Open-file report

USGS-4339-4
1973

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Federal Center, Denver, Colorado 80225

STABILITY OF SALT IN THE PERMIAN SALT BASIN OF KANSAS, OKLAHOMA, TEXAS, AND NEW MEXICO

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with a section on

Dissolved salts in surface water

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ABSTRACT

The Permian salt basin in the Western Interior of the United States is defined as that region comprising a series of sedimentary basins in which halite and associated salts accumulated during Permian time. The region includes the western parts of Kansas, Oklahoma, and Texas, and eastern parts of Colorado and New Mexico.

Following a long period of general tectonic stability throughout the region during most of early Paleozoic time, there was much tectonic activity in the area of the Permian salt basin during Late Pennsylvanian and Early Permian time just before bedded salt was deposited. The Early Permian tectonism was followed by stabilization of the basins in which the salt was deposited. These salt basins were neither contemporaneous nor continuous throughout the region, so that many salt beds are also discontinuous. In general, beds in the northern part of the basin (Kansas and northern Oklahoma) are older and the salt is progressively younger towards the south.

Since Permian time the Permian salt basin has been relatively stable tectonically. Regionally, the area of the salt basin has been tilted and warped, has undergone periods of erosion, and has been subject to a major incursion of the sea; but deep-seated faults or igneous intrusions that postdate Permian salt are rare. In areas of the salt basin where salt is near the surface, such as southeastern New Mexico and central Kansas, there are no indications of younger deep-seated faulting and only a few isolated igneous intrusives of post-Permian age.

On the other hand, subsidence or collapse of the land surface resulting from dissolution has been commonplace in the Permian salt basin. Some dissolution of salt deposits has probably been taking place ever since deposition of the salt more than 230 million years ago. Nevertheless, the subsurface dissolution fronts of the thick bedded-salt deposits of the Permian basin have retreated at a very slow average rate during that 230 million years.

The preservation of bedded salt from subsurface dissolution depends chiefly on the isolation of the salt from moving ground water that is not completely saturated with salt. Karst topography is a major criterion for recognizing areas where subsurface dissolution has been active in the past; therefore, the age of the karst development is needed to provide the most accurate estimate of the dissolution rate. The Ogallala Formation of Pliocene age is probably the most widespread deposit in the Permian salt basin that can be used as a point of reference for dating the development of recent topography. It is estimated that salt has been dissolved laterally in the vicinity of Carlsbad, New Mexico, at an average rate of about 6-8 miles per million years.

Estimates of future rates of salt dissolution and the resulting lateral retreat of the underground dissolution front can be projected with reasonable confidence for southeastern New Mexico on the assumption that the climatic changes there in the past 4 million years are representative of climatic changes that may be expected in the near future of geologic time.

Large amounts of salt are carried by present-day rivers in the Permian salt basin; some of the salt is derived from subsurface salt beds, but dissolution is relatively slow. Ground-water movement through the Permian salt basin is also relatively slow.

INTRODUCTION

This report by the U.S. Geological Survey, on behalf of the U.S. Atomic Energy Commission, results from a compilation of available information on the stability of bedded salt in the Permian salt basin in the Western Interior of the United States. The compilation began as an inquiry into the tectonic stability of the Permian salt basin to aid in decisions on the suitability of parts of the basin for emplacement of atomic waste products in salt beds. The inquiry shows that, although the region was tectonically active during Pennsylvanian and Permian time before the bedded salt was deposited, the region has been relatively stable since Permian time. The inquiry also suggests that tectonic activity may be of less importance to the stability of bedded salt in the region than is dissolution of salt beds. Subsurface dissolution of salt beds is now occurring locally in the Permian salt basin.

The term "Permian salt basin" in this report includes parts of western Kansas, Oklahoma, and Texas, and eastern Colorado and New Mexico (fig. 1). This region includes a series of discontinuous secondary sedimentary basins in which halite and associated salts accumulated during Permian time.

This study is concerned with the history of geologic processes that have produced and maintained the present geologic setting in the Permian salt basin. It is probable that bedded salt of Permian age once extended far beyond its present limits, but the original extent of salt deposition is a matter of speculation. The stability of bedded salt during the recent geologic past is more important in regard to the problem of waste disposal than the tectonism of the region in the distant past; therefore, this study has been directed toward the more recent geologic events and climatic conditions of the Permian salt basin.

Seas withdrew and the region was dry land by the close of Cretaceous time so that no extensive sedimentary deposits have been preserved as useful points or planes of reference until late Tertiary (Miocene and Pliocene) time. For this reason, the present terrain in the Permian salt basin is assumed to have begun development with the deposition of the sediments that now compose the Ogallala

Formation of Miocene and Pliocene age. Deposition of the Ogallala Formation began about 12 million years ago. Ogallala time was largely one of sedimentation in this region. Streams flowing eastward from the Rocky Mountains deposited an extensive blanket of gravel, sand, and related deposits over much of eastern Colorado, western Kansas, Oklahoma, Texas, and eastern New Mexico. The Ogallala Formation underlies most of the High Plains--called the Llano Estacado in western Texas and eastern New Mexico. Ogallala deposition ended about 4 million years ago with regional warping and uplift followed by the development of a carbonate "caprock" that was part of a soil-caliche complex on the top of the Ogallala.

Since Ogallala time, erosion has exceeded deposition in the general region of the Permian salt basin. The Ogallala Formation has been eroded from broad areas near the Rocky Mountain front, and new drainage systems have developed. During Pleistocene time climatic conditions fluctuated widely leading to variations in rainfall and ground-water movement. Most sink holes and other solution features visible in today's landscape began to form at this time.

Recent geologic history is the key to predicting the geologic processes that will be active in the Permian basin in the near geologic future. Erosion and dissolution are active in many areas but at other places there is little surface indication of active dissolution of major salt beds. The most immediate danger to a salt bed is the accessibility of a continuing supply of fresh ground water. Ground water may be circulated most freely by solution cavities, fractures or joints, and by improperly plugged drill holes. Literally hundreds of thousands of wells have been drilled in the Permian basin in the search for water, oil, gas, and potash. If not adequately plugged, drill holes that penetrate the salt beds and reach an underlying aquifer could mobilize the salt. Before any area in the Permian salt basin is approved for the emplacement of radioactive waste in bedded salt, the recent geologic history of that area should be studied carefully, with particular reference to rates of erosion and subsurface dissolution.

GENERAL GEOLOGY

Although rocks older than Permian age are not exposed in the Permian salt basin, they are in the subsurface and have been encountered in drill tests for oil and gas. The Precambrian rocks of this region, called "basement" (Bayley and Muehlberger, 1968), are largely metamorphosed clastic rocks intruded by silicic igneous rocks. Volcanic rocks occur locally. In western Oklahoma (central Anadarko basin, fig. 5) Lower Cambrian rhyolite is the "basement" rock.

Paleozoic rocks in the subsurface include thin glauconitic sandstone and dolomite of Late Cambrian or Early Ordovician age. These are overlain by shale, limestone, and dolomite beds with some thin beds of sandstone of Ordovician, Devonian, and Mississippian age. The aggregate thickness of these rocks probably does not exceed 3,000 feet at any place in the Permian salt basin.

Rocks of Pennsylvanian age include conglomerate, sandstone, shale, and limestone. These rocks are present everywhere in the Permian salt basin except in some parts of western Texas where they have been eroded from mountainous uplifts of Late Pennsylvanian and Early Permian age. In general, rocks of Pennsylvanian age range in thickness from about 1,000 feet in shelf areas to more than 20,000 feet in the Anadarko basin (fig. 5) in western Oklahoma.

Rocks of Permian age are present over all of the Permian salt basin but they are well exposed at the surface only in limited areas in southeastern New Mexico and along a narrow belt in the western parts of Texas, Oklahoma, and Kansas (fig. 1). They are usually rather poorly exposed because they are subject to rapid erosion in the atmosphere and are generally covered by surficial sediments. Permian rocks include dark-reddish-brown conglomeratic sandstone and sandstone interbedded with shales at the base. Fine-grained sandstone, shale, gypsum, halite and associated salts and some limestone and dolomite are characteristic of the later Permian sequence.

Permian rocks are variable in thickness and range from an eroded edge in the midcontinent region to more than 15,000 feet in southeastern New Mexico and southwestern Texas. Major salt-bearing beds in this Permian sequence in Kansas and Oklahoma are the Wellington Formation and Ninnescah Shale. The Hutchinson Salt Member of the Wellington Formation exceeds 600 feet in thickness in a few places in southern Kansas and northern Oklahoma (Kulstad, 1959). It averages about 300 feet in thickness in central Kansas. In southwestern Kansas, salt in the Ninnescah Shale aggregates more than 200 feet in thickness (Jewett and Merriam, 1959). The Salado and Rustler Formations in southeastern New Mexico and western Texas are salt bearing and have an aggregate thickness, including other lithologies, of more than 2,500 feet (Hayes, 1958).

Regionally, the Permian basin has been tilted, warped, eroded, and invaded by at least one major incursion of the sea since Permian time, but deep-seated faults since Permian time are rare, except along the extreme southwestern edge of the basin outside the area of salt preservation. Most of the modern geologic structures known are probably of shallow origin and do not appear to reflect recurrent movement along Paleozoic or older structural features.

On the other hand, subsidence and collapse of the land surface owing to dissolution have been commonplace. Some dissolution and movement of salt has probably been taking place since its deposition more than 230 million years ago. On balance, however, processes of preservation have been dominant over processes of dissolution; otherwise the halite and other highly soluble minerals could not have survived in bedded form throughout this extent of geologic time.

Ogallala Formation

The Ogallala Formation is of Pliocene and, locally, Miocene age, and underlies most of the High Plains. It is a major point of reference for any discussion of the Holocene geologic history of the Permian salt basin and for this reason is here treated separately from other stratigraphic units. The most recent summary of this unit is by Frye (1970), and some of his comments are paraphrased in the following discussion.

The Ogallala Formation is an extensive deposit in western Kansas, eastern Colorado, eastern New Mexico, and the panhandle of Oklahoma (fig. 1). It extends northward from the area of the Permian salt basin across Nebraska and into southeastern Wyoming and southern South Dakota. It was deposited mainly by streams that flowed eastward and southeastward from the Rocky Mountains. Locally, eolian and lake deposits are a part of this formation. It consists of sand and gravel capped by an extensive caliche "caprock" that is believed to be part of an old soil profile and the result of a long period of equilibrium. Ogallala time was brought to a close by "stream rejuvenation incident to renewed upwarping." (Smith, 1940, p. 94).

Ogallala deposition began about 12 million years before the present. Deposition of the Ogallala stopped before the end of Pliocene time, probably as much as 4 million years ago. The Pliocene-Pleistocene time boundary is in some dispute but it is presently placed about 1.8 million years ago (Berggren, 1972).

Permian salt basin since Ogallala time

Ogallala time was a time of deposition and preservation; geologic time since Ogallala deposition has been a time of erosion. The modern landscape in the Permian salt basin began to be sculptured with the beginning of erosion of the Ogallala. Deposits preserved in stream valleys and on pediment surfaces are presently the only basis for dating these modern events. One of the earliest dated Pleistocene deposits in this area rests in a channel that was eroded in the Ogallala. This deposit is in western Kansas at the site of the Borchers fauna, where a volcanic ash has been dated as 2 million years before the present (Naesser and others, 1971). Another ash fall has been used to date some surficial deposits on the High Plains (the Blancan fauna) as 1.4 million years before the present (Izett and others, 1972). Sites related to occurrences of early man on the High Plains can also be used to determine indirectly the dates of some more recent geologic events.

Major geologic events in the Permian basin are summarized in table 1.

GEOLOGIC SETTING OF SALT BEDS

Salt is not exposed in the Permian basin, but at many places the insoluble portions of salt-bearing rocks crop out as breccias along their belts of outcrop. The breccia represents the residum of the formation after the salt beds have been dissolved by surface and near-surface solution. A breccia of this kind has been observed near Carlsbad, New Mexico. This breccia is 100-150 feet thick and consists of red gypsum and blocks of reddish-brown siltstone that are believed to be a residum of the Salado Formation (Hayes, 1964, p. 15).

