Oklahoma Geological Survey
Jeremy Boak, *Director*

Open-File Report 19-2018

Evaluation of Permian Salt Deposits in the Texas Panhandle and Western Oklahoma for Underground Storage of Radioactive Wastes

Kenneth S. Johnson
Retired Geologist
Oklahoma Geological Survey
ksjohnson@ou.edu

The University of Oklahoma
Norman, Oklahoma
2018

Preface

This report was originally prepared for Union Carbide Corporation, Oak Ridge National Laboratories, Oak Ridge, Tennessee, as part of the United States government effort to identify a site suitable for building a repository for disposal of high-level radioactive wastes. A 1957 report by the National Academy of Sciences–National Research Council recommended that such wastes be buried in a solidified form in subsurface deposits of rock salt (halite). Union Carbide Corp. contracted with the author to study the thick Permian salt deposits in the Texas Panhandle and western Oklahoma to determine if the region might contain such a suitable site. Characteristics important for waste isolation and containment include: thickness, depth, lateral continuity, homogeneity, and dissolution of salt beds, as well as the structural/tectonic setting, hydrology, seismicity, and mineral resources of the region.

The three major salt basins in the study area are the Anadarko, Dalhart, and Palo Duro Basins. Salt deposits in all three basins were characterized in the report as to their thickness and depth, and the other factors important for safe, long-term disposal and containment of radioactive material. In 1976, this report recommended that, of the three basins studied, parts of the Palo Duro and Dalhart Basins appeared to be most favorable for underground storage of radioactive wastes.

As a result of this recommendation, in 1977 the U.S. Department of Energy (DOE) contracted with the Bureau of Economic (BEG) at The University of Texas at Austin, as well as several engineering and consulting firms, to conduct extensive geologic and hydrologic studies of the Palo Duro and Dalhart Basins. BEG has published many reports detailing their investigations, and finally, in 1983, DOE identified a potentially suitable site in the Palo Duro Basin near Hereford, in Deaf Smith County, Texas (referred to as the "Deaf Smith Site"). Here, it was felt that a repository might be developed more than 2,000 feet below land surface, in a 200-foot-thick salt unit in the San Andres Formation. In December 1987, the U.S. Congress amended the Nuclear Waste Policy Act to focus all future studies on the Yucca Mountain Site in Nevada, and further study of Palo Duro Basin as a potential repository site ceased.

Although this report is now dated, there is continued general interest in salt deposits in the Anadarko, Dalhart, and Palo Duro Basins. The original report had a very limited distribution, and an electronic copy has not been available. Thus, the Oklahoma Geological Survey is making it available online as an Open-File Report.

Suggested citation of this report is:
Johnson, K.S., 1976, Evaluation of Permian salt deposits in the Texas Panhandle and western Oklahoma for underground storage of radioactive wastes: unpublished report submitted to Union Carbide Corporation, Oak Ridge National Laboratories, Office of Waste Isolation, Y/OWI/Sub–4494/1, 73 p. Also available from: Oklahoma Geological Survey, Open-File Report 19–2018. http://www.ou.edu/content/dam/ogs/documents/data/OF19-2018.pdf

Kenneth S. Johnson

Y/OWI/Sub-4494/1

FINAL REPORT

Evaluation of Permian Salt Deposits in the Texas Panhandle and Western Oklahoma for Underground Storage of Radioactive Wastes

Submitted to

Union Carbide Corporation
Oak Ridge National Laboratories
Oak Ridge, Tennessee

Under Subcontract No. 4494
(W-7405-ENG 26)

Prepared by

Dr. Kenneth S. Johnson
School of Geology and Geophysics
The University of Oklahoma
Norman, Oklahoma

April, 1976

Y/OWI/SUB-4494/1

FINAL REPORT

Evaluation of Permian Salt Deposits
in the Texas Panhandle and Western Oklahoma
for Underground Storage of Radioactive Wastes

Submitted to

Union Carbide Corporation
Oak Ridge National Laboratories
Oak Ridge, Tennessee

Prepared by

Dr. Kenneth S. Johnson
University of Oklahoma
Norman, Oklahoma

April, 1976

CONTENTS

ILLUSTRATIONS

INTRODUCTION

This report concludes that thick salt deposits of the Palo Duro basin, and, to a lesser extent, those of the Dalhart basin, have many features that would be favorable for underground storage of radioactive waste. A number of factors detract from suitability of similar thick salt deposits in the Anadarko basin.

The principal parameters used in evaluating these three basins for radioactive-waste storage include salt thickness, depth, tectonic and seismic history, lithology, permeability, proximity to aquifers, mineral-resource content, extent of drilling and mining, and remoteness. Properties of salt (halite) that make it desirable as host rock for underground waste emplacement include its low permeability, low moisture content, high plasticity, and high gamma-ray shielding. A thickness of 200 feet of salt-bearing rock is herein considered minimal for insuring isolation of waste material that is buried 1,000 to 3,000 feet below the surface.

Emplacement of radioactive-waste products from nuclear plants, reprocessing plants, and other nuclear facilities can be accomplished by forming an underground cavern in a salt bed, using standard mining techniques. By creating the cavern about 1,000 to 3,000 feet below the surface, and by backfilling and sealing the cavern after the waste is emplaced, the radioactive material can be effectively isolated.

The purpose of this project was to study the Permian salt deposits in about 50,000 square miles of the Texas Panhandle and western

Oklahoma (fig. 1) to determine whether the region contained any areas that might be suitable for waste storage. No comprehensive study of the salts in this region had been done previously, although Jordan and Vosburg (1963) and Johnson (1967) did examine part of the Anadarko basin, and Tait and others (1962) presented a correlation of some salt units across the region. Reports on surrounding areas include those of Adams (1963), Brokow and others (1972), and Jones (1974, 1975) in West Texas and New Mexico, and Kulstad (1959) in Kansas. Summaries of salt in the Permian basin were presented by Bachman and Johnson (1973), Lefond (1969), McKee and Oriel and others (1967a, 1967b), Pierce and Rich (1962), and Smith (1975).

A major part of this project involved a study of electric logs and some sample logs for about 300 wells drilled in the region. The results of this geologic study are presented on plates 1 through 8 (in the pocket), and these data are also generalized in a series of figures in the text. These results are of a reconnaissance type, but they do show the general character, thickness, distribution, depth, and structure of the salt deposits.

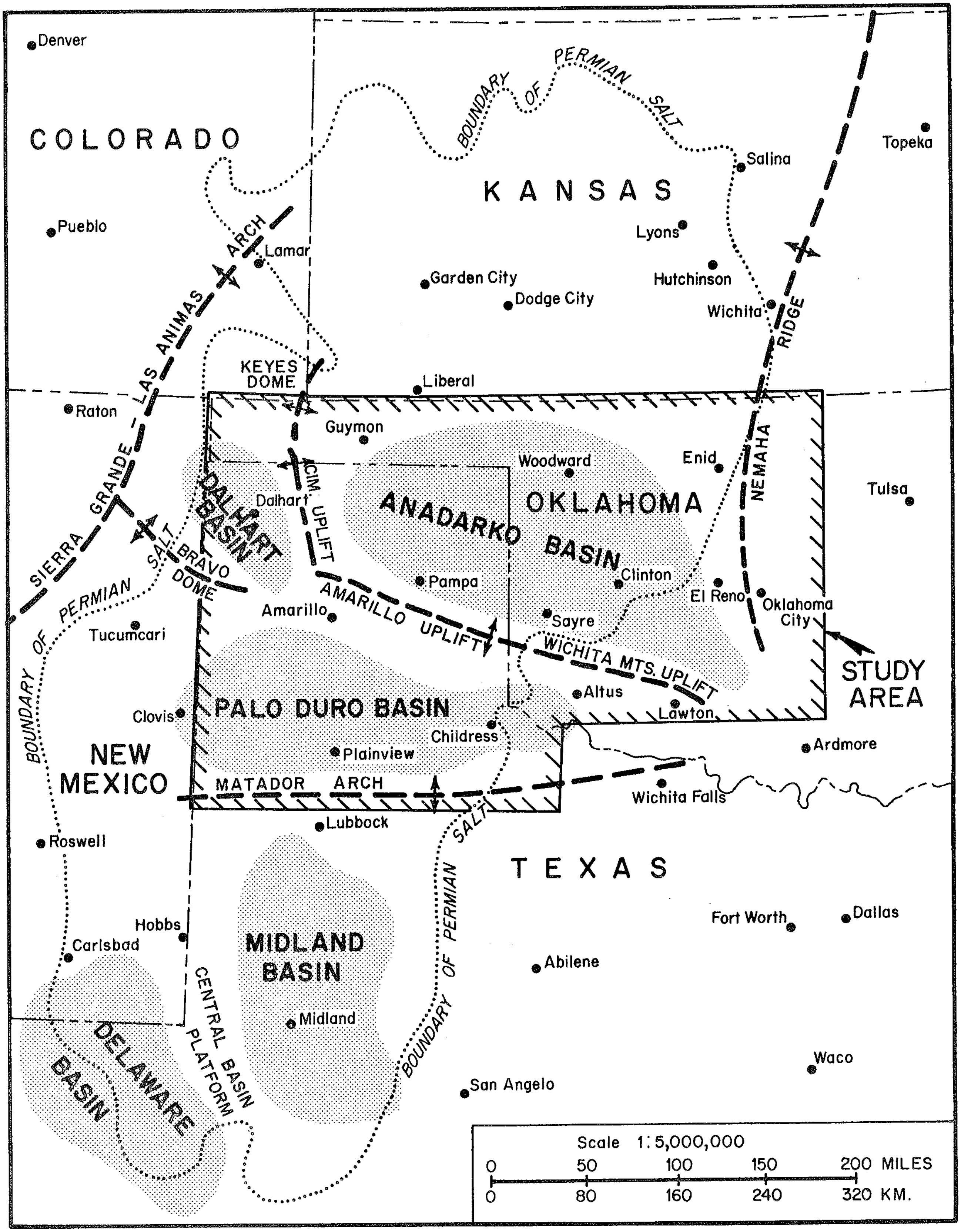


Figure 1. Map of Permian basin salt area in southwestern United States, showing principal tectonic provinces and outline of area studied for this report.

TECTONIC SETTING

The study area embraces 10 separate tectonic provinces, including 7 uplifts or domes that separate or border upon 3 principal basins (fig. 1, pl. 1).

These tectonic features were developed mainly during the Pennsylvanian Period, before deposition of the Permian salts. Although the tectonic activity had largely subsided by the end of Pennsylvanian time, most of these features still exercised some control on facies distribution and salt deposition during the Permian. Since Permian time, there has been some continued minor tectonic movement in these provinces, and the type of movement has been similar to that which was established during the Pennsylvanian; the basins have continued to subside slowly in comparison to the surrounding uplifts. These minor vertical movements may result from post-tectonic adjustments within the Earth's crust itself, or they may result from differential rates of compaction where a thicker column of Permian and pre-Permian sedimentary rocks in the basins permits a greater amount of settlement in the basins. Thus, although the pre-Permian rocks are locally faulted and complexly folded, the Permian and younger strata are virtually free of deformation and in most areas have a dip of less than $\frac{1}{2}^{\circ}$.

The present structure of Permian rocks is shown on the structure-contour map, drawn on the base of the Cimarron Anhydrite (top of Tubb sand), an excellent marker bed throughout the entire study area (figs. 2 and 3, pls. 1 and 2). Deeper marker beds, such as those in the

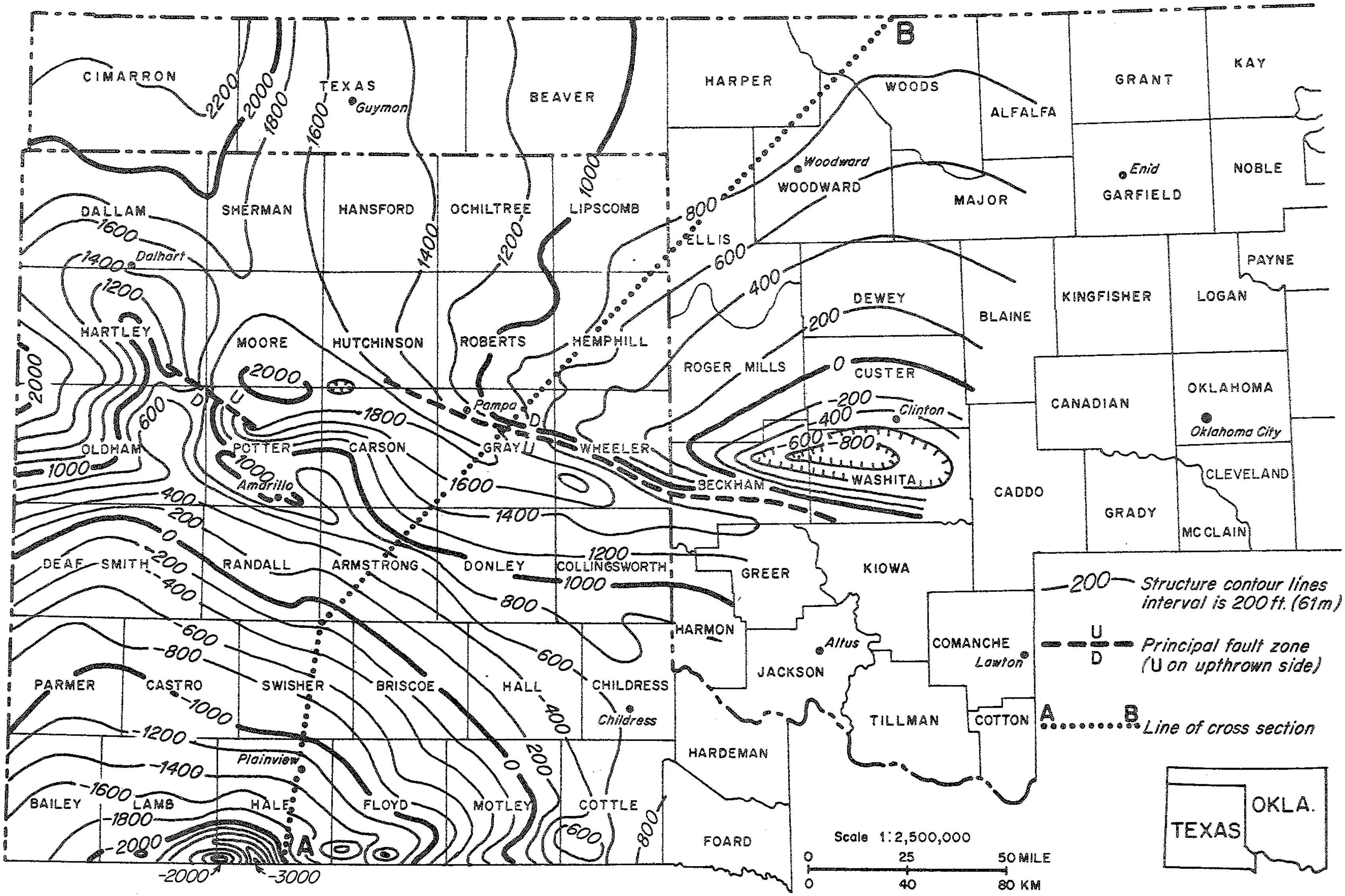
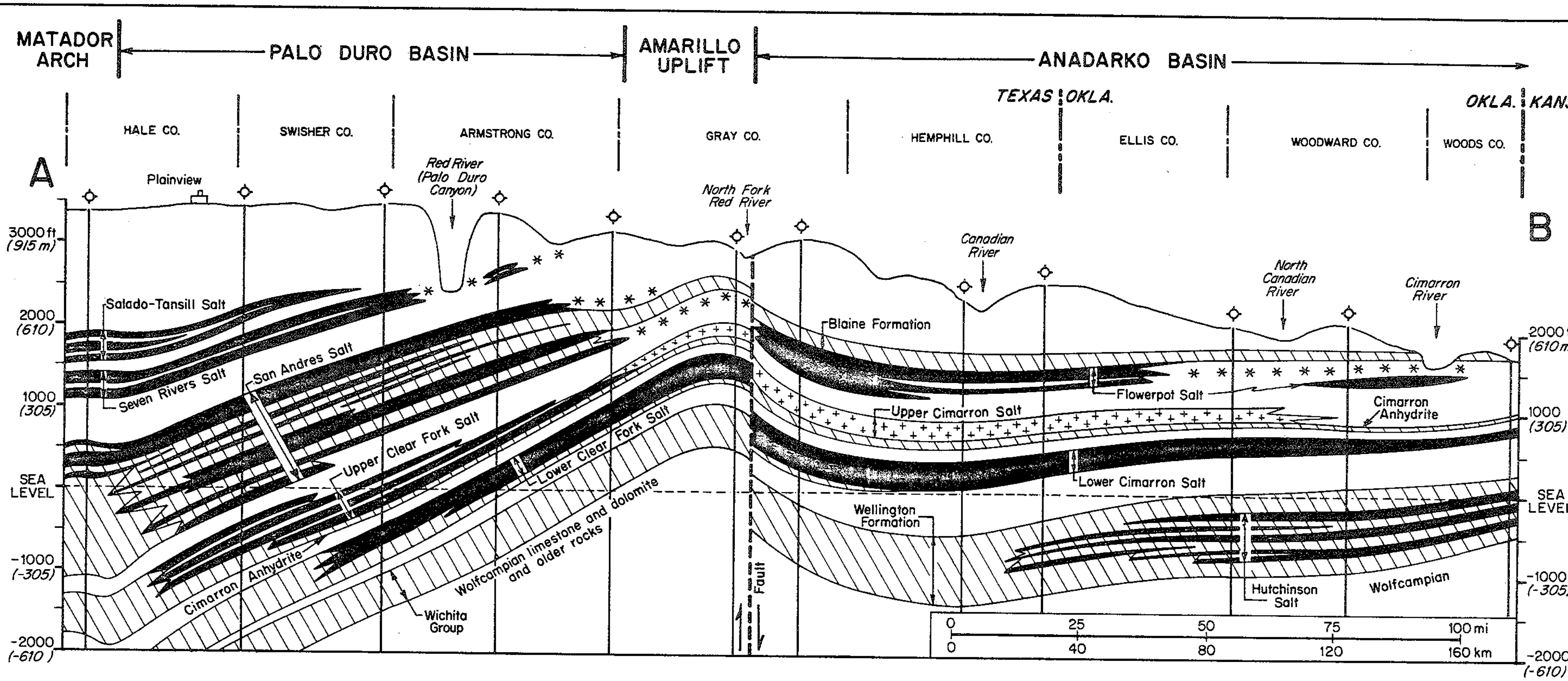


Figure 2. Structure-contour map drawn on base of Cimarron Anhydrite (generalized from pl. 1). See figure 3 for cross section A-B.



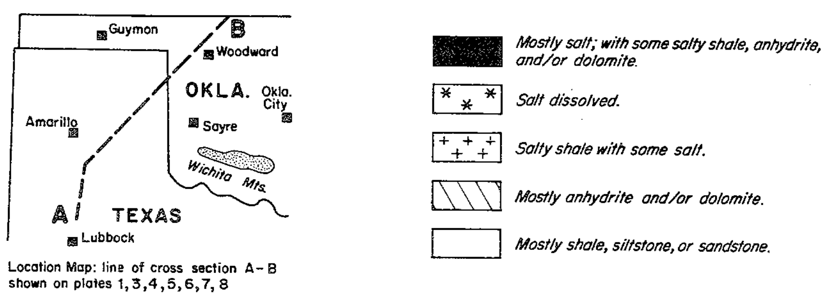


FIGURE 3
GENERALIZED STRUCTURAL CROSS SECTION SHOWING PERMIAN SALTS AND ASSOCIATED STRATA IN THE TEXAS PANHANDLE AND WESTERN OKLAHOMA

(reduced from plate 2)

Wellington Formation and Wichita Group, are not present in the Dalhart basin and some of the surrounding areas. Shallower marker beds, such as those in the San Andres, Blaine, and Alibates, are excellent datum beds for structural mapping locally, but in some places they are collapsed owing to dissolution of underlying salt strata. At no place is the Cimarron Anhydrite collapsed or disrupted as a result of solution of underlying strata.

Wichita Mountains Uplift

The Wichita Mountains uplift has a core of Cambrian granite, rhyolite, and gabbro that was thrust upward and slightly northward during Early and Middle Pennsylvanian orogeny. This crustal block, which is 20 to 40 miles wide, extends west-northwestward across southwestern Oklahoma and is continuous with the Amarillo uplift in the Texas Panhandle. The Wichita block is bounded on the north and the south by complex fault zones that separate the uplift from the Anadarko basin to the north and the eastern part of the Palo Duro basin to the south. The north Wichita fault zone vertically displaces the Cambrian basement rock as much as 40,000 feet in Beckham and southern Washita Counties, making this one of the greatest fault systems in all of the central United States. The south-bounding fault zone has a throw of several thousand feet in the basement rock. Faults with several hundred to several thousand feet of throw are also present within the Wichita block. Permian rocks draped across these deep-seated faults have also been faulted or flexed locally owing to minor post-Permian tectonic movements or differential compaction, and they are downthrown several hundred feet into the adjacent basins.

The upper surfaces of Cambrian igneous rocks and folded and faulted Cambrian and Ordovician sedimentary rocks are locally exposed, and they constitute the Wichita Mountains of southwestern Oklahoma.

Amarillo Uplift

The Amarillo uplift is a westward extension of the Wichita Mountains uplift. It extends west-northwest across the central part of the Texas Panhandle to the area just north of Amarillo, and typically it is 15 to 30 miles wide. It was thrust upward during the Pennsylvanian Period but then was worn down and finally covered by Early Permian sediments. The Amarillo uplift is bounded by the north Wichita fault zone, which separates it from the western part of the Anadarko basin; other faults are present on the uplift and along the south side of the uplift.

Matador Arch

The Matador arch is an east-west-trending sharp uplift just south of the Palo Duro basin. It separates the Palo Duro basin from the Midland basin and its associated platform and shelf areas. The arch is about 300 miles long and typically is 10 to 15 miles wide. It passes just north of Lubbock and Wichita Falls, and in the Wichita Falls area it is called the Red River uplift. The Matador arch was uplifted during Pennsylvanian time. On the structure-contour map (fig. 2, pl. 1) the Matador arch appears to be a series of domes, each of which has a structural relief of about 200 to 1,000 feet above adjacent parts of the Palo Duro basin.

Cimarron Uplift

The Cimarron uplift is a relatively low positive feature that separates the Anadarko basin from the Dalhart basin. It extends 70 miles in a north-south direction and connects the Amarillo uplift with the Keyes dome. The main part of the Cimarron uplift is 10 to 15 miles wide.

