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CHARACTERIZATION STUDY
OF THE OGALLALA AQUIFER,
NORTHWEST TEXAS

by

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INTRODUCTION

The Ogallala aquifer, which is the main water supply in the High Plains of Texas, is being severely depleted by extensive pumpage for irrigation. The aquifer overlies the Permian evaporites that are being considered as a potential repository for the disposal of high-level nuclear wastes. Potential contamination of the aquifer by these wastes and further depletion of the limited water resources are major concerns of the people in the area.

The purpose of this work is to develop a general hydrogeologic characterization of the aquifer that will serve as a firm basis for accurate evaluation of aquifer recharge mechanisms relevant to problems stemming from accidental spills of radionuclides at land surface and possible interactions of the radionuclides with deeper hydrologic units. Aquifer hydraulics relevent to problems that may be encountered in shaft construction were studied as well.

The existing geologic, hydrologic, geochemical, and isotopic data are integrated into a regional hydrogeologic model for water and solutes. The model enables (1) an understanding of recharge/discharge relationships, ages of water, and rock-water interactions, and (2) the tracing of cross-formational flow between the Ogallala and the underlying aquifers.

This report presents preliminary conclusions of research conducted from August 1984 through August 1985.

DESCRIPTION OF STUDY AREA

Location

The Ogallala aquifer is situated in the High Plains of northwest Texas (fig. 1). The High Plains of Texas are part of the southern extension of the Great Plains of North America. The aquifer extends westward through New Mexico and northward through

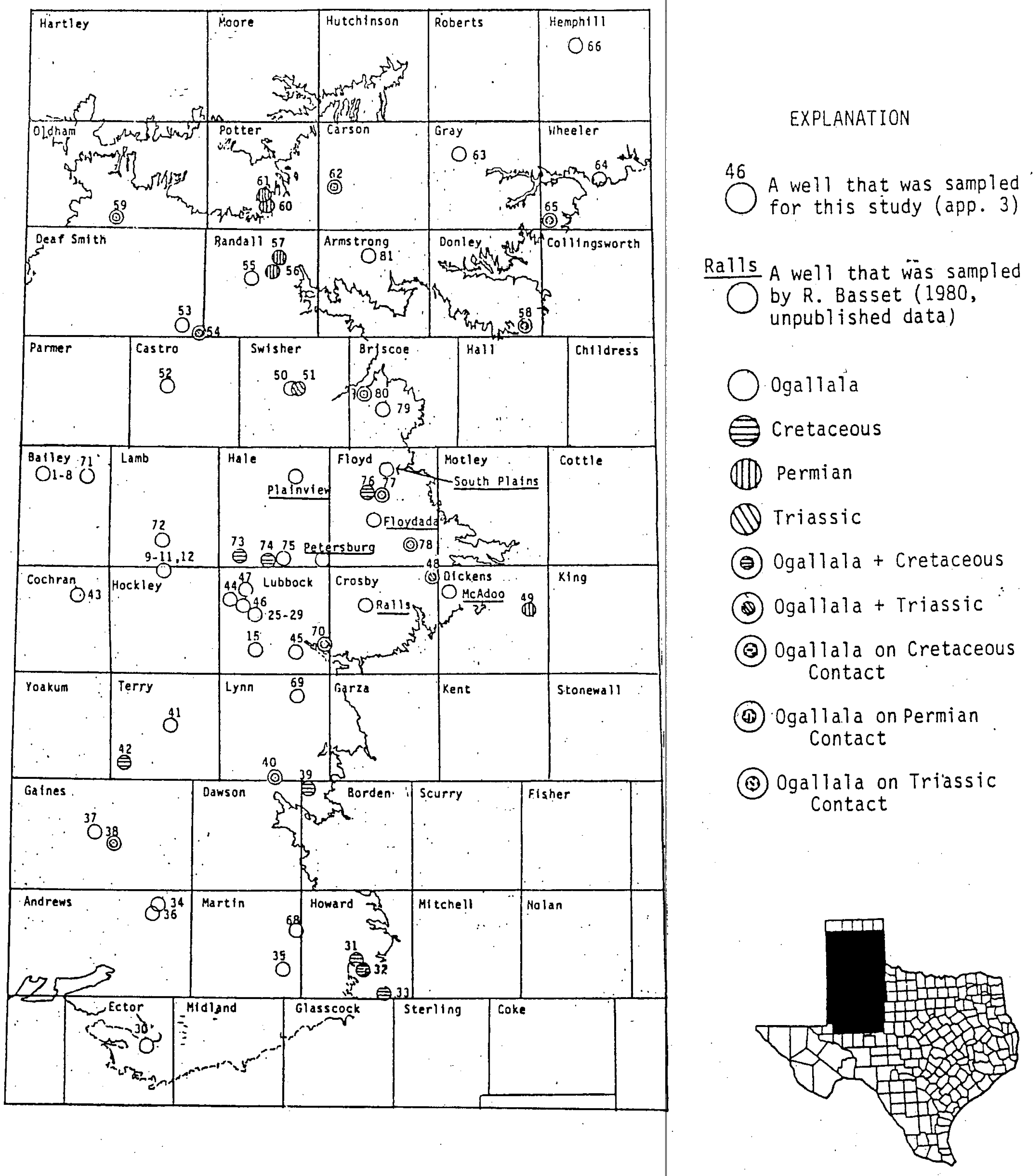

Figure 1. Study area and location of wells sampled in the High Plains.