Table 1.--Summary of major geologic events in the Permian salt basin

Era	Period	Events	Time in million years
Cenozoic	Quaternary	Recent--Present landscape developed. Sink holes, erosion. Pleistocene--Variable climate. Ice sheets to north.	-- 0
Cenozoic	Tertiary	Pliocene, Miocene } Deposition in area of present High Plains by rivers flowing from Rocky Mountains. Oligocene, Eocene } Rocks of this age not recognized. May have included minor igneous activity.	
Mesozoic	Cretaceous	Shallow seas intermittent over all of basin.	--100
Mesozoic	Jurassic	Sparse record preserved. Some windblown sand.	
Mesozoic	Triassic	Deposition by rivers. First indication of development of sink holes in west-central Permian basin.	--200
Paleozoic	Permian	Salt deposited in shallow seas.	
Paleozoic	Pennsylvanian	Fluctuation of sea level. Mountain building.	--300
Paleozoic	Mississippian	Minor encroachment of sea.	
Paleozoic	Devonian	Absent. Period of erosion(?)	--400
Paleozoic	Silurian	Absent. Period of erosion(?)	
Paleozoic	Ordovician	Limited advance of shallow seas during both Ordovician and Cambrian time.	--500
Paleozoic	Cambrian		--600
	Precambrian rocks. Metamorphic rocks intruded by granite and associated igneous rocks.		

Salt occurs almost everywhere beneath the surface of the Permian basin and is found in beds that range from a wedge edge to more than 1,000 feet in thickness. The beds are discontinuous and grade laterally and vertically into shale, limestone, and anhydrite. The true thicknesses of individual salt beds are not well known over the Permian basin because of the relatively small interest in logging these intervals during past drilling.

The salt-bearing formations of the Permian basin are the Rustler, Salado, and Castile Formations in the Delaware basin; the Rustler and the Salado Formations in the Midland basin, in the Central basin platform, and in eastern New Mexico; the Rustler Formation and the Clear Fork Group in the Texas panhandle; the Clear Fork Group in the Oklahoma panhandle; the Wellington Formation in central Oklahoma; and the Wellington Formation and Ninnescah Shale in Kansas (figs. 2 and 5). The thicknesses and lithologies of these formations vary unpredictably owing to the differences in depositional environments, leaching of soluble beds, and later erosion.

The Rustler Formation varies from 200 to 500 feet in thickness, and consists of salt and anhydrite with interbeds of dolomite, limestone, siltstone, and sandstone. In the Delaware basin, the Rustler unconformably overlies the Salado Formation in most of the area east of the Pecos River and overlies the Castile Formation west of the Pecos.

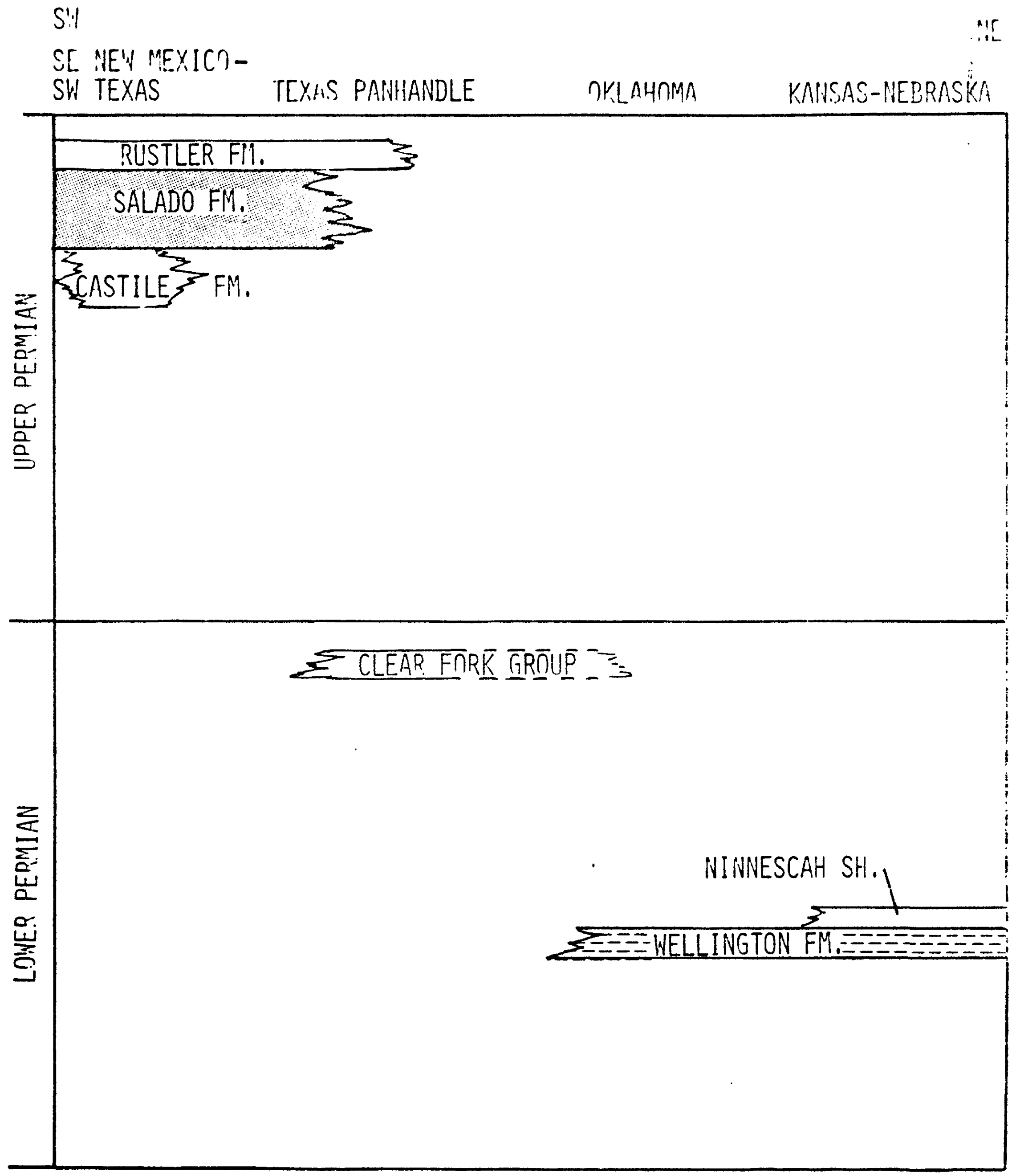

FIGURE 2.--DIAGRAM OF STRATIGRAPHIC RELATIONSHIP OF SALT-BEARING FORMATIONS IN PERMIAN SALT BASIN. VERTICAL DIMENSION SHOWS RELATIVE TIME OF DEPOSITION OF FORMATION, NOT THICKNESS OR DEPTH OF FORMATION BELOW PRESENT LAND SURFACE.

The Salado Formation exceeds 2,000 feet in thickness in the Delaware basin where it attains its maximum development. The formation is mainly rock salt (halite) with much anhydrite and lesser amounts of interbedded shale, sandstone, and other evaporite minerals. The salt alone is more than 1,600 feet thick (fig. 3). The Salado overlies the Castile Formation in the Delaware basin and overlies the Tansill Formation on the northwest shelf.

The thickness of the Castile Formation may approach 2,000 feet near the center of the Delaware basin. The formation is composed mainly of beds of anhydrite and halite, but also includes a few extensive limestone beds. The salt alone is more than 600 feet thick (fig. 3). The Castile overlies the Bell Canyon Formation.

The Clear Fork Group has been divided by petroleum geologists into three informal formations: the Red Cave mudstone and anhydrite; the Tubb sand, composed of anhydrite, salt, mudstone, siltstone, and sandstone; and the Cimarron anhydrite. The thickness of the group varies irregularly, but may be more than 600 feet.

The Wellington Formation is largely shale, anhydrite, and salt, and attains a thickness of about 700 feet (fig. 3). It underlies the salt-bearing Ninnescah Shale in Kansas and the barren Hennessey Shale in central Oklahoma.

The Ninnescah Shale is composed mostly of shale with interbeds of limestone, sandstone, anhydrite, and salt beds. The greatest thickness of the formation is nearly 400 feet.

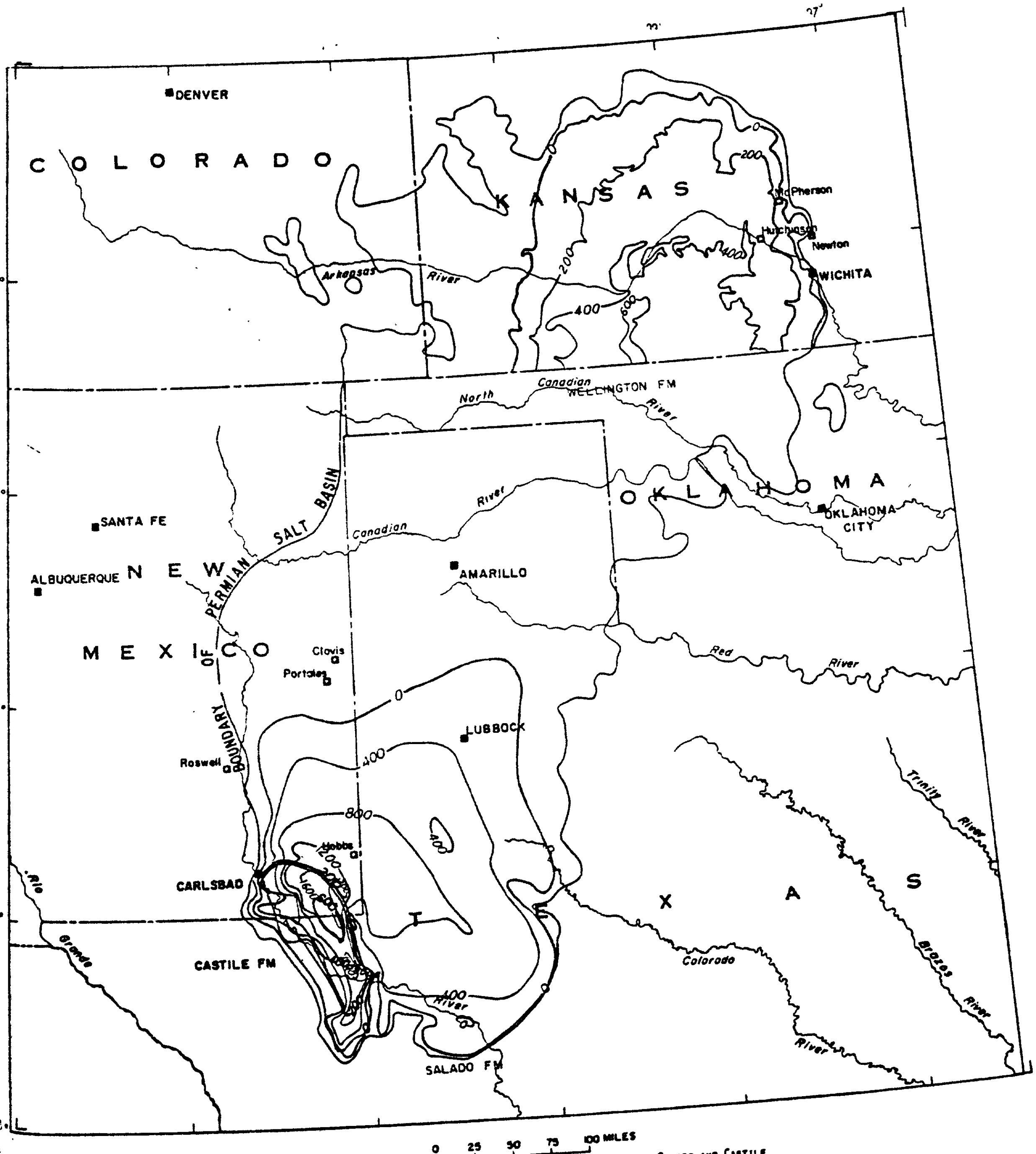

Figure 3.--Permian salt basin showing thickness of salt in the Salado and Castile Formations (after Hayes, 1958) and the Wellington Formation (after Kulstad, 1959). Contour interval is 400 feet on Salado Formation and 200 feet on Castile Formation and Wellington Formation.