Keyes Dome

The Keys dome is a subcircular uplift at the north end of the Cimarron uplift. It is a broad feature with gentle dips away from the center, and it appears to be about 20 to 30 miles in diameter. Deep-seated faults bound the east side of the Keyes dome, but Permian rocks apparently are merely flexed with slightly steeper dips over the deep fault zones.

Bravo Dome

The Bravo dome is an uplift that straddles the Texas-New Mexico state line. It partly separates the Dalhart basin on the northeast from the Palo Duro basin on the south. Although the Bravo dome was uplifted during the same Pennsylvanian tectonic episodes as the Wichita Mountains and Amarillo uplifts, it is about 20 miles to the south of the Wichita-Amarillo trend. A positive feature extends northwestward from the Bravo dome and connects with the larger Sierra Grande uplift of northeastern New Mexico.

Nemaha Ridge

The Nemaha ridge is a long north-south uplift that extends northward from central Oklahoma into Kansas and Nebraska. It developed during the Pennsylvanian Period as a number of small crustal blocks were raised sharply along the axis of the uplift. Uplifted crustal blocks in Oklahoma typically are 3 to 5 miles wide and 5 to 10 miles long and are bounded by faults on the east and/or west sides.

Uplifted blocks were eroded during Pennsylvanian time and were then covered by Late Pennsylvanian and Permian sediments. Apparently the Nemaha ridge had little or no effect on Permian deposition.

Anadarko Basin

The Anadarko basin is a large asymmetrical basin that extends in a west-northwesterly direction, just north of the Wichita Mountains and Amarillo uplifts. It is about 300 miles long, and extends from south-central Oklahoma into the northeastern part of the Texas Panhandle. It is bounded on the west by the Cimarron uplift and on the east by the Nemaha Ridge. The basin has the shape of a giant synclinal fold with the axis in the southern part. Sinking of the crust beneath the Anadarko basin was most pronounced during the Pennsylvanian Period, while the Wichita Mountains and Amarillo uplifts were being raised just to the south. About 15,000 feet of Pennsylvanian clastic sediments were dumped into the Anadarko basin adjacent to the rising Wichita uplift. They are underlain by 18,000 feet of pre-Pennsylvanian sedimentary rock, overlying the Cambrian basement, and are overlain by 7,000 feet of Permian sediments: thus the Anadarko basin contains about 40,000 feet of sedimentary rock along its axis in Beckham and Washita Counties, Oklahoma.

Permian rocks dip gently toward the axis of the basin. The dip is typically 10 to 20 feet per mile southward on the north flank of the basin, and 50 to 200 feet per mile northward on the south flank of the basin. Principal zones of faults cutting Permian rocks are known only on the south flank of the basin in the vicinity of the frontal fault zone that separates the Anadarko basin from the Wichita Mountains and Amarillo uplifts. The maximum structural relief, about 2,200 feet, is between the axis of the basin and the nearby Wichita Mountains uplift in Beckham and Washita Counties.

Palo Duro Basin

The Palo Duro basin is a large asymmetrical basin between the Matador arch on the south and the Wichita-Amarillo uplift and Bravo dome on the north. Its east-west-trending axis is about 5 miles north of the Matador arch. The basin has a length of about 175 miles and a width of about 60 miles. The eastern part of the basin, principally the area east of Childress, has at various times been called the Hollis, the Hardeman, or the Eastern Palo Duro basin.

Initial development of the Palo Duro basin began in Pennsylvanian time, while the adjacent uplifts were being raised. A total of 11,000 feet of sedimentary rocks overlie the basement complex of igneous and metamorphic rocks: pre-Pennsylvanian rocks are about 1,000 feet thick, Pennsylvanian rocks are about 1,000 feet thick, Permian rocks are about 7,000 feet thick, Triassic strata are about 1,500 feet thick, and the Tertiary sediments are several hundred feet thick. Although the Palo Duro basin became a distinct tectonic feature during Pennsylvanian time, the principal episode of downwarping and sedimentation occurred during the Permian Period. All Permian units are thicker in the southern part of the basin, and they are thinner northward toward the Amarillo uplift. Permian rocks dip gently to the south and southwest over most of the basin, and the rate of dip is typically 20 to 40 feet per mile.

Dalhart Basin

The Dalhart basin is a symmetrical though somewhat irregular basin in the northwestern corner of the Texas Panhandle and adjacent areas. It is bounded on the east by the Cimarron arch and the Keyes dome, and on the southwest and the west by the Bravo dome and the Sierra Grande uplift. The basin has an area of about 60 miles by 75 miles. It contains as much as 9,000 feet of sedimentary rocks over the basement complex; about 5,000 feet of these strata are of Permian age, and 1,000 to 1,500 feet are post-Permian. Permian strata dip gently at a rate of about 20 to 30 feet per mile toward the low point in the southern part of the basin.

PERMIAN PALEOGEOGRAPHY AND EVAPORITE DEPOSITION

During Permian time, the Texas Panhandle and western Oklahoma were in the central part of a broad shallow sea that covered much of the southwestern United States (fig. 4). Because of slow but continual sinking in the earth's crust beneath all parts of this inland sea, a thick sequence of red beds and evaporites (dolomite, gypsum, and salt) was deposited north of the major reefs and other carbonate deposits of the Midland basin and adjacent shelf areas.

Normal marine water entered the Delaware and Midland basins from the open ocean to the southwest, and after passing over the reefs it entered the shallow inland sea where evaporation of the water took place. Fresh water from land areas on the east and west mixed with the marine and saline waters; typically, clastic sediments were deposited in the alluvial and near-shore environments, whereas the evaporites were deposited in the more central part of the inland sea, or the deeper part of the three major basins.

Permian shales, siltstones, and sandstones deposited in the region were derived by erosion of land areas on the east and west sides of the inland sea. Land areas on the east side of the sea included much of central and eastern Texas, eastern Oklahoma, and eastern Kansas; the principal source areas for sediments were probably the Texas and Oklahoma portions of the Ouachita Mountain chain and the northeastern Oklahoma and eastern Kansas portions of the broadly uplifted Ozark

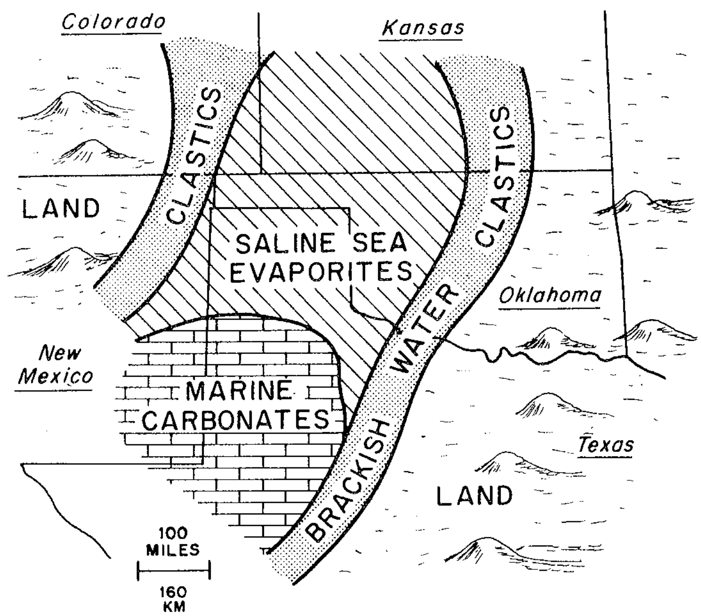


Figure 4. Paleogeography and principal facies of rocks deposited in Permian basin of southwestern United States during deposition of evaporites in early Guadalupean time (San Andres and Blaine Formations).

region. On the west side of the sea detritus came from eastern New Mexico and southeastern Colorado, from such regions as the Pedernal Hills, the Sierra Grande uplift, the Las Animas arch, and perhaps other land areas farther to the west. The various Pennsylvanian uplifts and domes within the study region were almost completely covered by sediments in early Permian time, and thus they contributed almost no detritus to Permian seas. The major exception is the Wichita Mountains uplift, which provided arkose and other detritus to the Anadarko basin in diminishing amounts through Early Permian time until it was completely covered by sediments in early Guadalupean time (beginning of the Late Permian).

Streams and rivers draining the land areas on the east and west carried mud and other fine sediments into the shallow seas, where they were deposited as layers alternating with the evaporite beds. At times, parts of the region were above sea level, and sands, silts, and clays were deposited in alluvial, deltaic, or aeolian environments. At other times, various parts or all of the region was covered by the shallow seas, and the evaporites and some of the fine clastic units were deposited over tens of thousands of square miles. Some of these evaporite units, such as the Cimarron Anhydrite and gypsum and anhydrite beds of the Blaine Formation, extend over an area of nearly 100,000 square miles that includes the study region as well as most of western Kansas.

Permian evaporites in the study region formed primarily as a result of evaporation of sea water. The concentration of dissolved solids in sea water was raised by evaporation until a series of "evaporite" rocks was precipitated on the sea floor. The typical cycle of evaporite precipitation from sea water begins with deposition of a carbonate (limestone or dolomite), followed by deposition of gypsum or anhydrite, and finally by deposition of salt (halite, NaCl). Potash salts are precipitated in some evaporite series after halite deposition, but there is no evidence that potash has been deposited in Permian rocks of the Texas Panhandle or western Oklahoma.

In some parts of the study area, the evaporite cycle is represented by a vertical sequence consisting of dolomite at the base, gypsum (or anhydrite) in the middle, and salt at the top; such a cycle is typically from 5 to 50 feet thick. In other areas the evaporite cycle is distributed horizontally over large areas; thick sequences of limestone in the south grade laterally and successively northward into dolomite, gypsum (or anhydrite), and, finally, salt. In this way, thick sequences of salt have been deposited in some areas after the marine waters have been depleted of their carbonates and sulfates elsewhere as the water crossed the shallow inland sea.

For a number of reasons, the complete evaporite sequence is not found everywhere within the region: evaporite precipitation may have been interrupted in some areas by an influx of less-concentrated water, certain chemicals may have been depleted from the saline waters before the water entered a particular region, or the more soluble units (salt, and sometimes gypsum) may have been deposited in some places but later dissolved. The dissolution of salt has occurred, and is still occurring, at a number of places within the study region: salt layers are now largely dissolved at depths less than 500 to 800 feet below the present land surface.

In addition to the salt that occurs as discrete beds and layers of rock salt interbedded with thin layers of dolomite, gypsum, shale, and sandstone, much of the salt also occurs as isolated and/or intergrown crystals of halite partially surrounded by red shale, siltstone, or sandstone. These large crystals of halite probably developed and grew in the salt sediments either just below the sea bottom or in a supratidal environment shortly after deposition of the encompassing mud, silt, or sand. Little is known about the character of the salts in the Permian of this region because it has been cored at only a few localities in the Texas Panhandle and western Oklahoma. And none of the cores was available for inspection at this time.

PERMIAN SALT DEPOSITS

Salt deposits in the Texas Panhandle and western Oklahoma are of Permian age. In the two-state region, the Permian is a thick sequence of reddish-brown shales and sandstones (red beds) that contain six principal salt-bearing units. The thickness of Permian strata is greatest (nearly 7,000 feet) in the Anadarko and Palo Duro basins; these rocks are as thick as 5,000 feet in the Dalhart basin and are about 3,000 feet over the Amarillo uplift area. The six principal salt units are, in ascending order, Hutchinson salt, Lower Clear Fork (Lower Cimarron) salt, Upper Clear Fork (Upper Cimarron) salt, San Andres (Blaine) Formation salt, Seven Rivers Formation (Artesia Group) salt, and Salado-Tansill salt (fig. 5).

Persistent anhydrite and/or dolomite units are key beds that assist in the correlation of Permian rocks in the three principal basins. The most valuable stratigraphic units for such interbasinal correlation are the Wellington-Panhandle lime-Wichita Group, the Cimarron Anhydrite, the Blaine-San Andres Formation, and the Alibates-basal Doxey. The chart showing stratigraphic nomenclature for the region (fig. 5) summarizes my correlations of key beds, salt units, and red-bed units in the three major basins and shows the nomenclature that is generally applied in each province.

Overlying the Permian strata in the region are Triassic, Cretaceous, and Tertiary sediments. The Triassic consists mainly of

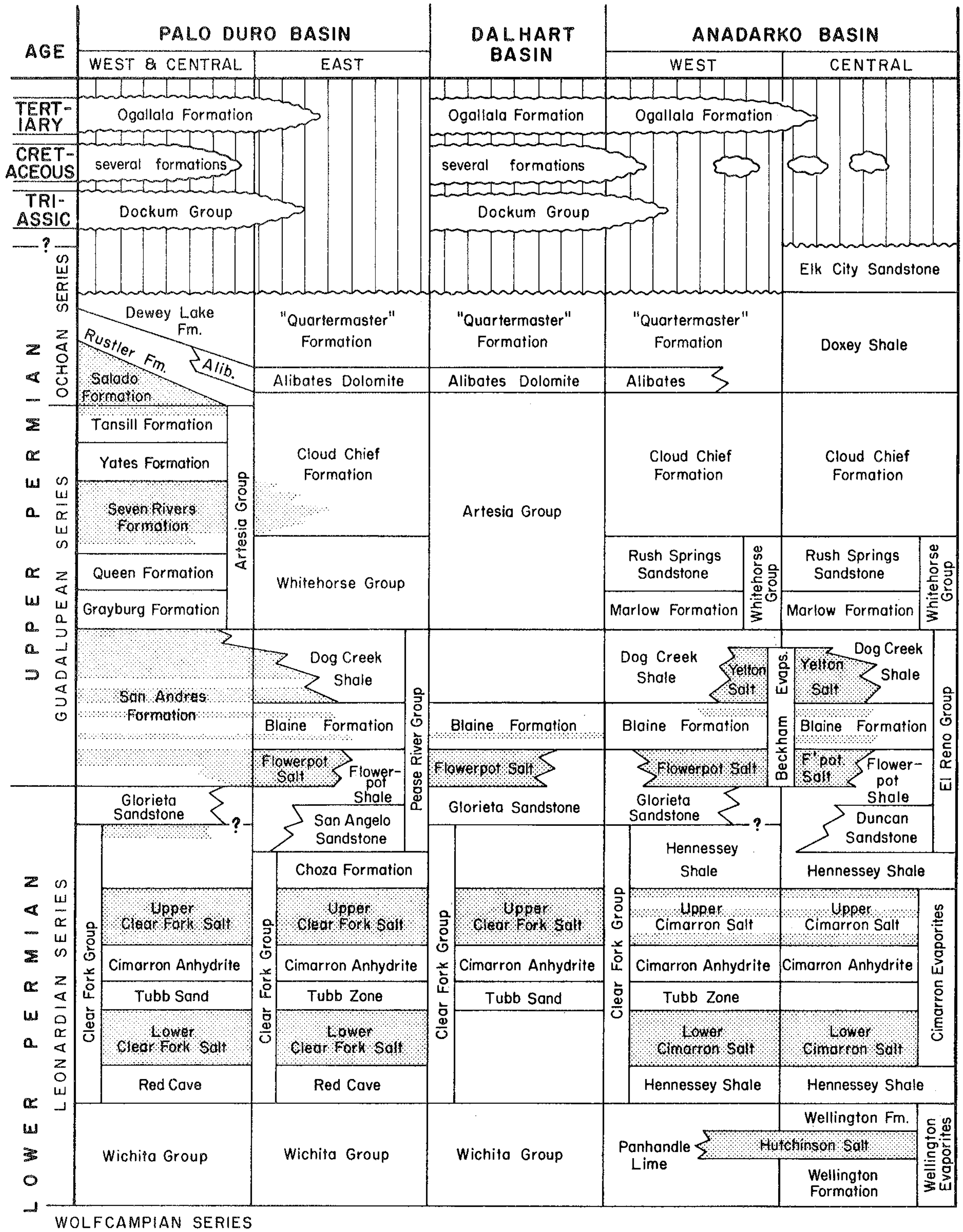


Figure 5. Stratigraphic nomenclature of Permian and younger strata in the Texas Panhandle and western Oklahoma. Principal salt units are shown in gray. Modified from data in Fay (1965), Jordan and Vosburg (1963), McKee and Oriel (1967a, b), and Tait and others (1962).

sandstone, shale, and conglomerate that are red, brown, gray, green, and purple; the thickness of the Triassic ranges from 100 to 1,500 feet in various parts of the region. Cretaceous strata are mainly sandstone, shale, and limestone that commonly are less than 100 feet thick. Tertiary sediments are mainly sand, silt, clay, gravel, and caliche that are tan, gray, and brown; the thickness of these typically unconsolidated sediments ranges from 100 to 400 feet in most areas.

Hutchinson Salt

Stratigraphic Relations.--The Hutchinson salt is the oldest Permian salt unit in the region. It is a part of the Wellington Formation and has been well documented in earlier studies in Kansas (Kulstad, 1959; Jones, 1965; Dellwig, 1968; Lefond, 1969). In Oklahoma it was considered part of the lower salt-anhydrite unit of the Wellington by Jordan and Vosburg (1963), but it is preferable to drop this usage in Oklahoma and the Texas Panhandle and refer to it as the Hutchinson salt member of the Wellington Formation.

The Hutchinson salt is underlain by a sequence of interbedded anhydrite and shale that is 200 to 300 feet thick. Individual beds within this sequence are typically 5 to 20 feet thick. The salt is overlain by 500 to 800 feet of shale (with some thin anhydrite beds) that extends up to the base of the overlying lower Cimarron salt. The thin anhydrite beds are about 100 feet above the salt and represent the upper anhydrite unit of the Wellington Formation (fig. 6).

Thickness, Distribution, and Depth.--The Hutchinson salt is about 200 to 500 feet thick and is limited to the north flank of the

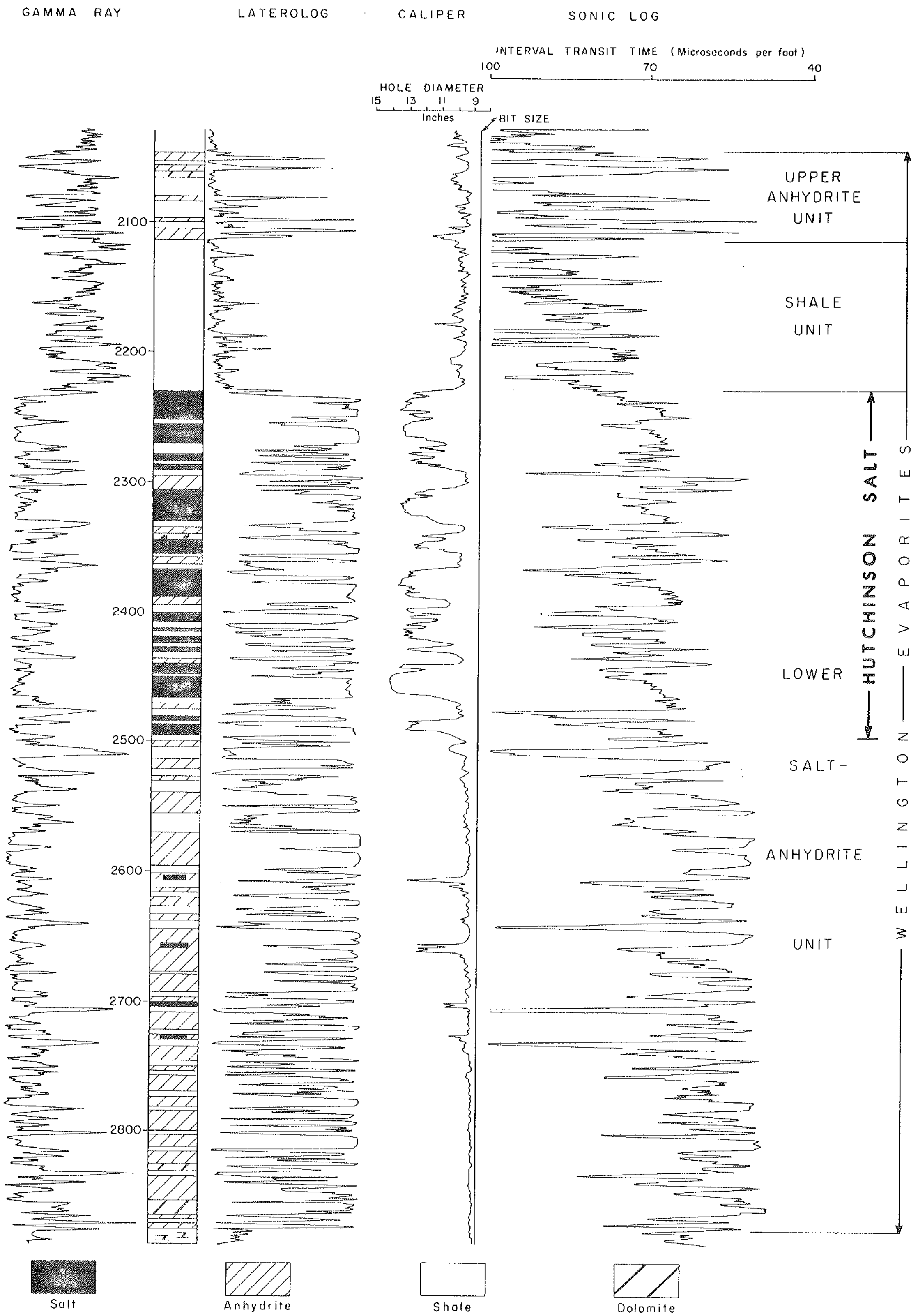


Figure 6. Subdivisions of the Wellington evaporites showing position of Hutchinson salt member. Logs of Gulf-Warren's Salt-Water-Disposal Well No. 1 Mocane Plant, sec. 18, T. 5 N., R. 25 ECM., Beaver County, Oklahoma. Lithology based on interpretation of various logs (from Jordan and Vosburg, 1963, p. 17).

Anadarko basin. It is present throughout most of northwestern Oklahoma and the northeastern corner of the Texas Panhandle (fig. 7, pl. 3). The maximum thickness of the salt unit is 565 feet in western Woodward County. The thickness of the salt is similar to its thickness farther north in much of Kansas (Kulstad, 1959; Lefond, 1969).

Salt beds within the Hutchinson unit grade laterally into shale to the east and into anhydrite and/or shale to the south and west. The thinning of the salt unit in these three directions is due to the loss of upper and/or lower salts as they grade laterally into other rock types. The present limits of the Hutchinson salt therefore reflect original depositional limits of the salt beds and they have not been modified by dissolution.

