Salt Deposits of the Williston Basin -- United States Portion

by

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ABSTRACT

The Williston Basin covers about 150,000 square miles in North and South Dakota, Montana, Saskatchewan and Manitoba. Salt was not known to exist on the United States' side until 1951, but now, largely as a result of oil drilling activity, at least eleven salt beds in four aged formations have been uncovered. These salt beds are found, for the most part, from 6000 to 9000 feet deep; about half the salt beds are up to 200 feet or more thick.

Two Jurassic salts are found in a red bed sequence. Most of the geologic evidence points to a continental origin. The upper salt was deposited in a regressive phase of an overall advancing Jurassic sea.

Permian salt has a similar depositional environment to the upper Jurassic salt bed.

Mississippian age formations contain seven salt beds, the top six of which are often found in the same column; the salt beds deposited under cyclic marine conditions. One outlying salt bed was formed as an arm of a sea and may have been associated with salt solution and collapse of an underlying salt bed.

The one thick Devonian salt bed contains potash which has possibilities for development because high natural temperatures should allow selective dissolving of the potash in a brine mining operation.

Tests have shown the top Mississippian salt bed to contain over 96% sodium chloride. This salt is utilized in a brine mining and LPG storage operation near Williston, North Dakota in what is the deepest exploitation of salt in this country and possibly in the world.

INTRODUCTION

Salt and potash had been found in the Williston Basin several hundred miles north of the border in Saskatchewan as early as 1943, but there was no positive evidence of salt on the United States' side until oil test holes in eastern Montana and western North Dakota encountered it in 1951. Successful oil discoveries that year touched off a drilling boom that has seen several thousand holes drilled in these two states and in northwestern South Dakota; an area that before 1951 had hardly felt the drill bit. The oil people found nearly 200 oil fields, production in excess of 100,000 barrels a day, and in the process uncovered eleven salt beds in four separate age formations.

There is still much to be learned about the salts of the Williston Basin. Only in a small number of holes was salt cored, indeed some of the salts have never been cored from top to bottom; there are hundreds of townships in the three state area of western North Dakota, eastern Montana and northwestern South Dakota that have never had a test hole to any of the salts. In the area where salt is found only a small percentage of the holes have penetrated all the salts, and in many cases log interpretation is difficult in determining the thickness if not the existence of the salt.

In spite of the difficulties, much has been learned about the salt since its discovery eleven years ago, and from the well data and few cores and outcrops we can quite reasonably trace the salts and reconstruct their geologic environment.

ACKNOWLEDGEMENTS

This paper would not have been possible without the cooperation and assistance of the North Dakota Geological Survey under the direction of Dr. Wilson Laird which has freely given their time and permitted reprints of their publications; also the oil industry, particularly Amerada Petroleum Corporation which has made core data and other information available; the Dakota Salt & Chemical Company which has given generous approval to release of core and log data; to Mr. E.C. Bredeson, Chemical Engineer for the Great Northern Railway Company, who prepared most of the discussion and both of the figures on potash; and to the Great Northern Railway Company which has allowed me the time to prepare and present this paper.

Many others too numerous to mention have helped piece together this story, some by direct contact and others through their papers that have been used for references.

HISTORY OF STUDY AND DEVELOPMENTS

Mississippian salt was cored as early as 1953, but it was 1954 before any significant work was done on the salts. At that time Shell Oil Company cored a Jurassic salt in eastern Montana, and even more important, Amerada Petroleum Corporation took several cores of Mississippian and Permian salt in western North Dakota. These salts were cored for the purpose of finding out the relationships of the salt to casing-collapse problems, but to those of us interested in commercial utilization of the salt, the North Dakota cores proved invaluable. Detailed descriptions were made of the salt and samples sent to Hooker Electrochemical Company for testing. These tests established the purity of the salt.

In May of 1955 Batelle Memorial Institute made a report entitled "Problems Connected with the Collapse of Oilwell Casing as a Result of Stresses Produced in Salt Formations" for Amerada Petroleum Corporation using cores of salt taken the previous year.

In 1957 the Great Northern Railway Company published a report on "Salt in the Williston Basin" with thickness maps, cross section, and with various other information on the salts. That same year the North Dakota Geological Survey published Report of Investigations #28 "Halite Deposits in North Dakota" complete with nine isopach maps of the various salts and other important geological information.

1957 was also the year that Shell Oil Company completed a salt well in eastern Montana for the purpose of providing salt water for their drilling program. Another salt source well was subsequently drilled and one of the holes is now used to store LPG.

In the latter part of 1957 Mr. N.N. Kohanowski, Associate Professor of Geology at the University of North Dakota, published an article in the October 1957 issue of Mines Magazine entitled "Salt Measures in the Williston Basin, North Dakota." This report was made for the North Dakota Research Foundation and has some interesting conclusions on paragenesis of salt.

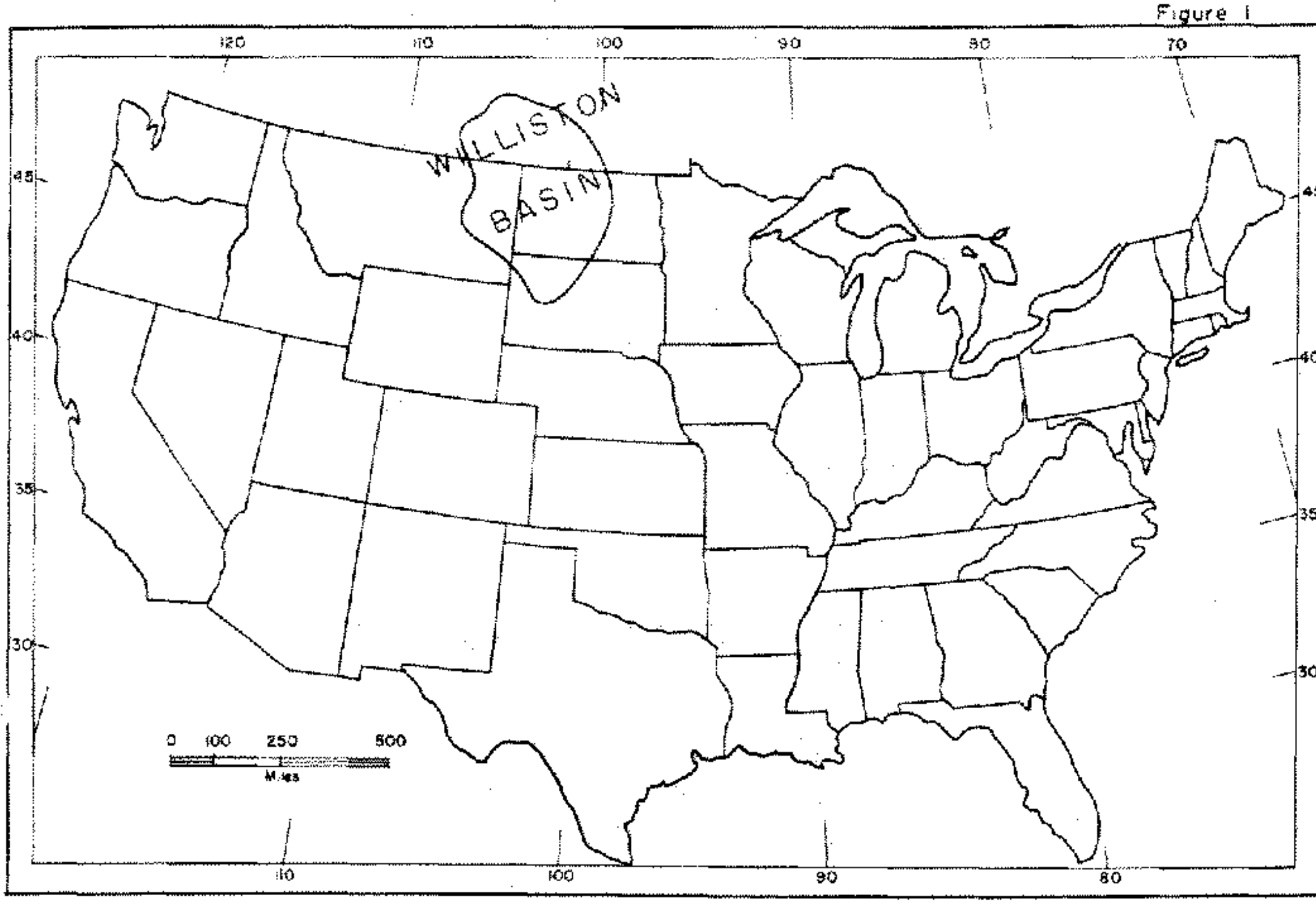
The Great Northern Railway, in February of 1959, published a revised edition of its salt report with additional emphasis on potash bearing salts of Devonian age. Later in 1959 Dakota Salt & Chemical Company was formed to build a salt plant and store LPG in resulting cavities. They cored the top Mississippian salt twice and began construction of a 300 ton a day salt plant. This plant was completed the next year and a third hole drilled in 1961.

Last year the Great Northern published a third report on salt — "Potash Occurrences in the Williston Basin." This report had much additional information on the Devonian salt and its potash beds.