Oklahoma, Colorado, Kansas, Wyoming, Nebraska, and South Dakota. However, this study is limited to the area of Texas south of the Canadian River. The southern boundary of the aquifer is the southern extension of the Ogallala Formation in Ector, Midland, and Glasscock Counties and the eastern boundary is the Rolling Plains. The western boundary of the section of the aquifer discussed in this study is arbitrarily placed at the Texas - New Mexico border, and therefore functions as an open hydrologic boundary. In future reports the western boundary will be extended to the western escarpment of the High Plains in New Mexico. The amount of hydrologic and chemical data from New Mexico is relatively small compared to that from Texas, so no major changes in the conclusions presented in this study are anticipated.

Physiography

The High Plains of Texas form a well-defined, topographically isolated plateau that dips toward the southeast into the Rolling Plains. Large parts of the High Plains have scattered depressions called playa lakes. These depressions range from a few feet to 50 ft (1 to 15 m) or more in depth, and from a few hundred feet to a mile or more in diameter. Runoff following large rains accumulates in these depressions and forms ponds. As a result, large areas of the High Plains have poorly developed drainage systems and all the streams that head on the Rolling Plains are intermittent or have very small perennial flow.

Climate

The High Plains of Texas have a semiarid climate. Annual mean precipitation, based on 30 years of records (Bomar, 1983), ranges from 14 inches across the southern Panhandle to 20 inches in the northern Panhandle (360 and 510 mm, respectively). Most precipitation falls between August and October. An isohyet map (fig. 2) shows a greater amount of rainfall in the northeastern part of the High Plains. Annual pan evaporation is about 60 inches (1.5 m) (Bomar, 1983). Other estimates (U.S. Geological Survey in Nelson and

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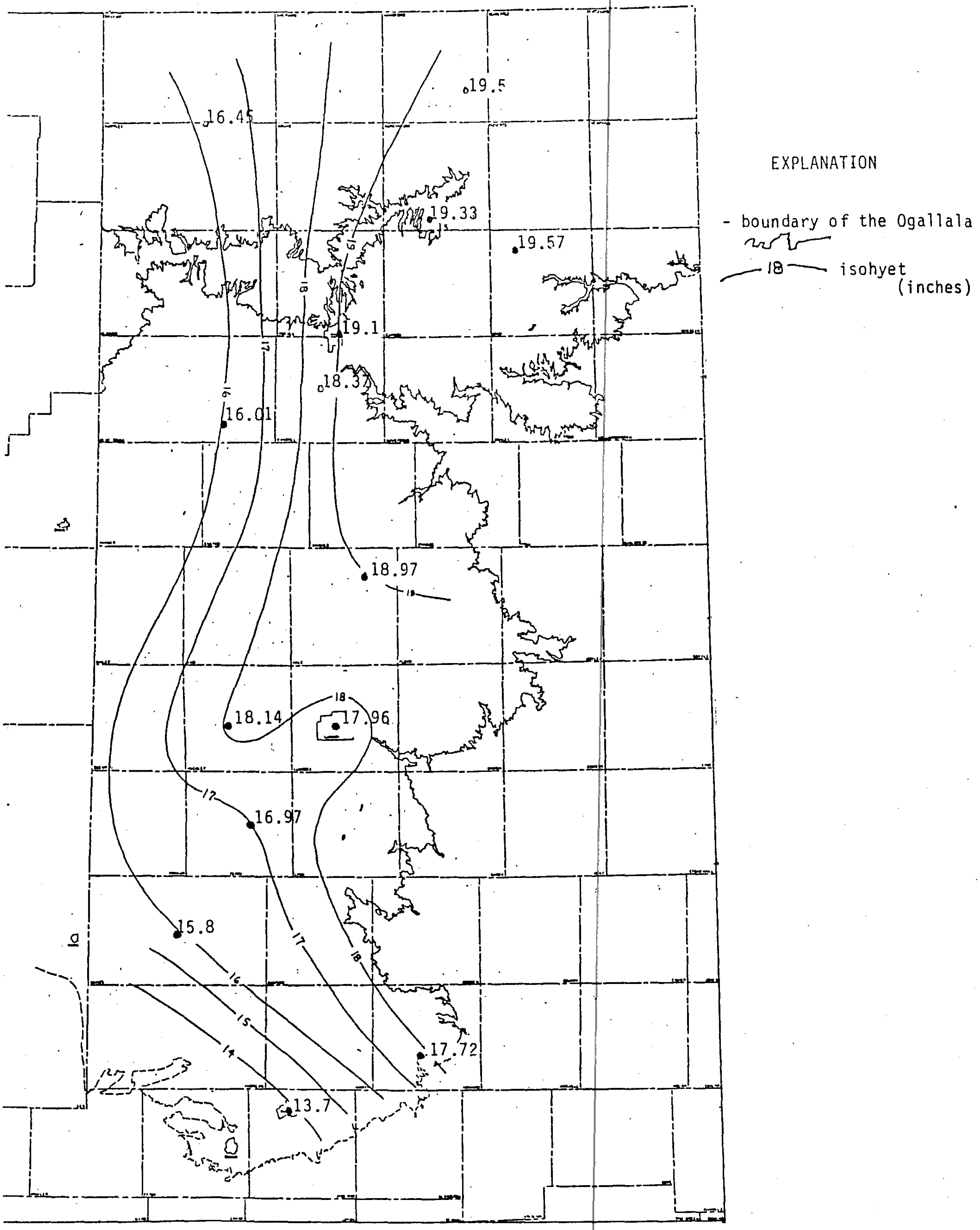

