Summary of Rock Salt Deposits in the United States as Possible Storage Sites for Radioactive Waste Materials

GEOLOGICAL SURVEY BULLETIN 1148

Prepared on behalf of the U.S. Atomic Energy Commission

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By W. G. PIERCE *and* E. I. RICH

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SUMMARY OF ROCK SALT DEPOSITS IN THE UNITED STATES AS POSSIBLE STORAGE SITES FOR RADIOACTIVE WASTE MATERIALS

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

ABSTRACT

This summary report on the rock salt deposits of the United States has been compiled from the literature as a part of the Radioactive Materials Management Program of the U.S. Atomic Energy Commission. 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 storage space within it coming in contact with ground water. Consequently, information on the geology 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 possible sites for disposal of radioactive waste 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 in 24 of the 50 States. 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.

The Silurian salt deposits of the Northeastern States underlie parts of New York, Pennsylvania, West Virginia, Ohio, and Michigan. The salt is in the Salina formation (group in western New York) of Late Silurian age and was deposited in two sedimentary basins connected at times by the Chatham sag on the Findlay arch. The dominant structural elements are the Michigan basin, which is an elliptical structural basin with its center in the Southern Peninsula of Michigan, and the Appalachian basin, which slopes southeastward in the area of the salt deposits and increases in structural complexity downdip. The greatest aggregate thickness of salt in the Silurian salt deposits is in the Michigan basin. The combined thickness of all the salt beds ranges from about 1,800 feet in the central part of the basin to about 500 feet on the margins. The maximum combined thickness of salt beds in New York State is 800 feet, just south of Seneca Lake; these beds thin to less than 100 feet in thickness within a distance of 60 miles to the east, south, and west, and within 35 miles to the north. Salt beds are absent on the west border of the Appalachian basin of deposition in eastern Ohio, and attain a maximum combined thickness of 300 feet at the east edge of the State. The salt is 100 to 200 feet thick along the west border of Pennsylvania, thins eastward, and is absent to the southeast. In Michigan, the depth to the top of the salt ranges from about 500 feet on the borders of the basin to 6,000 feet in the center. In northern Ohio, northwestern Pennsylvania, and southern New York the top of the salt is about 1,000 feet below the surface and the depth to salt increases southward.

In the northern half of the Southern Peninsula of Michigan, salt beds of Devonian age range in aggregate thickness from 0 to more than 400 feet and are at depths of 1,300 to 4,300 feet.

Interbedded gypsum, shale, and salt are known in the subsurface in southwestern Virginia at depths of 800 to 2,000 feet. The salt is of Mississippian age, and the aggregate thickness is about 175 feet.

In the Gulf Coast Embayment, salt beds in the Buckner formation of Jurassic age underlie southern Arkansas, northern Louisiana, and northeastern Texas, but are believed to pinch out downdip. The beds range in thickness from 0 to about 130 feet and are 3,000 to 10,000 feet below the surface. The Louann salt of Hazzard and others (1947) in the Eagle Mills formation of Permian(?) age underlies southern Arkansas, and is presumed to continue southward beneath the Gulf of Mexico. Along the Gulf Coast the Louann salt bed lies at a depth of 20,000 to more than 30,000 feet, but salt domes, in which the salt has migrated upward, are at various depths, some within a few feet of the surface. More than 300 salt domes are now known. The heights of salt domes above their bases are extremely variable; in domes near the present land surface, the base of the salt may be 10,000 to 20,000 feet below the surface. A caprock, composed mostly of anhydrite, gypsum, and limestone, often occurs on top of the salt dome; on shallow domes it has a thickness of 300 feet or more but it is thin or absent on deep domes. Formation of the salt domes may have begun as early as Late Cretaceous time, and movement of some domes has continued into very recent time.

The salt deposits of the Permian basin underlie an area in parts of Kansas, Colorado, Oklahoma, Texas, and New Mexico that has a linear extent of 650 miles and a width of 150 to 250 miles. The deposits in Kansas, Oklahoma, and the northern part of the Texas Panhandle belong to the Leonard series of middle Permian age, whereas in southeastern New Mexico and southwestern Texas they belong to the upper part of the Guadalupe and to the Ochoa series of Late Permian age. In Texas, New Mexico, and Oklahoma, abundant gypsum and anhydrite are in close association with the salt. In Kansas little anhydrite or gypsum is 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 of the Ochoa series. Salt beds in the Castile formation have a maximum total thickness of more than 600 feet but generally are less than 250 feet thick. Salt usually comprises 75 to 90 percent of the Salado formation; the thickest accumulation of salt is within a narrow band on the north and east edges of the Delaware basin, where the salt is more than 1,700 feet thick. On the adjacent shelf area, salt in excess of 1,000 feet thick is confined to a relatively small area. The depth to the salt of the Salado ranges from 400 feet in the southwestern part of its extent, to more than 2,500 feet in the northern part. The youngest Permian salt-bearing unit in western Texas and southeastern New Mexico is the Rustler formation, which has a relatively small amount of salt. In northwestern Texas, salt is interbedded with red shale, anhydrite, and some dolomite in the lower part of the Clear Fork group of Leonard age. Individual beds of salt are as much as 225 feet thick but usually are less than 50 feet thick. In southwestern Kansas the most widespread salt is in the Wellington formation. The thicker salt beds extend from near the center of Kansas southwestward to the easternmost part of the Oklahoma Panhandle. In central Kansas the aggregate thickness of salt is about 400 feet; the salt thins irregularly toward the margins of the basin. The salt beds range in depth 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 in southeastern Utah and southwestern Colorado that contains thick salt deposits in the Paradox member of the Hermosa formation of Pennsylvanian age. The salt occurs in an elongate northwestward-trending area 160 miles long and 80 miles wide, sharply bordered on the northeast by the Uncompahgre uplift. The Paradox basin is characterized by northwestward-trending folds which are low in structural relief and widely spaced in the southwestern part and are higher in relief and closer together in the central and northeastern part. Two factors control the thickness of salt in the Paradox basin—relative position in 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 of as much as 12,000 feet. The depth to the top of the salt varies greatly, owing to folding and other 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 salt anticlines on the northeastern flank of the basin, however, salt is near the surface.

In east-central Arizona and west-central New Mexico salt occurs in the Supai formation of Permian and Pennsylvanian age. Data from a few wells indicate a maximum aggregate thickness of salt of about 550 feet, with individual beds of salt from 80 to 160 feet thick. 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 from 11,000 to 12,000 feet. The total thickness of the salt is not known to exceed 30 feet.

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, but they are at considerable depth. The oldest and thickest bed of salt, in the Prairie formation of Devonian age, 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 more than 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 ranging from Permian to Jurassic in age, which contain the Pine and Dunham salt beds of local usage. These salt beds have maximum thicknesses of 300 and 100 feet, respectively, and lie 4,000 feet or more below the surface.

In addition to these larger deposits of salt, several other smaller deposits are known. In the Sevier River valley, near Redmond, Utah, salt in the Arapian shale of Jurassic age is mined from open pits. In southeastern Nevada, along the Virgin River, domelike deposits of rock salt occur in the Muddy Creek formation of Pliocene(?) age. In southwestern Wyoming and adjoining areas salt has been penetrated by drilling in the lower part of the Preuss sandstone of Jurassic age; and in the northwestern corner of Nebraska a well penetrates salt in rocks of Pennsylvanian and Permian age.

More than 24 million tons of salt is produced annually in the United States, of which about three-fourths is produced as brine or by evaporation of salt water and one-fourth as rock salt. The rock salt is produced from 16 operating mines. Five of the mines are in 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. The reserves of rock salt in the United States are so vast that they are almost inexhaustible for human consumption.

The development of underground cavities for storing liquefied petroleum gas furnishes some information pertinent to underground disposal of radioactive wastes. The cheapest and by far the greatest storage capacity has been developed by washing (dissolving) cavities in salt.

INTRODUCTION

The aim of this report is to assemble from the literature information 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 related to the problem of disposal or storage of radioactive waste.

The report was prepared by the U.S. Geological Survey on behalf of the Division of Reactor Development of the U.S. Atomic Energy Commission 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 wastes with a high level of radioactivity (Heroy, 1957; Gloyna and others, 1958; Theis, 1956). Consideration has also been given to disposal in deep wells (Pecsok, 1954; de Laguna and Blomeke, 1957; Roedder, 1957).

Although the general subject is commonly referred to as a problem of disposal of a waste product, it is recognized that the so-called radioactive wastes formed under current technical processes may be of use at some future time. From this point of view, the problem is better stated as one of storage or disposal of radioactive materials.

As storage or disposal of radioactive materials in salt envisions placement within a bed or mass of salt, there is no need to be concerned here 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. The salt deposits are composed almost entirely of the mineral halite, ($NaCl$) or common salt; the term "salt" as used in this report will refer to sodium chloride.

To present a simplified general picture of the salt deposits, it has been necessary in most places to give the aggregate thickness of salt beds in the areas described, rather than the thicknesses of the individual 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 thickness of salt at this place would be reported as 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 readily soluble, it is rarely found at the surface. For the same reason it is difficult to determine accurately the thickness or purity of salt beds in wells unless specific procedures are followed during the drilling operation, such as drilling with a saturated solution and running certain types of geophysical logs.

Rock salt deposits in the United States are more widely distributed than may be generally assumed, and are known in 24 of the 50 States (pl. 1). Some deposits are extensive, such as the Silurian salt which underlies most of Michigan and large parts of New York, Ohio, Pennsylvania, and West Virginia. The several areas discussed are divided geographically, in general, into the original basins of salt deposition.

The salt deposits of the United States cover a wide span of geologic time and range in age from Silurian to Pliocene(?) (pl. 1). The oldest deposits are in the Northeastern States and the youngest are in the southwest. The most numerous and widespread deposits are of Pennsylvanian to Jurassic age. During this time salt was deposited in several basins extending from the Gulf of Mexico northwestward to the Williston basin. The age and the distribution of the salt deposits in the United States as shown on plate 1 indicate that salt deposition usually does not occur in the same depositional basin during more than one geologic period. A striking exception is the Williston basin, where salt was deposited during the Devonian, Mississippian, Permian, and Triassic periods. The Gulf Coast Embayment may be another area where salt deposition recurred; the higher salt beds are of Jurassic age and opinion differs as to whether the Louann salt of Hazzard and others (1947) in the lower strata is of Jurassic or Permian age. Also, in the Michigan basin salt deposition continued into the Devonian, but on a much smaller scale than in the Silurian.

NORTHEASTERN STATES

SILURIAN SALT DEPOSITS

The Silurian salt deposits of the northeastern States are one of the great accumulations of salt in the world. These deposits are in the Salina formation or group which is of Late Silurian age, and which underlies parts of New York, Pennsylvania, West Virginia, Ohio, Michigan, and southwestern Ontario (fig. 1). The total area underlain by salt is approximately 100,000 square miles, and as the average thickness of the salt beds is on the order of 150 feet, about 2,800 cubic miles or 2.7×10^{13} tons of salt underlie the area.

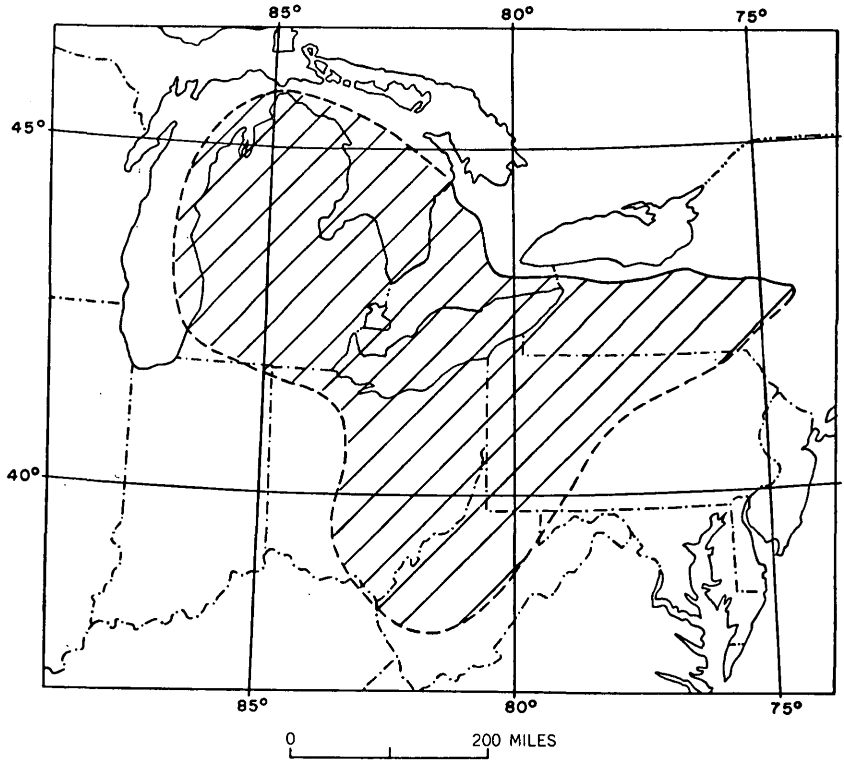

FIGURE 1.—Index map showing the approximate extent of the Salina formation or group. Dashed line indicates inferred position. (Compiled by R. L. Griggs.)

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

The information on Silurian salt deposits presented here and on plates 2 and 3 is mainly a synthesis of published material compiled by Roy L. Griggs of the U.S. Geological Survey. Extensive use was made of Landes' (1945) study of the stratigraphy of the Salina formation in the Michigan basin, the work of Pepper (1947) on the extent and thickness of salt in Ohio, of Alling (1928) and Kreidler (1957) on the occurrence and origin of salt in New York, and summary reports of Martens (1943) and Fettke (1955) on salt in West Virginia and Pennsylvania. In addition, some logs of well samples for the Michigan, Pennsylvania, and West Virginia parts of the salt basin were studied. Some unpublished data were furnished by J. F. Pepper of the U.S. Geological Survey.

STRATIGRAPHY

The Salina formation was named by Dana (1863, p. 246) from exposures in Onondaga and Cayuga Counties, N.Y. Subsequently, 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, most of which is in the subsurface, is shown on figure 1. The formation crops out in a narrow band through central and western New York and southwestern Ontario (pl. 2), and is poorly exposed in places along the Findlay 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 grades laterally into other formations in the subsurface. At its northeastern limit (pls. 2, 3), 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 the time of 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). In the subsurface the salt-bearing sequence changes eastward into marine and continental clastic deposits.

South of the salt basin, mostly in the subsurface along a line that trends northwestward across Ohio, the Salina thins rapidly and disappears. Along the Findlay arch in northwestern Ohio, however, there are poor exposures of dolomite which is probably correlative with the Salina formation.

The Salina formation ranges in thickness from 0 to nearly 3,000 feet and consists of shale, dolomite, limestone, salt, anhydrite, and gypsum. The Salina is thickest in southern New York and in the Michigan basin. Shale is the most abundant constituent near the eastern and northern limits of the formation, and carbonate rocks, mainly dolomite, increase in abundance to the southwest. Salt, anhydrite, and gypsum occur in several beds. The maximum thickness of salt is in the center of the Michigan basin.

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

NEW YORK

In New York the Salina group crops out in a narrow belt extending from the vicinity of Albany westward to Niagara Falls. It dips southward about 45 feet per mile and near the Pennsylvania border the top of the group locally is at a depth of nearly 5,000 feet.

The Salina group is divided into five formations, which are, in ascending order, the Pittsford shale, the Vernon shale, the Syracuse salt, the Camillus shale, and the Bertie limestone, as shown in table 1.

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

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

The Syracuse salt rests conformably on and possibly interfingers with the Vernon shale. It ranges in thickness from 0 near the eastern limit of the Salina group to 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 (pl. 2). According to Alling (1928, p. 25) traces of sylvite (KCl), polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$), and carnallite ($KMgCl_3 \cdot 6H_2O$) are present in the salt.

The Camillus shale ranges from about 40 to 600 feet in thickness. It rests conformably on the salt sequence in New York and consists of gray dolomitic and calcareous shale, shaly dolomite, and dolomitic limestone, gypsum, and anhydrite. According to Alling (1928, p. 25) the gypsum (and presumably the anhydrite) occurs as lenses.

Above the Camillus shale is the Bertie limestone, the uppermost member of the Salina group in New York. It consists of fine-grained argillaceous grayish-buff dolomitic limestone about 50 feet thick.

MICHIGAN

Exposures of the Salina formation are limited to a very small area in the southeastern corner of the State. In the center of the Michigan basin, the Salina reaches a thickness of nearly 3,000 feet, but it is at a depth of more than 6,500 feet. Studies of well records (Landes, 1945) have shown that the formation is divisible into seven

TABLE 1.—*Correlation chart of the Upper Silurian in the Silurian salt basin of the northeastern States (with lithologies indicated)*

Mackinac Straits area, Northern Peninsula of Michigan	Michigan basin	Southwestern Ontario	Ohio	Western Pennsylvania and western West Virginia	Central New York	
St. Ignace[1] dolomite	Bass Island dolomite	Bass Island dolomite	Bass Island dolomite	Tonoloway(?) limestone	Manlius limestone	
					Roundout limestone	
					Cobleskill dolomite	
Point aux Chenes formation Red and green shale, some thin beds of dolomite and gypsum	Salina formation Salt, dolomite and anhydrite, some beds of shale; seven members informally designated A to G	Salina formation Shale, dolomite, salt and anhydrite	Salina formation Dolomite, salt and anhydrite, some thin beds of dolomitic shale	Salina formation Dolomite, salt and anhydrite, some shale	Salina group	Bertie limestone
						Camillus shale Shale, some dolomite and gypsum
						Syracuse salt
						Vernon shale Red and green shale
						Pittsford shale Local

[1] Of George M. Ehlers *in* K. K. Landes and others (1945).

traceable members. These seven members have been designated A through G; A is the oldest and G the youngest (fig. 2). 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 plate 2.

Unit A rests with apparent conformity on beds of Middle Silurian age. It ranges in thickness from about 100 feet near the margin of

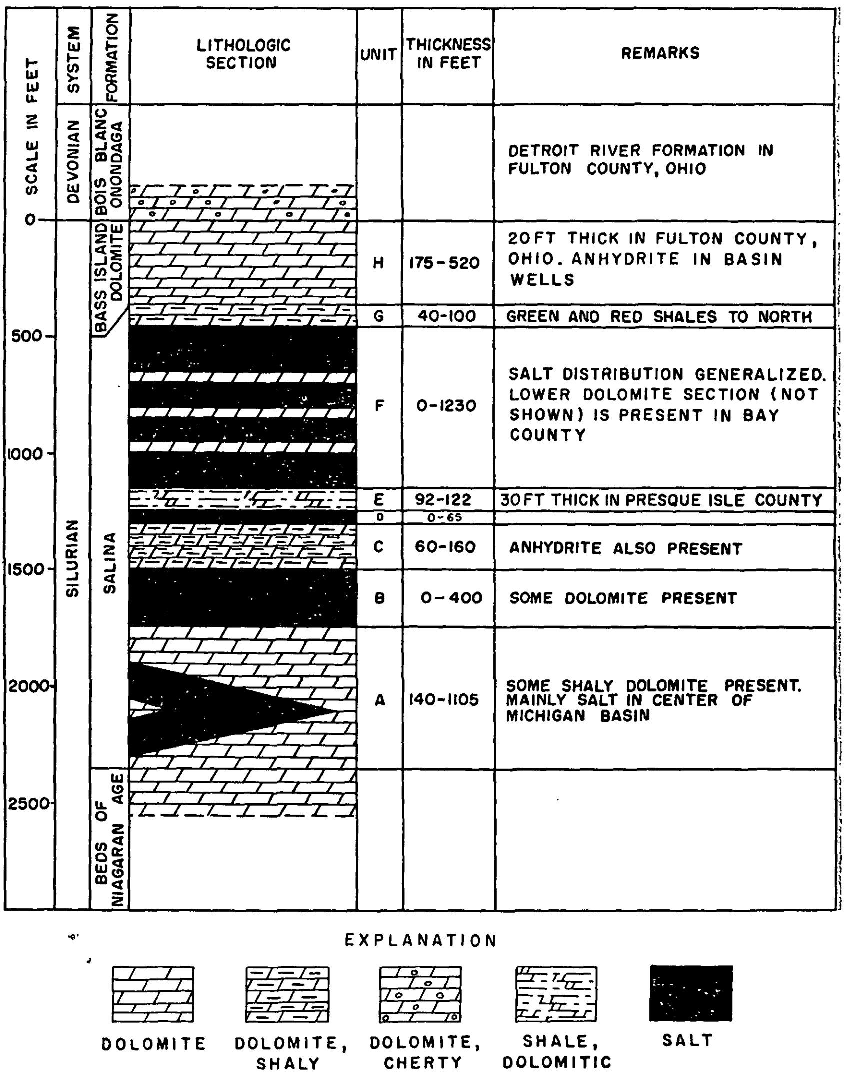

FIGURE 2.—Generalized column of Salina and Bass Island formations in the Michigan basin (after Landes, 1945).

the basin to more than 1,100 feet in the center of the basin. This member consists of dolomite and shaly dolomite around the basin margin, but toward the center of the basin it contains increasing amounts of salt. One well near the center of the basin penetrated 930 feet of unit A. In this well the salt sequence, which contains numerous paper-thin laminae of dolomite and anhydrite, is 872 feet thick, with a medial sequence of dolomite 58 feet thick.

Unit B is absent at the outer margin of the basin but has a relatively uniform thickness of about 240 to 275 feet over most of the basin. This member, about 90 to nearly 100 percent salt, contains some laminae of dolomite. A 30-foot sequence of dolomite is in the upper part of the member in the southeastern part of the basin.