The salt-bearing beds crop out in parts of the Permian basin, but lie beneath 2,500 feet or more of overburden in western Texas and in northeastern New Mexico. Salt deeper than 2,000 feet underlies large parts of southwestern Kansas, eastern New Mexico, and western Texas.

Figure 4 shows the approximate thickness of overburden above the salt-bearing rocks of the Permian basin, as well as the thickness of selected salt-bearing formations and the location of oil and gas fields. The thickness of overburden to the top of the uppermost salt bed was compiled from published cross sections (Adkison, 1966; Maher, 1960). The general configuration of the land surface was taken into account, although local surface irregularities were eliminated owing to the small scale of the map and the 500-foot contour interval used. The salt beds are discontinuous, but for the purpose of contouring the top of the salt-bearing rocks, the beds were treated as continuous.

Salt has maximum overburden in parts of the Midland, Palo Duro, and Tucumcari basins and on the Sierra Grande arch, and moderate to minimum overburden in parts of the Delaware, Midland, and Palo Duro basins, the Hugoton embayment, and the central Kansas uplift (fig. 5).

The oil and gas production of the Permian salt basin is from strata that lie beneath the salt beds.

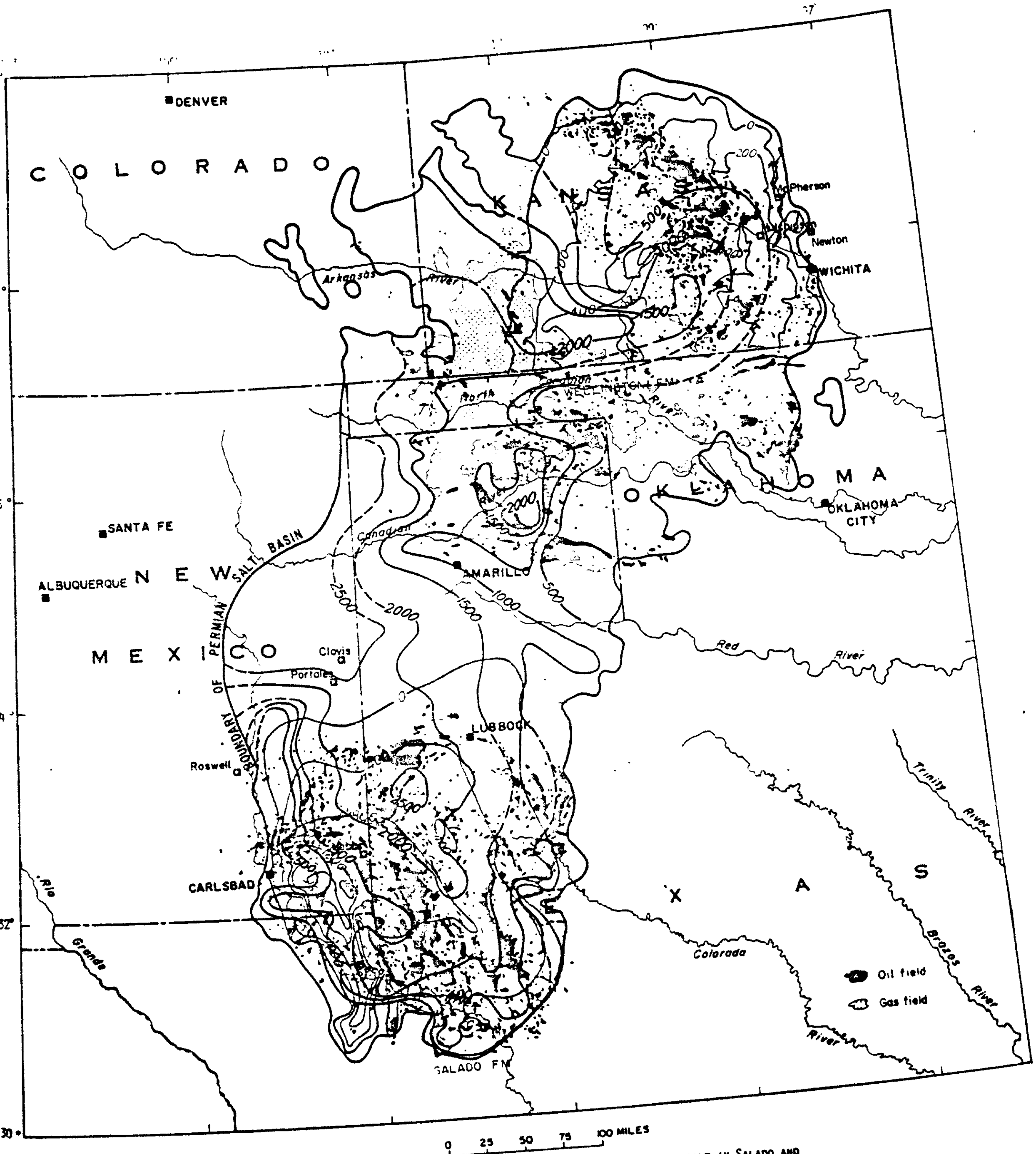

Figure 4.--Depth to salt-bearing formations, thickness of salt in Salado and Wellington Formations, and location of oil and gas fields in Permian salt basin. Depth to salt-bearing formations shown by red contours, 500-foot interval. Thickness of salt shown by blue contours; 400-foot interval for Salado Formation, 200-foot interval for Wellington Formation. Oil and gas fields shown in yellow.

TECTONIC FRAMEWORK OF PERMIAN BASIN

The Permian salt basin includes several variously oriented, but connected, smaller basins and uplifts that were structurally well established before Permian sedimentation began. The major tectonic elements of the region were completely formed before the deposition of Permian salt-bearing rocks (fig. 5), and crustal stability of the region has been maintained since Permian time. The Permian salt basin is composed of at least 17 well-defined lesser tectonic units (fig. 5).

Central basin platform

This platform is an ancient uplift of Precambrian and early Paleozoic rocks at the southern extremity of the Permian basin in the area of southeastern New Mexico and southwestern Texas. The platform separates the Delaware basin from the Midland basin, and extends in a northerly direction for as much as 200 miles to abut against the south flank of the east-west-trending Matador arch. Rocks of Early Permian and older age on the Central basin platform are broken by many large north- and northwest-trending faults, but all predate the salt deposits of the adjacent basins. The platform may have formed first during Precambrian time. It was an area of stability throughout the Paleozoic era except for some instability during Late Devonian time and considerable instability in Late Pennsylvanian and Early Permian time.

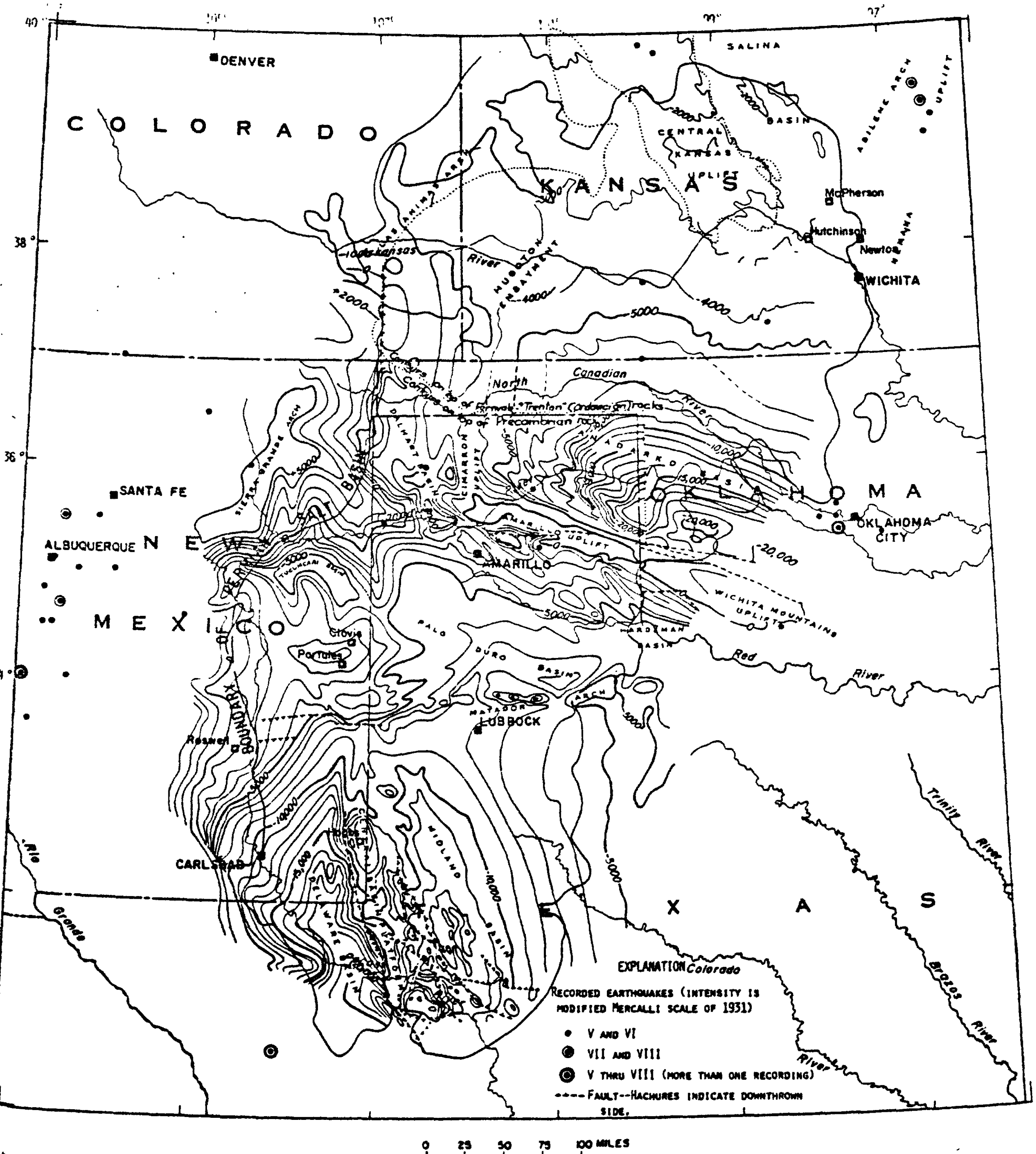

Figure 5.--Map showing major tectonic elements of the Permian salt basin (after Cohee and others, 1961) and epicenters of recorded earthquakes showing intensity according to the modified Mercalli scale of 1931 (after von Hake and Cloud, 1968). Structure contours on top of Precambrian rocks in southern part and on Fernvale "Trenton" rocks in northern part; contour interval 1,000 feet; dashed where uncertain.

Delaware basin

The Delaware basin is a deep asymmetric trough west of the Central basin platform in the vicinity of Pecos, Texas. The basin extends in an arc for more than 200 miles in a north-south direction, and has more than 20,000 feet of relief. In spite of its extreme depth, faulting is apparent only near its boundary with the Central basin platform, and this faulting occurred before deposition of salt. The Delaware basin may have begun to subside during Early Pennsylvanian time. Subsidence reached its maximum and the basin took its present shape during Permian time.

Midland basin

The Midland basin is a shallow symmetric basin east of the Central basin platform in the area of Midland, Texas. The Midland basin also extends for more than 200 miles in a north to northwest direction. Relief is only 4,000-5,000 feet. Extensive major faulting occurred before the deposition of salt in the southern part of the basin and on its west flank in proximity to the Central basin platform.