Figure 2. Mean annual precipitation (inches) 1951-1980 (data from Bomar, 1983).

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others, 1983) indicate a range from 80 to 96 inches (2 to 2.5 m). During the summer, evaporation may reach an equivalent of 100 inches (2.5 m). Evaporation increases from the northeastern Panhandle to the southwest.

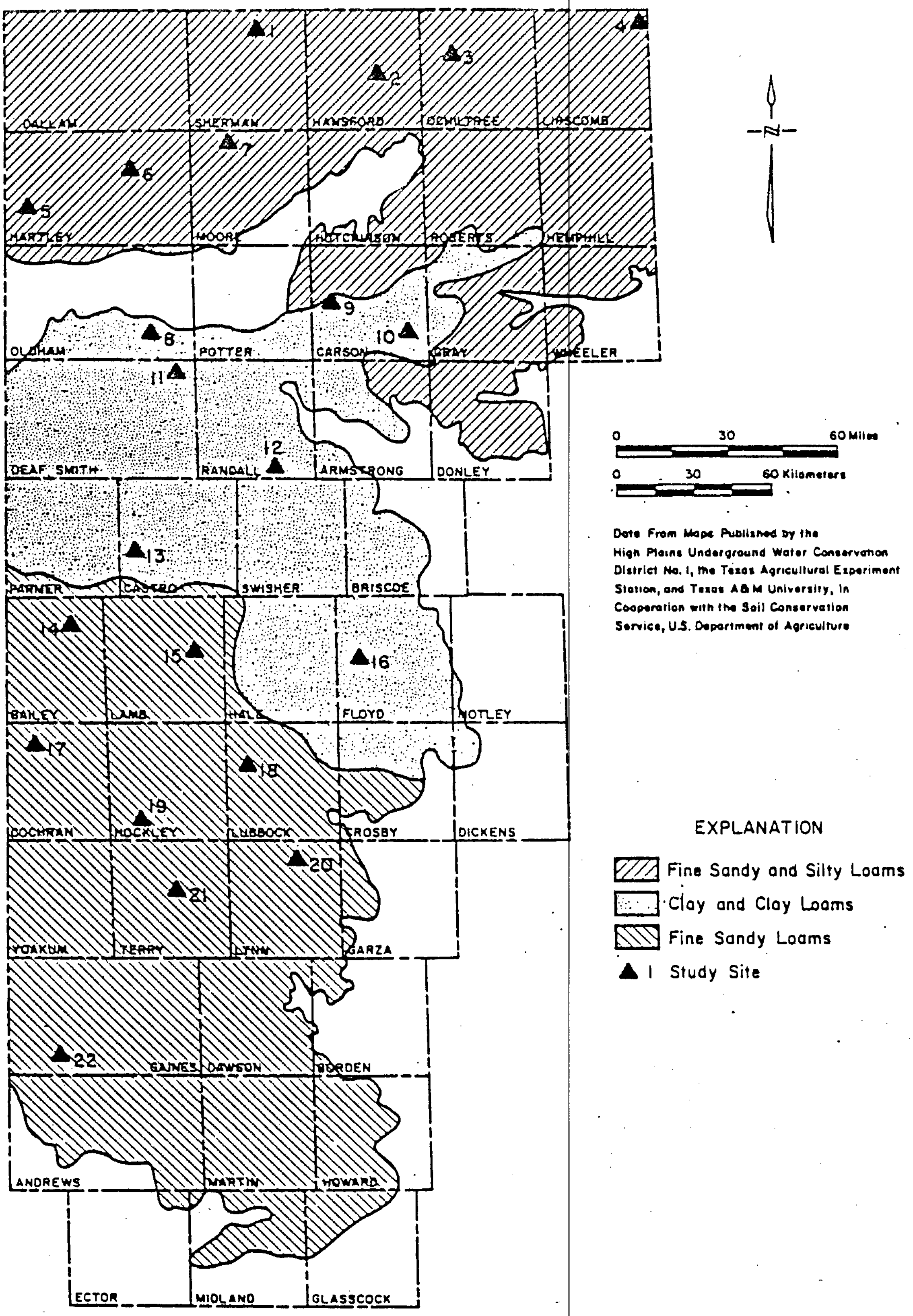
Mean annual low temperature ranges between 44°F in the northern part of the Panhandle to 50°F in the southern part (6.6 to 9.9°C, respectively). Mean annual high temperature ranges between 71°F (21.5°C) and 77°F (25°C), respectively (based on 30 years of records from Bomar, 1983). The average difference between summer and winter temperatures is about 29°F (16°C). The prevailing winds are from the southwest and south (summer) in the northern and central Panhandle, and from the south or south-southeast (spring and summer) in the southern Panhandle (Bomar, 1983).