Unit C ranges in thickness from 60 to 160 feet and consists of greenish-gray shale and shaly dolomite with some anhydrite. Buff dolomite is interbedded with the shale in the southern part of the Michigan basin.

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

Unit E ranges in thickness from about 90 to 125 feet except in the northern part of the basin where it consists of 30 feet of red shale. Elsewhere it is composed of shaly dolomite, anhydrite, and red or gray shale. In the southeastern part of the basin it grades into buff and gray dolomite with some anhydrite.

Unit F ranges in thickness from 0 to more than 1,200 feet; it is thin or absent near the margins and thickest at the center of the basin. It consists of thick sequences of salt separated by thin sequences of shale, shaly dolomite, and dolomite. Some anhydrite generally is present, particularly in the shale beds. According to Landes (1945) the unit is 50 to nearly 100 percent salt; the percentage of salt in this unit increases outward from the center of the basin and is highest 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 to about 50 feet in a short distance. The unit consists mainly of shaly dolomite and dolomite containing some anhydrite. Red and green shale appears 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, northwest of the Mackinac Straits connecting Lakes Michigan and Huron, the time equivalent of the Salina formation is the Pointe aux Chenes formation of Landes (1945). This formation is composed of red and green shale with some thin beds of dolomite and gypsum. It is almost identical with the Vernon shale of the Salina group in New York.

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OHIO

The Salina formation crops out along the Findlay arch in western Ohio, but for the most part its top is at 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; the formation thins toward the southwest and pinches out along a line that trends northwestward across the State.

Near its southwestern limit the Salina consists mainly of carbonate rocks and salt. The carbonate rocks are dolomite and dolomitic limestone that range from buff to brown to dark gray. Some beds are argillaceous, and a few thin beds are 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. The beds pinch out southwestward, and near the western margin of salt deposition there is only one bed of salt (Pepper, 1947, p. 230). For a short distance west and southwest of the pinchout of the salt the formation is represented by dolomite and dolomitic limestone.

The aggregate thickness of salt beds, as shown on plate 2, ranges from 0 to slightly more than 300 feet. The thickest individual salt bed is about 50 feet thick.

PENNSYLVANIA

The Salina formation is 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 (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 north-central Pennsylvania and as few as one or two in southwestern Pennsylvania. Individual salt beds 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 salt reaches a maximum of about 650 feet in north-central Pennsylvania near the New York line (pl. 2). The salt beds occupy an interval in the Salina formation ranging in thickness from less than 50 feet to more than 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 in that State. Under a large part of western West Virginia the top of the formation is at depths of 5,000 to 10,000 feet. The Salina ranges in thickness from 0 to about 1,000 feet; it is thickest in the northwestern part of the State and thins and pinches out southward. Eastward it grades into or interfingers with the Bloomsburg red beds. The Salina consists mainly of light-gray to brown dolomite and dolomitic limestone, but some thin beds of anhydrite and some beds which contain anhydrite mixed with dolomite occur in the formation. A few beds of dolomite are shaly, but in general shale is absent from the Salina formation in West Virginia.

Salt is present in the Salina formation only in the northwestern part of the State. It occurs in one main bed ranging in thickness from 0 to about 100 feet, and a few other beds less than 10 feet thick. The salt contains a small amount of anhydrite.

STRUCTURE

The dominant structural elements associated with the Silurian salt deposits are shown on figure 3. The Michigan basin, centered in the Southern Peninsula of Michigan, is an elliptical sedimentary basin into which sediments were deposited during the Silurian period. It is bounded on three sides by low arches, which were persistent throughout the Silurian. The Wisconsin arch forms the western limit and trends southerly through central Wisconsin into northern Illinois. The Kankakee arch forms the southwestern limit and extends from northeastern Illinois across Indiana to southwestern Ohio. A low

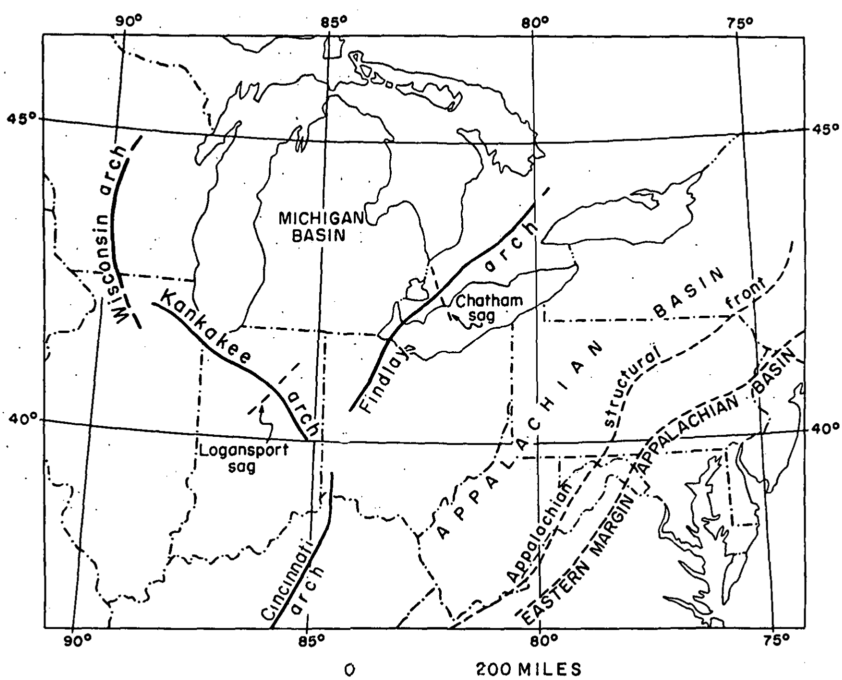

FIGURE 3.—Sketch map showing the regional structural features associated with the Silurian salt deposits of the Northeastern States (modified from map compiled by R. L. Griggs).

saddle on this arch in Indiana is known as the Logansport sag. The southeastern limit of the Michigan basin is the prominent Findlay arch, which is the northeastern segment of the Cincinnati arch. The Findlay arch has a low saddle near Chatham, Ontario, called the Chatham sag. The northern boundary of the basin is apparently an extensive curving monocline.

The general structure of the Michigan basin is simple: the rocks dip toward a point in the center of the Southern Peninsula of the State about 30 to 40 feet per mile. At the center of the basin the upper surface of Precambrian rocks is about 13,000 feet below sea level, or nearly 14,000 feet below the surface. Stratigraphic data indicate that the center of the basin sank relative to the margins during Middle Ordovician, Late Silurian, Late Mississippian, and post-Pennsylvanian times. The greatest deformation was during Late Silurian time and was coincident with the deposition of the salt beds of the Salina formation.

The Appalachian basin is a more complex structural and sedimentary basin than the Michigan basin. It is separated from the Michigan basin by the Findlay 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. 3) the structure is highly complex. Between the Appalachian front and the Findlay arch the general structure is relatively simple; a broad synclinorium extends from Kentucky across western West Virginia, western Pennsylvania, and into east-central New York. Over most of the synclinorium the rocks dip about 10 to 20 feet per mile, but near the east edge anticlines and synclines whose limbs dip as much as 30° are superimposed on the synclinorium. The positions of the axes of the basins of deposition within the Appalachian structural basin shifted many 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 (pl. 2).

The configuration and depth below sea level of the top of the uppermost salt bed penetrated by wells in the Salina formation (or group) are shown on plate 3. This is not meant to imply, however, that a single bed of salt covers the entire area of salt deposition. As shown by the contour lines drawn at intervals of 500 feet below sea level (fig. 3), the structure of the basin is very simple except for the northeastward-trending belt of anticlines and synclines that lies just northwest of the Appalachian structural front. To determine the approximate depth to the top of the salt, the elevation of the surface of the ground at a given point should be added to the depth below sea level of the salt at that point on plate 3.

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 many 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 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 pl. 2.)

The next greatest thickness of salt is in the Appalachian basin in south-central New York near the Pennsylvania border. In the central part of the basin, near the south end of Seneca Lake, the salt beds have a combined thickness of 800 feet. These beds thin to less than 100 feet within 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 on the west border of the basin of deposition to about 300 feet. The total thickness of salt beds is 100 to 200 feet along the west border of Pennsylvania, but is 100 feet or less in most of the western half of the State; the salt is absent in the southeastern part. In northern West Virginia the salt beds range in thickness from 0 to more than 100 feet. (See pl. 2.)

Specific data on the thickness of individual beds of salt are available and can be assembled for many specific localities from the several thousand wells which have been drilled, but the presentation of these details would require a much more comprehensive report. Generalized figures pertaining to the thickness of single beds of salt are contained in the preceding discussion of the stratigraphy of the salt deposits. For many places, however, such data are only semiquantitative because the salt is soluble in the drilling water, and representative cuttings of the salt cannot be recovered. It is necessary, therefore, to estimate the salt content largely from other information.

DEVONIAN SALT DEPOSITS

Salt beds of Devonian age occur in the northern half of the Southern Peninsula of Michigan (pl. 2). The salt in the upper part of the Lucas formation of the Detroit River group of Middle Devonian age ranges in aggregate thickness from 0 to more than 400 feet. It may be in as many as eight distinct salt beds and the thickest bed may exceed 100 feet (Landes, 1951). Depths to the top of this salt sequence are 1,300 feet on the northeast, 1,900 feet on the west, and 4,300 feet in the south-central area of its extent (Daoust, 1956).

MISSISSIPPIAN SALT DEPOSITS

Salt-bearing strata are known in the subsurface below the North Fork of the Holston River in southwestern Virginia (Eckel, 1903, p. 406–416; Stose, 1913, p. 232–255; Phalen, 1919, p. 85–86; Stow, 1951, p. 43–44). The salt, interbedded with gypsum, shale, and limestone, is Mississippian in age and is about 175 feet in aggregate thickness; however, the thickness of individual beds is not known.

The salt is not exposed at the surface, but is known from brine seeps and from wells. Little is known about the areal extent or depth to the top of the salt; however, the available data suggest that the salt, which occurs as irregularly shaped deposits along a northeastward-trending fault, is at depths of about 2,000 feet on the east side of the Holston Valley and 800 feet on the west side.

GULF COAST EMBAYMENT

Salt deposits underlie parts of southern Arkansas, Mississippi, Alabama, eastern and southern Texas, and Louisiana, and continue southward beneath the Gulf of Mexico (pl. 1). This large area is here referred to as the Gulf Coast Embayment. In southern Arkansas and northern Louisiana, bedded salt has been found at depth in drill holes. It is thought that this salt continues southward at a greater depth than has been reached in drilling. Presumably this salt, sometimes referred to as the "mother salt," is the source of the salt forming the many salt domes of the Gulf Coastal Plain.

The salt deposits of the Gulf Coast Embayment have been divided into three groups: (a) Louann salt of Hazzard, Spooner, and Blanpied (1947), which is the bedded salt of southern Arkansas, northern Louisiana, and northeastern Texas; (b) the interior salt domes of northeast Texas, northern Louisiana, and Mississippi; and (c) the coastal salt domes of Texas and Louisiana.

In addition to the above groups of salt deposits in the Gulf Coast Embayment, some bedded salt has been reported in northeastern Texas from the Buckner formation of Jurassic age (Clark, 1939,

p. 59–63; Imlay, 1943, p. 1529; Hazzard and others, 1947, p. 483–503; Swain, 1949, p. 1221–1222). The Buckner formation is not exposed, but has been penetrated in wells in an area extending from near Texarkana, Ark., southwestward into Texas and southeastward into northwestern Louisiana. The formation, which consists mainly of red shale, anhydrite, dolomite, dolomitic limestone, and locally contains some bedded salt, conformably overlies the Smackover limestone and is unconformably overlain by the Cotton Valley group (fig. 5). The Buckner formation has a maximum thickness of about 890 feet in northeastern Texas (Swain, 1949), pinches out to the north, east, and west, and is thought to grade into the Smackover formation southward. Salt within the Buckner formation is about 130 feet thick in Freestone County, Tex., and about 60 feet thick in Hunt County, Tex. In a well in the Rodessa oil field in northeastern Texas, 16 feet of salt is reported 3,300 feet below the top of the Cotton Valley group, which, on the basis of the thickness of the Cotton Valley, presumably would place the salt beds in the Buckner formation. Salt has not been reported in the Buckner in Arkansas or Louisiana.

In eastern Texas, the top of the Buckner formation lies from 3,000 to about 10,000 feet below the surface.

LOUANN SALT OF SOUTHERN ARKANSAS AND NORTHERN LOUISIANA

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

The locations of some of the wells that have penetrated the Louann salt are shown on figure 4. The thickness of the salt is highly variable as indicated by the records of these wells. Three well records show a salt thickness ranging from 76 to 101 feet, four show a range of from 465 to 857 feet, three show a range of 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 possibly some of the other large thicknesses also are due in part to flowage of salt.

The depth to the Eagle Mills formation, which contains the Louann salt, lessens northward, but the formation is truncated and overlain by rocks of Late Cretaceous and Tertiary age before it intersects the the surface. These relations are illustrated by figure 5, which contains a north-south cross section as inferred from well records, and shows that the approximate northern limit of the Louann salt lies south of the northern limit of the Eagle Mills formation.

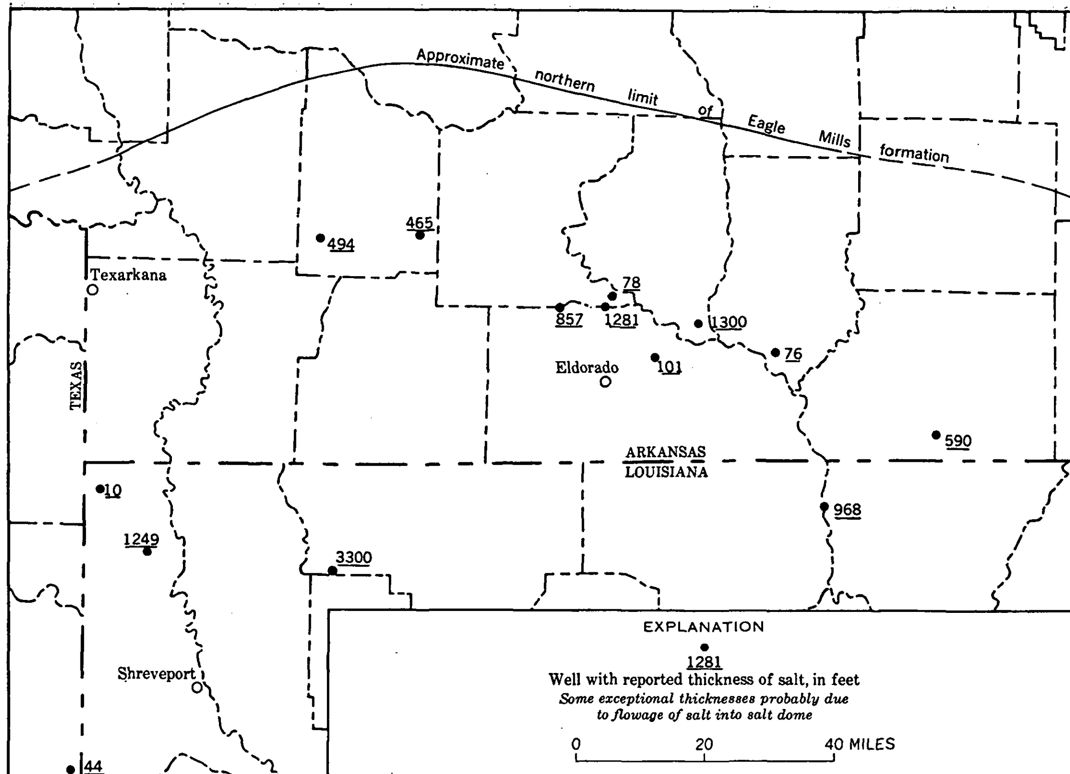

FIGURE 4.—Map showing thickness of Louann salt of Hazzard and others (1947) in Eagle Mills formation, southern Arkansas and northern Louisiana (after Imlay, 1940).

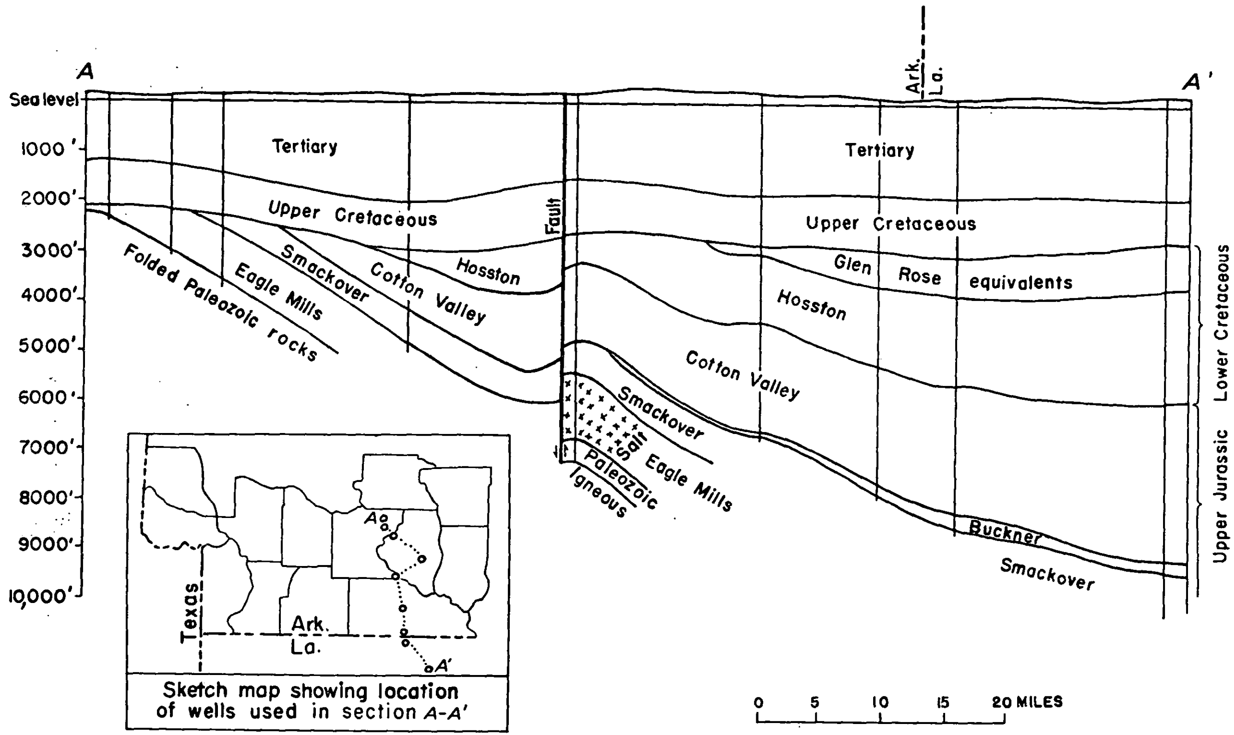

FIGURE 5.—North-south structure section showing relation of Louann salt of Hazzard and others (1947) in Eagle Mills formation to overlying beds (after Imlay, 1940).

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 geographic position.

There are more than 300 salt domes in the Gulf Coast Embayment. They have no particular geographic arrangement and appear to be randomly distributed.

SIZE AND SHAPE

The idealized sections shown on figure 6 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 1 mile to more than 4 miles. The mass commonly enlarges downward, and the top may be truncated. A salt spine projects above the general level of the top of some domes, owing to removal of the surrounding salt by solution.

The depths to the tops of the domes are highly variable. Some domes extend to within a few feet of the surface, but others are many thousands of feet deep. 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.

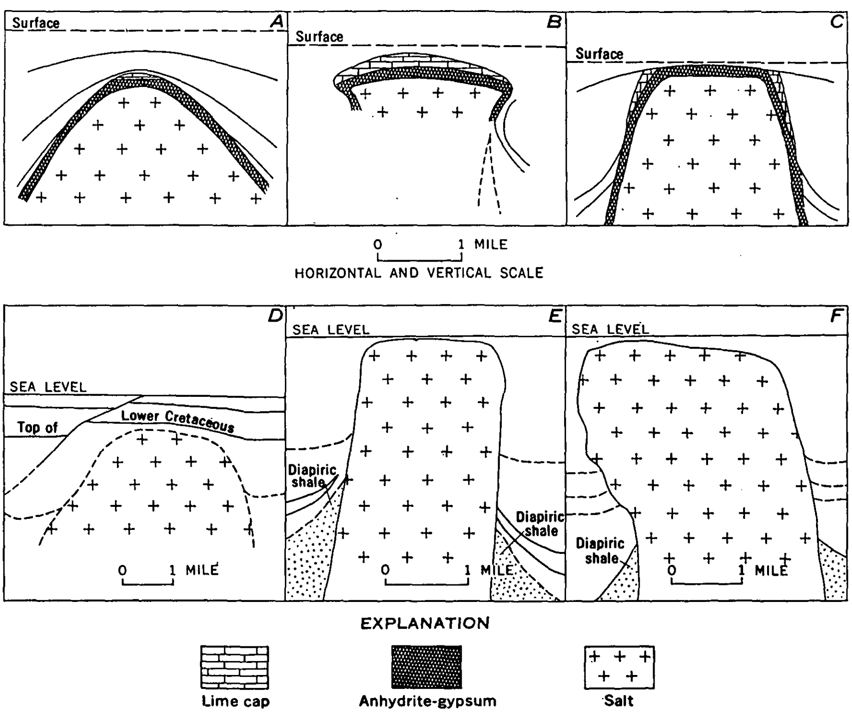

FIGURE 6.—Cross sections of salt domes. *A–C*, idealized sections after Hanna (1934); *D*, La Rue salt dome, Henderson County, Tex., after Bornhauser (1958); *E*, Weeks Island, and *F*, Cote Blanche Island salt domes, La., after Atwater and Forman (1959).

