is extremely variable, depending on the amount of piercement of the overlying sediments that has taken place. In domes that have risen to near the present land surface it may be 10,000 to 20,000 feet to the base of the salt in the salt dome structure. A caprock, composed mostly of anhydrite, gypsum and limestone, may cover the top of the salt dome and extend over the sides like a hood. The caprock has a thickness of 300 feet or more on shallow domes but on deep domes it is thin or absent. Formation of the salt domes began as early as early Eocene time, and on some has continued into very recent time. The composition of the salt-dome deposits is almost pure sodium chloride; anhydrite, in black color bands, is the principal impurity.

The salt deposits of the Permian basin, underlying parts of Kansas, Colorado, Oklahoma, Texas, and New Mexico, have a linear extent of 650 miles and a width of 150 to 250 miles. The salt deposits are progressively younger from northeast to southwest; those in Kansas, Oklahoma, and the northern part of the Texas Panhandle belong to the middle series of Permian age (Leonard series), whereas in southeastern New Mexico and southwestern Texas they belong to the upper series of late Permian age (Guadalupe and Ochoa series). In Texas, New Mexico, and Oklahoma, gypsum and anhydrite occur abundantly in close association with the salt. In Kansas there seems to be but little anhydrite or gypsum either interbedded with the salt or closely associated with it, although thick deposits of gypsum are reported from both higher and lower beds. The thickest and most extensive salt beds in the Permian basin are in the Castile, Salado and Rustler formations in the Ochoa series of late Permian age. Salt beds in the Castile formation have a maximum total thickness of more than 600 feet but usually have a total thickness of less than 250 feet. In the Delaware basin the halite beds are separated by beds of anhydrite 50 to 500 feet thick, with halite comprising less than 40 percent of the formation. Halite comprises 75 to 90 percent of the Salado formation except where much of the salt has been removed by solution, or near the depositional margins of the formation. The thickest accumulation of halite in the Salado is on the north and east edges of the Delaware basin, where more than 1,700 feet is present in a narrow band. On the adjacent shelf area, salt in excess of 1,000 feet is confined to a relatively small area. The thickness of overburden on the Salado salt ranges from 400 feet in the southwestern part of its extent, to more than 2,500 feet in the northern part. The Rustler formation, the highest Permian salt-bearing unit in western Texas and southeastern New Mexico, has a relatively small amount of salt. In the Panhandle of Texas, salt occurs in the lower part of the Clear Fork group of Leonard age. It is interbedded with red shale, anhydrite and some dolomite. Individual beds of salt are as much as 225 feet thick but usually are less than 50 feet and make up only 15 to 20 percent of the Clear Fork group. In southwestern Kansas the most widespread salt zone is in the Wellington formation. This salt has been mined at places such as Hutchinson, Lyons, and Kanopolis, Kansas. The area underlain by the thicker salt beds extends from near the center of Kansas southwestward across the State into the easternmost part of the Oklahoma Panhandle. In central Kansas the aggregate thickness of salt is about 400 feet, but it thins irregularly toward the margins of the basin where, together with anhydrite, the salt interfingers with shale. The thickness of the overburden above the salt beds ranges from about 400 feet in east-central Kansas to more than 1,500 feet east of the Oklahoma Panhandle.

The Paradox basin is a sedimentary basin, elongate northwesterly, covering 12,000 square miles in southeastern Utah and southwestern Colorado. The thick salt deposits are in the Paradox member of the Hermosa formation, of Pennsylvanian age. The salt occurs in an elongate northwest-trending area 160 miles long and 80 miles wide, sharply bordered on the northeast by the Uncompahgre uplift. Most of the Paradox basin is characterized by broad open folds trending northwest. Anticlinal folds in the southern and southwestern part are widely spaced and of relatively low structural relief, but in the central and northeastern parts the folds are closer together and are longer and higher. Two factors control the thickness of salt in the Paradox basin--the original basin of salt deposition and the subsequent flowage of salt into anticlines. Salt as much as 4,000 feet thick was deposited in the deepest part of the sedimentary basin. Subsequent flowage of salt into anticlines has formed thicknesses of salt from 3,000 to 12,000 feet. The depth to the top of the salt varies greatly, owing to folding and deformation of the salt-bearing beds. In many of the wells drilled on anticlinal folds, the depth to salt ranges from 5,000 to 8,000 feet. In some parts of the area, however, salt is near the surface.

In east-central Arizona and west-central New Mexico, salt occurs in the Supai formation of Permian age. Data from a few wells indicate a maximum aggregate thickness of salt of about 550 feet, in which individual beds of salt range from 80 to 160 feet in thickness. The depth to the top of the salt-bearing Supai formation ranges from 650 to 800 feet.

A few deep wells in southern Florida have penetrated salt in Lower Cretaceous rocks at depths to 11,000 to 12,000 feet. The total thickness of the salt is not known to exceed 30 feet.

Recent drilling in the Williston basin, in western North Dakota and adjacent parts of Montana and South Dakota, has disclosed a series of 11 salt beds at considerable depth below the surface. It has been calculated that these beds contain a total volume of about 1,700 cubic miles of salt in that part of the Williston basin lying in North Dakota. The oldest and thickest bed of salt is in the Prairie formation of Devonian age. The salt bed has a maximum thickness of about 400 feet, and lies at depths ranging from 6,000 to 12,000 feet. In the overlying beds of Mississippian age seven salt beds are known, with an aggregate maximum thickness of over 300 feet in the middle of the basin. These beds are from 5,000 to 9,000 feet below the surface. A salt bed ranging from 100 to 150 feet in thickness occurs in the Opeche formation of Permian age. Overlying it is a sequence of red beds containing the Pine and Dunham salt beds of Triassic or Jurassic age. These beds have maximum thicknesses of 300 and 100 feet and lie at depths of 4,000 feet or more below the surface.

In addition to these larger deposits of salt, several other occurrences are known. In the Sevier River valley, near Redmond, Utah, salt is present in the Arapien shale of Jurassic age. It occurs at the surface and is mined from open pits. In southeastern Nevada, along the Virgin River, several dome-like rock salt deposits occur in the Muddy Creek formation of Pliocene (?) age. In southwestern Wyoming and adjoining areas salt has been penetrated in drilling in the lower part of the Preuss formation of Jurassic age, and in the northwestern corner of Nebraska a well penetrated salt in rocks of Pennsylvanian age.

Over 24 million tons of salt is produced annually in the United States, of which about three-fourths is produced as brine or evaporated salt and one-fourth as rock salt. The rock salt is produced from 16 operating mines. Five of the mines are in the Silurian salt deposits of the northeastern States, six are in salt domes of the Gulf Coast embayment, three are in Kansas in the Permian basin deposits, and two small mines are in the Sevier Valley, Utah. Our reserves of rock salt are so stupendous as to be practically inexhaustible for human purposes.

The recent development in creating underground storage for liquified petroleum gas may furnish some information of use in considering underground disposal of radioactive wastes. In the last six years 34 million barrels of storage capacity has been created in underground cavities, of which over 28 million barrels is in salt deposits. The developed capacity in depleted oil and gas fields and similar geologic structures is about 4 million barrels, and about 1 million barrels of storage has been created in mined space in shale and chalk. Creating storage space in salt is the least expensive of the above types, the cost ranging from $1.00 or less to $2.00 per barrel for dissolved cavity space, compared to $3.00 to $7.00 for mined space in shale or chalk. Most of the liquified petroleum gas storage is in Texas, where over 25 million barrels of underground storage has been created. Of this, over 90 percent is contained in about 150 caverns in salt domes or salt beds.

# INTRODUCTION

This report has been prepared as a part of the study of the broad problem of radioactive waste disposal(Hedman, 1956; Culler and McLain, 1957; Hess, 1957). Previous work on the problem of atomic waste disposal has indicated that salt deposits have several favorable features as media for disposal of the wastes (Heroy, 1956; Gloyna and others, 1957; Theis, 1957). Some consideration has also been given to disposal in deep wells (Pecsok, 1954; de Laguna and Blomeke, 1957; Roedder, 1957). The aim of the present report is to assemble such information as is readily available on the rock salt deposits of the United States, so that factors such as geographic distribution, thickness, and depth of the salt can be considered in conjunction with the many other factors of the problem of disposal of radioactive waste. This work was done by the U. S. Geological Survey on behalf of the Division of Reactor Development of the U. S. Atomic Energy Commission.

Since possible disposal of radioactive waste products in salt envisions disposal in a bed or mass of salt, there is no need to be concerned with salt brines, salt springs, or surface deposits of salt. The deposits discussed are rock salt, either bedded like those in Michigan and New York, or plastically deformed masses such as the Gulf Coast salt domes. They are composed almost entirely of the mineral halite, or common salt, which is composed of sodium chloride (NaCl); the term salt as used in this report will refer to sodium chloride.

To avoid too much detail, and to present a simplified general picture of the salt deposits, it has been necessary in most instances to show the aggregate thickness of salt in the areas described, rather than the individual thickness of the beds of salt. For example, the log of a well may show 40 feet of salt, 60 feet of dolomite, 20 feet of salt, and 40 feet of dolomite and salt, of which salt makes up 50 percent. The single figure used for reporting the thickness of salt at this place is the aggregate thickness of 80 feet. In order to evaluate the suitability of specific salt deposits for disposal of radioactive waste materials, eventually it will be necessary to break the aggregate thicknesses of salt down into thicknesses of individual beds. In some areas or deposits, this can be done from existing information, but in others it will be necessary to conduct exploratory operations to obtain the information. Because salt is very soluble, it is rarely found at the surface. For the same reason it is difficult to ascertain accurate measurements of the thickness or purity of salt beds in wells unless unusual procedures are followed such as drilling with a saturated solution.

Rock salt deposits in the United States are more widely distributed than is generally assumed, being known in 23 States (fig. 1). Some deposits also are extensive, such as the Silurian salt which underlies most of Michigan and considerable parts of New York, Ohio, Pennsylvania and West Virginia. The various areas are discussed geographically, in general, by the original basins of salt deposition.

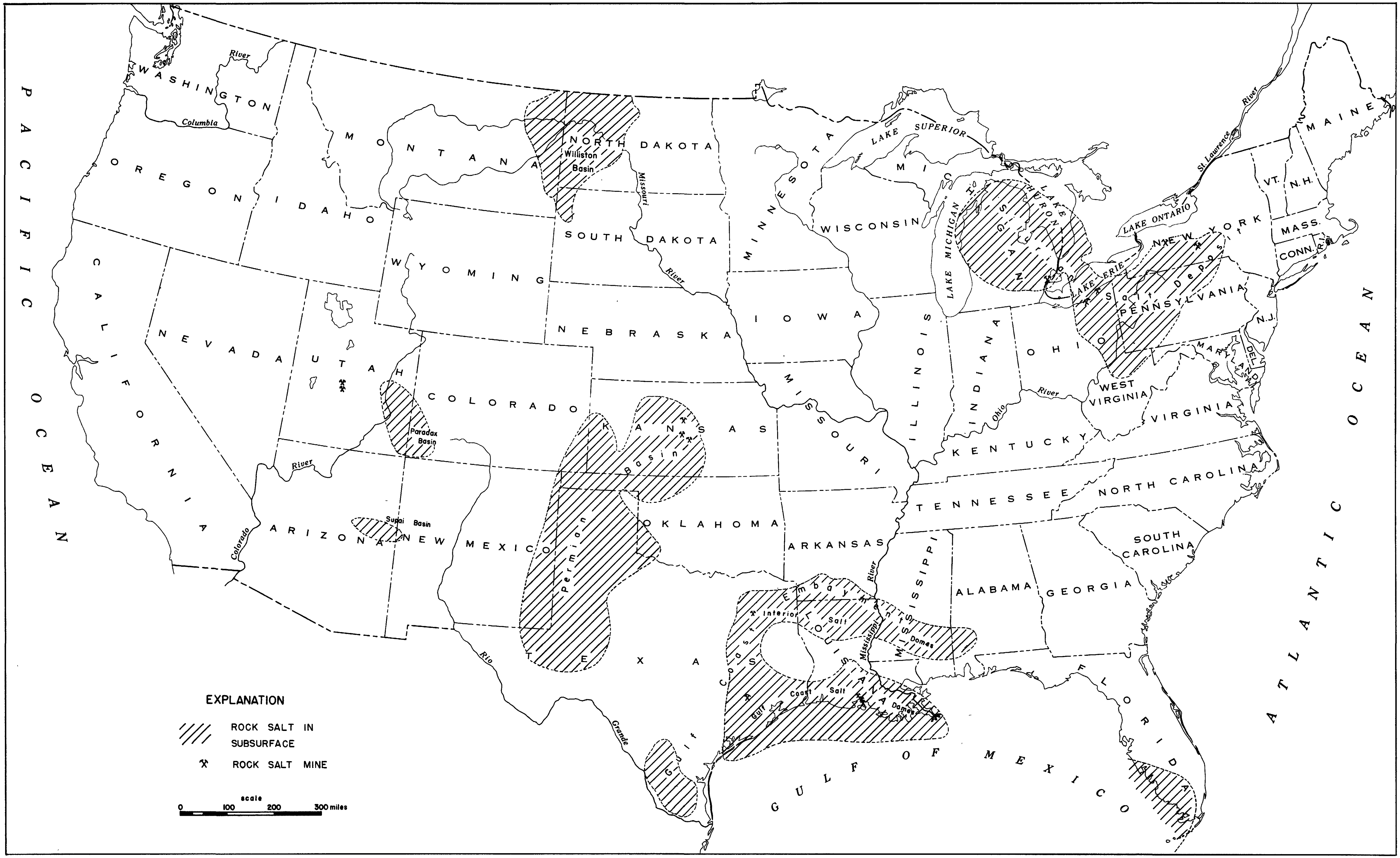



**Figure I. Index map of rock salt deposits in the United States.**

# SILURIAN SALT DEPOSITS OF THE NORTHEASTERN UNITED STATES

## Introduction

The Silurian salt deposits of the northeastern United States represent one of the great accumulations of salt in the world. These deposits are in the Salina formation of Late Silurian age, and underlie parts of New York, Pennsylvania, West Virginia, Ohio, and Michigan. They also extend into southwestern Ontario (fig. 2). The total area underlain by salt is approximately 100,000 square miles and, as the average thickness is of the order of 150 feet, about $4.18 \times 10^{14}$ cubic feet or about $2.7 \times 10^{13}$ tons of salt are present in the area.

The salt was deposited in two tectonic basins that were connected, at least at times, by a constriction that extended across southwestern Ontario. The eastern lobe of the salt basin lies in the Appalachian basin, the western lobe in the Michigan basin. The connecting constriction is along a sag on the Cincinnati arch. The present shape and extent of the salt basin is approximately the same as the original area of salt deposition, though in western New York there probably was a short northerly extension of deposition beyond the present northerly limit of salt beds.

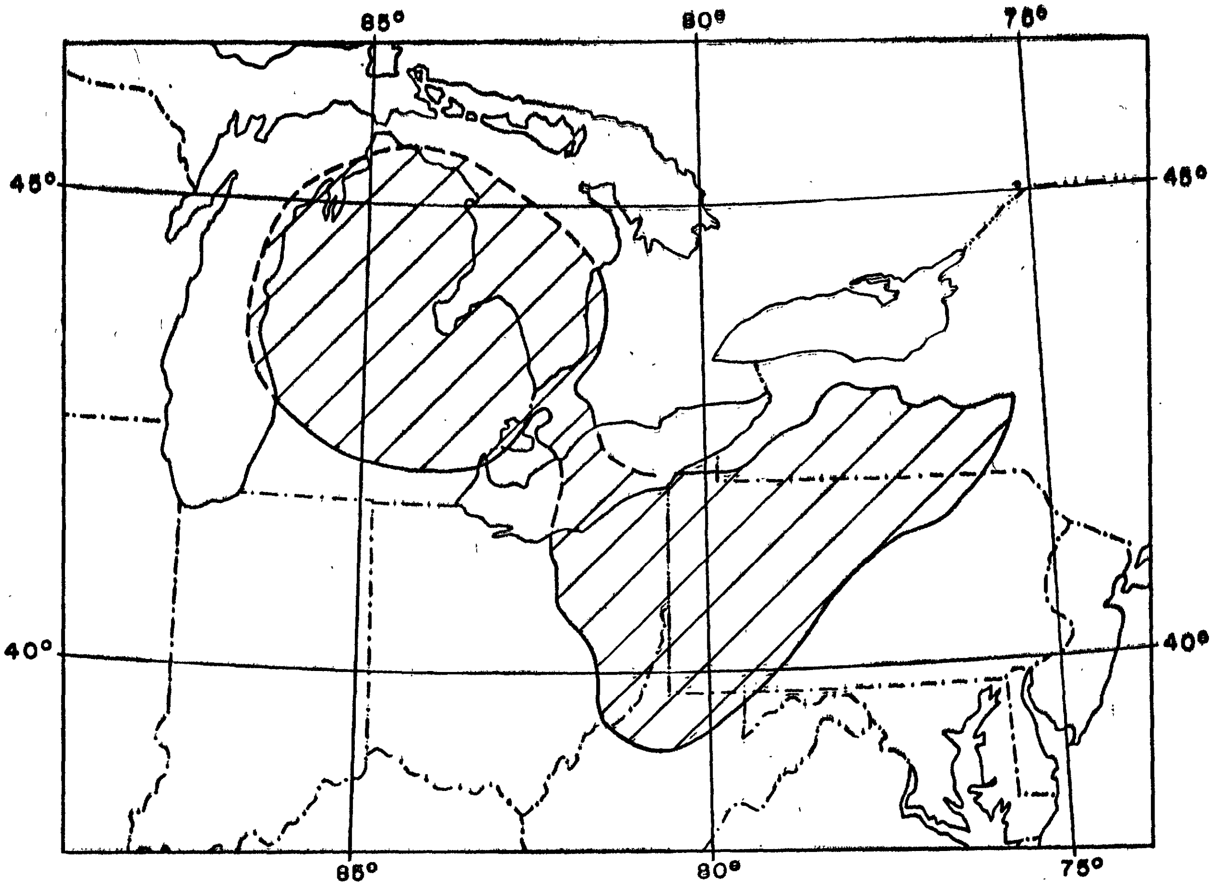



Figure 2. Index map showing the approximate extent of the Silurian salt deposits of the northeastern United States.

The information presented here is mainly a synthesis of published material compiled and integrated into an unpublished report by Roy L. Griggs, U. S. Geological Survey (in preparation). In that report, extensive use was made of Landes' (1945) study of the stratigraphy of the Salina formation in the Michigan basin. Likewise, the work of Pepper (1947) on the extent and thickness of salt in Ohio, of Alling (1928) on the occurrence and origin of the salt in New York, and summary reports of Martens (1943) and Fettke (1955) on the salt in West Virginia and Pennsylvania were most useful. In addition, many sample logs are available for the Michigan, Pennsylvania, and West Virginia portions of the salt basin. Some unpublished data were furnished by J. F. Pepper of the U. S. Geological Survey.

## Stratigraphy

The Salina formation, or group of some authors, was named by Dana in 1863 (Dana, 1863, p. 246) from exposures in Onondaga and Cayuga Counties, New York. Since 1863, the usage of Salina has been extended to those parts of Pennsylvania, West Virginia, Ohio, and Michigan where a salt-bearing sequence of Late Silurian age is recognizable. Locally, the name is used beyond the actual lateral extent of salt beds.

The approximate extent of the Salina formation is shown on figure 3. Most of this extent is in the subsurface. The outcrops of the formation form a narrow band through central and western New York and southwestern Ontario (fig. 4). Poor exposures also occur in places along the Cincinnati arch in northwestern Ohio. The remaining part of the outcrop belt on the north and west lies beneath Lakes Huron and Michigan. At its eastern limit, the Salina pinches out or passes into other formations in the subsurface. At its northeastern limit (fig. 4 and 5), the Salina terminates against a highland in the Helderberg area west of Albany, N. Y. (Goldring, 1931, p. 337). This local highland was an effective barrier throughout Salina deposition. Farther south, along the Appalachian Mountains to northeastern Tennessee, rocks equivalent in age to the Salina are represented on the outcrop by the Wills Creek shale and the Bloomsburg red beds (Swartz and others, 1942). The salt-bearing sequence has passed eastward in the subsurface into marine and continental clastic deposits. South of the salt basin the Salina thins rapidly and disappears. For the most part this thinning and disappearance takes place in the subsurface along a line that trends northwesterly across Ohio. There are poor exposures of dolomite, which should be referred to the Salina formation, along the Cincinnati arch in northwestern Ohio, however.

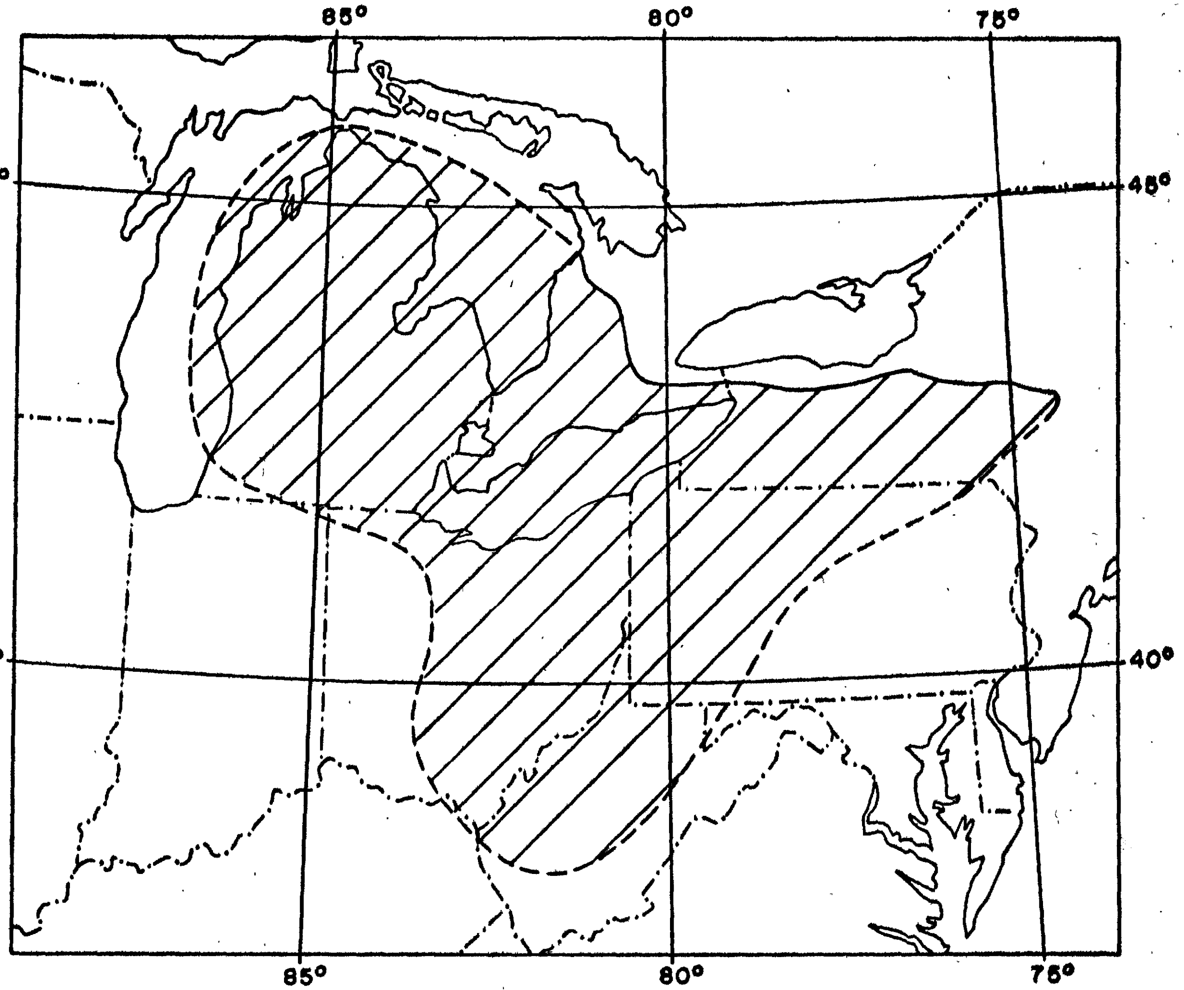



Figure 3. Index map showing the approximate extent of the Salina formation. Dashed line indicates inferred position.

The Salina formation ranges in thickness from 0 to nearly 3,000 feet and consists of shale, dolomite, limestone, salt, anhydrite, and gypsum. The thickest sections are in southern New York and in the Michigan basin. Shale is an important constituent near the eastern and northern limits of the formation. The carbonate, mainly dolomite, increases in abundance to the southwest. The salt, anhydrite, and gypsum occur in several beds, and the salt reaches its maximum thickness in the center of the Michigan basin.

Over much of its extent the Salina has not been subdivided, but in Michigan seven, and in New York, five, formal members have been recognized.

## New York

In New York the Salina formation crops out along a narrow belt from west of Albany westward to Niagara Falls. It passes southward into the subsurface dipping about 45 feet per mile. Near the Pennsylvania border the top of the unit locally reaches depths of nearly 5,000 feet. Five formal members are recognized. These are, in ascending order, the Pittsford shale member, the Vernon shale member, the Syracuse salt member, the Camillus shale member and the Bertie limestone member (fig. 6).

The Pittsford shale member is of local extent in western New York where it rests conformably on the Lockport dolomite of Middle Silurian age. It ranges in thickness from 0 to about 20 feet and consists of dark-gray to black shale.

| | Mackinac Straits area of the Northern Peninsula of Michigan | Michigan Basin | Southwestern Ontario | Ohio | Western Pennsylvania and western West Virginia | Central New York | |
|---|---|---|---|---|---|---|---|
| UPPER SILURIAN | St. Ignace formation (dolomite) | Bass Island dolomite | Bass Island dolomite | Bass Island dolomite | Tonoloway (?) limestone | Manlius ls. | |
| | | | | | | Roundout ls. | |
| | | | | | | Cobleskill dolo. | |
| | Pointe aux Chenes fm. (red and green shale with some thin beds of dolomite and gypsum). | Salina fm. (salt, dolomite and anhydrite with some beds of shale). Seven informal members designated A to G. | Salina fm. (shale, dolomite, salt, and anhydrite). | Salina fm. (dolomite, salt, and anhydrite with some thin beds of dolomitic shale). | Salina fm. (dolomite, salt, and anhydrite with some shale). | Salina formation | Bertie ls. member |
| | | | | | | | Camillus sh. member (shale with some dolomite and gypsum) |
| | | | | | | | Syracuse salt member |
| | | | | | | | Vernon sh. member (red and green shale) |
| | | | | | | | Pittsford sh. member (local) |

Figure 6. Correlation chart of the Upper Silurian in the area of the Silurian salt basin of the northeastern United States (with lithologies indicated).

The Vernon shale member is a purplish-red and grayish-green shale which, near its eastern limit, contains some thin beds of gypsum. This member is continuous along the strike in New York from the easternmost exposures of the Salina formation westward to near Niagara Falls. It rests conformably on the Pittsford shale member and on the Lockport dolomite. It attains a maximum thickness of about 600 feet near Syracuse, and thins both to the east and west. Presumably, this member passes southward in the subsurface into the Bloomsburg red beds of eastern Pennsylvania, Maryland, and West Virginia.

The Syracuse salt member rests conformably on and possibly interfingers with the Vernon shale member. It ranges in thickness from 0 near the eastern limit of the Salina formation to a maximum of about 2,500 feet in a basin southwest of Syracuse. This member consists of beds of salt and interbedded gray shale and dolomite. As many as six beds of salt are present in places, and the aggregate thickness of salt beds reaches a maximum of about 900 feet in the basin southwest of Syracuse. (See fig. 4.) According to Alling (1931, p. 24), traces of sylvite, polyhalite, and carnallite are present in the salt.

The Camillus shale member ranges from about 40 to 600 feet in thickness. This member rests conformably on the salt sequence in New York and consists of gray dolomitic to calcareous shale, shaly dolomite and dolomitic limestone, gypsum, and anhydrite. According to Alling (1931, p. 25) the gypsum (and presumably the anhydrite) occurs as lenses.

Above the Camillus shale member in New York is the Bertie limestone member. This, the uppermost member of the Salina formation in New York, is represented by about 50 feet of fine-grained, argillaceous grayish-buff dolomitic limestone.

## Michigan

The Salina is mainly a subsurface formation in Michigan. Exposures are limited to a very small area in the southeastern corner of the state. In the subsurface it reaches a thickness of nearly 3,000 feet in the center of of the Michigan basin where the top of the formation lies at a depth of over 6,500 feet. Studies of well records by Landes (1945) have shown that the formation is divisible into seven traceable members. These seven members have been designated A through G, A being the oldest and G the youngest (fig. 7). Three of the members (C,E,and G) are predominantly shale, three (B,D, and F) are predominantly salt, and one (A) is predominantly dolomite near the margin of the basin and predominantly salt near the center of the basin. The aggregate thickness of the salt beds is shown on figure 4.

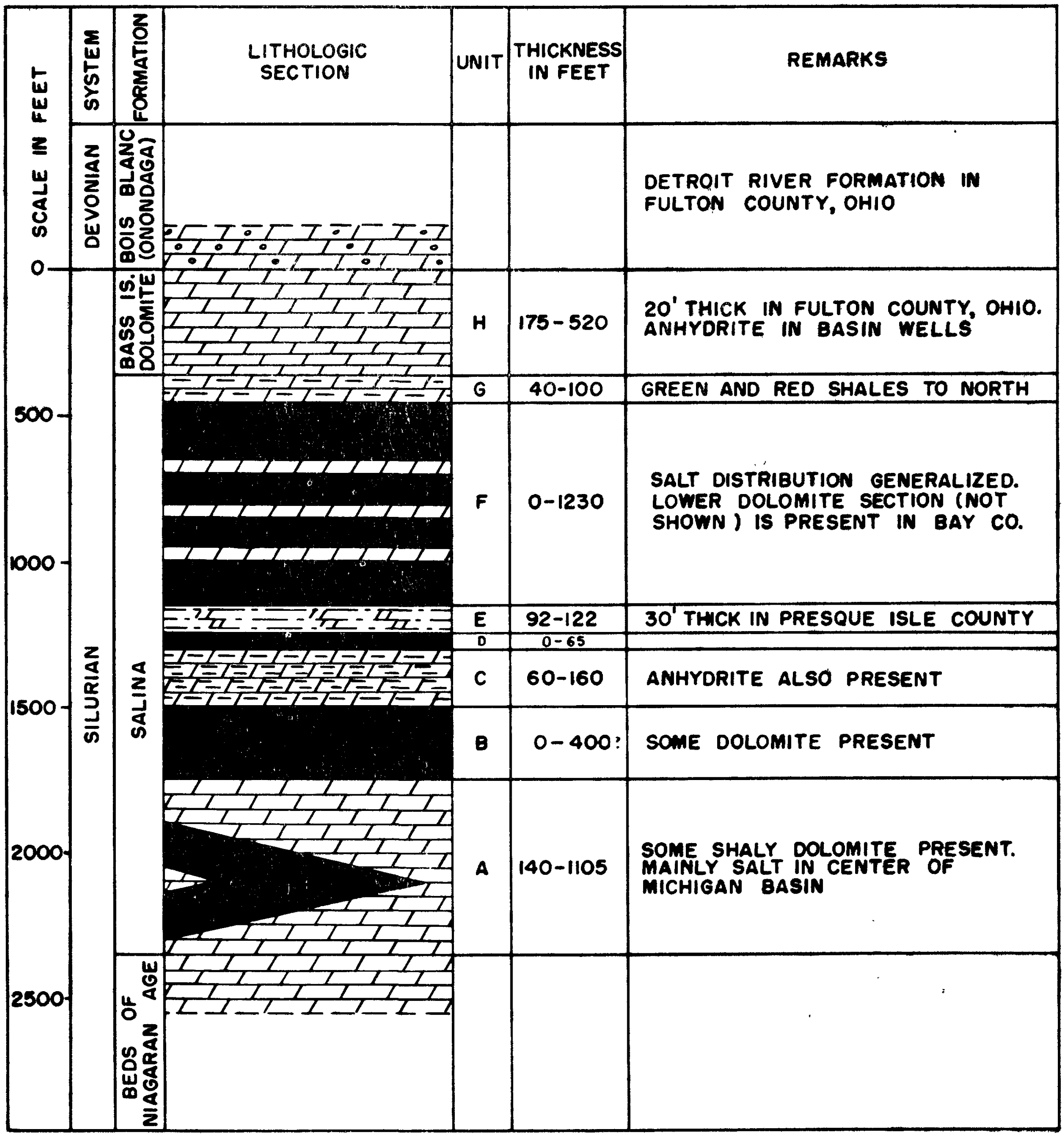



FIGURE 7. GENERALIZED COLUMN OF SALINA AND BASS ISLAND FORMATIONS IN THE MICHIGAN BASIN. (AFTER LANDES, 1945)

EXPLANATION

DOLOMITE
DOLOMITE, CHERTY
DOLOMITE, SHALY
SHALE, DOLOMITIC
SALT

Unit A, the oldest, rests with apparent conformity on beds of Middle Silurian age. It ranges in thickness from about 100 feet near the margin of the basin to over 1,100 feet in the center of the basin. This member consists of dolomite and shaly dolomite around the basin margin. Toward the center of the basin it contains increasing amounts of salt. One well near the center of the basin penetrated 872 feet of salt. This particular salt sequence, which contains numerous paper-thin laminae composed of dolomite and anhydrite, is actually 930 feet thick in the well, but it contains a medial sequence of dolomite 58 feet thick.