Soils

Soil cover in the northern part of the study area consists mainly of clays and clay loams, whereas in the southern part the soils are sandy loams (fig. 3). The difference in the grain-size distribution of the soil cover may affect the annual recharge rates and will be discussed later in the report.

GENERAL HYDROGEOLOGY OF THE OGALLALA AQUIFER

The Tertiary Ogallala Formation is composed of terrigenous deposits, such as sands, gravels, and finer materials. The aquifer is covered by Quaternary deposits and it unconformably overlies Cretaceous, Triassic, and Permian rocks. Some of these formations may be hydraulically connected to the Ogallala aquifer. Water-table conditions prevail throughout the aquifer. Flow directions follow the regional topographic dip from the northwest to the southeast. Local ground-water depressions, which have been formed by intensive pumpage, can lead to local changes in flow direction. The rate of water movement is approximately 7 inches (18 cm) per day. The aquifer is recharged by direct



Data From Maps Published by the High Plains Underground Water Conservation District No. 1, the Texas Agricultural Experiment Station, and Texas A&M University, in Cooperation with the Soil Conservation Service, U.S. Department of Agriculture

Figure 3. Generalized soil map (from Knowles and others, 1984).

precipitation and by resulting runoff that mainly accumulates in playa lakes as well as in riverbeds. Flow from the underlying formation can be another source for recharge. Pumpage of water from the aquifer far exceeds annual recharge. As a result, there is a substantial decrease in ground-water levels in the heavily pumped areas. However, in other locations a rise in water table was observed that can perhaps be related to percolation of surplus water from irrigation into the shallow ground water in these areas. Because of the water-level decline, springs along the eastern escarpment that discharged the aquifer ceased flowing. Most of the current discharge from the aquifer is by water pumpage.

CRITICAL ISSUES

This study of the Ogallala aquifer is part of a feasibility study for a high-level radioactive nuclear waste repository in the Texas Panhandle. Assuming a scenario of accidental spills on the surface or in the the subsurface, several problems need to be addressed:

(1) What are the transport rates of a surface spill from land surface to the water table; how long will it take before the Ogallala water is contaminated by it?

(2) What are the flow directions of the contaminant in the aquifer?

(3) What is the residence time of water (and spills) in the aquifer?

(4) What are the discharge locations where contamination can emerge into the biosphere or leak into another aquifer?

(5) In case of subsurface spill within the Permian host rocks, what are the possibilities that vertical flow will carry the contaminated fluid into the Ogallala and how long would it take?

To answer these questions a characterization study of the Ogallala aquifer had to be made. In this study we address major hydrogeologic areas, including:

(1) The nature of the geologic contacts between the Ogallala aquifer and the underlying formations,

(2) porosity and permeability distribution in the Ogallala aquifer and in the underlying formations,

(3) relations between the potentiometric surfaces of the Ogallala aquifer and the underlying formations,

(4) recharge methods and rates into the Ogallala aquifer and the overlying formations,

(5) discharge points and rates from the Ogallala aquifer, and

(6) geochemical similarities between the Ogallala aquifer and the underlying aquifers that may indicate flows between them.

DATA ACQUISITION

Characterization of the Ogallala aquifer involves the study of its geologic setting, hydrologic parameters, and geochemical features, as well as the underlying aquifers that may be hydraulically connected to it.

The contact between the Ogallala aquifer and the underlying formations was mapped to indicate permeable zones below the aquifer that may form one hydraulic system for cross-formational flow. Data were taken from well logs (McGowen and others, 1977; Presley, 1981) and type-section descriptions (Brand, 1953).

Water-level data for the Ogallala and the underlying aquifers were obtained from the computerized data base and open-file records of the Texas Department of Water Resources. Water-level maps were produced by the authors for the Permian and Cretaceous aquifers (the Ogallala water-level map is from Knowles and others [1984] and

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the Triassic water-level map is from Dutton and Simpkins [1985]). Water-level head difference maps were produced by the authors for water in the Ogallala and for water in each of the underlying aquifers.