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 domes that have risen to near the present land surface, it is probably on the order of 10,000 to 20,000 feet.

SURFACE EXPRESSION

Many of the deep salt domes are known only from drilling or geophysical data. The presence of shallow domes, however, may be indicated by several surface features. 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 salt domes is a caprock composed predominantly of anhydrite, gypsum, and limestone, with minor amounts of sulfur and sulfate, sulfide, and carbonate rocks. 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 in the caprock of the dome but is draped down the sides like a hood. (See fig. 6.) 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 1,000 feet thick.

Although several theories have been proposed to account for the origin of caprock, the evidence strongly favors its formation by solution of the salt with attendant concentration of disseminated anhydrite on the periphery of the salt dome (Goldman, 1931, 1952; Hanna, 1934; Taylor, 1938). Feely and Kulp (1957) made isotope studies of anhydrite caprock samples from 11 salt domes and compared the ratio of sulfur-32 to sulfur-34 with that of anhydrite inclusions in the salt and found that both types of anhydrite had the same sulfur isotopic composition. Their work thus supports the conclusion that the anhydrite caprock was formed by residual accumulation as the salt was removed by solution.

Native sulfur is found in small amounts in many salt domes, but it occurs in commercial amounts in only a few. The sulfur is most abundant in the transition zone between a layer of granular anhydrite below and cavernous calcite above (Feely and Kulp, 1957). The sulfur is generally believed to originate by reduction of the sulfate in the anhydrite of the caprock (Goldman, 1931, 1952; Taylor, 1938; Feely and Kulp, 1957) although there is no general agreement as to how either sulfate reduction or sulfide oxidation is brought about.

MOVEMENT OF THE SALT

The upbowing of beds of sedimentary rock 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 overlying strata have been pierced by the salt. The formation of the Gulf Coast salt domes may have begun as early as Late Cretaceous time, and movement on some has continued into very recent time. The evidence is not conclusive as to whether the movement was continuous, intermittent, or spasmodic, but Barton (1933) has shown that growth on different domes has ceased at different times, and it seems to be true that in one place or another salt movement has taken place since early Tertiary time. The thinning of stratigraphic units over salt domes suggests 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) concluded that growth of the shallow domes persisted into late Tertiary time; the growth of deep domes ceased in the middle Tertiary; and the growth of very deep domes in general ceased in early Tertiary time. Balk's (1949) detailed study of the structure of Grand Saline salt dome showed that the salt moved upward from a layered salt-anhydrite mass somewhere below. Thus, the evidence to date indicates that the Gulf Coast salt domes were produced by the deformation of a deeply buried bed of salt. The mechanism that produced the deformation most probably was plastic flow arising from the difference in density between the salt layer and the overlying layers (Halbouty and Hardin, 1956). The salt layer is slightly less dense than the overlying rocks, and an unstable relation exists under static pressure; when this pressure becomes great enough plastic flow of the salt is induced. As the salt flows upward from its original position in the bed to form a salt dome, a peripheral sink or rim syncline tends to form around the dome (Nettleton, 1934, 1943; Ritz, 1936). Clark (1949) noted that piercement domes in east Texas grew from the deepest part of local synclines.

The problems related to the genesis of salt domes will have a bearing on possible disposal of radioactive waste in them but will require much more detailed consideration than is given in this report. For the purposes of this report it will suffice to mention only a few recent papers on the subject. Nettleton (1955) has summarized the history of the concepts of the formation of the Gulf Coast salt domes that lead to the concept of fluidlike flow under gravitational forces. The recent model studies of salt-dome tectonics by Parker and McDowell (1955), carried out with attention to dimensional and model-ratio requirements, are informative. Bornhauser (1958) emphasized the importance of gravity flow and plastic flow in the formation of folds. Hanna [1] stressed the importance of solution of the salt and attendant collapse of the overlying strata in modifying the original structure produced by the upward movement of the salt. Atwater and Forman (1959) described the structural configuration of some southern Louisiana salt domes as determined from intensive drilling and noted that many salt cores are much larger than was previously recognized. They observed that many domal salt cores, in addition to salt, contain brecciated intrusive shale called diapiric shale.

COMPOSITION

The salt-dome deposits are almost pure sodium chloride except for the caprock in which the insoluble minor constituents of the salt are thought to have been concentrated by solution of the salt. Anhydrite is the principal impurity and usually occurs as black bands in the salt. Bands of sandstone 1 foot or less thick and 10 or more feet long are known at Avery Island and probably represent a bed of sandstone originally interbedded with the salt (Powers and Hopkins, 1922). Locally, fragments of the sediments through which the salt has been intruded were carried along with the rising salt.

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

Analyses of salt from salt domes in Louisiana and Texas

1: Black salt, Belle Isle, La.; depth 120 ft (Veatch, 1899).
2: White salt, Belle Isle, La.; depth 175 ft (Veatch, 1899).
3: Avery Island, La.; G. Bode, analyst (Veatch, 1899).
4: Old Hackberry Salt Dome; analysis from Mathieson Alkali Works, Inc., Lake Charles, La. (Taylor, 1938).
5 and 6: Grand Saline, Tex.; Morton Salt Co. (Balk, 1949, p. 1793).

	Coastal domes, Louisiana				Interior domes, Texas	
	1	2	3	4	5	6
Sodium chloride (NaCl)	92.750	96.405	99.252	95.720	98.883	98.926
Calcium sulfate ($CaSO_4$)	-------	3.053	.694	3.950	1.099	1.041
Magnesium chloride (MgCl)	-------	.074	.012	.008	Trace	-------
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	.140	-------	-------
Iron and aluminum oxides ($Fe_2O_3 \cdot Al_2O_3$)	.500	.025	-------	.012	-------	-------
Insoluble matter	3.325	.059	-------	[1] .03	Trace	-------

[1] SiO_2.

[1] M. A. Hanna, 1958, Salt dome structure: Paper presented at Petroleum indoctrination course for military officers and civilian employees of U.S. Defense Dept. conducted by Gulf Oil Corp., Apr. 14–24, 1958, p. 1–45.

INTERIOR SALT DOMES

The interior salt domes are in a belt extending from northeastern Texas through northern Louisiana and across south-central Mississippi (pl. 4). As previously noted under the general discussion of salt domes, there are some variations in size of the salt domes and great variations in the depth of the domes below the surface. No attempt has been made to assemble specific data on each salt dome for this report. The following table illustrates the variations in depth to the salt in some of the structures.

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

[From Powers and Hopkins (1922)]

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 approximate depth to the top of 36 salt domes in northeastern Texas and northwestern Louisiana is shown by generalized contour lines on figure 7.

The source bed of the salt in the salt domes lies at great depth, and has not been reached by drilling except in northern Louisiana and southern Arkansas. Swartz (1943) reported that reflection seismograph data obtained over two shallow salt domes in southern Mississippi indicated the base of the salt at about 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 distribution of salt domes, is shown on figure 8. 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 in a belt extending from the Mississippi

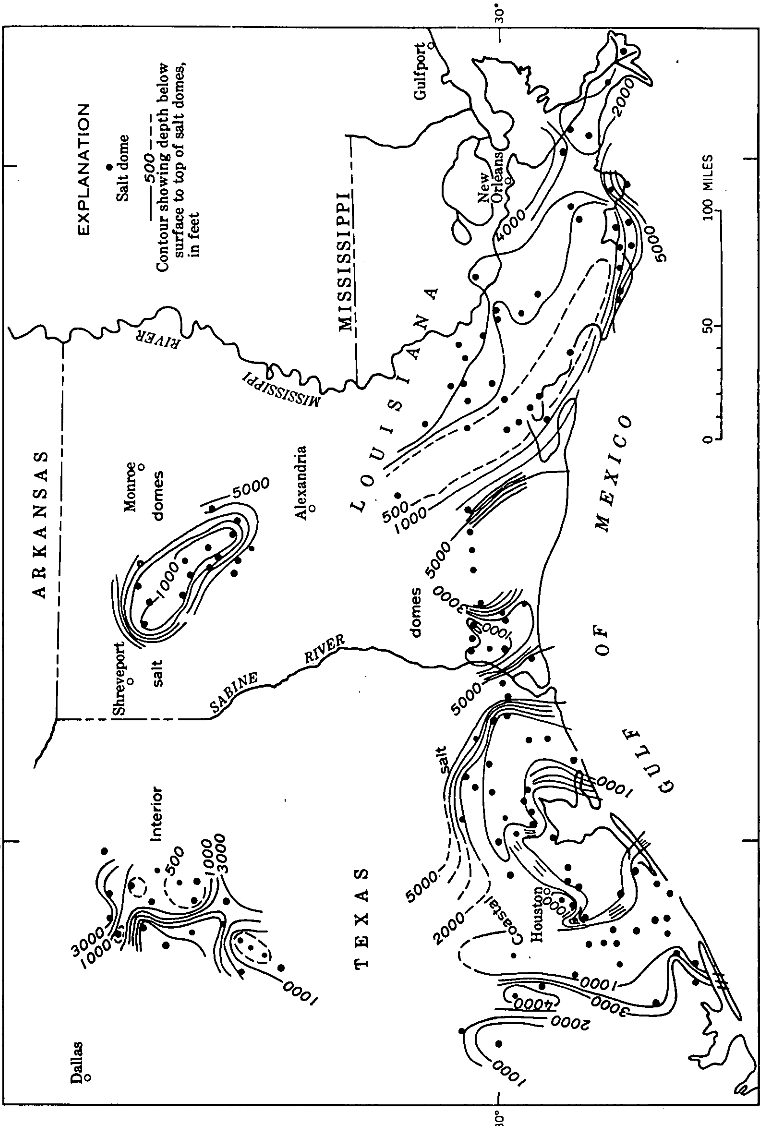

FIGURE 7.—Sketch map showing depth to top of some of the interior and coastal salt domes (after Barton, 1933).

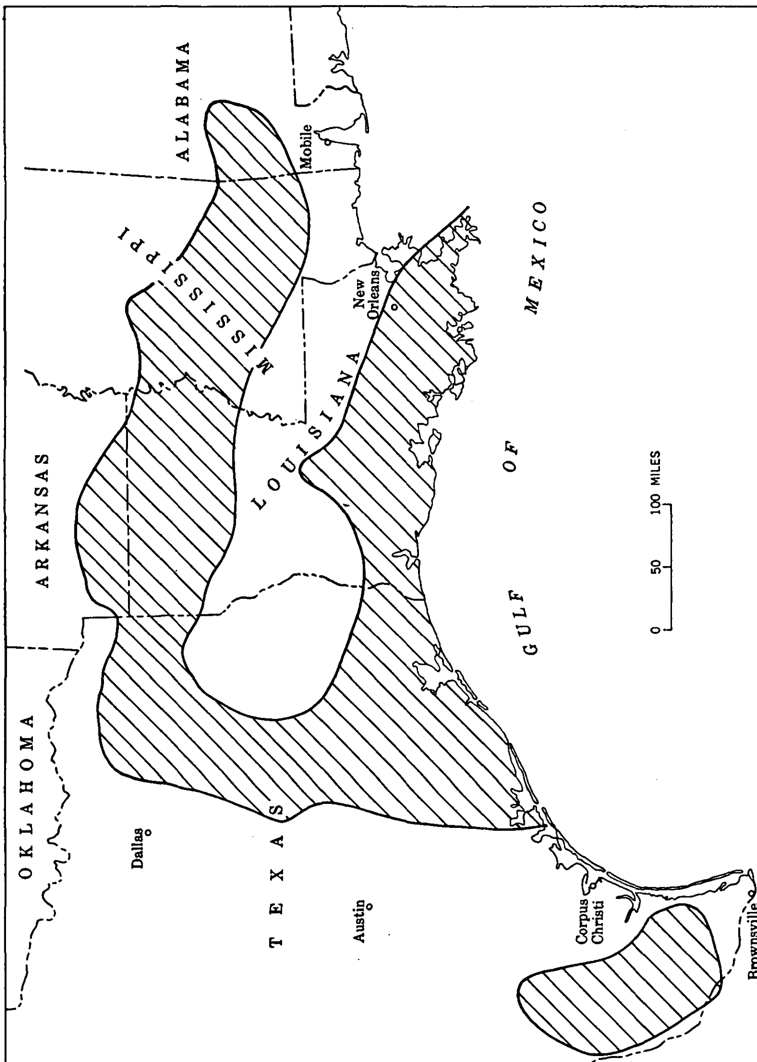

FIGURE 8.—Map of Gulf Coast Embayment showing area (crosslined) thought to be underlain by continuous salt beds (modified after map by L. L. Nettleton in Willis, 1948).

delta westward to Matagorda Bay. The salt domes between Corpus Christi and Laredo have been referred to as the South Texas domes in the Corpus Christi Geological Society guidebook (1957) but are here included with the coastal salt domes. Some salt domes lie beneath the waters of the Gulf of Mexico, particularly in the Mississippi River delta area (pl. 4).

When only a relatively small number of the salt domes in the Gulf Coast Embayment were known, a wide gap separated those of the interior area from those along the coast. As more salt domes were discovered, the gap separating the two became less, and it became more apparent that all of 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 were connected on the west by a northward-trending basin in eastern Texas (fig. 8).

According to Barton (1933, p. 1070), the depth to the tops of the salt domes tends to be less for domes of large diameter than for those of small diameter, but the correlation between depth and size of domes is statistically poor. Of 71 domes that he considered, the median depth to the tops of 20 large and very large domes is 550 feet and the median depth to the tops of 51 average and small domes is 950 feet. Figure 7 shows by means of generalized contour lines the approximate depths to more than 100 salt domes in southern Louisiana and southeastern Texas. Of these domes, 33 are listed in the following table.[2]

The depth to the salt bed assumed to underlie the Gulf Coast salt domes is estimated (Barton, 1933, p. 1054) to be 20,000 feet at Houston, Tex., 25,000 feet at Jennings, La., and 30,000 feet south of New Orleans, La. The interpretation of reflection seismograph data from Moss Bluff dome in southeastern Texas indicates a depth of 36,000 feet to the base of the salt (Hoylman, 1946; Nettleton, 1952); by extrapolation the depth to the salt at the coast line is about 40,000 feet (Nettleton, 1952, p. 1228).

[2] For a more complete list of salt domes, showing location of dome or related oil or gas field, depth to caprock, and depth to salt, see Sawtelle (1936), AAPG-SEPM-SEG Guidebook (1953, p. 14-20), Hough (1956, p. 39-43), and Morse (1956, p. 51-56).

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Depth to salt in coastal salt domes in Texas and Louisiana

[From Powers and Hopkins (1922)]

Location and name	*Depth (feet)*	*Location and name*	*Depth (feet)*
Texas		**Texas—Continued**	
Duval County:		Chambers County:	
Palangana	500	Barbers Hill	600
Piedras Pintas	500	Galveston County:	
Matagorda County:		High Island	1, 500
Big Hill (Matagorda)	1, 200	Jefferson County:	
Markham	2, 710	Spindletop	1, 650
Fort Bend County:		Hardin County:	
Big Creek	750	Saratoga	2, 050
Blue Ridge	400	Sour Lake	880
Washington County:		**Louisiana**	
Brenham	1, 400		
Brazoria County:		Calcasieu Parish:	
Bryan Heights	900	Vinton	1, 000
West Columbia (Kisers Mound)	800	Sulphur	1, 480
Damon Mound	500	Evangeline Parish:	
Stratton Ridge	1, 300	Pine Prairie (St. Landry)	500
Hoskins Mound	1, 250	Iberia Parish:	
Harris County:		New Iberia	800
Hockley	1, 000	Jefferson Island (Cote Caroline)	69
Pierce Junction	950	Avery Island (Petite Anse)	15
Humble	1, 400	Weeks Island (Grande Cote)	97
Liberty County:		St. Mary Parish:	
Hull	600	Cote Blanche	635
South Dayton	600	Belle Isle	373
Davis Hill	1, 385	St. Martin Parish:	
		Anse la Butte	260

PERMIAN BASIN

The Permian basin, as the term is used in this report, underlies parts of Kansas, Colorado, Oklahoma, Texas, and New Mexico (pl. 1). Salt, which occurs in strata of Permian age, underlies an area about 650 miles from north to south and 150 to 250 miles from west to east, or about 120,000 square miles. The thickness and succession of salt-bearing beds are variable. The aggregate thickness of the salt is about 2,800 feet in southeastern New Mexico, but over much of the basin it ranges from 0 to 600 feet.

In general, the upper or highest salt beds in the Permian basin are progressively older from southwest to northeast. The salt deposits of southeastern New Mexico and southwestern Texas are in the Guadalupe and Ochoa series of Permian age, whereas in Kansas, Oklahoma, and the northern part of the Texas Panhandle the salt deposits are in the Leonard series of Early Permian age. The formations within each of these series differ from State to State, and many differ within a State. A generalized summary of the formational relations is shown in tabular form in figure 9.

Data presented here are mainly a synthesis of data in published reports. The data on west Texas and southeastern New Mexico are

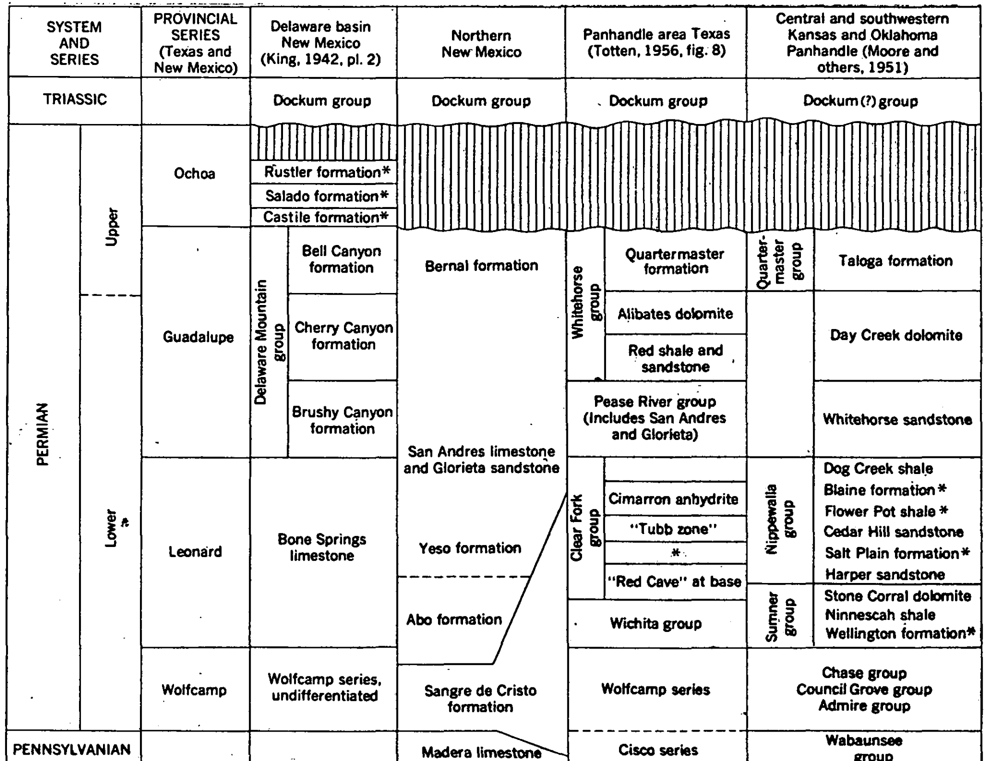

FIGURE 9.—Stratigraphic chart showing generalized formational relations in parts of the Permian basin. Some correlations are uncertain. Asterisk (*) indicates salt-bearing formations.

from an unpublished report by P. T. Hayes; those on the northern Panhandle of Texas are modified from a report by Hoots (1925); and those on the Kansas-Oklahoma salt deposits are taken principally from reports by Bass (1926) and Lee (1956).

The salt beds are in a succession of red shales and sandstones and are generally associated with gypsum, anhydrite, and dolomite. The salt bodies vary in thickness. 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 thick gypsum and anhydrite. In Kansas little anhydrite or gypsum seems to be interbedded in the salt measures or 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. 10). Most of the data pertaining to this area are from an unpublished report by P. T. Hayes. The area of salt deposits 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 36,000 square miles.

The thickest and most extensive beds of salt in the Permian basin are in the Ochoa series of Late Permian age. The Ochoa contains three salt-bearing formations (fig. 9): the Castile, Salado, and Rustler formations, in ascending order. The Castile 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. 10).