Unit B, absent at the very outer margin of the basin, is of relatively uniform thickness over most of the basin where it ranges from about 240 to 275 feet in thickness. This member is about 90 to nearly 100 percent salt. It contains some laminae of dolomite, and a 30-foot sequence of dolomite has been noted in the upper part of the member in the southeastern part of the basin.

Unit C consists of greenish-gray shale and shaly dolomite with some anhydrite. Beds of buff dolomite begin to appear in the southern part of the Michigan basin. This unit ranges in thickness from 60 to 160 feet.

Unit D generally ranges from 25 to 65 feet in thickness. It is nearly pure salt but contains a thin bed of buff dolomite in places.

Unit E ranges in thickness from about 30 to 125 feet and thickens to the south. In the northern part of the basin it consists of red shale. Farther south it is represented by shaly dolomite, anhydrite, and red or gray shale. In the southern part of the basin it grades to buff and gray dolomite with some anhydrite.

Unit F is mainly salt, but Landes (1945) has estimated that it ranges from about 50 to nearly 100 percent salt. It consists of thick sequences of salt separated by thin sequences of shale, shaly dolomite, and dolomite. Some anhydrite is generally present, particularly in the shale beds. This unit ranges in thickness from 0 to over 1,200 feet. It is absent near the margins and thickest at the center of the basin. According to Landes (1945) the percentage of salt in this unit increases outward from the center of the basin. The highest percentage of salt is near the north edge of the basin.

Unit G is about 80 to 100 feet thick over most of the Michigan basin, but near the southern limit of the basin it thins rapidly to about 50 feet. The unit consists mainly of shaly dolomite, dolomite, and some anhydrite with red and green shale appearing in the sequence in the northern part of the basin.

Unit G is overlain, apparently conformably, by the Bass Island dolomite of latest Silurian age.

In the Northern Peninsula of Michigan, beyond the Mackinac Straits connecting Lakes Michigan and Huron, the time equivalent of the Salina formation is the Pointe aux Chenes formation. This formation is composed of red and green shale with some thin beds of dolomite and gypsum. It is essentially identical in character with the Vernon shale member of the Salina formation in New York.

## Ohio

The Salina formation crops out along the Cincinnati arch in western Ohio, but for the most part the formation lies in the subsurface where its top extends to depths of as much as 6,400 feet. The Salina ranges in thickness from 0 to about 600 feet. The thickest sections are near the northeastern corner of the State. From there the formation thins toward the southwest and finally pinches out in the subsurface along a line that trends northwesterly across the State.

In Ohio, near the southwestern limit of the formation, the Salina consists mainly of carbonate and salt. The carbonate is dolomite and dolomitic limestone that ranges from buff to brown to dark gray. Some beds are argillaceous, and there are a few thin beds of dolomitic shale. The salt beds are most numerous in the northeastern part of the State where as many as eight have been recorded in wells. Southwestward these beds pinch out, and near the western margin of salt deposition there is only one bed of salt (Pepper, 1947, p. 230). Dolomite and dolomitic limestone represent the formation for a short distance west and southwest of the pinchout of the salt.

The aggregate thickness of salt beds is shown on figure 4. This thickness ranges from 0 to a little over 300 feet. The thickest individual salt bed is about 50 feet thick.

Pennsylvania

The Salina formation lies entirely in the subsurface in Pennsylvania. In places the top of the formation is at depths of as much as 9,000 feet. Studies of well records by Fettke (1955) indicate that the formation ranges in thickness from about 600 to nearly 2,500 feet. It is composed of dolomite, dolomitic limestone, dolomitic shale, salt, and anhydrite. There appear to be as many as eight beds of salt in the north-central part of the State and as few as one or two in the southwestern part of the State. Individual saltbeds range in thickness from less than 5 feet to nearly 200 feet, and the thickest beds are in the upper part of the formation. The aggregate thickness of beds of salt reaches a maximum of about 650 feet in the north-central part of the State near the New York line (fig. 4). The beds occupy an interval in the formation ranging from less than 50 feet to over 1,200 feet. The formation, at least in part, grades into or interfingers with the Bloomsburg red beds of eastern Pennsylvania.

West Virginia

The Salina formation does not crop out in West Virginia, and not until 1936 was it known to contain beds of salt. Under a large part of western West Virginia the top of the formation is at depths of about 5,000 to 10,000 feet. The Salina ranges in thickness from 0 to about 1,000 feet. The thickest sections are in the northwestern part of the State. It thins to the south and pinches out. On the east the Salina passes into the Bloomsburg red beds by gradation or interfingering. The rocks are mainly light-gray to brown dolomite and dolomitic limestone. There are some thin beds of anhydrite and some beds which contain anhydrite mixed with dolomite. A few beds of dolomite are shaly, but in general shale is absent from the Salina formation in West Virginia.

Page 36 follows.

The salt is present in the Salina formation only in the northwestern part of the State, pinching out to the east and south. There is only one main bed; it ranges in thickness from 0 to about 100 feet. A few other beds are less than 10 feet thick. Analyses indicate that small amounts of anhydrite are present in the salt.

## Structure

The dominant structural elements associated with the Michigan and Appalachian basins are shown on figure 8. The Michigan basin, with its center in the southern peninsula of Michigan, is an elliptical structural basin which at times has also been a sedimentary basin. It is bounded on three sides by low but prominent arches. The Wisconsin arch forms the western limit. This arch trends southerly through central Wisconsin into northern Illinois. The Kankakee arch, which forms the southwestern limit, extends from northeastern Illinois across Indiana to southwestern Ohio. A low saddle on this arch in Indiana is known as the Logansport sag. The southeastern limit of the Michigan basin is the prominent Cincinnati arch. This arch has a low saddle near Chatham, Ont., which is called the Chatham sag. The northern boundary of the basin is apparently a curving monocline.

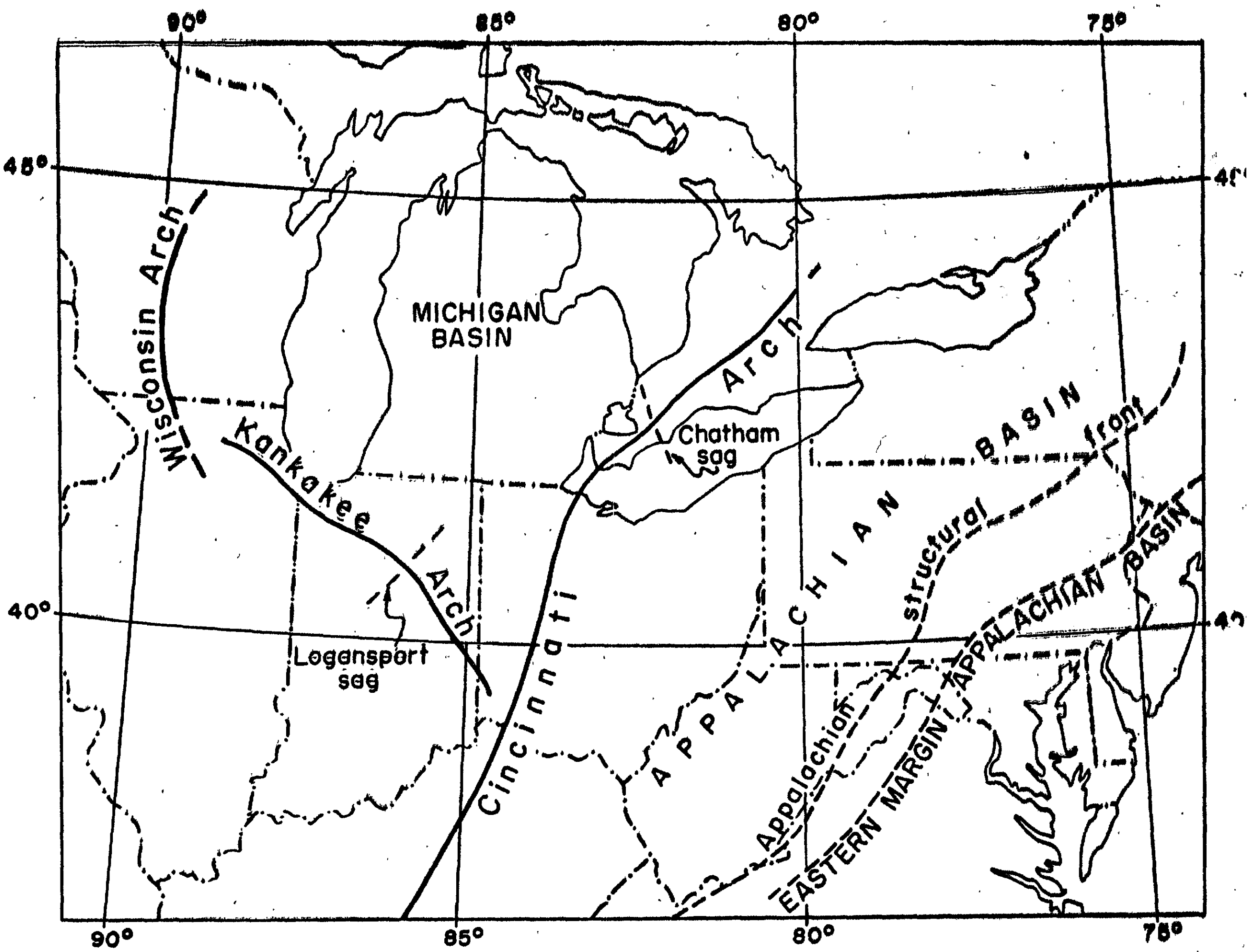



Figure 8. Sketch map showing the regional structural features associated with the Silurian salt deposits of the northeastern United States.

The general structure of the Michigan basin is simple. The rocks dip toward a central point in the center of the southern peninsula of the State at a rate of about 30 to 40 feet per mile. At the center of the basin the surface of the Precambrian lies approximately 13,000 feet below sea level, or at a depth of nearly 14,000 feet below the surface. Movement on the margins of the basin relative to the center has occurred at several times. Stratigraphic data indicate that the center sank relative to the margins in Middle Ordovician, Late Silurian, Late Mississippian, and post-Pennsylvanian time (George Cohee, informal communication). The greatest deformation was during Late Silurian time, and the deformation of Upper Silurian rocks was coincident with the deposition of the salt beds in the Salina formation.

The Appalachian basin is a more complex structural and sedimentary basin than is the Michigan basin. It is separated from the Michigan basin by the Cincinnati arch. The east boundary of the Appalachian basin is ill-defined, but in this report it has been placed along the generalized surface trace of the contact between the Precambrian and Paleozoic rocks through western Virginia, eastern Pennsylvania, northwestern New Jersey, and eastern New York. Between this boundary and the Appalachian structural front (fig. 8) the structure is highly complex. Between the Appalachian front and the Cincinnati arch the general structure is relatively simple and consists of a broad synclinorium whose axis extends from Kentucky across western West Virginia, western Pennsylvania, and into east-central New York. Near the eastern edge of this broad synclinorium are open anticlines and synclines whose limbs dip as much as 30 degrees, but over most of the broad synclinorium the rocks dip at about 10 to 20 feet per mile. The position of the axis of the Appalachian basin shifted a number of times during the Paleozoic era. During Late Silurian time the axis extended across western West Virginia and western Pennsylvania into south-central New York. The greatest subsidence of the basin during Late Silurian time was in south-central New York and was coincident with the thick accumulation of salt beds in this part of New York. (See fig. 4.)

The stucture on the top of the uppermost salt bed in the Salina formation is shown on figure 5. It is not meant to imply, however, that a single bed of salt has an extent that covers the entire area of salt deposition. Figure 5 indicates the depth below sea level of the uppermost bed of salt as indicated by the logs of wells. The structure of the basin is very simple except for the northeasterly trending belt of anticlines and synclines that lie near the eastern limit of salt deposition and just west of the Appalachian structural front (fig. 8).

## Thickness and distribution of salt beds

The foregoing discussion of the salt-bearing Salina formation has of necessity included a discussion of the thickness and distribution of salt beds, because they constitute very significant parts of the formation. The following discussion utilizes much of the same data, with the emphasis primarily on the location, depth, and thickness of salt.

The greatest aggregate thickness of salt beds in the northeastern United States is in the Michigan basin. In the center of the basin the combined thickness of the salt beds is about 1,800 feet. From this maximum, the salt thins in all directions--roughly to 500 feet at Lake Michigan on the west and Lake Huron on the east and north and wedges out roughly 35 miles north of the Michigan-Ohio State line. (See fig. 4.)

The next greatest thickness of salt is in the Appalachian basin in south-central New York near the Pennsylvania border. South of the south end of Seneca Lake the salt beds have a combined thickness of 800 feet in the central part of the basin. These beds thin to less than 100 feet within a distance of 60 miles to the east, south, and west, and within 35 miles to the north of the center of the basin.

In eastern Ohio the combined thickness of salt beds ranges from 0 feet on the western border of the basin of deposition to a maximum of about 300 feet. The total thickness of salt beds is 100 to 200 feet along the western border of Pennsylvania, but is 100 feet or less in most of the western half of the State; the salt is absent in the southeast. In northern West Virginia the salt beds range in thickness from 0 to more than 100 feet. (See fig. 4.)

Again it should be pointed out that these thicknesses represent the combination of the several salt beds occurring in the Salina formation, and that the maximum thickness of a single bed of salt is considerably less. It is possible from available data to be much more specific as to the probable thickness of individual beds of salt in many parts of the area, but these details would require a much longer report. Some generalized figures as to the thickness of single beds of salt are given in the preceding discussion of the stratigraphy of the salt deposits. Additional data are available and can be assembled for many specific localities from the several thousand wells which have been drilled. For many places, however, such data are only semiquantitative because the salt is soluble in the drilling water and hence, does not yield cuttings in normal drilling.

The depth of the top of the salt-bearing beds is shown in figure 5 by means of contour lines at intervals of 500 feet below sea level. To determine the approximate depth to the top of the salt, the elevation of the surface of the ground at a given point is added to the depth below sea level of the salt at that point.

# GULF COAST EMBAYMEMT

## Introduction

Salt deposits underlie parts of southern Arkansas, eastern and southern Texas, Louisiana, Mississippi, and Alabama. (See fig. 1.) This large area may be conveniently referred to as the Gulf Coast embayment. Along the northern part of this area, in southern Arkansas and northern Louisiana, bedded salt has been found at depth in drill holes. It is thought that this same bed or approximately the same bed or beds of salt continues southward but is at a greater depth than has been penetrated in drilling. Presumably it is this bed of salt, sometimes referred to as the "mother salt," which is the source of the salt forming the salt domes.

For the purposes of discussion, the salt deposits of the Gulf Coast embayment can be divided into three groups: (1) the bedded salt of southern Arkansas and northern Louisiana, known as the Louann salt, (2) the interior salt domes of northeast Texas, northern Louisiana, and Mississippi, and (3) the coastal salt domes of Texas and Louisiana.

## Louann salt of southern Arkansas and northern Louisiana

The Louann salt occurs in the Eagle Mills formation, of Jurassic (Imlay, 1943) or Permian age (Hazzard, Spooner and Blanpied, 1947). The Eagle Mills formation contains red shale, sandstone, anhydrite, and salt. It overlies with marked angular unconformity the upper Paleozoic shale and slate and is overlain by the Smackover limestone.

Some of the wells that have penetrated the Louann salt are shown on figure 9. The thickness of the salt is highly variable as indicated by these wells. Three wells show a salt thickness ranging from 76 to 101 feet, four show a range from 465 to 857 feet, three show a range from 968 to 1,300 feet, and one shows 3,300 feet of salt. It seems likely that the latter thickness is due to flowage of salt into a salt dome, and it is possible that some of the other large thicknesses are due in part to flowage of salt.

The Eagle Mills formation, which contains the Louann salt, rises northward, but before it reaches the surface it is truncated and overlain by rocks of Late Cretaceous and Tertiary age. These relationships are illustrated by figure 10, which shows a north-south cross section as inferred from wells. The approximate northern limit of the Eagle Mills formation is shown on figure 9. The northern limit of the Louann salt thus lies south of that line.

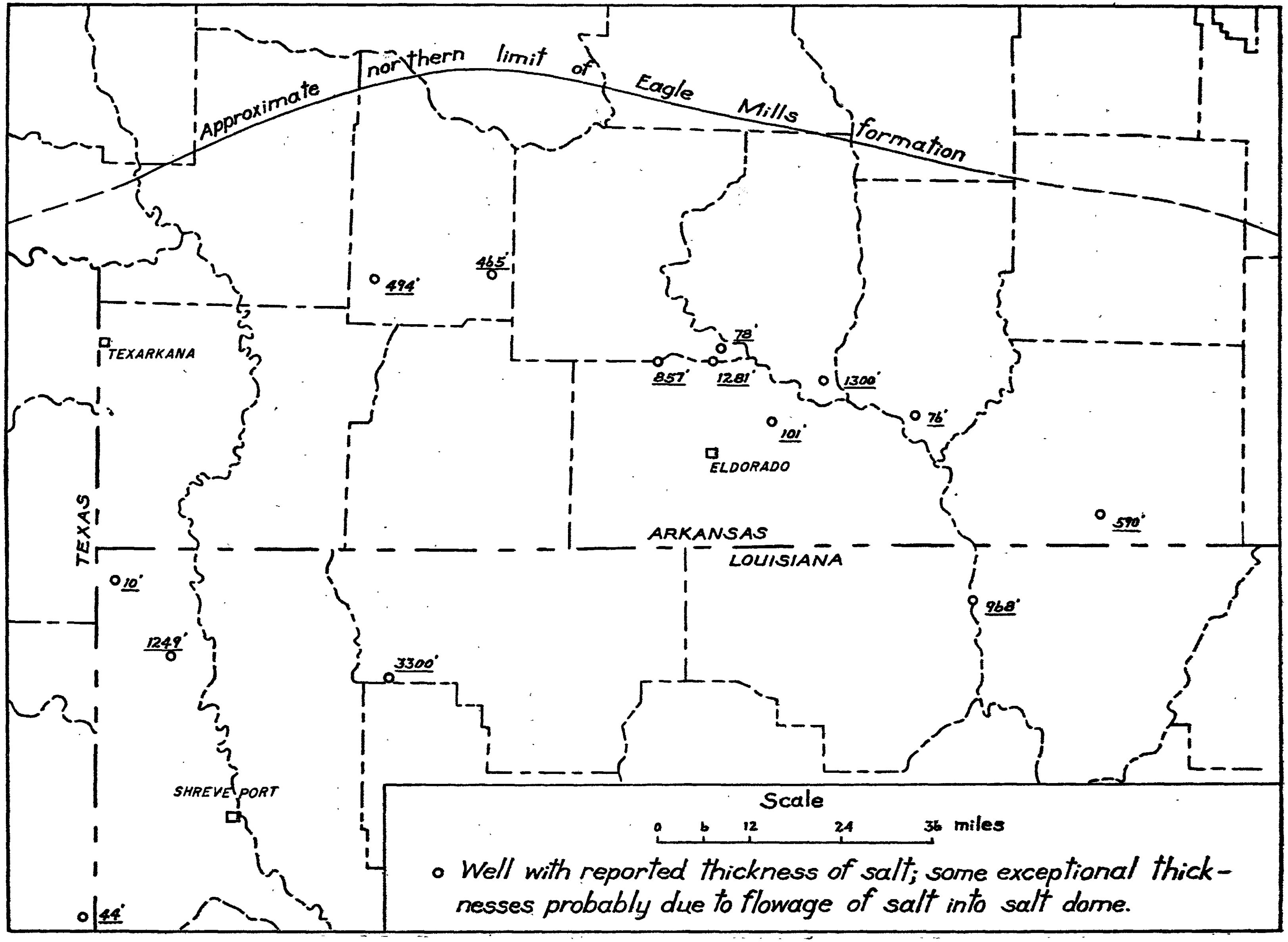



Figure 9.--Map showing thickness of Louann salt in Eagle Mills formation, southern Arkansas and northern Louisiana (after Imlay, 1940).

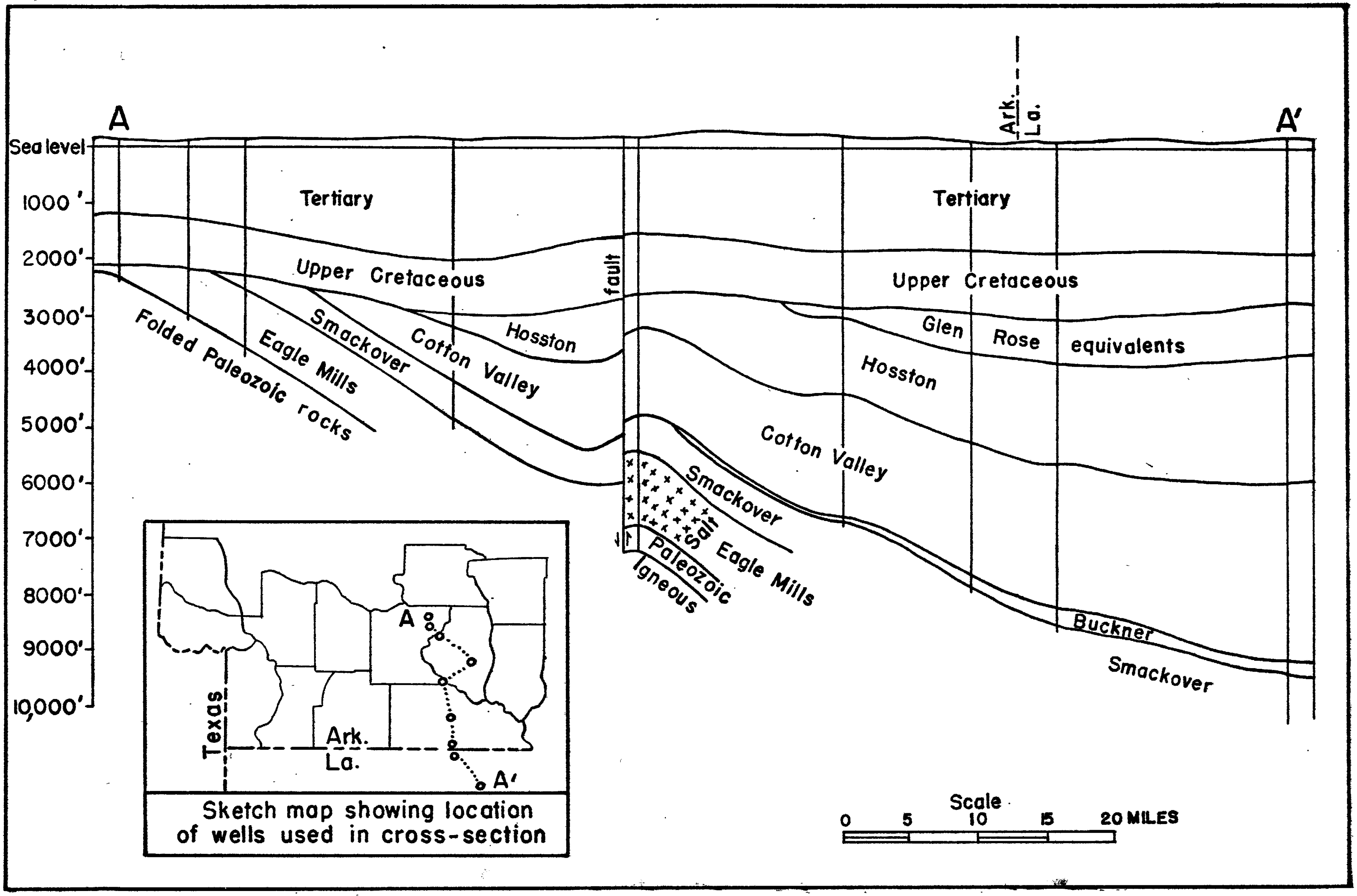



Figure 10.--North-south structure section showing relation of Louann salt in Eagle Mills formation to overlying beds (after Imlay, 1940).

## General features of salt domes

The general characteristics of salt domes are much the same whether in the interior belt or in the coastal belt, so most of their features can be considered without reference to a geographic position.

There are more than 200 salt domes in the Gulf Coast embayment. They do not have any particular arrangement, and appear to be randomly distributed.

### Size and shape

The idealized sections shown in figure 11 give an idea of some of the shapes of salt domes found in the Gulf Coast. In plan, these domes are roughly circular and range in diameter from less than a mile to more than 4 miles. The mass commonly enlarges downward and the top is often truncated. On some domes a salt spine projects above the general level of the top of the dome, owing to partial removal of the surrounding salt by solution. Water, moving laterally in a porous bed, may come in contact with the side of a salt dome and then migrate upward. As the water rises along the dome, salt is dissolved and a cavity with an overhanging edge is formed. The strata above the cavity then slump into the void, producing an intricate system of faults and collapse breccia (Hanna, 1958).

The depth of the top of the domes is highly variable. The tops of some domes are within a few feet of the surface, but others are many thousands of feet below. Domes more than 10,000 feet below the surface are considered deep, those from 4,000 to 10,000 feet are intermediate, and those less than 4,000 feet are shallow.

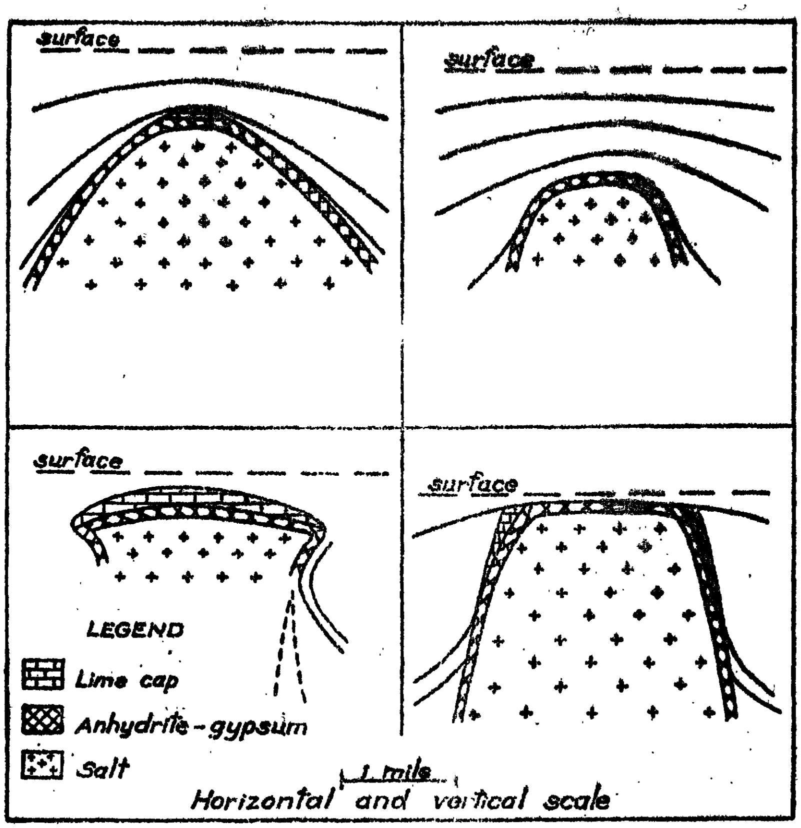



Figure 11.--Idealized cross sections of salt domes (after Hanna, 1934).

The height of the salt domes above their base is extremely variable, depending on the amount of piercement of the overlying sediments that has taken place. In those domes that have risen to near the present land surface, it may be 10,000 to 20,000 feet to the base of the salt in the salt dome.

## Surface expression

Many of the deep salt domes have no surface expression and are known only from drilling or geophysical data. The shallow domes, however, have several surface features indicating their presence. Spooner (1926) described the surface manifestations of salt domes as "...the result of truncation of highly localized structures of great relief. Truncation, assisted in some places where the salt mass lies near the surface by the removal of salt in solution, has produced the peculiar topographic forms consisting of a central basin area encircled by hills. ...Another topographic form, not uncommon in Texas, ... consists of a central hill surrounded by a circular drainage system. Where truncation is deep and the salt mass near the surface, salt licks or salines, barren or sparsely covered with vegetation, are usually grouped around the periphery of the central basin. Characteristic salt-dome features are steeply tilted rocks, outcrops of formations older than those usually found in the region, and springs of water, either fresh, slightly brackish, or mineralized with sulfur or alum."

## Caprock

At the top of many of the domes is a caprock composed predominantly of anhydrite, gypsum, and limestone, with minor amounts of sulfur and numerous sulfates, sulfides and carbonates. The limestone is generally at the top of the caprock, anhydrite at the base, and gypsum, anhydrite, and calcite in the middle. Anhydrite occurs not only on the top of the dome but down the sides like a hood. (See fig. 11.) Caprock is common on shallow domes, but is thin or absent on deep domes. On shallow domes it is normally 300 to 400 feet thick but may be as much as 1000 feet thick.

Hanna (1934, p. 648-651) cites several theories for the origin of caprock and concludes that the evidence favors its formation by solution of the salt with attendant concentration of disseminated anhydrite on the periphery of the salt dome.

Movement of the salt

The up-bowing of the sediments above salt domes indicates upward movement of the salt, and the upturning and truncation of the beds on the flanks of the salt dome shows that the salt has pierced the overlying sediments. The formation of the Gulf Coast salt domes began as early as early Eocene time, and on some has continued into very recent time. The evidence is not conclusive as to whether the movement was continuous, intermittent, or spasmodic, but as shown by Barton (1933) growth on different domes has ceased at different times, and it seems definite that in one place or another salt movement has taken place throughout the span from early Tertiary to Recent time. From the observed thinning of stratigraphic units over salt domes, it is concluded that the growth of the domes has been, in part, contemporaneous with the deposition of the strata that now surround and overlie them. Barton (1933, p. 1082) makes the generalization that growth of the shallow domes persisted into the late Tertiary; the growth of deep domes ceased in the middle Tertiary; and the growth of very deep domes in general ceased in the early Tertiary. It has been shown by Balk's (1949) detailed study of the structure of Grand Saline salt dome that the salt moved upward from a layered salt-anhydrite mass somewhere below. Thus, the evidence to date strongly favors the interpretation that the Gulf Coast salt domes are produced by the plastic deformation of a deeply buried bed of salt. The mechanism for producing the deformation most probably arises from the difference in density between the salt layer and the overlying layers. The salt layer is slightly less dense than the overlying rocks, thus forming an unstable relationship when the static pressure on the salt becomes great enough to induce plastic flow.

## Composition

The salt-dome deposits are almost pure sodium chloride except for the caprock or uppermost part, in which the insoluble minor constituents have been concentrated by removal of the soluble salt. Anhydrite is the principal impurity and usually occurs as black color bands. Bands of sandstone 1 foot or less thick and some 10 feet or more long are known at Avery Island and are probably sand originally interbedded with the salt (Powers and Hopkins, 1923).

Some analyses of salt from coastal and interior domes are as follows:

Analyses of salt from salt domes in Louisiana and Texas[a]

| | Coastal domes, Louisiana | | | | Interior domes, Texas | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Sodium chloride (NaCl) | 92.750 | 96.405 | 99.252 | 99.88 | 98.883 | 98.926 |
| Calcium sulfate ($CaSO_4$) | - | 3.053 | .694 | .782 | 1.099 | 1.041 |
| Magnesium chloride (MgCl) | - | .074 | .012 | .003 | tr. | - |
| Magnesium carbonate ($MgCO_3$) | .201 | - | - | - | - | - |
| Sodium carbonate ($Na_2CO_3$) | .067 | - | - | - | - | - |
| Sodium sulfate ($Na_2SO_4$) | .837 | - | - | - | .008 | .023 |
| Calcium carbonate ($CaCO_3$) | 1.804 | - | - | - | .010 | .010 |
| Calcium chloride ($CaCl_2$) | - | .226 | .042 | .402 | - | - |
| Iron and aluminum oxides ($Fe_2O_3Al_2O_3$) | .500 | .025 | - | - | - | - |
| Insoluble matter | 3.325 | .059 | - | .33 | tr. | - |

a) No's 1 to 4 from Veatch, 1899, p. 227, 248; no's 5 and 6 from Balk, 1949, p. 1793

1. Black salt, Belle Isle, La.; depth 120 feet.
2. White salt, Belle Isle, La.; depth 175 feet.
3. Avery Island, La.; G. Bode, analyst.
4. Avery Island, La.; C. A. Goessman, analyst.
5. Grand Saline, Texas; Morton Salt Co.
6. Grand Saline, Texas; Morton Salt Co.