Depth to the top of the Hutchinson salt ranges from about 800 feet in Grant County in the northeast to about 4,000 feet near the axis of the Anadarko basin in Washita County (fig. 7). The top of the salt is 1,000 to 3,000 feet below the surface in an area that comprises about 12,000 square miles.

Character.--The Hutchinson member is a sequence of interbedded salt, anhydrite, and shale. Salt occurs in layers that typically are 5 to 25 feet thick, and they are separated by shale and/or anhydrite layers that commonly are 1 to 10 feet thick. Salt normally represents 40 to 55 percent of the rock in the sequence; anhydrite commonly is about 30 percent of the sequence, and shale is about 25 percent.

The purity of the salt in Oklahoma and Texas has not been reported upon, but it probably is as pure as farther north, where it is

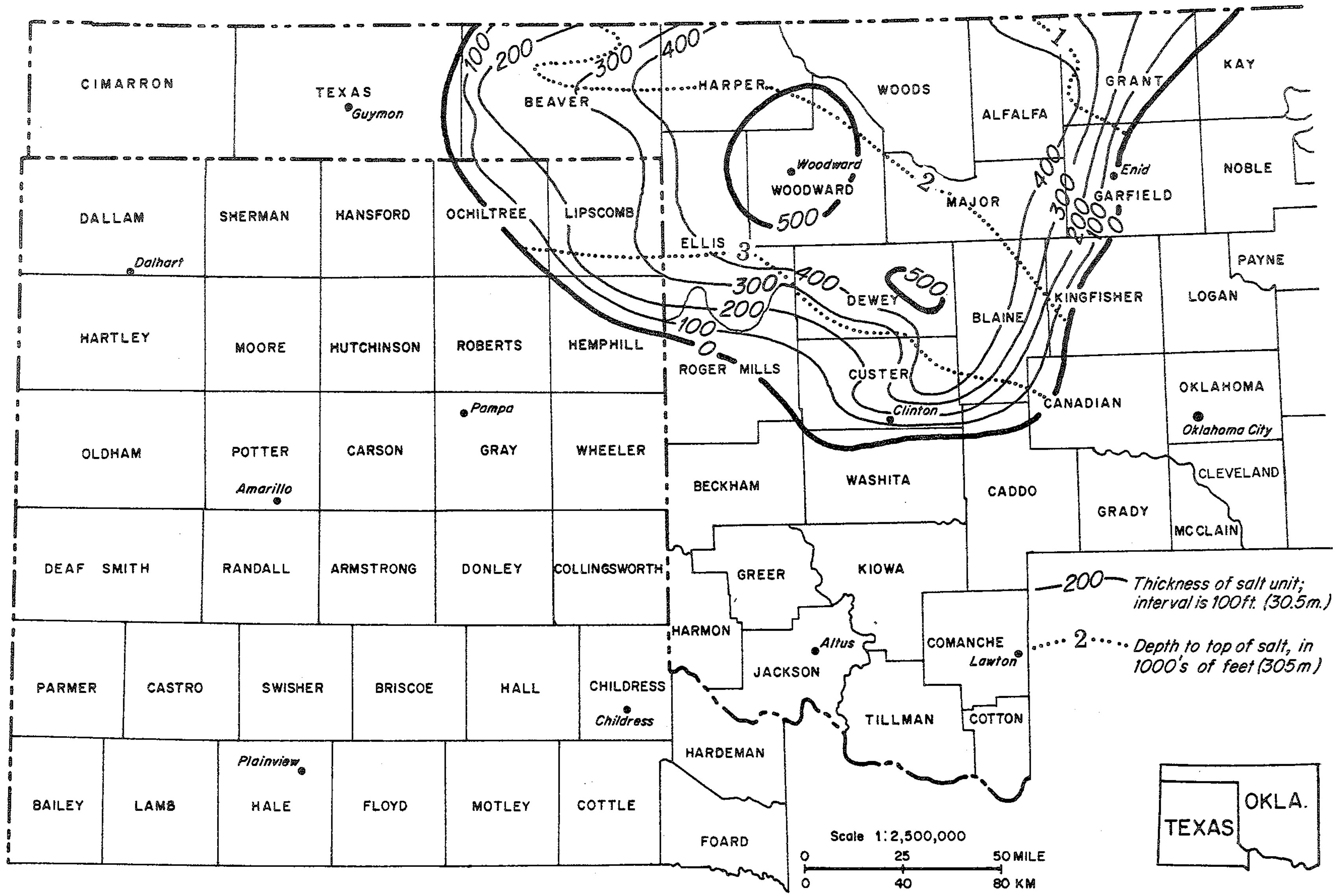


Figure 7. Map showing thickness and depth to top of salt-bearing strata in Hutchinson salt member of Wellington Formation (generalized from pl. 3).

being mined in central Kansas. Lefond (1969) reported that the Hutchinson is typically 95-97 percent NaCl and 2-4 percent $CaSO_4$ in the salt mines of central Kansas.

Lower Clear Fork (Lower Cimarron) Salt

Stratigraphic Relations.--In the Palo Duro basin, the name Lower Clear Fork salt is applied to the salt strata below the Cimarron Anhydrite and above the Wichita Group (fig. 5). Equivalent strata in the Anadarko basin, north of the Amarillo uplift, are called the Lower Cimarron salt (fig. 8). It is desirable to retain this dual nomenclature for the salt at the present time because these terms are well established in each area.

In the Anadarko basin, the Lower Cimarron salt is underlain by shale that commonly is 300 to 500 feet thick, at the base of which are the thin anhydrite beds of the uppermost Wellington evaporites. Above the Lower Cimarron salt is 25 to 100 feet of shale, and this in turn is overlain by the Cimarron Anhydrite.

In the Palo Duro basin, the Lower Clear Fork salt is commonly underlain by 300 to 500 feet of shale and anhydrite that are part of the Lower Clear Fork evaporites and the Red Cave. Directly beneath the Red Cave are the anhydrite, shale, and dolomite beds of the Wichita Group. Above the Lower Clear Fork salt, separating it from the Cimarron Anhydrite, is 100 to 200 feet of shale and sandstone of the Tubb sand.

Thickness, Distribution and Depth.--Distribution of the salt unit is limited to a 125-mile-wide area that extends northeast to southwest across the study area (fig. 9, pl. 4). The salt unit is present in

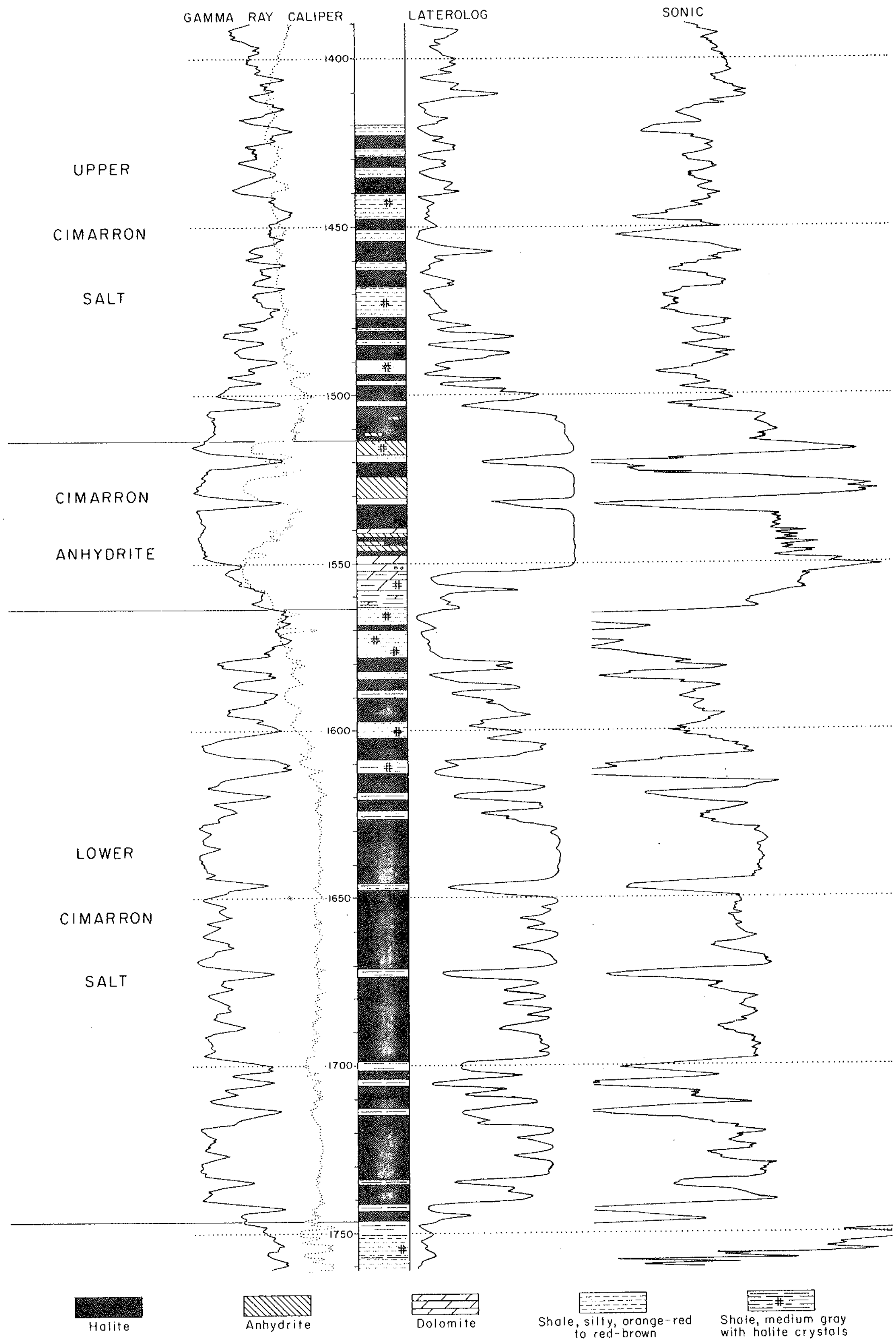


Figure 8. Lower Cimarron salt, Cimarron Anhydrite, and Upper Cimarron salt in Gulf-Warren Salt-Water-Disposal Well No. 1 Mocane Plant, sec. 18, T. 5 N., R. 25 ECM., Beaver County, Oklahoma. Lithology based on cores (from Jordan and Vosburg, 1963, p. 28).

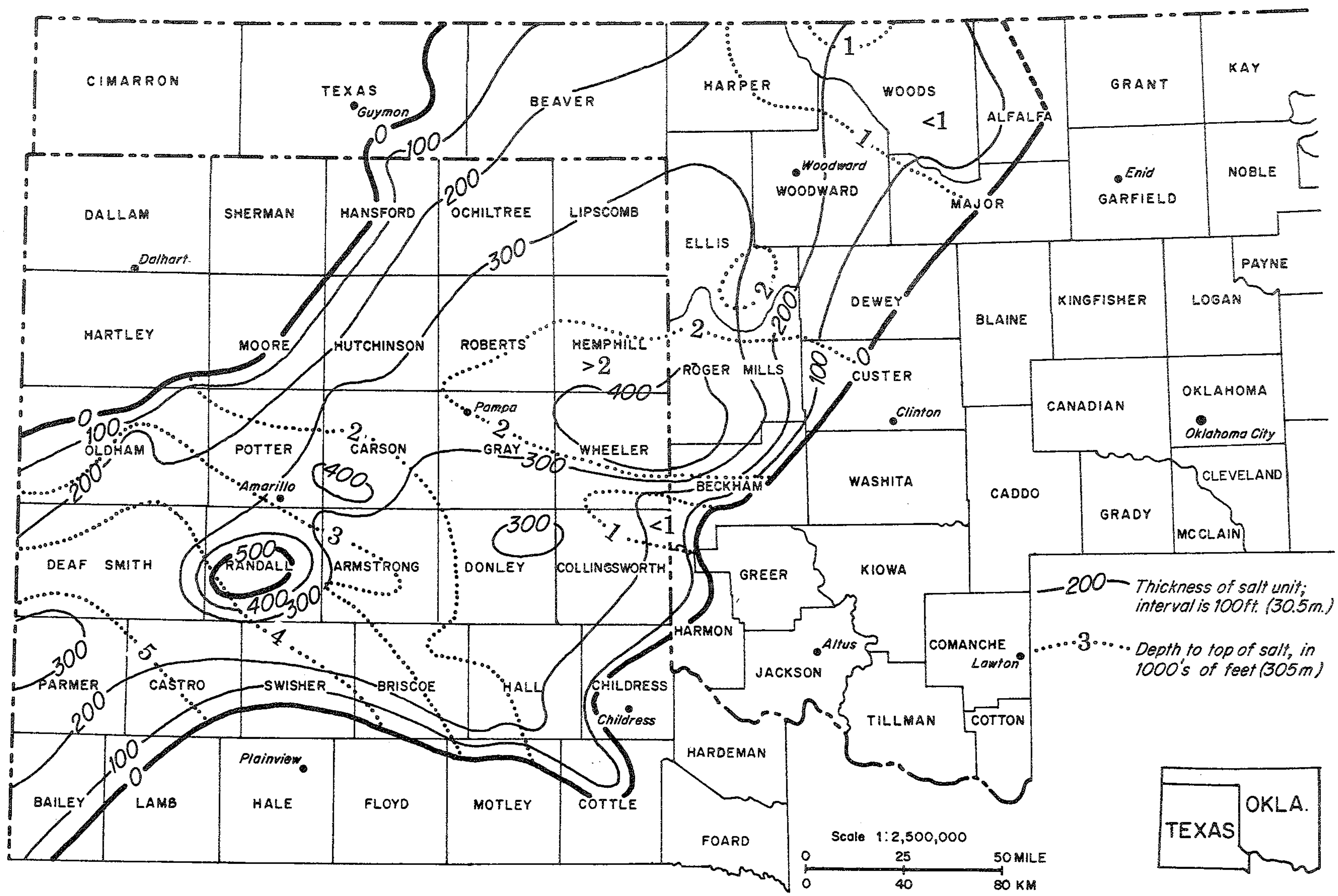


Figure 9. Map showing thickness and depth to top of salt-bearing strata in Lower Clear Fork (Lower Cimarron) salt (generalized from pl. 4).

most of the Anadarko basin; it extends across the Wichita Mountains uplift and is present in all but the southern part of the Palo Duro basin. The total thickness of the salt unit ranges from 200 to 500 feet in most of the area. The unit reaches its greatest thickness, 550 feet, in the Palo Duro basin in Randall County, Texas. It also reaches a thickness of 415 feet in southwest Carson County, Texas, and 420 feet in several areas of the Anadarko basin.

Salt strata grade laterally into shales to the east and northwest and into anhydrite and dolomite to the south. The present limits of salt in all areas represent the original depositional limits of salt layers, except in the extreme northeast, where salt is within several hundred feet of the land surface and apparently is being dissolved to produce natural brines that are emitted at Great Salt Plains in Alfalfa County, Oklahoma.

The top of the salt unit is several hundred feet to 5,800 feet below the land surface in the study region, with the depth generally increasing into the Anadarko and Palo Duro basins (fig. 9). Salt is less than 1,000 feet below the surface only in the northeastern corner of the area, and is more than 3,000 feet below the surface only in the southwestern part of the Texas Panhandle. It is between 1,000 and 3,000 feet below the surface in an area comprising approximately 20,000 square miles in the study region.

Character.--The salt unit is characterized as a sequence of interbedded salt, shale, and anhydrite. Individual beds of rock salt are typically 5 to 25 feet thick, and they are interbedded with shale in the Anadarko basin and with anhydrite and shale in the Palo Duro basin. Shale and anhydrite beds are typically 1 to 15 or 20 feet thick.

In most areas, salt makes up 30 to 70 percent of the total thickness of the Lower Clear Fork or Lower Cimarron salt. The unit is 78 percent salt in Beaver County, Oklahoma (fig. 8), where it is described from cores as halite with relatively few interbeds of reddish-brown or greenish-gray shale (Jordan and Vosburg, 1963). Much of the salt here is colorless and coarsely crystalline, but clay between the crystals gives a gray appearance. No other mineralogic or petrographic descriptions of the salt strata have been reported in the literature.

Upper Clear Fork (Upper Cimarron) Salt

Stratigraphic Relations.--The next youngest salt unit in the region lies directly above the Cimarron Anhydrite throughout the area. This salt is called the Upper Clear Fork salt in the Palo Duro and Dalhart basins and is called the Upper Cimarron salt in the Anadarko basin (figs. 3, 5).

The underlying Cimarron Anhydrite is typically 10 to 25 feet thick in the north half of the region and is typically 50 to 100 feet thick in the south. The Cimarron Anhydrite commonly consists of a series of anhydrite beds that are 5 to 15 feet thick and are interbedded with shale and dolomite.

Overlying the salt unit is 200 to 500 feet of shale and some salty shale, which extends up to the base of an overlying sandstone or the next salt unit.

Thickness, Distribution, and Depth.--The Upper Clear Fork salt is commonly 100 to 600 feet thick in the study area (fig. 10, pl. 5). It is more than 300 feet thick in most parts of the Palo Duro basin and reaches a maximum thickness of 600 to 650 feet in Parmer County, Texas, and adjacent areas.

In most parts of the Anadarko basin, only salty shale with some salt occupies the stratigraphic position of this principal salt unit. These salty strata are 50 to 600 feet thick, but they do not contain enough salt to be considered a major salt unit. In a similar manner, 300 to 550 feet of salty shale and some salt occupy this position in the Dalhart basin.

Salt strata grade laterally into shale to the north and east and into anhydrite and/or dolomite to the south. The present limits of salt within this unit appear to be depositional limits in almost all areas; only in the far east (Blaine County, Oklahoma) is solution of salt apparently going on at the present time, whereas in other areas to the north and northwest salt apparently has been dissolved at some time in the past.

The top of the Upper Clear Fork salt is 1,000 to 3,000 feet below land surface in a large area extending from the southeastern part of the region across the north-central and northwestern parts of the region (fig. 10). This area includes both the Dalhart basin and the eastern and northern parts of the Palo Duro basin. It embraces about 5,000 square miles where the salt is at least 200 feet thick. The top of the salt is deepest to the southwest, in the central and western Palo Duro basin, where it is 3,000 to 5,100 feet below the surface.

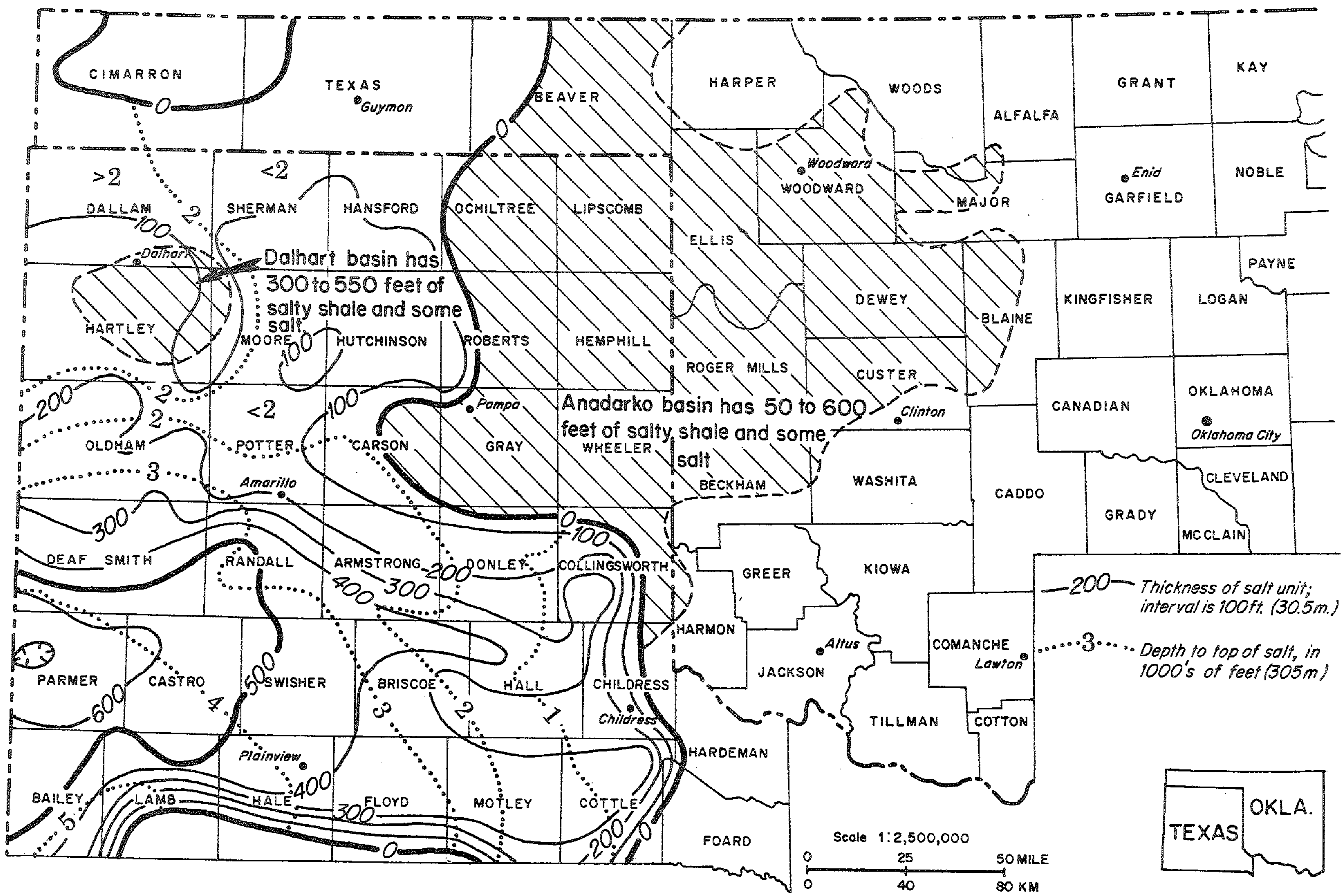


Figure 10. Map showing thickness and depth to top of salt-bearing strata in Upper Clear Fork (Upper Cimarron) salt (generalized from pl. 5).

Character.--The only known cores of this unit are from eastern Beaver County, Oklahoma, where the Upper Cimarron salt is mostly shale and contains some salt (fig. 8). At this site, about one-third of the 184-foot-thick section consists of salt beds 1 to 3 feet thick, and the remainder consists principally of shale and salty shale (Jordan and Vosburg, 1963). The cores are of interbedded and intermingled halite and reddish-brown shale, and most of the halite contains clay that imparts an overall dull-reddish-brown appearance.