CASTILE FORMATION

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

The basal few feet of the Castile formation in most areas is 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 salt which range

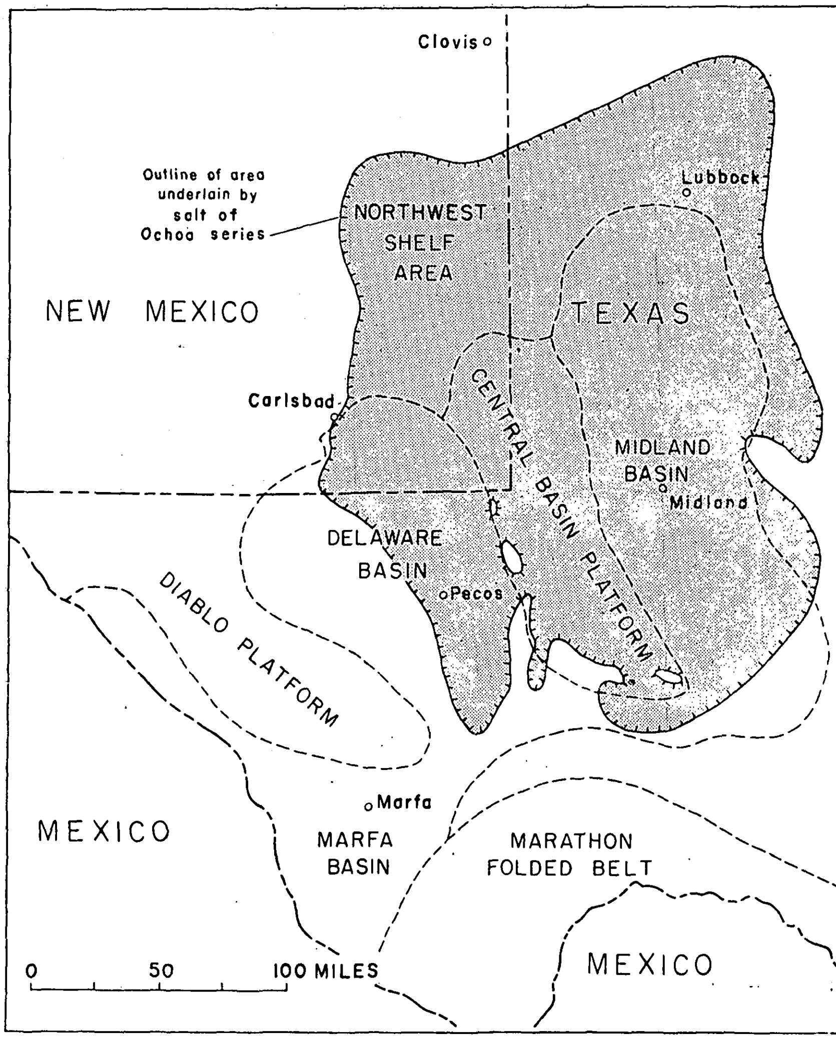

FIGURE 10.—Index map showing relation of structural and physiographic features of Permian age to area underlain by salt beds of the Ochoa series (modified from King, 1948).

in thickness from 0 to more than 700 feet but are usually less than 250 feet thick. In southwestern Lea and eastern Eddy Counties N. Mex., the maximum aggregate thickness of salt beds in the Castile formation is about 1,000 feet. Everywhere in the Delaware basin the salt beds are separated by beds of anhydrite 50 to 500 feet thick and in no place does the salt comprise more than 60 percent of the formation. Figure 11 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

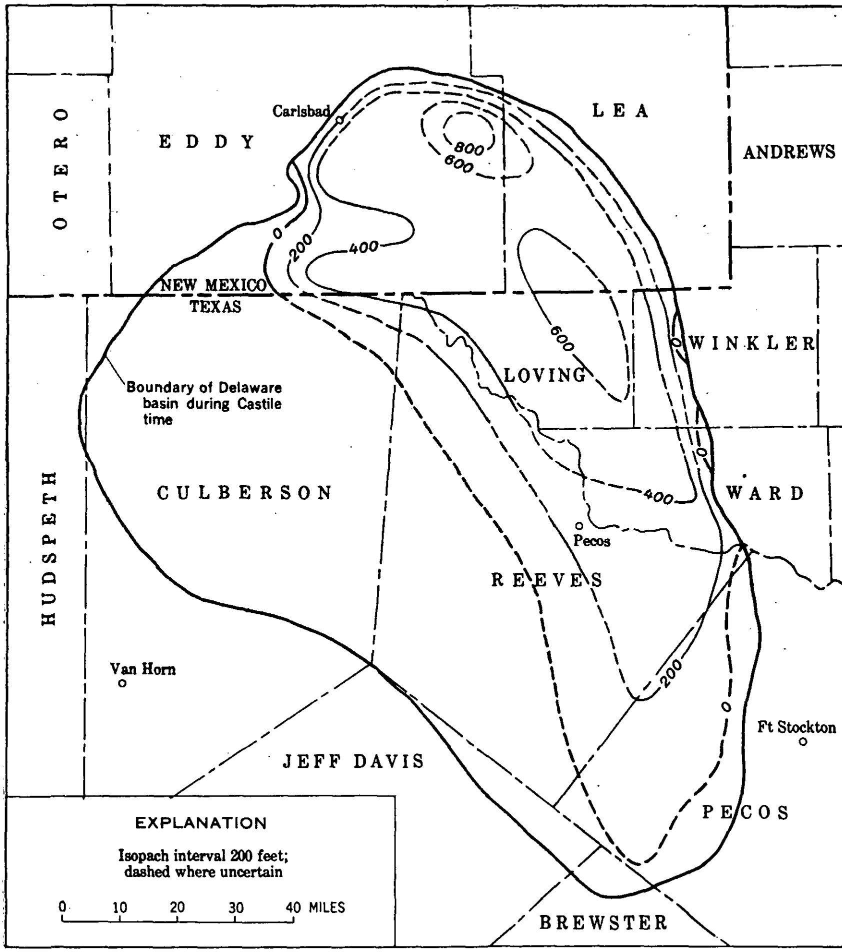

FIGURE 11.—Map showing aggregate thickness of salt in Castile formation, Ochoa series, New Mexico and Texas (modified from map compiled by P. T. Hayes.

part of the Delaware basin, in eastern Reeves and western Pecos Counties, Tex., it is overlain by the basal salt 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.

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, is considered to consist predominantly of interlaminated anhydrite and limestone, several beds of pure salt, and nonlaminated anhydrite. The Salado formation consists predominantly of sodium chloride but contains minor clastic beds and many of the rarer salts. This definition of the formations restricts the Castile formation to the Delaware basin (fig. 12).

In exposures of the Castile formation along the west side of the Delaware basin all the salt has been removed by solution and the anhydrite has been hydrated to gypsum. The alteration of the evaporite rocks 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 out within a distance of about 1 mile (fig. 12).

SALADO FORMATION

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

The Salado formation consists of salt, anhydrite, and potassium salts with varying amounts of clastic material. Salt comprises about 75 to 90 percent of the formation except in areas where subsurface solution has removed much of it, 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, and numerous less abundant potassium minerals.

The most abundant potassium minerals in the formation are polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$), sylvite ($KCl$), langbeinite ($K_2SO_4 \cdot 2MgSO_4$), carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$), kainite ($KCl \cdot MgSO_4 \cdot 3H_2O$), and leonite ($K_2SO_4 \cdot MgSO_4 \cdot 4H_2O$). Of these minerals polyhalite is the most abundant and widespread, but it is not ecnomically valuable. The deposits of potassium minerals of economic interest are in the middle part of the Salado formation (fig. 13); These deposits are compact mineral bodies and have a sharp outline against the adjoining salt beds. They consist of a mixture of halite with minor clay and quartz and contain from 25 to 40 percent of one or more of the highly soluble potassium minerals. The deposits have a maximum thickness of about 21 feet but average 4 to 5 feet (Jones and others, 1960).

The salt of the Salado formation, with the exception of the basal beds in the Delaware basin area, is less pure than that in the Castile

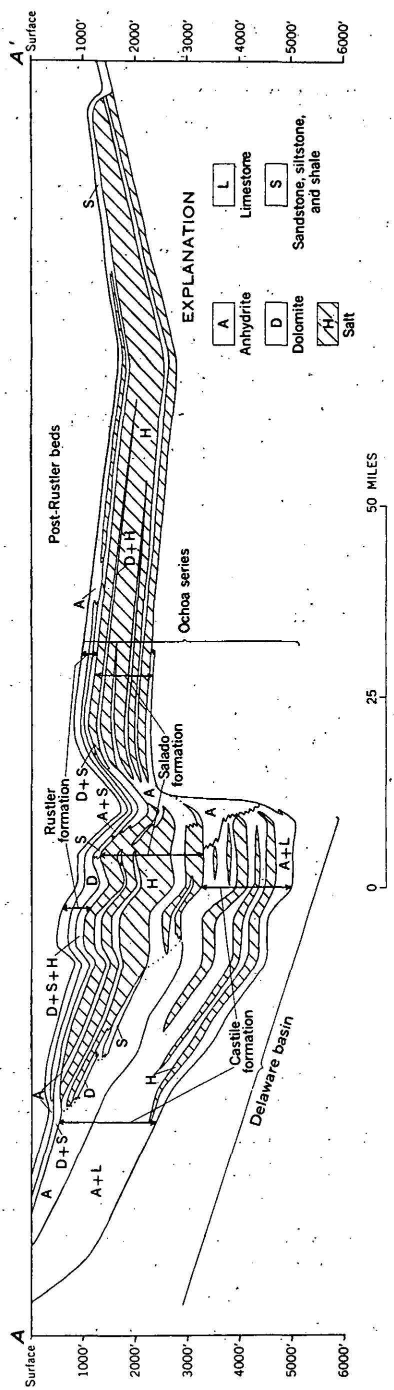

FIGURE 12.—Generalized stratigraphic diagram of Ochoa series along line *A–A'*. See plate 5 for location of section. (Diagram by P. T. Hayes.)

formation. Much of the Salado salt, especially where soluable potassium salts are present, has a pinkish color. Considerable grayish salt, the color of which was caused by admixed black mud and clay, occurs throughout the formation. In places minor amounts of blue halite are found in close association with the most soluble potassium salts. Anhydrite and silt in the form of very thin beds and inclusions are common impurities in the salt beds.

The thickest accumulation of salt in the Salado formation is on the north and east edges of the Delaware basin where more than 1,700 feet of salt occurs in a narrow band (fig. 13). On the shelf area adjacent to the Delaware basin, salt in excess of 1,000 feet thick is confined to a relatively small area. It gradually thins out to the north and east of the shelf area (fig. 12).

The contact between the Salado and the Rustler formations is conformable and gradational. The contact is usually placed arbitrarily at the top of the highest thick salt bed in the Salado formation.

RUSTLER FORMATION

The Rustler formation is the youngest Permian salt-bearing unit in western Texas and southeastern New Mexico, but unlike the Castile and Salado formations, it contains a relatively small amount of salt. Salt occurs in a few thin discontinuous beds, generally in the lower part. Anhydrite is the dominant rock type in the Rustler formation, but dolomite occurs as persistent beds and polyhalite and soluable potassium salts are also present locally.

THICKNESS, DEPTH, AND STRUCTURAL CONFIGURATION OF SALT

The maximum aggregate thickness of salt in the Ochoa series (pl. 5) is about 2,800 feet at the northwest end of a northwestward trending zone along the east edge of the Delaware basin. The thickness of the salt decreases rapidly away from the zone of maximum thickness within the limits of the Delaware basin, but the thinning is less rapid over the Central Basin platform and in the Midland basin west of the Delaware basin.

In general, the depth to the salt 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. The depth to salt in the Delaware basin area ranges from 700 to 800 feet on the west and south sides of the basin to about 1,500 feet on the northeast side, and from 1,000 to 2,000 feet on the adjacent shelf area (West Texas Geol. Soc., 1949, 1951, 1953).

The configuration of the top of the salt-bearing formations is complicated by (a) the lenticularity of the salt beds, (b) the local solution of salt and collapse of the overlying strata, particularly near the margins of the basin, and (c) an erosional unconformity at the

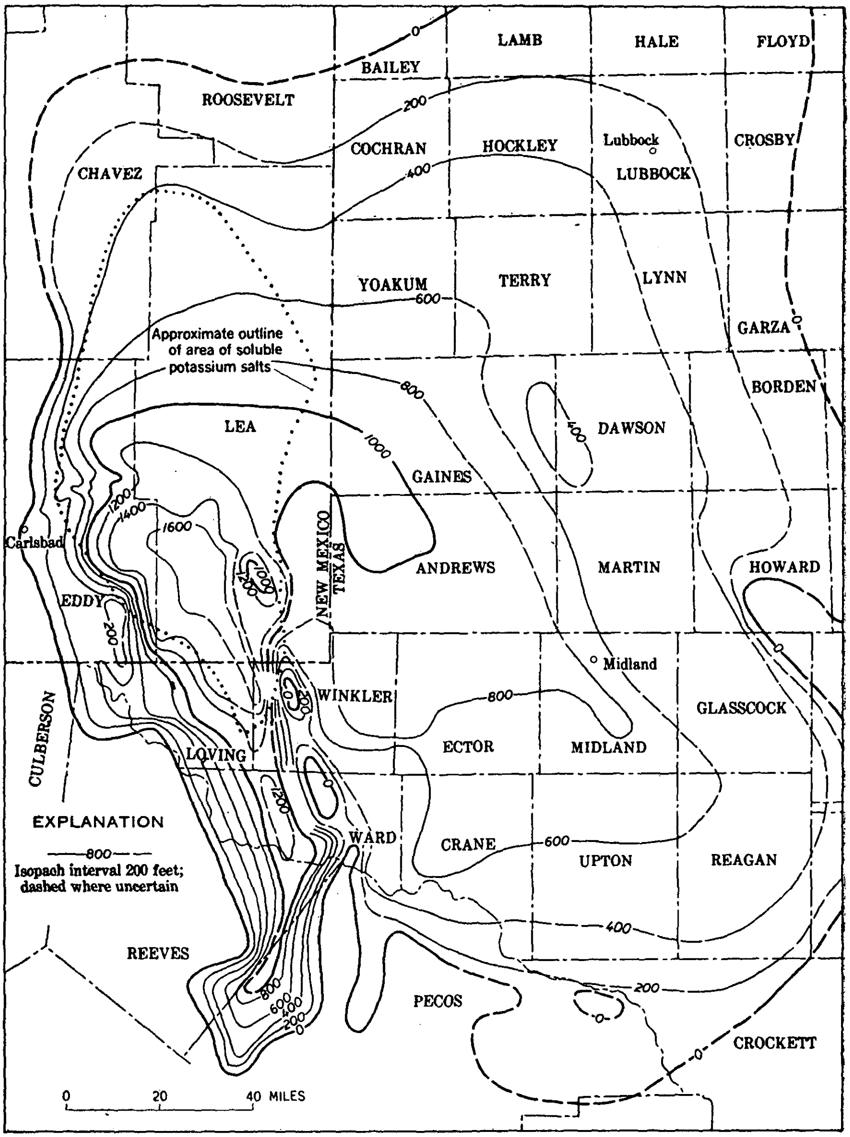

FIGURE 13.—Map showing aggregate thickness of salt in Salado formation, Ochoa series, New Mexico and Texas (compiled by P. T. Hayes, 1957).

top of the salt bearing formations. Thus the reliability of a generalized structure-contour map is limited. A structure-contour map by Hoots (1925) suggests that the top of the salt-bearing formation forms a northeastward-trending syncline, the axis of which lies 30 or 40 miles east of the Texas Panhandle-New Mexico border. This synclinal structure may be a reflection of the Central Basin platform (fig. 13) rather than the structural configuration of the top of the salt. Structure contour maps by King (1942), Maley and Huffington (1953), and Galley (1958), although in agreement on the general configuration of the top of the salt-bearing formations, vary considerably in detail. The variations are possibly due to local collapse features and to the unconformable relations between the salt-bearing formations and the overlying strata.

SALT BASIN WEST OF GUADALUPE MOUNTAINS

Rather extensive deposits of salt are exposed in a salt basin west of the Guadalupe Mountains in western Texas and southeastern New Mexico, about 70 miles southwest of Carlsbad, N. Mex. (Richardson, 1904, p. 61–64; King, 1948, p. 160–162). No data are available on the age, areal extent, depth, or thickness of the salt. These deposits are in or near existing salt lakes. It is not known whether the salt is introduced into the waters of the lakes as a dissolved constituent in surface water or by the percolation of ground water from deeply buried salt beds.

TEXAS PANHANDLE AREA

The Permian salt beds have been penetrated by numerous 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 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 general relation of the lithologic groups as used in this report is shown on figure 9.

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 about 735 feet near the west side of the Texas Panhandle. About 50 miles west of the Texas Panhandle-New Mexico border the salt decreases in thickness and pinches out or interfingers with shale (pl. 5). The southern limit of the Texas Panhandle salt deposit is uncertain, but it probably extends to near the salt-bearing formations of Ochoa age 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 salt bed in the Salt

Plain formation (as used by Moore and others, 1951) in eastern Colorado and western Kansas (pl. 5).

OKLAHOMA PANHANDLE AND SOUTHWESTERN KANSAS AREA

The most widespread zone of salt in the Oklahoma Panhandle and southwestern Kansas area is in the Hutchinson salt member of the Wellington formation. From this member, which contains salt beds with an aggregate thickness of as much as 400 feet, 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 Hutchinson salt member occurs in an area from 100 to 175 miles east of the southwest corner of Kansas (pl. 5). The higher salt bed may belong to the Salt Plain formation of the Nippewalla group. This upper salt accounts for the greater part of the combined thickness of salt beds near the Kansas-Oklahoma boundary. Several beds of salt have been reported in the stratigraphic interval between the Wellington formation and the Blaine formation (fig. 9) in Kansas (Jewett and Merriam, 1959, p. 14–16; Norton, 1939, fig. 2; Jordan, 1960, p. 23–28), but the areal extent, depth, and thickness of these salt beds cannot be compiled on a regional scale from the data presently available.

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 (fig. 14). The anhydrite beds consist of gray shale alternating with anhydrite. The Hutchinson salt member consists of salt interstratified with beds and laminae of anhydrite. The upper unnamed member consists of gray shale and subordinate red shale.

In the Carey salt mine at Hutchingson, Kans., the Hutchinson salt member consists of a "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 plasticlike 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 plate 5.

The Hutchinson salt member is thickest in the northeastern part of the central Kansas area, where the aggregate thickness of the

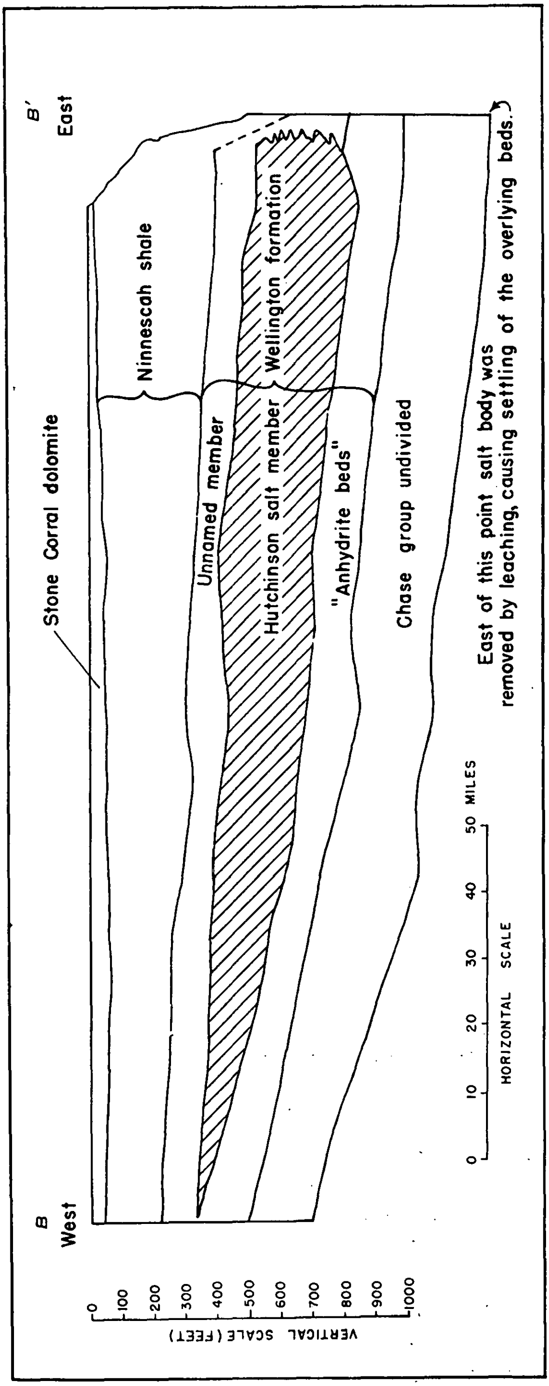

FIGURE 14.—Generalized stratigraphic diagram of Wellington formation along line *B–B'*. See plate 5 for location of section. Vertical scale greatly exaggerated. (Modified from Lee, 1956.)