Matador arch

The Matador arch is an east-west-trending Paleozoic highland of irregular outline and relief that extends for 300 miles entirely across the Permian basin near the latitude of Lubbock, Texas. The Matador arch separates the Delaware and Midland basins from the Hardeman, Palo Duro, and Tucumcari basins to the north. Large faults break the basement rocks only on the southern flank of the arch near its western extremity. Here, too, occur some of the rare igneous intrusives in the Permian salt basin: Railroad Mountain and Camino del Diablo--east-west-trending dikes.

Hardeman, Palo Duro, and Tucumcari basins

These three basins are separate lows that are parts of a separate larger composite basin that roughly parallels the Matador arch to the south. These three small basins extend in a line across the Texas panhandle from southwestern Oklahoma to eastern New Mexico. The composite basin is asymmetric, and its relief varies locally and irregularly from 4,000 to 10,000 feet. The Hardeman and Palo Duro basins were relatively stable throughout Paleozoic time but the Tucumcari basin was unstable in Late Devonian and again in Late Pennsylvanian and Early Permian time.

Sierra Grande arch, Amarillo and Wichita Mountains uplifts

These ancient tectonic features extend across the entire Permian basin near the latitude of Amarillo, Texas, in a general east-west direction to separate the Hardeman, Palo Duro, and Tucumcari basins from the Dalhart and Anadarko basins. These three uplifts are parts of the same highland, which is very irregular in cross section and in plan. The presalt rocks are broken by long faults on both flanks of the Amarillo and Wichita Mountains uplifts. Faulting is particularly complex in the basement rocks of the Wichita Mountains, but the older rocks appear to be relatively unbroken on the Sierra Grande arch.

Dalhart basin

The Dalhart basin extends north and south between the Sierra Grande arch and the Cimarron uplift for about 100 miles in the northwest corner of the Texas panhandle. It is a symmetric, though somewhat irregular, feature in that its maximum depths are separate features in the southern part of the basin. Relief varies from less than 2,000 feet to more than 10,000 feet.

Cimarron uplift

This low upland area extends north-south across the Texas and Oklahoma panhandles for less than 100 miles as an extension of the Amarillo uplift between the Dalhart and Anadarko basins. Presalt rocks appear to be unfaulted in the vicinity of the Cimarron uplift.

Anadarko basin

The Anadarko is a large asymmetric basin north of the Amarillo and Wichita Mountains uplifts, the trough extends in a general east-west direction across the northeastern corner of the Texas panhandle and western Oklahoma for about 300 miles. The Anadarko basin has nearly 25,000 feet of relief, but in spite of its extreme depth basement rocks seem to be faulted only on the north flanks of the Wichita Mountains uplift.

Hugoton embayment

This is a broad and shallow northwestward extension of the Anadarko basin into western Kansas between the Las Animas arch and the central Kansas uplift. The surface of the basement rocks here is generally featureless with no more than 2,000 feet of relief over the entire embayment.

Las Animas arch

The Las Animas arch is a low divide in southeastern Colorado that extends between the Sierra Grande arch and the central Kansas uplift and outlines the northwestern part of the Hugoton embayment.

Central Kansas uplift

This uplift is a broad, low, and irregular upland that extends southward for 150 miles from Nebraska into the Permian basin of central Kansas to separate the Salina basin from the Anadarko basin.

Salina basin

This small, regular, and symmetric basin in northern Kansas forms the northeastern extent of the Permian basin. It has less than 2,000 feet of relief, and is a subsidiary basin to the larger Anadarko basin. The Abilene arch and the Nemaha uplift extend beyond the boundaries of the Permian basin to form the eastern margin of the Salina basin. These features were formed before salt deposition.

FAULTS AND IGNEOUS INTRUSIONS

Although faulting is commonplace in the Rocky Mountains and some adjacent areas, faults that displace Permian salt-bearing rocks in the Western Interior of the United States are rare. The Bonita fault is a northeasterly trending fault in Quay County, New Mexico (fig. 8), that displaces rocks of Triassic and Cretaceous age. Presumably this fault also displaces Permian rocks in the subsurface. The Meade fault in Meade County, Kansas, may be related both to tectonics and solution of Permian salt in the subsurface. This fault displaces rock of Pliocene age at the surface. Neither fault is large enough to show on figures 1 or 5.

Numerous faults have been mapped in the Guadalupe Mountains in Texas (King, 1948) and New Mexico (Hayes, 1964) west of the Delaware basin, but these faults do not project into the salt beds. Kelley (1971) has mapped faults and "buckles" on the backslope of the Sacramento Mountains west of the Permian basin in New Mexico but these structures cannot be projected with certainty into the salt beds. Kelley (1971) has also interpreted as a fault a lineament along the Carlsbad reef on the eastern front of the Guadalupe Mountains in southeastern New Mexico. This fault would separate the Guadalupe Mountains from the Delaware basin, but we do not agree with this interpretation.

There are at least two east-trending dikes of augite diorite east and northeast of Roswell, New Mexico (Semmes, 1920). The southernmost of these is Devils Racetrack, which is east of Roswell about 9 miles. It is about 30 feet wide and about 25 miles long. The second well-known dike is Railroad Mountain, which is about 15 miles north of the Devils Racetrack. It is an olivine gabbro and is about 70-100 feet wide and more than 30 miles long (Semmes, 1920). Three igneous dikes of alkali syenite (Pratt, 1954) occur in the Castile Formation south of Carlsbad, New Mexico. They strike about N.60°E., dip about 80° N., and are 1,000-4,000 feet long on the outcrop (Hayes, 1964, p. 39).

EROSIONAL HISTORY

Underground dissolution as well as surface erosion have characterized the geologic history of the Permian basin. Some removal of salts may have begun locally soon after the deposition of salt beds. During Triassic time sink holes were formed in parts of the Pecos Valley (Gorman and Robeck, 1946). Little is known about the Jurassic history of the area but some solution and surface erosion probably occurred. During much of Cretaceous time the region may have been relatively stable except for being covered by shallow seas.

Continental instability in Late Cretaceous and Tertiary time began the development of the modern topography of the basin. Seas withdrew from the continental interior and terrestrial geologic processes became dominant. Rocks of early Tertiary age are not represented in the Permian basin but the Ogallala Formation of late Tertiary age is widespread.

The Ogallala Formation underlies much of the High Plains throughout the Permian basin and is the latest blanketing deposit that can be used for correlative purposes. The Ogallala was deposited by streams that drained generally eastward and southeastward from the ancestral Rocky Mountains and the basin ranges of southern New Mexico.

Ogallala deposition probably began during the Miocene [illegible] and ended during the Pliocene. The exact time that erosion began is not known, but it probably did not begin at the same time over all the High Plains. Nevertheless, at the end of Ogallala deposition this continental formation probably blanketed essentially all of the Permian salt basin.

SURFACE FEATURES

In the search for criteria that indicate subsurface dissolution of bedded salt in the Permian basin, the authors have made a general study of geomorphic features and surficial deposits in the region. Geomorphic features have been classified on the basis of form rather than origin: internally drained basins and sink holes, linear features, and domal structures. Surficial deposits such as soils, sand dunes, alluvium, and caliche are of importance in dating recent geologic events and in determining areas of ground-water recharge.

Internally drained basins and sink holes

Internally drained basins, depressions, and sink holes are numerous in the Permian basin and have attracted the attention of observers since the last century (Haworth, 1896; Johnson, 1901). Subsidence and sinking of the land surface may be the result of various processes.

In Kansas, Frye (1950) has broadly classified depressions with internal drainage as: (1) solution-subsidence depressions produced by solution of salt, gypsum, chalk, or limestone, or

(2) nonsolutional features produced by differential eolian deposition or deflation, compaction, silt infiltration, and animal action. All depressions observed during the present study may also be placed in these categories.

The most spectacular of internally drained basins are those that have formed by solution of subsurface soluble rocks followed by collapse of the surface into the solution cavity. These vary from openings less than 1 foot across to large sink holes with accompanying ring fractures, such as the Meade Salt Well in Meade County, Kansas (fig. 8). When it collapsed in March 1879 the central sink and associated ring fractures measured more than 175 feet in diameter (figs. 6 and 7). Other striking examples of subsidence include the Ashland-Englewood Basin and associated features in southwestern Kansas (fig. 8), and Inman Lake with its associated belt of sink holes near Hutchinson, Kansas. Salt springs and sink holes in western Oklahoma and the panhandle of Texas are also features directly related to the dissolution of bedded salt deposits not far beneath the surface. Parts of the Cuneva depression in Quay County, New Mexico (fig. 8), collapsed about the turn of the present century and again in 1934 (Judson, 1950, p. 264). Some of these features are several miles across but the larger ones are composite or compound features that are the result of repeated periods of solution and collapse within a limited area.

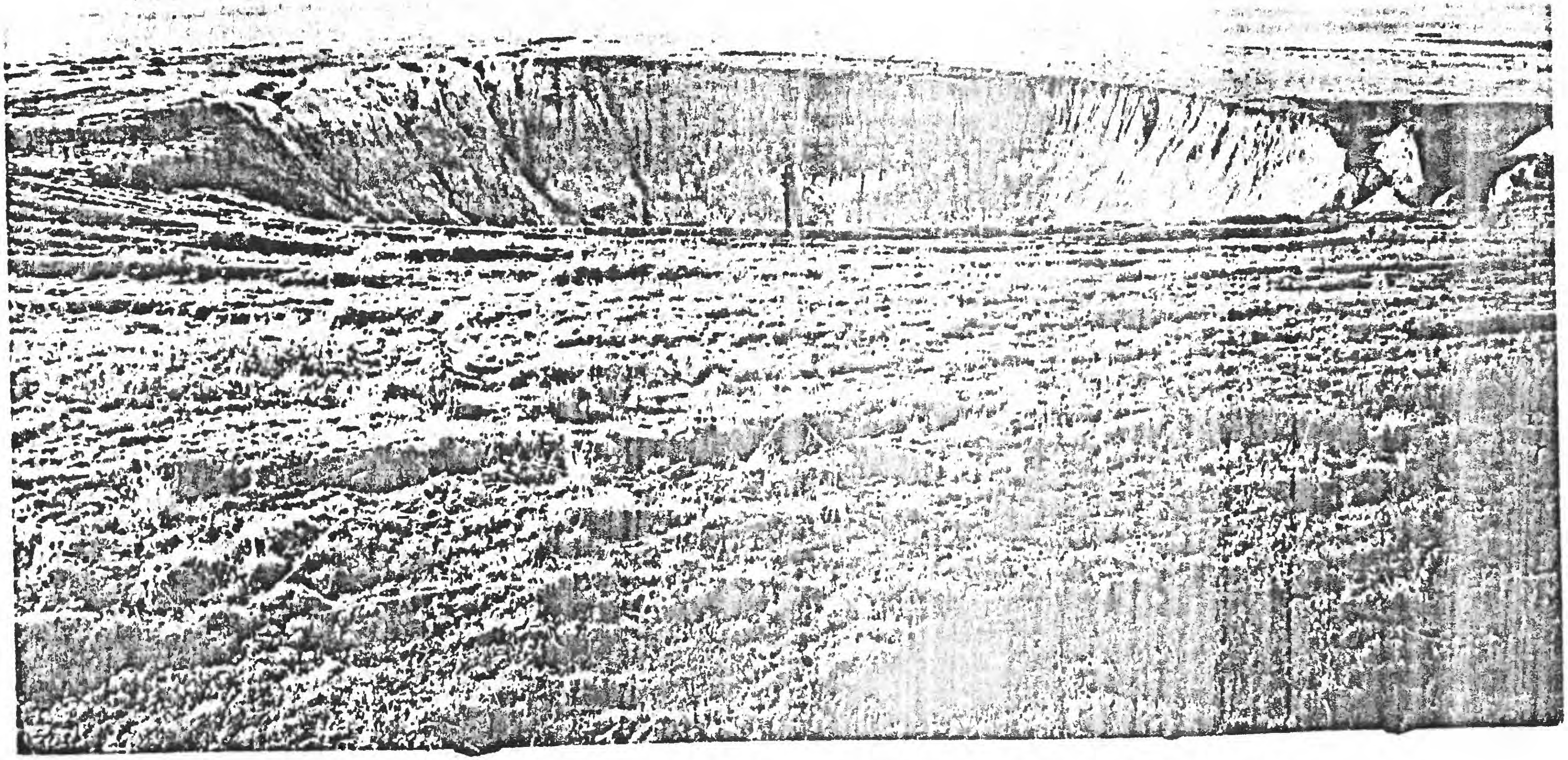

Figure 6.--Meade Salt Well, Meade County, Kansas (photograph by W. D. Johnson, 1897).