Based upon the study of electrical logs elsewhere in the region, the Upper Clear Fork salt consists of salt beds 5 to 20 feet thick interbedded with shale, anhydrite, and dolomite beds that also are 5 to 20 feet thick. Non-salt strata consist mostly of shale in the north part of the study area and consist of shale, anhydrite, and dolomite in the south. Layers of salt generally make up 30 to 50 percent of the unit in most parts of the study region.

San Andres (Blaine) Formation Salt

Stratigraphic Relations.--Salt deposits associated with the San Andres Formation and the Blaine Formation are widely distributed in the study region. They are referred to the San Andres Formation in the central and western Palo Duro basin (fig. 11), but in the Anadarko, Dalhart, and eastern Palo Duro basins they are subdivided into (in ascending order) the Flowerpot salt, the Blaine Formation, and the Yelton salt (figs. 5, 12). In the Anadarko basin they have been called Beckham evaporites by Jordan and Vosburg (1963).

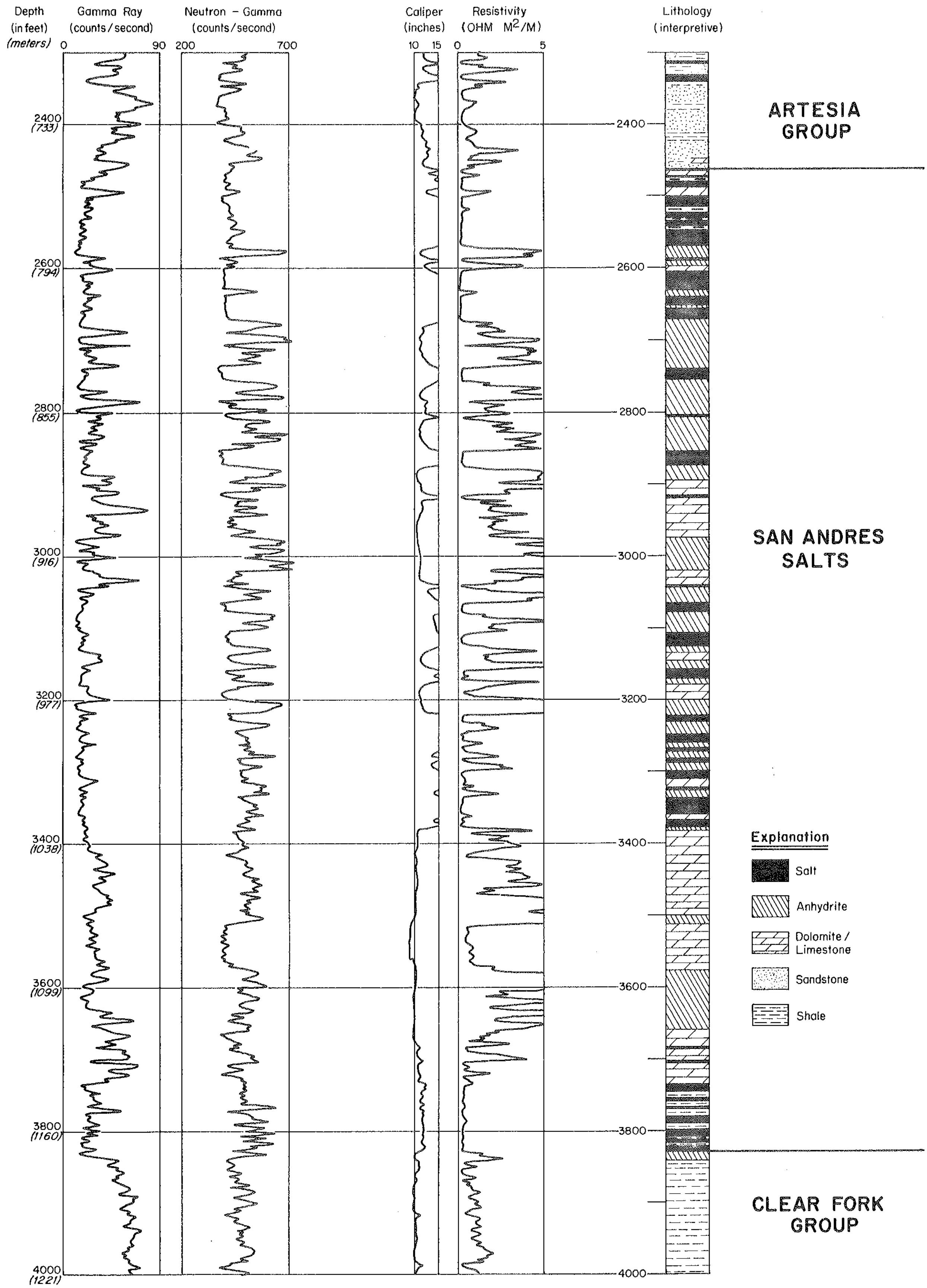


Figure 11. Salt and other rocks in the San Andres Formation of the Palo Duro basin. Logs from Consolidated Gas and Equip. Co., No. 1 Thompson, sec. 17, blk. C-4, surv. L&SV, south-central Swisher County, Texas. Lithology based on interpretation of logs.

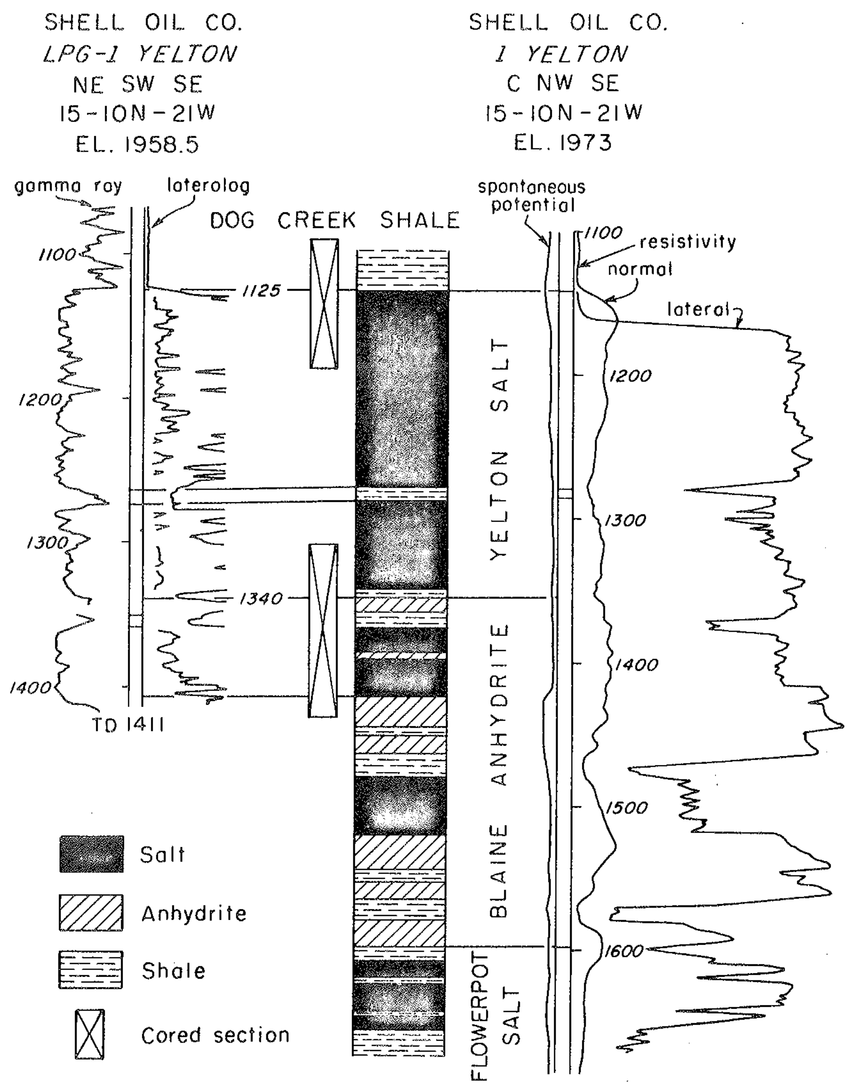


Figure 12. Stratigraphic sequence of Flowerpot salt, Blaine Formation, and Yelton salt in Anadarko basin, Beckham County, Oklahoma (from Jordan and Vosburg, 1963, p. 46). These units, constituting the Beckham evaporites in the Anadarko basin, are equivalent to the San Andres Formation of the Palo Duro basin.

Salts of the San Andres and equivalent formations are underlain by shale or by the Glorieta Sandstone in all areas. The Glorieta is a salt-water-bearing sandstone 50 to 200 feet thick in the western half of the Texas and Oklahoma Panhandles. In the southwest the Glorieta is underlain by about 100 feet of salt beds that are herein considered part of the San Andres salt. The Duncan and San Angelo Sandstones are restricted to the eastern part of the study area and are separated from the base of the salt by at least 50 to 100 feet of shale.

Overlying the salt unit is 50 to 200 feet of shale that separates this salt from the sand and shale of the Whitehorse or Artesia Group.

Thickness, Distribution, and Depth.--The San Andres salt and the salts associated with the Blaine Formation make up the thickest salt-bearing unit in the study area. Salt-bearing strata are 800 to 1,590 feet thick in the central and western parts of the Palo Duro basin and are 400 to 720 feet thick along the axis of the Anadarko basin (fig. 13, pl. 6). Elsewhere, the salt-bearing unit is typically 200 to 400 feet thick.

Salt is now limited to the basin areas and has been dissolved from areas where it once was present over the Wichita Mountains, Amarillo, and Cimarron uplifts. Salt may not have been deposited on the Bravo dome, although data from this area are not conclusive. Evidence for dissolution of salt in this unit is: (1) the abrupt thinning of these salts where they are at shallow depths (commonly 500 to 800 feet below the surface; (2) the absence of salt at almost all places where it would be less than 500 feet below the surface; (3) the collapse and disruption of strata above some areas where salt is believed to have been dissolved;

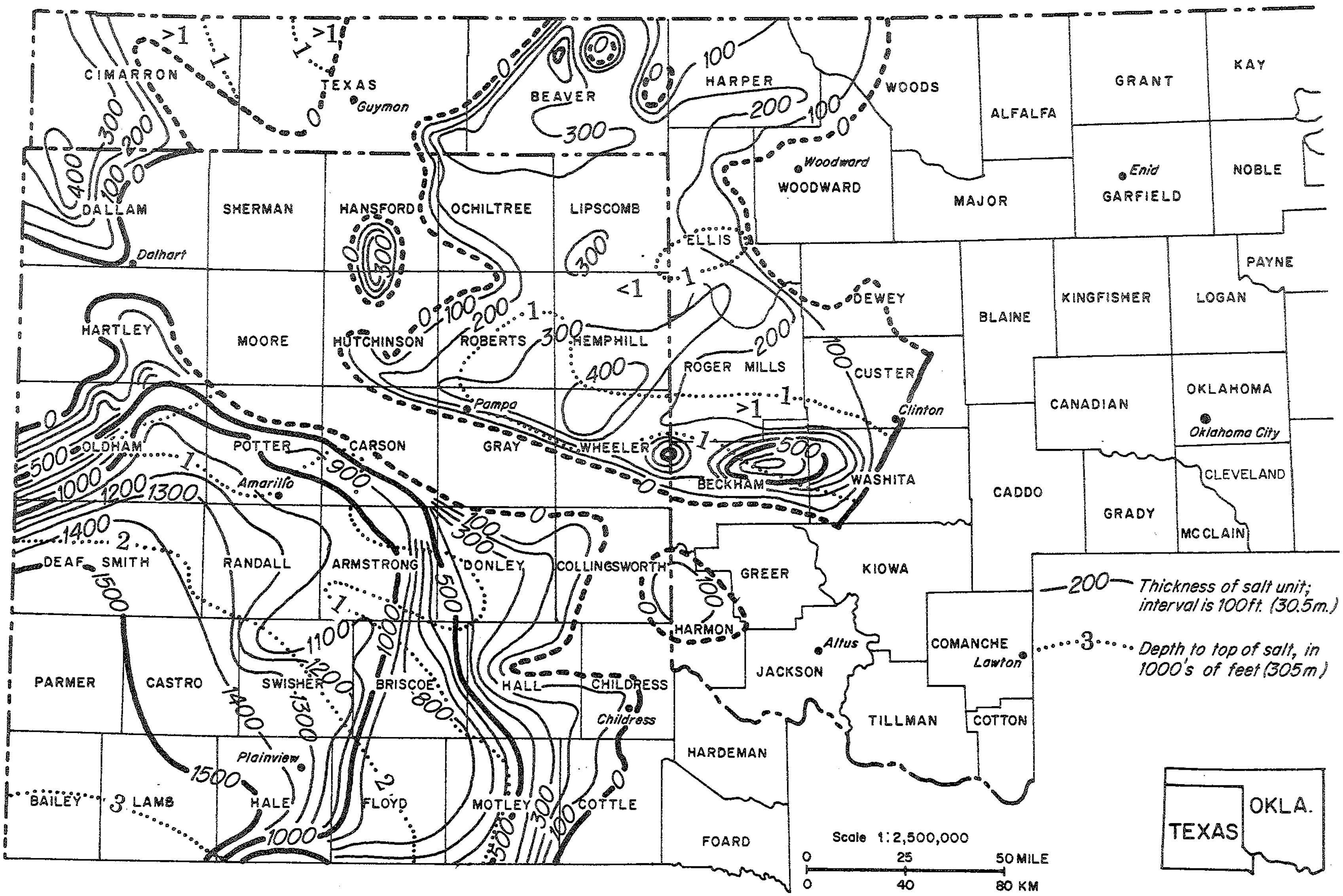


Figure 13. Map showing thickness and depth to top of salt-bearing strata in San Andres Formation and equivalent units (Flowerpot salt, Blaine Formation, and Yelton salt). Generalized from pl. 6.

and (4) the presence of outlying undissolved masses of salt in southwestern Oklahoma and the northern part of the Texas Panhandle. Further evidence lies in the fact that these salts are being dissolved actively on the east side of the salt area: natural brine formed by salt dissolution is reaching the land surface in Harmon, Woods, Woodward, and Harper Counties, Oklahoma, and in Hall, Childress, and Cottle Counties, Texas.

The depth to the top of the salt is less than 1,000 feet in most parts of the Anadarko basin, but it is 1,000 to 1,390 feet along the axis of the Anadarko basin. The top of the salt is 1,000 to 3,000 feet below the surface in most parts of the Palo Duro basin, and the depth increases to a maximum of 3,240 feet in the far southwest. In the Dalhart basin, the depth to the top of salt is 1,200 to 1,765 feet in most areas. The salt-bearing unit is more than 200 feet thick and is from 1,000 to 3,000 feet below the surface in 11,000 square miles of the Palo Duro basin, in 1,500 square miles of the Anadarko basin, and in 1,000 square miles of the Dalhart basin.

Character.--Salt occurs in separate beds 5 to 20 feet thick in some areas, and in other areas it occurs in massive units that are 50 to 200 feet thick with only a few thin layers of shale. Non-salt strata are shale and some anhydrite in the north and anhydrite, dolomite, and shale in the south.

The entire San Andres Formation is commonly 20 to 40 percent salt in the Palo Duro basin, whereas the individual massive salt units are as much as 90 percent salt. In the Anadarko and Dalhart basins, salt generally makes up 40 to 70 percent of the total thickness of the mapped unit, and constitutes 90 percent of some of the individual massive salt units.

Seven Rivers Salt

Stratigraphic Relations.--The Seven Rivers Formation is in the middle of the Artesia Group, and it contains salt only in the southern part of the Texas Panhandle. The boundaries of the Seven Rivers Formation are the same as those established by Jones (1974) in the Clovis-Portales area of New Mexico, just west of the study area. The Seven Rivers salt embraces the entire Seven Rivers Formation in the southwestern part of the area (fig. 14), but is limited to the middle and/or upper part of the formation to the north and east. My study indicates that the Seven Rivers Formation is equivalent to the lower part of the Cloud Chief Formation farther to the east and northeast (fig. 5).

Underlying the Seven Rivers salt are 300 to 400 feet of shales, interbedded with sandstones and anhydrites, that make up the Queen and Grayburg Formations (Whitehorse Group). Overlying the Seven Rivers salt are shales, locally interbedded with anhydrite and sandstone; the shales are about 100 feet thick where overlain by the Salado-Tansill salt unit and are several hundred feet thick (up to the base of the Alibates Bed) where the Salado-Tansill salt is not present.

Thickness, Distribution, and Depth.--Salt in the Seven Rivers Formation is limited to the central and western parts of the Palo Duro basin (fig. 15, pl. 7). The thickness of the salt unit ranges from about 100 feet in the north to more than 500 feet in the south, and it reaches

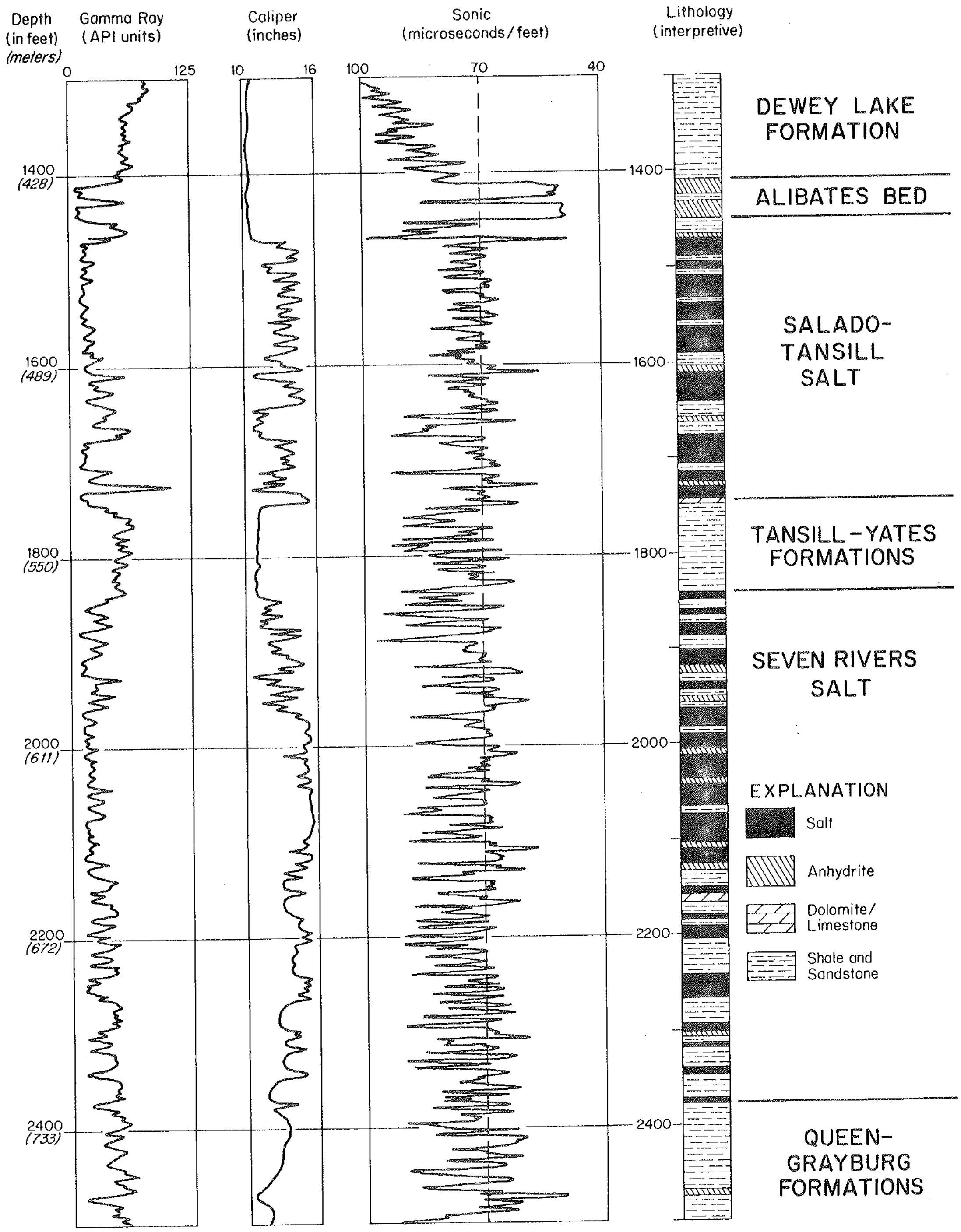


Figure 14. Salt and other rocks in Seven Rivers and Salado-Tansill salts in Palo Duro basin. Logs from Mobil Oil Corp., No. 1 Carl Laney, sec. 8, blk. JD, surv. EL&RR, west-central Hale County, Texas. Lithology based on interpretation of logs.

Figure 15. Map showing thickness and depth to top of Seven Rivers salt (generalized from pl. 7).

530 to 540 feet along the axis of the basin. The salt is somewhat thinner over the Matador arch.

The abrupt thinning and disappearance of salt in the eastern part of the Palo Duro basin is due to dissolution of the salt at shallow depth. The apparent full thickness of the salt is present at depths of 540 to 980 feet, and at greater depths, but just to the east of this area salt is missing where it should be 300 to 640 feet below the surface. Natural brines being emitted in Armstrong, Briscoe, and Hall Counties, Texas, apparently are forming by subsurface dissolution of this salt. The northern limit of the salt appears to be a depositional limit, where the salt beds grade laterally into shale and some sandstone.

The depth to the top of the Seven Rivers salt is 1,000 to 2,000 feet in almost all parts of the Palo Duro basin. The maximum depth is 2,275 feet in Bailey County, Texas. Salt is at least 200 feet thick and more than 1,000 feet below the surface in an area of about 7,500 square miles.

Character.--Salt beds in the Seven Rivers Formation are typically 5 to 20 feet thick and are interbedded with shale and with some anhydrite and sandstone. Salt makes up about 50 percent of the unit throughout the area. These data are interpreted from electrical logs and sample logs, inasmuch as cores of the Seven Rivers salts are not available for study.

Salado-Tansill Salt

Stratigraphic Relations.--Salado-Tansill salt is the youngest salt in the region, and it is limited to the southern part of the Texas

Panhandle. The salt unit embraces all of the Salado Formation and the upper part of the Tansill Formation, as established by Tait and others (1962); there is no convenient way of separating the salts of these two formations in the study area.

The underlying 100 feet of shale, anhydrite, and sandstone separates this salt from a deeper Seven Rivers salt (fig. 14). Overlying the Salado is 10 to 50 feet of shale that separates the Salado-Tansill salt from the Alibates Bed (top of Rustler Formation).