GEOLOGICAL SETTING

The Williston Basin is an enormous geologic feature covering about 150,000 square miles in North and South Dakota, Montana, Saskatchewan and Manitoba. Figure 1 shows the geographic

Figure 1



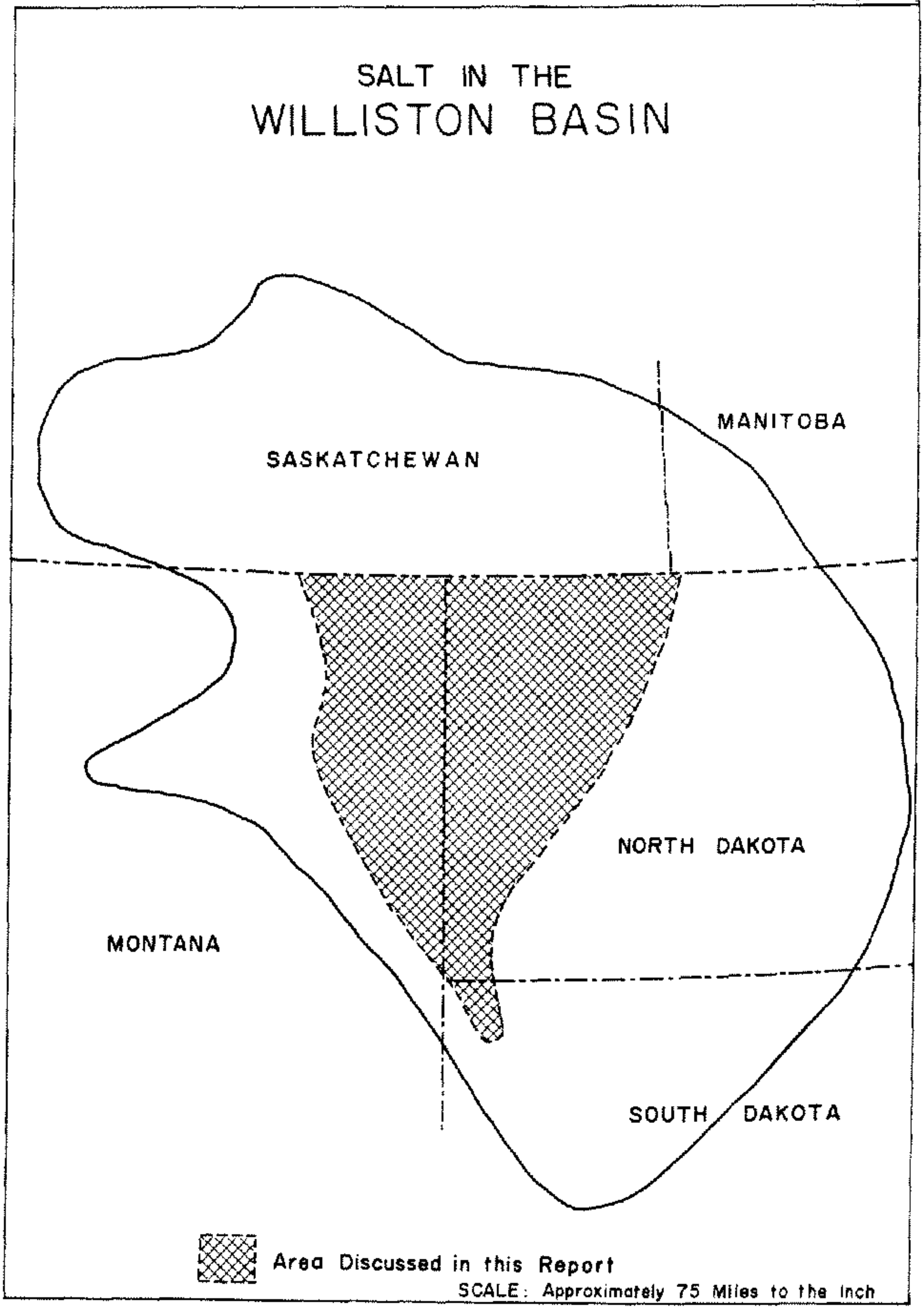
spread of the hugh Basin. Figure 2 is a larger scale map of the Williston Basin and the area discussed in this report. The limits of the Basin shown on Figures 1 and 2 are the sea level contour of the Cretaceous Dakota Formation. The rocks vary in thickness up to more than 15,000 feet and constitute one of the largest single volumes of sedimentary rocks in the United States.

The Williston Basin by the tectonic classification of Krumbein and Sloss (1955) is an intracratonic basin in which the rate of subsidence decreases from the center outward resulting in a circular or elliptical area. It is characterized by stable environment, shallow water deposition, and steady subsidence.

The Williston Basin is bounded by the Sioux Uplift in southeastern South Dakota; the Pre-Cambrian shield on the north, northeast and east; and it merges with the Moose Jaw Syncline to the northwest. The Basin is separated from the Rocky Mountains by the Black Hills, Porcupine Dome, Bowdoin Dome and Sweetgrass Arch in central Montana (Burg, 1952). The Basin has been through its geologic history a negative area that has been accumulating sediments. Seas have invaded it from the Cordillerian Geosyncline across central Montana (Sloss, 1950).

Figure 3 is an idealized east-west cross section through North Dakota and eastern Montana showing the general stratigraphy of the Williston Basin, and the relative position of the salt beds. Rocks of almost every age from Pre-Cambrian to Present are represented. In the center of the Basin the top 7000 feet from the surface to the lower Jurassic are mostly shales and sand. The

FIGURE 2


SALT IN THE
WILLISTON BASIN
MANITOBA
SASKATCHEWAN
NORTH DAKOTA
MONTANA
SOUTH DAKOTA
Area Discussed in this Report
SCALE: Approximately 75 Miles to the Inch

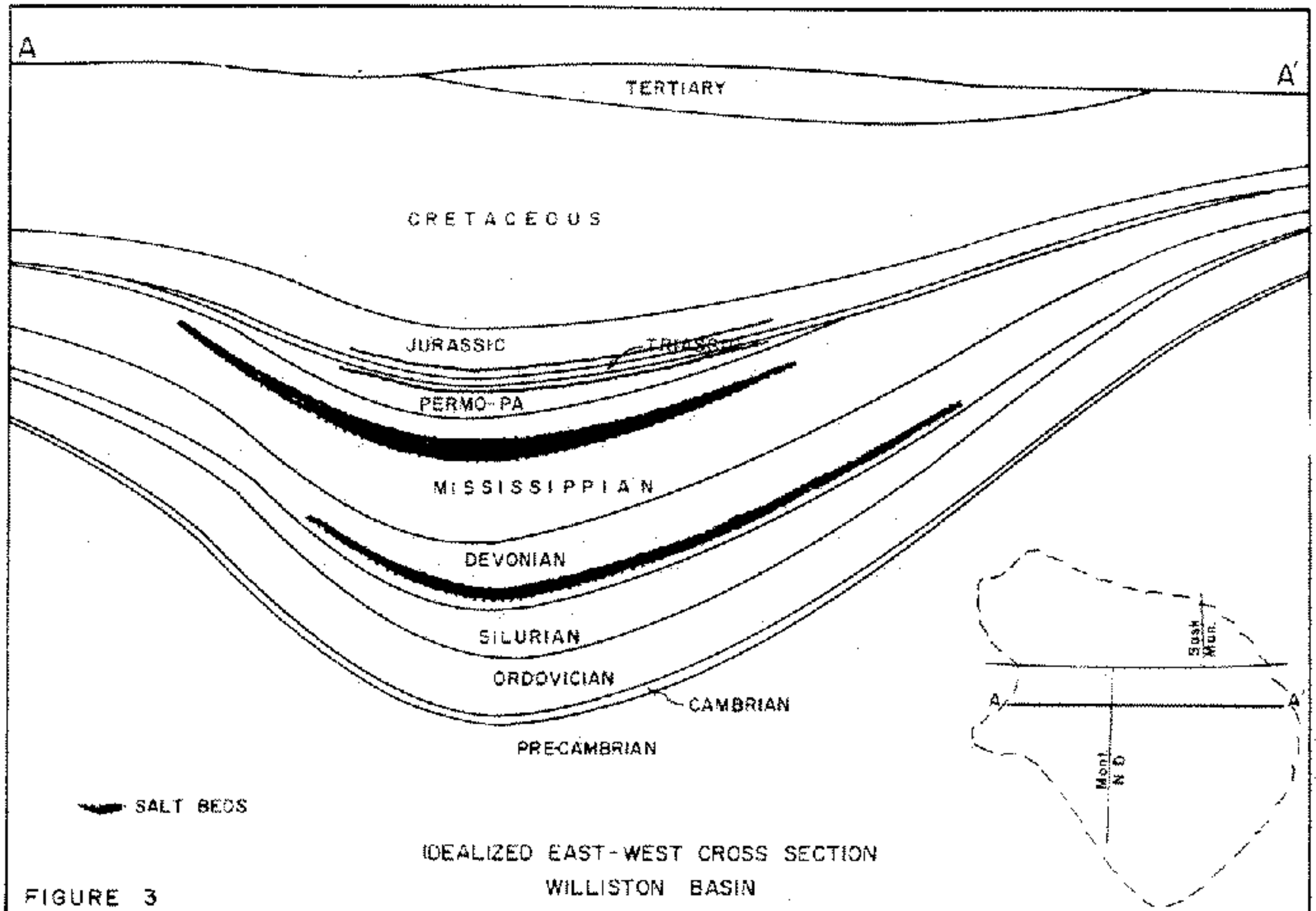


FIGURE 3

next 2000 feet from the lower Jurassic to the lower Mississippian consists of carbonates, evaporites, and clastics. From 9000 to 15,000 feet -- lower Mississippian to basement -- the rocks are basicly carbonates and a few significant evaporites.

Salt is found in four ages: Jurassic, Permian, Mississippian, and Devonian. The Jurassic has two widespread salts at depths of 5000 to 7000 feet in various parts of the Basin; the Permian one less widespread salt at about the same depth range; the Mississippian seven salts, one of small aerial extent at 4000 feet and the rest widespread and at depths of 6000 to 9000 feet; and the Devonian has one far-reaching salt that ranges in depth from 6000 feet to 12,000 feet.

From the above it is obvious that the salts have varying geographic spread, thus the variance in depths. However, there is an area in west central North Dakota near the center of the Williston Basin where all but the outlying seventh Mississippian salt are found. The Carter Lockwood well in Dunn County, North Dakota encountered two Jurassic salts, Permian salt, and the six top Mississippian salts. It did not go deep enough to penetrate Devonian salt, but from wells in that area it is apparent that this salt is present at that location.

INTERPRETATION

On the United States' side of the Williston Basin there has never been, and probably never will be, a shaft sunk to any of the salt horizons. Depths to the salt make underground mining costs prohibitive, particularly in view of a water-bearing zone 1300 feet or more above the salt.

There is a certain amount of core data on most of the salts, but if you had to depend on them for isopaching the salts you would be in trouble. The top Mississippian salt, for example, has been cored more than any other salt in the Williston Basin — U.S. side — but there's been fewer than ten wells that have cored this salt which extends over some 10,000 square miles. Correlating on the basis of one core per thousand square miles would leave a lot to the imagination.

Fortunately, correlations can be made over great distances in the Williston Basin using samples, mechanical logs and even drilling time logs. Salt is often recovered as samples in the drilling process, particularly when a salt-base mud is used. Drilling time logs can virtually pinpoint the salt in some areas and particularly in the Mississippian where salt drills faster than the shales and anhydrite normally associated with it.