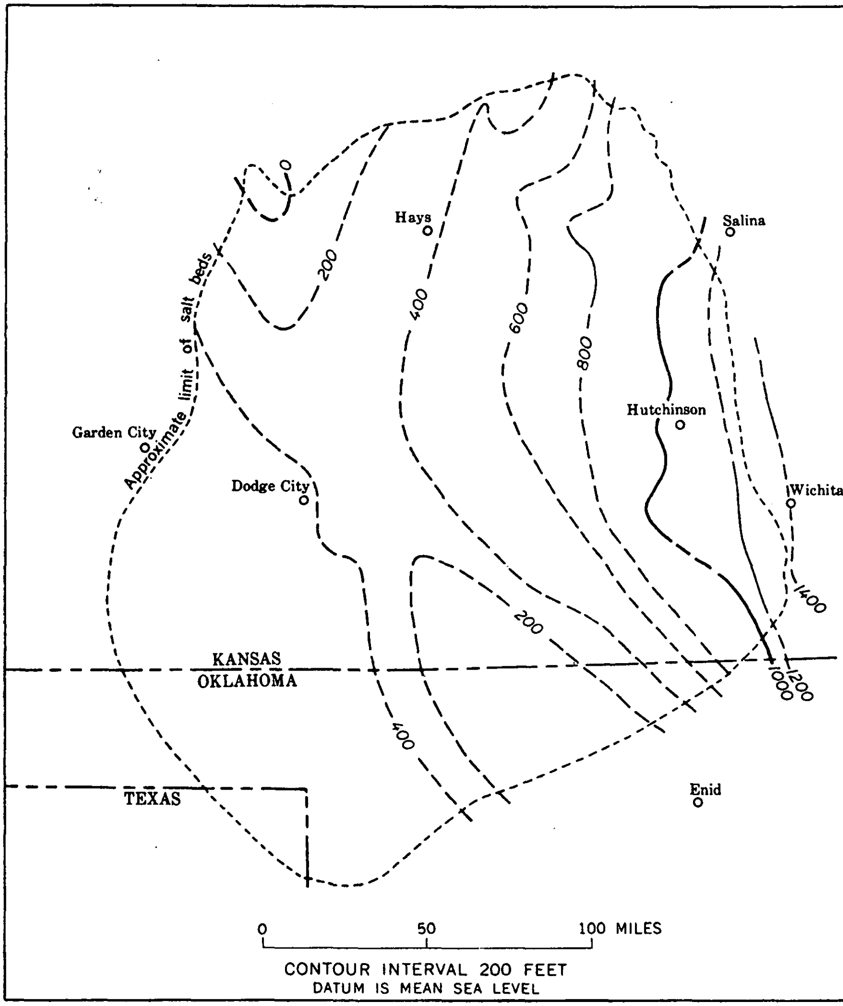

FIGURE 15.—Structure contour map showing altitude above sea level of top of salt beds in the Wellington formation in Kansas and adjoining parts of Oklahoma (after Bass, 1926).

Hutchinson is about 400 feet. The salt member thins irregularly toward the margins of the basin where the member and associated anhydrite interfinger with shale (fig. 14). In outcrops of the Wellington formation along the margins of the basin the salt has been removed by surface waters; leaching of the salt extends downdip for several miles.

The salt in eastern Colorado and southwesternmost Kansas seems to represent only the upper salt bed of the Salt Plain formation. It is probably not continuous throughout the region from central Kansas into Colorado.

The depth to 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 depth to the thickest salt ranges from 700 to 1,100 feet. The configuration of the top of the Hutchinson salt member of the Wellington formation is shown on figure 15.

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

PARADOX BASIN, SOUTHEASTERN UTAH AND SOUTHWESTERN COLORADO

The Paradox basin is a sedimentary basin of Pennsylvanian age in southeastern Utah and southwestern Colorado. It is about 160 miles long from northwest to southeast, about 80 miles wide, and covers about 12,000 square miles.

The account which follows is abstracted in part from an unpublished report prepared by E. H. Baltz. He noted that, although the general distribution of salt is known from drilling data, the drill holes are too widely spaced to give detailed quantitative data on the regional thickness and volume of salt; it was therefore necessary to rely heavily on geologic interpretation and extrapolation in portraying the occurrence of salt in the Paradox member of the Hermosa formation.

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. The formation ranges in thickness from less than 1,000 feet near the borders of the basin to more than 14,000 feet in deformationally thickened masses in the Paradox Valley anticline. The formation has been divided into three members: a lower unnamed member, composed chiefly of limestone; the Paradox member, which is the salt-bearing unit; and an upper unnamed member (Bass, 1944) composed chiefly of limestone. The Hermosa formation rests on the Molas formation of Pennsylvanian age and is overlain by the Rico formation of Middle and Late Pennsylvanian age.

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 due to the variations in thickness of evaporite rocks in the Paradox member.

The potassium salts sylvite (KCl) and carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) are present in the Paradox member. The first potassium deposits were found in the northwestern part of the Paradox basin, particularly in the Salt Valley, Moab, and Cane Creek areas (Dyer, 1945), but as more drill data accumulated the deposits were found to extend southeastward (Hite and Gere, 1958), and now appear to underlie most of the salt anticline area. Hite and Gere (1958, p. 225) reported that the grade of the potassium salt deposits compares favorably with ore now being produced in the Permian basin, but depth and structural deformation are handicaps to exploitation of the deposits.

STRUCTURE

The Paradox basin is elongate in a northwest direction and is sharply bordered on the northeast by the Uncompahgre uplift. The basin is asymmetrical in northeast-southwest cross section; the deepest part is only a few tens of miles southwest of the Uncompahgre uplift.

Most of the Paradox basin (pl. 6) is characterized by broad open folds that trend northwestward, roughly parallel to the Uncompahgre uplift. In the southwestern part of the basin the structural trend is more to the north parallel to the Monument uplift. 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 closer together and longer and have greater structural relief. Also, the axial parts of these larger anticlines have been complexly downfaulted, forming grabens many miles in length. The structural features of the faulted anticlines are even more complex in the vicinity of the La Sal Mountains igneous intrusions. Two other areas of large-scale igneous intrusion in the Abajo Mountains west of Monticello, Utah, and the Ute Mountains near the southwest corner of Colorado are in less severely folded and faulted parts of the basin.

Erosion in most of the large anticlines in the northeastern part of the Paradox basin 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. The great thickness of salt which probably was associated with some of these beds presumably has been leached near the surface. Detailed mapping by Baker (1933), Dane (1935), and McKnight (1940) in Utah, and by Stokes and Phoenix (1948), Cater (1954, 1955a, 1955b, 1955c), Shoemaker (1954, 1956), and Shoemaker and others (1958) in Colorado and Utah has shown that the beds overlying the salt cores of the anticlines are mainly Triassic and Jurassic strata but at places Upper Pennsylvanian, Permian, and Cretaceous strata are also present. Growth of the salt anticlines began in pre-Triassic or pre-Late Triassic time, continued into Jurassic time in most of them, and locally may have continued into the Cretaceous (Shoemaker and others, 1958, p. 39).

The crests 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 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, inducing salt to flow backward, causing collapse.

Several of the salt anticlines are thought to be composed of a number of discrete structural cells, linked end to end like a chain of sausages (Shoemaker and others, 1958). Many of these cell-like plugs and composite masses are probably connected at depth to a low ridge of salt that is continuous for the length of the anticline.

DISTRIBUTION AND THICKNESS OF SALT

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

The greatest thickness of salt in the Paradox basin probably was deposited in the deepest part near the northeast side of the basin parallel to the southwest border of the Uncompahgre uplift, and may have been more than 5,000 feet thick (Shoemaker, 1954, p. 51). Subsequent to the deposition of salt, regional deformation or differential loading by the overlying strata (Jones, R. W., 1959) caused the salt to flow into anticlinal folds. The thickness of the salt in these anticlines ranges from 2,000 feet to more than 10,000 feet (Shoemaker and others, 1958).

The thickness and distribution of the salt-bearing part of the Paradox member are indicated by isopach lines on plate 6. 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 evaporite rocks so that the actual thickness of salt at any given place will be less than that represented by the isopach lines. Near the line of zero salt thickness, salt beds may make up no more than 10 percent of the total thickness of the salt-bearing sequence. The average salt content of the section logged in 30 wells on the salt anticlines is 72.4 percent (Shoemaker and others, 1958). The percentages of other constituents are: shale and siltstone, 17.8; gypsum and anhydrite, 4.4; limestone and dolomite, 3.1; sandstone and conglomerate, 2.3. Table 2 contains data from 23 wells in Utah and 11 wells in Colorado showing depth to top of the salt and, for most wells, the total thickness and the percentage of salt in the salt-bearing beds.

The thickest salt-bearing rocks are in the area of large collapsed anticlines in the northeastern part of the Paradox basin. The Continental Oil Co. well on the Paradox Valley anticline in western Montrose County, Colo., penetrated more than 13,000 feet of evaporite rocks, mainly salt. (See well 27, table 2.) Comparison of gravity anomaly maps (Joesting and Byerly, 1958, p. 14–15) of Sinbad Valley, Paradox Valley, and Gypsum Valley anticlines supports the thicknesses indicated by wells.

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 indicate that little or no salt is present north of Paradox Valley anticline and between the Paradox Valley and Gypsum Valley anticlines (Joesting and Byerly, 1958, p. 15). 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 either partial or complete removal of salt from the synclinal areas adjacent to the major anticlines.

In the central and southern parts of the Paradox salt basin, anticlinal folds show much less structural relief, and there is no evidence of salt piercement on these structures. Thickening of the salt seems to have occurred mainly as a response to slight flowage from the limbs of anticlines, perhaps aided 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 large anticlinal and synclinal folds and piercement of the salt through the overlying beds.

TABLE 2.—*List of selected wells in the Paradox basin, showing depth and thickness of salt*

Location No. on pl. 6	County	Name of well	Date completed	Total depth (feet)	Depth to top of salt-bearing rock (feet)	Thickness of salt-bearing rock (feet)	Salt (percent)	Approximate combined thickness of salt beds (feet)	Source of data
				Utah					
1	Emery	Equity Oil Co., Govt. 1	1952	8,134	6,040	----------	----------	----------	Hansen and others, 1955.
2	Grand	Potash Co., of Am., Wright 2	1943	5,012	4,357	655	89	580	Shoemaker and others, 1958.
3	do	Defense Plant Corp., 1	1949	10,350	2,091	3,976	72	2,860	Do.
4	do	Crescent Eagle Oil Co., 1	1925	4,009	2,060	1,949	31	600	Dane, 1935.
5	do	Potash Co. of Am., McCarthy State 1	1943	5,250	3,975	1,275	88	1,120	Shoemaker and others, 1958.
6	do	Pacific Western and Equity Oil Co., Thompson Unit 1.	1949	13,766	12,200	1,566	80(?)	1,250(?)	Am. Stratigraphic Co. as reported by Elston and Shoemaker (oral communication 1960).
7	do	Pure Oil Co. 1	1949	3,036	2,780	256	----------	----------	Hansen and others, 1955.
8	do	Utah Southern Oil Co., King 1	1932	3,829	1,570	2,259	78	1,760	Dane, 1935.
9	do	Utah Southern Oil Co., Balsley 1	1949	6,120	883	5,237	----------	----------	Dyer, 1945.
10	do	McRae Oil & Gas Corp., McRae Federal 1	1957	8,778	4,634	3,586	71	2,550	Elston and Shoemaker (oral communication 1960).
11	do	Great Lakes Carbon Corp., Utah State 1	1946	3,655	2,725	930	72	670	Shoemaker and others, 1958.
12	do	Columbia Crude Corp., Pitts 1	1938	4,243	2,440	1,803	77	1,390	Do.
13	do	Embar-Big Six Oil Cos	1928	5,345	1,910	2,075	17	350	Baker, 1933.
14	do	Big Six-Western Allied Oil Co	1920	2,450	931	719	99	709	Baker, 1933; well log only to depth of 1,650 ft.
15	do	Utah Southern Oil Co., J. L. Shafer 1A	1929	4,107	2,136	1,971	72	1.420	Baker, 1933.
16	do	Midwest Exploration Co., Frank Shafer 1	1927	5,000	1,498	3,502	70	2,450	Do.
17	San Juan	Snowden-McSweeney Co., Prommel 1	1927	3,520	2,140	1,380	70	970	Do.
18	do	Midwest Exploration Co., J. H. Shafer 1	1927	5,863	1,610	3,905	71	2,760	Do.
19	do	Reynolds Mining Corp., Gibson Dome 1	1955	6,036	1,952	3,148	79	2,490	Elston and Shoemaker (oral communication 1960).
20	do	Union Oil Co. 1	1927	5,010	1,620	3,390	78	2,630	Baker, 1933.
21	do	Midwest Exploration Co., Hughes 1	1927	4,422	1,617	331	23	75	Elston and Shoemaker (oral communication 1960).
22	do	Pan American Pet. Corp., Elk Ridge Unit 2.	1957	4,347	3,215	702	44(?)	300(?)	Do.
23	do	Western Natural Gas Co., Redd 1	1948	8,678	5,885	1,870	68	1,270	Wengerd and Matheny, 1958; Elston and Shoemaker (oral communication 1960).

TABLE 2.—*List of selected wells in the Paradox basin, showing depth and thickness of salt*—Continued

Location No. on pl. 6	County	Name of well	Date completed	Total depth (feet)	Depth to top of salt-bearing rock (feet)	Thickness of salt-bearing rock (feet)	Salt (percent)	Approximate combined thickness of salt beds (feet)	Source of data
		Colorado							
24	Mesa	J. M. Huber Corp., Sinbad Valley Unit 1	1953	10,316	395	9,905	67	4,160	Elston and Shoemaker (oral communication 1960).
25	Montrose	General Petrol. Corp., Wilcox 1	1927	3,548	1,030	2,518	56	1,400	Barb, 1946.
26	do	General Petrol. Corp., Wilcox 2	1927	6,300	925	5,375	65	3,490	Do.
27	do	Continental Oil Co. Scorup and others 1	1958	15,000	630	13,714	72	9,870	Elston and Shoemaker (oral communication 1960).
28	do	General Petrol. Corp., Mullen 1	1926	4,073	1,290	2,783	74	2,060	Barb, 1946.
29	do	Am. Liberty Oil Co	1948	10,846	1,080	9,766	84	8,200	Shoemaker and others, 1958.
30	San Miguel	Reynolds Mining Corp., Egnar 1	1955	10,220	5,440	4,260	78	3,320	Do.
31	do	Prestridge-Allison, Long 1	1952	6,211	6,137	74			Am. Stratigraphic Co. as reported by Elston and Shoemaker (oral communication 1960).
32	Dolores	Byrd-Frost & Western Natural Gas 1-A, Uhl-A.	1948	7,680	6,070	1,515	65	980	Am. Stratigraphic Co. as reported by Elston and Shoemaker (oral communication 1960.)
33	do	Moody Oil Corp., Stathopulous 1	1927	6,747	6,060				Barb, 1946.
34	do	Continental Oil Co., Lone Dome 1	1955	9,959	6,485	2,790	80	2,230	Am. Stratigraphic Co., as reported by Elston and Shoemaker (oral communication 1960).

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 was not attempted for this report. However, data from 34 wells have been assembled in table 2 showing the depth to the top of the salt. In Salt Valley and Moab Valley the depth to salt commonly ranges between 1,000 and 4,000 feet. In Sinbad and Paradox Valleys the salt is at shallower depths, ranging from 400 to 1,290 feet in the five wells from which data were obtained. Wells in the Cane Creek and Shafer Dome areas encountered salt at depths of 1,498 to 2,140 feet. A well in the northwestern part of Lisbon Valley reached the top of the salt-bearing rocks at a depth of 1,620 feet, but in the southeastern part the depth to the top of the salt is 5,440 feet in the Reynolds Mining Corp. well.

IGNEOUS INTRUSIVE ROCKS

Three large groups of laccolithic igneous bodies intrude the sedimentary rocks in the Paradox salt basin, and other igneous bodies occur near the margin of the basin. The groups within the basin are the Abajo and La Sal Mountain laccoliths in Utah, and Ute Mountain laccolith in Colorado. Little is known of the effect of the intrusive igneous rocks on the salt beds. Some evidence, however, indicates that in places near the La Sal Mountains and Ute Mountain igneous rock was injected selectively in the form of sills and other bodies 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 formed mainly near the top of the salt-gypsum bodies (Shoemaker, 1954, p. 56), and domes above stocks of igneous rock are superimposed on the salt anticlines. The total effect on the salt in this area is not known.

Thick sills cut 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.

SUPAI BASIN, ARIZONA AND NEW MEXICO

Bedded salt occurs in the Supai formation of Pennsylvanian and Permian age in east-central Arizona and west-central New Mexico (pl. 1). The salt beds do not crop out, and are known only from logs and cores of wells.

The salt-bearing Supai formation is conformable with, and gradational upward from, the underlying Naco formation of Pennsylvanian and Permian age. In the area underlain by salt, the Supai formation has been divided into three members (Huddle and Dobrovolny, 1945):

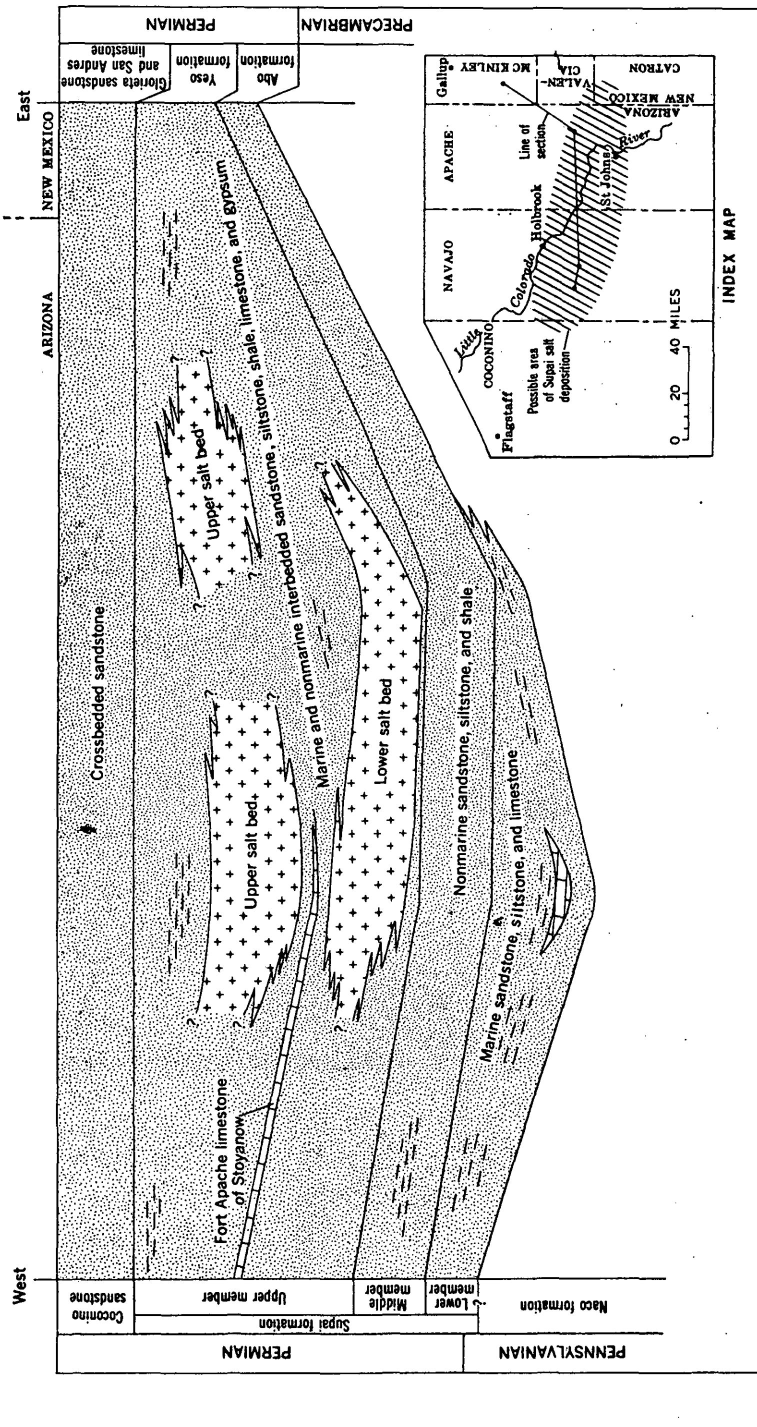

FIGURE 16.—Schematic cross section showing an interpretation of occurrence of salt in the Supai formation, eastern Arizona and western New Mexico (adapted from Huddle and Dobrovolny, 1945).

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 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 and the thickness relations suggest that the area in which the salt beds were laid down was a closed or partly closed oval basin. McKee (1951, p. 491) suggests that this basin may have been an extension or arm of the sea that covered central and southeastern New Mexico and western Texas during Permian time. The long axis of the basin in which salt is known to occur may have trended southeastward from near Flagstaff, Ariz., at least 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, pl. 2) suggest that the basin may have had a maximum width of about 70 miles. The areal distribution of the salt beds within the basin is not known, and the salt may have been deposited at several times 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 (1945) reported 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 salt, and another well about 40 miles east of Holbrook penetrated several beds of salt ranging in thickness from 10 to 80 feet (P. W. Johnson, written communication, 1958). In general, salt makes up from 5 to 15 percent of the Supai formation. Figure 16 is a generalized west to east cross section of the salt-bearing Supai formation, showing a possible interpretation of the distribution of 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, was furnished by Paul L. Applin of the U.S. Geological Survey (written communication, 1958).

Twelve wells in southern Florida penetrated bedded salt, and seven of them are shown on figure 17 and table 3. Salt was recovered in the cores of three of the seven wells (3, 4, and 7); in the other four

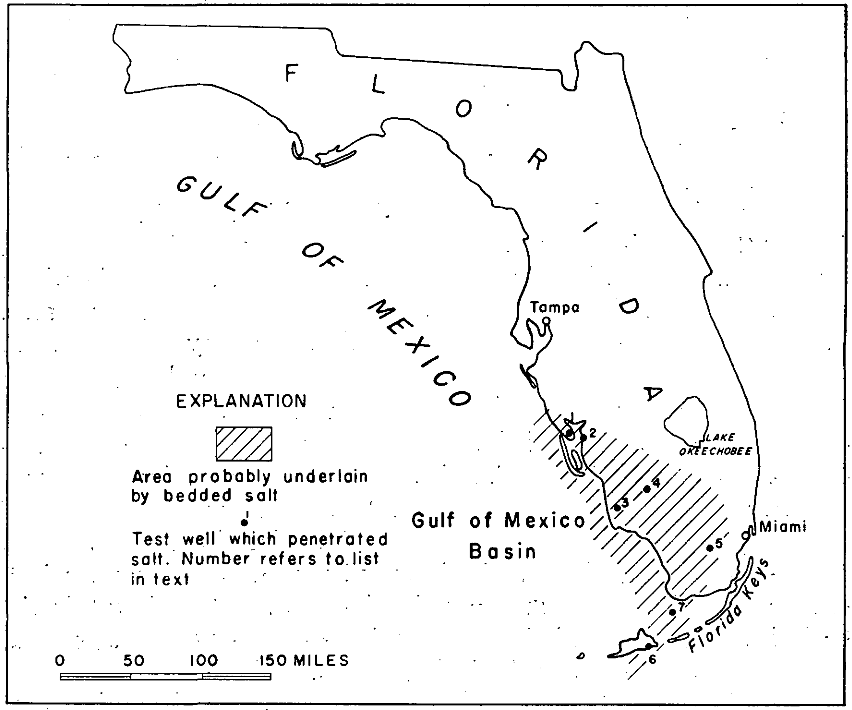

FIGURE 17.—Map showing area in southern Florida probably underlain by some bedded salt.