Figure 7.--Ring fractures around Meade Salt Well, Meade County, Kansas (photograph by W. D. Johnson, 1897).

Another large area of collapse that may be attributed to the dissolution of salt in the subsurface is San Simon Sink in southern Lea County, New Mexico (figs. 8 and 9). San Simon Sink is a compound collapse feature about 2 miles long and 1 mile wide. It is situated in the central part of San Simon Swale--a southeasterly trending depression that ranges from about 2 to 6 miles in width and is about 25 miles long. Windblown sand of late Quaternary age covers much of the area and masks the relief.

San Simon Swale is bordered on the northeast and the southwest by the Ogallala Formation resting on Triassic red beds that are as much as 1,270 feet thick in parts of this area (Nicholson and Clebsch, 1961, p. 35). These red beds rest in turn on the salt-bearing Rustler Formation. Triassic red beds are exposed at the surface both to the northeast and southwest of San Simon Swale, but "drillers for seismic exploration crews have reported drilling over 400 feet into the San Simon Sink without encountering red beds" (Nicholson and Clebsch, 1961, p. 46).

Based on the numerous ring fractures around San Simon Sink, it is apparent that the sink has had a long history of successive collapse events. A local resident informed us that one collapse event occurred in 1922 with the development of a fissure along the western side of the sink. Nicholson and Clebsch (1961, p. 46) estimated that alluvium is being deposited in the sink at a rate of about 1 foot in 5 years. Presumably the salt is being dissolved from the underlying Rustler Formation and is being carried as a ground-water brine in a southeasterly direction toward Texas.

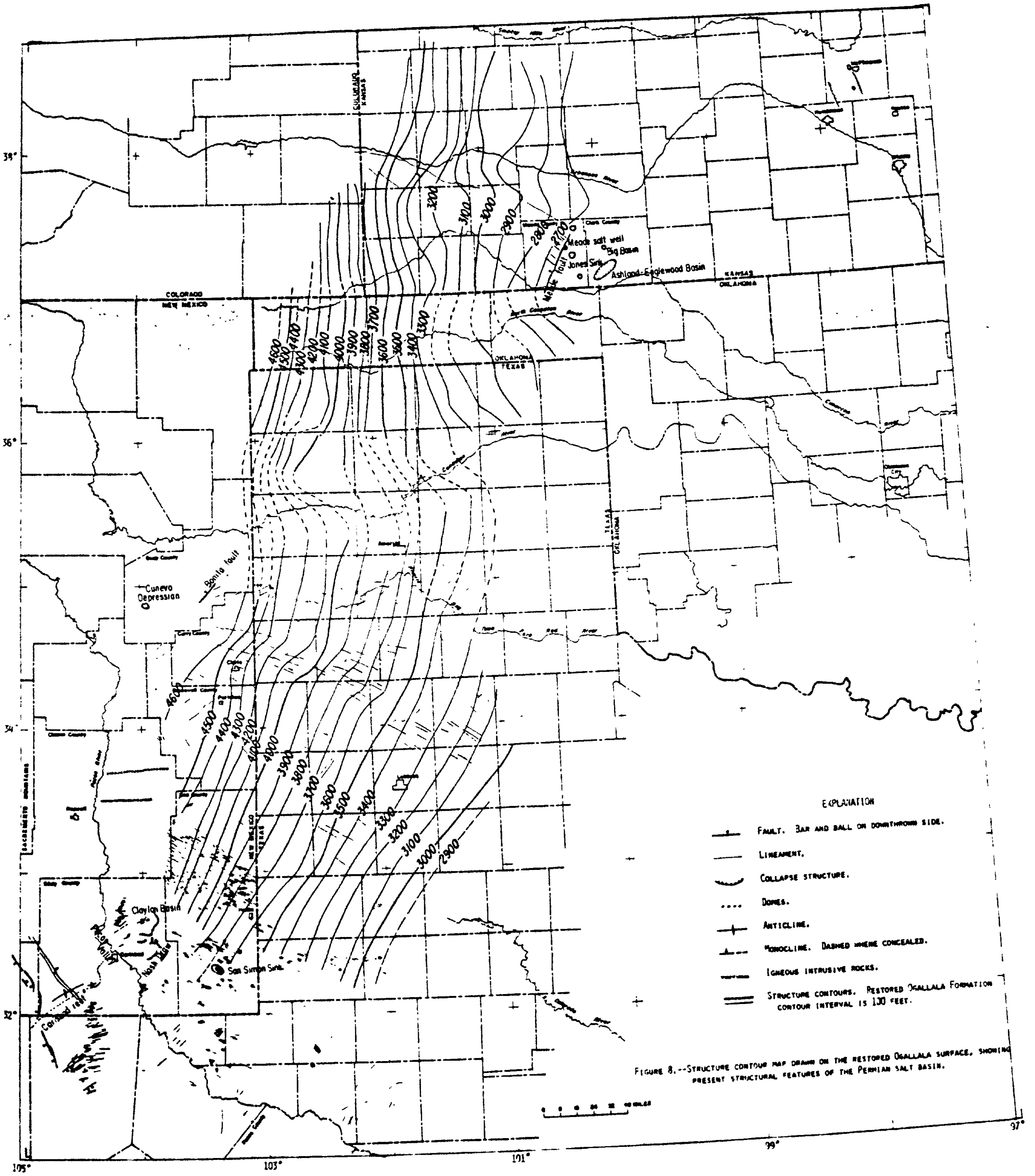

FIGURE 8.--Structure contour map drawn on the restored Ogallala surface, showing present structural features of the Permian salt basin.

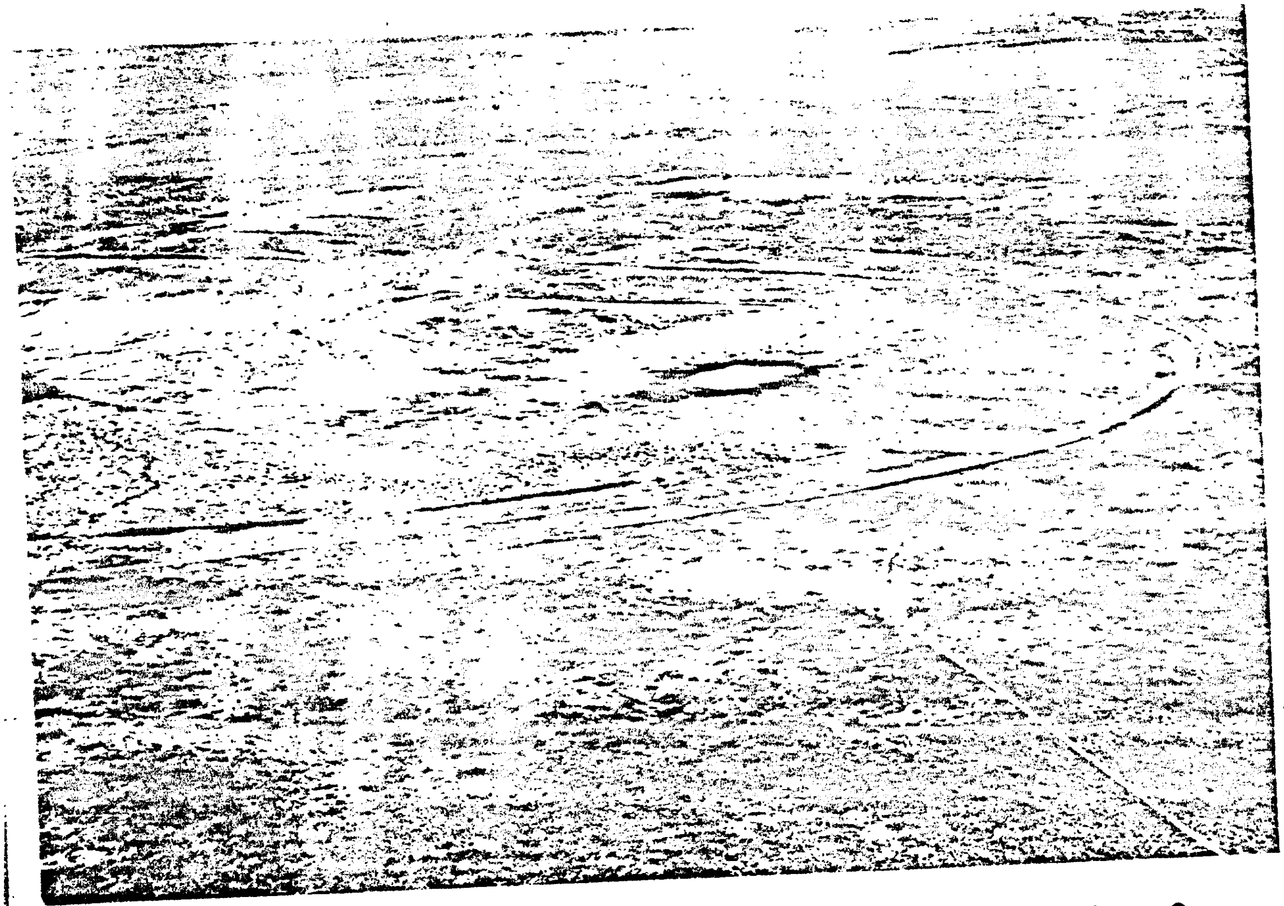

FIGURE 9.--OBLIQUE AERIAL PHOTOGRAPH OF SAN SIMON SINK, LEA COUNTY, NEW MEXICO, SHOWING CENTRAL SINK AND RING FRACTURES AROUND OUTER EDGE OF SINK AREA. VIEW IS TOWARD THE SOUTHWEST. SINK AREA IS ABOUT 2 MILES LONG AND 1 MILE WIDE.

We believe that the history of salt dissolution in San Simon Sink and the Cenozoic history of southeastern New Mexico are closely interrelated. At the close of Pliocene time the Ogallala Formation covered all of southeastern New Mexico as far west as the present Guadalupe Mountains southwest of Carlsbad. At the outset of extensive erosion during Pleistocene time the Ogallala included the carbonate "caprock" at the top. This caprock was near the land surface and in places was a barrier to the penetration of surface water into the underlying salt beds. During Pleistocene time Pecos River drainage was restricted to southeastern New Mexico, with the area of southern Lea and Eddy Counties forming the Pecos headwaters. The area now drained by the upper Pecos River was then drained east from the vicinity of Santa Rosa, New Mexico, through the depression now known as Blackwater Draw, southeast toward Lubbock, Texas, to the Double Mountain Fork of the Brazos River (Baker, 1915, p. 52-53).

We believe that a major tributary of the Pleistocene Pecos River flowed southeasterly through what is now San Simon Swale and southward from there into Texas. The course of this San Simon drainage may have been determined by leaching of the Ogallala caprock as discussed elsewhere in this report. Streams in the San Simon drainage eroded the Triassic red beds and water from those streams penetrated into the subsurface and dissolved salt from the underlying Rustler Formation.

Thus, San Simon Sink began to collapse in a Pleistocene stream course. The absence of salt in the underlying Ochoan rocks and the great thickness of overlying Cenozoic fill along the course of this postulated Pleistocene stream extending southward from San Simon Swale into Texas (fig. 10) seems to confirm this theory, suggesting that Cenozoic deposition partly filled the topographic depression caused by the dissolution and removal of the underlying salt-bearing rocks. Coalescence of sink holes probably was a major contributing process in the formation of San Simon Swale.