In the early days of drilling in the Williston Basin it was a simple matter to correlate salts by Schlumberger Well Surveying Company micro type logs or caliper logs. One of the micro types was often run on wildcat wells. These logs recorded by means of pads that touch the sides of the hole. These early wells were drilled without salt-base muds and the result was washouts in the salt sections. These pad type logs would not touch the sides in clean salt sections and would register zero readings. There are still areas where salts are thin and drilling mud is not saturated with salt; in those wells the micro type logs and caliper logs still show the salt sections.

In the thicker salt sections most of the drilling is done with salt-base muds to overcome hole trouble, casing collapse and related problems; in these wells the before-mentioned types of logs are useless for determining salt. Interpretation of salt can still be made with some degree of accuracy from the neutron log or a resistivity log like the Laterolog; both of these logs show high readings in the salt. Either of these logs used in conjunction with gamma ray logs, which show salt as gamma lows, gives moderately good interpretations in some areas.

A relatively new log, the Sonic Log, has given workers a new tool to aid in interpretation of salt. This tool works on the principle that sound travels through various types of rock at various speeds. Thus anhydrite and dense carbonates show high velocities and unconsolidated sands and shales low. Salt is about in the middle at 15,000 feet per second velocity. Used with a resistivity log, the Sonic Log can be very diagnostic. Figure 9 described later in this paper shows some good correlations between core data and the Sonic Log.

JURASSIC SALTS

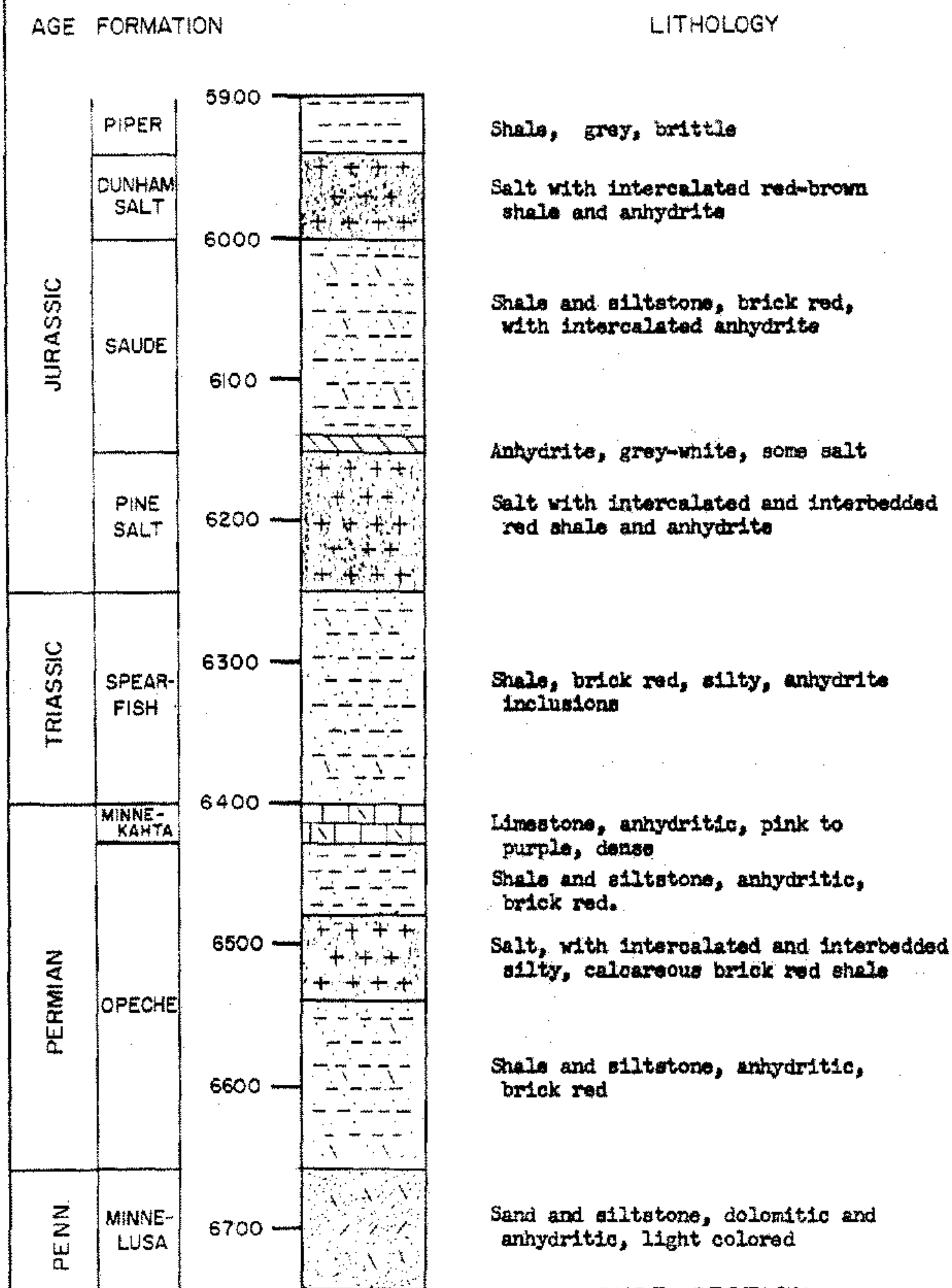
General Stratigraphy: A red bed sequence of Jura-Triassic age is found in western North Dakota, eastern Montana and northwestern South Dakota. The sequence consists of two units of brick red shale, siltstone and sandstone, sometimes anhydritic and gypsiferous, and two major salt beds that can be correlated in the sub-surface and traced for long distances. (Zieglar, 1955, 1956.) The overall red bed section is up to 700 feet thick (Middleton, 1959).

Two writers, H.F. Middleton of Amerada Petroleum Corporation and D.L. Zieglar of California Company, have made studies of this red bed series and much of this discussion on Jurassic salts is taken from their work, particularly that of Zieglar who has three papers on the red bed series. Zieglar separated the red beds into four units: a lower shale and siltstone -- the Spearfish Formation, a salt which will be called "Pine Salt" in this report, an upper siltstone and sandstone -- the Saude Formation, and an upper salt which is called "Dunham Salt" in this report. Zieglar believes that the top three units are Jurassic and the bottom one Triassic, but in the absence of "diagnostic fossils of use in age determination (Francis, 1956) there is still room for doubt. In this report the salts will be called Jurassic in age.

Pine Salt

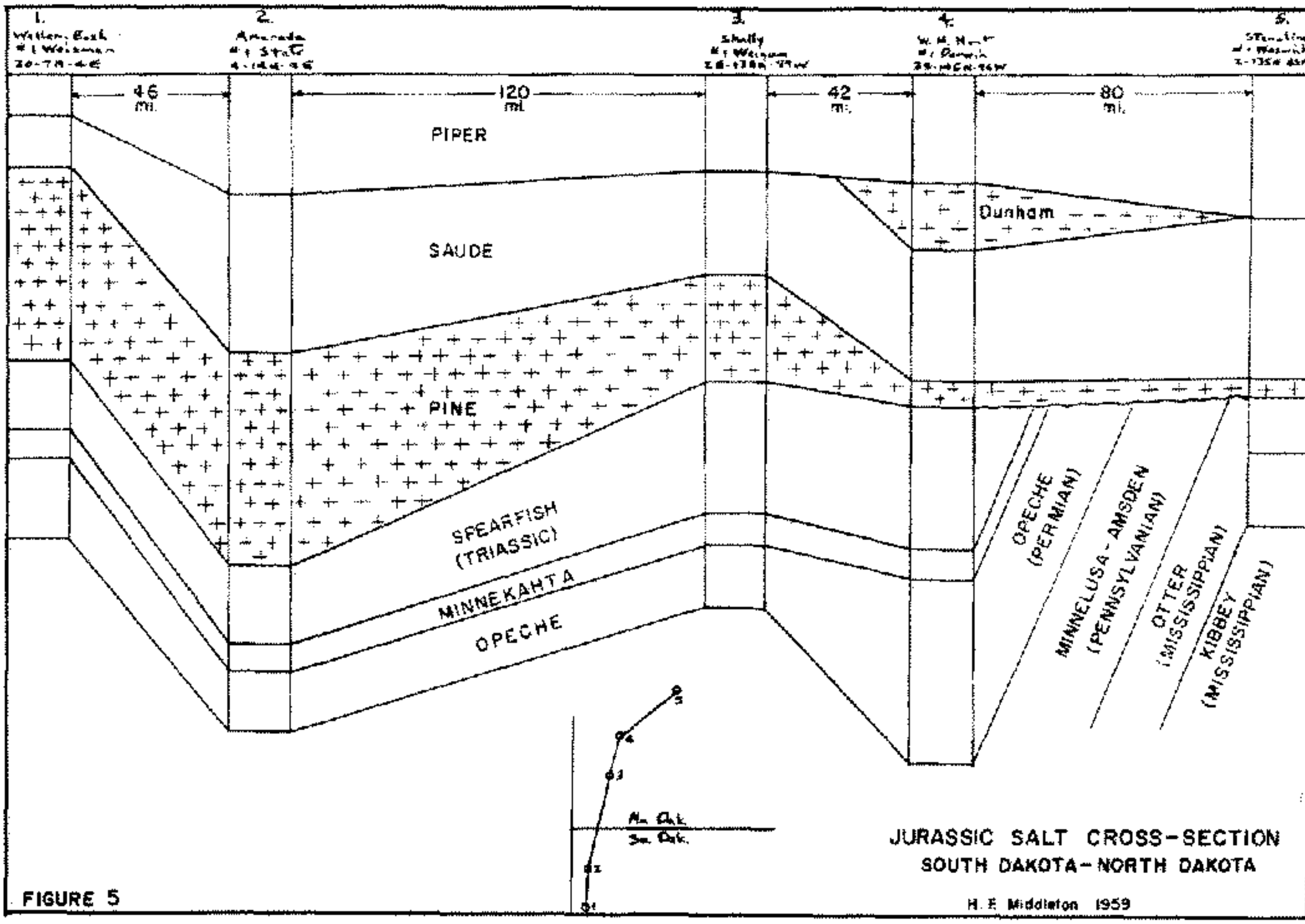
Stratigraphy: Figure 4 is a type section from the top Jurassic salt through the Permian and into the Pennsylvanian Minnelusa Formation, which shows the two Jurassic salts and the red beds in between. The lower salt or Pine Salt lies on the Triassic shale and siltstone unit in an unconformable relationship on the margins of the salt. It may be conformable basinward. This "salt progressively overlaps older truncated beds ranging in age from" Triassic through Mississippian (Middleton, 1959). Figure 5 is a cross section taken from Middleton's report from western South Dakota to north central North Dakota, a distance of 250 miles that shows the above relationship.