TABLE 3.—*List of wells in southern Florida that penetrated rock salt*

[Data furnished by P. L. Applin (written communication, 1958). A, electric log; B, Baroid log; C, well core]

Location No. (fig. 17)	Name of well	Elevation (feet)	Total depth (feet)	Depth to top of salt (feet)	Approximate thickness of salt (feet)	Method of determination of salt	Remarks
1	Gulf Oil Corp. Vanderbilt 1.	22	12,722	11,650	20	A	
2	Humble Oil & Refining Co., Treadwell 1A.	20	13,304	11,745	15	A, B	
3	Humble Oil & Refining Co., Collier Corp. 1.	25	12,600	12,452?	----------	C	Reported in salt at total depth; salt thickness uncertain.
4	Humble Oil & Refining Co., Gulf Coast Realties Corp. 2.	34	13,512	11,978	11	A, C	In Sunniland oil field; bottomed in salt.
5	Coastal Petroleum Co., Lease 340-A.	33	11,520	11,230	20	A, B	
6	Gulf Oil Corp., Lease 373 on Big Pine Key.	23	15,455	12,525	25	A	Deepest test in Florida.
7	Gulf Oil Corp., Lease 826-G in Florida Bay.	21	12,631	12,150	17	C	Another 10-ft bed of salt 350 ft below 17-ft bed.

the presence of salt was interpreted from electric logs (1 and 6) or from the combined use of electric logs and mud records on Baroid logs (2 and 5). The wells are too widely separated, however, for the correlation of individual beds.

The salt is 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 salt is 50 to 200 feet below the top of the unit. 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 most beds are 10 feet thick or less. The beds lie at a depth of more than 11,000 feet. The general area underlain by salt is shown on figure 17, but it is not known whether the salt is continuous or was deposited in several detached salt basins.

WILLISTON BASIN, NORTH DAKOTA, MONTANA AND SOUTH DAKOTA

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

Recent drilling for oil and gas in the Williston basin has disclosed 11 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. Other beds of salt are found in the Opeche formation of Permian age, in the Spearfish formation of Permian and Triassic age, and near the base of the Jurassic sequence. These 11 beds contain a total volume of about 1,700 cubic miles of salt in that part of the Williston basin underlying North Dakota (Anderson and Hansen, 1957).

The stratigraphic position of the salt beds and their relation to the enclosing formations is shown graphically on figure 18. 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.

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, 1958) and the Dawson Bay formation. The following discussion of the salt in the Prairie formation was prepared by C. A. Sandberg.

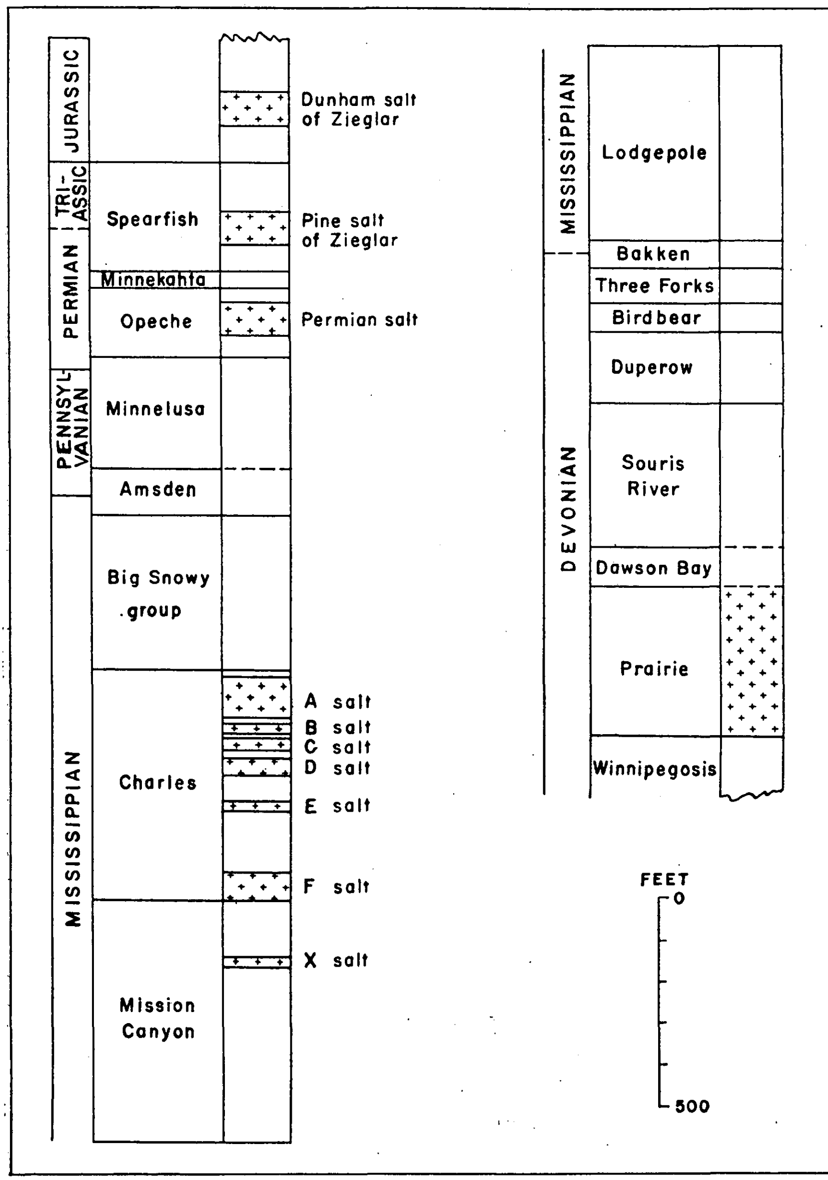

FIGURE 18.—Generalized columnar section of salt-bearing beds in Williston basin (modified after Anderson and Hansen, 1957; and Zieglar, 1956).

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 salt and shale, and an upper member, which is largely salt, designated as the salt member. The salt member contains colorless, moderately reddish-orange and grayish-red salt and a few thin beds of light-brown and grayish-red dolomitic shale. The bright color is due to disseminated argillaceous constituents in the salt. Baillie (1953) reported a little anhydrite and sylvite in this sequence. The sylvite (KCl) generally appears on radioactivity logs as a strong deflection of the gamma-ray curve to the right, indicating higher radioactivity than the salt. 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 basal part of the salt member was deposited in the center of the basin contemporaneously with the higher parts of the lower member on the margins.

The lower member of the Prairie formation changes to interbedded anhydritic dolomite, dolomitic–anhydritic shale, and siltstone containing inclusions of halite near the peripheral limit of the salt member. A short distance beyond the limit of the salt member, the lower member grades laterally 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 (fig. 19) the contact between the lower member of the Prairie formation and the underlying Winnipegosis is sharp; the Prairie is predominantly salt and anhydrite and the Winnipegosis is predominately 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 salt in the area south of the Nesson anticline and in northeastern Montana. The thickness and distribution of the salt member is shown on figure 19. In North Dakota the maximum thickness penetrated is 390 feet in a well at the north 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 200 feet to 0 in less than 7 miles.

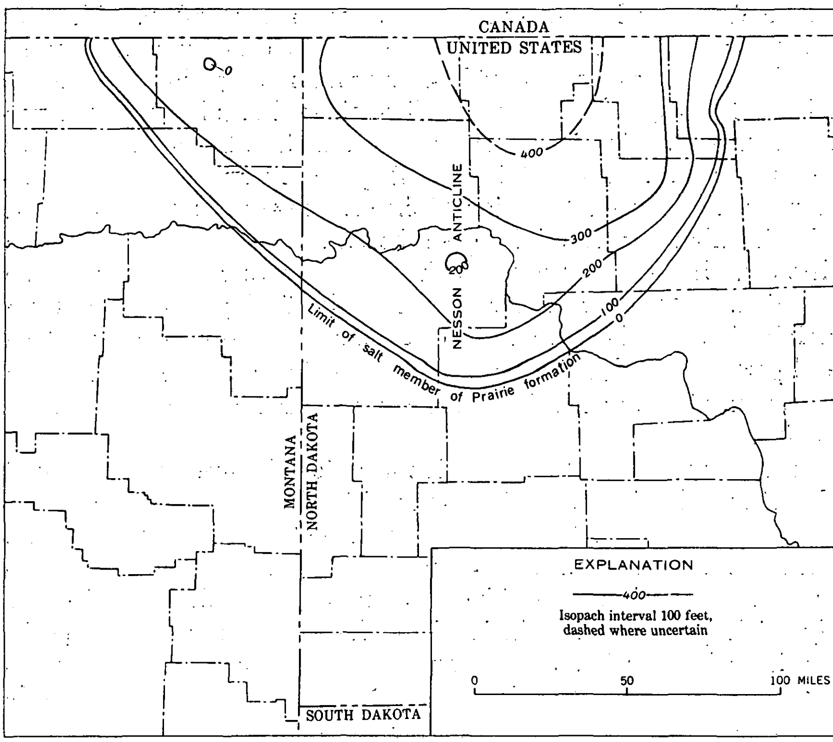

FIGURE 19.—Map showing thickness of salt member of Prairie formation (Middle Devonian) in the Williston basin (by C. A. Sandberg).

The salt member of the Prairie formation has undergone partial or complete solution in some areas. Where the member was predominantly salt, a residual mudstone, derived from disseminated argillaceous material and thin stringers of shale within the salt, remains; where anhydrite and dolomite were interbedded with salt, evaporite solution breccias were formed. An anomalously thin section of the formation in northeastern Montana is shown on figure 19. The zero line there represents the location of the Amerada Petroleum Corp. 1 Tange discovery well of the Outlook field in which the salt member apparently 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, Milner (1956, p. 111) has found evidence for salt solution taking place locally (a) after deposition of the Mission Canyon formation of Mississippian age but prior to the peneplanation of the Paleozoic rocks, (b) after the post-Paleozoic erosion but prior to the deposition of Jurassic sediments, and (c) 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 stated:

> 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 springs high in sodium chloride content that flow from the upper beds of the Winnipegosis formation in the Manitoba outcrop area, as further evidence that salt solution is still going on, because the Prairie formation lies at greater depths and because the salinity and pressure of waters in the formation have not been studied, the extent to which solution is taking place in the southern Williston basin is not known.

The lowest elevation of the top of the salt member is almost 10,000 feet below sea level (fig. 20). The greatest recorded depth to the top of the Prairie formation is 12,120 feet below the surface in the Texas Co. 1 Donahue well about halfway between the Nesson anticline and

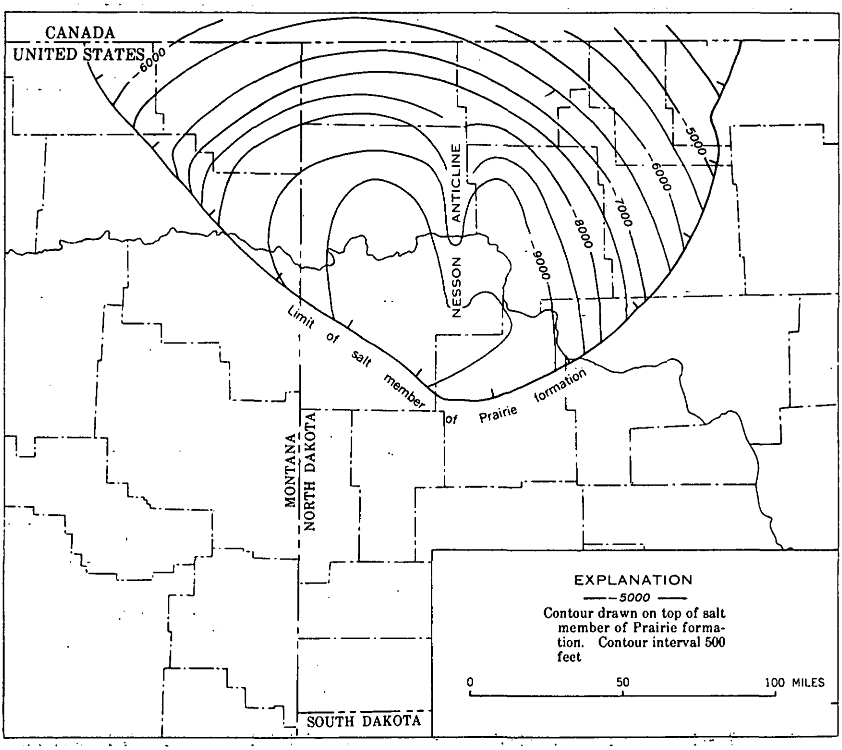

FIGURE 20.—Structure contour map showing depth below sea level to top of salt member of Prairie formation (Middle Devonian) in Williston basin (by C. A. Sandberg).

the North Dakota-Montana State line. The shallowest depth recorded in the southern Williston basin is 6,065 feet in the Dakota Oil Co. 1 Anderson well near the northeastern limit of the contour lines shown on figure 20.

SALT OF MISSISSIPPIAN AGE

The Madison group of Mississippian age in the Williston basin comprises, in ascending order, the Lodgepole, Mission Canyon, and Charles formations. The Madison group overlies the Bakken formation of Late Devonian(?) and early Mississippian age and is unconformably overlain by rocks ranging in age from Late Mississippian to Middle Jurassic. 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 more than 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.

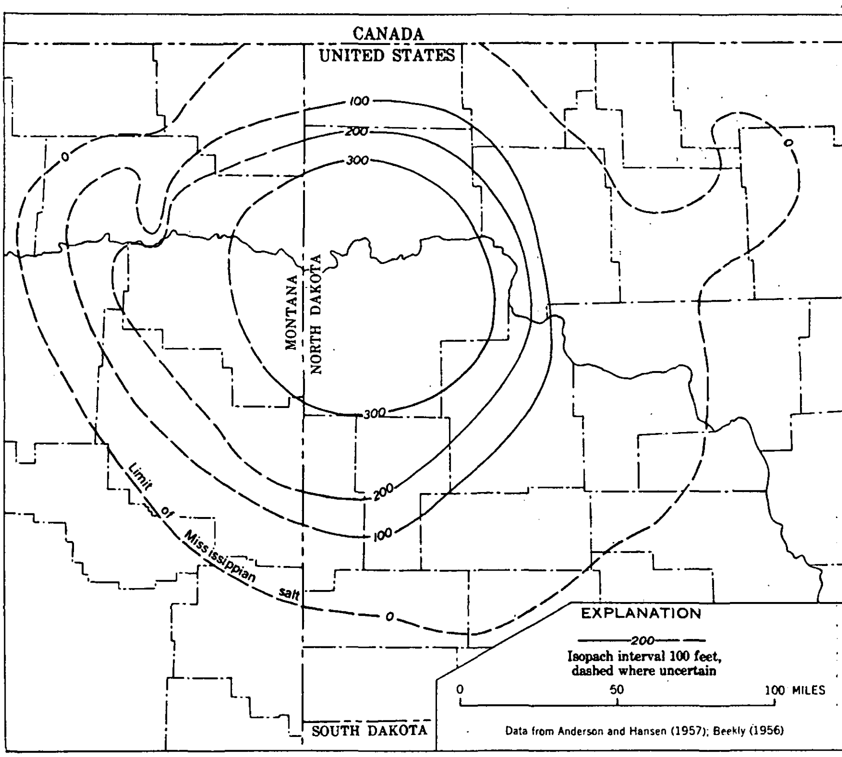

FIGURE 21.—Map showing aggregate thickness of salt beds of Mississippian age in Williston basin.

Practically all of the salt of Mississippian age is 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 and aggregate thickness of the seven Mississippian salt beds are shown by isopach lines drawn at intervals of 100 feet on figure 21. 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 in the A bed, which contains a maximum thickness of 150 feet of salt.

The depth below sea level to the top of the highest Mississippian salt bed is shown on figure 22 by contour lines drawn at intervals of 500 feet. Much of the area is between 2,000 and 3,000 feet above sea level; thus most of the Mississippian salt is 5,000 to 9,000 feet below the surface.

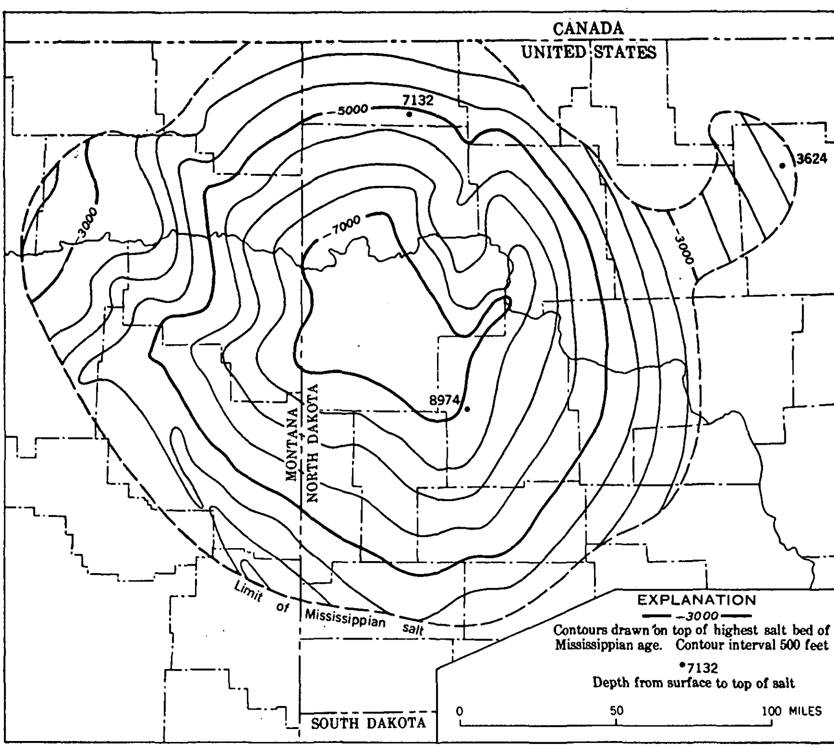

FIGURE 22.—Structure contour map showing depth below sea level to top of highest salt of Mississippian age in Williston basin (adapted from Kunkel, 1954).

SALT OF PERMIAN AGE

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

The principal salt bed in the Opeche formation is in the upper part. The extent and thickness of that bed is shown on figure 23. As indicated in that figure, there is a small area in which the salt bed is 150 or more feet thick, and a much larger area in which the bed is 100 or more feet thick. The depth to the top of the salt ranges from about 5,700 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 extensive (Anderson and Hansen, 1957).

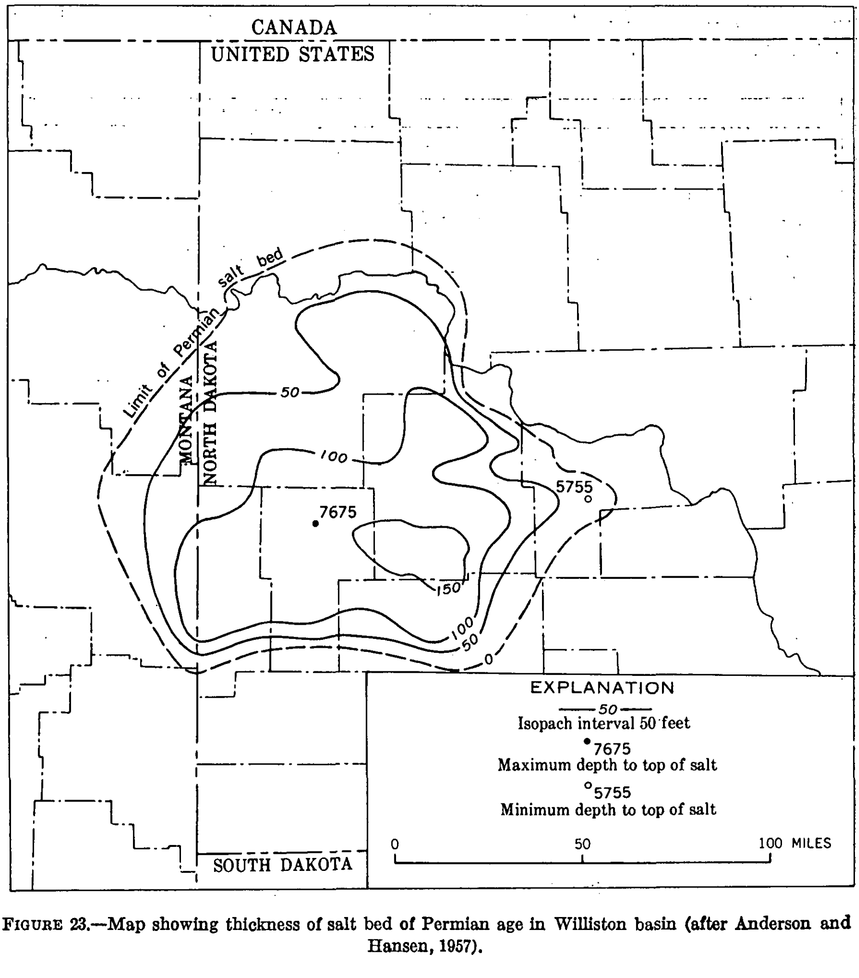

FIGURE 23.—Map showing thickness of salt bed of Permian age in Williston basin (after Anderson and Hansen, 1957).