## Interior salt domes

The interior salt domes occur in a belt extending from northeastern Texas through northern Louisiana and across south-central Mississippi. (See figure 12.) As previously noted under the general discussion of salt domes, there is some variation in size and a great variation in depth below the surface. No attempt has been made to assemble specific data on each salt dome for this report. The following table (abstracted from U. S. Geol. Survey Bull. 736-G) serves to illustrate the variation in depth to the salt in some of the structures.

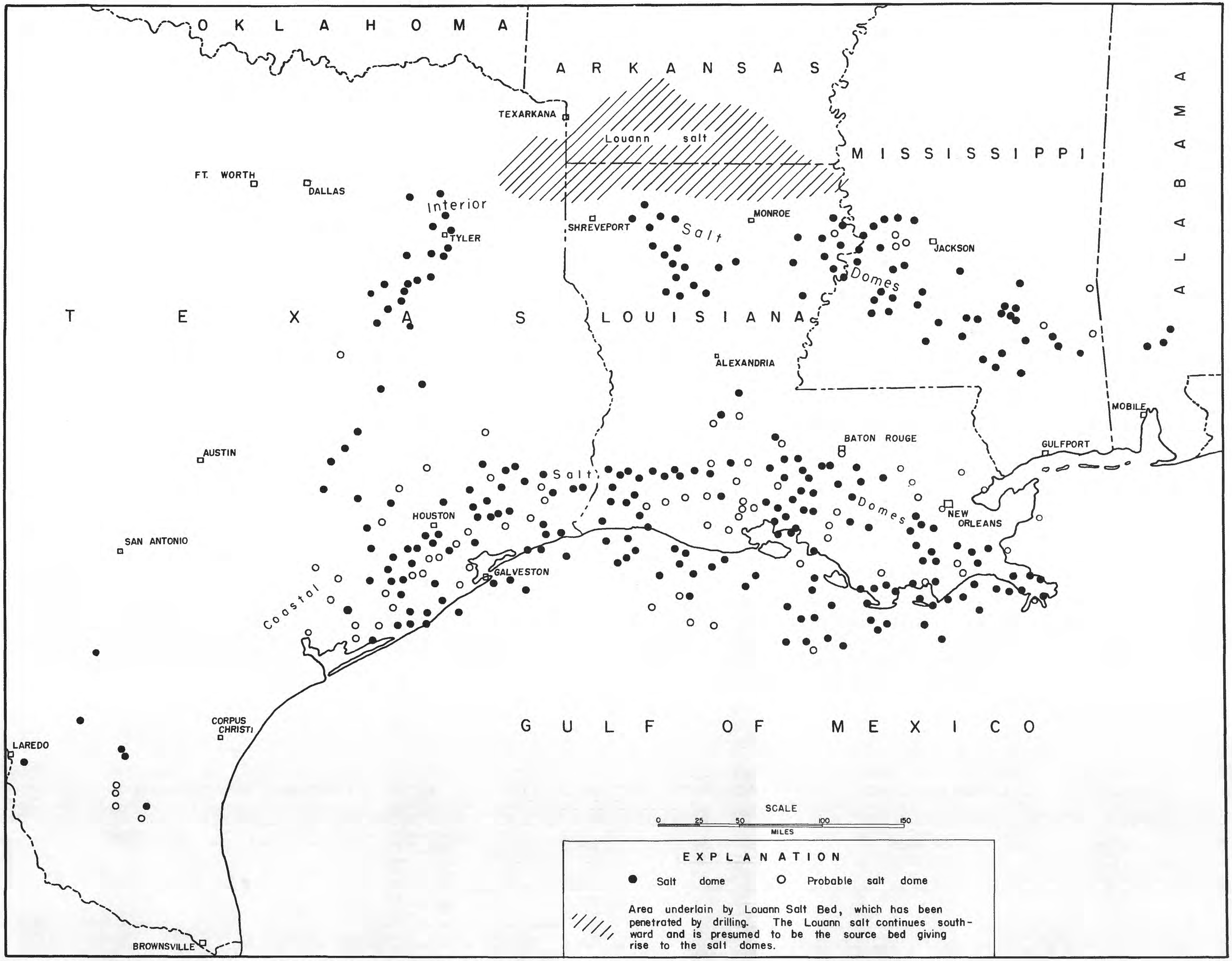



Figure 12.— Map of Gulf Coast embayment showing location of salt domes and the Louann salt bed.

Depth to salt in Interior salt domes in Louisiana and eastern Texas

(From U. S. Geol. Survey Bull. 736-G)

| Location and Name | Depth (feet) |
|---|---|
| **Louisiana** | |
| Winn Parish: | |
| Drake saline (Goldonna), sec. 21, T. 12 N., R. 5 W. | 910 |
| Winnfield marble quarry, secs. 19-24, T. 11 N., R. 3 W. | 999 |
| Bienville Parish: | |
| Acadia, sec. 29, T. 18 N., R. 5 W. | 1,400 |
| Webster Parish: | |
| Bashawa, sec. 16, T. 17 N., R. 5 W | 799 |
| **Texas** | |
| Van Zandt County: | |
| Grand Saline | 212 |
| Smith County: | |
| Steen | 300(?) |
| Brooks | 220 |
| Anderson County: | |
| Keechi | 2,162 |
| Palestine | 140 |
| Freestone County: | |
| Butler | 400 |

The depth to the top of 36 salt domes in northeastern Texas and northwestern Louisiana is shown by generalized contour lines in figure 13.

The source bed of the salt in the salt domes lies at great depth below the surface, and has not been reached by drilling except in northern Louisiana and southern Arkansas. Swartz (1943) reports reflection seismograph data from two shallow salt domes in southern Mississippi as indicating the base of the salt at approximately 22,000 feet at Arm dome and 26,000 feet at D'Lo dome. The lateral extent of this deeply buried salt bed can only be surmised. An interpretation, based on the known extent of salt domes, is shown in figure 14. As indicated, the interior salt dome area is thought to be underlain by a salt bed roughly 50 to 120 miles wide and 500 miles long, extending from northeastern Texas into southwestern Alabama.

## Coastal salt domes

The coastal salt domes are most abundant in southern Louisiana and southeastern Texas, extending along a coastal belt from the Mississippi delta westward to Matagorda Bay. Some salt domes lie beneath the waters of the Gulf of Mexico, particularly in the Mississippi River delta area. (See figure 12.) A few salt domes occur in south Texas, in Duval and adjoining counties.

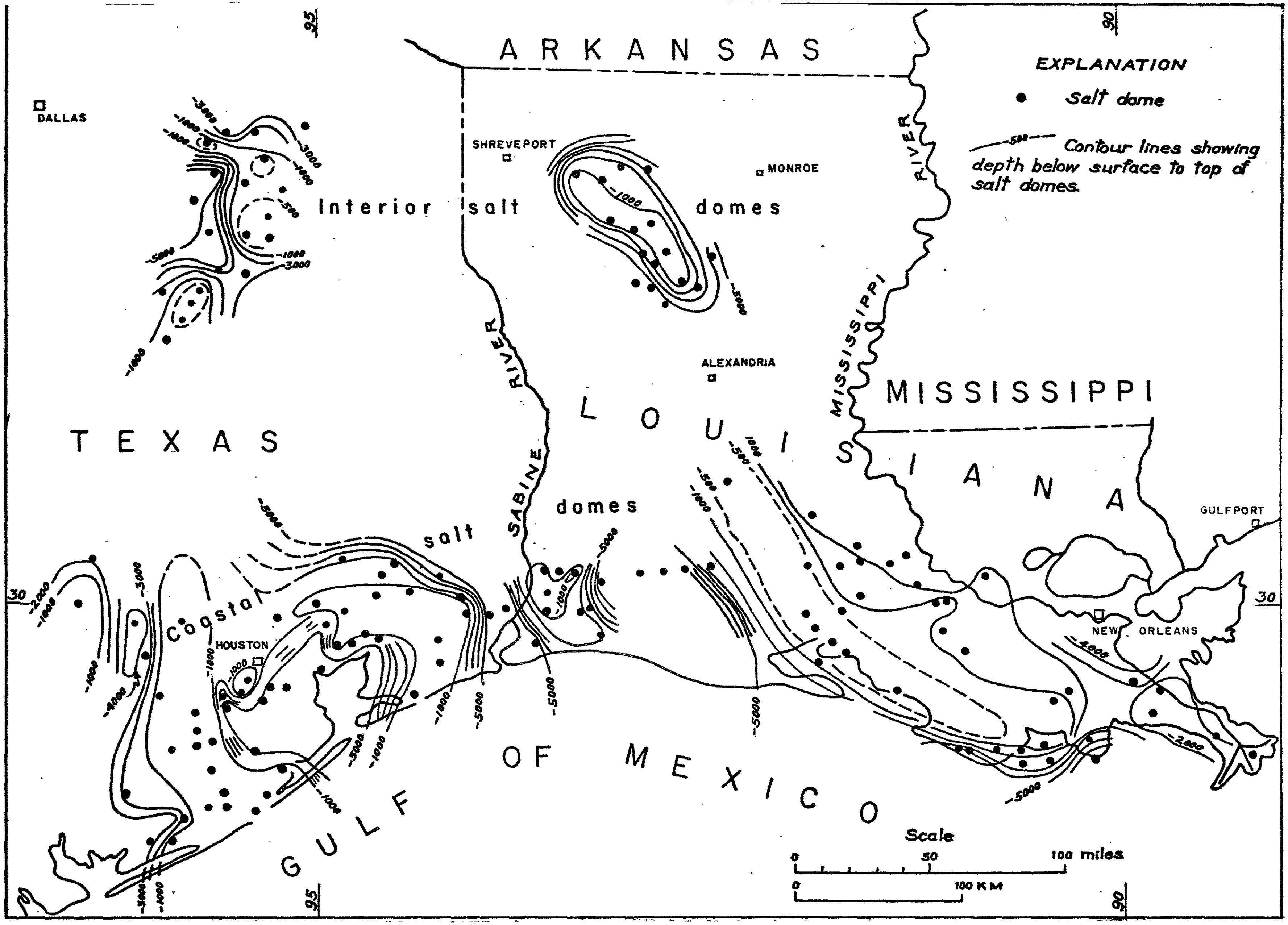



Figure 13.--Sketch map showing depth to top of some of the interior and coastal salt domes (after Barton, 1933).

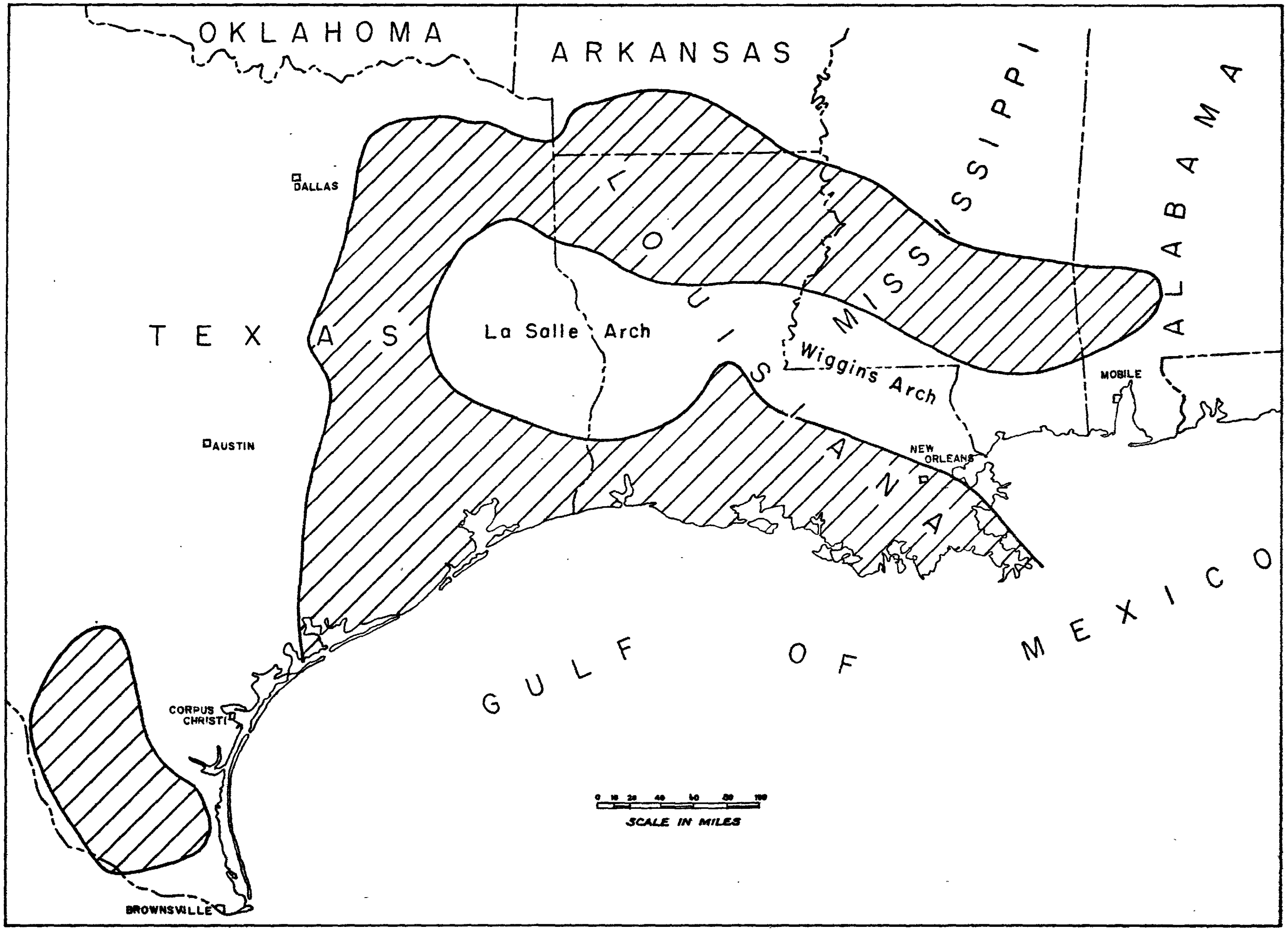



Figure 14.--Map of Gulf Coast embayment showing area (cross-lined) thought to be underlain by continuous salt beds (modified after map by L. L. Nettleton in Willis, 1948).

When only a relatively small number of the salt domes in the Gulf Coast embayment were known, there was thought to be a wide gap between those of the interior area and those along the coast. As more of the salt domes were discovered, the "gap" separating the two became less, and it became apparent that the domes could have come from the same salt bed. From the distribution of salt domes as now known, it seems likely that the basins of salt deposition which gave rise to the interior and coastal domes are connected on the west by a north-trending basin in eastern Texas. A ridge composed of the La Salle arch and the Wiggins arch (Halbouty and Hardin, 1956, fig. 5) which trends east-southeast may have separated the two basins in Louisiana and southern Mississippi. These relationships are indicated in figure 14.

According to Barton (1933, p. 1070), the depth to the top of the salt domes tends to be less for the domes of large diameter than for those of small diameter, but statistically the degree of correlation between depth and size of domes is poor. Of 71 domes that he considered, the median depth of 20 large and very large domes is 550 feet and the median depth of 51 average and small domes is 950 feet. Figure 13 shows by means of generalized contour lines, the approximate depth to more than 100 salt domes in southern Louisiana and southeastern Texas. Of these, 33 are listed in the following table:

Depth to salt in coastal salt domes in Texas and Louisiana

| Location and Name | Depth (feet) |
|---|---|
| **Texas** | |
| Duval County: | |
| Palangana | 500 |
| Piedras Pintas | 500 |
| Matagorda County: | |
| Big Hill (Matagorda) | 1,200 |
| Markham | 2,710 |
| Fort Bend County: | |
| Big Creek | 750 |
| Blue Ridge | 400 |
| Washington County: | |
| Brenham | 1,400 |
| Brazoria County: | |
| Bryan Heights | 900 |
| West Columbia (Kisers Mound) | 800 |
| Damon Mound | 500 |
| Stratton Ridge | 1,300 |
| Hoskins Mound | 1,250 |
| Harris County: | |
| Hockley | 1,000 |
| Pierce Junction | 950 |
| Humble | 1,400 |
| Liberty County: | |
| South Dayton | 600 |

Depth to salt in coastal salt domes in Texas and Louisiana--Continued

| Location and Name | Depth (feet) |
|---|---|
| *Texas--Continued* | |
| Liberty County--Continued: | |
| Hull | 600 |
| Davis Hill | 1,385 |
| Chambers County: | |
| Barbers Hill | 600 |
| Galveston County: | |
| High Island | 1,500 |
| Jefferson County: | |
| Spindletop | 1,650 |
| Hardin County: | |
| Saratoga | 2,050 |
| Sour Lake | 880 |
| *Louisiana* | |
| Calcasieu Parish: | |
| Vinton | 1,000 |
| Sulphur | 1,480 |
| Evangeline Parish: | |
| Pine Prairie (St. Landry) | 500 |
| Iberia Parish: | |
| New Iberia | 800 |
| Jefferson Island (Cote Caroline) | 69 |
| Avery Island (Petite Anse) | 15 |
| Weeks Island (Grande Cote) | 97 |

Depth to salt in coastal salt domes in Texas and Louisiana--Continued

| Location and Name | Depth (feet) |
|---|---|
| Louisiana--Continued | |
| St. Mary Parish: | |
| Cote Blanche | 635 |
| Belle Isle | 373 |
| St. Martin Parish: | |
| Anse la Butte | 260 |

The depth to the salt bed assumed to underlie the Gulf Coast salt domes is great. Barton (1933, p. 1054) estimated its depth to be 20,000 feet at Houston, 25,000 feet at Jennings, La., and 30,000 feet south of New Orleans. Reflection seismograph data from Moss Bluff dome in southeastern Texas are interpreted as indicating a depth of 36,000 feet to the base of the salt (Hoylman, 1946; Nettleton, 1952). Extrapolations of the depth to the salt at the coast line indicate a depth of around 40,000 feet, according to Nettleton (1952, p. 1228).

# PERMIAN BASIN

## Introduction

The Permian basin, in west-central United States, underlies parts of Kansas, Colorado, Oklahoma, Texas, and New Mexico (fig. 1). Salt, which occurs in strata of Permian age, underlies an area approximately 650 miles from north to south and 150 to 250 miles from west to east. The thickness and succession of salt-bearing beds are variable. The aggregate thickness of the contained salt in many places is more than 400 feet; a maximum of about 2,200 feet is reported in southeastern New Mexico.

In general, the salt deposits of the Permian basin are progressively older from southwest to northeast. The salt deposits of southeastern New Mexico and southwestern Texas are of late Permian age (Guadalupe and Ochoa series), whereas in Kansas, Oklahoma, and the northern part of the Texas Panhandle, the salt deposits are of middle Permian age (Leonard series). The formations within each of these series vary from State to State, and many vary within a single State. A summary of the formational relationships is shown in tabular form in figure 15.

| SYSTEM | SERIES | Delaware Basin New Mexico (King, 1942, pl. 2) | Northern New Mexico | Panhandle Area Texas (Totten, 1956, fig. 8) | Central and South-western Kansas and Oklahoma Panhandle (Moore et al., 1951) |
|---|---|---|---|---|---|
| Triassic | | Dockum Group | Dockum Group | Dockum Group | Dockum(?) Group |
| PERMIAN | Ochoa | Dewey Lake fm.<br>Rustler fm.*<br>Salado fm.*<br>Castile fm.* | | | |
| | Guadalupe | Delaware Mt. Group: Bell Canyon fm.<br>Cherry Canyon fm.<br>Brushy Canyon fm. | San Andres fm. (Glorietta ss at base) | Whitehorse Group: Quartermaster fm.<br>Alibates dol.<br>Pease River Group (Including San Angelo or Glorietta ss at base) | Quartermaster fm.(?)<br>Whitehorse Group: Big Basin fm.<br>Day Creek dol.<br>Whitehorse ss |
| | Leonard | Bone Springs limestone | Yeso fm.<br>Abo fm. | Clear Fork Group *<br>Wichita Group | Dog Creek sh<br>Blaine fm.<br>Flower Pot sh<br>Cedar Hill ss<br>Salt Plain fm.<br>Harper ss<br>Stone Corral dol.<br>Ninnescah sh<br>Wellington salt* |
| | Wolfcamp | Hueco limestone | Sangre de Cristo fm. | Cisco Group | Chase Group<br>Council Grove Group<br>Admire Group |
| Penn-sylvanian | | Magdalena limestone | Madera limestone | | Wabaunsee Group |

Fig. 15.—Stratigraphic chart showing generalized formational relationships in various parts of

Data presented here are mainly a synthesis of published reports. The data on west Texas and southeastern New Mexico are extracted from an unpublished report by P. T. Hayes (in preparation); the data on the northern Panhandle of Texas are modified from a report by Hoots (1925); and the data on the Kansas-Oklahoma salt deposits were taken principally from the reports by Bass (1926) and Lee (1956). Other reports used are included in the list of references. The salt beds occur in a succession of red shales and sandstones and are generally associated with gypsum, anhydrite, dolomite, and limestone. The salt bodies vary in thickness and are doubtless lenticular. In Texas, New Mexico, and Oklahoma abundant gypsum and anhydrite occur in close association with the salt. In southeastern New Mexico the main body of salt is overlain and underlain by considerable thicknesses of gypsum and anhydrite. In Kansas little anhydrite or gypsum seem to be interbedded in the salt measures cr closely associated with them, although thick deposits of gypsum are reported from both higher and lower beds.

## Distribution, thickness, and stratigraphy of the salt-bearing formations

### West Texas-southeast New Mexico area

The west Texas-southeast New Mexico area, as considered in this report, includes the Delaware and Midland basins and the adjacent shelf areas in southeastern New Mexico and western Texas (fig. 16). The area of salt deposition extends from northern Floyd County, Tex., southward to Pecos County, Tex., and from Mitchell County, Tex., westward to Eddy County, N. Mex. Salt thus underlies an area of about 25,000 square miles.

The thickest and most extensive beds of salt in the Permian basin are confined to the Ochoa series of late Permian age. The Ochoa series contains three salt-bearing formations (fig. 15): the Castile formation, the Salado formation, and the Rustler formation. The Castile formation is confined to the Delaware basin but the two younger formations extend northward and eastward into the shelf area, the central basin platform, and the Midland basin (fig. 16).

Castile formation.--The Castile formation contains the oldest Permian salt deposits of the west Texas-southeast New Mexico area, although earlier Permian formations contain back-reef evaporite deposits on the shelf areas surrounding the Delaware basin and in the Midland basin.

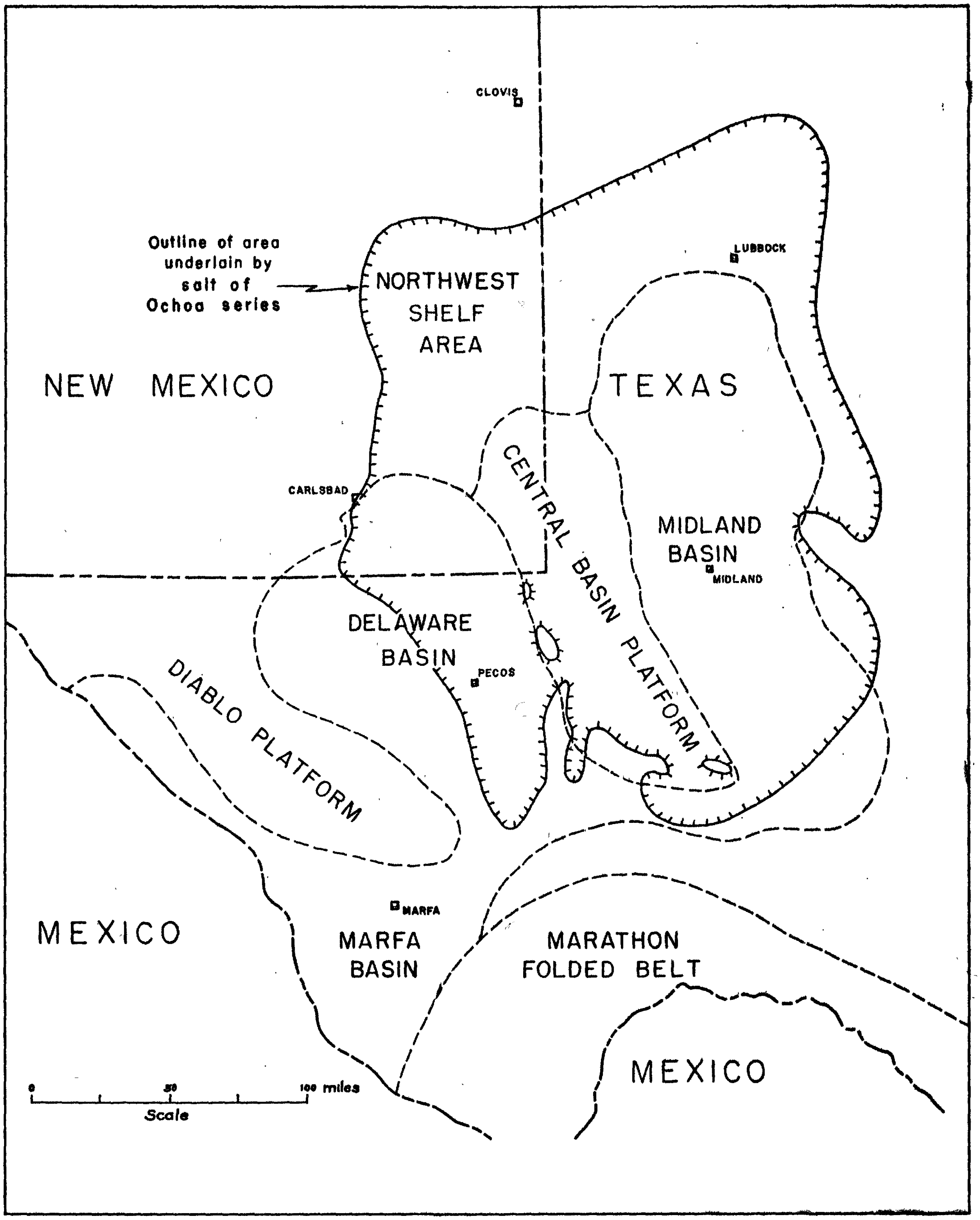



Figure 16.--Index map showing relationship of Permian structural and physiographic features to area underlain by salt beds of Ochoa Series (from King, 1948).

The basal few feet of the Castile formation in most areas consists of thinly laminated nonfossiliferous brownish limestone which rests with apparent conformity on thinly bedded very fine grained sandstone of the Bell Canyon formation. The basal limestone of the Castile formation grades upward into interlaminated white anhydrite and brownish limestone--the so-called "banded anhydrite." Interbedded with the "banded anhydrite" are several beds of relatively pure halite which range in thickness from 0 to more than 350 feet but which are usually less than 250 feet thick. In southwestern Lea County, N. Mex., and eastern Loving County, Tex., the maximum aggregate thickness of the halite beds in the Castile formation is about 635 feet. Everwhere in the Delaware basin the halite beds are separated by beds of anhydrite 50 to 500 feet thick and in no place does the halite comprise more than 40 percent of the formation. Figure 17 shows the aggregate thickness and distribution of salt in the Castile formation.

Over most of the Delaware basin the "banded anhydrite" grades upward into pure-white anhydrite, but in the extreme southeastern part of the Delaware basin, in eastern Reeves and western Pecos Counties, Tex., it is overlain by the basal halite bed of the Salado formation. In this part of the basin thin beds of the "banded anhydrite" are present in the lower part of the Salado formation, but northward and along the margins of the basin the top of the "banded anhydrite" is well below the top of the Castile formation.

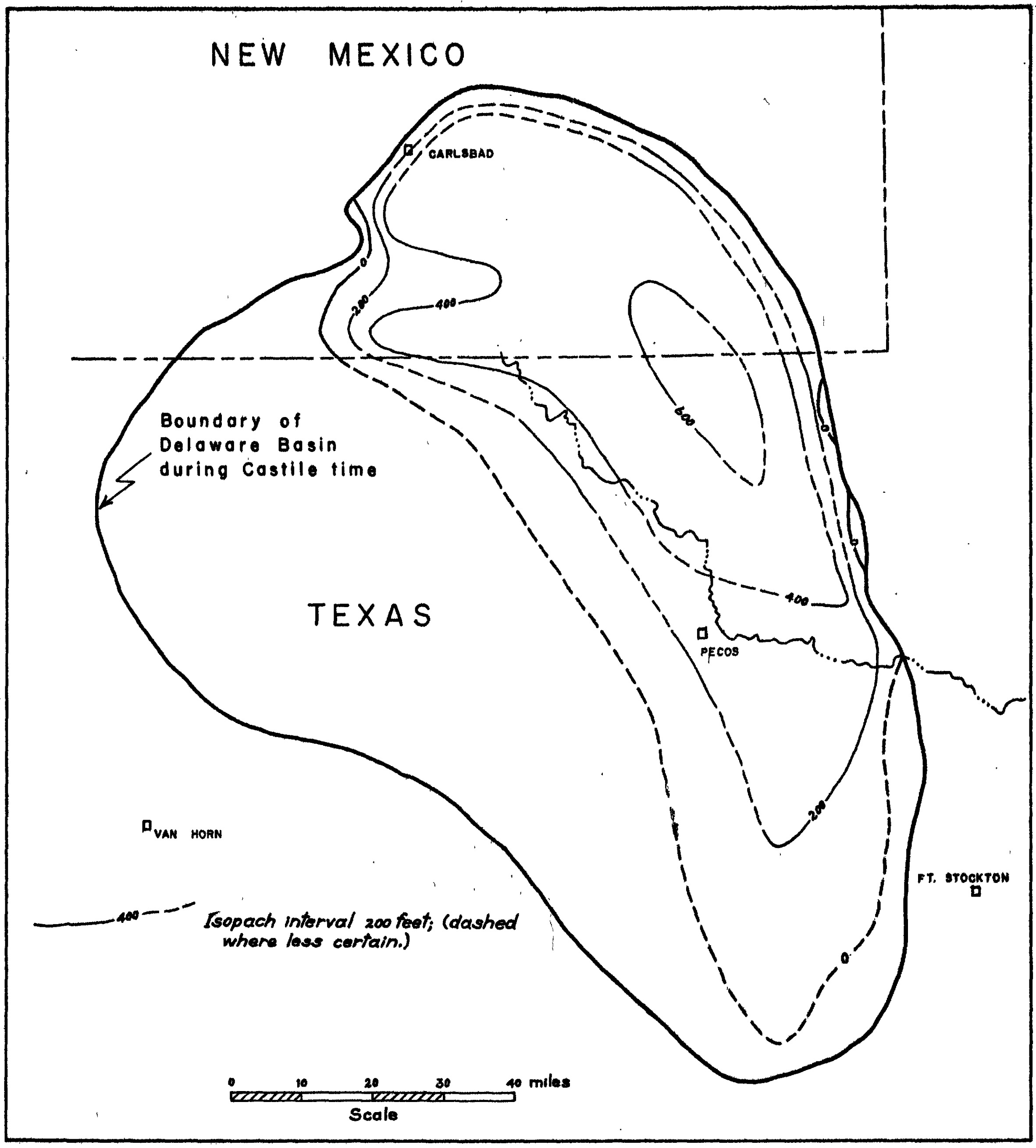



Figure 17.--Map showing aggregate thickness of salt in Castile formation, Ochoa series, New Mexico and Texas (from P. T. Hayes, in preparation).

The exact position of the boundary between the Castile formation and the overlying Salado formation has been the subject of considerable debate (Lang, 1937, 1939, 1942; Kroenlein, 1939; King, 1942; Adams, 1944; Newell and others, 1953; Jones, 1954). However, for purposes of this report, the Castile formation, in general, consists predominantly of interlaminated anhydrite and limestone, several beds of pure halite, and nonlaminated anhydrite. The Salado formation, on the other hand, consists predominantly of halite but contains minor clastic beds and many of the rarer salts. This placement of the boundary restricts the Castile formation to the Delaware basin (fig. 18).

The Castile formation is exposed on the surface along the western side of the Delaware basin, but there all of the salt has been removed by solution and the anhydrite has been hydrated to gypsum. This alteration of the evaporite extends to depths ranging from 100 to 500 feet. Stratigraphic sections measured at the surface therefore, do not give a true representation of the thickness or composition of the formation. In the subsurface the Castile formation ranges in thickness from 1,500 to 2,000 feet except near the north and east margins of the Delaware basin where it thins to a wedge-edge in a distance of about one mile (fig. 18).

Salado formation.--The Salado formation, unlike the Castile formation, is not confined to the Delaware basin but extends more than 100 miles to the north and to the east of the basin, underlying an area of about 25,000 square miles.