Permeability and porosity data (Myers, 1969; Knowles and others, 1984) were studied for the Ogallala and the underlying aquifers.

A total of 4,400 chemical analyses of water in the Ogallala aquifer, plus 187 analyses of water samples from the Triassic aquifer, 87 analyses of water samples from the Cretaceous aquifer, and 157 analyses of water samples from the Permian aquifer (all from the Texas Department of Water Resources data bank), were carefully studied (app. 1). Major chemical features of each aquifer were described (major ions, general distribution patterns, Piper diagrams, and bivariate plots). Detailed chemical study was conducted wherever cross-formational flow was suggested, based on geologic and hydrologic considerations.

Because isotope data of ground water were available for only the Triassic aquifer (Dutton and Simpkins, 1985), 53 ground-water samples from the Ogallala aquifer were collected from 25 counties across the Panhandle, in addition to 9 water samples from the Cretaceous aquifer and 7 water samples from the Permian aquifer. Areas where cross-formational flow seemed possible were included in this sampling program. All samples were analyzed for general chemical constituents and for oxygen-18, deuterium, tritium, sulfur-34, and carbon-13 (app. 2).

Contamination by oil field brines that may affect Ogallala geochemistry was studied using 530 chemical analyses of water samples taken from all major oil-producing formations across the High Plains. Data were taken from Burnitt and others (1963), Reed (1963), Burnitt (1964), McAdoo (1964), and Crouch (1965). A well in Hockley County that injects brine produced from the Permian (Clear Fork) Formation and three Ogallala wells in its vicinity were also sampled for contamination (app. 2).

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The study of recharge mechanisms was based on comparison of rainfall and playa lake analyses with ground-water analyses. Precipitation was collected on a daily basis at four stations in the High Plains (Amarillo, Clovis, Lubbock, and Midland) and at one station in the Rolling Plains (Paducah), during one year (November 1984 through October 1985). Samples were analyzed for oxygen-18, deuterium, and occasionally for tritium. Only preliminary results are included in this report. Two playa lakes and six wells in their vicinity were sampled in Lubbock County.

The well numbering method used in this study (app. 2) follows the system adopted by the Texas Department of Water Resources (TDWR) (Knowles and others, 1984). When sampling a well with an unknown TDWR number, a temporary name was assigned to it; the name includes the first four digits of the area (according to TDWR), the initials "RN," and another letter.

GEOLOGY RELATED TO HYDROLOGY

The base of the Tertiary Ogallala Formation rests unconformably on Permian, Triassic, and Cretaceous strata (fig. 4). Quaternary sediments cover the Ogallala rocks in most parts of the Panhandle. In this section the geologic features of the Tertiary Ogallala Formation and of the underlying formations that are related to the hydrology of the Ogallala aquifer are described.

Quaternary Strata

Quaternary eolian, fluvial, and lacustrine sediments cover the Tertiary Ogallala Formation. The Blackwater Draw Formation, the most widespread unit, ranges in age from at least 1,400,000 yr to late Holocene (Machenberg and others, 1985). It covers the Ogallala with loess deposits to a depth of 80 ft (25 m). Windblown sands that blanket the Ogallala in some locations can also be included in this formation. Alluvium,