Figure 6 shows isopach maps of the two Jurassic salts in North Dakota. Geologists are almost entirely dependent on logs in mapping these salts, as the Dunham salt has not been cored and the Pine was cored but twice -- and those two in the same general area. What little information there is suggests that the salt is often interbedded with red beds. Furthermore, the thickness of the salt is known to make radical changes in short distances which might be the result of salt



TYPE SECTION
JURASSIC – PERMIAN SALTS

FIGURE 4



JURASSIC SALT CROSS-SECTION
SOUTH DAKOTA-NORTH DAKOTA

H. E. Middleton 1959

FIGURE 5

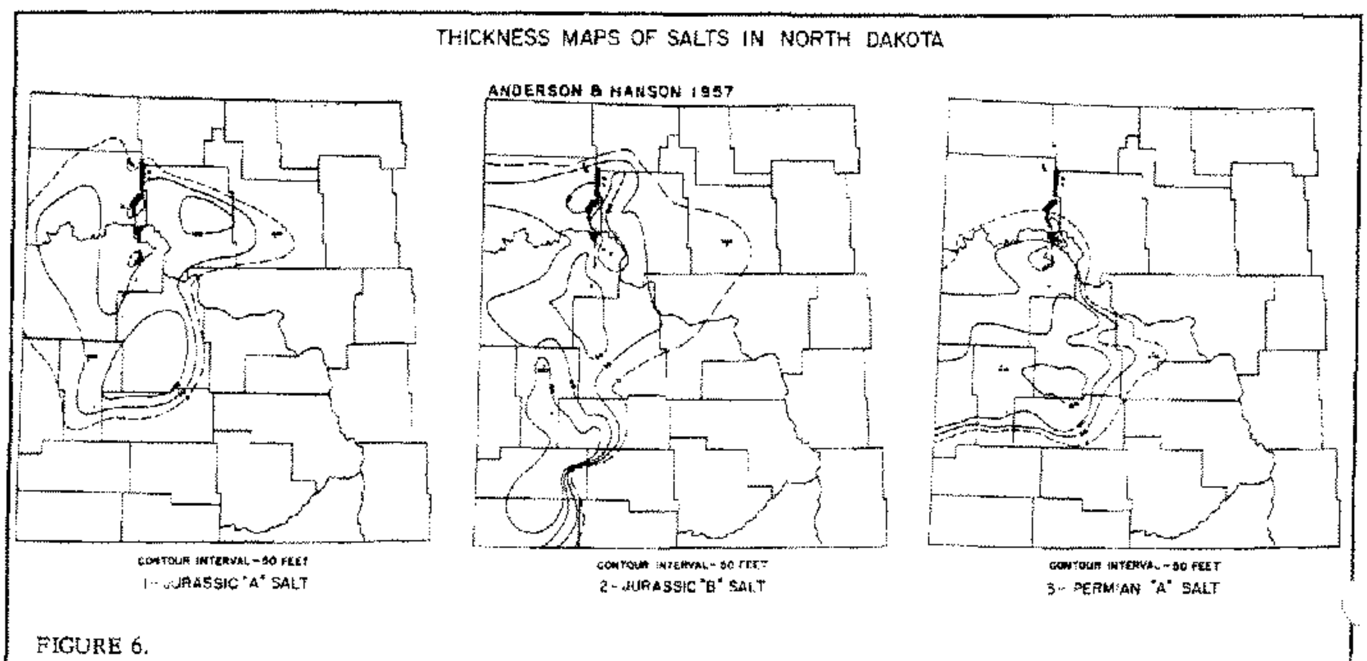


FIGURE 6.

solution and/or deposition over uneven topography. A typical well in eastern Montana has about 130 to 150 feet of Pine Salt at a depth of 5500 feet. In North Dakota the Pine Salt is typically 100 feet thick at about 6400 feet, but one well in southwestern North Dakota had nearly 200 feet at that depth. In western South Dakota our information is sketchy, but there appears to be a possibility of 150 feet of Pine Salt at a depth of 5600 feet in the northwestern part of the State, and further south there may be some salt as shallow as 4500 feet.

Shell Oil Company cut and recovered a 58 foot core in the Pine oil field in eastern Montana. This core is about two thirds salt and the balance is interbedded and intercalated red shale and anhydrite.

Environment: The overall environment of the Jura-Triassic red bed sequence was arid to semi-arid climate, general subsidence, and shallow water and shelf deposition. The red clastics were apparently derived from low lying Paleozoics surrounding the basin and were deposited in deltas, lagoons, and in near-shore highly oxygenated waters. Absence of organic material precluded iron reduction — thus the red coloration. Zieglar is of the opinion that the Pine Salt is continental in origin. He is satisfied that during the time of Pine Salt deposition there was no apparent seaway from the Cordillerian Geosyncline, and marine waters did not cover this area until after the salt was deposited. He feels that tilting and structural adjustments along zones of weakness would make satisfactory conditions for a closed drainage basin. Evaporite sediments of Permian through Devonian ages would have outcropped to the north, northwest and east of the Pine salt basin and waters flowing over these sediments would bring in dissolved salts. Further support for Zieglar's thinking is the absence of carbonates in or at the base of the salt. Absence of carbonates either as beds or cement is hard to explain in either a marine or non-marine origin for the Pine Salt. The drainage system at that time would be mainly in carbonates and yet the carbonates do not show in the salt basin. Zieglar explains this by reasoning that the streams became so high in salinity that waters were less able to dissolve carbonates and that deposition of carbonates was confined to areas removed from the salt basin; he supports this theory with evidence of a zone of secondary cementation on the flanks of the salt basin.

Drilling samples are poor through this red bed section and cores are few, thus making it difficult to make accurate determinations of the geologic environment. A logical theory would entail a combination marine and continental origin accepting the thinking that streams have made important contributions of clastics and some dissolved salts to the Pine Salt basin, but also recognizing that marine waters invaded the area from the south intermittently (Gallup & Hamilton, 1953) thus replenishing the salt water supply, and during time of prolonged restriction of the sea the Pine Salt deposited. Deposition of Pine Salt over older truncated beds indicates early stages of basin subsidence to the north. As more submerged area was developed, free from additional sea water there would be a tendency to increase concentrations of brine to the point of salt deposition (Middleton, 1959).

Dunham Salt

Stratigraphy: The upper salt or Dunham salt lies conformably on the upper siltstone and sandstone and is overlain by marine beds of anhydrite and shale. A concentration of wells in northwestern North Dakota establish that this salt is an added section to the top of the red bed sequence and not just a facies change from the underlying red bed unit (Zieglar, 1956). The Dunham Salt has the least aerial extent of the four units of the red bed sequence (Middleton, 1959). Looking back at Figure 6, a comparison of the Dunham and Pine salts shows that the Dunham is pretty well confined to western North Dakota while the Pine extends into Montana and South Dakota. It is also thinner — usually in the 50 to 100 foot range, but is 142 feet thick at a depth of 5900 in a small depositional basin in northwestern North Dakota. It is about 100 feet thick at a depth of 6700 feet one hundred miles to the southwest.

To our knowledge this salt has never been cored. Zieglar felt that from drilling time information this salt was less contaminated than the Pine Salt.

Environment: Marine beds of light gray dolomite, pink limestone, and, higher up in the column, variegated shales overlie the Dunham Salt. It is reasonable to agree with Ziegler that by Dunham time marine waters entered the Williston Basin and during a minor regressive phase of an overall advancing sea the Dunham salt deposited. There may have been some contributions of salines from continental origins, but by Dunham time the underlying Spearfish covered most of the salt-bearing formations.

Salt Solution: In the case of both the Pine and Dunham salts, local salt solution and caving occurs. There is one area in the southwestern corner of North Dakota where it is almost a certainty. In the Stanolind Brusich well in Bowman County the Pine Salt is 199 feet thick; two miles away the Worley & Harrell Benz well has no Pine Salt. In both salt beds compensatory thickening is in upper Jurassic rocks, and any salt solution and removal is apparently pre-Cretaceous.

PERMIAN SALT

General Stratigraphy: Permian strata is represented by two formations, the Opeche and Minnekahta — see Figure 4. The lower of the two, the Opeche, is similar to the Jura-Triassic in that it is mainly a red bed sequence with an extensive salt bed. Its contact with the underlying Pennsylvanian Minnelusa Formation is possibly unconformable (Anderson & Hansen, 1957).

Permian Salt

Stratigraphy: There is not a great deal of information on the Permian salt. It is contaminated with red limey shale and not always easy to pick from logs. Actually there are two salts, but the lower salt is thinner and less extensive so is not considered in the thickness discussion. Figure 6 shows the extent of the Permian salt — it covers roughly the same area as the Jurassic Dunham salt in North Dakota, but is more extensive in eastern Montana. Thicknesses are mainly in the 50 to 100 foot range and it is found at depths of 5800 to 7500 feet.

Permian salt was cored in the Tioga, N.D., area by Amerada Petroleum Corporation. Two salts were encountered 40 feet apart; the core data shows that the salts are interbedded and intercalated with red limey shale.

Environment: Pennsylvanian seas advanced from the west through Central Montana and on to the Williston Basin depositing dolomitic sand and siltstone. The basin area became more isolated and in Opeche time red clastics deposited. In this regressive environment salt and clastics were laid down as the seas dried up and streams brought in muds from the surrounding area. Following salt and red bed deposition, subsidence and inflow of marine waters brought the above conditions to a temporary end, and anhydritic carbonates were deposited over the red beds.