SALT OF PERMIAN, TRIASSIC, AND JURASSIC AGE

In the Williston basin a red-bed sequence that is divided by a major unconformity consists of shale, siltstone, and fine-grained sandstone referred to the Spearfish formation by Anderson and Hansen (1957). The age of this sequence, which contains two salt beds, ranges from Permian to Jurassic. Zieglar (1956) concluded that only the beds below the lower of these two salt beds are of Triassic age; he 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 terms Triassic "A" and Triassic "B" for these salt beds, but placed the entire sequence in the Spearfish formation. Goldsmith (*in* McKee and others, 1959) placed the strata between the two salt beds in the Triassic, but put the Pine salt in the Permian and the Dunham salt in the Jurassic. In this report the names proposed by Zieglar (1956) are retained for the salt beds. The Dunham salt of Zieglar is placed in the Jurassic, after Zieglar (1956) and Goldsmith (in McKee and others, 1959), but the Pine salt is placed at the approximate Permian-Triassic boundary within the Spearfish formation, after C. A. Sandberg (written communication, based on an oral communication from E. K. Maughan, 1961).

The Pine salt of Zieglar 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 salt bed of appreciable thickness that extends into northwestern South Dakota. It reaches a maximum thickness of slightly more than 300 feet both in the southwest corner of North Dakota and in the northwest corner of South Dakota, as shown on figure 24.

The altitude of the salt ranges from about 1,000 to 5,000 feet below sea level (fig. 25), and much of the ground surface is 2,000 to 3,000 feet above sea level. Therefore, the depth to the Pine salt bed ranges from 4,000 feet in the south to 8,000 feet in the north.

The Dunham salt of Zieglar, the highest known salt bed of appreciable thickness in the Williston basin, is chiefly in western North Dakota, as shown on figure 26. It has a maximum thickness of about 100 feet, and thins and is locally absent along the Nesson anticline. As shown on figure 27, the Dunham salt ranges in altitude from 3,100 to 4,700 feet below sea level. When the surface elevation is taken into account, the depth to the salt ranges from about 5,000 to 7,000 feet.

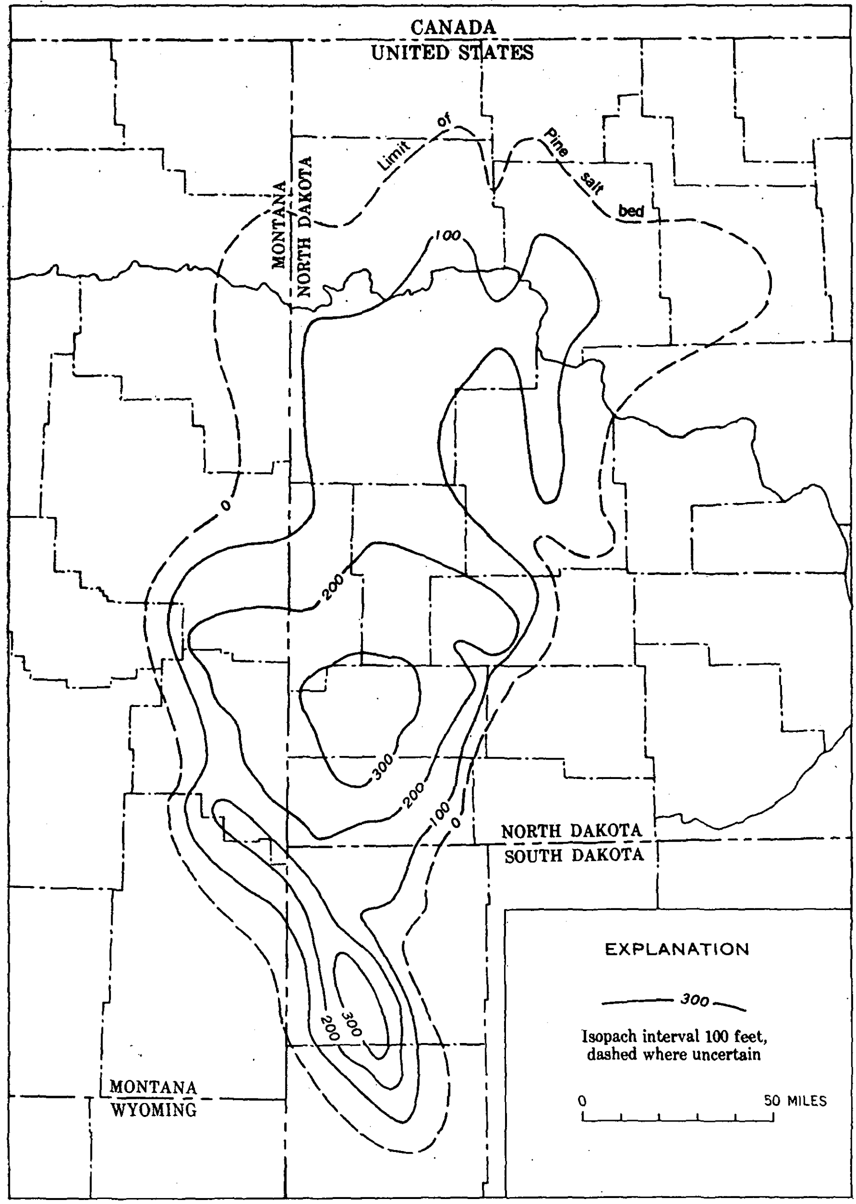

FIGURE 24.—Map showing thickness of Pine salt of Zieglar in Williston basin (after Zieglar, 1956).

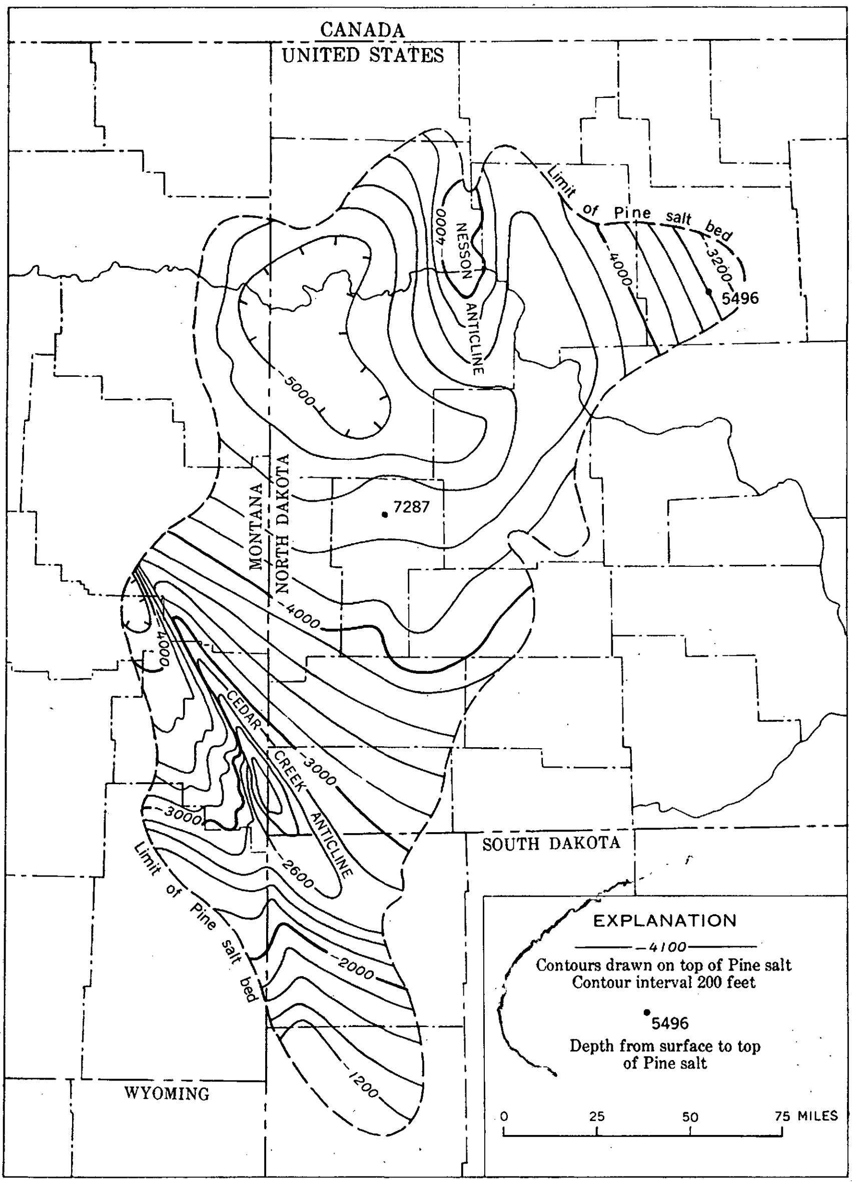

FIGURE 25.—Structure contour map showing depth below sea level of top of Pine salt of Zieglar in Williston basin (adapted from D. T. Sandberg, 1959).

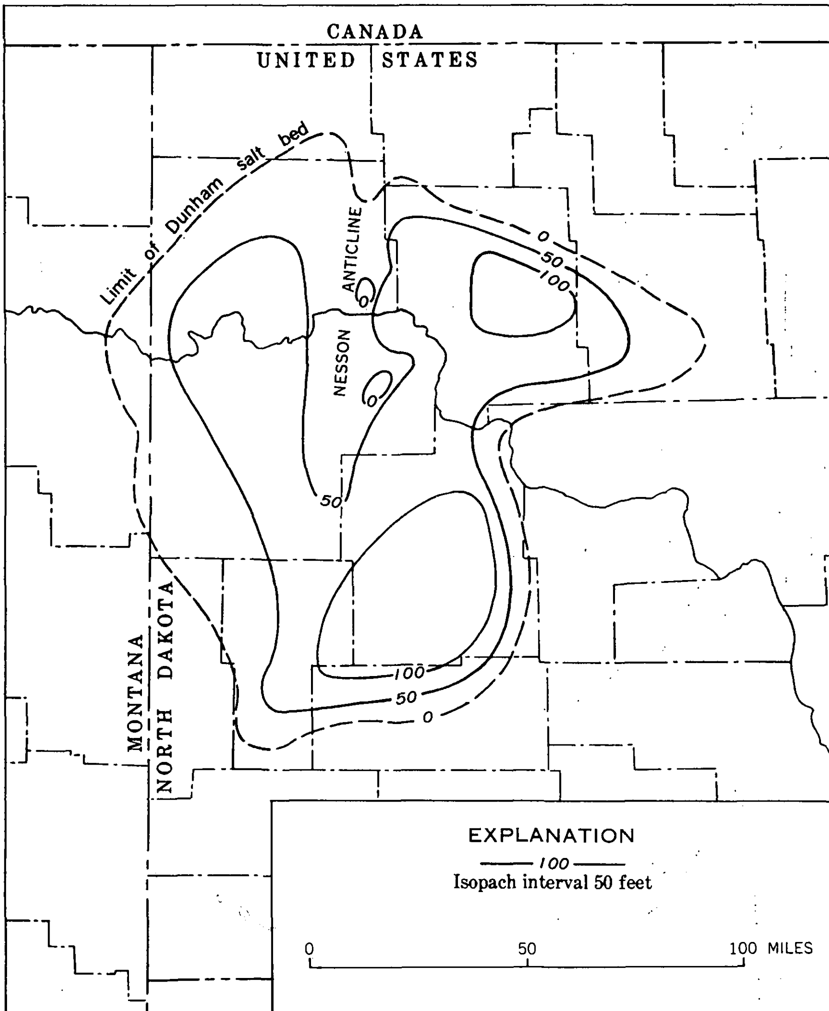

FIGURE 26.—Map showing thickness of Dunham salt of Zieglar in Williston basin (after Anderson and Hansen, 1957).

OTHER DEPOSITS

SEVIER RIVER VALLEY, UTAH

Salt occurs in the Arapien shale of Late Jurassic age in the Sevier River valley, Sanpete and Sevier Counties, Utah. The Arapien shale, which is correlated with the Carmel formation in eastern Utah, has been divided (Gilliland, 1951, p. 12) into five units, designated by letters A to E in ascending order; the combined thickness is 3,000 to 7,000 or more feet. Structural complexities within the

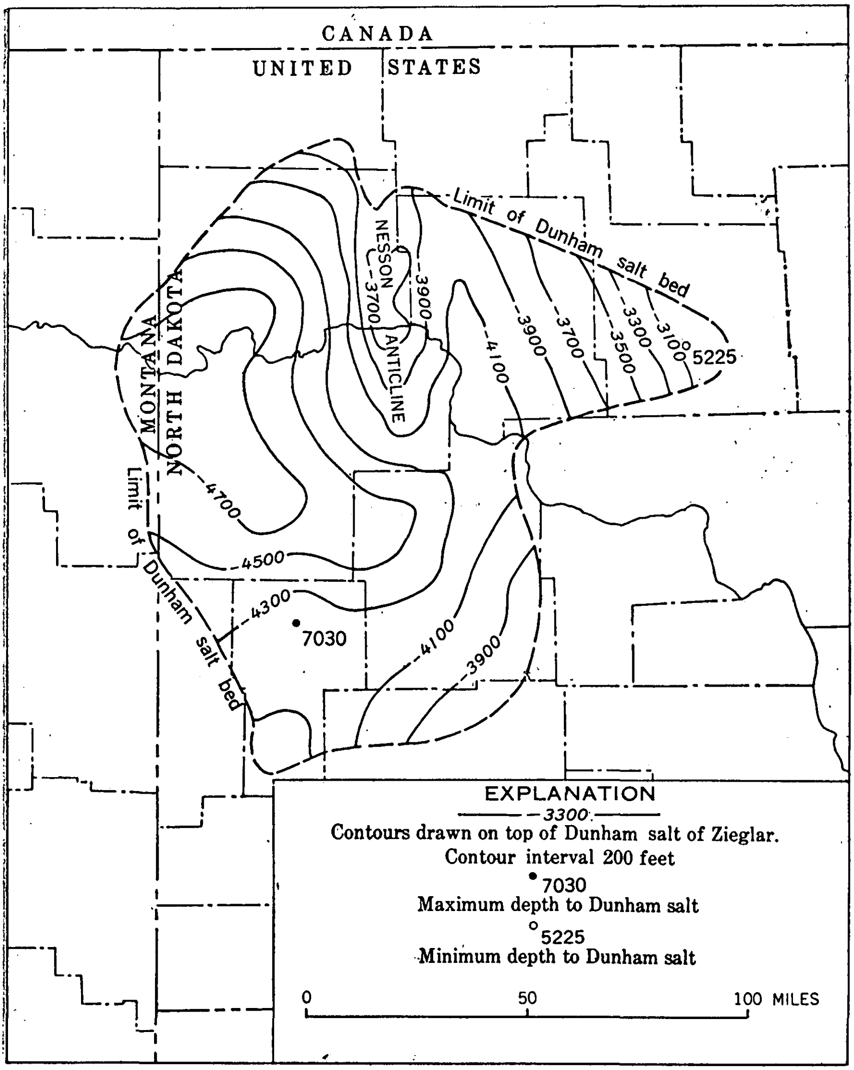

FIGURE 27.—Structure contour map showing depth below sea level to top of Dunham salt of Zieglar in Williston basin (after Anderson and Hansen, 1957).

formation, perhaps due in part to plastic deformation of the evaporites, have made it difficult to determine its thickness with accuracy. The salt is 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 comprises the top unit southeast of Salina, but there the unit either contains no salt or the salt 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° SE. (Spieker, 1949).

Salt has been mined in open pits at several 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) reports 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) suspected 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 concluded 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 (from Gilliland, 1951) is as follows:

	Percent
Salt (NaCl)	95. 60
Silica	2. 16
Sulfates	1. 10
Calcium	. 51
Iron and alumina	. 04
Magnesium	. 04
Iodine	. 03
Total	**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.

VIRGIN RIVER AREA, NEVADA AND NORTHWESTERN ARIZONA

Several outcrops of rock salt along the Virgin River in southeastern Nevada (pl. 1) were reported by Longwell (1928, p. 93; 1949, p. 936) and by the U.S. Bureau of Reclamation (1950, p. 217–225). The salt deposits, now partly covered by the Overton arm of Lake Mead, may belong to the lower part of the Muddy Creek formation of Pliocene(?) age. However, the salt has domed and pierced the Muddy Creek strata in some places and may be older than that formation.

Ransome (*in* U.S. Bur. Reclamation, 1950, p. 218) who examined the salt deposits prior to their inundation by Lake Mead, estimated that about 22 acres of salt were exposed at the surface. One of the areas of salt exposure examined by Longwell (1928, p. 93) is dome shaped and was estimated to be more than 1,600 feet long and 1,000 feet wide; the salt had an exposed thickness of about 100 feet, but its base was not seen. Other outcrops of salt along the Virgin River indicate that the salt beds are lenticular and range in thickness from a fraction of an inch to about 50 feet. Both Ransome and Longwell suggested that the areal extent and total thickness of salt may be greater in the subsurface than is indicated by surface outcrops.

Longwell (1928, p. 95–96) suggested that the salt was deposited in an intermontane basin, similar to a playa (see Playa deposits, p. 67), in which water entering from the highlands formed a lake during the wet season; during times of extreme aridity the lake waters filled only the deeper depressions where continous evaporation caused thin to thick lens-shaped bodies of rock salt to accumulate.

Drilling south of the Colorado River in northwestern Arizona penetrated salt at Red Lake and in Detrital Wash (pl. 1). The salt apparently is in the Muddy Creek formation. At Red Lake the salt was reported to be about 1,000 feet thick. In the Detrital Wash area, several drill holes put down by the Goldfield Consolidated Mines Co. found salt at a depth of 420 to 600 feet. The salt is 500 to 700 feet thick, has few impurities, and is largely recrystallized. The deposit is known from drilling to extend over several square miles.

SOUTHWESTERN WYOMING AND ADJOINING AREA

Salt-bearing strata of early Late Jurassic age are exposed at the surface in southeastern Idaho and have been penetrated by wells drilled in northeastern Utah and southwestern Wyoming (pl. 1). The salt is in a sequence of interbedded red shale, anhydrite, and limestone in the lower part of the Preuss sandstone.

Many years ago rock salt was mined from surface pits on Crow Creek (Breger, 1910) near the east border of Idaho about 40 miles north of the southeast corner of the State. One of the pits is reported to have penetrated 20 feet of rock salt without reaching the bottom. The Wallace-Wyoming Oil Co. well, 10 miles to the north, is reported by Mansfield (1927, p. 340) to have penetrated about 456 feet of salt-bearing strata that contain six beds of salt ranging in thickness from 6 to 29 feet; the aggregate thickness of the salt is about 96 feet. Peterson (1955, p. 76) reported that as much as 700 feet of salt and anhydrite was penetrated by the Hatch well in northeastern Utah about 15 mile north and 2 miles west of the southwest corner of Wyoming. The salt-bearing strata appear to thin eastward, as no salt was found in a well drilled in southwestern Wyoming about 55 miles east of the Hatch well (Peterson, 1955, p. 76).

Data on the salt beds are meager and the extent of the area underlain by this salt is not known. The salt was probably deposited in a southeast-trending basin or series of basins that may have extended about 100 miles from southeastern Idaho through southwestern Wyoming into northeastern Utah. The east-west dimension of the basin of salt deposition is uncertain, but may have been as much as 75 miles. However, the basin now lies in a region of intense folding and faulting. The salt beds, therefore, are probably not continuous and in places may be cut off by faults.

The depth to the salt at the above-mentioned localities is as follows: at or near the surface in the Crow Creek area in Idaho; about 125 feet below the surface in the Wallace-Wyoming Oil Co. well 10 miles to the north; and about 6,000 feet below the surface in the Hatch well in northeastern Utah.

NORTHWESTERN NEBRASKA AND ADJOINING PART OF WYOMING

In Sioux County, Nebr., in the northwest corner of the State, salt was penetrated in a well drilled on the Agate anticline by the Union Oil Co. (pl. 1). As reported by 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." Three other wells in northwestern Nebraska are reported by Reed (1956) to contain salt of Permian age at depths ranging from about 3,200 to 5,800 feet.

Privrasky and others (1958, p. 54) reported salt in an evaporite sequence in the Goose Egg formation in east-central Wyoming and suggested that it may correlate with the Permian salt in northwestern Nebraska. The original area of deposition of the salt thus may have extended from northwestern Nebraska into east-central Wyoming; however, data on the salt is too meager to outline precisely the area of deposition or to determine the thickness of the salt and depth at which the salt occurs.

PLAYA DEPOSITS

Playa deposits, some of which include salt, 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. During periods of heavy rainfall the playa becomes a temporary lake, and thinly stratified layers of silt and clay are deposited in the lakebed. As a temporary lake dries up, the dissolved salts in the water are deposited as evaporites, among which salt and several carbonates and sulfates of sodium are most abundant. With repeated lake-filling and drying out, thick deposits of interstratified silt, clay, and crystalline salts may accumulate in the lower parts of the playa.

Muessig and others (1957) reported that as much as 1,070 feet of playa deposits underlie Soda Lake in San Bernardino County, Calif. These deposits, however, contain only minor amounts of saline material. The waters entering the playa basin probably escapes by spilling and percolating rather than by drying up, which explains the absence of salt beds.