Thickness, Distribution, and Depth.--The Salado-Tansill salt is restricted to the south-central part of the Palo Duro basin. The unit is typically 100 to 300 feet thick and reaches a maximum thickness of 340 feet in southern Hale County, Texas (fig. 16, pl. 8). The unit is slightly thinner over parts of the Matador arch.

The eastern margin of the salt unit is abrupt, owing to dissolution of the salt at shallow depth. The salt is still present in areas where it is more than 400 feet below the surface, but it is absent just to the east where its stratigraphic position is less than 400 feet below the surface. Natural brines formed by the dissolution of this salt may be reaching the surface in Briscoe County, Texas.

In a northerly direction the salt pinches out between, or grades laterally into, shales of the lower Rustler Formation or upper Tansill (Cloud Chief) Formation.

The depth to the top of the Salado-Tansill salt is 1,000 to 2,000 feet in almost all places where it is present. It is a maximum of 2,070 feet below the surface in southern Bailey County, Texas. The

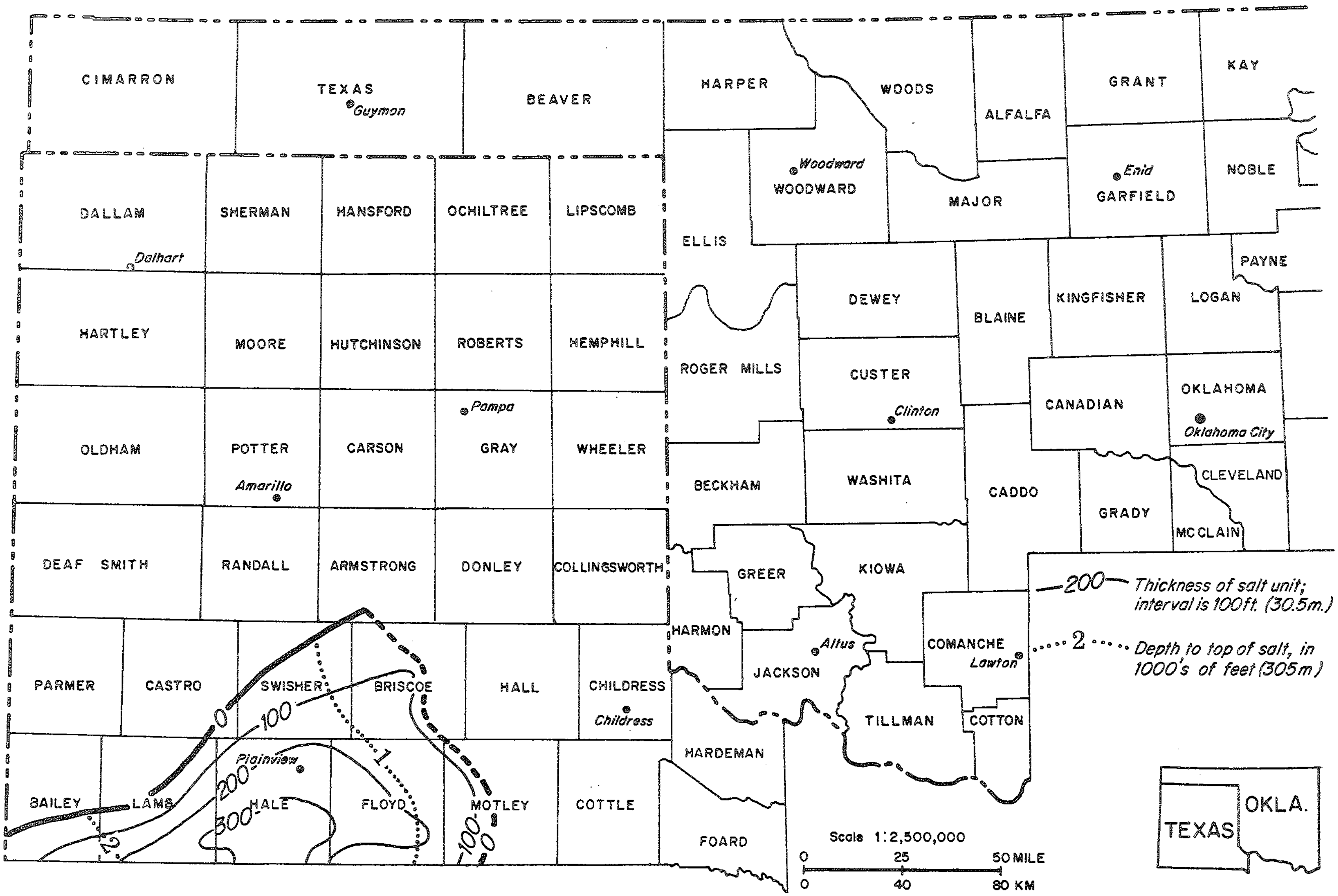


Figure 16. Map showing thickness and depth to top of Salado-Tansill salt unit (generalized from pl. 8).

salt is at least 200 feet thick and is 1,000 to 2,000 feet deep in an area of about 1,500 square miles.

Character.--Individual salt beds in this unit are typically 5 to 30 feet thick and are interbedded with shale and minor amounts of anhydrite. The non-salt beds are commonly 3 to 20 feet thick. Salt constitutes 40 to 70 percent of the unit in most areas. These data are based on interpretations of electrical logs and sample logs; cores of the Salado and Tansill Formations are not available for study.

HYDROLOGY

Surface Water

Surface drainage consists of east-flowing streams and rivers (fig. 17). The headwaters for these rivers are either in eastern New Mexico or within the study region. Principal rivers crossing the area are, starting on the north: Salt Fork of Arkansas, Cimarron, North Canadian, Canadian, Washita, North Fork of Red, Salt Fork of Red, Prairie Dog Town Fork of Red, Pease, and Wichita Rivers. Also, in the southwest are tributaries to the Salt Fork of Brazos and Double Mountain Fork of Brazos Rivers.

These rivers are mostly supplied by precipitation and runoff, but some of them are locally recharged by springs emerging from the Ogallala and from sandstone, gypsum, and dolomite aquifers in the Permian. Average annual precipitation is 16 to 22 inches in the Texas and Oklahoma Panhandles and is 22 to 30 inches in the remainder of western Oklahoma.

Streams and rivers crossing the region contain fresh water in the High Plains and in much of the area where they flow on Permian bedrock. But the surface water is degraded by natural sodium chloride brines emitted at 16 salt plains and salt springs in western Oklahoma and in the southeastern Texas Panhandle areas where the rivers cross the shallow eastern limits of several salt units (Ward, 1963; Swenson, 1973, 1974). Salt units being dissolved in western Oklahoma are the Lower Cimarron salt, the Upper Cimarron salt, and the Flowerpot salt; those

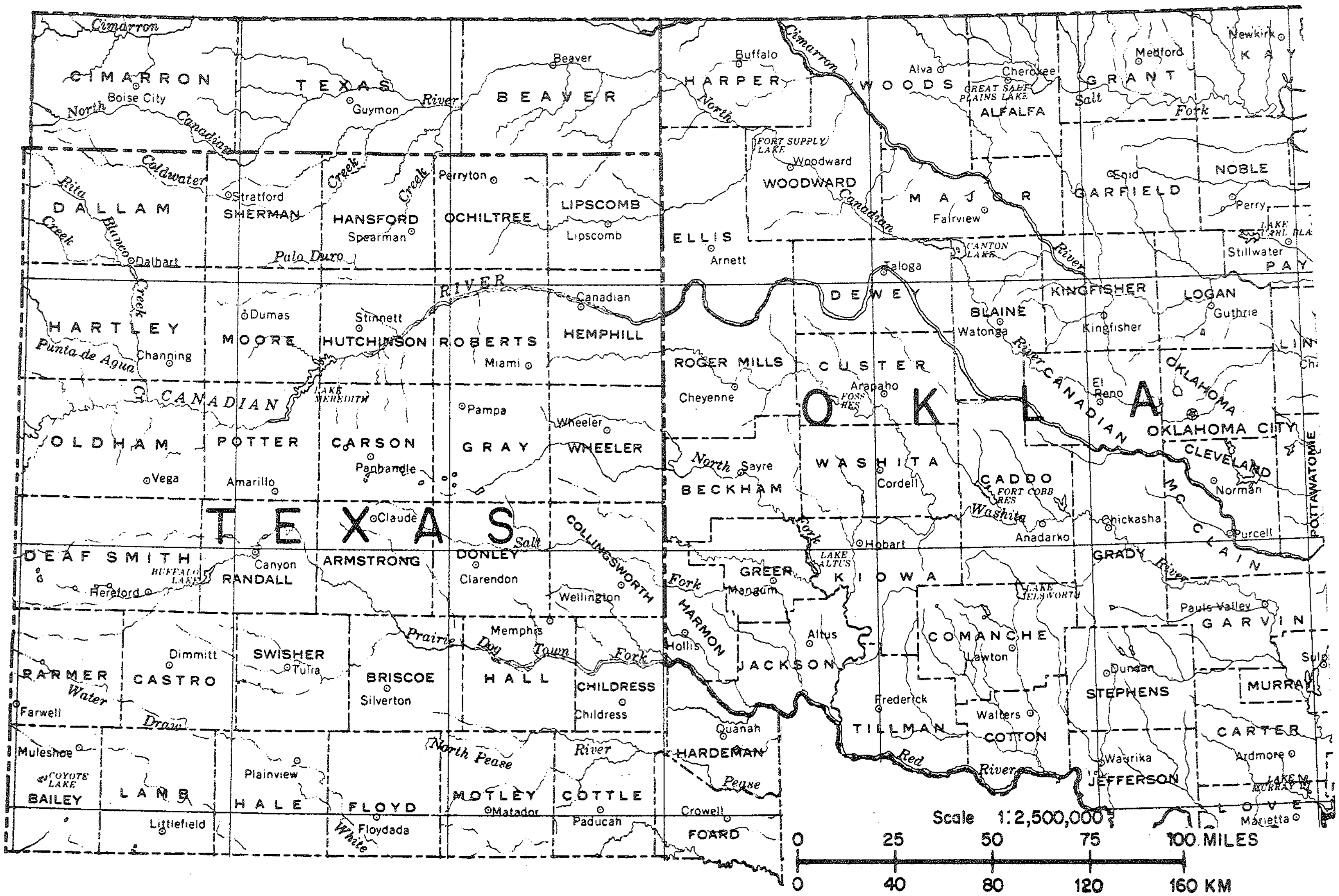


Figure 17. Map showing principal surface drainage in Texas Panhandle and western Oklahoma.

being dissolved in the southeastern Texas Panhandle include the San Andres salts, the Seven Rivers salts, and the Salado-Tansill salts. In all cases, it appears that local meteoric water is migrating down to the salt beds and is returning to the surface as a saturated brine.

Ground Water

All bedrock formations in the region, from the Santa Rosa Sandstone (Dockum Group) of Triassic age to the basement rocks of Precambrian age, contain strongly saline water except locally at and near the outcrop, where they may be flushed by meteoric recharge (Swenson, 1974). Included in this group of salt-water-bearing formations are the Tubb sand and the Glorieta Sandstone; also, the Duncan, San Angelo, Marlow, and Rush Springs Sandstones contain salty water where they are more than several hundred feet below the surface and have not been flushed.

In contrast to the strongly saline waters mentioned above, there are some excellent fresh-water aquifers in the Texas Panhandle and in western Oklahoma. The Ogallala Formation of Tertiary age is the major source of ground water throughout the High Plains region, and it is widely used for municipal and irrigation water (Irwin and Morton, 1969). Also, large yields of fresh water from Permian rocks are obtained from the Rush Springs and Elk City Sandstones in western Oklahoma, and fairly good (gypsiferous) irrigation water comes from the Blaine Formation in southwestern Oklahoma and the southeastern part of the Texas Panhandle.

The Santa Rosa Sandstone (Dockum Group) of Triassic age locally produces fresh water in the Oklahoma Panhandle, and the Dakota and Cheyenne Sandstones of Cretaceous age are good aquifers in the western Oklahoma Panhandle and nearby areas. The Edwards-Trinity aquifer of Cretaceous age provides water in the southwestern part of the Palo Duro basin. Throughout the region, thick deposits of Quaternary terrace and alluvial material also yield large supplies of fresh water along present-day and ancient courses of the major rivers.

SALT DISSOLUTION

Dissolution of salt beds is now occurring at shallow depths, mainly in the eastern part of the study region (east of the High Plains). This phenomenon is important because of its adverse effect on long-term safe storage of radioactive waste in underground salt beds.

Saturated NaCl brines are being emitted at the surface at about 16 natural salt plains and salt springs in western Oklahoma and the southeastern corner of the Texas Panhandle (Ward, 1963; Swenson, 1973, 1974). These reported springs are principally in Alfalfa, Harper, Woods, Woodward, Blaine, Beckham, and Harmon Counties, Oklahoma, and in Armstrong, Briscoe, Hall, Childress, and Cottle Counties, Texas. It is estimated that a total of about 8,000 tons of NaCl are emitted daily through these salt springs (Ward, 1963).

Where salt deposits are near the land surface, ground waters can migrate through the surrounding rocks and dissolve the salt. The water must continue to move through the system, otherwise water in contact with the salt becomes saturated and further solution is not possible. The movement of water occurs through aquifers (sandstone beds and porous or cavernous layers of gypsum, dolomite, and salt) and also through fractures, joints, sinks, collapse features, and other openings that enable vertical interconnections between formations. Radioactive-isotope (tritium) dating of brine discharged at several sites indicates that most of the water is meteoric water that has moved down from the land surface and has migrated only short distances to the discharge areas (Ward, 1963; Swenson, 1973, 1974).

Data presented in this report indicate that salt has been and is being dissolved at fairly shallow depths. The Lower Cimarron salt is absent in an area where it should be less than several hundred feet below the surface in the vicinity of the Great Salt Plains in northwestern Oklahoma (pl. 4). Natural brines emitted in Blaine County, northwestern Oklahoma, appear to be derived by dissolution of Upper Cimarron salt about 400 to 600 feet below the surface. Salts associated with the San Andres and Blaine Formations (including the Flowerpot and Yelton salts) generally are thin or missing in areas where they would be less than 500 feet deep and generally are fully present where more than 800 feet deep: the depth at which these salts are still present, but at least partly dissolved, appears to range from a minimum of 30 feet to a maximum of 1,000 feet below the surface (pl. 6).

Dissolution of the San Andres-Blaine salts over the Amarillo uplift and in the western end of the Anadarko basin, where the salt is absent at depths of 800 to 1,100 feet, may be the result of an earlier episode of dissolution during Triassic or perhaps Tertiary time. The land surface was closer to the salts during Triassic through Tertiary time, thus possibly causing fresh ground water at that earlier time to come into greater contact with the salt. Furthermore, there are no reports of modern-day emissions of brine at the surface in the area.

The Seven Rivers salt is dissolved at depths shallower than 590 feet to 980 feet (pl. 7), and the Salado-Tansill salt is dissolved in areas where it is less than 435 to 780 feet below the surface (pl. 8).

Thus, a tentative observation can be made that salt is being dissolved most commonly at depths of 500 to 800 feet below the surface, although at some places the dissolution occurs as deep as 1,000 feet and at other places salt is still present as shallow as 30 feet below the surface. The areas where the salt beds are abruptly terminated by solution appears to coincide with the areas of brine emissions on the eastern side of the study region, and thus underground waste storage should not be considered at a site near these dissolution zones. The rate of dissolution and the relationships between the dissolution zones and the brine-emission sites are not clearly understood and need to be studied in more detail.

SEISMIC ACTIVITY

Recorded seismic activity in the Texas Panhandle and in western Oklahoma is low, compared to most other parts of the United States. Earthquakes of Modified Mercalli Intensity V (MM V) or greater are sparse in the region (fig. 18). The only part of the study area underlain by salt that has undergone significant activity is on the flanks of the Amarillo uplift and along its west-northwesterly continuation across the Bravo dome and the Dalhart basin. Areas that are free of recorded earthquakes of MM V or greater are the central and most of the western Anadarko basin (the eastern Anadarko basin has had 7 events of MM V to MM VII at El Reno and Edmond) and all parts of the Palo Duro basin, except in the far north adjacent to the Amarillo uplift and the Bravo dome. The Palo Duro basin appears to be most favorable seismically for radioactive-waste emplacement, although the two other basins may also have areas that will be found suitable.

The entire region of investigation is within zone 1 on the seismic-risk map prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969). Only seven earthquakes of MM V or greater are known within the salt-study region, and all of them are in the Texas Panhandle (Coffman and von Hake, 1973; Person, 1974). Two of the earthquakes occurred near the town of Panhandle, in Carson County: one in 1917 (MM VI), and the other in 1925 (MM V). Two earthquakes also occurred near Borger, in Hutchinson County: one in 1936 (MM V), and the other

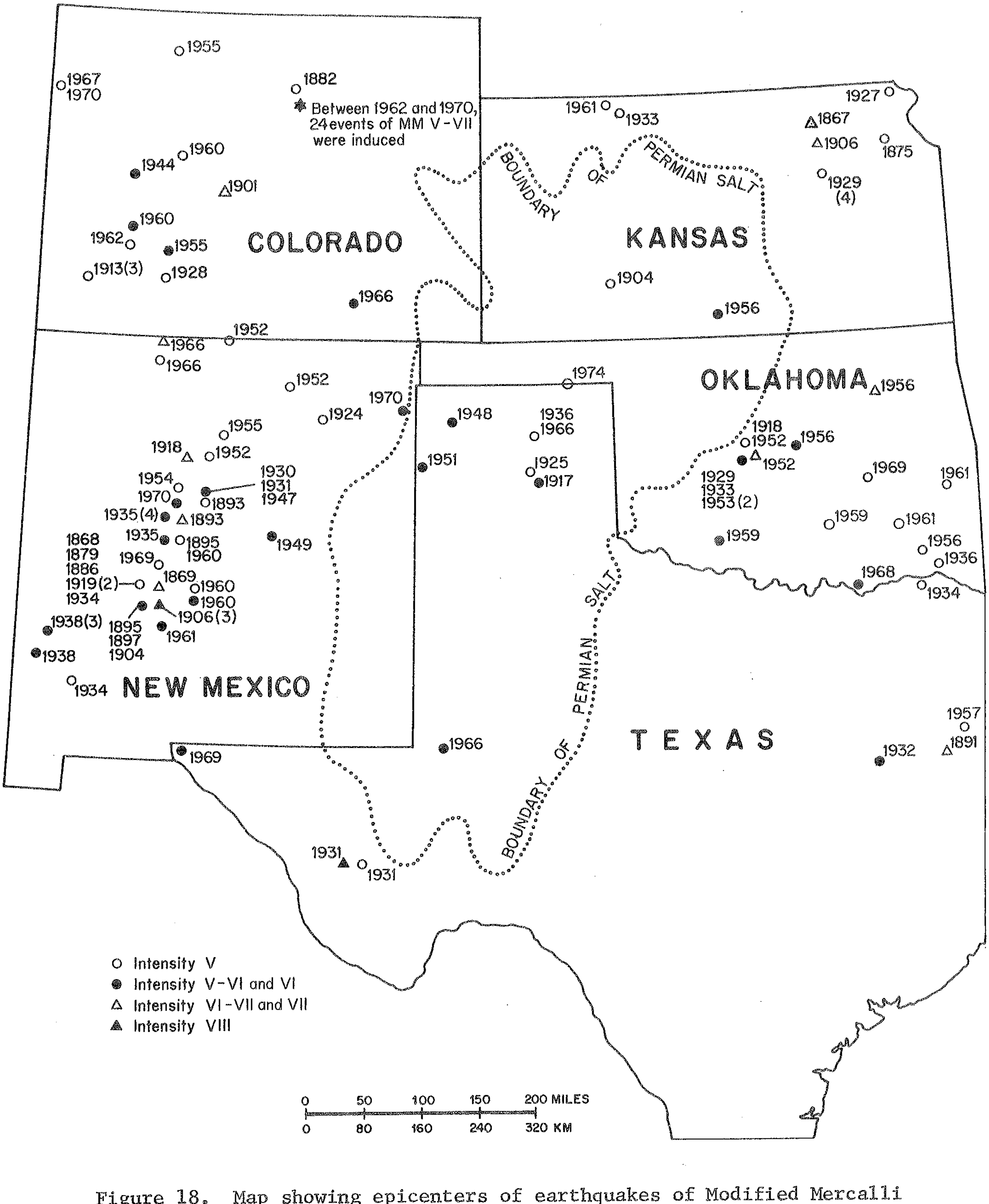


Figure 18. Map showing epicenters of earthquakes of Modified Mercalli Intensity V, or greater, in southwestern United States through 1970 (except for 1974 event in Texas Panhandle) (from Coffman and von Hake, 1973; Person, 1974).

in 1966 (MM V). The fifth quake was near Dalhart in Hartley County, in 1948 (MM VI). The sixth earthquake was in western Oldham County, just east of Nara Visa, New Mexico, in 1951 (MM VI). The remaining event occurred on February 15, 1974 (MM V), and according to newspaper accounts it centered on the Perryton area in Ochiltree County.

Several earthquakes greater than MM VI have occurred outside the salt-study area in the surrounding states. Oklahoma earthquakes include the El Reno event in 1952 (MM VII), and the Catoosa event in 1956 (MM VII). An earthquake was reported at Manhattan, Kansas, in 1906 (MM VII). One of the largest earthquakes in nearby areas was the one at Valentine, in West Texas, during 1931 (MM VIII). A total of four earthquakes of MM VII, VII-VIII, and VIII have been reported from Socorro, New Mexico, with one event in 1869 and the other three events in 1906. Two other earthquakes in New Mexico include an event near Valencia in 1893 (MM VII) and another event in Santa Fe County during 1918 (MM VII-VIII). One earthquake occurred along the New Mexico-Colorado border in 1966 (MM VII). An earthquake near Denver, Colorado, in 1967 (MM VII) was one of a series of events induced by the subsurface injection of waste materials.

Data used in compiling this report were taken mainly from Coffman and von Hake (1973), but additional information is contained in reports by Docekal (1970) and Northrop and Sandford (1972).

MINERAL RESOURCES

Oil and Gas

Major natural-gas fields and some oil fields are present within the study region. Natural gas and some oil are produced in the Panhandle field over the Amarillo uplift and in the Hugoton field overlying the Cimarron arch and Keyes dome and the western part of the Anadarko basin (fig. 19). Production in these fields is mainly from Lower Permian and Pennsylvanian strata, with all of the producing zones being below the lowest salt layers.

Current activity centers on deeper drilling in the north and northwest shelf of the Anadarko basin and on deep drilling (depths of 17,000 to 21,000 feet) for Silurian and Devonian gas reservoirs along and near the axis of the Anadarko basin in Texas and Oklahoma. The Anadarko basin undoubtedly will continue to attract exploration interest in years to come, and it will remain one of the great petroleum provinces of the continental United States.