MISSISSIPPIAN SALTS

General Stratigraphy: Lower Mississippian sediments are mainly carbonates and evaporites in the Williston Basin. Figure 7, prepared by the North Dakota Geological Survey is a 100 mile east-west cross section from northwestern North Dakota to a point in north central North Dakota a few miles from the Canadian border. The Bakken Formation at the bottom of the column is a black shale and siltstone unit deposited on top of the Devonian; it is overlain by the three formations of the Madison Group: Lodgepole, Mission Canyon and Charles which together total over 2000 feet of carbonates and evaporites. The Madison Group consists of a thick argillaceous limestone -- Lodgepole -- overlain by clean carbonates and anhydrites of the Mission Canyon Formation, which in turn is overlain by a series of limestones, dolomites, evaporites and shale of the Charles Formation. The Charles contains six widespread salts and the Mission Canyon one salt.

Charles Salts

Stratigraphy: As seen by Figure 7 the Charles is basically limestone and anhydrite from its eastern limits where it is truncated against Jura-Triassic red beds to the deeper part of the basin where the salts begin. The far west well on the cross section, Amerada H.O. Bakken #1, contains six Charles salts separated by limestone, dolomite, anhydrite and red shale. In this well the salts comprise one third of the total Charles section. Figure 7 shows the great number of facies changes — mostly limestone to anhydrite and porous to dense limestones (Anderson, 1958) — and points up the difficulty in establishing a contact between Charles and underlying Mission Canyon. The intent of most geologists is to establish a contact of essentially carbonate-evaporite rocks to clean carbonates, but shoreward anhydrites make this a difficult task. The contact of the

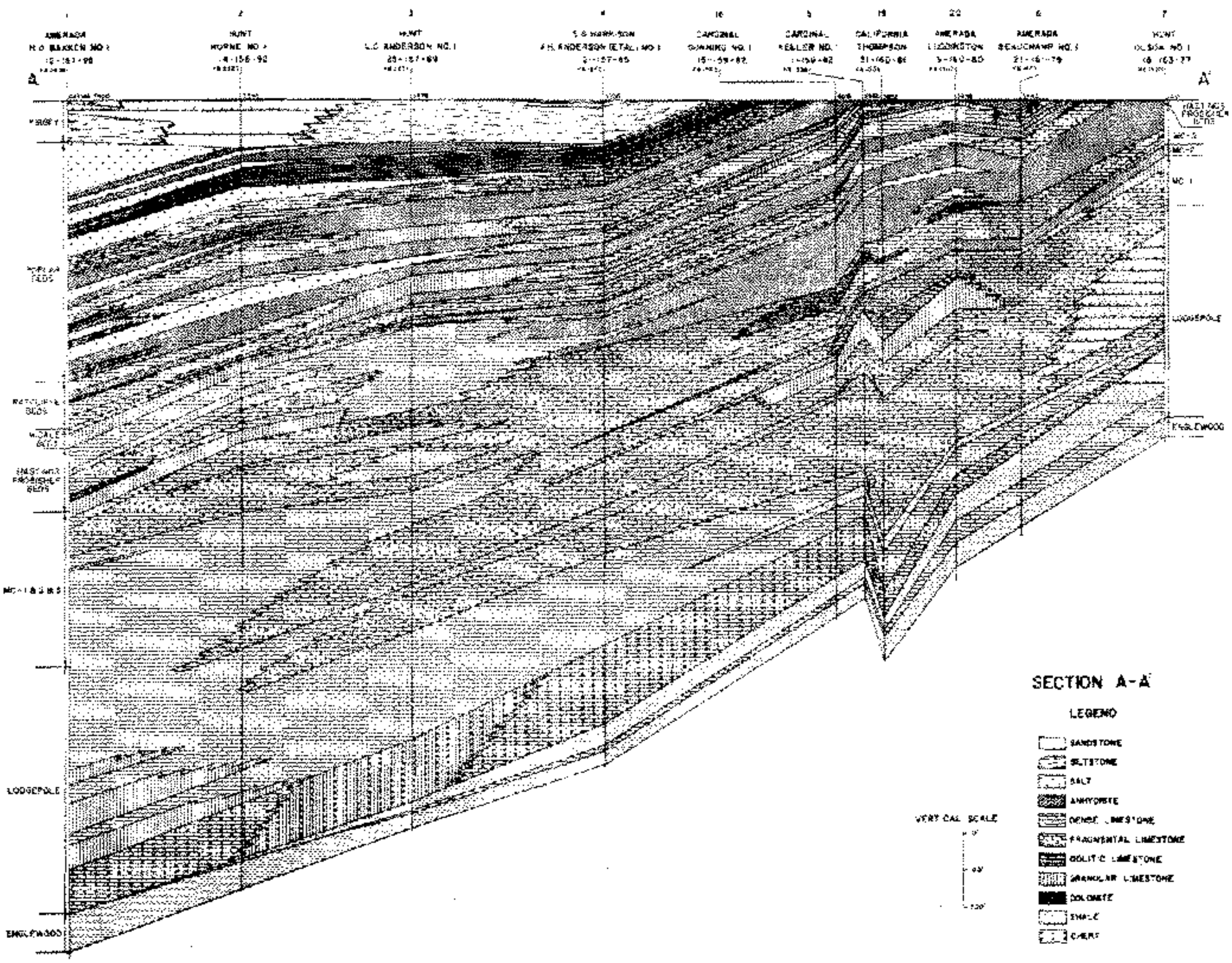


Figure 7.

two formations is conformable, transitional, and in part, time equivalent (Anderson, 1958). Overlying the Charles are Jura-Triassic red beds on the sub-crop and red-brown, silty calcareous shale of the Kibbey Formation in the basin area.

Figure 8 shows the thicknesses and extent of the Charles salts in North Dakota. The six salt beds have been designated Mississippian A through F by the N.D. Geological Survey. A typical well near Tioga, North Dakota, in the northwestern part of the State has the following thicknesses for the salt beds starting from the top: A 150 feet, B 10 feet, C 30 feet, D 50 feet, E 25 feet, and F 30 feet. Distances between the salts are: A to B 20 feet, B to C 20 feet, C to D 50 feet, D to E 90 feet, and E to F 140 feet.

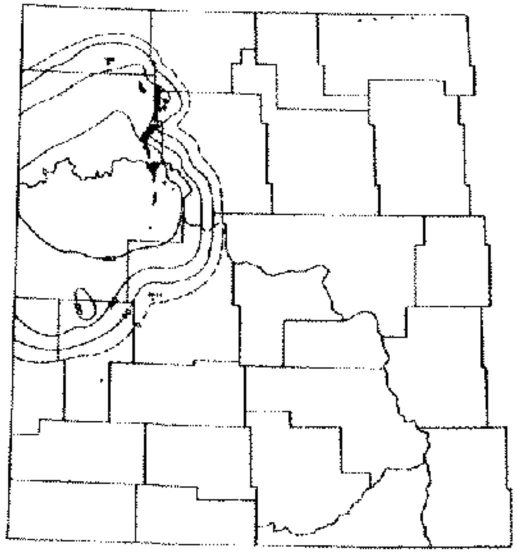
The top, or A salt, is the thickest and is the only one on the United States' side of the Williston Basin that is in production for the manufacture of salt. This salt covers an area 120 miles north and south and about the same distance east-west for a total area of over 12,000 square miles. The salt bed is usually 100 to 175 feet thick, but locally exceeds 200 feet. Depth to the salt bed ranges from 6000 to 9000 feet. Spot thicknesses and depths are: 150 feet at 7500 feet in depth near Tioga, N.D., 230 feet at 8250 feet in depth near Williston, N.D., and 160 feet at 6500 feet in depth near Poplar, Montana.

Purity of the A salt was first established in a hole that was cored by Amerada Petroleum Corporation near Tioga, N.D. At that location 32 samples were taken at five foot intervals in a 158 foot salt section and tested by Hooker Electrochemical Company. Average sodium chloride was 96.5% water insolubles 1.5% and SO_3 0.4%. The salt portion averaged 93% salt by

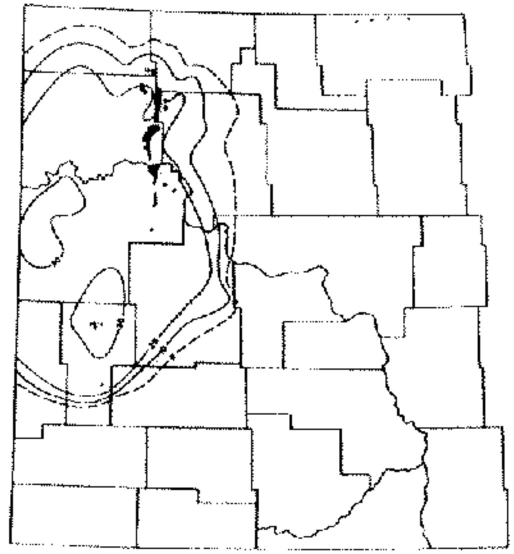
THICKNESS MAPS OF SALTS IN NORTH DAKOTA

ANDERSON & HANSON, 1957

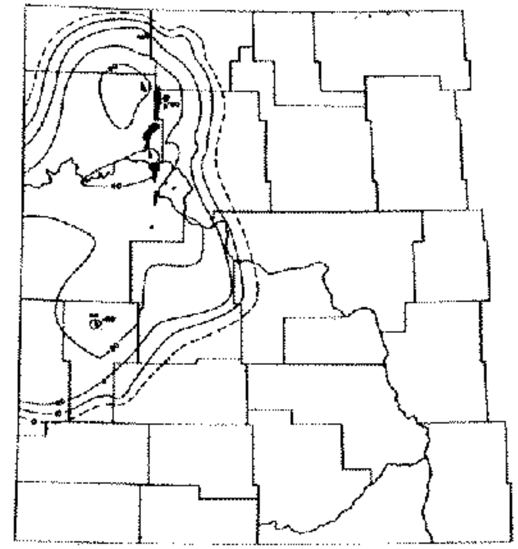
FIGURE 8.