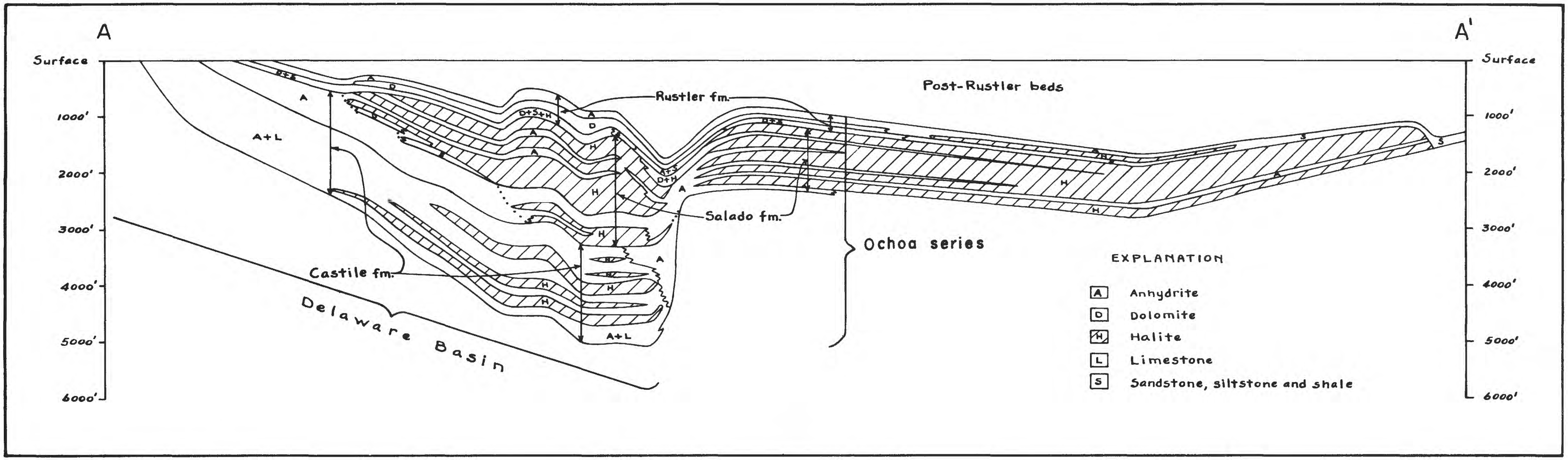



Figure 18.— Generalized stratigraphic diagram of Ochoa series along line A-A'. See fig. 19 for location of section. (After P.T. Hayes, in preparation)

The Salado formation consists of halite, anhydrite, and potassium salts with varying amounts of dolomite, limestone, and clastic material. Halite comprises about 75 to 90 percent of the formation except in areas where subsurface solution has removed much of the salt, and toward the depositional edges of the formation where variegated mudstone predominates (Maley and Huffington, 1953). The next most abundant constituent in the formation is anhydrite. The remainder of the formation consists of sandstone, siltstone, shale, polyhalite, numerous less abundant potassium minerals, dolomite, and limestone.

The halite of the Salado formation, with the exception of the basal beds in the Delaware basin area, is less pure than that in the Castile formation. Much of the Salado halite, especially in the area where soluble potassium salts are present, has a pinkish color probably caused by minor traces of iron oxide. Considerable grayish halite, the color of which was caused by admixed black mud and clay, is present throughout the extent of the formation. Minor amounts of blue halite are found in places in close association with the more soluble potassium salts. Anhydrite in the form of very thin beds and inclusions is a common impurity in the halite beds.

The thickest accumulation of halite in the Salado formation is on the north and east edges of the Delaware basin where more than 1,700 feet is present in a narrow band (fig. 19). On the shelf area adjacent to the Delaware basin, halite in excess of 1,000 feet thick is confined to a relatively small area. It gradually thins and wedges out to the north and east of the shelf area (fig. 18).

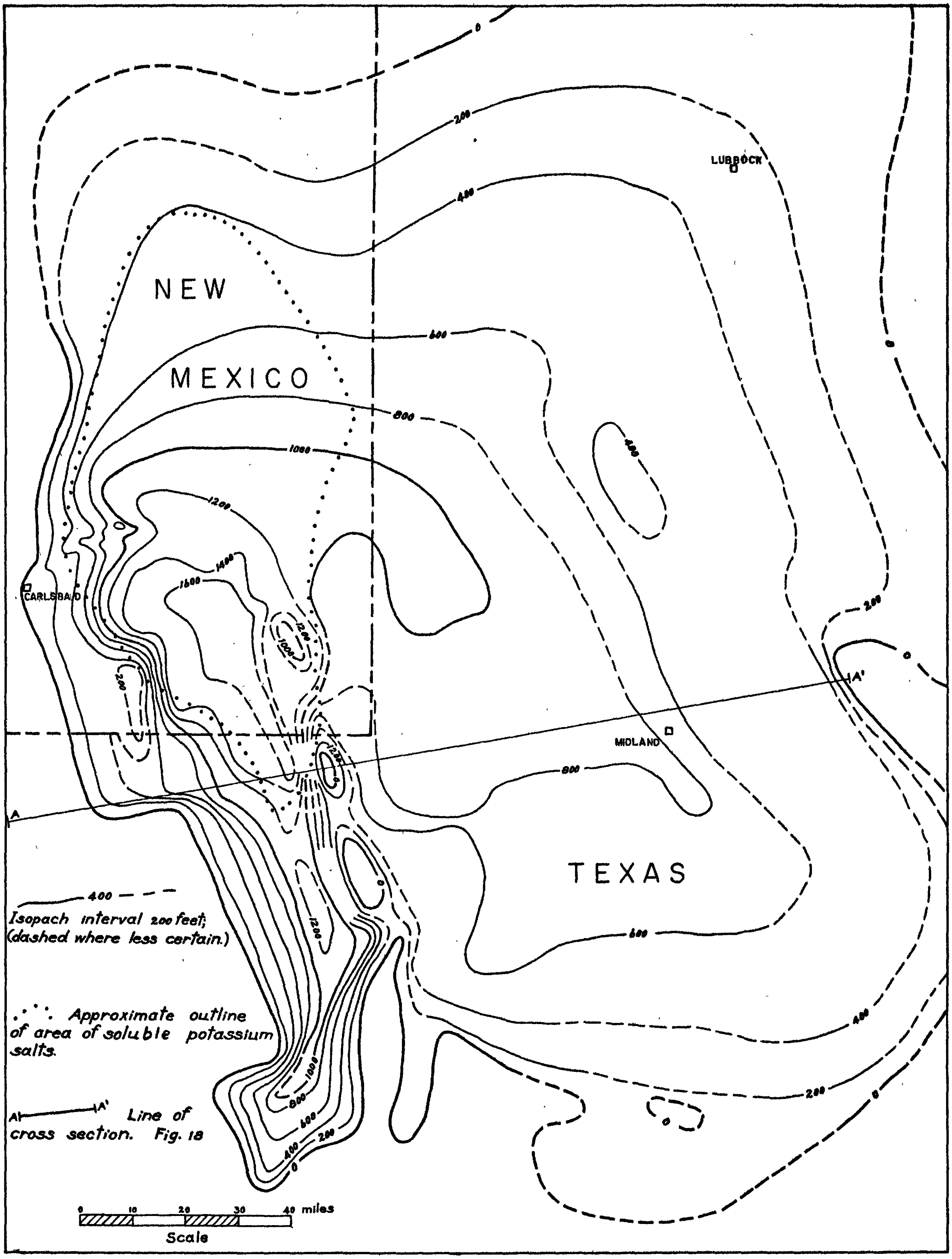



Figure 19.--Map showing aggregate thickness of salt in Salado formation, Ochoa series, New Mexico and Texas (from P. T. Hayes, in preparation).

Figure 20 shows the combined thickness of the salt in the Castile and Salado formations. The contact between the Salado and the Rustler formations is conformable and gradational. The exact position of the contact is arbitrary but is usually placed at the top of the highest thick halite bed in the Salado formation.

The thickness of the overburden above the halite in the Salado formation ranges from 400 feet near the southwestern part of the area to more than 2,500 feet in the northern part. In general, the thickness of the overburden in the Delaware basin area ranges from 700 to 800 feet on the west and south sides to about 1,500 feet on the northeast side, whereas on the adjacent shelf area it generally ranges from 1,000 to 2,000 feet (West Texas Geological Society, 1949, 1951, 1953).

Figure 21 shows the structural configuration of the top of the salt-bearing formations in the west Texas-southeast New Mexico area. The greater thickness of salt occurs on the western limb of a syncline, the axis of which is "S" shaped and trends in a northeast to southwest direction. In general, however, the thickness of salt has only incidental relation to the synclinal structure which developed during post-Permian time; the thickness is related to the shape, size, and relative depths of various parts of the Delaware and Midland basins during the time of salt disposition (Adams, 1944, p. 1616-1622).

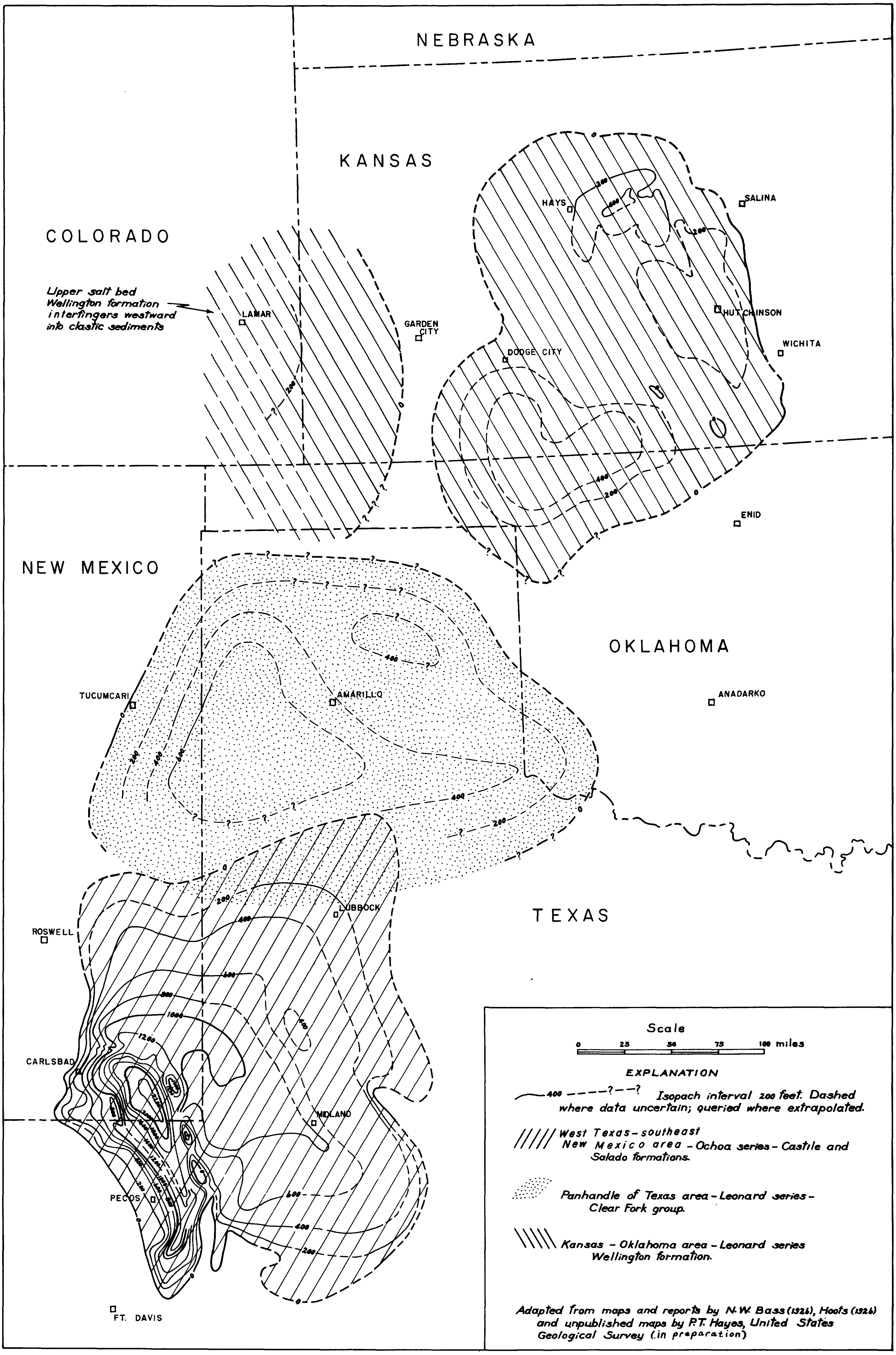



Figure 20. - Map showing aggregate thickness of salt in Permian basin of Kansas, Oklahoma, Texas, and New Mexico.

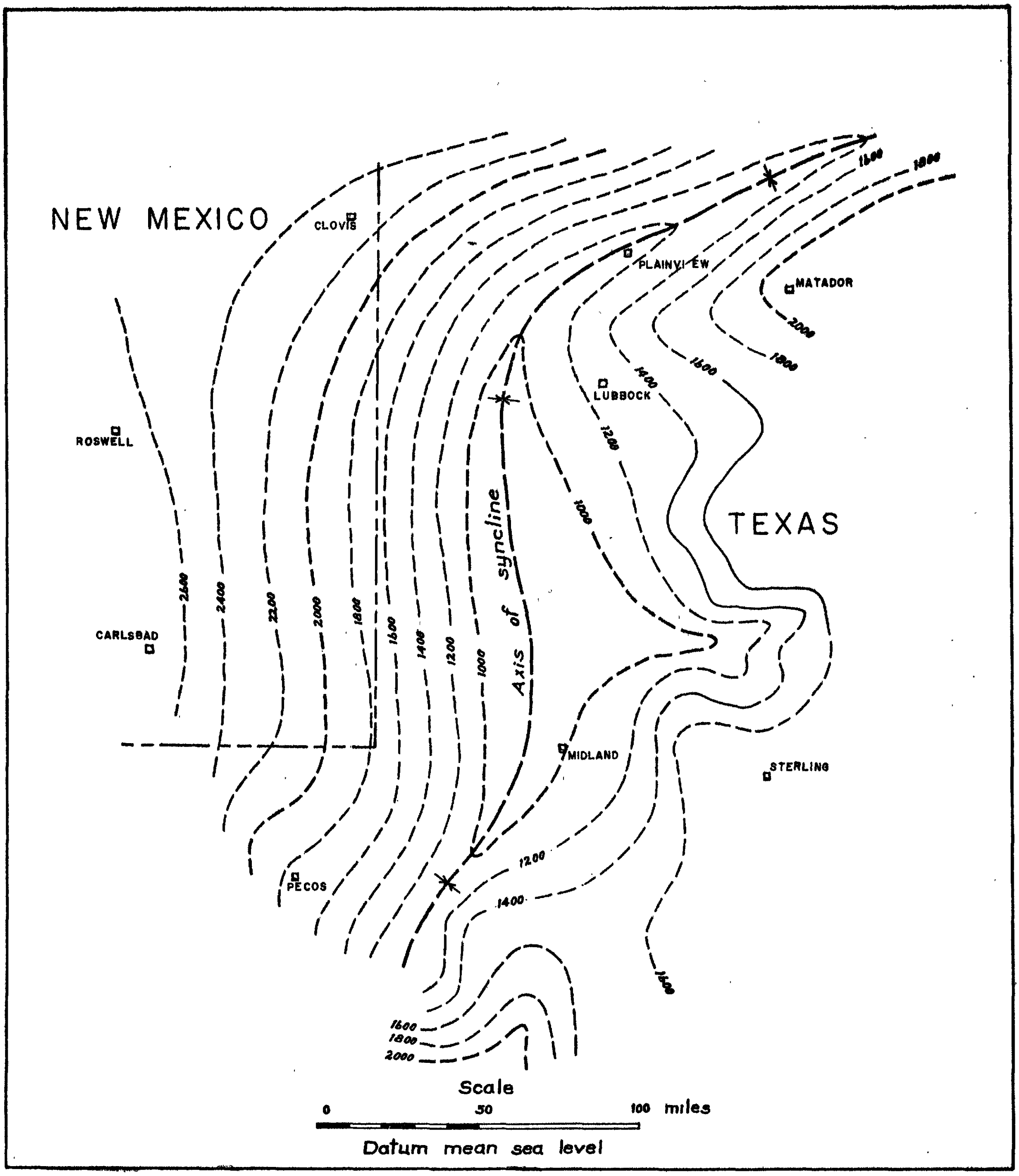



Figure 21.--Structure contour map of southeast New Mexico-west Texas showing altitude of top of salt-bearing formations (from Hoots, 1925).

Rustler formation.--The Rustler formation is the highest Permian salt-bearing unit in western Texas and southeastern New Mexico, but unlike the Castile and Salado formations, halite comprises only a relatively small percentage of the total thickness of the formation. Halite occurs in a few thin discontinuous beds, especially in the lower part. Anhydrite is the dominant rock type in the Rustler formation but polyhalite and soluble potassium salts and dolomite are also present locally.

## Texas Panhandle area

The Permian salt beds have been penetrated by numerous drilled wells in the Texas Panhandle area but useful data regarding the salt beds have been given in only a few reports. In general, however, the salt beds are older than those of the Delaware basin.

The salt is in a succession of red and gray shale, gypsum, and anhydrite that is referred to the Leonard series of the Permian system. The stratigraphic nomenclature and correlation of the Permian units in the Texas Panhandle area are not clear, but the relationship of the various lithologic groups as used in this report is shown in figure 15.

In the Texas Panhandle the salt occurs in the lower part of the Clear Fork group of the Leonard series. It is interbedded with red shale, anhydrite, and some dolomite. Individual beds of salt are as much as 225 feet thick but generally are less than 50 feet thick and make up only 15 to 20 percent of the Clear Fork group. The salt in the Clear Fork group increases in thickness westward from 0 in southwestern Oklahoma to a maximum of about 735 feet near the west side of the Texas Panhandle. Westward from the Texas Panhandle-New Mexico border, the salt decreases in thickness and pinches out or interfingers with shale roughly 50 miles west of the State line (fig. 20). The southern limit of the Texas Panhandle salt deposit is uncertain, but it probably extends to near the Ochoa salt-bearing formations and may underlie them in part. The northern limit of the salt beds is not known. Available data (Sellards and others, 1932, p. 185) indicate that the salt in the Texas Panhandle is somewhat younger than the salt in the Wellington formation of northwestern Oklahoma and Kansas. The salt in the Texas Panhandle area is possibly equivalent in age to the upper salt bed of the Wellington formation in eastern Colorado and western Kansas (fig. 20). Further investigations may show that these two salt beds are stratigraphic as well as temporal equivalents.

Oklahoma Panhandle and southwestern Kansas area

The most widely spread zone of salt in the southwestern Kansas area occurs in the Wellington formation. It is from this zone that commercial salt has been produced at Hutchinson, Lyons, and Kanopolis, Kans. In general, the area underlain by thick salt beds extends from near the center of Kansas southwestward across the State into the easternmost part of the Oklahoma Panhandle. A second deposit of salt about 200 feet thick and a little more than 1,000 feet above the Wellington salt occurs in an area from 100 to 175 miles east of the southwest corner of Kansas (fig. 20). This upper salt accounts for the greater part of the combined thickness of salt beds near the Kansas-Oklahoma boundary.

The Wellington formation can be divided into three members (Lee, 1956, p. 116): The "anhydrite beds" at the base, the "salt beds" or Hutchinson salt member in the middle, and an unnamed member at the top. The "anhydrite beds" consist of a sequence of gray shale alternating with anhydrite. The Hutchinson salt member is an evaporite zone consisting of halite interstratified with beds and laminae of anhydrite. The upper unnamed member consists of gray and red shale.

In the Carey salt mine at Hutchinson, Kans., the Hutchinson salt member consists of "rather irregular alternation of clear, white coarsely crystalline halite, in beds several inches thick, with thin laminae of gray silty shale, gypsum, and anhydrite" (Swineford, 1955, p. 33). Lee (1956, p. 119-126) noted that the thickness of the Hutchinson salt member varies sharply from place to place but in general it tends to be thicker in anticlinal or domal structures that were probably formed after the deposition of the Permian rocks. The greater thickness of salt in anticlines is attributed, by Lee, to the movement of plastic-like salt into these local upwarps. An anticlinal or domal accumulation of salt is suggested by the thickness of the salt in central Kansas, as shown on figure 20.

The Hutchinson salt member is thickest in the northeastern part of the Permian basin. In central Kansas, the aggregate thickness of the Hutchinson salt is about 400 feet, but it thins irregularly toward the margins of the basin where the salt and associated anhydrite interfinger with shale. In outcrops along the margins of the basin the salt has been removed by surface waters. This leaching of the soluble salt extends down dip for several miles.

The salt found in eastern Colorado and southwesternmost Kansas appears to represent only the upper salt bed, although it is probably not continuous throughout the region from central Kansas into Colorado.

The thickness of the overburden above the salt beds ranges from about 400 feet in east-central Kansas to more than 1,500 feet east of the Oklahoma Panhandle. In general, the overburden above the thickest salt ranges from 700 to 1,100 feet. The structural configuration of the top of the Hutchinson salt member of the Wellington formation is shown in figure 22.

The salt bed is folded into a syncline, the axis of which trends in a general northwest-southeast direction. Notably, the areas of thicker salt are in the structurally higher limbs of this syncline.

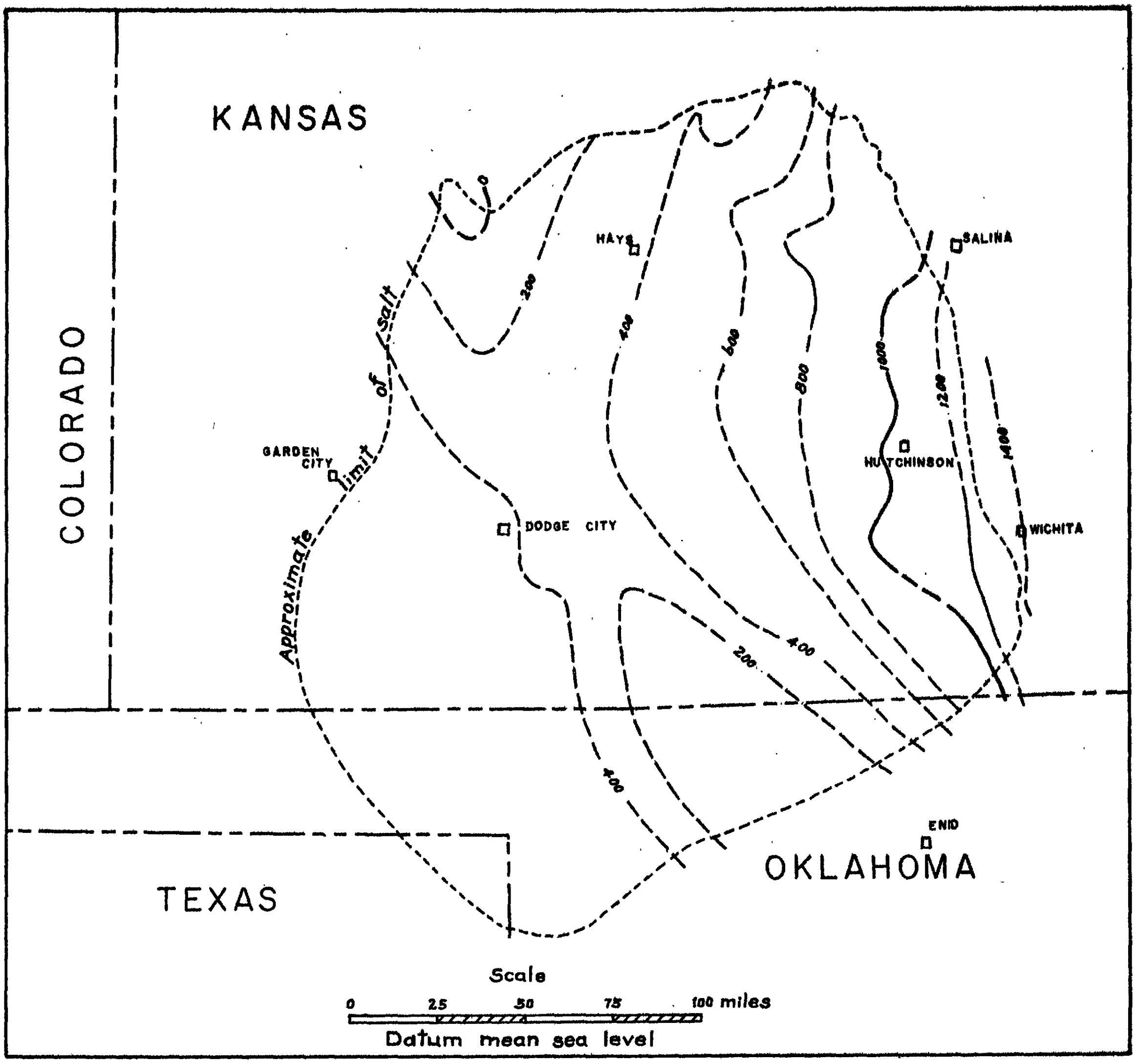



Figure 22.--Structure contour map showing altitude of top of salt beds of Wellington formation in Kansas and adjoining parts of Oklahoma (after Bass, 1926).

# THE PARADOX BASIN,

# SOUTHEASTERN UTAH AND SOUTHWESTERN COLORADO

## Introduction

The Paradox basin is a sedimentary basin of Pennsylvanian age which has subsequently been elevated and severely folded and faulted. It is elongate in a northwesterly direction and covers about 12,000 square miles in southeastern Utah and southwestern Colorado. The thick salt deposits are in the Paradox member of the Hermosa formation.

The account which follows is largely abstracted from an unpublished preliminary report prepared by E. H. Baltz (1957). Baltz found that, although the general distribution of salt is known from drilling data, the drill holes are too widely spaced to give detailed quantitative data. In order to develop a regional picture of the distribution of salt, it was therefore necessary to rely heavily on geologic interpretation and extrapolation.

## Hermosa formation

The Hermosa formation, of Pennsylvanian age, is predominantly of marine origin, and is composed of limestone, dolomite, sandstone, shale, gypsum, anhydrite, and salt, in varying proportions. It ranges in thickness from less than 1,000 feet toward the borders of the basin to as much as 8,000 feet in the deepest part. The formation has been divided into three members: a lower unnamed member; the middle Paradox member, which is the salt-bearing unit; and an upper unnamed member (Bass, 1944). These units and their relation to the underlying and overlying formations are shown diagrammatically as follows:

<table>
<tr><th>Age</th><th colspan="2">Formation</th></tr>
<tr><td>Permian</td><td colspan="2" rowspan="2">Rico formation</td></tr>
<tr><td rowspan="5">Pennsylvanian</td></tr>
<tr><td rowspan="3">Hermosa formation</td><td>Upper member</td></tr>
<tr><td>Paradox member (salt-bearing)</td></tr>
<tr><td>Lower member</td></tr>
<tr><td colspan="2">Molas formation</td></tr>
</table>

Only the Paradox member contains salt deposits.

Paradox member

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. Most of the variation in thickness of the Hermosa formation is thought to take place in the Paradox member and is believed to be due to the presence of evaporite rocks.

The salt in the Paradox basin is in an elongate northwest-trending area approximately 160 miles long and 80 miles wide. The basin is sharply bordered on the northeast by the Uncompahgre uplift and the deepest part of the sedimentary and structural basin lies only a few tens of miles southwest of the uplift. Thus the basin is asymmetrical in a northeast-southwest cross section.

Some potassium-bearing salts are reported in the Paradox member in the northwestern part of the Paradox basin, particularly in the Salt Valley, Moab, and Cane Creek areas. Some exploratory drilling has been done by the Delhi-Taylor Oil Corporation, but the results obtained are not known.

## Structure

Most of the Paradox basin is characterized by broad open folds that trend northwesterly roughly parallel to the Uncompahgre uplift. In the southwestern part of the basin the structural trend is in a more northerly direction parallel to the Monument upwarp. Anticlinal folds in the southern and southwestern part are widely spaced and have relatively low structural relief. In the central and northeastern parts the folds are crowded more closely together, and are longer and higher. In this region the axial parts of the larger anticlines have been complexly downfaulted and form grabens many miles in length. 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 the area of the intrusive complex. Other areas of large-scale igneous intrusion in the Paradox folded and faulted area are the Abajo Mountains west of Monticello, Utah, and the Ute Mountains near the southwestern corner of Colorado.

In the northeastern part of the Paradox basin erosion or downfaulting of Mesozoic rocks in most of the large anticlines has exposed cores of greatly contorted anhydrite, gypsum, black shale, and limestone of the Paradox member of the Hermosa formation in abnormal contact with younger rocks. Below the zone of leaching the Paradox member is composed mainly of salt. Detailed mapping of the faulted anticlines by Baker (1933); Dane (1935), and McKnight (1940) in Utah, and by Stokes and Phoenix (1948), Cater (1954, 1955 a, b, and c) and Shoemaker (1954, 1956) in Colorado has shown that the gypsum and salt have risen in places as a semi-plastic mass and pierced overlying sedimentary rocks. These writers agree that flowage began in early Permian time and continued intermittently during parts of Permian and Triassic time; however, opinion differs as to whether piercement occurred prior to Late Cretaceous or early Tertiary time. The Morrison formation of Jurassic age in the Colorado part of the Paradox basin is the oldest Mesozoic formation to overlap the salt bodies (Stokes and Phoenix, 1948). Apparently upward movement of the salt bodies halted shortly after the deposition of the Morrison formation and a thick sequence of Upper Cretaceous marine sediments was deposited across the area. Cretaceous rocks are involved in the final phase of folding which seems to have been oriented along the pre-existing folds. The earlier folds seem to have been much broader but shorter than the later folds.

The axial parts of the anticlines sagged or were downfaulted into the salt masses during the final phase of deformation. This may have occurred as early as early Tertiary time and may have continued in places until middle or late Tertiary time. Several mechanisms have been suggested to account for the collapse of the anticlines. Baker (1933, p. 65) has suggested that some of the faulting in the Moab anticline is relatively recent and resulted from uplift of the sedimentary strata overlying the rising salt mass and the later settling of the 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 general, it can be concluded that the long, narrow grabens or structural troughs are related in some manner to expanded thicknesses of salt. This concept was utilized in isopaching salt in 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 of salt expansion, but to a lesser degree than that of the great anticlines to the northeast. Folding that involves both competent beds, such as sandstone and limestone, and incompetent beds, such as shale, gypsum, and salt, usually causes some flowage of the incompetent rocks away from the flanks of the structures into the crests of anticlines and troughs of flanking synclines. In the broad, low folds of the central and southern Paradox basin this effect probably would have been slight, but erosion of the crestal parts of these anticlines would cause a static imbalance between crest and flanks causing further expansion of salt into the anticlines. Thus it seems likely that some expansion has occurred on nearly all of the anticlines situated in the region of fairly thick evaporite deposits.

## Distribution and thickness of salt

Two factors control the thickness of salt in the Paradox basin: the original basin of deposition, and the subsequent flowage of salt into anticlines.

The estimated original thickness of salt in the Paradox basin is shown in figure 23. The greatest thickness of salt was deposited near the northeastern side of the basin parallel to the southwestern border of the Uncompahgre uplift. Salt as much as 4,000 feet thick was deposited in the deepest part of the sedimentary basin.

Subsequent to the deposition of salt, regional deformation caused the salt to flow into anticlinal folds, and thus the salt thickened in the anticlines and thinned in the synclines. The location and trend of the salt anticlines or zones of salt piercement are also shown in figure 23. The thickness of the salt in these anticlines ranges from 3,000 feet to about 12,000 feet.