In addition to San Simon Swale some other depressions and river basins have been created by dissolution of soluble rocks and the subsequent lowering of the ground level. Prominent among these in southeastern New Mexico are Nash Draw and Clayton Basin (fig. 8); in Clayton Basin nearly 30 square miles has subsided more than 100 feet. Clayton Basin and Nash Draw are thought to be the result of coalescence of trains of sinks (Morgan and Sayre, 1942). The Ashland-Englewood Basin in southern Clark County, Kansas, is the largest solution-subsidence feature in Kansas topography and is believed to be the result of coalescence of several solution-subsidence depressions (Frye and Schoff, 1942). Much of the broad Pecos Valley in Eddy County, New Mexico, in the vicinity of Carlsbad is thought to be the result of regional solution of salt and subsidence of the valley floor (Morgan and Sayre, 1942). A belt of lakes across McPherson County, Kansas, is the result of surface collapse because of subsurface dissolution (Landes, 1963). Most, if not all, of these basins and depressions were formed in Pleistocene or Holocene time.

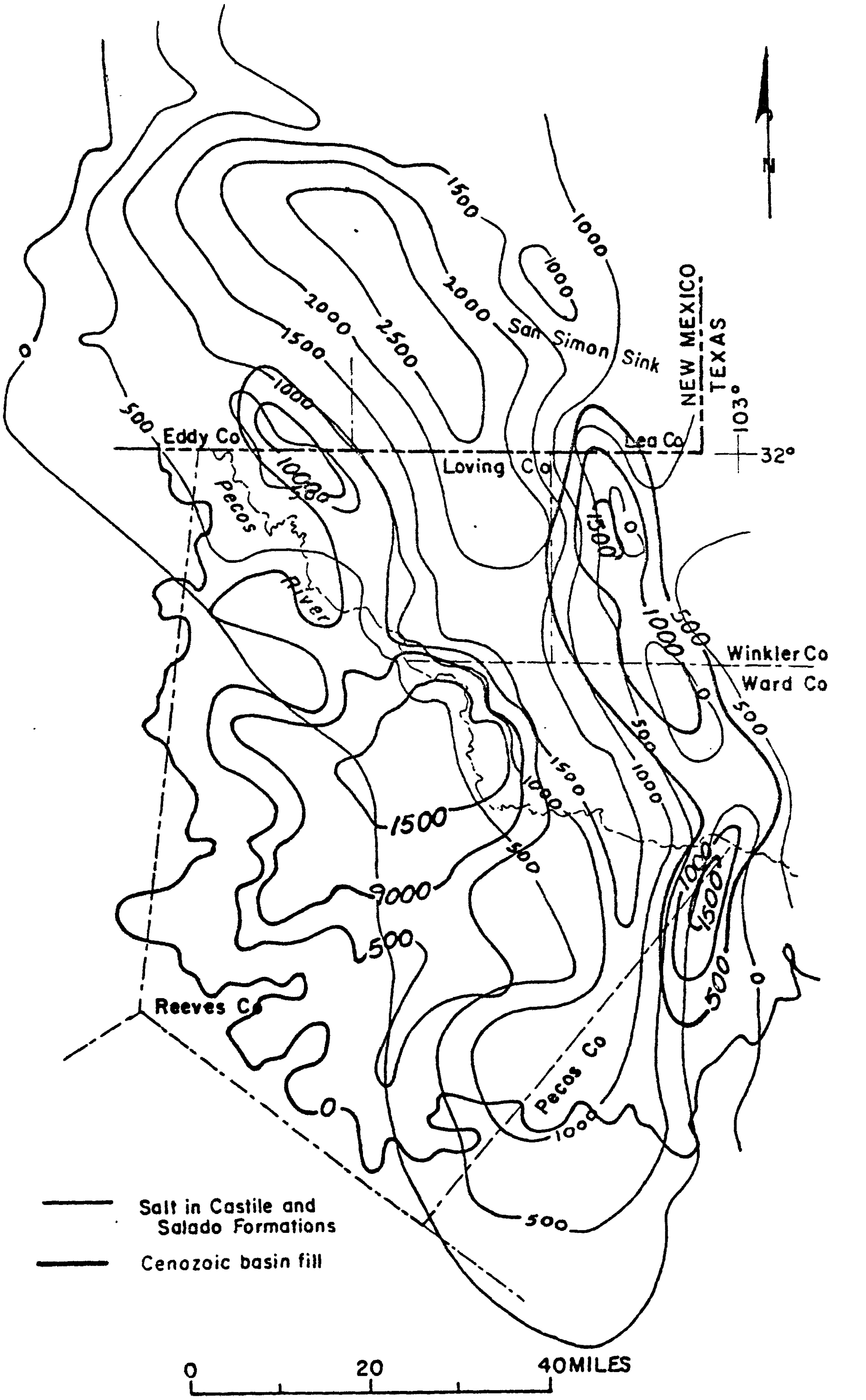

FIGURE 10.--MAP SHOWING TOTAL THICKNESS OF SALT BEDS IN THE CASTILE AND SALADO FORMATIONS, AND THICKNESS OF BASIN FILL ACCUMULATED DURING CENOZOIC TIME (GENERALIZED FROM MALEY AND HUFFINGTON, 1953, PLATES 1 AND 2).

Linear features

Linear features, including alinements of depressions, are common on the High Plains of eastern New Mexico and western Texas. They are best observed from the air and on aerial photographs because their expression is subtle (fig. 11). Their relief may be measured in a few tens of feet and their length in miles. On the High Plains both northeast and southwest of San Simon Swale in Lea County, New Mexico, numerous linear features are present (fig. 8). These are readily apparent on aerial photographs but are difficult to observe on the ground. They consist of swales and minor arroyos oriented about N.60°W., and generally parallel to San Simon Swale. Similar orientation of linear features is observed north of Hobbs, New Mexico, and in oriented depressions in the vicinity of Clovis, New Mexico.

These linear features have been interpreted as the result of deflation and scouring between former longitudinal sand dunes (Price, 1958). One system of lineations in the vicinity of Clovis has been described as reflecting a zone of structural weakness (Finch and Wright, 1970). A system of similar lineations in southern Eddy County, New Mexico, and northern Pecos County, Texas, has been explained as solution-subsidence troughs along joint systems in gypsum (Olive, 1957).

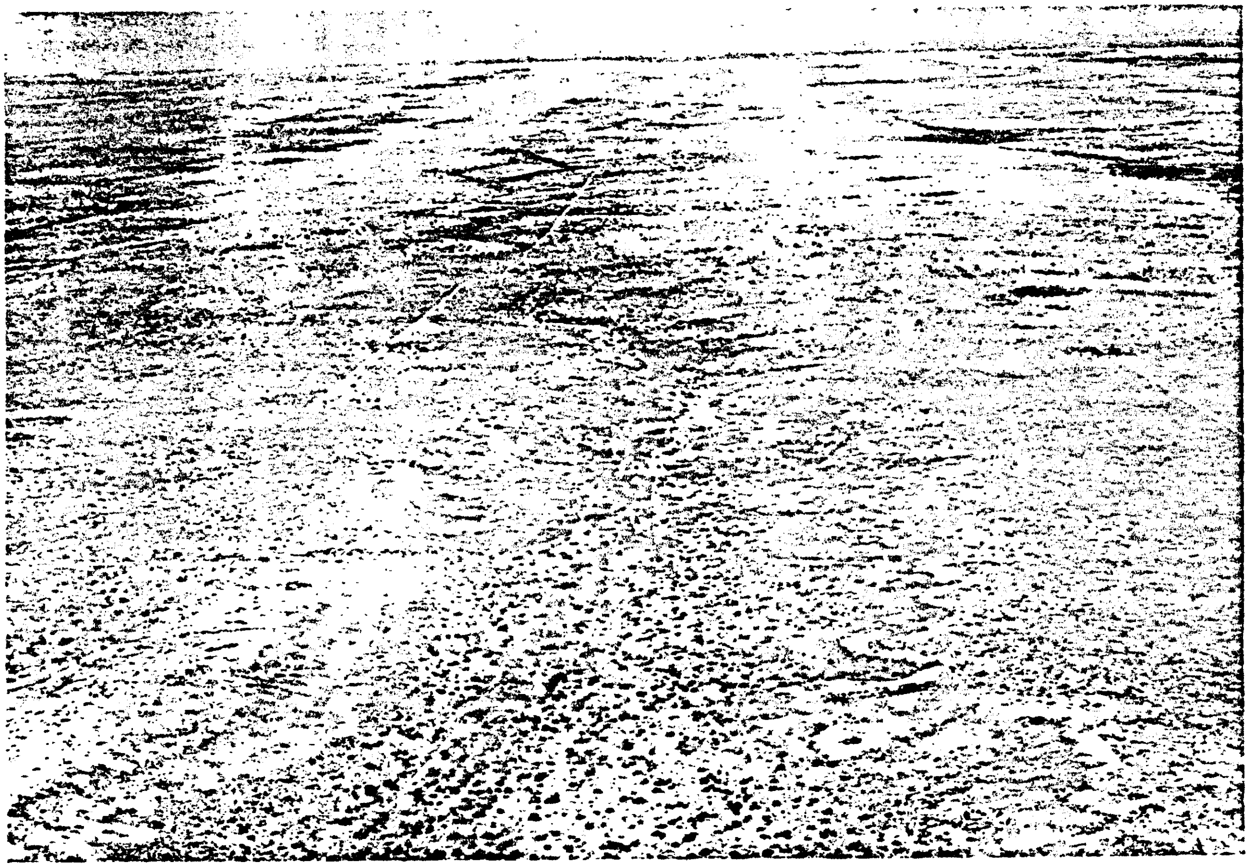

FIGURE 11.--OBLIQUE AERIAL PHOTOGRAPH OF LINEAR FEATURES ON SOUTHERN HIGH PLAINS. PLANT GROWTH IS MOST PROMINENT IN SWALES. VIEW IS TOWARD THE NORTHWEST.

Lineaments with an east-west orientation are present north of Carlsbad, New Mexico (fig. 8). These consist of alined drainages and small interior-drained depressions. These also are believed to represent an area of former longitudinal dunes with elongate deflated troughs between.

During the present study it was noted that many of these linear features are located on caliche surfaces. It has been suggested by other writers that some depressions on the High Plains are the result of alternate leaching and wind deflation and not to collapse (Judson, 1950; Price, 1958). This process has not been adequately studied but it is here suggested that the following sequence of events combined to form the linear features observed in Chavez, Eddy, and Lea Counties, New Mexico:

1. Longitudinal sand dunes formed on a caliche surface. Some of these dunes were several miles long and may have approached the size of similar dunes in Australia (Madigan, 1936) and the Sahara (Capot, 1945).

2. At some time after these dunes were formed there were enough periods of eolian quiescence so that plants could grow between the dunes. Ground water in small amounts is present between dunes, and this is the optimum environment in dune fields for plant growth. These plants, by decomposition and by exuding carbon dioxide from their roots, acidified the ground water to the extent that the caliche was leached. Reactivation of eolian action at intervals removed the leached sediments between dunes.

3. At a later date the dune sands were redistributed in blanket deposits and other dune forms in these and nearby areas. The swales that are now visible are those leached areas that mark the former extent of fields of longitudinal dunes.

Regardless of the origin of these linear features they are of interest to any considerations of waste disposal in certain areas of the Permian basin. Water collects in the depressions that develop along these lineaments and they are major factors in recharge of ground water. In addition, solution and erosion along these lineaments may have opened conduits to the subsurface and contributed to the more rapid solution of underlying soluble rocks. In view of its orientation and location, San Simon Swale is a collapse feature that may have developed as a part of the Pleistocene drainage system located along such a belt of lineaments.