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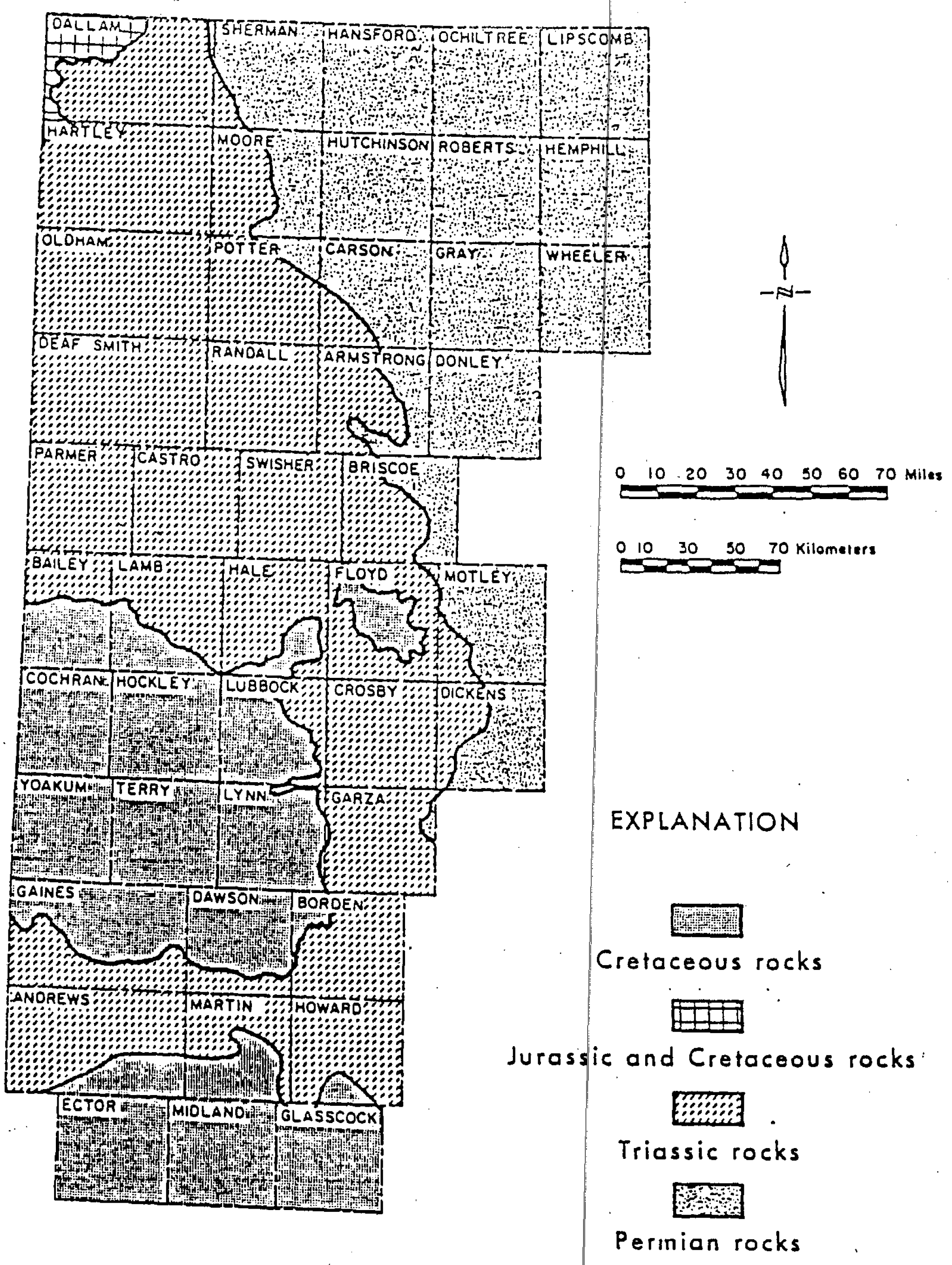

Figure 4. Geologic units underlying the Ogallala Formation (from Knowles and others, 1984).

which consists of gravels, sands, and silts, occur along riverbeds, and silt and clay materials line the bottom of most playa lakes. Quaternary deposits control the amount of recharge into the Ogallala aquifer. Their diverse lithology is the factor that affects their distribution of vertical permeabilities, and thereby the vertical water flux into the Ogallala.

The Tertiary Ogallala Formation

The Tertiary Ogallala Formation was deposited as a set of humid alluvial fans (Seni [1980] identified three fan lobes). The terrigenous components of the fans include sands, gravels, and finer materials; their relative abundance is a function of the distance from the major channel system. Ogallala sediment thickness, which reaches 800 ft (250 m) (fig. 5), thins in all directions toward the escarpment of the High Plains. The thickness is mainly controlled by the relief of the underlying topography, which has resulted from Permian dissolution collapses and from Triassic or Cretaceous erosion valleys filled with Ogallala sediments. When the northern topographical lows were filled by the Dalhart-Amarillo lobe deposits, sedimentation shifted south to the Triassic valley, which lies between the first lobe and the southern Cretaceous mesa. After the second lobe (Clovis-Plainview) filled the Triassic low, sedimentation of the third southern lobe (Brownfield-Lubbock) started around, and later covered, the Cretaceous deposits in the southern Panhandle. Because these Cretaceous remnants form a regional high, the Ogallala section is thinner there (Seni, 1980).

Wind and stream erosion have cut into the Ogallala Formation and eroded its deposits. Consequently, Cretaceous rocks are exposed in some saline lakes in the southern Panhandle, and Triassic and Permian rocks crop out along the Canadian and Red Rivers. Generally, the Ogallala is thicker in the northern part of the High Plains (0 to 800 ft or 250 m) compared to the southern part (0 to 500 ft or 150 m).

As a result of this depositional pattern, sediments along the major channels are coarser, whereas interfan materials are finer (fig. 6). In addition, a general upward-fining