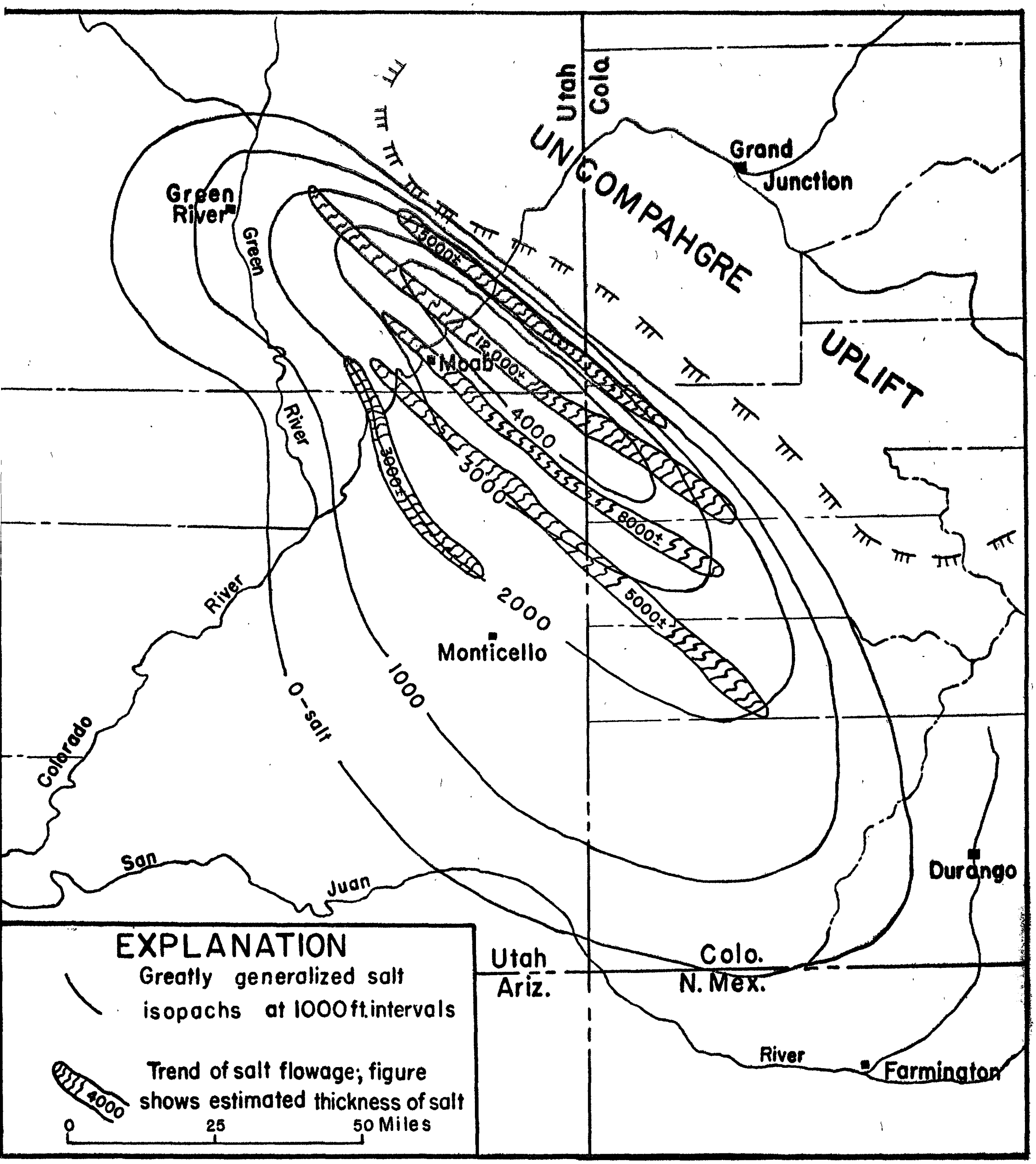



Figure 23 Map showing estimated original thickness of salt in the Paradox basin, and trends of subsequent flowage of salt (After Wengerd and Strickland).

The present thickness and distribution of the salt-bearing part of the Paradox member are indicated by isopach lines on figure 24. The stratigraphic interval used in drawing the isopach lines does not represent the entire Paradox member; it includes only that part between the top of the highest bed of salt and the base of the lowest salt bed. The interval is composed of varying proportions of interbedded shale, limestone, salt, and other evaporites so that the actual thickness of salt at any given place is less than that represented by the isopach lines. Near the zero salt 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. From the well data available from 11 wells in Colorado and 12 wells in Utah, the total thickness of the salt-bearing beds and the percent of this thickness which is composed of salt has been estimated. The results are tabulated on table 1. Electric logs in most cases were excellent for estimating the salt content, if micrologs or short lateral resistivity curves were plotted on the log.

Table 1.--Estimated percentage of salt in selected wells in Paradox basin

| No. on fig. 24 | County | Name of well | Thickness of salt-bearing rocks (feet) | Total thickness of salt beds (feet) | Salt (percent) | Remarks |
|---|---|---|---|---|---|---|
| | | | Colorado | | | |
| 2 | Mesa | Huber No. 1 Sinbad | 9196 | 5125+ | 56 | Residual gypsum, dolomite, shale, 4 sandstones 1100' thick above salt. Hole does not penetrate total Paradox. |
| 12 | San Miguel | Reynolds No. 1 Egnar | 4200 | 3290 | 78 | One thick salt section with numerous shale and anhydrite breaks. |
| 14 | Dolores | Byrd Frost West Nat. No. 1-A Uhl | 1510 | 640 | 42 | One 400'+ bed, rest interbedded salt, shale, and anhydrite. |
| 16 | do. | Continental No. 1 Lone Dome | 3215 | 2565 | 79 | 1 thick salt section with numerous shale and anhydrite breaks. |

Table 1.- Estimated percentage of salt in selected wells in Paradox basin--Continued

| No. on fig. 24 | County | Name of well | Thickness of salt-bearing rocks (feet) | Total thickness of salt beds (feet) | Salt (percent) | Remarks |
|---|---|---|---|---|---|---|
| | | | Colorado--Continued | | | |
| 19 | Montezuma | Byrd Frost West Nat. No. 1 Driscoll | 1820 | 800 | 44 | 1-400'± bed and 3-100'± salt beds. |
| 22 | do. | Hathaway No. 1 USC (Lyon-Fed) | 1362 | 964 | 70 | 1-575' bed, 1-120' bed, and 5-60'± salt beds. |
| 23 | do. | Gulf No. 1 Fulks | 1148 | 810 | 70 | One thick salt zone with numerous small shale and anhydrite breaks. |
| 24 | do. | Stanolind No. 1 Schmidt | 1545 | 530 | 34 | No thick salt beds. Salt occurs in 5-100'± zones. |
| 27 | La Plata | Great Western No. 1 Ft. Lewis | 800 | -- | -- | No salt beds. Salt casts in anhydrite. |
| 29 | do. | Skelly No. 1 Lloyd Benton | 165? | 165? | ? | 165' of no sample--may indicate salt dissolved in drilling fluid. |

Table 1.--Estimated percentage of salt in selected wells in Paradox basin--Continued

| No. on fig. 24 | County | Name of well | Thickness of salt-bearing rocks (feet) | Total thickness of salt beds (feet) | Salt (percent) | Remarks |
|---|---|---|---|---|---|---|
| | | | Colorado--Continued | | | |
| 30 | Montezuma | Continental No. 1 Ute Mtn. | 150? | 150? | -- | 150' of no sample. |
| | | | Utah | | | |
| 39 | Emery | Equity No. 1 Government | 1450 | 700 | 48 | Occurs in 6-100'± beds. |
| 43 | do. | General Pet., 45-5-G | 969 | 345 | 36 | 1-180'±, 5-50'± beds. |
| 51 | Grand | Tidewater No. 74-11 Big Flat | 3455 | 2900 | 84 | Very thick salt section with numerous shale, anhydrite and limestone beds. |
| 55 | San Juan | Midwest No. 1 Shafer | 3880 | 2520 | 65 | Very thick salt section with numerous breaks. |

Table 1.--Estimated percentage of salt in selected wells in Paradox basin--Continued

| No. on fig. 24 | County | Name of well | Thickness of salt-bearing rocks (feet) | Total thickness of salt beds (feet) | Salt (percent) | Remarks |
|---|---|---|---|---|---|---|
| | | | Utah--Continued | | | |
| 60 | San Juan | Western National Gas No. 1 Redd | 1690 | ? | -- | No salt recovered, only salt casts in anhydrite. Salt probably dissolved in drilling fluid. |
| 61 | do. | Midwest No. 1 Hughes | 380 | 100 | 26 | 3 very thin beds. |
| 65 | do. | Reynolds No. 1 Hatch | 1100 | 685 | 62 | Good soft section. Some shale and anhydrite breaks. |
| 66 | do. | Hathaway 1-B Glasco-Fed. | 1120 | 530 | 47 | Good salt section. 1 thick bed of salt; 3 thin shale breaks. |

Table 1--Estimated percentage of salt in selected wells in Paradox basin--Continued

| No. on fig. 24 | County | Name of well | Thickness of salt-bearing rocks (feet) | Total thickness of salt beds (feet) | Salt (percent) | Remarks |
|---|---|---|---|---|---|---|
| | | Utah--Continued | | | | |
| 67 | San Juan | Glasco Shell No. 1 Government | 1225 | 670 | 55 | No pure salt beds. All have anhydrite and pyrite. 180' of no samples. |
| 69 | do. | Carter No. 1 Bluff Bench | 770 | 370 | 48 | Occurs as 4 impure salt zones. |
| 70 | do. | Shell No. 1 Bluff Unit | 725 | 390 | 43 | Generally impure salt. |
| 71 | do. | Shell No. 1 Hovenweep | 923 | 325 | 35 | 1 thick bed with some impurities. |

The thickest salt-bearing rocks are in the area of large collapsed anticlines in the northeastern part of the Paradox basin. Wells drilled on the Gypsum Valley and Sinbad Valley anticlines in western Montrose and southwestern Mesa Counties, Colo., indicate at least 10,000 feet of evaporite rocks, mainly salt, in parts of these anticlines. Comparison of gravity anomaly maps (Joesting and Byerly, 1956) of Sinbad Valley, Paradox Valley, and Gypsum Valley anticlines supports the thicknesses indicated by wells. Estimates of maximum evaporite thickness in parts of Salt Valley-Fisher Creek anticlines and Moab 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, as previously mentioned, to flowage of evaporites into the anticlines during deformation.

Flowage of salt toward the anticlinal areas during and after regional folding may have removed all or nearly all of the salt from the flanks of the folds at least in 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, 1956, p. 49). A strong positive anomaly west and southwest of the Gypsum Valley anticline may indicate complete withdrawal of salt from this area. Additional knowledge of the history of the anticlines may provide further evidence indicating complete removal of salt from the synclinal areas adjacent to the major anticlines. The apparent cessation of upward movement on the anticlines in Late Jurassic time may thus be due to the exhaustion of salt from the synclinal areas.

In the central and southern parts of the Paradox salt basin, anticlinal folds show much less structural relief and no evidence indicates 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, perhaps aided in some measure by isostatic adjustments.

## Depth to top of salt beds

The depth to the top of the salt-bearing beds varies greatly over the area, owing to the structural deformation to which the beds have been subjected. The large anticlinal and synclinal folds cause large differences in the depth to the salt, so that the structural position of the salt at a given locality is only one controlling factor. The amount of piercement of the salt through the overlying beds is another factor affecting its depth.

A map depicting the depth to the top of the salt thus would require considerable detail; a generalized, small-scale map would be impractical and has not been attempted for this report. However, available data from 31 wells in Colorado and 44 in Utah have been assembled in table 2, which shows the depth to the top of the salt, and the thickness of salt-bearing beds penetrated. The table shows that the depth to salt commonly ranges from 5,000 to 8,000 feet. Inasmuch as these wells were drilled for oil and gas, they were presumably located on anticlinal structures. Hence, they do not portray an average or representative depth, but probably show considerably less than average depth to salt for the region.

In addition to the depths to salt shown in table 2 by Baltz, it is reported by E. M. Shoemaker (written communication, April 1, 1958) that the shallowest known salt in the Paradox basin is in Sinbad Valley, where a 110-foot section of salt was penetrated between 400 and 510 feet. In Salt Valley salt is reported at a depth of 775 feet.

Table 2.--List of wells in the Paradox basin, with depth to top of salt and thickness of salt-bearing beds

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Colorado | | | | |
| 1 | Mesa | Pure No. 1 Gateway | No Paradox | -- | -- | 7939 | Precambrian |
| 2 | do. | Huber No. 1 Sinbad Valley | At surface | 1120 | -- | 10,316 | Paradox |
| 3 | Montrose | Continental No. 1 Nucla | 5105 | No salt | -- | 7618 | Devonian(?) |
| 4 | do. | Chicago No. 1 Ayers | -- | -- | -- | 6860 | Upper Hermosa |
| 5 | do. | Amer. Liberty No. 1 Federal | At surface | 4590 | -- | 10,544 | Paradox |
| 6 | do. | Pure No. 1 San Miguel | 7201 | -- | -- | 7480 | Do. |
| 7 | do. | Pure No. 1 Horsefly | No Pennsylvanian | -- | -- | 5035 | Sawatch(?) |
| 8 | do. | Indian No. 1 Mastbrook | 5060(?) | -- | -- | 5185 | Paradcx(?) |

Table 2.--List of wells in the Paradox basin, with depth to top of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Colorado--Continued | | | | |
| 9 | Montrose | Penrose Tatum No. 1 Orme | -- | -- | -- | 1753 | Tertiary(?) igneous |
| 10 | San Miguel | Penrose Tatum No. 1 Marie Scott | -- | -- | -- | 2561 | Hermosa |
| 11 | do. | Turner No. 1 Buss | 6793 | No salt | -- | 8790 | Tertiary (?) igneous |
| 12 | do. | Reynolds No. 1 Egnar | 4955 | 5440 | 9640 | 10,220 | Leadville |
| 13 | do. | Prestidge-Ailison No. 1 Long | 5820 | 6137 | -- | 6211 | Paradox |
| 14 | Dolores | Byrd Frost No. 1-A Uhl | 6000(?) | 6070 | -- | 7680 | Do. |

Table 2.--List of wells in the Paradox basin, with depth to top of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Colorado--Continued | | | | |
| 15 | Dolores | Moody No. 1 Stathopulous | 5920 | 6240 | -- | 6747 | Paradox |
| 16 | do. | Continental No. 1 Lone Dome | 5923 | 6170 | 9385 | 9950 | Leadville |
| 17 | Montezuma | Colo. 3 States No. 2 White | 5885 | -- | -- | 6202 | Paradox |
| 18 | do. | Byrd Frost West. Nat. No. 1 White | 6010 | -- | -- | 6202 | Do. |
| 19 | do. | Byrd Frost No. 1 Driscoll | 5590 | 6000 | 7820 | 8286 | Leadville |
| 20 | do. | H.E.R. No. 1 Eva Marr | 5865 | -- | -- | 6158 | Paradox |
| 21 | do. | H.E.R. No. 1-A Lane-Coffee | 5705 | 6016 | -- | 6031 | Do. |
| 22 | do. | Hathaway No. 1 USC (Lyon-Fed.) | 5298 | 5543 | 6905 | 7628 | Leadville |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Colorado--Continued | | | | |
| 23 | Montezuma | Gulf No. 1 Fulks | 5760 | 5982 | 7130 | 8787 | Precambrian |
| 24 | do. | Stanolind No. 1 Schmidt | 4395 | 4850 | 6395 | 7099 | Elbert |
| 25 | do. | Byrd Frost No. 1 MacIntosh | 4510 | -- | -- | 4965 | Paradox(?) |
| 26 | do. | Slick Moorman No. 1 Weaver | 6074 | 6322(?) | -- | 6701 | Paradox |
| 27 | La Plata | Gr. Western No. 1 | 8330 | 8600 | 9400 | 10,214 | Elbert |
| | | Ft. Lewis | | | | | |
| 28 | Montezuma | Tidewater No. 1 Ute | 8702 | 8920 | -- | 9502 | Paradox |
| 29 | La Plata | Skelly No. 1 | 8495 | 8855(?) | 9020(?) | 10,388 | Elbert |
| | | Lloyd Benton | | | | | |
| 30 | Montezuma | Continental No. 1 | 5850 | 6050(?) | 6200(?) | 7227 | Precambrian(?) |
| | | Ute Mountain | | | | | |
| 31 | La Plata | Delhi No. 2 Barker | 8800 | No salt | -- | 7550 | Paradox |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | Utah | | | | | |
| 32 | Emery | Hancock Utah No. 1 Cedar Mtn. | No Paradox | -- | -- | 4940 | Leadville |
| 33 | Grand | Cont. Union, Mtn. Fuel No. 1 Cisco Dome | do. | -- | -- | 4743 | Precambrian |
| 34 | Emery | 3 States Nat. Gas No. 1 Sinbad | do. | -- | -- | 4183 | Do. |
| 35 | Grand | Amerada No. 1 Green River | 4815 | 5125 | -- | 5645 | Paradox |
| 36 | do. | Crescent Eagle | 1981? | 2155 | -- | 4009 | Do. |
| 37 | do. | Pacific West. Equity No. 1 Thompson | 12,135 | 12,200 | -- | 13,766 | Do. |
| 38 | do. | Equity No. 1 Govt. | No Paradox | -- | -- | 3810 | Precambrian |
| 39 | Emery | Equity No. 1 Govt. | -- | 6040 | 7490 | 8130 | Leadville |
| 40 | Grand | Pacific West. No. 1 Sharp St. | 4680 | 4990 | -- | 5046 | Paradox |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | Utah--Continued | | | | | |
| 41 | Grand | Pure No.1 Salt Valley | 2480 | 2750 | -- | 3036 | Paradox |
| 42 | Emery | Std. of Calif. No. 2 San Rafael | No Paradox | -- | -- | 4900 | Precambrian |
| 43 | do. | General Pet. 45-5-G | 3981 | 5386 | 6355 | 7161 | Leadville |
| 44 | Grand | Equity No. 1 Donahue | -- | 5516 | 5962 | 6618 | Penn.-Miss.? |
| 45 | do. | Equity No. 1 State | 5390 | 5450 | 5840 | 6140 | Hermosa? |
| 46 | do. | Utah South No. 1 Southern King | 1015 | 1570 | -- | 3829 | Paradox |
| 47 | do. | Utah South No. 1 Balsley | At surface | -- | -- | 6120 | Do. |
| 48 | do. | Harry Hubbard No. 1 Federal | No Paradox | -- | -- | 7955 | Hermosa |
| 49 | Emery | Blackwood Nicols No. 1-28 San Rafael | do. | -- | -- | 4182 | Cambrian |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Utah--Continued | | | | |
| 50 | Emery | Delhi No. 1 U. N. Russell | No Paradox | -- | -- | 6008 | Leadville |
| 51 | Grand | Tidewater No. 74-11 Big Flat | 4220 | 4270 | 7725? | 8408 | Leadville? |
| 52 | Emery | Tidewater No. 6-25 | 4700 | No salt | -- | 5472 | Molas |
| 53 | Wayne | Philips No. 1 Schick | 4093 | do. | -- | 5191 | Leadville |
| 54 | Grand | Midwest No. 1-A Shafer | 2048 | 2130 | -- | 3095 | Paradox |
| 55 | San Juan | Midwest No. 1 J. H. Shafer | 1580 | 1610 | 5490 | 5863 | Leadville |
| 56 | do. | Reynolds No. 1 Gibson Dome | -- | 1953 | 4496 | 6036 | Miss.-Dev.? |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | Utah--Continued | | | | | |
| 57 | San Juan | Union No. 1 Utah St. | 1155 | 1615 | -- | 4960 | Paradox |
| 58 | do. | Byrd-Frost No. 1 Sitton | 5661 | -- | -- | 5828 | Do. |
| 59 | do. | Byrd-Frost No. 1 Randall | 5654 | -- | -- | 6265 | Do. |
| 60 | do. | West. Nat'l Gas No. 1 Redd | 5575 | 5910 | 7600 | 8678 | Elbert |
| 61 | do. | Midwest No. 1 Hughes | 1260 | 1570 | 1950 | 4422 | Precambrian |
| 62 | do. | Gulf No. 1 Coalbed Canyon | 5568 | 5875 | -- | 5912 | Paradox |
| 63 | do. | Gr. West. Drlg. No. 1 Fish Cr. | No tops | -- | -- | 4840 | Cambrian |
| 64 | do. | Woodward Hawkings No. 1 Butler Wash | 6410 | -- | -- | 6548 | Paradox |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Utah--Continued | | | | |
| 65 | San Juan | Reynolds No. 1 Hatch | 5764 | 6050 | 7150 | 8815 | Cambrian |
| 66 | do. | Hathaway No. 1-B Glasco, Fed. | 5415 | 5800 | 6920 | 7621 | Leadville |
| 67 | do. | Glasco, Shell No. 1 Govt. | 5341 | 5650 | 6875 | 8054 | Elbert |
| 68 | do. | Carter No. 1 Cedar Mesa | 2545 | No salt | -- | 5000 | Cambrian |
| 69 | do. | Carter No. 1, Bluff Bench | 5810 | 6040 | 6810 | 7811 | Elbert |
| 70 | do. | Shell No. 1, Bluff Unit | 5942 | 6135 | 6860 | 8762 | Precambrian |
| 71 | do. | Shell No. 1, Hovenweep | 5820 | 6050 | 6973 | 7915 | Elbert |

Table 2.--List of wells in the Paradox basin, with depth of salt and thickness of salt-bearing beds--Continued

| No. on fig. 24 | County | Name of well | Depth to top of Paradox member | Depth to top of salt-bearing rock | Depth to base of salt-bearing rock | Total depth | Lowest formation penetrated |
|---|---|---|---|---|---|---|---|
| | | | Utah--Continued | | | | |
| 72 | San Juan | U.O.R. No. 1 U.S.O. Noble | 1180 | No salt | -- | 3630 | Precambrian |
| 73 | do. | Al Hill No.1 State | 1402 | do. | -- | 3214 | Elbert |
| 74 | do. | Superior No. 1 Navajo | 5917 | -- | -- | 6152 | Paradox |
| 75 | do. | Ohio No. 1 Navajo | 5110 | No salt | -- | 6944 | Cambrian |

## Igneous intrusive rocks

Three large groups of laccolithic igneous bodies intrude 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 of igneous rock were injected selectively into the salt-bearing part of the Paradox member of the Hermosa formation. Little or nothing is known of the 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 inject the salt on the north flank of Ute Mountain as shown in well logs. Whether the igneous rocks were intruded by stoping and digestion of salt or whether the salt was forced out by the igneous rocks is not known. Increased 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 an expanded salt section.

The Byrd-Frost No. 1-A Uhl well (No. 14 on fig. 24) on the Dolores anticline in Colorado bottomed at a depth of 7,680 feet in metamorphosed Paradox beds after penetrating approximately 1,610 feet of salt-bearing rocks. The metamorphosed rocks are believed to overlie Tertiary igneous rocks which have invaded the Paradox member.

The Continental No. 1 Lone Dome well (No. 16 on fig. 24), drilled several miles southeast of the Dolores anticline, penetrated the entire Paradox member and went through a sill of igneous rock enclosed in salt beds between 8,320 and 8,430 feet.

A large pluglike body of igneous rock in the central part of Castle Valley anticline northwest of the La Sal Mountains in Utah cuts 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 igneous intrusion.

## SUPAI BASIN, ARIZONA AND NEW MEXICO

Bedded salt occurs in the Supai formation of Permian age in east-central Arizona and west-central New Mexico (fig. 1). Inasmuch as the salt beds do not crop out, they are known only from logs and cores of drilled wells. The published data on only a few wells are used here but, if more information is needed, additional well data are obtainable.

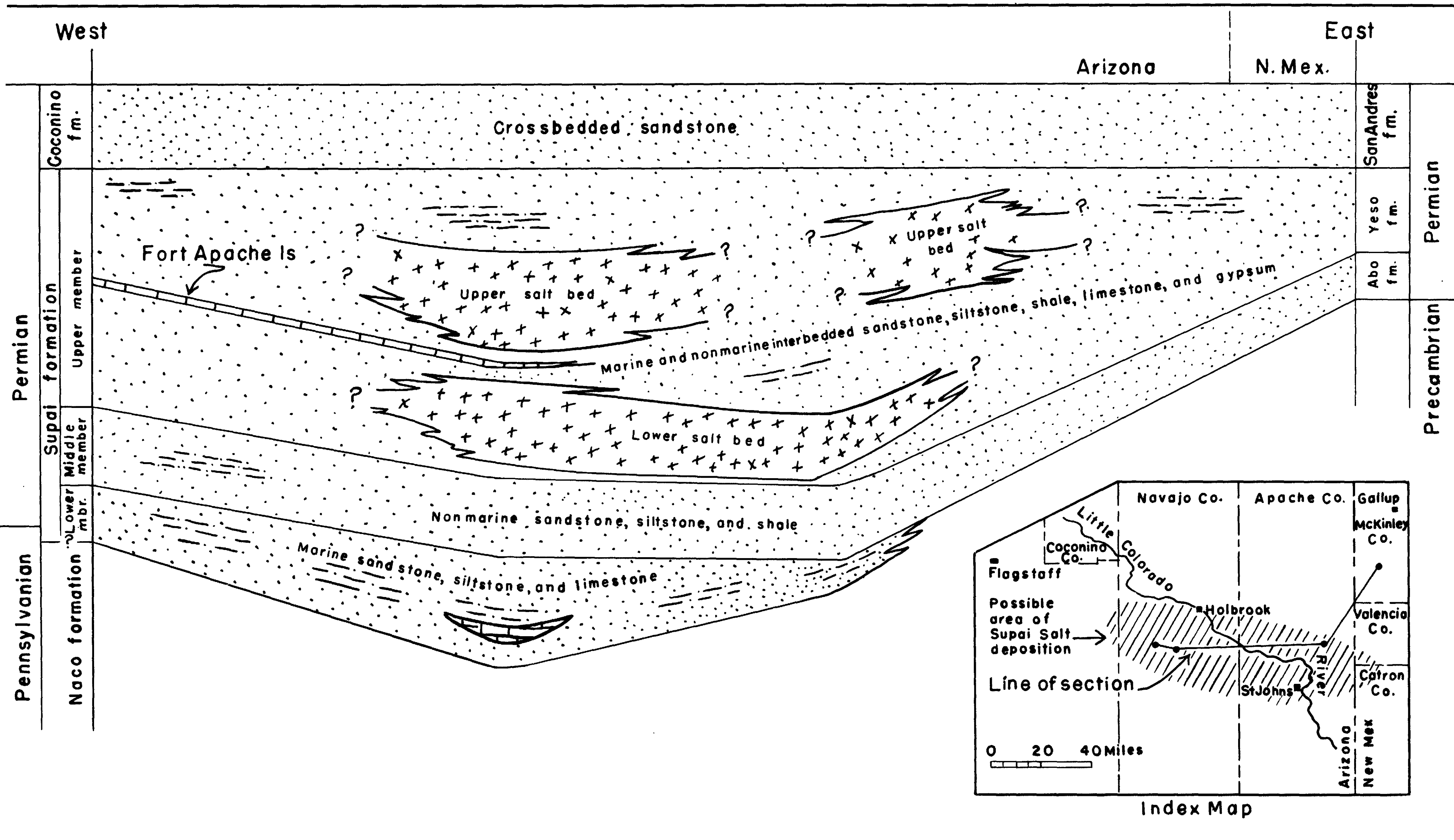
The salt-bearing Supai formation is conformable with, and gradational upward from the underlying Naco formation of Pennsylvanian age. In the area underlain by salt, the Supai formation has been divided into three members (Huddle and Dobrovolny, 1945): a lower member consisting of sandstone, shale, and limestone which is possibly of Pennsylvanian age in the lower part; a middle member made up of interbedded nonmarine sandstone, siltstone, and shale; and an upper member consisting of interbedded sandstone, siltstone, limestone, gypsum, and salt. The Coconino sandstone of later Permian age unconformably overlies the Supai formation.

The Supai formation attains a maximum thickness of about 2,500 feet south of Holbrook, Ariz. It appears to thin rapidly away from this area (McKee, 1951, p. 492) and the thickness relationships suggest that the formation and its salt beds were laid down in a closed or partially closed oval basin. The long axis of the basin may have trended southeastward from near Flagstaff, Ariz., to the northwestern part of Catron County, N. Mex. The northeast-southwest dimension of the basin is uncertain but isopach maps of the Permian rocks (McKee, 1951, plate 2) suggest that the basin may have had a maximum width of about 70 miles. Although the areal distribution of the salt beds within the Supai basin is not known, salt may have been deposited at various horizons over much of the basin during Permian time.

From drilling data of a well about 19 miles south-southeast of Holbrook, Ariz., Huddle and Dobrovolny (1954) report an aggregate thickness of about 550 feet of salt in the upper member of the Supai formation but individual beds do not exceed 160 feet. A well about 15 miles northeast of St. Johns, Ariz., penetrated a 200-foot bed of fairly pure halite and another about 40 miles east of Holbrook penetrated several beds of salt ranging in thickness from 10 to 80 feet (P. W. Johnson, personal communication, 1958). In general, salt makes up from 5 to 15 percent of the Supai formation. Figure 25 is a generalized west to east cross section of the salt-bearing Supai formation, showing a possible interpretation of the salt deposits from the data available. The thickness of the strata overlying the salt-bearing Supai formation ranges from 650 feet near the Arizona-New Mexico boundary to about 800 feet near Holbrook.

## SOUTHERN FLORIDA

Published data on salt in southern Florida are extremely meager. The following information, based on several deep tests drilled for oil and gas, has been furnished by Paul L. Applin, U. S. Geological Survey (personal communication, February 1958), from his own observations and unpublished data.




igure 25.- Schematic cross-section showing an interpretation of occurrence of salt in the Supai formation, eastern Arizona and western New Mexico (adapted from Huddle and Dobrovolny, 1945)

Twelve wells in southern Florida penetrated bedded salt and seven of them shown on figure 26. Of these, there were three wells, nos. 3,4, and 7, in which salt was recovered in the cores; in the other wells the occurrence of salt was determined from the interpretation of electric logs (wells 1 and 6) or from the combined use of electric logs and Baroid logs (wells 2 and 5). The wells are too widely separated, however, for the correlation of individual beds in the wells.

The salt occurs in a stratigraphic unit of Early Cretaceous (Comanche) age, locally called the "thick anhydrite" or the "lower massive anhydrite." The unit is composed chiefly of anhydrite with lesser amounts of irregularly bedded limestone, dolomite, dark shale and salt. The highest occurrence of salt in the unit is from 50 to 200 feet below its top. Available data suggest that salt beds may lie at three different levels.

The total thickness of salt is not known to exceed 30 feet and, for most beds, is considerably thinner, 10 feet or less. They lie at a depth of over 11,000 feet below the surface. The general area underlain by salt is shown in figure 26, but it is not known whether the salt is continuous or was deposited in several detached salt basins.

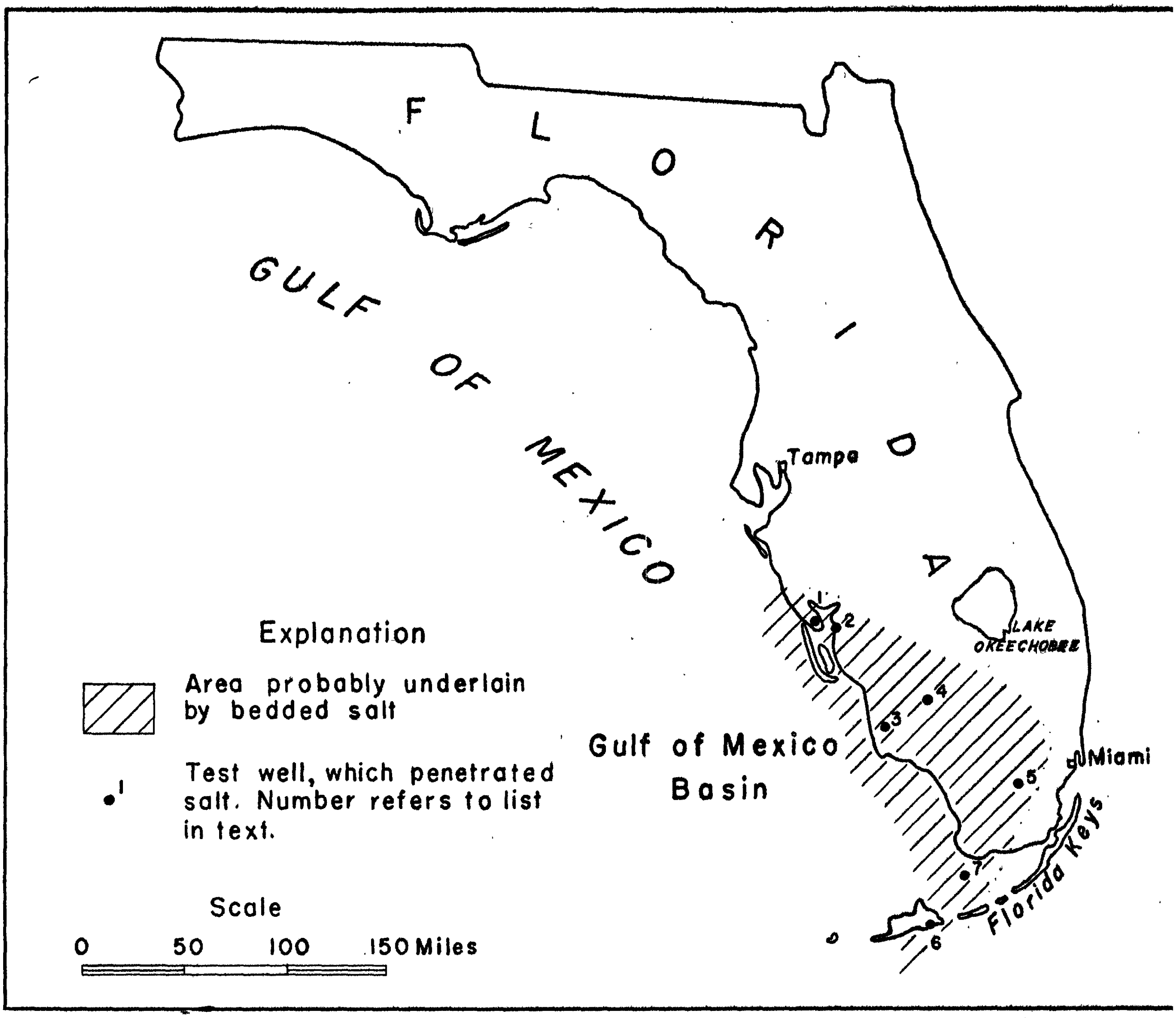



Figure 26.--Map showing area in southern Florida probably underlain by some bedded salt.