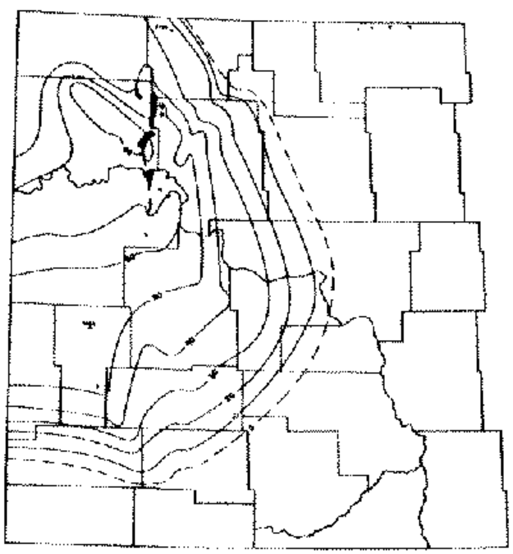
CONTOUR INTERVAL - 50 FEET
4 - MISSISSIPPIAN "A" SALT



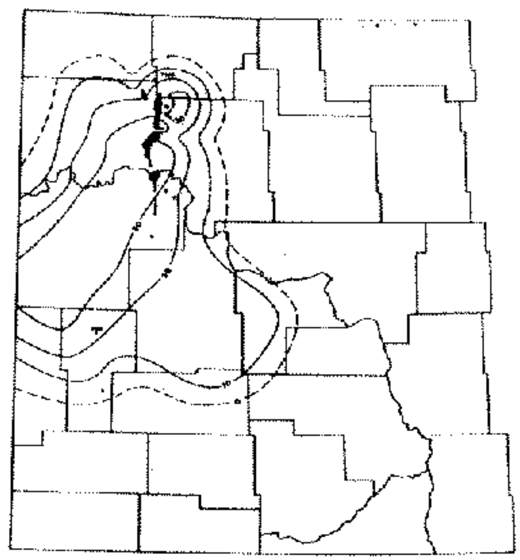
CONTOUR INTERVAL - 10 FEET
5 - MISSISSIPPIAN "B" SALT



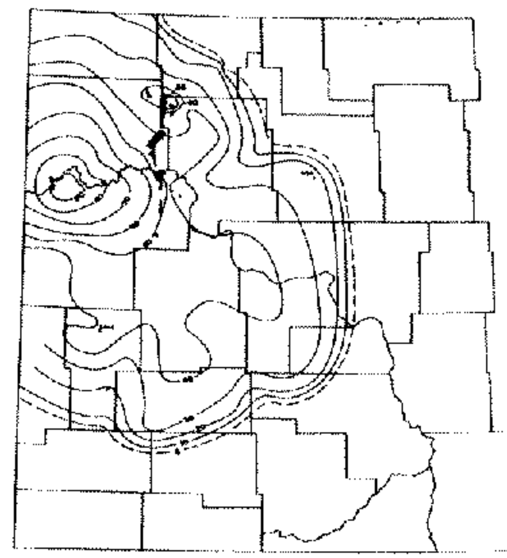
CONTOUR INTERVAL - 10 FEET
6 - MISSISSIPPIAN "C" SALT



CONTOUR INTERVAL 10 FEET
7 - MISSISSIPPIAN "D" SALT



CONTOUR INTERVAL - 10 FEET
8 - MISSISSIPPIAN "E" SALT



CONTOUR INTERVAL - 10 FEET
9 - MISSISSIPPIAN "F" SALT

examination, with the balance largely red, silty, limey shale, probably the result of lime muds that seeped into the salt during its deposition. Not included were more than twenty 1 to 8" bedded impurities which totalled about 4 feet in thickness. Analyses of the Tioga well made by Hooker Electrochemical Company are shown on Figure 9.

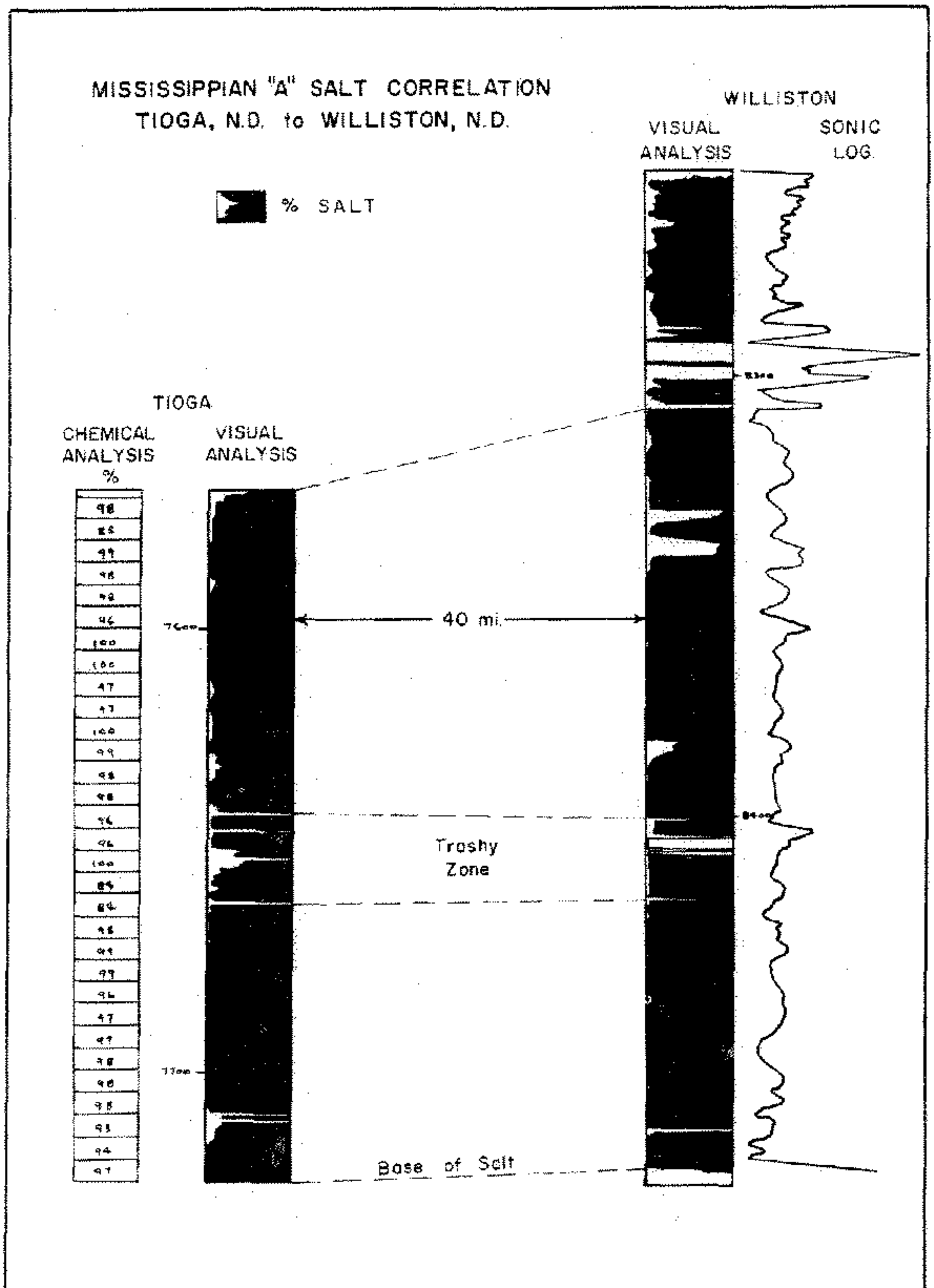


FIGURE 9

Figure 8 shows that the second through sixth salts -- B through F -- are all less than 100 feet thick in North Dakota, and usually they are 30 to 40 feet thick. The F salt is the next thickest to the A and has the greatest lateral extent to the east. The D salt, probably the most extensive of the Charles salts, spreads further north, south, and west than the others.

The A salt has been cored three times near Tioga, N.D., and three times near Williston, North Dakota; the two areas are 40 miles apart. Figure 9 shows the correlation between wells of the two areas. In both cases there is a trashy zone of red shale and anhydrite about 80 feet from the base of the salt. Another trashy zone in the well near Williston ending 170 feet from the base of the salt correlates with the top of the salt in the Tioga area; the salt above the top trashy zone at Williston is added section. Also shown on Figure 9 is a Sonic Log of the well used for correlation at Williston. In most cases the interbeds of anhydrite and shale are identified by higher velocities on the log.

Only two feet of the B salt has ever been cored -- that near Williston; C D and E salts were partly cored in a well near Sidney, Montana, near the North Dakota border; and the F salt has been cored in the Tioga area. Piecing together the few available cores and other information, the general stratigraphic column shows red shale above the A salt; anhydrite and shales between A and B; anhydrite between B and C; anhydrite, gray shale and some limestone from C to D; thick anhydrite and some dark gray shale from D to E; and from E to F a zone of banded anhydrite and shale, followed by limestone and anhydrite, then limestone including shelf types, dark gray shale, and about ten feet of anhydrite on top of the F salt. Under the F salt, is up to ninety feet of anhydrite, dolomitic in part, and under the anhydrite shelf type limestones.

Environment: Lower Mississippian strata is characterized by one cycle of marine transgression and regression. Seas advanced from the Cordillerian Geosyncline through the Central Montana trough and on the negative area of the Williston Basin (McCabe, 1959). Sedimentation was influenced by the Wyoming shelf to the south and west, by the Alberta shelf to the northwest, and by the shelf area in Manitoba and in eastern Dakotas on the east.

McCabe (1959) has a fine section on "General Williston Basin Palaeogeography" and much of this paragraph is taken from that section. The advancing seas first deposited black shale and siltstone on the Devonian surface -- the Bakken Formation; then with further advance a thick argillaceous limestone -- the Lodgepole. At that time rapid subsidence caused a marked differentiation of shelf and basin deposition. Later the rate of subsidence was reduced and under extreme shoaling conditions shallow water limestones were deposited -- the Mission Canyon. At the end of Mission Canyon time there was a lowering of the sea level; Mississippian seas regressed and marginal areas became restricted with the cyclic fluctuations of the sea level. Evaporites, mostly anhydrite, but also one salt were deposited. These evaporites moved basinward with further retreat of the sea and finally under severely restricted conditions the Charles salt beds were deposited. Mississippian seas withdrew from the basin area to the west and both marine and non-marine sandstone beds of the Kibbey Formation were deposited over the salt.