Domal features

Numerous Holocene domal structures that are related to salt or other soluble rock have been described in southeastern New Mexico (Vine, 1960). These structural features have quaquaversal dips away from brecciated cores. They range from several hundred to several thousand feet in diameter. Deformation includes rocks of Permian, Triassic, and Holocene ages. These features occur in areas where subsurface dissolution of salt has been in progress.

Vine (1960, p. 1910-1911) has suggested that these domal features began as sink holes in the Rustler Formation. He further suggested several processes by which they may have developed into domal structures: the rising of salt by upward flow into a sink, the erosion of rocks surrounding the brecciated core of a sink, or the change of anhydrite to gypsum with a resulting increase in volume. Although the process by which these domes have developed is not fully understood, their presence indicates an area of dissolution of soluble rocks in the subsurface.

Rate of dissolution

Rapid dissolution of salt requires a continuing supply of fresh water to dissolve the salt and carry it away in solution. Without a supply of fresh water, the water in contact with the salt becomes a saturated brine that protects the remaining salt rather than dissolving it. The funnel effect of sink holes provides fresh surface water direct access to any immediately underlying salt beds resulting in their relatively rapid dissolution.

The dissolution rate of salt beds and their subsurface retreat on a regional scale are directly related to the regional stratigraphy and structure, to climate, and to topography. We believe that in southeastern New Mexico at the end of Ogallala deposition, about 4 million years ago, the underlying salt-bearing Salado Formation extended no farther west than the reef escarpment along the western edge of the Delaware basin (fig. 12). During Pleistocene and Holocene time extensive erosion stripped the protective Ogallala

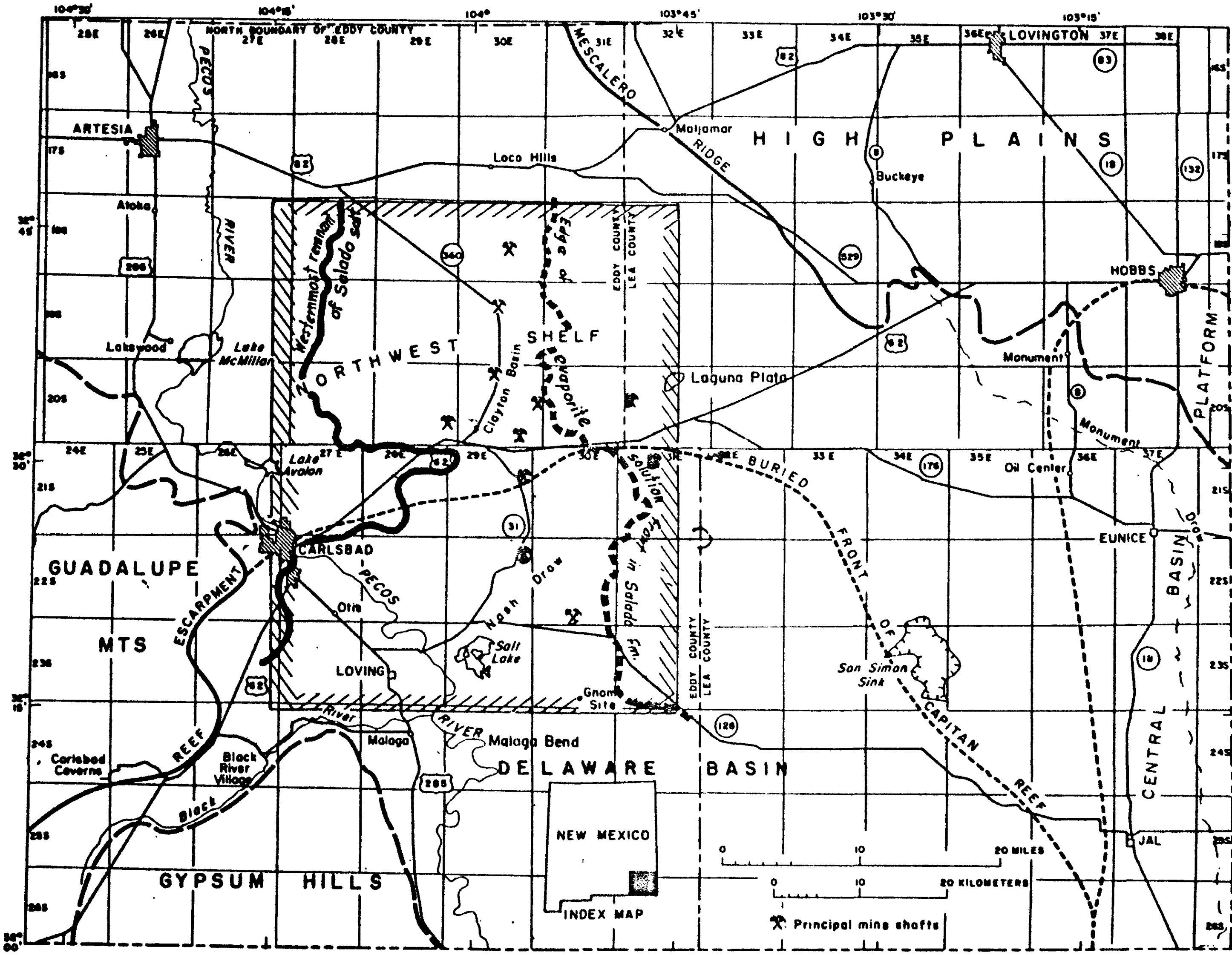

Figure 12.--Map of southeastern New Mexico showing salt dissolution in part of Permian salt basin. Northern boundary of Delaware basin is defined by reef escarpment and buried front of Capitan reef. Mine symbol indicates potash mine (modified after fig. 1 of Brokaw, Jones, Cooley, and Hayes, 1972; hachures outline area of fig. 4).

Formation from the western part of the area and cut into the underlying rocks developing the present Pecos River drainage. During that time any underlying salt beds west of the Pecos were dissolved, and the dissolution front of the buried salt retreated downdip to its present location about 23 miles east of Carlsbad (fig. 12). We, therefore, infer that since the close of Ogallala time, about 4 million years ago, the salt front in Permian rocks has retreated eastward from 25 to 35 miles. Accordingly, the average rate of movement is inferred to have been about 6-8 miles per million years.

Surface contours

In an additional effort to determine if tectonic movements had affected the region of the Permian basin since Ogallala time, we restored the approximate surface of the Ogallala by following the method used by Finch and Wright (1970). They state that "on the 1:250,000-scale National Topographic Maps, the approximate contours on the post-Ogallala surface of the High Plains were restored on the basis of present-day topography. The present-day contours are believed to represent slight modification of the land surface developed on the Ogallala Formation during the Quaternary Period. The post-Ogallala contour lines were drawn smoothly and slightly downslope from present-day topographic noses and into the heads of conspicuous valleys. This is a common method of restoring ancient topography." By this method they discovered an irregularity in the surface contours trending southeast from a point about 10 miles north of Clovis, New Mexico, to a point about 25 miles north of Lubbock, Texas. They attributed the trend of this irregularity in the contours to a zone of structural weakness.

Using similar methods we were able to duplicate the results of Finch and Wright in the vicinity of Clovis and Lubbock; then we extended the contours northward on the High Plains into Kansas and southward to the southern limit of Ogallala exposures. We discovered that irregularities in the contours are also present in the vicinity of major drainage systems: the Arkansas, Cimmaron, and Canadian Rivers (fig. 8). The irregularity first described by Finch and Wright (1970), and named by them the "Running Water Draw-White River lineament" is in the vicinity of the ancestral Pecos River drainage. These drainages may occupy zones of structural weakness but we do not find evidence that movement has occurred along these zones, except possibly the movement related to surface collapse resulting from solution. Instead, we suggest that these linear irregularities in the regional surface contours are related to major drainage systems and result either from wind erosion during late Pliocene or early Pleistocene, or from river erosion during the Pliocene.

OTHER THEORETICAL CONSIDERATIONS

Throughout the geologic history of the Permian basin many factors have combined to preserve the salt beds from dissolution. Foremost among these has been deep burial beneath other sediments. The areas where overburden is greatest are the areas of least salt dissolution. It is noteworthy that some areas of major salt solution are at or near the present boundaries of preservation of the Ogallala Formation. This may indicate that the processes that are removing the Ogallala Formation from the High Plains are also contributing to the dissolution of salt from the underlying Permian beds.

The Ogallala Formation is a major aquifer on the High Plains. At present, water is being mined from this aquifer at a rapid rate. Recent projections indicate that available water in the Ogallala Formation will be reduced to less than 20 percent of its present quantity by the year 2020 (New Mexico Bur. Business Research, 1972). This continuing change in water-table levels might affect ground-water circulation and salt dissolution in underlying beds sometime in the future.

Presumably it would not be feasible, economically and technically, to withdraw all fresh water from the Ogallala aquifer; but it is theoretically possible that enough fresh water might be withdrawn at some time in the future so that the fresh-water head would be reduced radically. Under those circumstances supersaturated salt solutions might rise near enough to the surface to permit new supplies of fresh water to enter the system and increase the rate of dissolution. The rate of dissolution under those conditions would be unpredictable with the data now available.

EARTHQUAKES

A generalized seismic risk map of the United States has been prepared by the U.S. Coast and Geodetic Survey indicating relative degree of seismic risk (Coffman and Cloud, 1970, p. 8-9). The degree of risk ranges on an arbitrary scale from predictable risk of no damage by earthquakes (Zone 0) to predictable major damage by earthquakes (Zone 3). All of the Permian basin is indicated as within Zone 1 on this map. Zone 1 is the area of predictable minor damage where "distant earthquakes may cause damage to structures" (Coffman and Cloud, 1970, p. 9).

Recorded epicenters of tremors exceeding an intensity of IV on the modified Mercalli scale of 1931 (Eppley, 1965) within the area of the Permian basin are very widely spaced and without geologic continuity. In fact, the southern half of the salt basin has never received a recorded shock with an intensity greater than IV.

In the northern half of the basin most of the stronger (V-VI) tremors appear to have occurred in the Texas panhandle in the vicinity of the Amarillo uplift. Epicenters of a few widely scattered earthquakes are placed in north-central and south-central Kansas. Between October 27, 1904, and April 13, 1961, only nine of these stronger earthquakes were recorded in the northern half of the Permian basin and none exceeded an intensity of VI (fig. 5). During that period, therefore, the average time spacing of those V and VI intensity earthquakes was one in about 7 years.

Specific reasons for earthquakes in the Permian basin are unknown. Smith (1940, p. 140) suggests "It is entirely possible either that they represent the delayed readjustments incident to warping long past, or that they are associated with gentle movements now in progress."

RECOMMENDATIONS

Areas in the Permian salt basin where the least dissolution of salt is apparent are those areas overlain by the Ogallala Formation. Unfortunately, over most of the Permian salt basin, thick salt deposits underlying the Ogallala may be at too great depth to be considered for waste disposal. Those parts of the Permian salt basin where thick salt deposits are reasonably near the surface and have been least disturbed by dissolution offer the greatest potential for safe emplacement of radioactive wastes. These areas include parts of Kansas and southeastern New Mexico.

A north-south belt of dissolution along the retreating salt front is present in central Kansas. A belt of salt deposits behind (west of) this front should be considered for waste disposal. In southeastern New Mexico a north-south belt of dissolution is present east of the Pecos valley. A belt of salt deposits behind (east of) this withdrawal front should be considered. However, care must be taken in this area that the site is not selected so far to the east that it includes San Simon Swale where some dissolution has taken place. In southeastern New Mexico the area where least dissolution is apparent is west of San Simon Swale and east of Clayton Basin and Nash Draw.