List of wells in southern Florida that penetrated rock salt[1/]

| Well no. on fig. 26 | Name of well | Total depth | Eleva-tion | Depth to top of salt | Approx. thickness of salt (feet) | Method of determina-tion of salt [2/] | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | Gulf Oil Corporation Vanderbilt 1 | 12,722 | 22 | 11,650 | 20 | A | -- |
| 2 | Humble Oil & Ref. Co. Treadwell 1A | 13,304 | 20 | 11,745 | 15 | A,B | -- |
| 3 | Humble Oil & Ref. Co. Collier Corp. 1 | 12,600 | 25 | 12,452? | -- | C | Reported in salt at total depth; salt thickness uncertain. |
| 4 | Humble Oil & Ref. Co. Gulf Coast Realties Corp., 2 | 13,512 | 34 | 11,978 | 11 | A,C | In Sunniland oil field; bottomed in salt. |
| 5 | Coastal Petroleum Co. Lease 340-A | 11,520 | 33 | 11,230 | 20 | A,B | -- |

List of wells in southern Florida that penetrated rock salt[1/] --Continued

| Well no. on fig. 26 | Name of well | Total depth | Eleva- tion | Depth to top of salt | Approx. thickness of salt (feet) | Method of determina- tion of salt[2/] | Remarks |
|---|---|---|---|---|---|---|---|
| 6 | Gulf Oil Corporation Lease 373 on Big Pine Key | 15,455 | 23 | 12,525 | 25 | A | Deepest test in Florida. |
| 7 | Gulf Oil Corporation, Lease 826-G in Florida Bay | 12,631 | 21 | 12,150 | 17 | C | Another 10-foot bed of salt 350 feet below 17-foot bed. |

1/ Data furnished by P. L. Applin, U. S. Geological Survey, Jackson, Miss.

2/ A, electric log, B, Baroid log; C, well core.

WILLISTON BASIN, NORTH DAKOTA, MONTANA, AND SOUTH DAKOTA

The Williston basin is a large sedimentary and structural basin underlying most of North Dakota, the eastern part of Montana and the northern and central part of South Dakota. Roughly half of the basin is in the United States and half in Canada. The following discussion will be limited mostly to that part of the basin in the United States.

Recent drilling for oil and gas in the Williston basin has disclosed eleven salt beds. The oldest and thickest is in the Prairie formation of Middle Devonian age. In the overlying beds of Mississippian age seven salt beds have been recognized. One thick bed of salt is in the Opeche formation of Permian age, and two similar salt beds are in the Spearfish formation of Triassic age. Rough calculations (Anderson and Hansen, 1957) show that these eleven beds contain a total volume of about 1,700 cubic miles of salt in that part of the Williston basin lying in North Dakota.

The stratigraphic position of the salt beds and their relation to the enclosing formations is shown graphically in figure 27. The thickness and extent of the salt beds, or groups of beds, will be discussed under the four major age groups, beginning with the oldest.

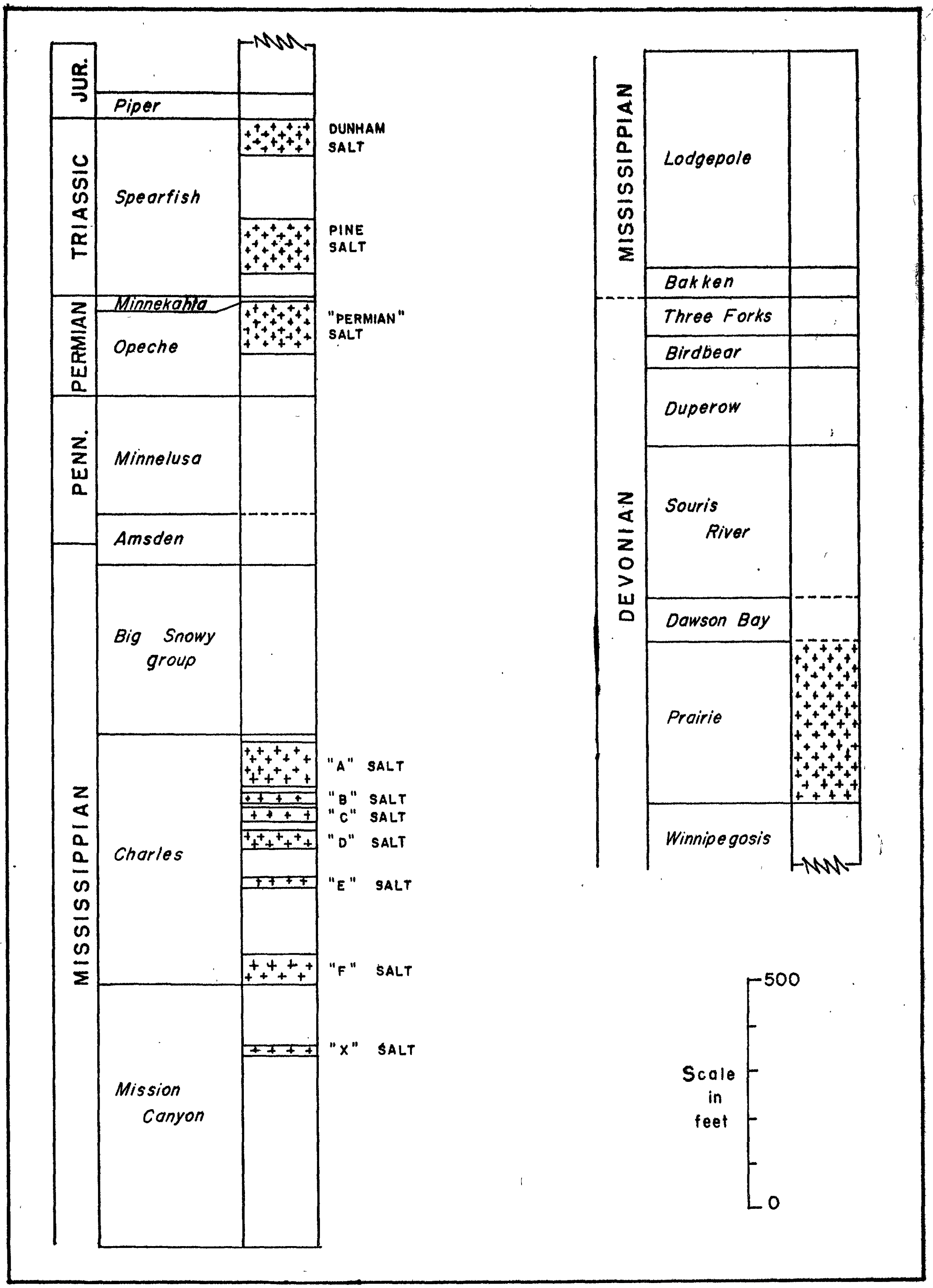



Figure 27.—Generalized columnar section of the salt-bearing beds in the Williston Basin (modified after Anderson and Hansen, 1957).

## Salt of Middle Devonian age

The Middle Devonian series consists, in ascending order, of the Winnipegosis and Prairie formations of the Elk Point group (Sandberg and Hammond, in press) and the Dawson Bay formation. The following discussion of the salt in the Prairie formation has been prepared by C. A. Sandberg.

The Prairie formation ranges in thickness from a fraction of a foot to almost 500 feet. It is not so widespread as the Winnipegosis and underlies northeastern Montana and northwestern North Dakota. It consists of a lower member containing mostly anhydrite and dolomite interbedded with thin beds of halite and shale, and an upper member which is largely halite, designated the salt member. The salt member contains colorless, moderate reddish-orange, and grayish-red halite and a few thin beds of light-brown and grayish-red dolomitic shale. The bright coloring is due to disseminated argillaceous constituents in the halite. Baillie (1953) reports the presence of a little anhydrite and sylvite in this sequence. The sylvite generally appears on radioactivity logs as a strong deflection of the gamma-ray curve to the right, indicating higher radioactivity than the halite. In the area of maximum thickness, the salt member constitutes about three-quarters of the formation. The salt member represents the final phase of evaporite precipitation and is more restricted than the lower member. The lower part of the salt member was deposited in the center of the basin contemporaneously with the upper part of the lower member on the margins.

Near the peripheral limit of the salt member, the lower member changes to interbedded anhydritic dolomite, dolomitic anhydritic shale, and siltstone containing inclusions of halite. A short distance beyond the limit of the salt member, the lower member grades into argillaceous limestone and dolomite that are only slightly more anhydritic than the underlying Winnipegosis. This lateral gradation from evaporite to carbonate rocks suggests that anhydrite was precipitated at the center of the basin while carbonate rocks were deposited near the margins. In the vicinity of the Nesson anticline the contact between the lower member of the Prairie formation and the underlying Winnipegosis is sharp, the Prairie being predominantly halite and anhydrite and the Winnipegosis being predominantly limestone. In a belt extending 40 miles beyond the eastern and southern limits of the salt member, the carbonate facies of the lower member interfingers with, and is difficult to differentiate from, the underlying Winnipegosis formation.

The lower member of the Prairie formation has a maximum thickness of 120 feet east of the Nesson anticline in North Dakota, but is not everywhere present beneath the salt member. The formation is predominantly halite in the area south of the Nesson anticline and in northeastern Montana. The thickness and distribution of the salt member is shown in figure 28. In North Dakota the maximum thickness penetrated is 390 feet in a well at the northern end of the Nesson anticline. However, because a thickness of 525 feet is recorded in a well several miles north of the international boundary in Saskatchewan, a thickness greater than 400 feet is inferred for the area northeast of the Nesson anticline. The thickness of the salt member is fairly uniform except along the present limits, where it may thin from two hundred feet to zero in less than seven miles.

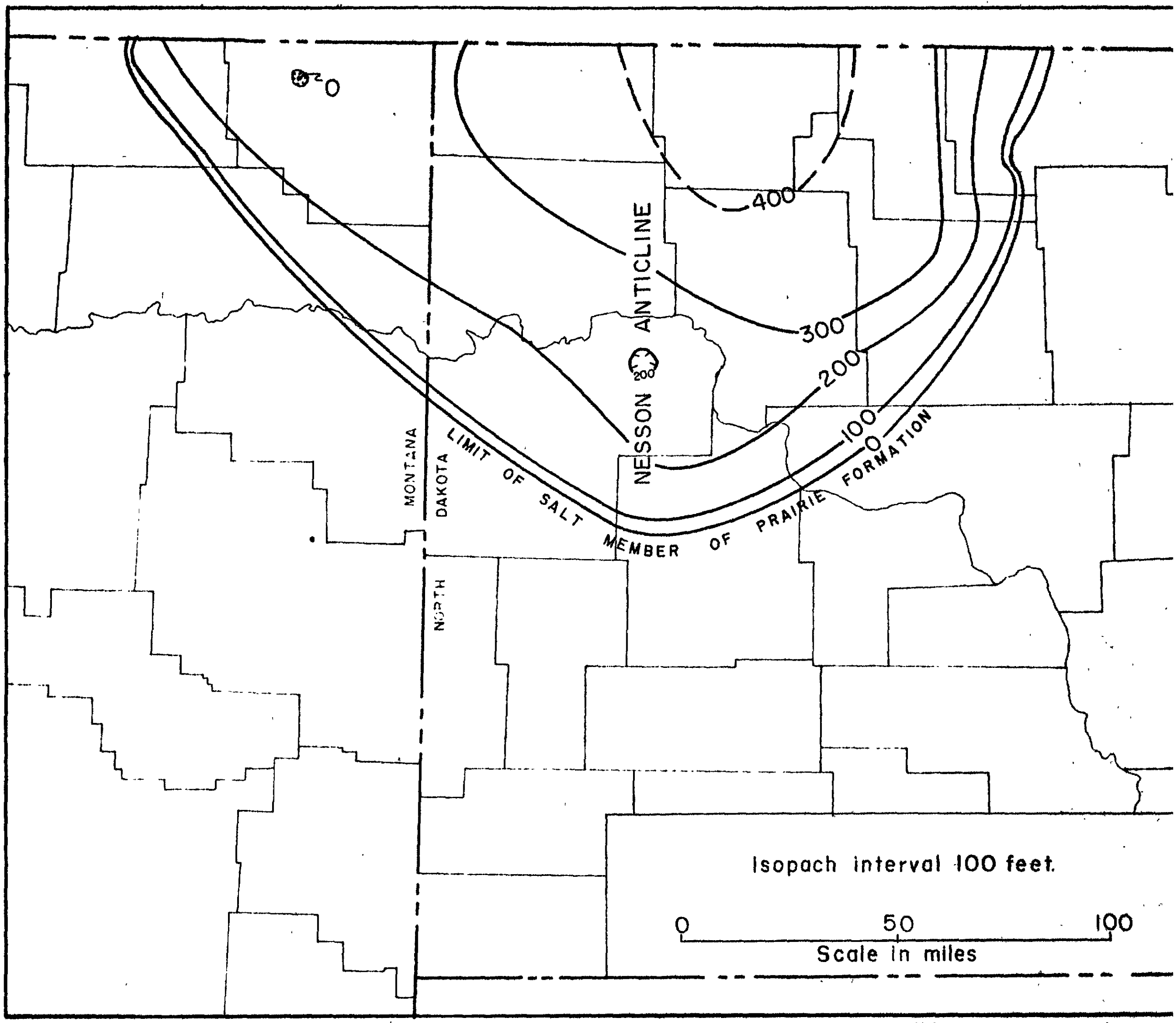



Figure 28.—Map showing thickness of salt member of Prairie formation (Middle Devonian) in the Williston Basin.

The salt member of the Prairie formation has undergone partial or complete solution in some areas. Where the member was predominantly halite, a residual mudstone, derived from disseminated argillaceous material and thin stringers of shale within the halite, remained; where it contained anhydrite and dolomite interbedded with halite, evaporite solution-breccias were formed. An anomalously thin area in northeastern Montana is shown in figure 28. The zero line there represents the location of the Amerada Petroleum Corp. No. 1 Tange discovery well of the Outlook field in which the salt member was completely dissolved. In this area solution probably took place before or during Late Devonian time. Similar areas of solution have been found in Saskatchewan and many more probably have yet to be discovered in the southern Williston basin. In Saskatchewan, R. L. Milner (1956, p. 111) has found evidence for salt solution taking place locally (1) after deposition of the Mississippian Mission Canyon formation but prior to the peneplanation of the Paleozoic rocks, (2) after the post-Paleozoic erosion but prior to the deposition of Jurassic sediments, and (3) in post-Paleozoic but pre-Cretaceous time. In addition Milner has found large areas that were affected by salt solution in post-Cretaceous but pre-Pleistocene time. Milner also states that:

"The solution of the salt is attributed to movement of subsurface waters across the Province [of Saskatchewan] Studies of the salinity and formation pressures indicate that this movement is in a general northeast direction and is still taking place today. The Prairie Evaporites are being dissolved at the present time and local earth movements have been recorded in recent times."

Baillie (1953, p. 25) mentioned brine springs, high in sodium chloride content, that flow from the upper beds of the Winnipegosis formation in the Manitoba outcrop area, further evidence that salt solution is still going on. Because the Prairie formation lies at greater depths and because the salinity and pressure of formation waters have not been studied, it is not known to what extent solution is taking place in the southern Williston basin.

The lowest elevation of the top of the salt member is almost 10,000 feet below sea level (fig. 29). The greatest recorded depth to the top of the Prairie formation is 12,120 feet below the surface in the Texas Company No. 1 Donahue well about half-way between the Nesson anticline and the North Dakota-Montana State line. The shallowest depth recorded in the southern Williston basin is 6,065 feet in the Dakota Oil Company No. 1 Anderson well near the northeastern limit of the contour lines shown on figure 29.

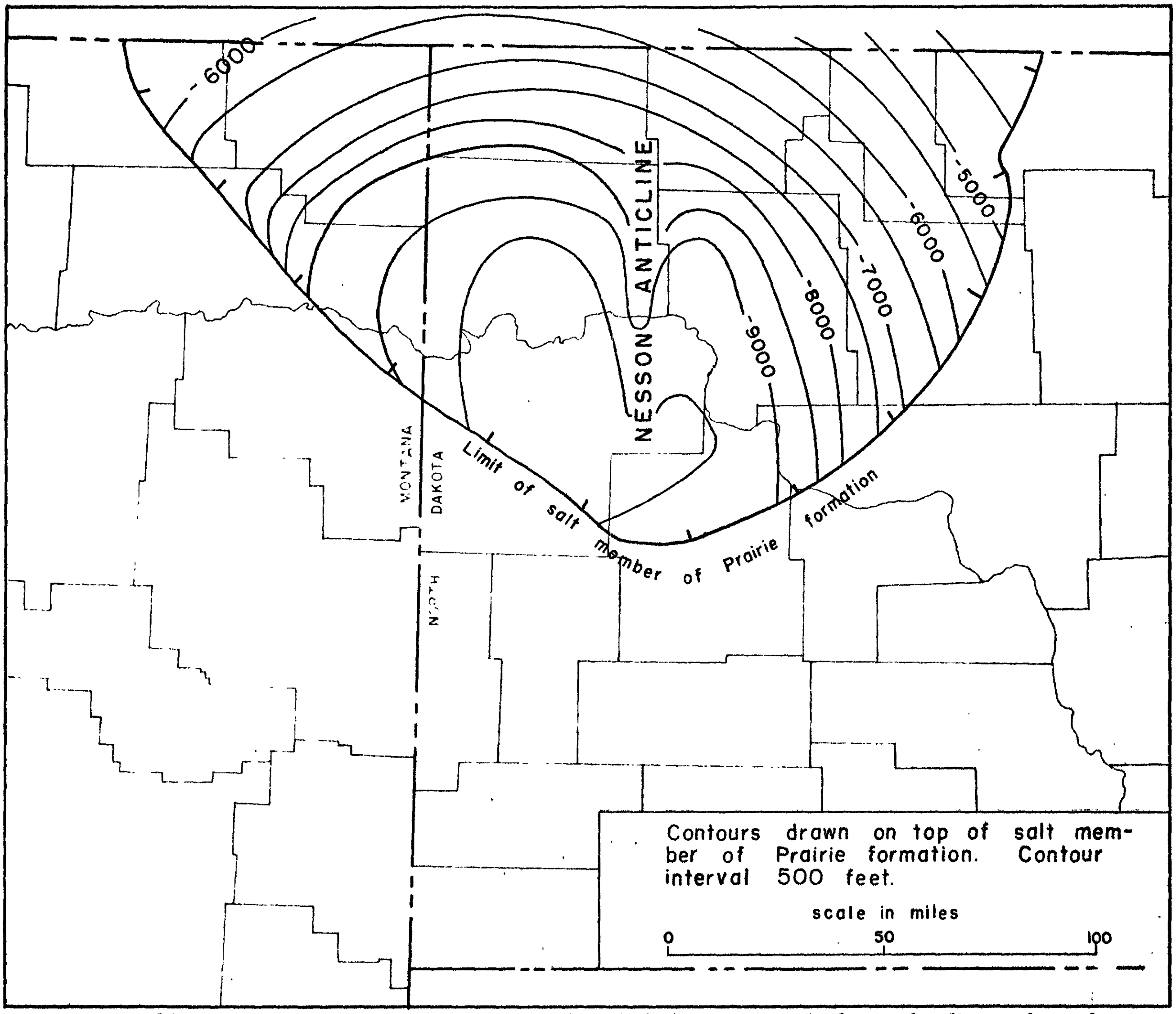



Figure 29.—Structure contour map showing altitude below sea level of top of salt member of Prairie formation (Middle Devonian) in Williston Basin.

## Salt of Mississippian age

The formations of Mississippian age in the Williston basin are, in ascending order, the Bakken, Lodgepole, Mission Canyon, and Charles. The Bakken formation (Nordquist, 1953) consists of about 100 feet of black fissile shale and calcareous siltstone and sandstone. The Lodgepole and Mission Canyon formations are composed of limestone and dolomite, with a combined thickness of over 1,000 feet. The Charles formation is about 700 feet thick in the central Williston basin and consists of massive salt beds, anhydrite, limestone and dolomite. The Charles is overlain by the Big Snowy group, consisting of the Kibbey, Otter and Heath formations.

Practically all of the salt occurs in the Charles formation. The North Dakota Geological Survey (Anderson and Hansen, 1957) has recognized six salt beds in the Charles, which have been designated by letters from "A"(highest) to "F" inclusive. Below the "F" salt bed, a thin salt bed in the upper part of the Mission Canyon is designated as the "X" salt bed.

The extent of the Mississippian salt beds is shown on figure 30. On this map the aggregate thickness of the seven salt beds is shown by isopach lines drawn at intervals of 100 feet. The combined thickness of the salt beds exceeds 300 feet in the central part of the basin. Between a third and a half of the total thickness of salt within the 200-foot isopach line is contained in the "A" or highest Mississippian salt bed, which attains a maximum thickness of 150 feet of salt.

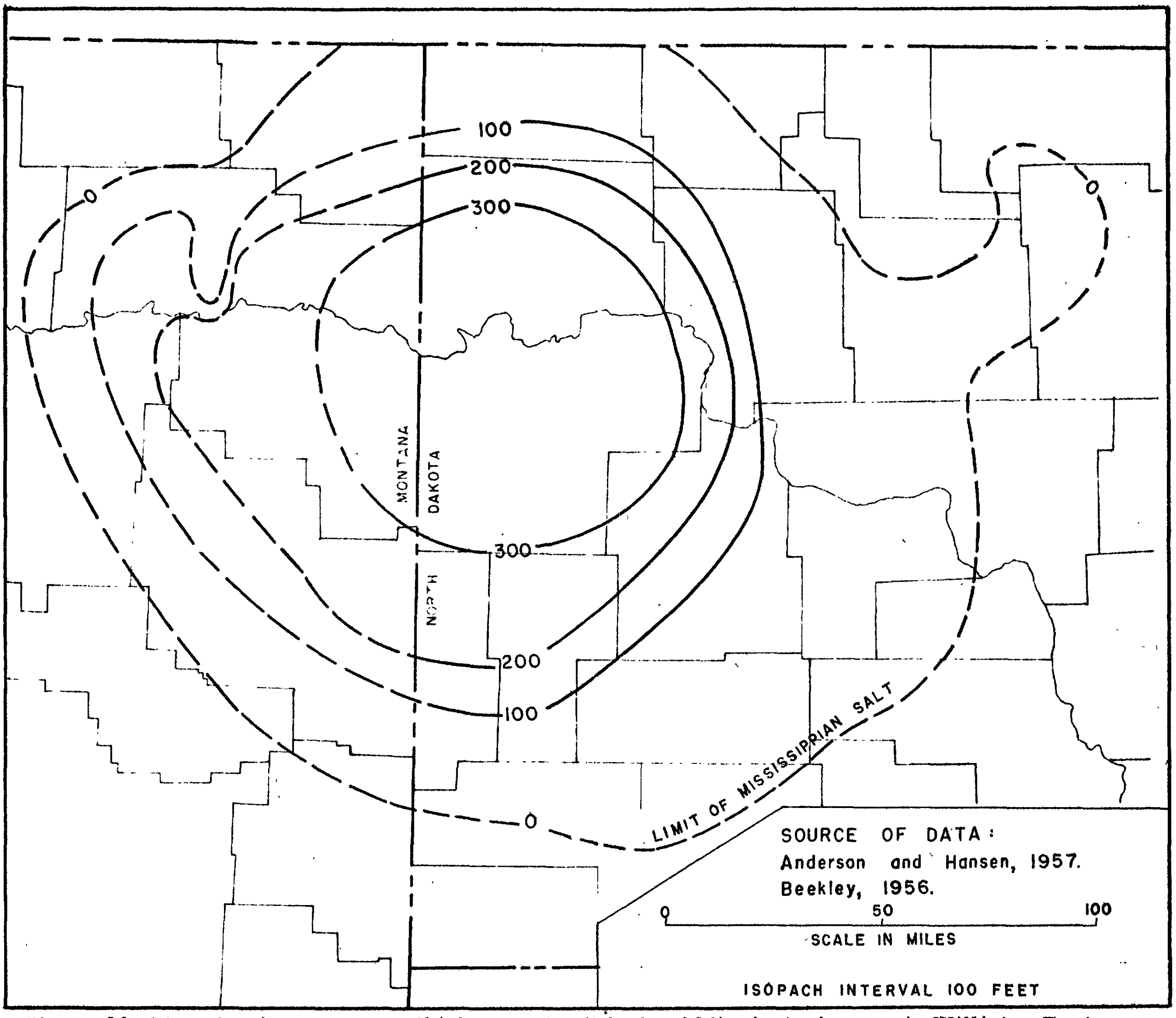



Figure 30.–Map showing aggregate thickness of salt beds of Mississippian age in Williston Basin.

The depth below sea level to the top of the highest Mississippian salt bed is shown on figure 31 by means of contour lines drawn at intervals of 500 feet. Much of the area is between 2,000 and 3,000 feet above sea level, so that most of the Mississippian salt is 5,000 to 9,000 feet below the surface.

## Salt of Permian age

The salt of Permian age occurs in the Opeche formation. Where it is salt-bearing, primarily in the central part of the Williston basin in western North Dakota, the Opeche formation consists of red shale, salt, anhydrite, and some siltstone, with a maximum thickness of 400 feet.

The principal salt bed in the Opeche formation is in the upper part. The extent and thickness of that bed is shown in figure 32. As indicated on that figure, there is a small area in which the salt bed is 150 or more feet thick, and a considerably larger area in which the bed is 100 or more feet thick. The depth to the top of the salt ranges from a minimum of about 5,700 feet to more than 7,500 feet.

A second salt bed below the one just discussed has been noted in a few wells, but it does not seem to be very extensive (Anderson and Hansen, 1957).

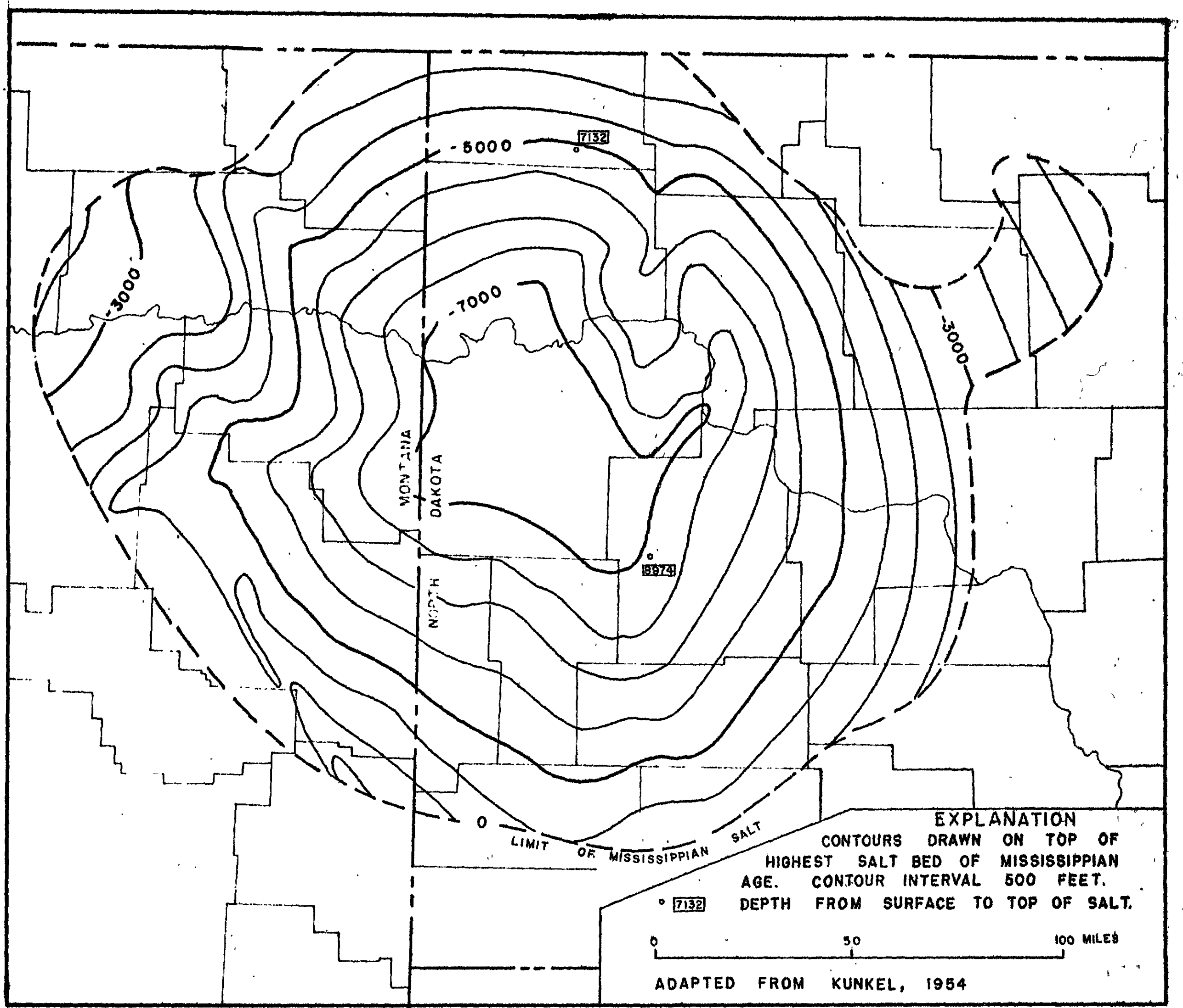



Figure 31.—Structure contour map showing altitude below sea level to top of highest salt of Mississippian age in Williston Basin.

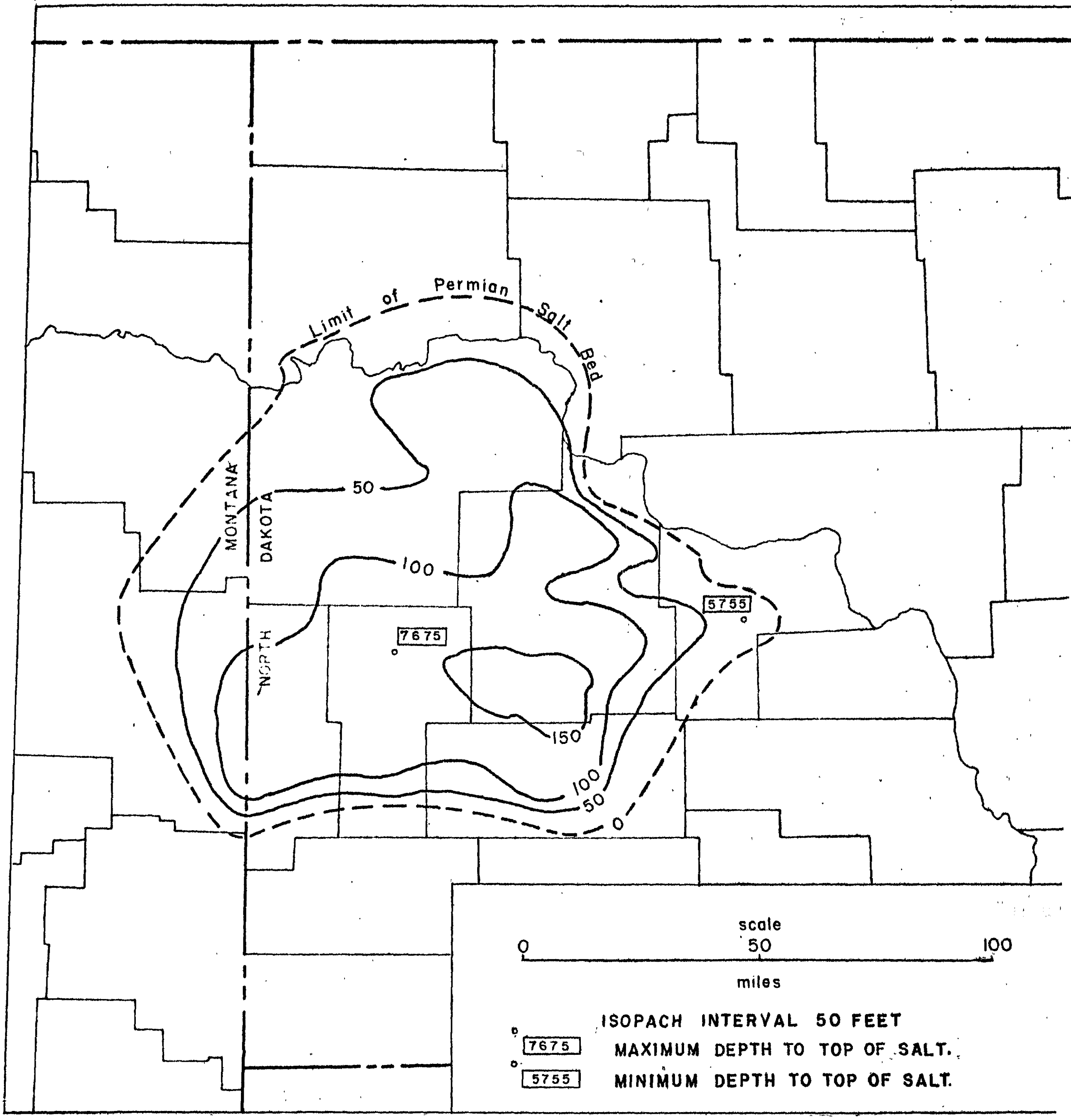



Figure 32.--Map showing thickness of salt bed of Permian age in Williston Basin (after Anderson and Hanson, 1957).