Oil and natural gas are absent, or occur only in small fields, in the Dalhart basin and the Palo Duro basin. The low ratio of successful wells drilled in these two basins has inhibited exploration for oil and gas, and I estimate there is an average of 1 oil or gas test per 30 to 40 square miles in much of the Palo Duro basin. Oil is produced at a few sites in the Dalhart basin from Pennsylvanian rocks, and also is produced from several fields along the crest of the Matador arch on the

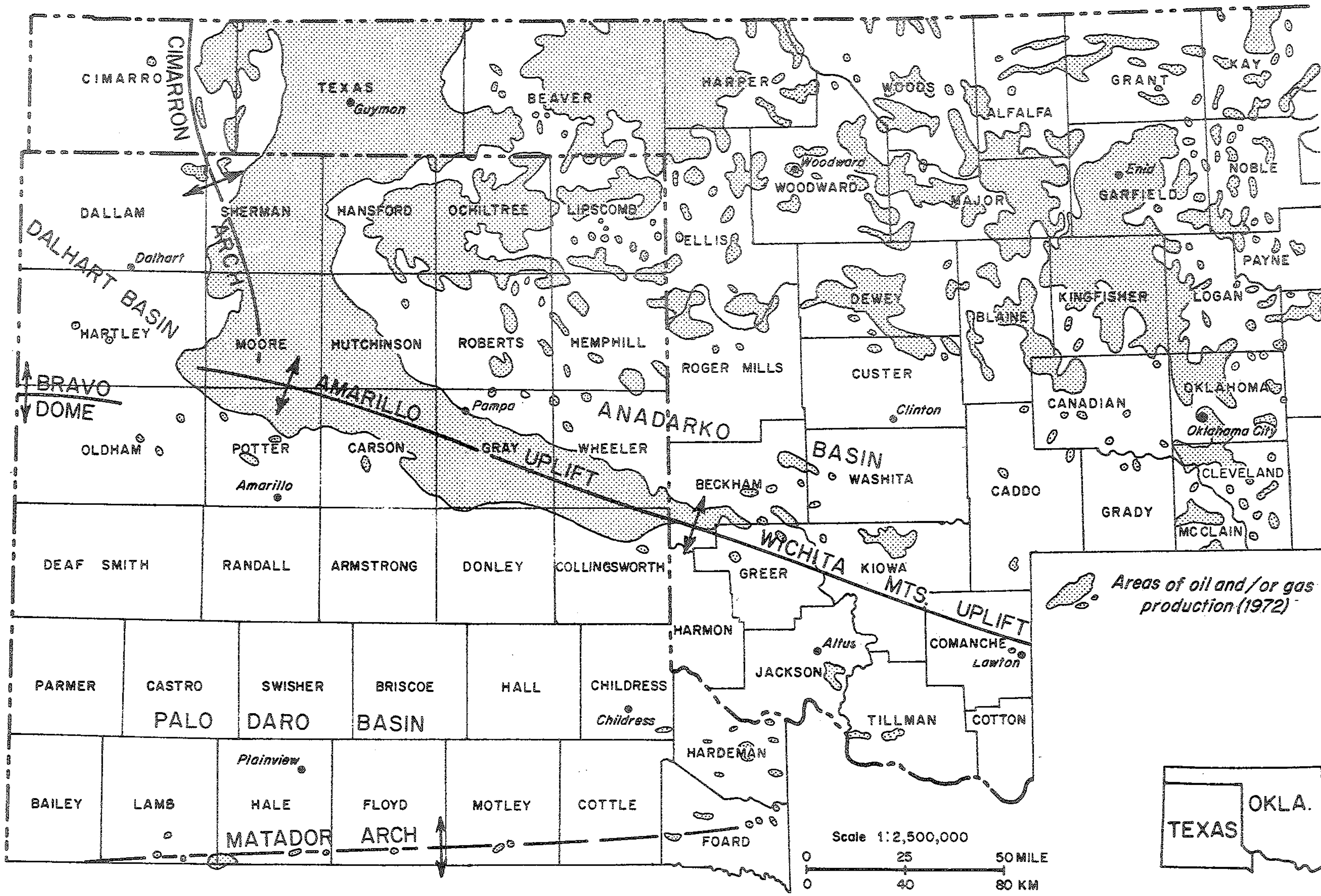


Figure 19. Map of oil and gas fields in Texas Panhandle and western Oklahoma.

south side of the Palo Duro basin. Farther south of the Matador uplift is the large and important oil-producing province of the Midland basin and its adjacent shelf areas.

Other gaseous minerals associated with oil and natural gas are also being produced in and near the study region. Helium is produced at three localities in eastern Cimarron County, Oklahoma, and in Hansford and Moore Counties, Texas. Carbon dioxide is produced from Permian rocks about 30 miles west of the study region at the Bueyeros field in Harding County, New Mexico.

It therefore appears that development of an underground waste-storage facility in the Palo Duro or Dalhart basin would have minimum (if any) impact on petroleum production, and the scarcity of test holes in these two basins decreases the possibility of accidental migration of fluids from a storage facility.

Salt

Salt resources of the region are vast. Jordan and Vosburg (1963) estimated that nearly 22 trillion tons of salt are present in the Anadarko basin, and I believe there may be another 35 trillion tons of salt in the Palo Duro and Dalhart basins. Such resources are a staggering amount, especially when in 1972 the total United States production was 50 million tons of salt and the total world production was 150 million tons (U.S. Bureau of Mines, 1972).

Only limited use is currently being made of the salt resources in the region (Johnson, 1972). Two companies produce a total of about 10,000 tons of salt annually by solar evaporation from brine springs at natural salt plains in southwestern and northwestern Oklahoma. A two-well brine field in Beckham County, Oklahoma, has been producing brine and evaporative salt intermittently since 1934; brine is produced by pumping fresh water into the Upper Cimarron salt at a depth of 1,518 feet.

The only reported production of brine in the Texas Panhandle is in Hutchinson County, where Phillips Petroleum Company operates a brine well (U.S. Bureau of Mines, 1972).

Another use of the salt is the underground storage of liquefied petroleum gas (LPG) in man-made cavities. Oklahoma has four LPG-storage facilities in salt (Jordan and Vosburg, 1963): Shell Oil Company operates the Elk City storage facility (Beckham County) in the Blaine Formation at a depth of 1,360 to 1,411 feet; Texaco, Inc., operates a storage cavern in the Camrick district (Beaver County) in the Flowerpot salt below a depth of 833 feet; Warren Petroleum Corporation has four caverns at the Mocane plant (Beaver County) in the Lower Cimarron salt below 1,579 feet; and Continental Oil Company has a facility near Medford (Grant County) in the Hutchinson salt at a depth of 900 feet. In addition, 13 LPG-storage facilities are operated in Texas in the Panhandle field over the Amarillo uplift in the following counties: Moore (5 storage facilities), Hutchinson (2), Potter (1), Carson (2), and Gray (3).

With the vastness of salt resources in the region, it is unlikely that use of underground salt beds for radioactive-waste emplacement at one or several sites will have any impact on the future availability of adequate salt resources for this part of the United States.

Other Minerals

Gypsum and anhydrite resources of the region are great: reserves of surface and near-surface gypsum (maximum overburden, 30 feet) in Oklahoma alone are estimated to be 48 billion tons (Johnson, 1972), and additional near-surface reserves in the southeastern part of the Texas Panhandle are probably about 5 to 10 billion tons. All gypsum and anhydrite in the region are in rocks of the Permian System.

Eight companies annually produce about 1 million tons of gypsum from surface mines in the eastern part of the region. Gypsum and anhydrite are too deep in most areas (especially in the Texas and Oklahoma Panhandles) to compete with the near-surface reserves, and it is not likely that the deep gypsum or anhydrite beds associated with or below the salt deposits will be regarded as commercial minerals in the foreseeable future.

Potash is being mined underground by 7 companies near Carlsbad in southeastern New Mexico: 6 mines are in Eddy County, and one is in Lea County. The potash is interbedded with salts in the Salado Formation (Brokaw and others, 1972; Jones, 1975). There is no evidence that significant amounts of potash were deposited in the Texas Panhandle and western Oklahoma region.

Other minerals being mined in western Oklahoma include dolomite, caliche, volcanic ash, bentonite, and sand and gravel (Johnson, 1969; U.S. Bureau of Mines, 1972); those produced in the Texas Panhandle include stone, lime, cement, clays, and sand and gravel (U.S. Bureau of Mines, 1972). All of these operations are relatively small surface mines, and there should be no conflict between the continued use of surface minerals and the use of underground salt beds for radioactive-waste emplacement (except in the immediate vicinity of an emplacement site).

WATER PRODUCED FROM HEATING OF ROCKS

I will not attempt in this report to assess fully the effects that stored radioactive waste would have on the rocks and minerals within and adjacent to the salt units, but several preliminary statements concerning the study area can be made in light of the work done by various subcontractors for Oak Ridge National Laboratory (Beane, 1974; Beane and Popp, 1975; Billings and others, 1972; Kopp and Combs, 1975; and Kopp and Fallis, 1973). The work by these investigators indicates that when various rocks are heated to temperatures of 102°C, the amounts of water that might be given off by these rocks are: about 15 percent for gypsum-rich rocks, 6 to 7 percent for average shales, and 0.5 percent or less for halite and anhydrite. In addition to water released from gypsum, clays, and other minerals, water may also be present as connate water or as fluid inclusions.

The fact that so many of the shallow samples (305 to 1,293 feet deep) from the Lyons, Kansas, cores had a high water loss results from the abundance of shale and gypsum in those cores. Samples of anhydrite and salt (halite) from the Lyons site and the Carlsbad, New Mexico, cores (1,044 to 2,948 feet deep) had consistently low water losses, regardless of the depth. Most of the halite and anhydrite samples from Carlsbad had water losses of 0.0 to 0.4 percent, and almost all those that lost 0.5- to 3.4-percent water contained a trace of gypsum or at least 5-percent clay minerals or polyhalite (which can lose up to 6-percent water).

Rocks and minerals commonly associated in various salt units in the Texas Panhandle and western Oklahoma are halite, anhydrite, dolomite, limestone, and shale. Siltstone and sandstone are sparingly present, and there is no evidence (based on examination of neutron logs) that gypsum is present in significant quantities as deep as 1,000 feet below the surface. Thus, of the dominant lithologies, shale alone appears to represent a possible significant source of water loss upon heating. A more complete assessment of this question should be made in further studies.

REGIONAL EVALUATION FOR STORAGE OF RADIOACTIVE WASTE

Based upon the current study, and upon review of available geologic data, some of the Permian salt deposits in the Texas Panhandle and western Oklahoma (particularly those in the Texas Panhandle) appear to be suitable for underground storage of radioactive waste. Some deposits have thick, massive beds of rock salt (halite) at moderate depth; they have not been structurally deformed or fractured; and there are large areas where the salt has not been dissolved. Almost the entire region has been tectonically stable since deposition of the salt beds, and the few recorded earthquakes in the salt region are primarily related to one tectonic province (the Amarillo uplift). Almost all lands are rural, sparsely populated, and used for agriculture or ranching; the climate is semiarid, with average annual precipitation ranging from 16 inches in the far west to 30 inches in the east.

Petroleum exploration and production in the Anadarko basin and adjacent uplifts make those regions unattractive for waste-storage sites. Many boreholes have been drilled through the salt deposits in the Anadarko basin, the Amarillo uplift, and the Cimarron arch provinces, and they constitute one of the major oil and gas provinces of the United States.

The Palo Duro and Dalhart basins, on the other hand, have had few test holes drilled through the salts, and thus they remain attractive provinces for waste-storage sites. Oil is produced only from a few small fields within the Dalhart basin and only on the edge of the Palo Duro basin; and neither basin is currently regarded as a significant petroleum province.

Nonpetroleum mineral exploration and production in the region are minimal. There are no underground mines, and the small surface mines are widely scattered. The vastness of salt deposits in the region should permit use of one or several sites for waste storage without affecting the availability of salt resources. The only current use being made of the salt is in the Anadarko basin and over the Amarillo uplift: LPG is stored underground in solution cavities at 4 localities in Oklahoma and 13 localities in Texas; brine wells are operated at 2 localities; and 2 small companies produce solar-evaporated salt from brine springs. Other minerals normally associated with salt (e.g., potash, gypsum, anhydrite) either are not known in the study area or are not commercially exploitable at depths of 1,000 feet.

Following is an assessment of the general conditions that are favorable and unfavorable for radioactive-waste storage in each of the three principal basins.

Palo Duro Basin

A number of factors favor underground waste storage in salts of the Palo Duro basin:

1. Five salt-bearing units are each more than 200 feet thick: Lower Clear Fork salt (200-550 feet thick); Upper Clear Fork salt (200-650); San Andres salt (200-1,590); Seven

Rivers salt (200-540); and Salado-Tansill salt (200-340). These units are typically 20- to 60-percent salt.

2. These five units are 1,000 to 3,000 feet below the surface over an area of about 12,000 square miles.
3. Some of the salt units are overlain and underlain by impermeable shales.
4. Permian and younger rocks are not fractured or otherwise deformed.
5. The region is entirely within seismic-risk zone 1.
6. No earthquakes of MM V or greater have been recorded.
7. The area is mostly rural and agricultural land.
8. Excluding salt, there are no known significant mineral deposits within or below the salt units.
9. No oil or gas has been discovered in the basin.
10. Few boreholes have been drilled through the salt units.
11. No underground mines exist in the region.
12. There is no evidence of dissolution of salt beds at depths greater than about 1,000 feet.

The unfavorable factors in the Palo Duro basin are as follows:

1. Fresh-water aquifers at and near the surface in various areas include the Ogallala Formation, Edwards-Trinity strata, the Blaine Formation, and Quaternary terrace and alluvial deposits.
2. Salt-water-bearing sandstones (Tubb, Glorieta, and parts of the Artesia Group) are above or below several of the salt units in parts of the basin.

3. Salt is partly or completely dissolved by circulating ground water at most places where the salt is less than 500 to 800 feet below the surface, and locally the resultant brine is emitted at the surface.

In summary, the Palo Duro basin is most favored of all areas considered in this study. It has numerous salt units at suitable depths, it lacks seismic activity and petroleum production, and it has few boreholes drilled through the salt units. The adverse factors are considered minor.

Dalhart Basin

The following factors favor underground storage of waste in salts of the Dalhart basin:

1. The Flowerpot salt and Blaine Formation make up the only salt-bearing unit that is 200 to 410 feet thick. This unit is typically 50- to 65-percent salt.
2. The salt unit is 1,200 to 1,765 feet below the surface in an area of about 1,000 square miles.
3. Permian and younger rocks are not fractured or otherwise deformed.
4. The region is in seismic-risk zone 1.
5. The area is mostly rural and agricultural land.
6. Excluding petroleum and salt, there are no known significant mineral deposits within or below the salt units.

7. Oil is produced at only a few small fields, and the basin is not considered a significant petroleum province.
8. Few boreholes have been drilled through the salt units in most areas.
9. No underground mines exist in the region.
10. There is no evidence of dissolution of salt at depths of 1,260 to 1,765 feet in most of the area.

Unfavorable factors in the Dalhart basin are as follows:

1. Fresh-water aquifers in various areas include the Ogallala Formation, the Santa Rosa Sandstone, the Dakota and Cheyenne Sandstones, and Quaternary terrace and alluvial deposits.
2. Interbedded sandstone, shale, and gypsum/anhydrite layers overlie the salt unit, and the salt-water-bearing Glorieta Sandstone underlies the salt.
3. Salt is dissolved in an area where it is 950 to 1,200 feet below the surface.
4. A single earthquake of MM VI has been recorded in the basin.

In summary, the Dalhart basin is not as well suited as the Palo Duro basin; it contains only one salt-bearing unit, it has had one earthquake, and there are a few small oil fields. But the favorable factors locally outweigh the unfavorable, and parts of the Dalhart basin may be suitable for radioactive-waste storage.

Anadarko Basin

The Anadarko basin has the following features favoring underground waste storage in salt:

1. Three salt-bearing units are more than 200 feet thick: Hutchinson salt (200 to 565 feet thick); Lower Cimarron salt (200 to 420); Flowerpot salt, Blaine Formation, and Yelton salt (200 to 710). These units typically are 40- to 70-percent salt.
2. These three units are 1,000 to 3,000 feet below the surface over an area of about 17,000 square miles.
3. The salt units are generally overlain and underlain by impermeable shales.
4. Permian and younger rocks are not fractured or otherwise deformed.
5. The region is entirely within seismic-risk zone 1.
6. The area is mostly rural and agricultural land.
7. Excluding petroleum and salt, there are no known significant mineral deposits within or below the salt units.
8. No underground mines exist in the region.
9. There is no evidence of dissolution of salt beds at depths greater than about 1,000 feet.

The unfavorable factors in the Anadarko basin include:

1. Many boreholes have been drilled through the salt units in search of oil and gas.

2. The Anadarko basin and adjacent uplifts make up one of the major petroleum-producing provinces in the nation, and continued exploration is anticipated in all parts of the basin.
3. Three earthquakes of MM V have occurred in the western part of the basin, and seven events of MM V to MM VII have occurred in the eastern part of the basin.
4. Brine wells and LPG-storage facilities have been developed in the salt units at six widely scattered localities.
5. Fresh-water aquifers at and near the surface in various areas include the Ogallala Formation, the Elk City Sandstone, the Rush Springs Sandstone, and Quaternary terrace and alluvial deposits.
6. The salt-water-bearing Glorieta Sandstone underlies the Flowerpot salt in the western Anadarko basin.
7. Salt is partly or completely dissolved by circulating ground water at most places where the salt is less than 500 to 800 feet below the surface, and locally the resultant brine is emitted at the surface.

In summary, the Anadarko basin is the least favorable of the three basins under consideration: seismic activity and petroleum exploration and production are incompatible with use of almost any part of the area as a waste-storage site.

CONCLUSIONS

As a result of this study of Permian salt deposits of the Texas Panhandle and western Oklahoma, parts of the Palo Duro basin appear to be most suitable for underground storage of radioactive waste. Five salt-bearing units, each 200 to 1,590 feet thick, underlie about 12,000 square miles of the basin at moderate depths. The basin lacks a history of earthquakes or petroleum production, and it has few boreholes drilled through the salt units. (The favorable and unfavorable features of each basin are discussed in the preceding chapter.)

Of secondary interest is the Dalhart basin, which contains one salt-bearing unit 200 to 410 feet thick at moderate depth beneath about 1,000 square miles. It has had one recorded earthquake (MM VI), and there are a few small oil fields.

Of least interest as a possible waste-storage region is the Anadarko basin. The basin contains three salt units 200 to 710 feet thick at moderate depth beneath about 17,000 square miles, but it also is a major petroleum province and has many boreholes drilled through the salt units. Several earthquakes have also occurred in the eastern and western parts of the basin.

Detailed studies of all data available on the Palo Duro basin and Dalhart basin are needed now in order to determine more accurately the mineralogy, petrology, facies changes, percentages of salt, thicknesses of individual salt beds, hydrology, geologic structure, solution phenomena, and location of boreholes. With these data, the most favorable sites in the two basins can be identified and then scheduled for intensive investigation and evaluation.

REFERENCES CITED

Adams, J. E., 1963, Permian salt deposits of west Texas and eastern New Mexico: N. Ohio Geol. Soc. (First) Symposium on Salt, p. 124-130.

Bachman, G. O., and Johnson, R. B., 1973, Stability of salt in the Permian salt basin of Kansas, Oklahoma, Texas, and New Mexico: U.S. Geol. Survey Open-File Rept. (4339-4), p. 1-45.

Beane, R. E., 1974, Quantitative mineralogy of selected shale samples from the Lyons, Kansas, nuclear-waste burial site, and probable effect of raising temperature in the column: unpublished report submitted to Union Carbide Corp., Oak Ridge National Laboratory, under subcontract 3673-2 (supplement 2), 22 p.

Beane, R. E., and Popp, C. J., 1975, Chemical, mineralogical, and thermogravimetric analyses of selected core samples from Carlsbad, New Mexico: unpublished report submitted to Union Carbide Corp., Oak Ridge National Laboratory, under subcontract 3673-3 (supplement 3), 51 p.

Billings, G. K., Beane, R. E., Sonderegger, J. L., and Hayslip, D. L., 1972, Qualitative mineralogical analysis and quantitative chemical analysis of selected shale samples from the Lyons, Kansas nuclear-waste burial site: unpublished report submitted to Union Carbide Corp., Oak Ridge National Laboratory, under subcontract 3673, 22 p.

Brokow, A. L., Jones, C. L., Cooley, M. E., and Hays, W. H., 1972, Geology and hydrology of the Carlsbad potash area, Eddy and Lea Counties, New Mexico: U.S. Geol. Survey Open-File Rept. 4339-1, 86 p.

Coffman, J. L., and von Hake, C. A., eds., 1973, Earthquake history of the United States: National Oceanic and Atmospheric Administration, Pub. 41-1, Revised Edition (through 1970), 208 p.

Dellwig, L. F., 1968, Significant features of deposition in the Hutchinson salt, Kansas, and their interpretation, in Saline deposits, a symposium based on papers from the International Conference on Saline Deposits, Houston, Texas, 1962: Geol. Soc. America Spec. Paper 88, p. 421-426.

Docekal, Jerry, 1970, Earthquakes of the Stable Interior, with emphasis on the Midcontinent: Nebraska, Univ., unpublished Ph.D. dissertation, 2 vols., 169 p. and 332 p.

ESSA/Coast and Geodetic Survey, 1969, Seismic risk map of the United States: U.S. Dept. Commerce map.

Fay, R. O., 1965, Geology and mineral resources of Woods County, Oklahoma: Oklahoma Geol. Survey Bull. 106, 189 p.

Irwin, J. H., and Morton, R. B., 1969, Hydrogeologic information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and adjoining areas as related to underground waste disposal: U.S. Geol. Survey Circ. 630, 26 p.

Johnson, K. S., 1967, Stratigraphy of the Blaine Formation and associated strata in southwestern Oklahoma: Univ. of Illinois, unpublished Ph.D. dissertation, 247 p.

________, 1969, Mineral map of Oklahoma (exclusive of oil and gas fields): Okla. Geol. Survey Map GM-15, scale 1:750,000.

________, 1972, Gypsum and salt resources in Oklahoma: Industrial Minerals, no. 62 (Nov.), p. 33-39.

Jones, C. L., 1965, Petrography of evaporites from the Wellington Formation near Hutchinson, Kansas: U.S. Geol. Survey Bull. 1201-A, 67 p.