DISSOLVED SALTS IN SURFACE WATER

By

Frank A. Swenson

General considerations of salt solution

In considering the long-term storage of radioactive materials in salt beds,it is important to know the relative rate of solution of the salt and how long it may take for solution to impair the safety of such storage. In order for solution to continue, water must move through the system, for salt-saturated water does not dissolve salt. The major fluid discharge from the system is by surface flow in the streams draining the area being considered. It is known that considerable amounts of sodium chloride are carried by the Arkansas, Canadian, Red, Trinity, Brazos, Colorado, and Pecos Rivers as they leave the area. Numerous stream-gaging and water-quality-measurement stations have been established on these streams and somewhat detailed studies have been made of fairly localized areas, mainly with a view to reducing salt discharge and so improving the water quality. By using data gathered over a period of years, and by making certain assumptions, I have estimated the approximate rate of salt solution for various subbasins of the major streams draining the Permian basin.

All bedrock formations from the Santa Rosa Sandstone of Triassic age to the basement rocks of Precambrian age contain strongly saline water, except locally near outcrops where they may be flushed by recharge. Potentiometric maps prepared by McNeal (1965) and P. R. Stevens (written commun., 1972) show that the probable movement of the saline ground-water is generally toward the east, with local variations. The strongly saline water is under sufficient artesian pressure to maintain a water column close to the land surface across much of the area. Natural hydraulic interconnections between formations are provided by faults, joints, and unconformities. The thousands of boreholes for oil and gas drilled in the area also provide hydraulic interconnections between formations. Although potentiometric data indicate potential easterly movement of fluids, the actual quantity and rate of movement across the entire basin is very limited. Using the best data he could obtain during a comprehensive ground-water study lasting several years, P. R. Stevens (written commun., 1972) states that the average velocity of water movement in the Santa Rosa Sandstone is about 0.4 foot per year. At that rate, it would take at least 2.5 million years for a water molecule to cross the Permian salt basin from recharge areas in the west to the salt seeps and springs in the east. Stevens estimates that the average velocity of water movement in the San Andres Limestone of Permian age is about 0.015 foot per year. At that rate, the time required for a water molecule to cross the Permian basin may be about 80 million years.

Discharge from the brine seeps and springs along the eastern edge of the High Plains is nearly all derived from local recharge. Recharge to the salt- and anhydrite-bearing outcrops in interstream areas enters the weathered outcrop zones through fractures and sink holes, dissolves the salt, and moves underground to nearby incised drainageways where the brine is discharged as salt seeps and springs. Radioactive-isotope dating of spring discharge (P. R. Stevens, written commun., 1972; and Ward, 1963) shows that most of the brine-spring discharge on the eastern side of the High Plains is meteoric water that has moved down from the land surface, and only a very minor part is old enough to be of connate origin or to have moved across the Permian salt basin from the western outcrops of these rocks.

Specific data

Data compiled from U.S. Geological Survey observations of the quality of surface waters of streams draining the area of interest are shown on figure 13. Major river basins are divided into subbasins at the gaging stations where sufficient water-quality data are available. For each subbasin, estimates are given of the tonnage of sodium chloride discharged by surface water each day and the average incremental tonnage of sodium chloride discharged each year per square mile in that subbasin. The upper part of some streams heading on the High Plains may contribute little or no flow from sizable areas. Locations of major saline springs are shown with tonnage of sodium chloride discharged per day. Most of the data used in figure 13 come from the records for 1966 (U.S. Geological Survey, 1971).

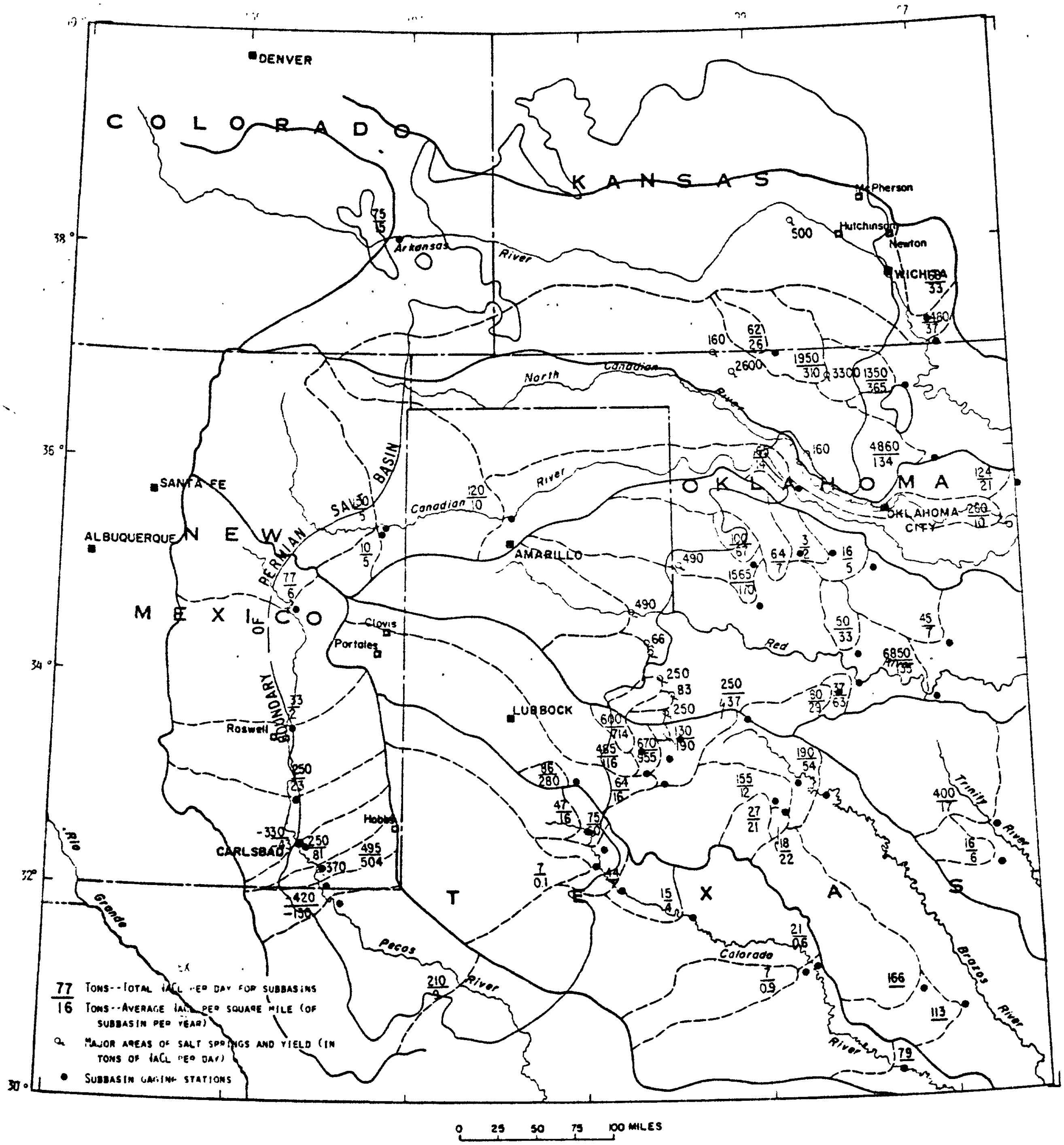

FIGURE 1[illegible].-- SODIUM CHLORIDE DISCHARGE VIA SURFACE WATER FLOW, PERMIAN SALT BASIN. SODIUM CHLORIDE CONTENT SHOWN FOR SUBBASINS OF MAJOR STREAMS: (1) IN TONS PER DAY, AND (2) IN TONS PER YEAR FOR EACH SQUARE MILE OF SUBBASIN.

Two subbasins of the Pecos River drainage show losses of sodium chloride, but these anomalous figures can be explained. Between Red Bluff, New Mexico, and Orla, Texas, the Pecos River shows a loss of 420 tons of sodium chloride per day. This salt loss is believed to take place in the Red Bluff Reservoir. Concentrated brine is known to be present in the deeper parts of the reservoir and precipitation of salt may occur there at times. The records for 1964 through 1967 show that, although in some years there is a loss of salt between the Red Bluff and Orla gaging stations, in other years there is a gain of salt between these two points. Between the Artesia and Carlsbad, New Mexico, gaging stations a loss of 330 tons of sodium chloride per day is recorded. Much water is diverted for irrigation between these two gaging stations, so that the water with its dissolved salt does not pass the Carlsbad gage.

Surface or near-surface disposal of oil- and gas-field brines may distort the picture locally but probably has no significant regional effect.

Figure 13 shows wide variations in the amount of sodium chloride accumulation in the surface water draining from the various subbasins. The highest sodium chloride discharge is from the 253-square-mile increment of the Salt Fork of the Brazos River (between the gaging stations on Croton Creek and upper Salt Creek). This small subbasin has an average yield of 670 tons of sodium chloride per day and a yield of 955 tons of sodium chloride per square mile per year.

Even though this seems like a very large amount of solution, it would only amount to a thickness of about half a foot of salt dissolved in 1,000 years if it were spread evenly over the 253 square miles of the subbasin. In this area the salt-bearing beds crop out or occur at very shallow depth. Local recharge enters the slumped and broken formation, dissolves the salt, and during a period measured in tens of years moves underground to discharge at salt springs. As in other parts of the Permian basin, it is highly unlikely that any appreciable solution of salt takes place at depths of more than a few hundred feet.

Individual drainage basins

The pattern of major salt discharge is closely related to the geology and topography of the area. The broad valley of the Pecos River is deeply incised in the Permian beds and forms a ground-water drain south of Roswell. Salt discharge downstream from this point increases greatly. A major point of salt discharge is Malaga Spring, about 20 miles southeast of Carlsbad where some 370 tons of sodium chloride a day are discharged. The ground-water divide east of the Pecos valley follows closely the outcrop of the Triassic rocks that cap the highlands. Very little recharge from precipitation is believed to occur in the badland escarpment east of the Pecos.

The Colorado River drainage is not deeply incised and large parts of its upper basin do not contribute any appreciable flow. The 1,027 square miles of drainage basin that contributes water upstream from the Ira, Texas, gaging station discharges only

47 tons of sodium chloride per day, but the 455 square miles of drainage between the Ira and Colorado City gages contributes an additional 75 tons per day. The reason for the contrast is that this short reach of the Colorado River at the edge of the High Plains is incised into salt-bearing Permian rocks and receives their discharge of saline ground water.

The Brazos River is notorious for the saltiness of its water. Very little flow or salt is contributed in the upper part of its drainage basin on the High Plains, but at the edge of the High Plains the Brazos is deeply incised into the Permian rocks, and seeps and salt springs are numerous. It is here that we find the highest rate of sodium chloride solution--as much as 955 tons per square mile per year.

The Trinity River heads in the central lowlands east of the topographic break from the High Plains, and its salt load is relatively minor.

In the Red River basin there is a zone of high sodium chloride discharge where the stream is deeply incised at the eastern edge of the High Plains. Although the areas of maximum salt discharge are shown as springs, only one, Estelline Spring on the Prairie Dog Town Fork, is a true spring; the rest are not point sources but are diffuse areas of seeps and minor spring discharge. As we do not have enough data on the areas contributing to the spring discharge, we cannot provide figures on the tons of salt dissolved per square mile per year. The total amount of sodium chloride discharged by the drainage basin above Lake Texoma is more than 8,600 tons per day from an area of 24,846 square miles contributing flow.

The Canadian River has a large drainage basin, but the basin is narrow where it crosses the zone of major salt discharge at the eastern edge of the High Plains, so it does not obtain a heavy salt load.

The Arkansas River, heading high in the mountains of Colorado, has by far the largest drainage basin of those being considered. The salt load is low until it reaches south-central Kansas and Oklahoma where there is major salt discharge from zones of seeps and springs. The sodium chloride discharge at the Great Salt Plain in Alfalfa County, Oklahoma, is about 3,300 tons per day, and that at Big Salt Plain about 50 miles to the west totals 2,600 tons per day. These areas of brine discharge and other smaller areas of discharge are the northeastward continuation of the zone of brine discharge in the Brazos and Red Rivers, and reflect the northeastward extension of the outcrop of salt-bearing Permian rocks.

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