The Charles Formation is placed near the end of the above regional history. This formation shows a number of depositional cycles of argillaceous carbonates, limestones, dolomites, anhydrites, shales and salts. The thick dolomitic anhydrite below the bottom Charles salt shows gradual restriction and finally increased salinity of the sea to the point of salt deposition. Following deposition of the F salt, subsidence and inflow of marine waters diluted the sea and anhydrite was deposited; then with further subsidence and inflow, stagnant conditions resulted in the deeper waters and shale was deposited. Later the basin became tectonicly stabilized and limestones deposited. Cyclic conditions continued until the end of Charles time. In periods of aridity streams brought clastics into the basinal areas. There is some difference in thinking on barriers confining the Williston Basin in Charles time, but Edie (1958) reports precipitated barrier banks in southern Saskatchewan in lower Charles time and bioclastic limestones forming on the basinward margins of the bank. Shallow water limestones, some that may have developed banks, are numerous at the top of the Mission Canyon, and apparently there was sufficient build-up to cause restriction.

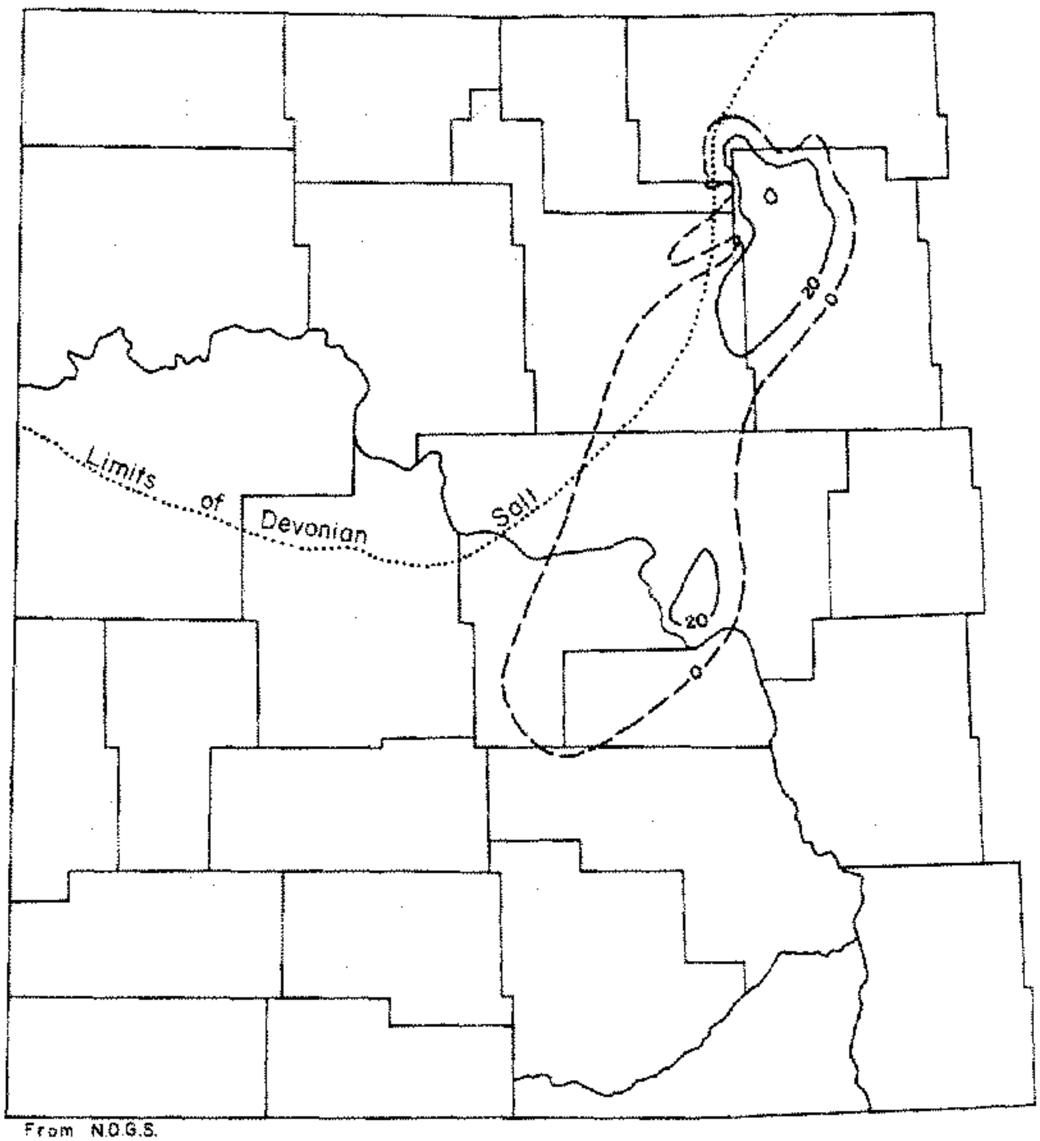
Mission Canyon Salt

Stratigraphy: Difficulty in establishing a Mission Canyon-Charles contact has been previously discussed. Figure 7 shows the outlying Mission Canyon salt in a thick anhydrite section which grades basinward to dense limestone. Our correlations show this salt to be about 80 feet below the top of the Mission Canyon. Actually there are two salts separated by 15 to 30 feet of anhydrite, but the second salt is a local occurrence and is not considered in this study.

Figure 10 is an isopach of the Mission Canyon salt. This salt bed is the shallowest and the smallest in aerial extent of all the salt beds studied. One of the thicker occurrences is in the Hunt Harrington well toward the north end of the salt; here there is 34 feet of salt at a depth of 3700 feet. Depths are over 4000 feet in areas to the south.

The Mission Canyon salt was cored once in the California Company Thompson well 25 miles south of the Canadian border. Thirteen feet of an 18 foot salt bed were recovered and was described as "Salt, clear, course crystalline" (North Dakota Geological Survey #7). Underlying the salt is ten feet of anhydrite under which is grayish-red shale, dolomite, and finally anhydrite.

FIGURE 10



CONTOUR INTERVAL – 20 FEET

MISSION CANYON SALT

Environment: As indicated previously, at the end of Mission Canyon time there was a drop in sea level and marginal areas became restricted. During this time evaporite lagoons formed and in most cases anhydrite deposited, but in this one case, restriction was more pronounced and salt was deposited.

Figure 10 shows the approximate limits of Devonian salt deposition. In north central North Dakota the Devonian salt is about 2000 feet below the Mission Canyon salt, and further south the interval is greater. The California Company Thompson well mentioned above had no Devonian salt and yet a well less than 2 miles to the southwest, the Cardinal Keeler, had 160 feet of it, all of which is strong evidence for salt solution and collapse. Figure 7 shows these two wells and the apparent collapse of lower Mississippian beds. Over two thirds of the loss in section from the collapse is made up in the Tilston sub-unit of the Mission Canyon — some 300 feet below the Mission Canyon salt. The Keeler well which had the Devonian salt had only 6 feet of the Mission Canyon salt while the Thompson well with no Devonian salt had 18 feet of Mission Canyon salt in spite of the fact that it is the more shoreward of the two wells. It is very possible that collapse of Devonian salt during Mission Canyon time formed a marginal basin much deeper than the usual pans in which anhydrite deposited; and in this basin greater amounts of saline water were restricted until ultimate deposition of salt.

DEVONIAN SALT

Dr. Pearson of the Saskatchewan Department of Natural Resources in Regina will present a more comprehensive study of the Devonian Prairie Evaporite Formation of the Williston Basin in this symposium.

Figure 11 is an isopach of the one Prairie Evaporite salt. This salt reaches thicknesses of up to 500 feet in northwestern North Dakota but normally runs 200 to 300 feet in thickness. Depths