Beds of pure rock salt, 3 to 9 feet thick, are recorded at depths of less than 120 feet at the Bristol Dry Lake, San Bernardino County, Calif. A well drilled to a depth of 152 feet penetrated five beds of rock salt ranging in thickness from 1 to 9 feet and aggregating 28 feet of salt (Gale, 1951, p. 17). In a deep test hole, salt beds alternating with clay were found at a depth of nearly 1,000 feet (Ver Planck, 1958). Gale reported an appreciable amount of water, usually a saturated brine, in all the strata penetrated by test holes in the central part of the playa. Water in the salt beds presumably would render them unsuitable as a waste disposal or storage medium.

In Death Valley a well drilled to a depth of 1,000 feet penetrated a series of hard evaporite strata, each ranging from 1 to more than 20 feet in thickness, alternating with similar strata of clay or mud, all relatively salty (Bain, 1914). The evaporite beds from the surface to a depth of about 250 feet are essentailly sodium chloride, but the evaporite beds below that depth are mostly sodium sulfate. At the south end of Death Valley, in the northern foothills of the Avawatz Mountains, salt occurs in folded and faulted Tertiary lakebeds. Exploration in the Boston-Valley claims disclosed that solid salt covered by an average of 30 feet of overburden extends to depths of at least 275 to 300 feet (Ver Planck, 1958).

Many playas, both ancient and recent, are known throughout the more arid parts of the United States. The area of greatest concentration of playas and the location of some of the better known

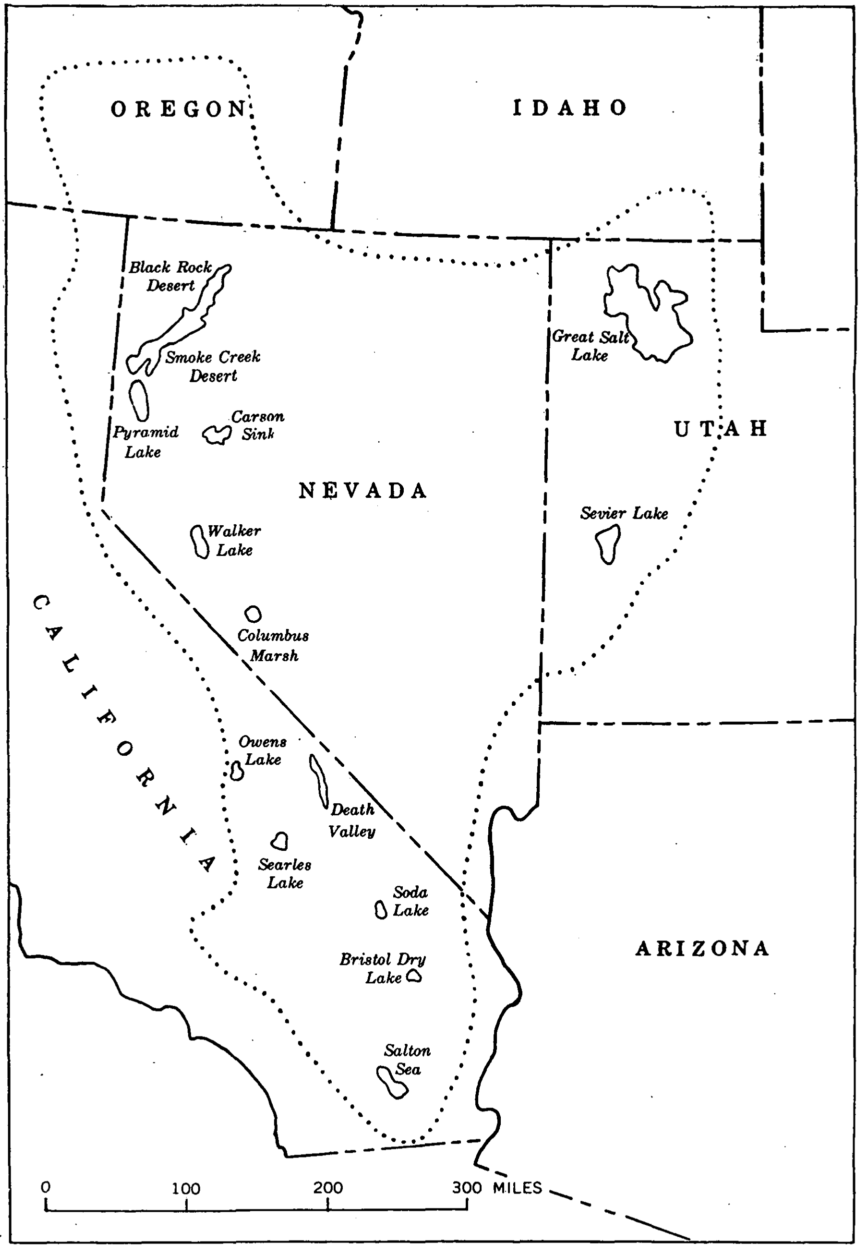

FIGURE 28.—Map of western States showing area of greatest concentration of playas and location of some of the better known ones.

ones is shown on figure 28. Some of the playas within the area outlined may not have salt deposits but may have large concentrations of carbonates or sulfates of sodium or potassium. On the other hand, judging from some thick deposits of salt associated with nonmarine strata in northwestern Arizona, some playa basins may have undiscovered deposits of salt several hundred feet thick, particularly in some of the deeper older beds.

FEATURES OF THE PRINCIPAL SALT DEPOSITS PERTAINING TO STORAGE OF RADIOACTIVE LIQUIDS

Impermeable enclosing beds are a prime requisite for the safe storage or retention of radioactive liquids. Pure salt, or salt with only a small percentage of disseminated impurities, meets this requirement, as it will be impervious to a salt-saturated solution.[8] However, beds of pure salt thick enough for the development of a storage cavity within a single bed are not common. The normal bedded rock-salt deposit is composed of a number of separate beds, which have slight to large variations in composition. A 40-foot vertical section, selected at random in a salt sequence, might consist of:

	Feet	Inches
Salt	9	0
Anhydrite	----	2
Salt	7	6
Shale	----	2
Salt	----	6
Shale	2	0
Salt	12	0
Shale and anhydrite	----	8
Salt	8	0
Total	40	0

The question then arises: how much of the indicated section is suitable for safe storage of waste? Do any of the thin beds of shale or anhydrite between the salt beds have sufficient permeability to allow salt-saturated radioactive solutions to pass through them? Laboratory and field tests may be necessary to determine the permeability of a given sequence of beds. In this regard the salt cavern in Beckham County, Okla. (Jordan, 1959), which was made in 1953 for the storage of liquified petroleum gas is of interest. The 16,000-barrel cavity, at a depth of 1,360 to 1,411 feet in the Blaine formation of Permian age, is filled with salt water, and as gas is pumped in, salt water is withdrawn into surface storage. Hence, when the cavity is nearly empty of gas the space is mostly occupied by salt water under pressure, and when the cavity is nearly full of gas only a little salt water remains in the bottom. As reported by

[8] Excluded from consideration here is the possibility of an exothermic solution taking salt into solution at the top of the liquid body, where the temperature would be the highest, and depositing salt at the base of the liquid body, where the temperature would be slightly lower.

Jordan (1959, p. 34) the 51-foot section of beds in which the storage cavern is formed consists of, from the top downward, 21 feet of salt, 3 feet of anhydrite, 5 feet of salt, 1 foot of shale, 1 foot of salt, 1 foot of shale, and 19 feet of salt. In this instance, apparently the interbedded sequence of salt, shale, and anhydrite is almost impermeable to both gas and salt water under the confining pressures used. The following generalized discussion summarizes some of the characteristics of the larger salt deposits that bear on the problem of containment of radioactive liquids.

NORTHEASTERN STATES

In the vicinity of the New York–Pennsylvania boundary, where the combined thickness of salt ranges from 200 to about 900 feet (pl. 2), a sequence as much as 150 feet thick might be composed almost entirely of salt. Locally an individual salt bed may be as much as 300 feet thick (Fettke, 1955). However, available data suggest that over much of the remainder of these States, the common maximum thickness of individual beds of salt is between 20 and 80 feet. In eastern Ohio, where the total thickness of salt is for the most part 100 to 300 feet, the maximum thickness of an individual bed of salt is probably about 30 feet. The data suggest that in Michigan the area of greater combined thickness of salt is also the area in which the thicker individual beds of salt are likely to be. The minimum depth to salt in several parts of the Northeastern States is from 500 to 1,000 feet, but in most places the beds are likely to be thin at these shallow depths.

GULF COAST SALT DOMES

The salt domes of the Gulf Coast Embayment may be the type of salt deposit most favorable for safe containment of liquid radioactive waste because of the great thickness of the salt mass. The tops of some of the salt domes are within a few feet of the surface, many are between 500 and 1,000 feet below the surface, and in all of them the salt continues downward for thousands of feet. The salt is relatively pure; the few impurities that are present do not occur as beds or pockets of foreign material but are more or less mixed through the salt. In general, oil and gas deposits are associated with the coastal salt domes but not with the interior salt domes.

PERMIAN BASIN

The thickest salt-bearing sequence in the Permian basin is in southeastern New Mexico, where the maximum aggregate thickness of the salt is about 2,800 feet. However, beds of strictly pure salt are rare—nearly all contain from 1 to 10 percent polyhalite, anhydrite, or silt. C. L. Jones (written communication, 1959) has described the salt-bearing section of the Salado formation as consisting of the following average percentages of thin-layered and interstratified components: rock salt 38.6, argillaceous rock salt 45.0, sulfate rocks 12.5, and clastic rocks 3.9. The thickest bed of relatively pure salt for which data are available is in the Salado formation. It is about 65 feet thick and the top of the bed is about 1,335 feet below the surface. Other beds of salt range from 4 to 50 feet in thickness, but most of them are about 20 feet thick. In the southwestern Kansas-Oklahoma Panhandle part of the Permian basin the salt-bearing strata have an aggregate thickness of about 400 feet. The thickest bed of relatively pure salt, about 30 feet thick, is near the base of the salt-bearing sequence. Its top is about 600 feet below the surface. Other beds of salt, ranging in thickness from less than 1 to 11 feet, are at shallower depths, but they are less pure. It should be kept in mind, however, that generalizations such as these are not meaningful if applied to a specific locality, for lateral variations can be of considerable magnitude.

PARADOX BASIN

The salt anticlines of the Paradox basin are similar to the salt domes of the Gulf Coast in that they contain a great thickness of salt which has been extruded by plastic flow from an original bedded position. Unlike the Gulf Coast salt, the salt in the Paradox basin salt anticlines contains many shale and anhydrite beds. Consequently, some care would be needed in locating a thick salt bed that is relatively free of these beds.

WILLISTON BASIN

In the Williston basin the minimum depth to the top of the salt-bearing sequence is much greater than in any of the other major deposits of the United States. The shallowest salt is in McHenry County, N. Dak., at a depth of about 3,600 feet, but the bed is only about 20 feet thick. The Pine salt (Zieglar, 1956) of Triassic age has thicker salt beds, but it is 4,300 to 7,000 feet below the surface. Perhaps the thickest individual beds of salt in the Williston basin are in the Prairie formation of Devonian age, but they also are at the greatest depth—from 6,000 to 12,000 feet.

SALT MINES

In connection with the possibility that consideration may be given to the disposal of radioactive waste material in the mined-out space in existing mines in salt, the following brief summary on operating mines is presented. Making use of mined-out space would save the cost of excavating access and storage space in the salt, but presumably it would mean cessation of salt production at the mine.

The production of rock salt by States during the year 1953 and an estimate of the space vacated by this production are indicated in the following table.

Estimated production by States and space vacated by underground mining of rock salt[1] *for the year 1953 (from Heroy, 1957)*

	Tons produced [1]	Equivalent space (acre-feet [2])	Average thickness of salt (feet)	Acres mined out [3]
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	[4] 5, 000	2	--------	--------
Total	4, 478, 655	1, 547		145

[1] Does not include salt mining associated with potash production.
[2] Approximately 2,900 tons per acre-foot.
[3] Assuming 50 or 60 percent left as pillars, according to locality.
[4] Mostly produced by surface mining.

The preceding table shows that nearly 1,550 acre-feet of mined space in an area equivalent to 145 acres is 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 (1957) has calculated that during a 20-year period (1934–1953), assuming that the average thickness of salt mined was 10 feet, the area mined would be about 2,100 acres, or 21,000 acre-feet of salt. These figures give the 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 on plate 1. Additional data on them are given below, by States.

NEW YORK

Two rock-salt mines are active in New York (Kreidler, 1957). The Cayuga Rock Salt Co., Inc. has a mine between Portland Point and Myers, about 15 miles north of Ithaca on the east side of Cayuga Lake. The Retsof mine, 5 miles northwest of Geneseo, now operated by the International Salt Co., is the largest salt mine in the western hemisphere (Root, 1953). At the Fuller No. 1 shaft a thickness of 9 to 10 feet of salt is mined from a 1,063-foot shaft (La Vigne, 1936). An estimated 1,200,000 short tons of rock salt was mined in the State in 1953 (Heroy, 1957).

OHIO

The Morton Salt Co. has a mine at Fairport, near Painesville. The International Salt Co. has started a salt mine beneath Lake Erie; the salt is to be mined from a 2,000-foot shaft on Whiskey Island in Cleveland (Eng. and Mining Jour., 1957).

MICHIGAN

In 1955, the most recent year for which published figures are available (Gustavson and Klyce, 1957), Michigan produced more than 5 million short tons of salt, which was about 25 percent of the entire United States production. Most of this salt, however, was from artificial brines obtained by the solution of rock salt. All the mined rock salt came from a 20-foot bed of salt at a depth of 1,020 feet in the International Salt Co. mine in Wayne County near Detroit. Drilling at the bottom of the shaft revealed 30 feet of interstratified salt and dolomite at a depth of 1,110 feet (Sherzer, 1917, p. 19).

KANSAS

Three rock salt mines were operating in Kansas in 1956 (F. C. Foley, "personal communication," *in* Heroy, 1957, p. 125). The Carey Salt Co. mines from a 10-foot bed of salt reached by a 645-foot shaft near Hutchinson. The upper half of the bed has several dark stylolitelike bands. The Independent Salt Co. at Kanopolis is mining a 10-foot bed which is reached by a shaft 865 feet deep. Immediately overlying the bed being mined is a 22-foot bed of salt, and higher in the shaft, at a depth of 648 feet, is an 18-foot bed. The American Salt Co. mine near Lyons produces from an 8½-foot bed of salt at a depth of 993 feet.

Several other salt mines in Kansas are either closed or abandoned (Jewett, 1956). The largest of these are the connected Crystal and Royal mines near Kanopolis. These mines, owned by the Morton Salt Co., were closed in 1948. The shaft at the Crystal mine is 810 feet deep, and the average ceiling height is 9 feet. The Carey Salt Co. mine at Lyons was closed in 1948. Its depth is 1,024 feet and the average ceiling height is 10 feet. Mines near Little River and Kingman are reported to be flooded (Jewett, 1956).

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

LOUISIANA

In recent years four shaft mines have been producing salt in Louisiana (Weigel, 1935; Heroy, 1957), 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 Diamond Crystal Co. mine is on the Jefferson Island dome 9 miles west of New Iberia. The shaft is 900 feet deep, but enters the salt 100 feet below the surface, and the actual working level is 800 feet deep.

The International Salt Co. mine on Avery Island is about 10 miles southwest of New Iberia. The irregular top of the salt is in places 16 to 20 feet below the surface; the mine has a shaft 518 feet deep which was completed in 1899 (Howe and Moresi, 1931). Mining operations at Avery Island before 1900 were 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 Morton Salt Co. Mining operations there date back to 1898. The top of the salt is within 96 feet of the surface (Howe and Moresi, 1931). The total depth of the shaft is 805 feet.

The Carey Salt Co. mine near Winnfield, Winn Parish, is in 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 Corp. mine near Hockley, Harris County, produces from a shaft 1,525 feet deep. The top of the limestone caprock is at a depth of 76 feet, the top of the gypsum in the caprock is at 107 feet, and the top of the anhydrite is at a depth of 125 feet. The anhydrite continues downward to the top of the salt at a depth of 1,010 feet (Teas, 1931).

The Morton Salt Co. Kleer mine at Grand Saline, Van Zandt County, is in 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, the latest year for which published information is readily available, rock salt was produced at two open-pit mines in Utah (Kelley and others, 1957): These are the Royal Crystal Salt Co. at Axtell, in Sanpete County; and the Poulson Bros. Salt Co. 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 total production of rock salt in 1953 from these mines was 6,000 tons (Luff, 1956).

The salt produced in this area is shipped as mined, mostly for livestock consumption in 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 extruded at a rate of as much as 0.9 millimeter per day. Holes were drilled in the salt at different depths in the mine, and the holes were filled with lead bars that 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-meter depth (984 feet), the bars jammed after 2 years; and above 250-meter depth (820 feet) the holes stayed open.

Balk (1949, p. 1824), in discussing mines in Gulf Coast salt domes, reports that timbers more than 6 inches thick were bent and broken by movement of the salt, and that drill holes were appreciably reduced in diameter.

Dellwig (1958) conducted measurements on the flowage of salt in the pillars of the American Salt Co. mine at Lyons, Kans. The salt layer being mined is 9 feet thick and 1,000 feet below the surface. During an interval of about a year the salt flowed outward from the center of the pillar, so that the distance to surrounding pillars was decreased by about three-tenths of a foot. As this flowage took place, the lower part of the salt bed also moved, forcing the floor of the mine to buckle up in a broad arch. It should be noted that the flowage of salt in mine pillars is related not only to the weight of the overlying rock or the depth below the surface, but to the ratio of the area of the mined-out space to the area of the supporting pillars.

E. C. Robertson (written communication, 1958) says that "As an approximation, large plastic flow probably will begin to predominate over fracturing in workings in salt at 3,000 to 4,000 feet depth."

SALT RESERVES AND PRODUCTION

In considering bedded salt as a possible storage medium for radioactive waste, questions may raise as to the value of salt deposits and what effect their use may have on reserves of salt. It has been stated that salt is such an abundant commodity that the price paid by the consumer is largely the sum of extracting, processing, packaging, marketing, and transportation costs (Landes and others, 1945, p. 193).

Our salt reserves are very large indeed. No attempt was made here to prepare an estimate, but the following statement (Barton, 1928, p. 48), although now out of date, gives 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 [about 1926] amounts to less than 0.01 cubic kilometer per year, the very easily minable 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, at the present rate of consumption. Of course, this does not take into account the very large reserves of salt elsewhere in the United States, such as the 2.7×10^{13} tons of salt estimated to underlie the Northeastern States, the estimated 1,700 cubic miles of salt underlying North Dakota, or the salt recoverable from sea water. Jewett and Schoewe (1942, p. 76) estimated that 5×10^{12} tons of salt lie beneath the surface of Kansas alone, which at the rate of consumption at the time of the estimate would supply the United States for a period of a half million years. The following table shows the tonnage of salt produced in the United States in 1956.

United States salt production in 1956

[From MacMillan and Mattila, 1957]

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

Of the above total, 77 percent was produced as brine or from evaporation of salt water, and 5,622,887 short tons, or 23 percent, was produced as rock salt. The United States annual production of salt is slightly less than 40 percent of the world production.

DEVELOPMENT OF CAVITIES FOR UNDERGROUND STORAGE

The underground storage of liquified petroleum gas, which began in a small way in depleted oil and gas fields, has greatly increased 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 are in shale, a few are in granite, and many are in salt. These developments 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 (1958) and Petroleum Week (1958), and the report on "Underground Storage of Liquid Petroleum Hydrocarbons in the United States" published by the Interstate Oil Compact Commission, Oklahoma City, Okla.

As of 1958, the storage capacity created in underground cavities was about 42 million barrels, of which 36 million barrels was in salt deposits. The developed storage capacity in depleted oil and gas fields and similar geologic structures now stands at about 3½ million barrels, and about 2½ million barrels of storage space 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, because it can be formed by dissolving out the salt. Six barrels of water will dissolve enough salt to form cavern space of one-barrel capacity. The cost is about $2.00 per barrel for dissolved cavity space in salt; $4.00 to $7.00 per barrel for mined space in shale or chalk; and $20 or more for above-ground storage in steel tanks.

One of the early underground storage cavities in salt was the publicized test conducted in 1950 in the Keystone oil field, Winkler County, Tex., where a well was drilled about 1,600 feet into Permian salt beds, and the salt was dissolved out to form a cavity. The development of other storage cavities soon followed, such as the one at Lowell, Mich., in 1951 by Cities Service Oil Co., which started with a conventional drill hole to the top of the salt bed at a depth of 3,798 feet (Oil and Gas Journal, 1951). 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 and stored. The recovery of liquified propane, the principal stored product, is reported to be generally good. Its recovery from salt cavities is usually more than 90 percent and in some projects is as high as 99 percent. Recovery as low as 57 percent has been experienced in a salt dome in Louisiana, but in another cavity at the same 2,000-foot depth on the same salt dome the recovery was 89 percent (Hough, 1956).

Most of the liquified petroleum-gas storage is in Texas, where more than 29 million barrels of underground storage has been created. Of this storage capacity, 90 percent is in about 150 caverns in salt domes or salt beds. Between 2 and 3 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. The salt cavern in southwestern Oklahoma has been mentioned on page 69.

Two mined caverns in chalk near Demopolis, Ala., have proved very successful. The chalk is impervious and requires no sealant. Caverns mined in shale 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 has been mined in granite, 300 feet below the surface. Water seepage has been a problem in some created cavern space, but it has been successfully sealed off by using a new grouting technique that uses a water-sealing gel.

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