## Salt of Triassic age

In the Williston basin there is a red-bed sequence of shale, siltstone and fine-grained sandstone containing two salt beds. There is some uncertainty as to whether the entire sequence is of Triassic age, or whether only the lower part is Triassic and the middle and upper parts are of Jurassic age. Zieglar (1956) concluded that only the beds below the lower of the two salt beds are of Triassic age and restricted the Spearfish formation to that unit, and applied in ascending order the names Pine salt, Saude formation, and Dunham salt, all of Jurassic age, to the overlying units. Anderson and Hansen (1957) used the letters "A" and "B" for the salt beds, but placed the entire sequence in the Spearfish formation. For simplification in this report, the names proposed by Zieglar for the salt beds are used, but the entire sequence is placed in the Spearfish formation, following Anderson and Hansen.

The Pine salt has a greater areal extent than most of the underlying salt beds. It has a north-south extent of more than 250 miles, and is the only bed of appreciable thickness that extends into northwestern South Dakota. It reaches a maximum thickness of about 300 feet both in the southwestern corner of North Dakota and in the northwestern corner of South Dakota, as shown in figure 33. The altitude of the salt ranges from about 1,000 to 5,000 feet below sea level (fig. 34). Much of the ground surface is 2,000 to 3,000 feet above sea level, so the depth to the Pine salt bed ranges from 4,000 feet at the south end to 8,000 feet in the north.

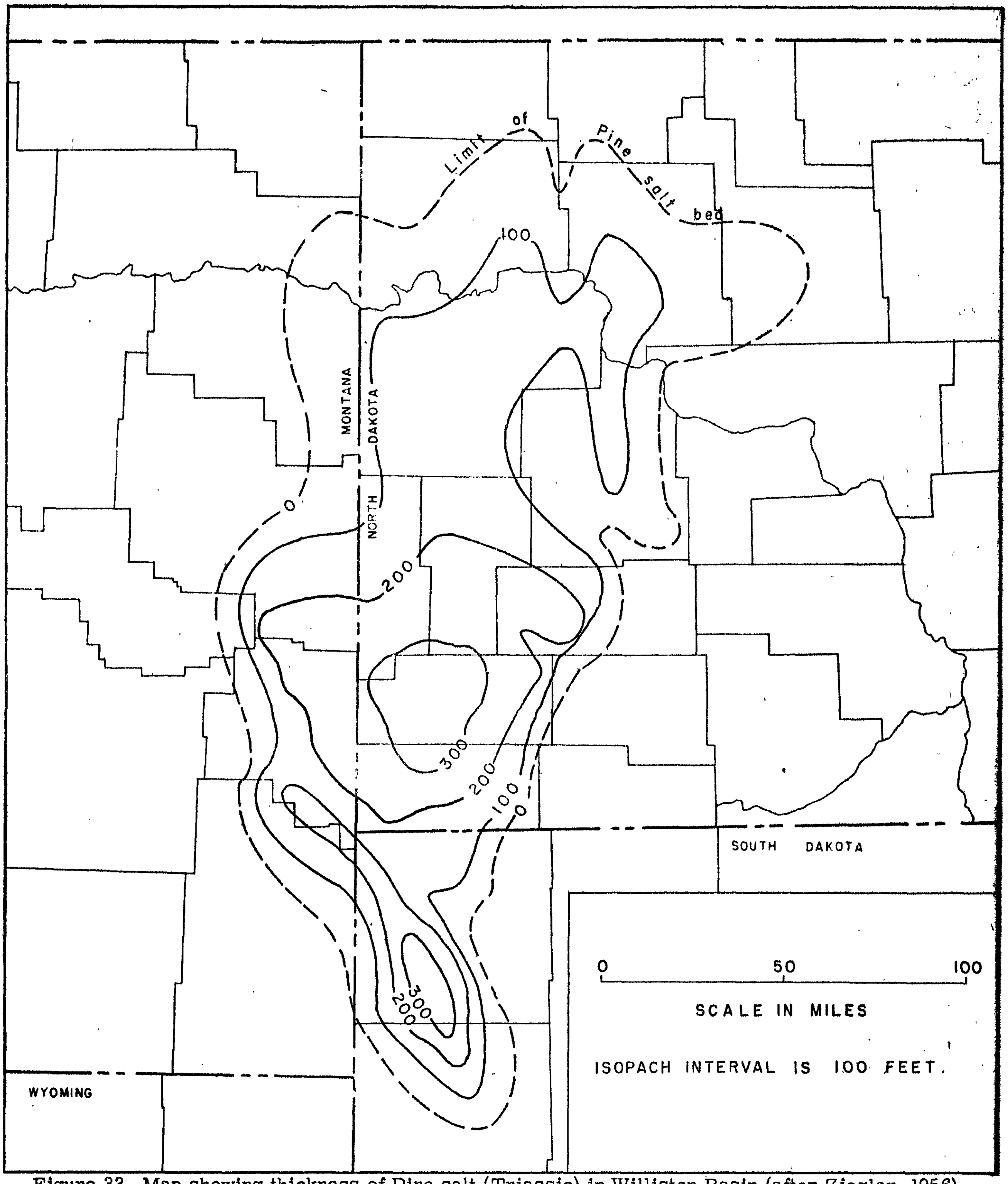



Figure 33.—Map showing thickness of Pine salt (Triassic) in Williston Basin (after Zieglar, 1956).

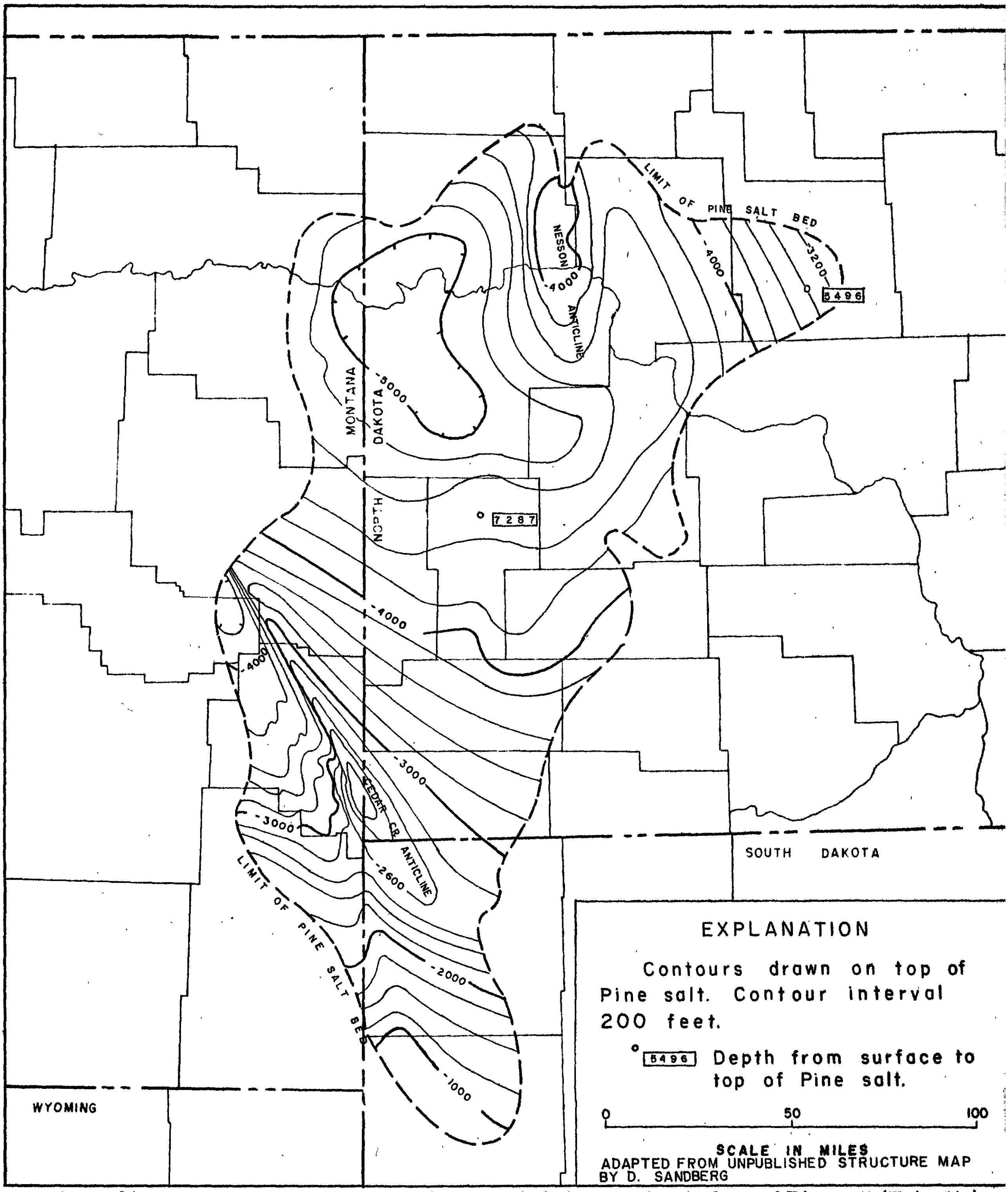



Figure 34.—Structure contour map showing altitude below sea level of top of Pine salt (Triassic) in Williston Basin.

The Dunham salt is the highest known salt bed of appreciable thickness in the Williston basin. Its distribution, which is confined essentially to western North Dakota, is shown on figure 35. It has a maximum thickness of about 100 feet, and thins and is locally absent along the Nesson anticline. As shown on figure 36, the Dunham salt ranges in altitude from 3,100 to 4,700 feet below sea level. Taking into account the surface elevation, the depth to the salt ranges from about 5,000 to 7,000 feet.

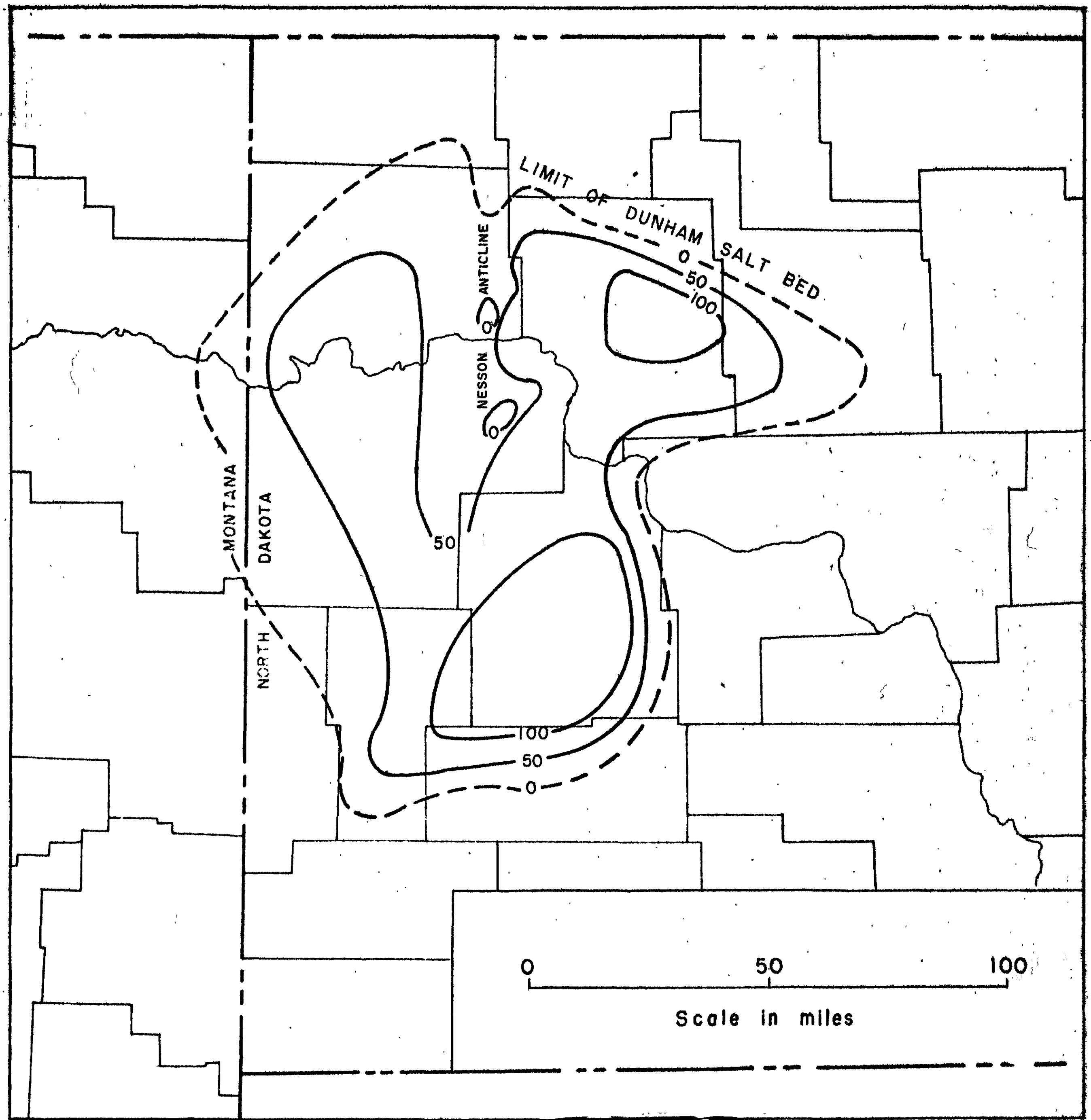



Figure 35.—Map showing thickness of Dunham salt (Triassic) in Williston Basin Isopach interval 50 feet (after Anderson and Hansen, 1957).

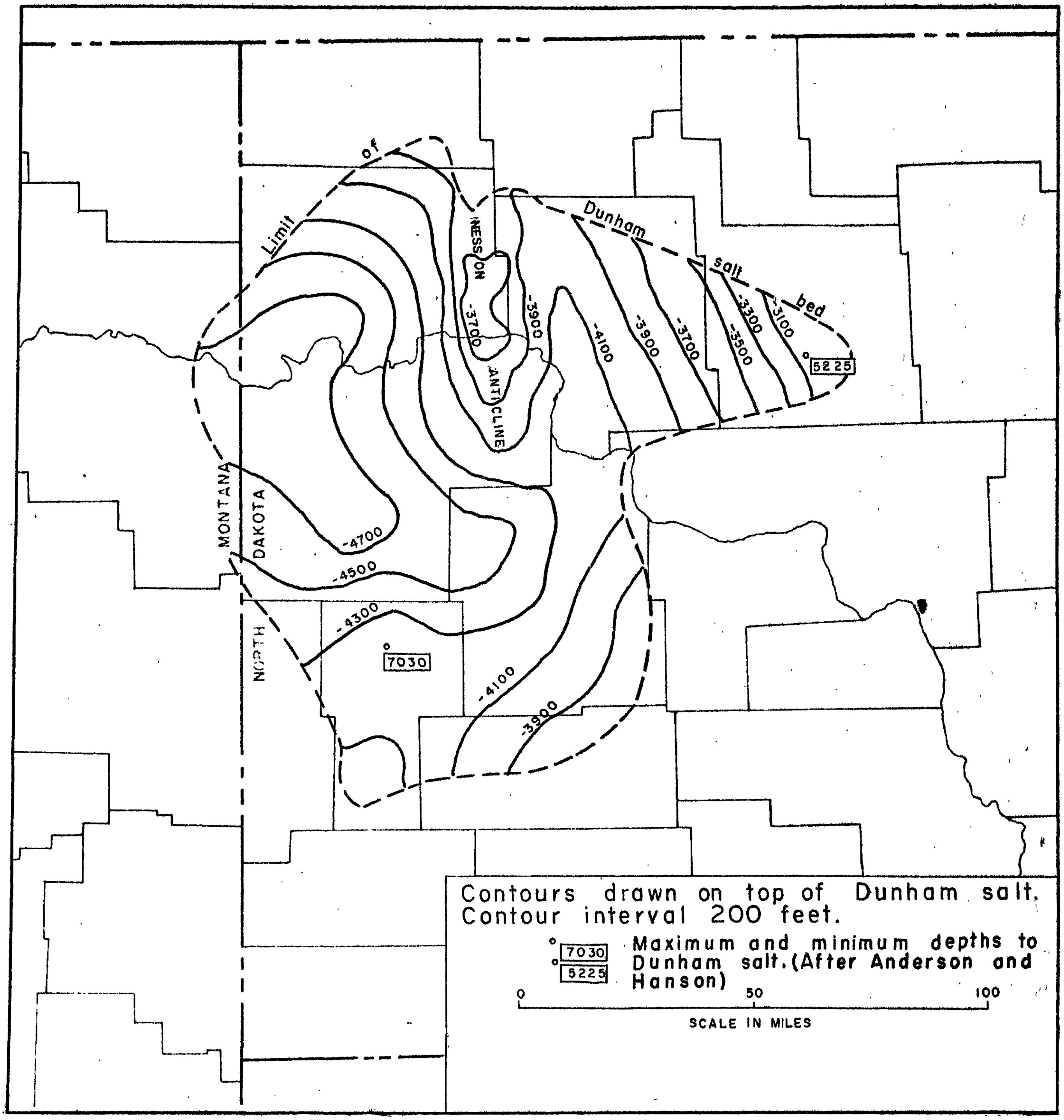



Figure 36.--Structure contour map showing altitude below sea level of top of Dunham salt (Triassic) in Williston Basin.

## OTHER DEPOSITS

### Sevier River valley, Utah

Salt occurs in the Arapien shale of Jurassic age in the Sevier River valley, Sanpete and Sevier Counties, Utah. The Arapien shale, which is correlated with the Carmel formation, has been divided into five units, with a combined thickness of 3,000 to 7,000 or more feet. Structural complexities within the formation, perhaps due in part to plastic deformation of the contained evaporites, have made it difficult to determine its thickness with any accuracy. The salt occurs in the top unit (Unit E), described by Hardy (1952, p. 15) as "brick-red silty shale, locally salt-bearing. The salt appears to be stratified and commonly contains a considerable amount of red clay." A thickness of 165 feet of red silty shale is described as comprising the top unit southeast of Salina but there the unit either contained no salt or it has been removed by solution or flowage.

As described by Gilliland (1951, p. 13) in the area roughly 4 miles east of Redmond, and in the Redmond Hills which lie from 2 to 5 miles due north of Redmond, the compact, red, salt-bearing strata "consist largely of rock salt, which contains a minor amount of finely disseminated red clay sufficient to give the salt a brick-red appearance. Occasional layers of nearly pure white salt, generally not exceeding two feet in thickness, alternate with thick red layers. At least 200 feet of salt is exposed in the Redmond Hills. The readily weathered salt beds are covered by a blanket of red residual clay and the actual thickness of salt may be much greater than is exposed."

Hardy (1952, p. 22) describes one of the principal occurrences of salt as follows: "East of Redmond, in the abandoned pit of the Great Western Salt Company, about 200 feet of bedded salt is exposed. The salt in this area contains a large amount of red clay and silt, and the outcrop is largely covered by red residual clay which obscures the structure." The salt bed dips 50° southeast (Spieker, 1949).

Salt has been mined in open pits at many places in the Redmond Hills; in the Poulson Brothers mine 3 miles north of Redmond and in the Albert Poulson mine 4 miles north of Redmond, Gilliland (1951, p. 81) says that "The salt beds are vertical, and the depth to which they extend is unknown. Albert Poulson (personal communication) has estimated the thickness of the salt beds as about 800 feet, most of which is covered by residual clay streaked with salt. Assuming that salt underlies the entire area covered by the distinctive residual clay, the width of the area indicates a thickness of about 1,000 feet for the vertical beds. Core drilling in the vicinity of the salt might disclose even greater thicknesses."

Spieker (1949, p. 68) suspects that the intricately deformed, salt-bearing Arapien shale has been moved as a surficial sheet, independent of the underlying, much less deformed, Navajo sandstone. He concludes that it is not likely that the closely folded structure of the salt-bearing formation continues in predictable pattern very far in depth. Hence, extrapolation of surface data on the salt very far into the subsurface is uncertain.

An analysis of the salt from the Poulson Brothers mine is as follows:1/

| | Percent |
|---|---|
| Salt (NaCl) | 95.60 |
| Silica | 2.16 |
| Sulfates | 1.10 |
| Calcium | .51 |
| Iron and alumina | .04 |
| Magnesium | .04 |
| Iodine | .03 |
| | 99.48 |

Although most of the salt is deep red because of finely disseminated red clay, the above analysis indicates that the percentage of impurities is less than the red color suggests.

1/ Analysis furnished by Poulson Brothers Salt Company, as reported by Gilliland (1951).

## Virgin River area, Nevada

Several dome-like rock salt deposits along the Virgin River in southeastern Nevada are reported by Longwell (1928, 1949). These deposits, now partially covered by the Overton arm of Lake Mead, are in the Muddy formation of Pliocene (?) age. The salt may belong to the lower part of this formation; but, because the deposits are found in large plugs that have domed and in many places have cut across the Muddy Creek strata, the salt may be somewhat older. One of these domes of salt has an exposed thickness of about 100 feet; however, the base of the salt is not seen. This dome is estimated to be more than 1,600 feet long and 1,000 feet wide. Recent drilling south of the Colorado River in the Black Mountain area of Arizona has penetrated salt as much as 200 feet thick that may be stratigraphically related to the salt domes in Nevada; however, data on this drilling are not available and the thickness or distribution of the salt beds cannot be determined.

## Southwestern Wyoming and adjoining area

Salt-bearing strata of early Late Jurassic age have been penetrated by wells drilled in northeastern Utah and southwestern Wyoming. The salt is in the lower part of the Preuss formation in a sequence of interbedded red shale, anhydrite, and limestone.

In northeastern Utah, Peterson (1955, p. 76) reports as much as 700 feet of salt and anhydrite strata penetrated by the Hatch well located about 15 miles north of the southwest corner of Wyoming. Mansfield (1927, p. 340) reports about 456 feet of salt-bearing strata in eastern Idaho that includes six beds of salt ranging in thickness from 6 to 29 feet with an aggregate thickness of 96 feet.

The extent of the area underlain by salt is not known inasmuch as data on the salt beds are meager. It seems, however, that the salt was deposited in a north-south trending basin or series of basins that may have extended from northeastern Utah through southwestern Wyoming into southeastern Idaho, a distance of about 100 miles. The east-west dimension of the basin of salt deposition is uncertain, but it also may have been as much as 100 miles. Whatever may have been the original extent of the salt basin, it now lies in a fault zone. The salt beds, therefore, are probably not continuous and in places may be cut off by faults. The depth to the top of the evaporite sequence in the Hatch well is about 6,000 feet.

## Northwestern Nebraska

In Sioux County, Nebr., in the northwestern corner of the State, salt was penetrated in a well drilled on the Agate anticline by the Union Oil Company. The salt is of Pennsylvanian age, and according to Noble (1939, p. 102), "Several very pure beds of salt were cored, varying in thickness from 20 to 40 feet. First bed of pure salt cored was at 5,890 feet."

Subsequently, other wells in western Nebraska have penetrated salt in rocks of Pennsylvanian age, but the data on them have not been assembled. The presence of some salt in western Nebraska and eastern Wyoming is thus indicated, but the data at hand are insufficient for determining its thickness and extent.

## Playa deposits

In considering the bedded rock salt deposits of the United States, some mention should be made of the playa deposits that occur through much of the western part of the country. A playa, sometimes referred to as a "dry lake", is defined as a level or nearly level area that occupies the lowest part of a completely closed topographic basin. The level area or playa is covered with water at irregular intervals, and for short periods of time may form a temporary lake. During periods of heavy rainfall, fine silt, along with dissolved salts, is brought into the playa to be deposited as thinly stratified layers of silt and clay. As the playa dries up, the dissolved salts in the water are deposited as evaporites, among which halite and various carbonates and sulfates of sodium are most abundant. With repeated lake-filling and drying out, thick deposits of interstratified silt, clay, and crystalline salt may accumulate in the lowest part of the playa.

Muessig and others (1957) report as much as 1,070 feet of playa deposits in Soda Lake, San Bernardino County, Calif. In this playa, however, there are only minor amounts of salines. The absence of salt beds is accounted for by assuming that the water entering the playa basin disappears by spilling and percolating rather than by drying up.

Beds of pure rock salt, 3 to 9 feet thick, are recorded at depths up to 120 feet at the Bristol Dry Lake, San Bernardino County, Calif. (Gale, 1951, p. 17). A well drilled to a depth of 152 feet penetrated 5 beds of rock salt ranging in thickness from 1 to 9 feet and aggregating 28 feet of salt. This well did not test the full thickness of the playa deposits in the Bristol Dry Lake, so additional beds of salt may be found at depths greater than 152 feet. Gale reports an appreciable amount of water, usually a saturated brine, in all of the strata penetrated by test holes in the central part of the playa. Water in the salt beds may render them unsuitable as a waste-disposal medium.

The area of greatest concentration of playas, within which are plotted some of the better known playas, is shown in figure 37. Some of the playas within the area outlined may not have halite deposits but may have high concentrations of carbonates or sulfates of sodium or potassium.

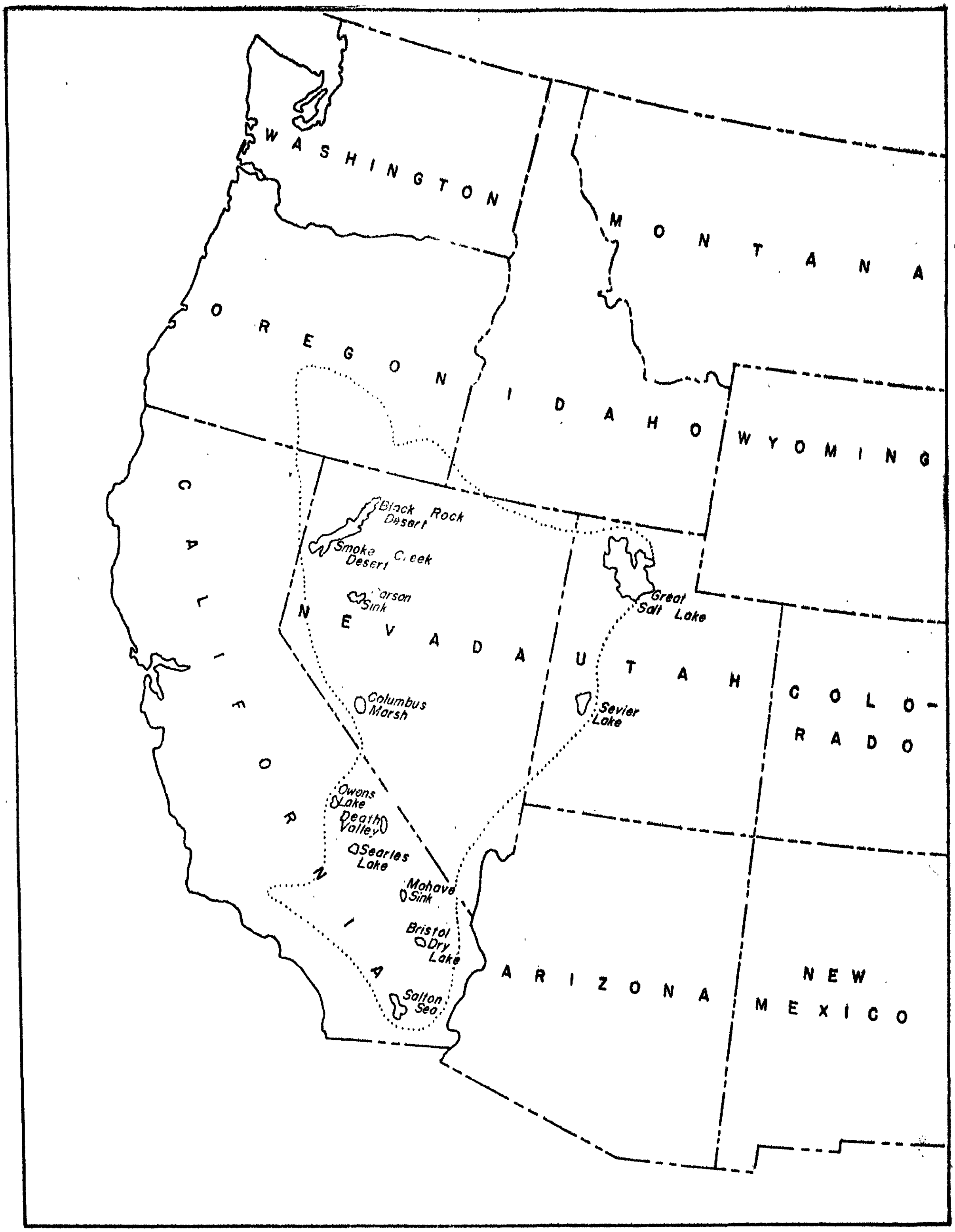



Figure 37 — Map of Western United States showing area of greatest concentration of playas and location of some of the better known ones.

## SALT MINES

With the possibility that consideration may be given to disposal in existing salt mines, the following brief summary on operating mines is presented.

The production of rock salt by States during the year 1953 is indicated in the following table, which also contains an estimate of the space vacated by this production.

Estimated production by States and space vacated by underground mining of rock salt for the year 1953 (from Heroy, 1956)

| | Tons produced 1953 | Equivalent space (acre-feet 1/) | Average thickness of salt (feet) | Acres mined out 2/ |
|---|---|---|---|---|
| Kansas | 534,658 | 185 | 10 | 37 |
| Louisiana | 1,338,997 | 462 | 80 | 10 |
| Michigan | 1,000,000 | 346 | 30 | 25 |
| New York | 1,200,000 | 414 | 10 | 68 |
| Texas | 400,000 | 138 | 60 | 5 |
| Utah | 5,000 | 2 | -- | -- |
| Totals | 4,478,655 | 1,547 | | 145 |

1/ Approximately 2,900 tons per acre-foot.

2/ Assuming 50 to 60 percent left as pillars, according to locality.

The preceding table shows that nearly 1,550 acre-feet or about 145 acres of mined space are vacated annually by the production of rock salt. Of this amount nearly 50 percent is in the Michigan-New York region and 40 percent is in the Gulf Coast region. Heroy (1956) has calculated that during a recent 20-year period, assuming that the average thickness of salt mined was 10 feet, the area mined would be roughly 2,100 acres, or 21,000 acre-feet, which gives an order of magnitude of the space that has been and is being created by underground mining of salt.

The general location of the 16 operating salt mines in the United States is shown in figure 1. Additional data on them are given below, by States:

## New York

Two rock salt mines are active in New York. The International Salt Company has a mine at Portland Point, about 15 miles north of Ithaca, on the east side of Cayuga Lake. The Retsof mine, now operated by the International Salt Company, is the largest salt mine in the western hemisphere (Root, 1953). It is at Retsof, 5 miles northwest of Geneseo. A thickness of 9 to 10 feet of salt is mined from a 1063-foot shaft (La Vigne, 1936). An estimated 1,200,000 short tons of rock salt was mined in the State in 1953 (Heroy, 1956).

## Ohio

The Morton Salt Company has a mine at Fairport, near Painesville. The International Salt Company is reported planning to mine salt from beneath Lake Erie, from a shaft on Whiskey Island, in Cleveland.

## Michigan

In 1955, the most recent year that published figures are available (Gustavson and Klyce, 1957), Michigan produced over 5 million short tons of salt, which was about 25 percent of the entire United States production. Most of the 25 percent, however, was from artificial brines obtained by the solution of rock salt. All of the mined rock salt came from the International Salt Company mine in Wayne County near Detroit. Before exploratory drilling for salt beneath the Wayne County airport began, it was reported (Mining World, 1953) that mining was anticipated at a depth of at least 1,000 feet below the surface.

An estimated 1,000,000 short tons of rock salt was mined in Michigan in 1953 (Heroy, 1956).