________, 1974, Salt deposits of the Clovis-Portales area, east-central New Mexico: U.S. Geol. Survey Open-File Rept. 74-60, 22 p.

________, 1975, Potash resources in part of the Los Medanos area of Eddy and Lea Counties, New Mexico: U.S. Geol. Survey Open-File Rept. 75-407, 37 p.

Jordan, Louise, and Vosburg, D. L., 1963, Permian salt and associated evaporites in the Anadarko basin of the western Oklahoma-Texas Panhandle region: Oklahoma Geol. Survey Bull. 102, 76 p.

Kopp, O. C., and Combs, D. W., 1975, Mineral sources of water in evaporite sequences (Salado salt and adjacent beds at the proposed waste disposal facility near Carlsbad in Lea and Eddy Counties, New Mexico): unpublished report submitted to Union Carbide Corp., Oak Ridge National Laboratory, under subcontract 3670 (supplements 3 and 4), 34 p.

Kopp, O. C., and Fallis, S. M., 1973, Mineral sources of water in evaporite sequences: unpublished report submitted to Union Carbide Corp., Oak Ridge National Laboratory, under subcontract 3670, 40 p.

Kulstad, R. O., 1959, Thickness and salt percentage of the Hutchinson salt, in A symposium on geophysics in Kansas: Kansas, State Geol. Survey Bull. 137, p. 241-247.

Lefond, S. J., 1969, Handbook of world salt resources: New York, Plenum Press, 384 p.

McKee, E. D., Oriel, S. S., and others, 1967a, Paleotectonic maps of the Permian System: U.S. Geol. Survey Misc. Geol. Inv. Map I-450, 164 p.

_______, 1967b, Paleotectonic investigations of the Permian System on the United States: U.S. Geol. Survey Prof. Paper 515, 271 p.

Northrop, S. A., and Sanford, A. R., 1972, Earthquakes of northeastern New Mexico and the Texas Panhandle, in Guidebook of east-central New Mexico: N. Mex. Geol. Society Guidebook, 23rd field conference, Sept. 28-30, 1972, p. 148-160.

Person, W. J., 1974, Earthquakes, January-February, 1974: Earthquake Information Bull., vol. 6, no..2, p. 18-19.

Pierce, W. G., and Rich, E. I., 1962, Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials: U.S. Geol. Survey Bull. 1148, 91 p.

Smith, J. W., 1975, The Permian basin as a radioactive waste repository: unpublished report submitted to Union Carbide Corp., Oak Ridge National Laboratory, 76 p.

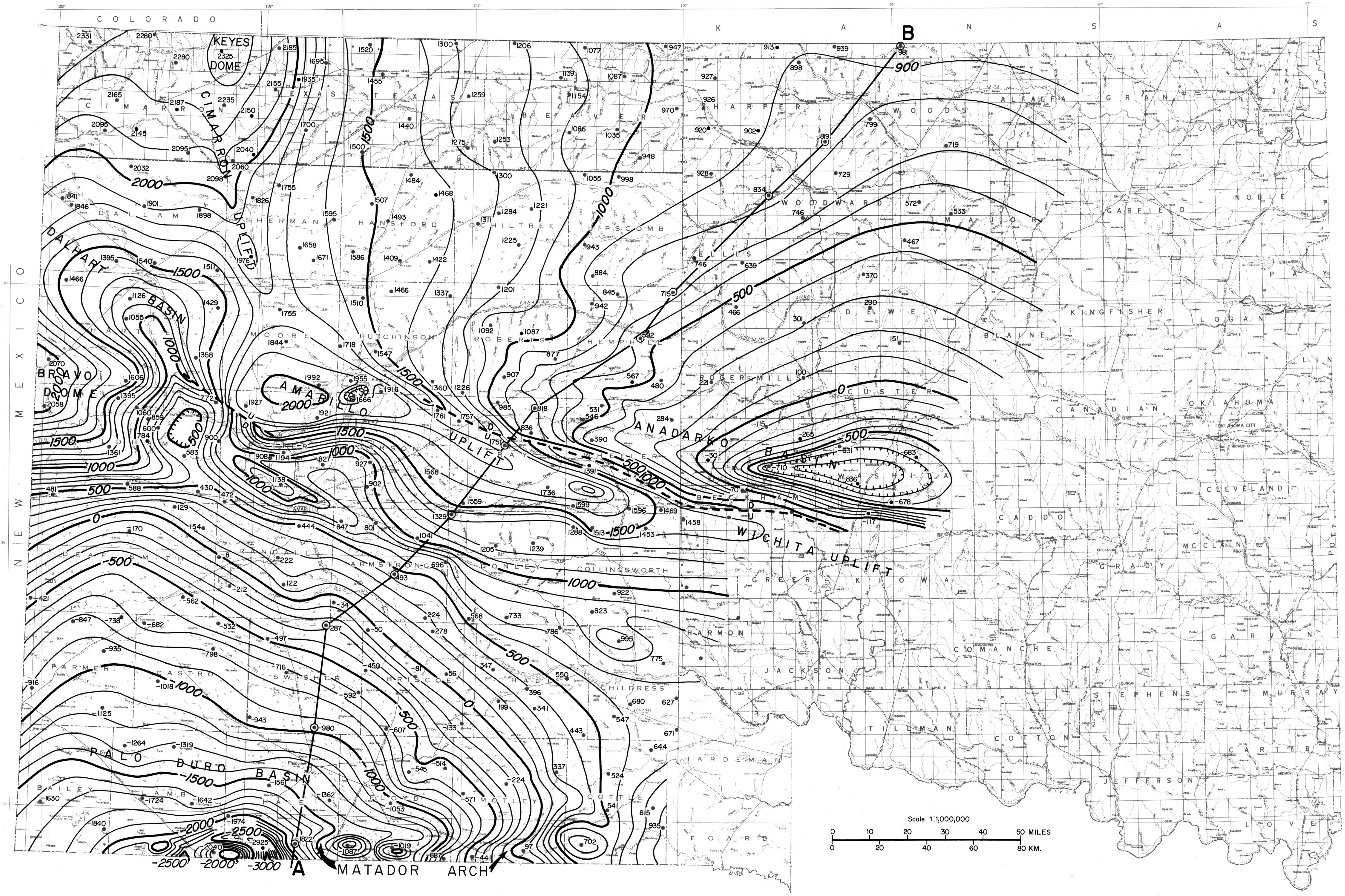
Swenson, F. A. 1973, Dissolved salts in surface water, in Stability of salt in the Permian salt basin of Kansas, Oklahoma, Texas, and New Mexico: U.S. Geol. Survey Open-File Rept (4339-4), p. 46-53.

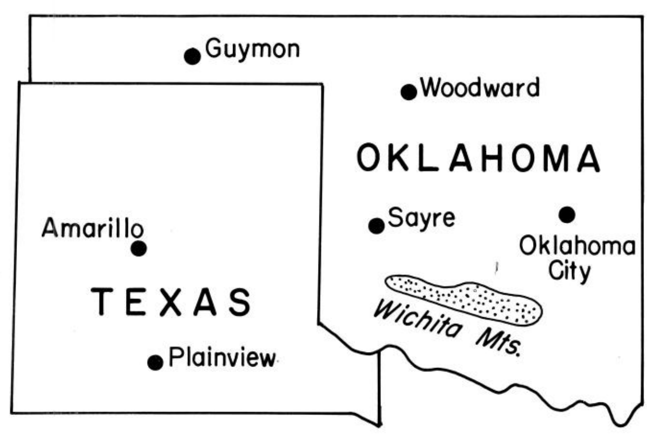
_______, 1974, Rates of salt solution in the Permian basin: Jour. Research U.S. Geol. Survey, vol. 2, p. 253-257.

Tait, D. B., and others, 1962, Artesia Group of New Mexico and West Texas: Amer. Assoc. Petroleum Geologists Bull., vol. 46, p. 504-517.

U.S. Bureau of Mines, 1972, Minerals Yearbook, 1972, vol. 11, area reports, domestic: U.S. Bur. Mines.

Ward, P. E., 1963, Geology and ground-water features of salt springs, seeps, and plains in the Arkansas and Red River basins of western Oklahoma and adjacent parts of Kansas and Texas: U.S. Geol. Survey Open-File Rept., 82 p.





AREA SHOWN ON MAP

• Borehole; oil and/or gas test, electric log
1220 Elevation (in feet) of base of Cimarron Anhydrite; sea level datum

—1000— Structural contour lines; interval is 100 feet (30.5 meters)

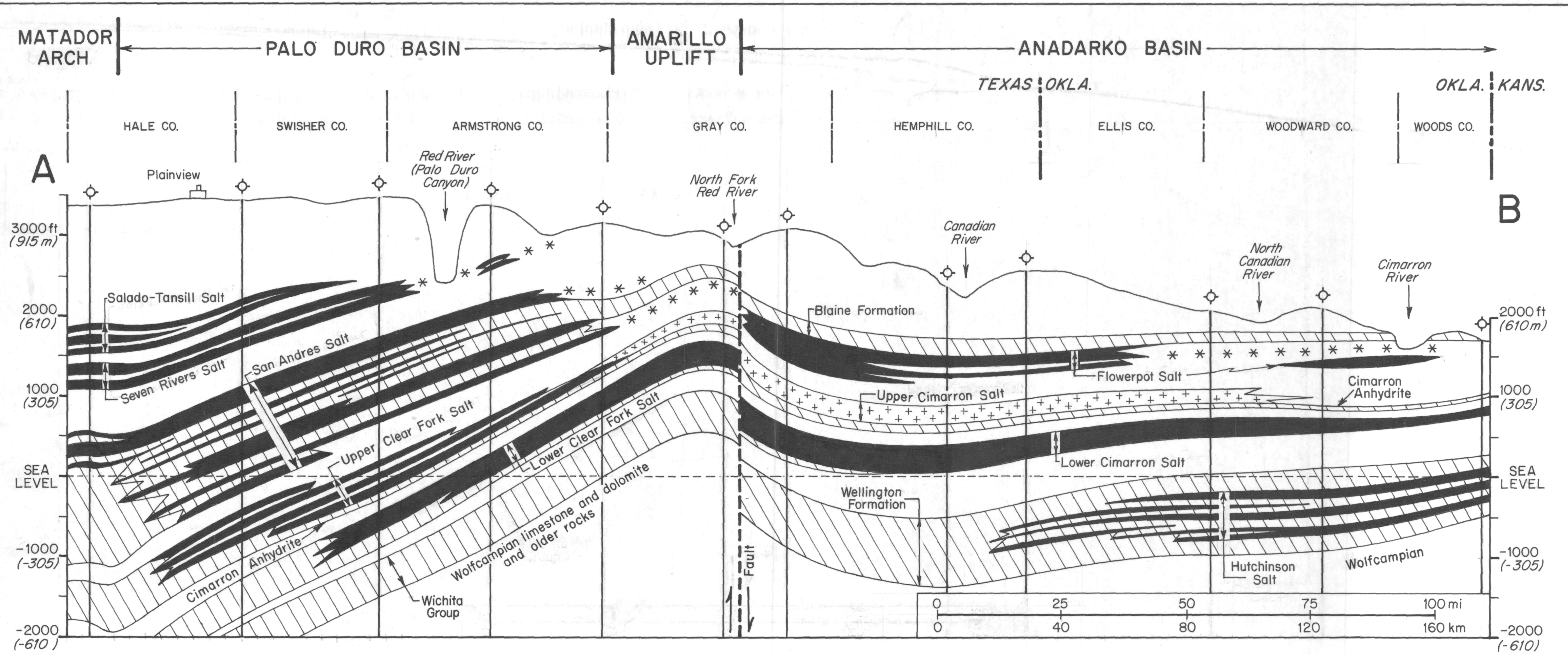
– – – U/D – – – Principal fault zone; U on upthrown side, D on downthrown side

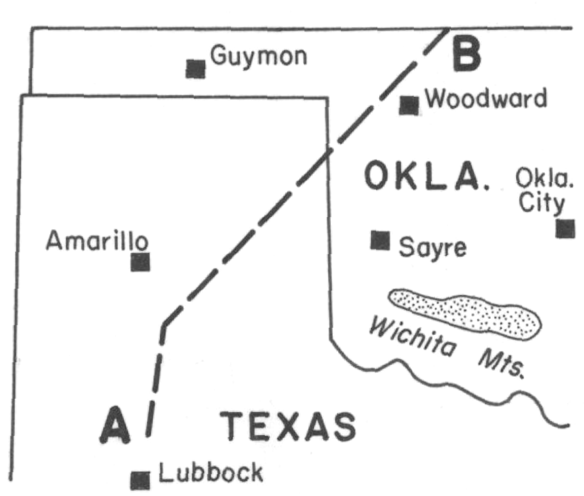
A◎—◎—◎B Line of cross section A-B (Plate 2)

PLATE 1

STRUCTURAL CONTOUR MAP
BASE OF CIMARRON ANHYDRITE
TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson





Location Map: line of cross section A–B shown on plates 1, 3, 4, 5, 6, 7, 8

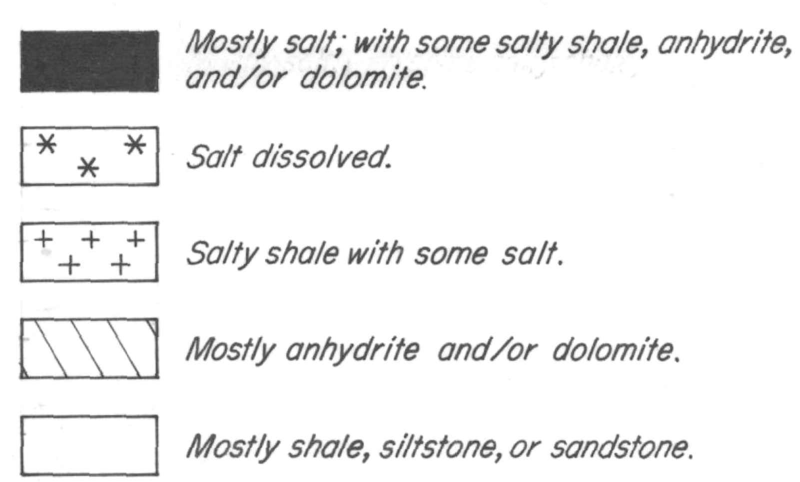
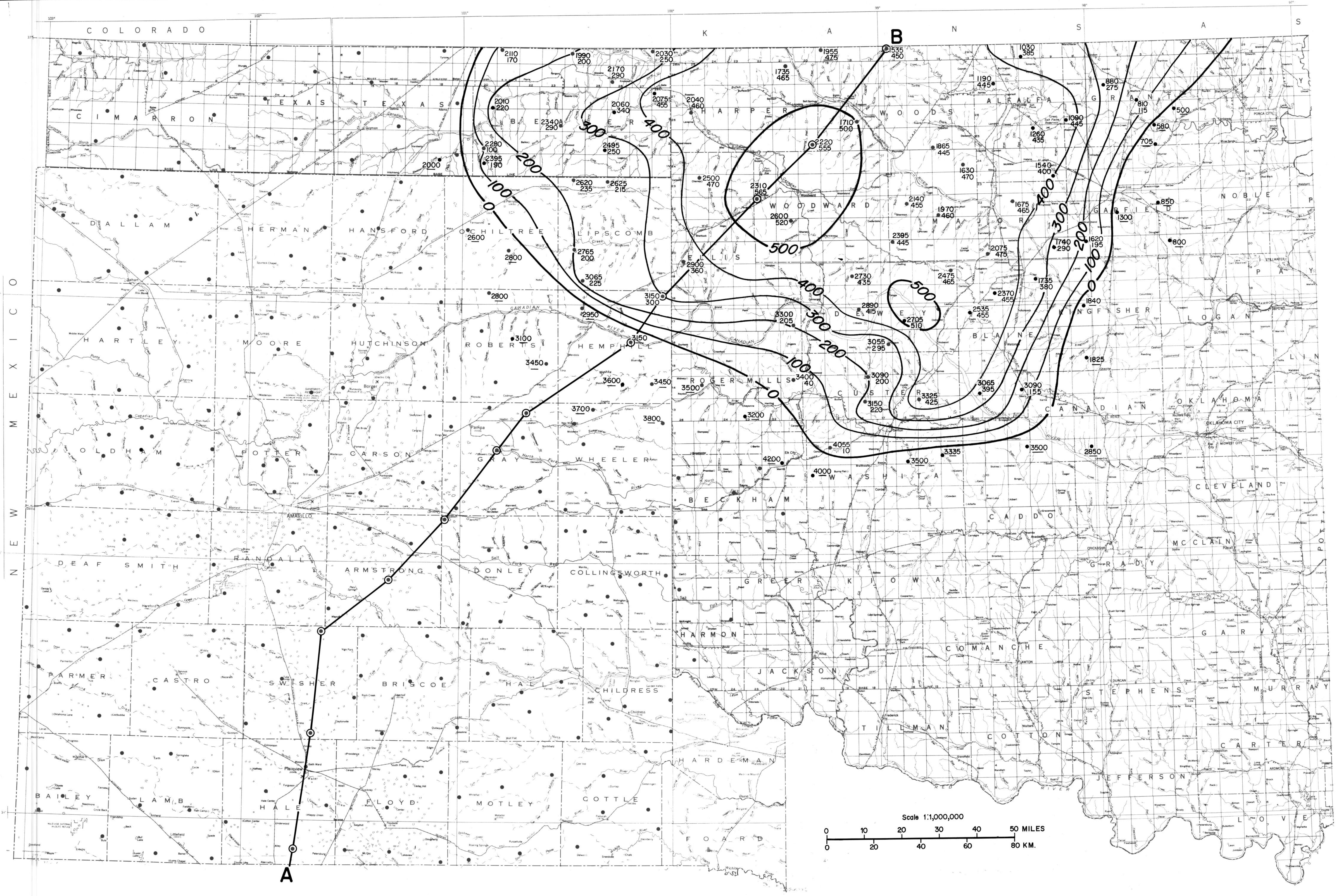


PLATE 2

GENERALIZED STRUCTURAL CROSS SECTION SHOWING PERMIAN SALTS AND ASSOCIATED STRATA IN THE TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson



AREA SHOWN ON MAP

• Borehole; oil and/or gas test, electric log

1260 Depth (in feet) to top of salt, or equivalent strata where salt is absent
435 Thickness (in feet) of salt unit; where salt is absent, shown by dash (–)

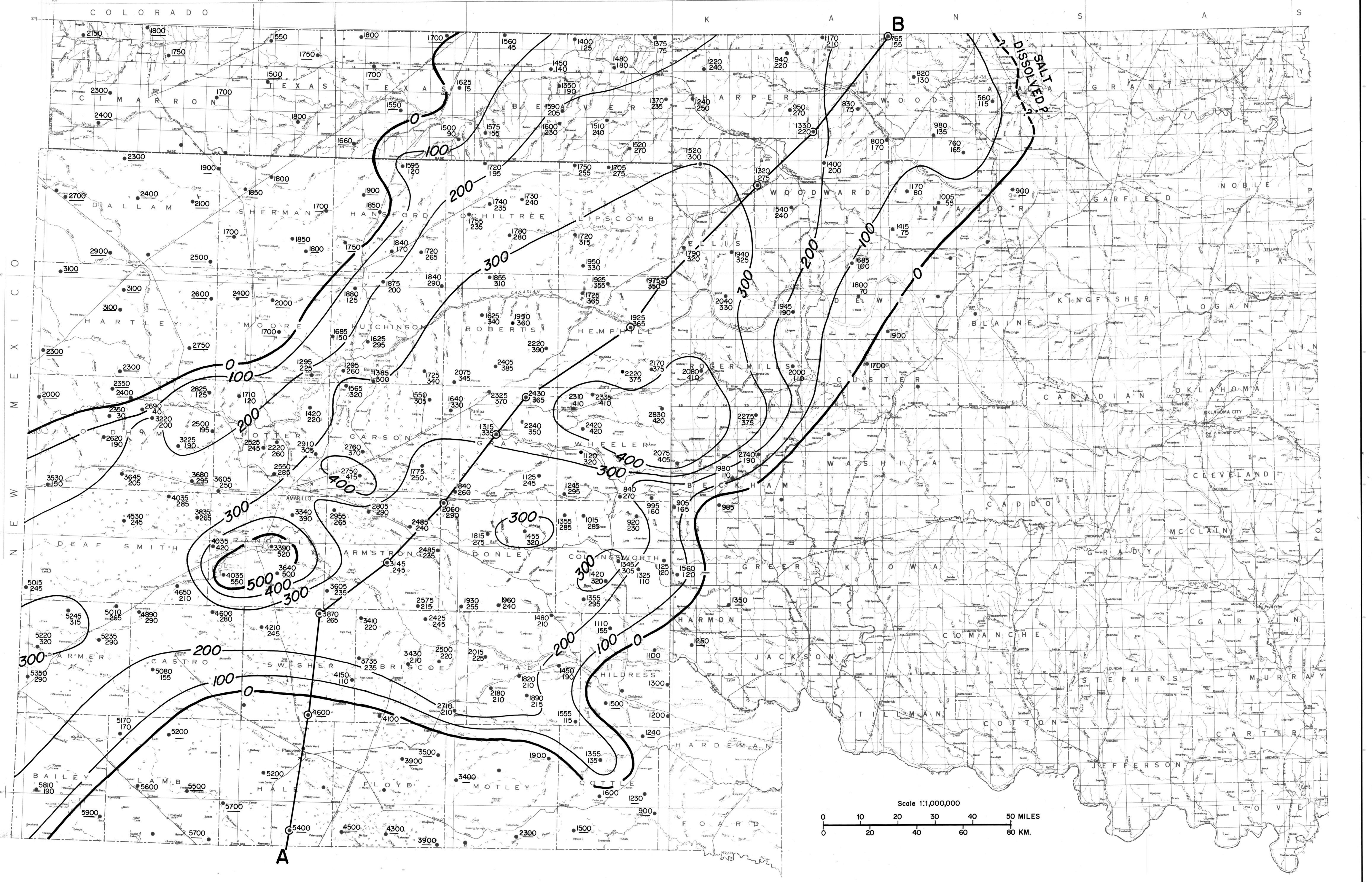
—200— Line of equal thickness of salt unit; interval is 100 feet (30.5 meters)