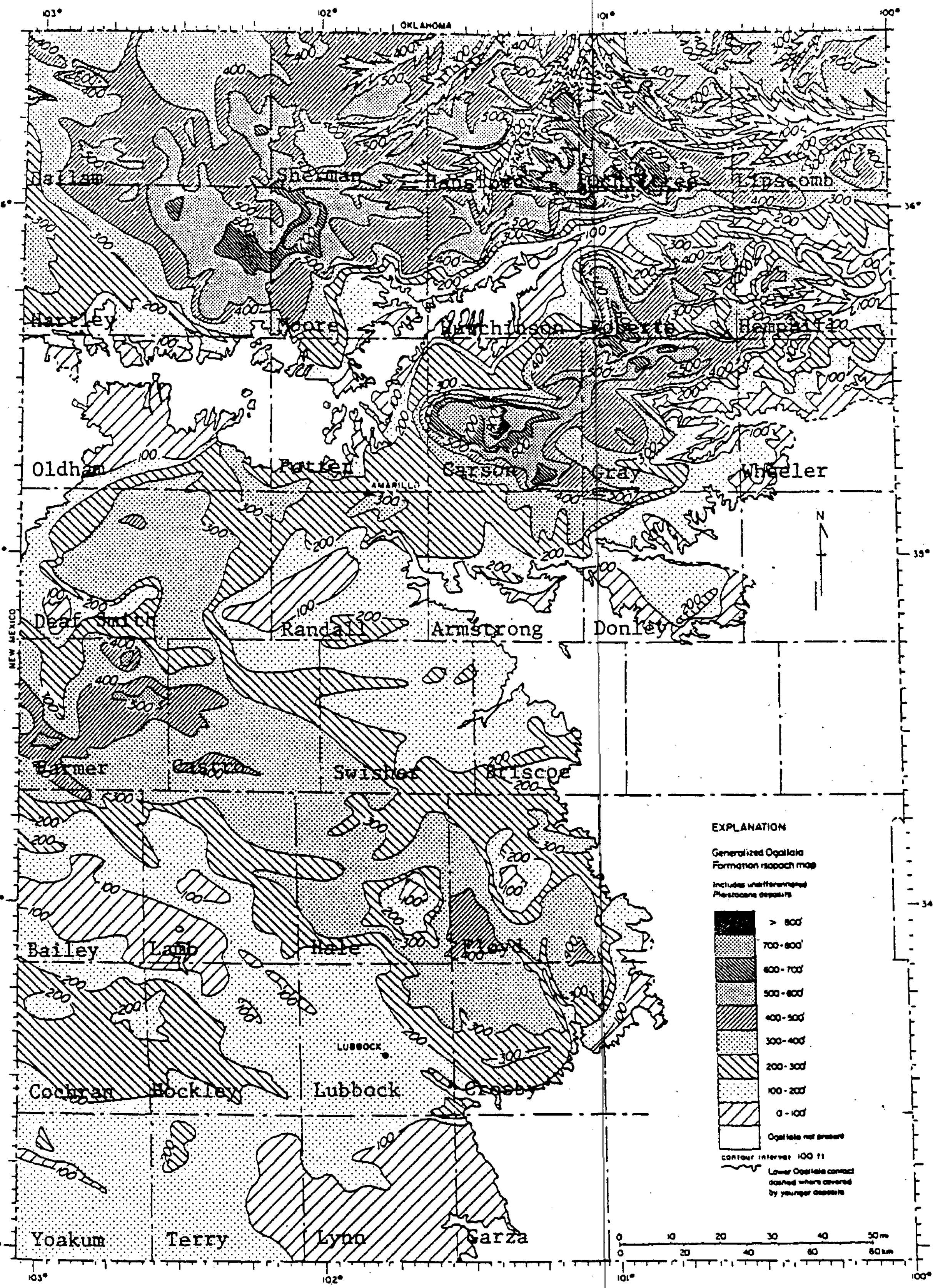

Figure 5. Isopach map of the Ogallala Formation (from Seni, 1980).