## Kansas

Three rock salt mines were operating in Kansas in 1956 (Heroy, 1956; F. C. Foley, personal communication). The Carey Salt Company mine near Hutchinson mines from a 10-foot bed of salt reached by a 645-foot shaft. The Independent Salt Company mine at Kanopolis is mining a 15- to 16-foot bed which is reached by two shafts 846 feet deep. The American Salt Corporation mine near Lyons produces from an $8\frac{1}{2}$-foot bed of salt at a depth of 993 feet.

Several other salt mines in Kansas are either closed or abandoned (Heroy, 1956). The largest of these is the Morton Salt Company mine near Kanopolis, which closed in 1948. It is 810 feet to the bottom of the shaft, and the mine is thought to be still dry. Average ceiling height is about 9 feet. The Carey Salt Company mine at Lyons was closed in 1948. Its depth is 1,024 feet and the average ceiling height is 10 feet.

In 1954, a total of 520,622 short tons of rock salt was produced (Sanford, Diamond, and Schoewe, 1957).

## Louisiana

In recent years four shaft mines have been producing salt in Louisiana (Weigel, 1953; Heroy, 1956), three of them from coastal salt domes and one from an interior salt dome.

The mines on the coastal domes are on three islands of the well-known Five Islands group. The Morton Salt Company mine is on the Jefferson Island dome, 9 miles west of New Iberia. The shaft is 900 feet deep; 800 feet to the actual working level, but enters the salt 100 feet below the surface.

The International Salt Company mine on Avery Island is about 10 miles southwest of New Iberia. The top of the salt is 54 feet below the surface; mining is conducted from a shaft 518 feet deep which was completed in 1899. Mining operations at Avery Island before 1900 were too near the top of the salt and were difficult because of excessive water and caving (Vaughan, 1925).

Salt is mined on Weeks Island, 15 miles south of New Iberia, by the Myles Salt Company, whose operations date back to 1898. The top of the salt is about 100 feet below the surface. The total depth of the shaft is 645 feet (Vaughan, 1925).

The Carey Salt Company mine, near Winnfield, Union Parish, is on one of the interior salt domes. The depth to the salt on Winnfield dome is 440 feet, and the salt is mined from a depth of 838 feet.

In 1954, 989,224 tons of rock salt was produced in Louisiana (Rollman and Hough, 1957).

## Texas

The United Salt Corporation mine near Hockley, Harris County, produces from a shaft 1,525 feet deep. The top of the caprock on the salt dome is 117 feet below the surface (Weigel, 1935).

The Morton Salt Company's Kleer mine at Grand Saline, Van Zandt County, is on one of the interior salt domes. The present shaft, which was completed in 1931, encountered many difficulties in penetrating the water-bearing strata overlying the top of the salt. The shaft enters the salt at a depth of 213 feet and continues to slightly below the working level at 700 feet.

## Utah

In 1954 (Kelley and others, 1957), the latest year for which information is readily available, rock salt was produced at 2 open pit mines in Utah. These are the Royal Crystal Salt Company at Axtell, in Sanpete County, and Poulson Bros. Salt Company at Redmond, in Sevier County; Axtell is about 4 miles north of Redmond. Production from the Poulson Bros. mine in 1953 was 1,500 tons and in 1954, 1,800 tons. The production of rock salt in 1953 from the above 2 mines was 6,000 tons (Luff, 1956).

The salt produced in this area is mostly shipped as mined for livestock consumption throughout central Utah and adjoining States.

## Plastic flowage of salt in mines

A discussion of the physical properties of salt is not within the scope of this report, but a few observations made in salt mines on the deformation of salt may be of interest. Balk (1949, p. 1822-23) has summarized a report by Busch (1907) of measurements of plastic salt deformation in the Neu-Stassfurt mine in Germany. Busch's attention to salt movement was aroused by the inward bending of the walls of a newly excavated shaft, and a series of measurements was taken. It was found that at a depth of 750 meters (2,460 feet) salt was capable of extruding at speeds of as much as 0.9 millimeter per day. Holes were also drilled in the salt at various depths in the mine, and the holes were filled with lead bars so that they just fitted when inserted. It was found that at a depth of 500 meters (1,640 feet) the bars jammed after a few months; at 300-meters depth (984 feet), the bars jammed after 2 years; and above 250-meters depth (820 feet), the holes stayed open.

Few of the salt mines in the United States operate below 1,000 feet, so data on plastic flow are meager. However, Balk (1949, p. 1824) reports timbers more than 6 inches thick which were bent and broken by movement of the salt, and drill holes which were appreciably reduced in diameter.

# SALT RESERVES AND PRODUCTION

In considering bedded salt as a possible storage medium for radioactive-waste disposal, the question may arise as to what effect the use of such methods may have on our reserves of salt.

## Reserves

Our salt reserves are very large indeed. No attempt is made at this time to prepare an estimate, but the following statement (Barton, 1928, p. 48), although now out of date, will serve to give an idea of the order of magnitude of our reserves in relation to consumption:

"The reserves of rock salt are so stupendous as to be inexhaustible for human purposes. The total reserves in 15 Texas and Louisiana salt domes, above a depth of 1,000 feet, is about 10 cubic kilometers. The reserves above a depth of 2,500 feet is about 40 cubic kilometers. As the world consumption of rock salt at the present (i.e., about 1926) amounts to less than 0.01 cubic kilometer per year, the very easily mineable reserves of the Texas-Louisiana salt domes would suffice for the world demand for 1,000 years and the reserves to a depth of 2,500 feet would suffice for world demand for 4,000 years."

Salt production, however, has roughly doubled since that estimate was made. If a factor of 50 percent recovery is used, then the above figures would be reduced to 250 and 1,000 years, respectively. Of course, this does not take into account the very large reserves of salt elsewhere in the United States. The U. S. annual production of salt is slightly less than 40 percent of the world production.

United States salt production in 1956

(MacMillan and Mattila, 1957)

| State | Short tons |
|---|---|
| California | 1,444,211 |
| Hawaii | 270 |
| Kansas | 1,004,042 |
| Louisiana | 3,703,500 |
| Michigan | 5,548,178 |
| New Mexico | 57,157 |
| New York | 3,872,777 |
| Ohio | 2,971,702 |
| Oklahoma | 9,980 |
| Puerto Rico | 9,936 |
| Texas | 3,962,778 |
| Utah | 183,701 |
| West Virginia | 680,964 |
| Other states | 766,428 |
| Total | 24,215,623 |

Of the above total, 77 percent was produced as brine or evaporated salt, and 5,622,887 short tons, or 23 percent, was produced as rock salt.

RECENT TRENDS IN DEVELOPMENT OF UNDERGROUND STORAGE

The underground storage of liquified petroleum gas, which began in a small way in depleted oil and gas fields, has taken a new turn in the past few years. Instead of relying on anticlinal or domal structures that have contained or are suitable for retaining oil or gas, the industry is creating its own underground storage reservoirs, some of them in shale, a few in granite, and a large number in salt. The progress that is being made in this kind of storage, and the experience that is being obtained, may well have some applications in the waste disposal problem. The following information is based largely on reports appearing in the Oil and Gas Journal and Petroleum Week.

In the last half dozen years the storage capacity created in underground cavities is about 34 million barrels, of which over 28 million barrels is in salt deposits. The developed capacity in depleted oil and gas fields and similar geologic structures now stands at about 4 million barrels, and about 1 million barrels of storage has been created in mined space in shale and chalk.

The storage space which has been created in salt deposits is of particular interest. It is the least expensive type of storage, since it can be formed by dissolving out the salt. Six barrels of water will dissolve one barrel of cavern space. The range in cost is from less than $1.00 to $2.00 per barrel for dissolved cavity space in salt, compared to $3.00 to $7.00 for mined space in shale or chalk, whereas it costs roughly $20 for above-ground storage in steel tanks.

One of the first underground storage cavities in salt was at Lowell, Mich. In 1951 Cities Service Oil Company dissolved out a cavity in a salt bed. A conventional drill hole reached the top of the salt bed at a depth of 3,798 feet. Casing was set 7 feet above the top of the salt, and the hole was drilled 250 feet into the salt. A 125,000-barrel cavity was dissolved by circulating water through the tubing. Liquid propane is injected into the brine-filled cavity under pressure.

Most of the liquified petroleum gas storage is in Texas, where over 25 million barrels of underground storage has been created. Of this, storage capacity over 90 percent is in about 150 caverns located in salt domes or salt beds. Between 1 and 2 million barrels of underground storage has been created in each of the States of Kansas, Mississippi, and Louisiana, almost entirely in salt domes or salt beds.

Two mined caverns in chalk near Demopolis, Ala., have proved very successful. The chalk is impervious and requires no sealant. Mined shale caverns are in use or are being prepared in Illinois, New Jersey, Ohio, Kentucky, Oklahoma, Pennsylvania, and West Virginia. At Bayway, N. J., two caverns in shale, 330 feet below the surface, will be used to store 675,000 barrels of liquified gas, and at Marcus Hook, Pa., a cavity is being mined in granite, 300 feet below the surface.

REFERENCES

Adams, J. E., 1944, Upper Permian Ochoa series of Delaware basin, West Texas and southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 28, no. 11, p. 1596-1625.

Alling, H. L., 1928, The geology and origin of the Silurian salt of New York State: New York State Mus. Bull. 275, 139 p.

Ames, J. A., 1950, Northern Appalachian salt: Mining Engineer, v. 2 (i. e., v. 187, no. 5), p. 557-559.

Anderson, S. B., and Hansen, D. E., 1957, Halite deposits in North Dakota: North Dakota Geol. Survey Rept. Inv. no. 28, pls. 1-3.

Arundale, J. C., and Marks, A. L., 1956, Salt: U. S. Bur. Mines Minerals Yearbook 1953, v. 1, p. 943-954.

Atomic Energy Commission, 1949, Handling radioactive wastes in the Atomic Energy program: Washington, U. S. Govt. Printing Office, p. 1-30.

Baillie, A. D., 1953, Devonian system of the Williston basin area [U. S.--Canada]: Manitoba Dept. Mines and Nat. Res., Mines Br., Pub. 52-5, 105 p.

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.

Balk, Robert, 1949, Structure of Grand Saline salt dome, Van Zandt County, Tex.: Am. Assoc. Petroleum Geologists Bull., v. 33, no. 11, p. 1791-1829.

__________, 1953, Salt structure of Jefferson Island salt dome, Iberia and Vermilion Parishes, La.: Am. Assoc. Petroleum Geologists Bull., v. 37, no. 11, p. 2455-2474.

Barton, D. C., 1928, The economic importance of salt domes: Texas Univ. Bull. 2801, p. 7-53.

__________, 1933, Mechanics of formation of salt domes with special reference to Gulf Coast salt domes of Texas and Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 17, no. 9, p. 1025-1083.

Bass, N. W., 1926, Structure and limits of the Kansas salt beds, in Geologic investigations in western Kansas: Kansas State Geol. Survey Bull. 11, p. 90-95.

__________, 1944, Correlation of basal Permian and older rocks in southwestern Colorado, northwestern New Mexico, northeastern Arizona, and southeastern Utah: U. S. Geol. Survey Oil and Gas Inv. Prelim. Chart 7, accompanied by paper on Paleozoic stratigraphy as revealed by deep wells in parts of southwestern Colorado, northwestern New Mexico, northeastern Arizona, and southeastern Utah.

Beebe, B. W., 1956, Northwestern Anadarko Basin: Oklahoma City Geol. Soc. Field Conference Guidebook, p. 120-125.

Bizal, R. B., 1957, L. P. G. industry is ready for winter: Oil and Gas Jour., v. 55, no. 41, p. 101-105.

Briggs, L. I., 1958, Evaporite facies: Jour. Sed. Petrology, v. 28, p. 46-56.

Cater, F. W., Jr., 1954, Geology of the Bull Canyon quadrangle, Colo.: U. S. Geol. Survey Geol. Quad. Map GQ-33.

__________, 1955a, Geology of the Gypsum Gap quadrangle, Colo.: U. S. Geol. Survey Geol. Quad. Map GQ-59.

__________, 1955b, Geology of the Naturita NW quadrangle, Colo.: U. S. Geol. Survey Geol. Quad. Map GQ-65.

Cater, F. W., Jr., 1955c, Geology of the Hamm Canyon quadrangle, Colo.: U. S. Geol. Survey Geol. Quad. Map GQ-69.

Clark, G. C., 1949, Interior salt domes of East Texas /abs./: Am. Assoc. Petroleum Geologists Bull., v. 33, no. 12, p. 2067-2068.

Culler, F. L., Jr., and McLain, S., 1957, Status report on the disposal of radioactive wastes: CF-57-3-114 (Rev.), issued by U. S. Atomic Energy Comm. Tech. Inf. Service Ext., Oak Ridge, Tenn.

Dana, J. D., 1863, Manual of geology: New York, Ivision, Blakeman, and Taylor, 798 p.

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/.

Darton, N. H., 1921, Permian salt deposits of the south-central United States: U. S. Geol. Survey Bull. 715-M, p. 205-223.

De Golyer, E., and others, 1926, Geology of salt dome oil fields: Tulsa, Okla., Am. Assoc. Petroleum Geologists, 797 p.

de Laguna, W., and Blomeke, J. O., 1957, The disposal of power reactor wastes into deep wells: CF-57-6-23, issued by U. S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

Dellwig, L. F., 1955, Origin of the Salina salt of Michigan: Jour. Sed. Petrology, v. 25, no. 2, p. 83-110.

Evans, C. S., 1950, Underground hunting in the Silurian of southwestern Ontario: Geol. Assoc. Canada Proc., v. 3, p. 55-85.

Fettke, C. R., 1955, Preliminary report, occurrence of rock salt in Pennsylvania: Pennsylvania Geol. Survey, 4th ser., Prog. Rept. 145.

Freie, A. J., 1930, Sedimentation in the Anadarko Basin: Oklahoma Geol. Survey Bull. 48, 80 p.

Frost, F. E., 1957, Radioactive waste processing and disposal (1950-1957)--Bibliography: Calif. Univ. Radiation Lab., UCRL-4891, p. 1-23.

Gale, H. S., 1951, Geology of the saline deposits, Bristol Dry Lake, San Bernardino County, Calif.: California Dept. Nat. Res., Div. Mines Spec. Rept. 13, 21 p.

Gilliland, W. N., 1951, Geology of the Gunnison quadrangle, Utah: Nebraska Univ. Studies, new ser., no. 8, 101 p.

Goldring, Winifred, 1931, Handbook of paleontology for beginners and amateurs, Pt. 2, The formations: New York State Mus. Handb. 10, 488 p.

Gould, C. N., and Lewis, F. E., 1926, The Permian of western Oklahoma and the Panhandle of Texas: Oklahoma Geol. Survey Circ. 13, 29 p.

Green, D. A., 1937, Major divisions of Permian in Oklahoma and southern Kansas: Am. Assoc. Petroleum Geologists Bull., v. 21, no. 12, p. 1515-1529.

Gustavson, S. A., and Klyce, D. F., 1957, The minerals industry of Michigan: U. S. Bur. Mines Minerals Yearbook 1955 [preprint].

Halbouty, M. T., and Hardin, G. C., Jr., 1956, Genesis of salt domes of Gulf Coastal Plain: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 737-746.

Hanna, M. A., 1934, Geology of the Gulf Coast salt domes, <u>in</u> Problems of petroleum geology (Sidney Powers Memorial Volume): Tulsa, Oklahoma, Am. Assoc. Petroleum Geologists, p. 629-678.

Hardison, S. G., 1956, Potash in the Permian salines of the Panhandle: Panhandle Geonews, v. 3, no. 3, p. 4-10.

Hardy, C. T., 1952, Eastern Sevier Valley, Sevier and Sanpete Counties, Utah, with reference to formations of Jurassic age: Utah Geol. Mineralog. Survey Bull. 43, 98 p.

Hayes, P. T., 1957, Geology of the Carlsbad Caverns East quadrangle, N. Mex.: U. S. Geol. Survey Geol. Quad. Map GQ-98.

Hazzard, R. T., Spooner, W. C., and Blanpied, B. W., 1947, Notes on the stratigraphy of the formations which underlie the Smackover limestone in south Arkansas, northeast Texas, and north Louisiana: Shreveport Geol. Soc. 1945 Reference Rept., v. 2, p. 483-503.

Hedman, F. A., 1956, A survey of radioactive waste disposal (by Chemical Corps, U. S. Army): U. S. Dept. Commerce, Office Tech. Services, PB 131085, p. 1-10.

Herald, F. A., 1957, Occurrence of oil and gas in West Texas: Texas Univ. Bull. 5716.

Hess, H. H., (chm.), 1957, The disposal of radioactive waste on land: Nat. Acad. Sci., Nat. Research Council, Report of the Committee on waste disposal of the Div. Earth Sci., Pub. 519, p. 1-142.

Hoots, H. W., 1925, Geology of a part of western Texas and southeastern New Mexico, with special reference to salt and potash: U. S. Geol. Survey Bull. 780-B, p. 33-126.

Hoylman, H. W., 1946, Seismograph evidence of depth of salt column, Moss Bluff dome, Tex.: Geophysics, v. 11, no. 2, p. 128-134.

Huddle, J. W., and Dobrovolny, Ernest, 1945, Late Paleozoic stratigraphy of central and northeastern Arizona: U. S. Geol. Survey Oil and Gas Inv. Prelim. Chart 10.

Imlay, R. W., 1940, Lower Cretaceous and Jurassic formations of southern Arkansas and their oil and gas possibilities: Arkansas Geol. Survey Inf. Circ. 12, 64 p.

____________, 1943, Jurassic formations of Gulf region: Am. Assoc. Petroleum Geologists Bull., v. 27, no. 11, p. 1407-1533.

Imlay, R. W., 1952, Marine origin of Preuss sandstone of Idaho, Wyoming, and Utah: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 9, p. 1735-1753.

Jones, C. L., 1954, The occurrence and distribution of potassium minerals in southeastern New Mexico, in New Mexico Geol. Soc. Guidebook, 5th Field Conf., Oct. 1954: p. 107-112.

Kaufmann, D. W., and Slawson, C. B., 1950, Ripple marks in rock salt of the Salina formation: Jour. Geology, v. 58, no. 1, p. 24-29.

Kelley, F. J., Kerns, W. H., Parker, B., and Ransome, A. L., 1957, Mineral industry of Utah: U. S. Bureau Mines Minerals Yearbook 1954 [preprint].

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: New Mexico Univ. Pub. Geology, no. 5, 120 p.

King, P. B., 1942, Permian of west Texas and southeastern New Mexico, Pt. 2 of West Texas-New Mexico symposium: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 4, p. 535-763.

King, R. H., 1947, Sedimentation in Permian Castile sea [U. S.]: Am. Assoc. Petroleum Geologists Bull., v. 31, no. 3, p. 470-477.

Kreidler, W. L., 1957, Occurrence of Silurian salt in New York State: New York State Mus. Bull. 361, p. 1-56.

Kroenlein, G. A., 1939, Salt, potash, and anhydrite in Castile formation of southeast New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 11, p. 1682-1693.

Kunkel, R. P., 1954, Structure contour map of the base of Mississippian rocks in the Williston basin and adjoining areas of Montana, North Dakota, South Dakota, and Wyoming: U. S. Geol. Survey Oil and Gas Inv. Map OM 165.

Landes, K. K., 1945, The Salina and Bass Island rocks in the Michigan basin: U. S. Geol. Survey Oil and Gas Inv. Prelim. Map 40.

Landes, K. K., Ehlers, G. M., and Stanley, G. M., 1945, Geology of the Mackinac Straits region and sub-surface geology of the northern part of the southern peninsula: Michigan Dept. Conserv., Geol. Survey Div., Pub. 44, Geol. ser. 37, 204 p.

Lang, W. T. B., 1937, The Permian formations of the Pecos Valley of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 21, no. 7, p. 833-898.

__________, 1939, Salado formation of the [Texas and New Mexico] Permian basin: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 10, p. 1569-1572.

__________, 1942, Basal beds of Salado formation in Fletcher potash core test, near Carlsbad, N. Mex.: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 1, p. 63-79.

La Vigne, E. F., 1936, Mining and preparation of rock salt at the Retsof mine: Am. Inst. Mining Engineers Tech. Pub. 661.

Lee, Wallace, 1956, Stratigraphy and structural development of the Salina basin area: Kansas State Geol. Survey Bull. 121.

Levorsen, A. I., 1954, Geology of petroleum: San Francisco, W. H. Freeman and Co., 703 p.

Longwell, C. R., 1928, Geology of the Muddy Mountains, Nevada: U. S. Geol. Survey Bull. 798, 152 p.

__________, 1949, Structure of the northern Muddy Mountain area, Nev.: Geol. Soc. America Bull., v. 60, no. 5, p.923-967.

Lowenstam, H. A., 1948, Biostratigraphic studies of the Niagaran inter-reef formations in northeastern Illinois: Illinois State Mus., Sci. Papers, v. 4, 146 p.

Luff, Paul, 1956, The mineral industry of Utah: U. S. Bur. Mines Minerals Yearbook 1953, v. 3.

MacMillan, R. T., and Mattila, A. L., 1957, Mineral industry surveys: U. S. Bur. Mines Mineral Market Rept. MMS no. 2709.

Maher, J. C., and Collins, J. B., 1953, Permian and Pennsylvanian rocks of southeastern Colorado and adjacent areas: U. S. Geol. Survey Oil and Gas Inv. Map OM 135.

Maley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporate [evaporite] solution in the Delaware basin, Tex. and N. Mex.: Geol. Soc. America Bull., v. 64, no. 5, p. 539-545.

Mansfield, G. R., 1927, Geography, geology, and mineral resources of part of southeastern Idaho: U. S. Geol. Survey Prof. Paper 152, 453 p.

Martens, J. H. C., 1943, Rock salt deposits of West Virginia: West Virginia Geol. Survey Bull. 7, 67 p.

McKee, E. D., 1951, Sedimentary basins of Arizona and adjoining areas: Geol. Soc. America Bull., v. 62, no. 5, p. 481-505.

McKnight, E. T., 1940, Geology of area between Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 908, 147 p.

Milner, R. L., 1956, Effects of salt solution in Saskatchewan [abs.]: North Dakota and Saskatchewan Geol. Societies, Williston basin symposium, p. 111.

Mining World, 1953, Precipitates--central and eastern; central states [5th paragraph]: v. 15, no. 9, p. 101.

Mohr, C. L., 1939, Subsurface cross section of Permian from Texas to Nebraska: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 11, p. 1694-1710.

Moore, R. C., 1920, Oil and gas resources of Kansas, Part 2, Geology of Kansas: Kans. State Geol. Survey Bull. 6, 98 p.

Moore, R. C., Frye, J. C., Jewett, J. M., Lee, Wallace, and O'Connor, H. G., 1951, The Kansas rock column: Kansas State Geol. Survey Bull. 89, 132 p.

Muessig, Siegfried, White, G. N., and Byers, F. M., Jr., 1957, Core logs from Soda Lake, San Bernardino County, Calif.: U. S. Geol. Survey Bull. 1045-C, p. 81-96.

Nettleton, L. L., 1934, Fluid mechanics of salt domes: Am. Assoc. Petroleum Geologists Bull., v. 18, no. 9, p. 1175-1204.

____________, 1943, Recent experimental and geophysical evidence of mechanics of salt-dome formation: Am. Assoc. Petroleum Geologists Bull., v. 27, no. 1, p. 51-63.

____________, 1952, Geophysical aspects, Pt. 6 of Murray, G. E., Sedimentary volumes in Gulf Coastal Plain of the United States and Mexico: Geol. Soc. America Bull., v. 63, no. 12, pt. 1, p. 1221-1228.

____________, 1955, History of concepts of Gulf Coast salt dome formation: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 12, p. 2373-2383.

Newell, N. D., Rigby, J. K., Fischer, A. G., Whiteman, A. J., Hickox, J. B., and Bradley, J. S., 1953, The Permian reef complex of the Guadalupe Mountains region, Tex. and N. Mex.--A study in paleoecology: San Francisco, W. H. Freeman and Co., 236 p.

Noble, E. B., 1939, Test on Agate anticline, northwestern Nebraska: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 1, p. 101-102.

Nordquist, J. W., 1953, Mississippian stratigraphy of northern Montana, in Billings Geol. Soc. Guidebook 4th Ann. Field Conf., Sept. 1953: p. 68-82.

Norton, G. H., 1939, Permian red beds of Kansas: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 12, p. 1751-1819.

O'Donnell, Lawrence, 1935, Jefferson Island salt dome, Iberia Parish, La.: Am. Assoc. Petroleum Geologists Bull., v. 19, no. 11, p. 1602-1644.

Parker, T. J., and McDowell, A. N., 1955, Model studies of salt-dome tectonics: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 12, p. 2384-2470.

Pecsok, D. A., 1954, Disposal of nuclear power reactor wastes by injection into deep wells--preliminary report: CF-54-10-64, issued by U. S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

Pepper, J. F., 1947, Areal extent and thickness of the salt deposits of Ohio: Ohio Jour. Sci., v. 47, no. 6, p. 225-239.

Peterson, J. A., 1955, Marine Jurassic rocks, northern and eastern Uinta Mountains and adjacent areas [Colo.--Utah--Wyo.], in Wyoming Geol. Assoc. Guidebook 10th Ann. Field Conf. 1955: p. 75-79.

Peterson, J. A., 1957, Marine Jurassic of northern Rocky Mountains and Williston basin: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 399-440.

Powers, Sidney, and Hopkins, O. B., 1922, The Brooks, Steen, and Grand Saline salt domes, Smith and Van Zandt Counties, Tex.: U. S. Geol. Survey Bull. 736-G, p. 179-239.

Richardson, G. B., 1904, Report of a reconnaissance in trans-Pecos Texas, north of the Texas and Pacific Railway: Texas Univ. Min. Survey Bull. 9, 119 p.

____________, 1907, Underground waters in Sanpete and central Sevier Valleys, Utah: U. S. Geol. Survey Water-Supply Paper 199, 63 p.

Roedder, Edwin, 1957, Atomic waste disposal by injection into aquifers, in Advances in nuclear engineering: Nuclear Eng. and Science Conf., 2d, Philadelphia 1957, Proc., v. 1, p. 359-371.

Roliff, W. A., 1949, Salina-Guelph fields of southwestern Ontario: Am. Assoc. Petroleum Geologists Bull., v. 33, no. 2, p. 153-188.

Rollman, H. E., and Hough, L., 1957, The mineral industry of Louisiana: U. S. Bur. Mines Minerals Yearbook, 1954 [preprint].

Root, Bradley, 1953, The largest salt mine in the Western Hemisphere: Explosives Engineer, v. 31, no. 2, p. 49-52, 59.

Roth, R. I., 1955, Paleogeology of Panhandle of Texas: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 4, p. 422-443.

Sandberg, C. A., and Hammond, C. R., Devonian system in Williston basin and central Montana: Am. Assoc. Petroleum Geol. Bull. (in press).

Sanford, R. S., Diamond, W. G., and Schoewe, W. H., 1957, The mineral industry of Kansas: U. S. Bur. Mines Minerals Yearbook, 1954 [preprint].

Sellards, E. H., Adkins, W. S., and Plummer, F. B., 1932, The geology of Texas: Texas Univ. Bull. 3232, 1007 p. [1933].

Seminar, 1955, Sanitary engineering aspects of the Atomic Energy Industry- A seminar sponsored by the Atomic Energy Comm. and Public Health Service, Cincinnati, Ohio, Dec. 6-9, 1955; TID 7517, pt. la and lb, 635 p., issued by U. S. Atomic Energy Comm. Tech. Inf. Service Ext., Oak Ridge, Tenn.

Shoemaker, E. M., 1954, Structural features of southeastern Utah and adjacent parts of Colorado, New Mexico, and Arizona, in Stokes, W. L., ed., Utah Geol. Soc. Guidebook no. 9: p. 48-69.

____________, 1956, Geology of the Roc Creek quadrangle, Colo.: U. S. Geol. Survey Geol. Quad. Map GQ-83.

Skinner, J. W., 1946, Correlation of Permian of west Texas and southeast New Mexico: Am. Assoc Petroleum Geologists Bull., v. 30, no. 11, p. 1857-1874.

Spieker, E. M., 1946, Late Mesozoic and early Cenozoic history of central Utah: U. S. Geol. Survey Prof. Paper 205-D, p. 117-161.

____________, 1949, The transition between the Colorado plateaus and the great basin in central Utah: Utah Geol. Soc. Guidebook no. 4, 106 p.

Spooner, W. C., 1926, Interior salt domes of Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 10, no. 3, p. 217-292.

____________, 1932, Salt in Smackover field, Union County, Ark.: Am. Assoc. Petroleum Geologists Bull., v. 16, no. 6, p. 601-608.

Swartz, C. A., 1943, Seismograph evidence on the depth of the salt in southern Mississippi: Geophysics, v. 8, no. 1, p. 1-2.

Swartz, C. K., and others, 1942, Correlation of the Silurian formations of North America: Geol. Soc. America Bull., v. 53, no. 4, p. 533-538.

Swineford, Ada, 1955, Petrography of upper Permian rocks in south-central Kansas: Kansas State Geol. Survey Bull. 111, 179 p.

Taylor, M., 1930, Shaft sinking at Texas salt mine: Mining and Metallurgy, v. 2, p. 580-583.

Tomlinson, C. W., 1939, Standard Permian section of North America, A committee report: Am. Assoc. Petroleum Geologists Bull., v. 23, p. 1673-1681.

Totten, R. B., 1956, General geology and historical development, Texas and Oklahoma Panhandles: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 1945-1967.

Vaughan, F. E., 1925, The Five Islands, Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 9, no. 4, p. 756-797.

Veatch, A. C., 1899, The Five Islands: Louisiana Geol. Survey Report for 1899, p. 227, 248.

Wallace, W. E., Jr., 1944, Structure of south Louisiana deep-seated domes: Am. Assoc. Petroleum Geologists Bull., v. 28, no. 9, p. 1249-1312.

Warn, G. F., 1955, Geology of northeastern New Mexico and adjacent Colorado, Kansas, Oklahoma, and Texas [abs.]: Panhandle Geonews, v. 2, no. 2, p. 14-17.

Weeks, W. B., 1938, South Arkansas stratigraphy with emphasis on the older Coastal Plain beds: Am. Assoc. Petroleum Geologists Bull., v. 22, no. 8, p. 953-983.

Weigel, W. M., 1935, The salt industry of Louisiana and Texas: Am. Inst. Min. Met. Eng. Tech. Pub. no. 620, 19 p.

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

West Texas Geological Society, 1949, East-west cross section through Permian basin of west Texas: Midland, Texas.

__________, 1951, North-south cross section through Permian basin of west Texas: Midland, Texas.

__________, 1953, North-south cross section through Permian basin of west Texas: Midland, Texas.

Willis, Bailey, 1949, Artesian salt formations: Am. Assoc. Petroleum Geologists Bull., v. 32, no. 7, p. 1227-1264.

Woodward, H. P., 1941, Silurian system of West Virginia: West Virginia Geol. Survey [Repts.], v. 14, 326 p.

Zieglar, D. L., 1956, Pre-Piper-post-Minnekahta red beds in the Williston basin: North Dakota Geol. Soc.-Saskatchewan Geol. Soc., Williston basin symposium, p. 170-178.

Anonymous, 1951, Cities Service's Lowell project storing propane, Michigan: Oil and Gas Jour., v. 50, no. 34, p. 101.

__________, 1958, Rocks or no, LPG storage goes below: Petroleum Week, v. 6, no. 6, p. 38-40.

UNPUBLISHED REPORTS

Baltz, E. H., 1957, Distribution and thickness of salt in the Paradox basin of southwestern Colorado and southeastern Utah, a preliminary report: U. S. Geol. Survey TEI-706 [1958].

Gloyna, E. F., Schechter, R., and Serata, S., 1957, Storage of reactor-fuel wastes in salt formations: unpublished abstract of paper presented at meeting on Fixation of radioactivity in stable solid media, Johns Hopkins Univ., June 1957.

Griggs, R. L., in preparation, The Silurian salt deposits of the northeastern United States: U. S. Geol. Survey TEI-710.

Hanna, M. A., 1958, Salt dome structures: paper presented before session of petroleum indoctrination course for military officers and civilian employees of U. S. Defense Dept., April 14-24, 1958.

Hayes, P. T., in preparation, Salt in the Ochoa series, N. Mex. and Tex.: U. S. Geol. Survey TEI-709.

Heroy, W. B., 1956, Disposal of radioactive waste in salt cavities: unpublished report prepared for Div. Earth Sci., Natl. Research Council, Committee on disposal of radioactive waste products in geologic structures, July 1956. (See also Hess, H. H., Chairman, 1957, Appendix F.)

Joesting, H. R., and Byerly, P. E., 1956, Regional geophysical surveys of the Uravan area, Colo.: U. S. Geol. Survey TEI-399, 55 p.

Theis, C. V., 1957, Problems of ground disposal of nuclear wastes: U. S. Geol. Survey groundwater notes, Radiology, no. 32, p. 1-12.