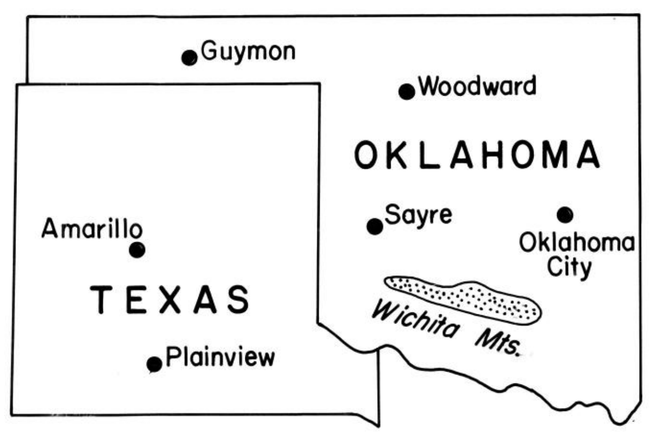
A◉—◉—◉B Line of cross section A–B (Plate 2)

PLATE 3

THICKNESS OF SALT-BEARING STRATA
HUTCHINSON SALT
TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson





AREA SHOWN ON MAP

• Borehole; oil and/or gas test, electric log

1355 Depth (in feet) to top of salt, or equivalent strata where salt is absent
285 Thickness (in feet) of salt unit; where salt is absent, shown by dash (–)

——200—— Line of equal thickness of salt unit; interval is 100 feet (30.5 meters)

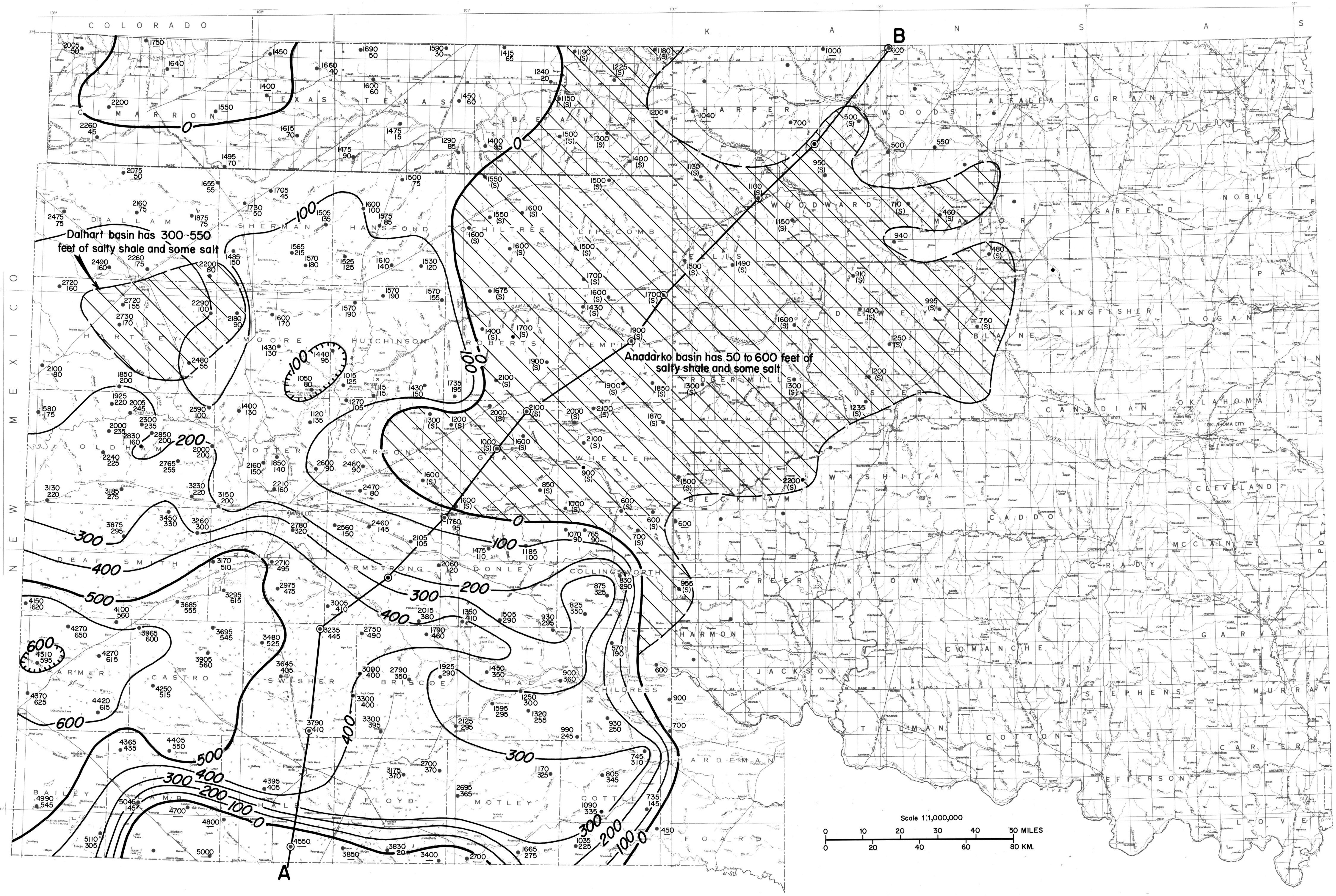
— —?— —?— — Approximate limit, where salt is dissolved

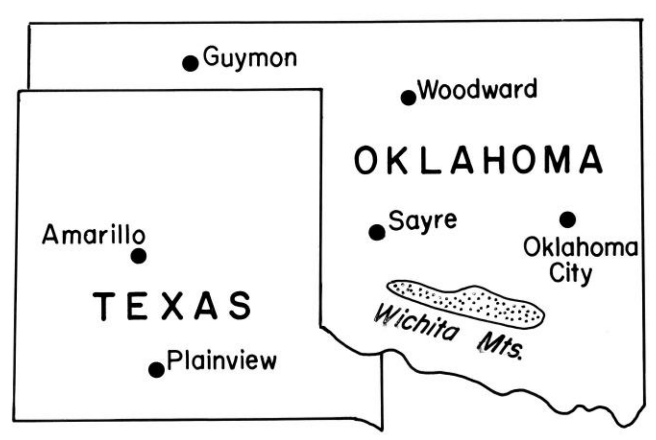
A◉——◉——◉B Line of cross section A–B (Plate 2)

PLATE 4

THICKNESS OF SALT-BEARING STRATA LOWER CLEAR FORK (LOWER CIMARRON) SALT TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson





AREA SHOWN ON MAP

• Borehole; oil and/or gas test, electric log

1850 Depth (in feet) to top of salt, or equivalent strata where salt is absent
140 Thickness (in feet) of salt unit; where salt is absent, shown by dash (–)

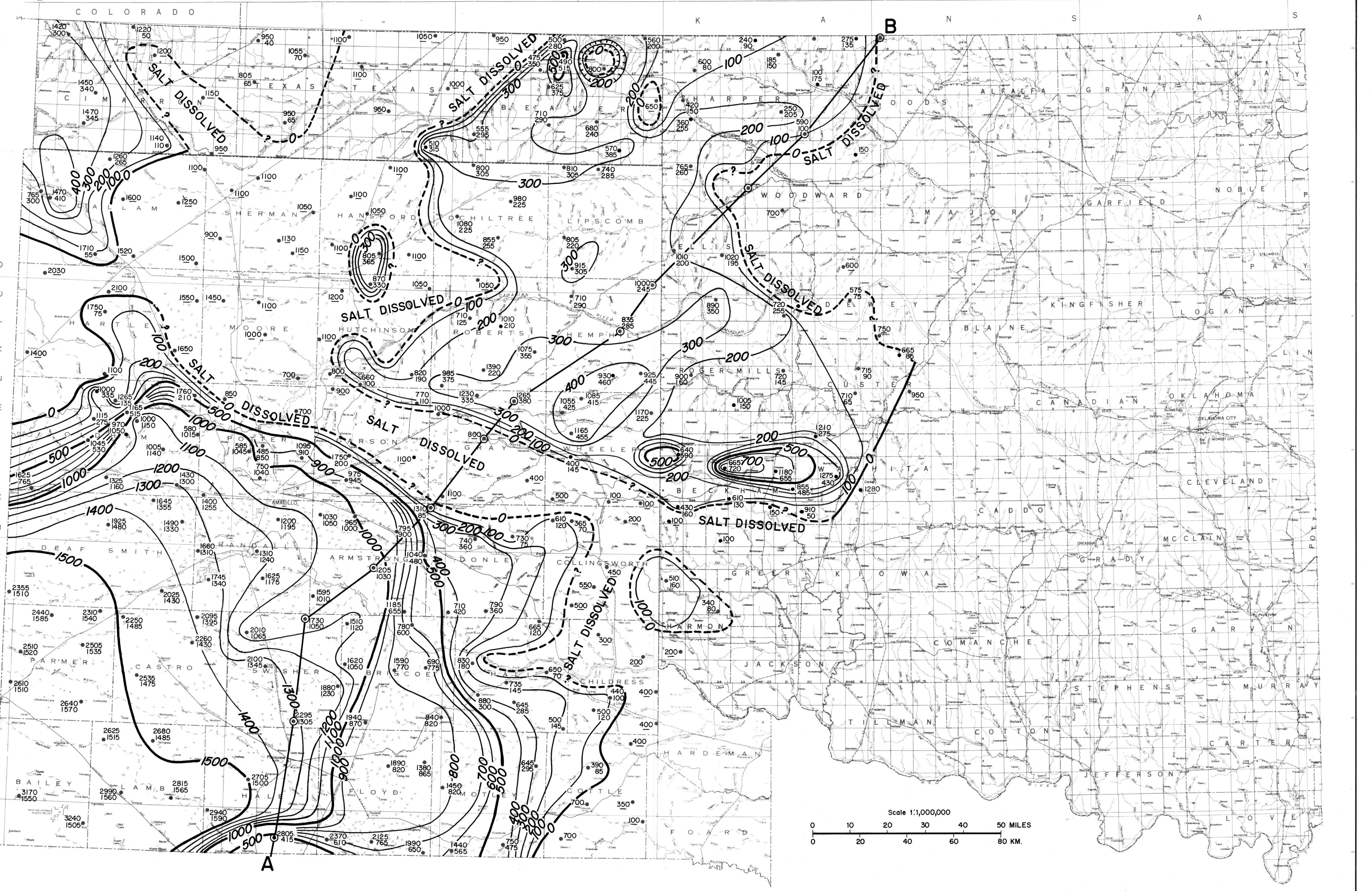
—200— Line of equal thickness of salt unit; interval is 100 feet (30.5 meters)

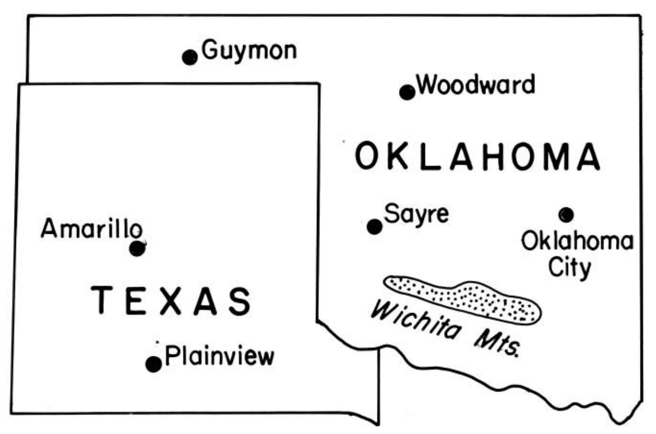
A◎—◎—◎B Line of cross section A–B (Plate 2)

PLATE 5

THICKNESS OF SALT-BEARING STRATA UPPER CLEAR FORK (UPPER CIMARRON) SALT TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson





AREA SHOWN ON MAP

• Borehole; oil and/or gas test, electric log

1880 Depth (in feet) to top of salt, or equivalent strata where salt is absent
1230 Thickness (in feet) of salt unit; where salt is absent, shown by dash (–)

—200— Line of equal thickness of salt unit; interval is 100 feet (30.5 meters)

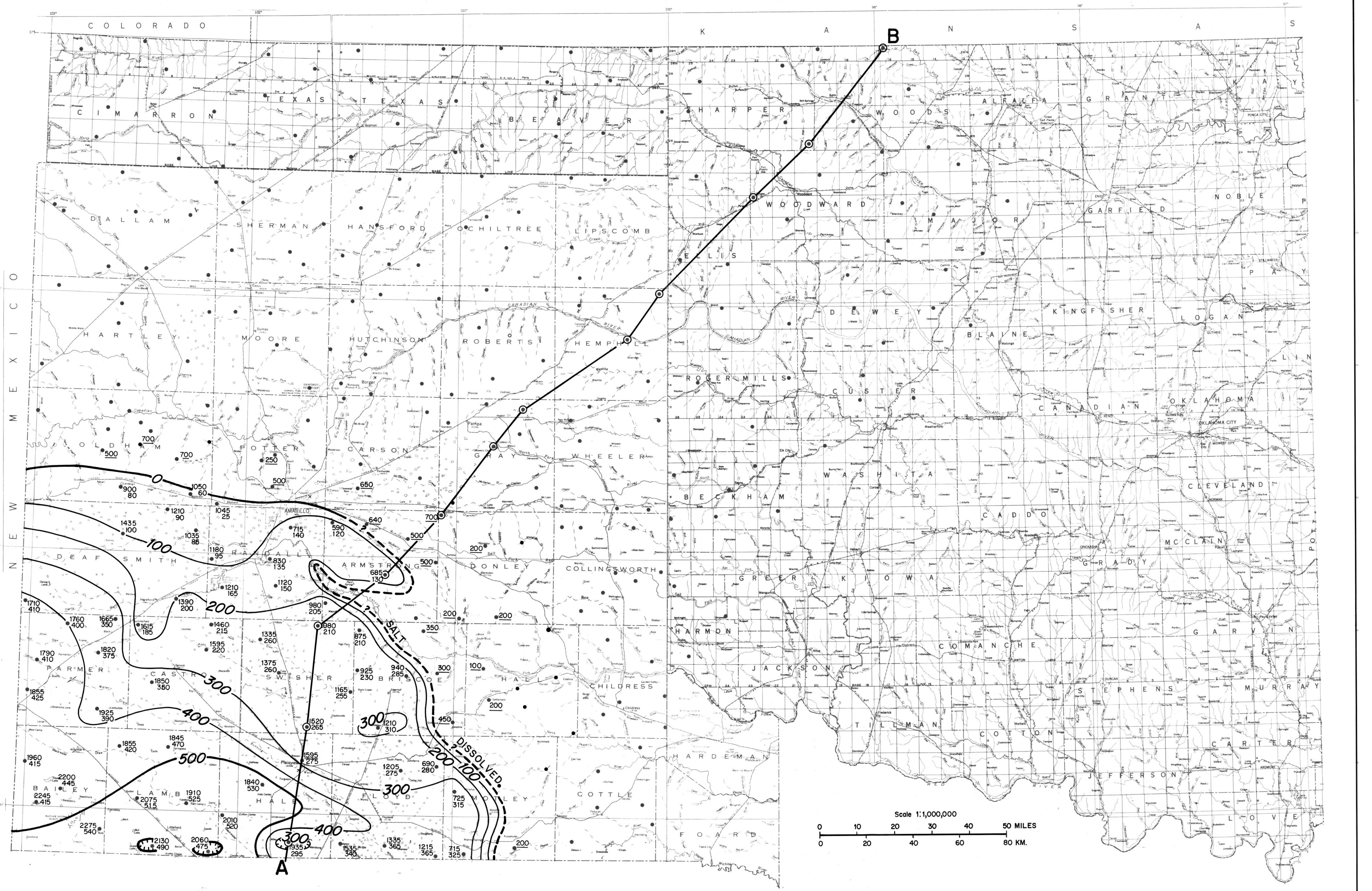
– –?– –?– – Approximate limit, where salt is dissolved

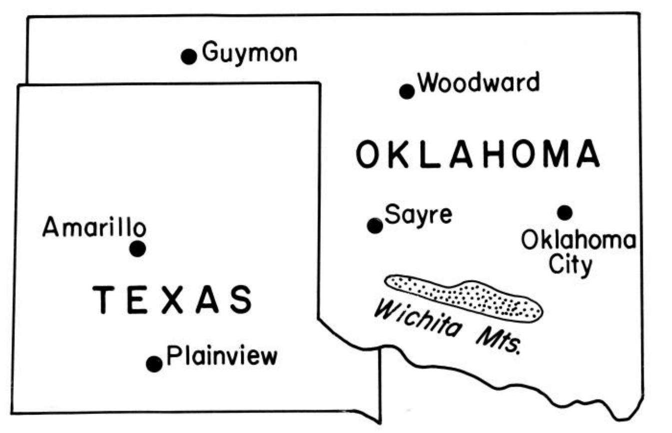
A◎—◎—◎B Line of cross section A–B (Plate 2)

PLATE 6

THICKNESS OF SALT-BEARING STRATA
SAN ANDRES (BLAINE) SALT
TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson





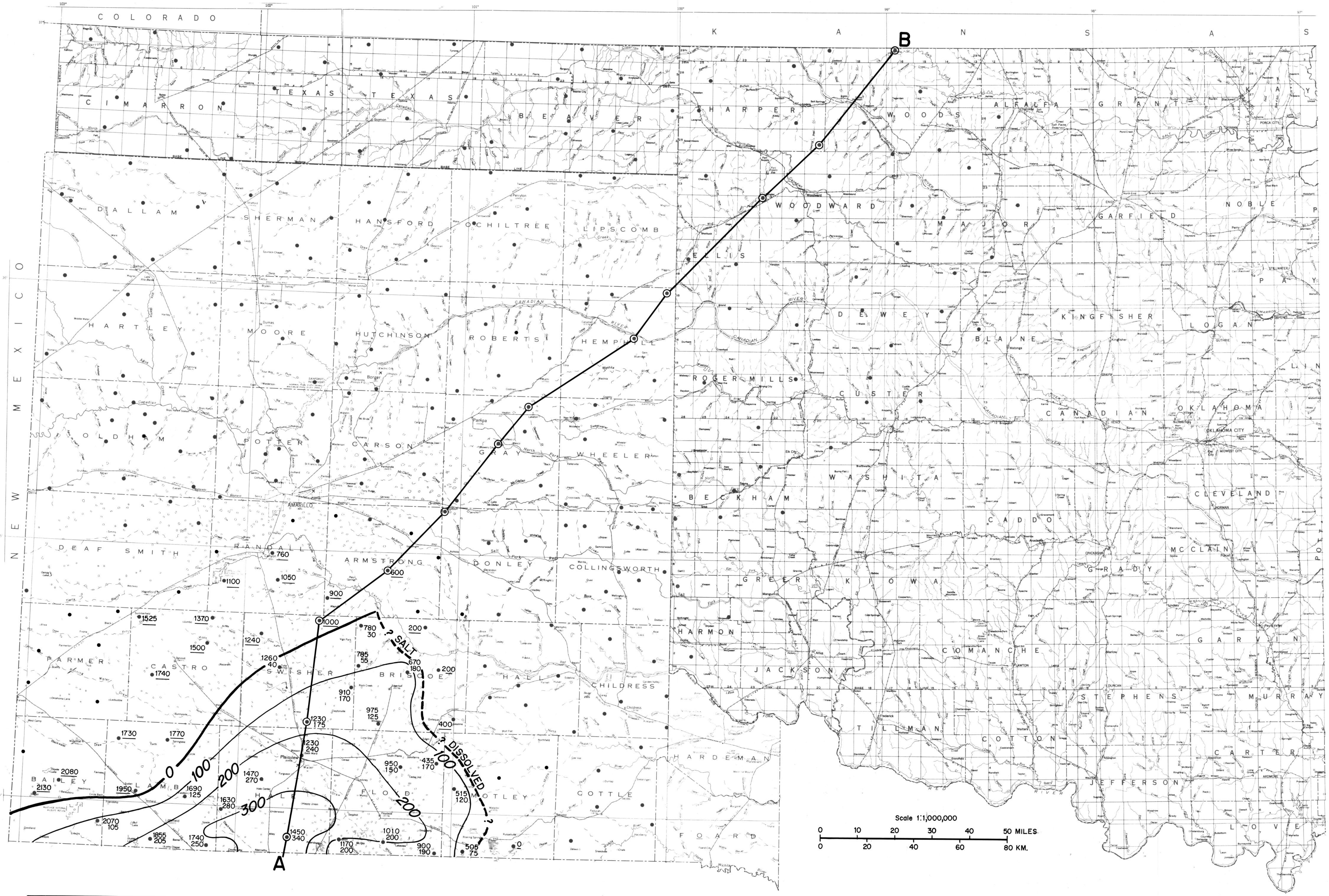
AREA SHOWN ON MAP

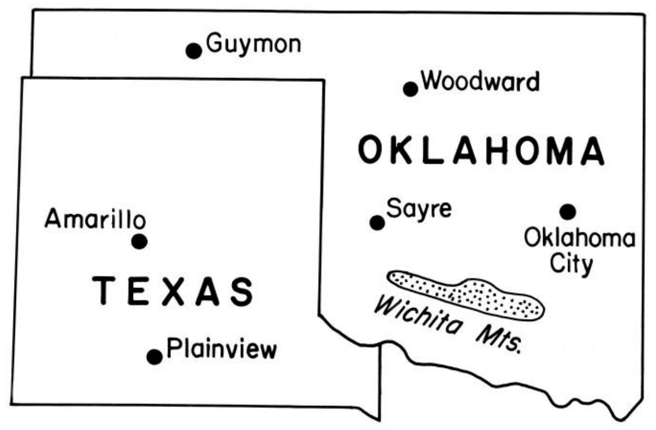
- Borehole; oil and/or gas test, electric log
- 1520 Depth (in feet) to top of salt, or equivalent strata where salt is absent
- 265 Thickness (in feet) of salt unit; where salt is absent, shown by dash (–)
- —200— Line of equal thickness of salt unit; interval is 100 feet (30.5 meters)
- – – ? – – ? – – Approximate limit, where salt is dissolved
- A—B Line of cross section A-B (Plate 2)

PLATE 7

THICKNESS OF SALT-BEARING STRATA SEVEN RIVERS SALT TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson





AREA SHOWN ON MAP

- Borehole; oil and/or gas test, electric log
- 1630 Depth (in feet) to top of salt, or equivalent strata where salt is absent
- 280 Thickness (in feet) of salt unit; where salt is absent, shown by dash (–)
- 200 Line of equal thickness of salt unit; interval is 100 feet (30.5 meters)
- —?—?— Approximate limit, where salt is dissolved
- A—B Line of cross section A-B (Plate 2)

PLATE 8

THICKNESS OF SALT-BEARING STRATA SALADO-TANSILL SALT TEXAS PANHANDLE AND WESTERN OKLAHOMA

Kenneth S. Johnson