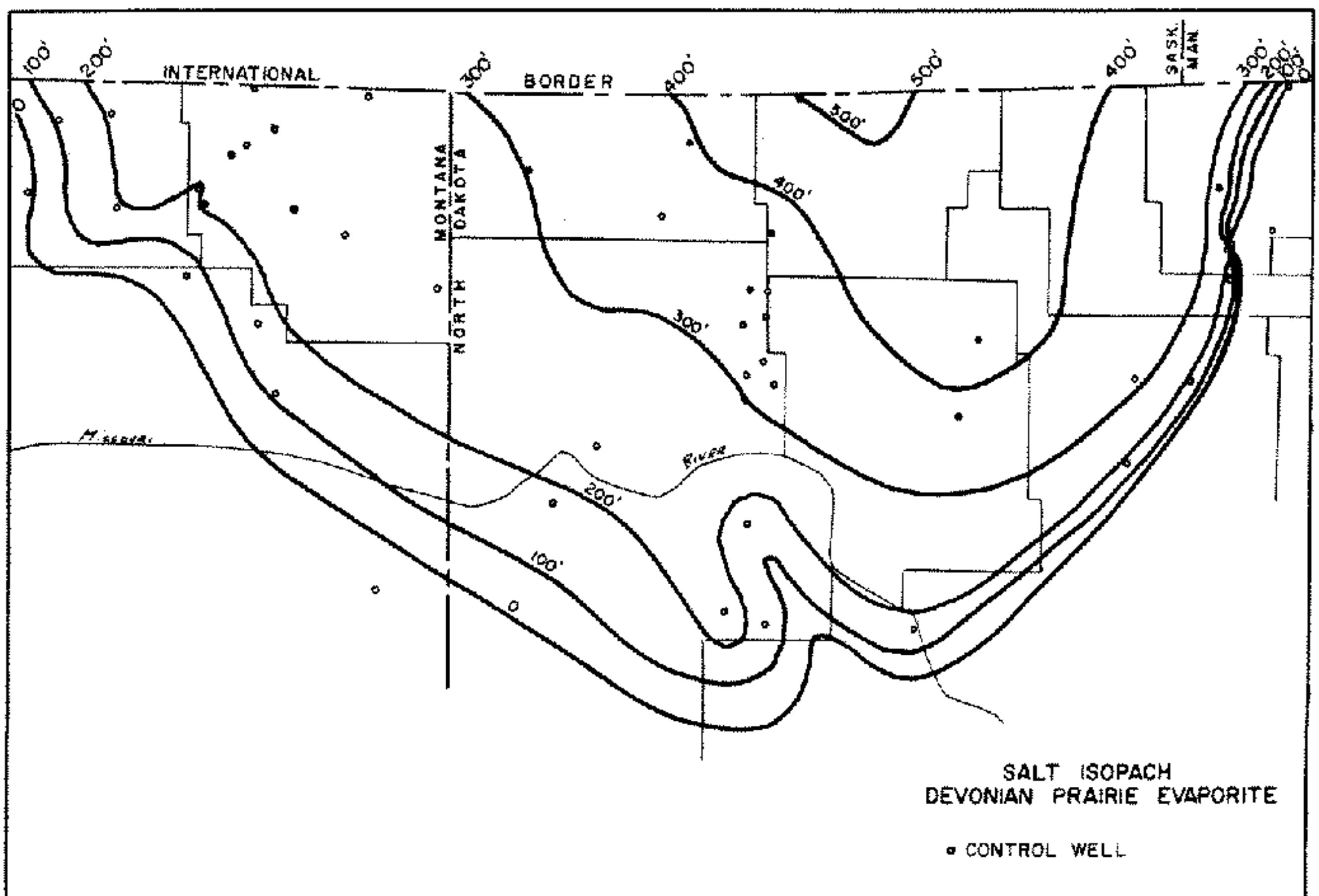


FIGURE 11

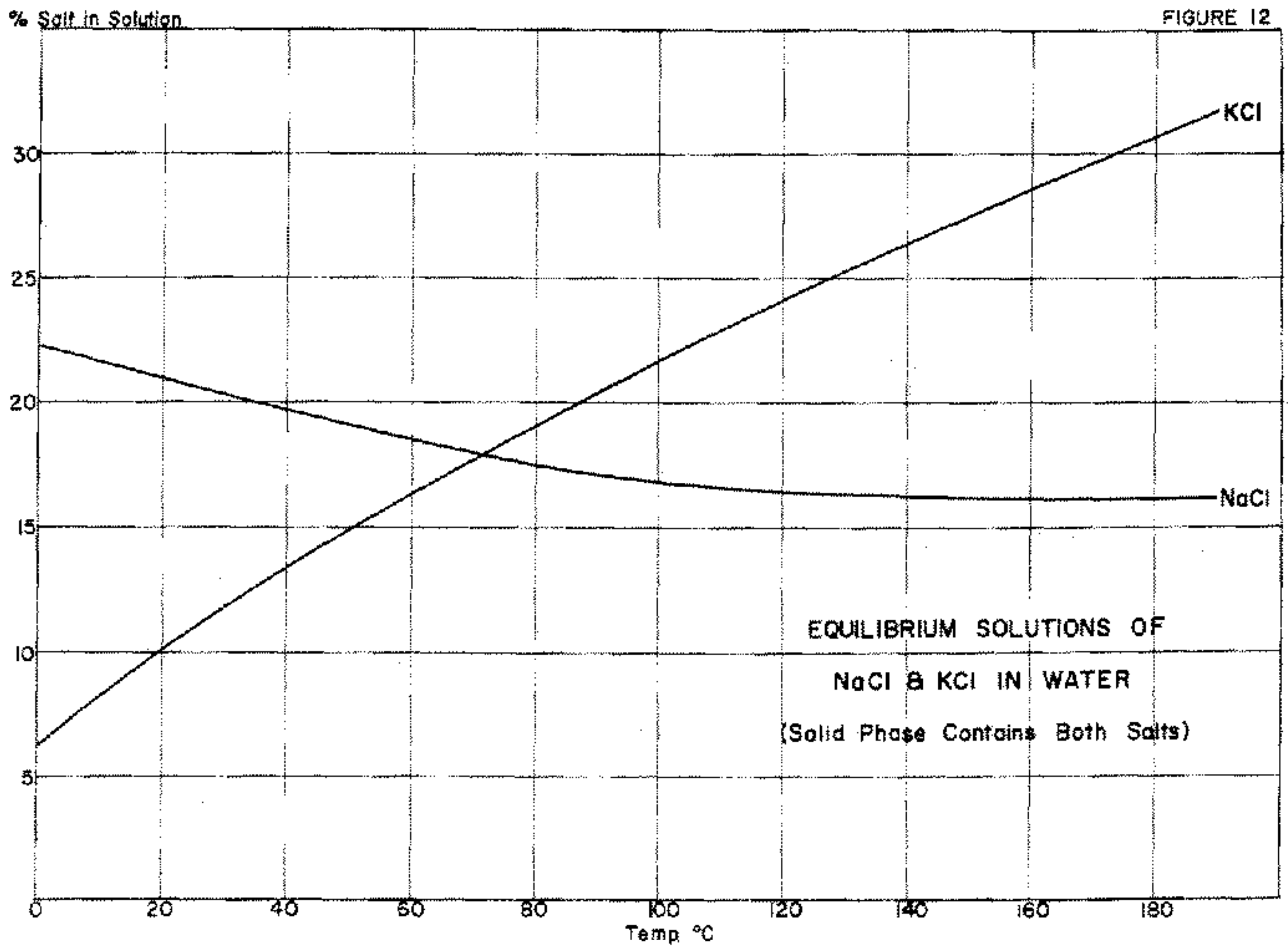
to the salt range from 6000 to 12,000 feet. Typical thicknesses and depths are: north central North Dakota -- 160 feet at 6300; Minot, N.D. area -- 185 feet at 7500; Tioga, N.D. area -- 300 feet at 11,000; Williston, N.D. area -- 230 feet at 12,000; eastern Montana -- 200 feet at 8400.

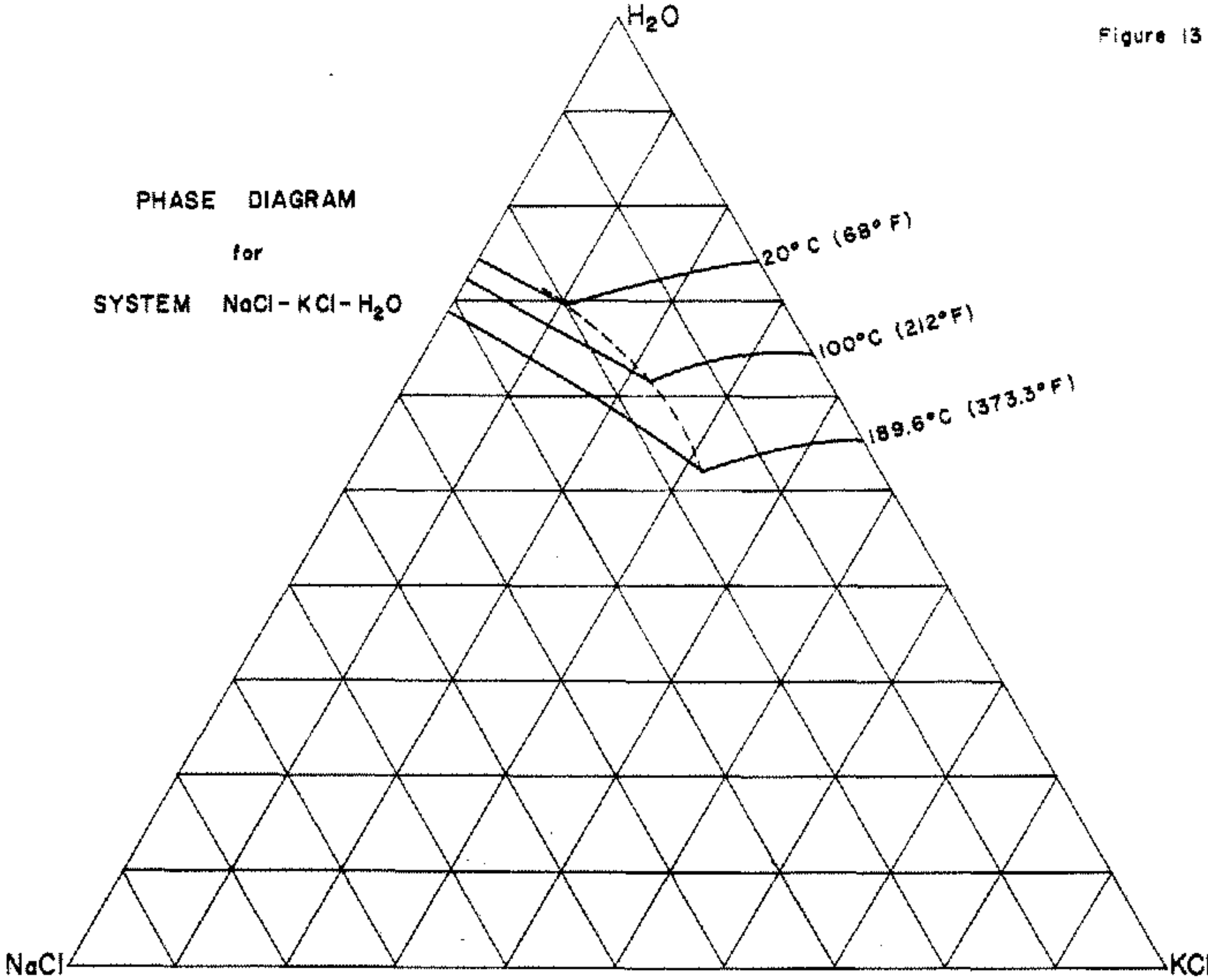
Potash beds, which have been cored and exploited in Saskatchewan, are indicated in North Dakota and Montana by Gamma Ray logs. These beds are normally ten to fifteen feet thick, but range up to nearly thirty feet. Because of the depth, the only feasible way of exploiting them on the United States' side of the border is by solution mining.

The kinds and amounts of impurities present in the potash beds will determine whether or not solution mining is feasible. If the potash bed is made up of only halite and sylvite, it will offer no serious problems in brining out the KCl. Figures 12 and 13 show the mutual solubilities of the two salts in water. Figure 12 shows the variation with temperature of the two salts in a solution that is in equilibrium with a solid phase containing both salts. It can be readily seen that the high formation temperatures that prevail at depth of the Prairie Evaporite in North Dakota will be an advantage in solution mining. Figure 13 is a phase diagram for the system KCl -- NaCl -- H_2O showing the phase relationships at three separate temperatures. The broken line is the locus of the intersection of the saturation curves.

Minor amounts of calcium and magnesium chlorides in the formation will reduce the solubility of KCl but not to an extent which will render solution mining infeasible. On the other hand, large amounts of carnallite in the formation will reduce the solubility of KCl to a point where solution mining can not be used. Calcium salts in the form of anhydrite or gypsum should have very little affect.

FIGURE 12





If our assumptions are correct regarding the similarity of potash beds on both sides of the International Border, then it is reasonable to say that there are many areas in which solution mining of potash is feasible.

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