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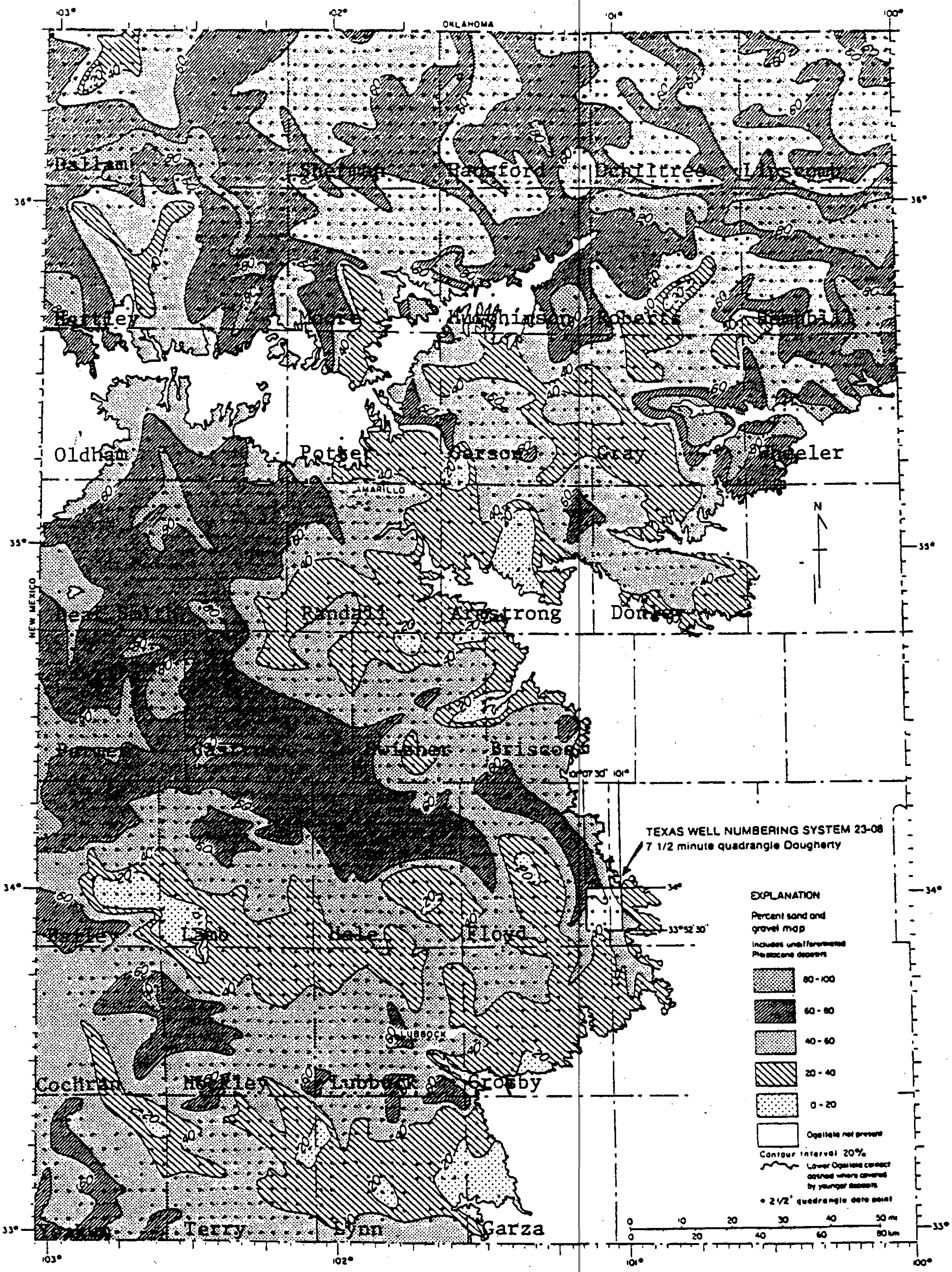

Figure 6. Percentage sand and gravel map of the Ogallala Formation (from Seni, 1980).

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texture trend occurs in the Ogallala Formation. Fan facies characterize the lower parts of the Ogallala section, as the upper parts are dominated by eolian or perhaps lacustrine facies (Seni, 1980). These textural trends may have an effect on the spatial distribution of porosity and permeability in the Ogallala aquifer.

A resistant calcite layer called caliche lies at or near the surface of the Ogallala Formation and forms a caprock. Caliche develops as an authigenic accumulation of calcium carbonate that results from soil-forming processes, precipitation from ground water, or some combination of both (Stone, 1985). In the northern part of the Panhandle several layers of caliche are encountered, whereas in the southern Panhandle their number and thickness decrease. Caliche is commonly regarded as a barrier to recharge because its permeability is considered very low (Knowles and others, 1984).

Cretaceous Strata

Three separate subcrops of southeast-dipping Cretaceous strata underlie the southern part of the Ogallala Formation (fig. 4). These isolated remnants represent a larger area that was probably covered by Cretaceous rocks, the original extent of which is not known (Brand, 1953). The rocks were deposited in an epineritic and littoral environment of stable shelf seas whose subsidence was slow (Brand, 1953). The rocks were classified into three groups (for detailed description refer to Brand, 1953):

(1) The Trinity Group consists of the sandy, permeable Paluxy/Antlers Formation.

(2) The Fredericksburg Group includes several limy to shaly formations, of which only the Edwards Limestone is considered an aquifer.

(3) The Washita Group consists of the shaly Duck Creek Formation, which has relatively low permeability.

Following the Laramide Revolution and the withdrawal of the Cretaceous sea, parts of the deposited material were removed by early and middle Tertiary erosion where deep valleys were cut into Triassic rocks. Because erosion truncated various formations at different locations, there are places where the top of the permeable Edwards Limestone or the Paluxy Sandstone form the contact with the Ogallala aquifer. In these locations, a continuous permeable sequence may exist below the Ogallala (fig. 7). In other places only a thin, shaly layer separates these permeable Cretaceous formations from the Ogallala.

Triassic Strata

The Triassic Dockum Group underlies large areas of the Ogallala aquifer in the study area (fig. 4). The sediments accumulated in a variety of depositional systems, including braided and meandering streams, alluvial fan deltas, lacustrine deltas, lacustrine systems, and mud flats, which are all of continental origin (McGowen and others, 1977). The terrigenous clastics were mainly derived from older sedimentary rocks that accumulated in Texas, Oklahoma, and New Mexico. The maximum preserved thickness of Triassic rocks (2,000 ft) occurs in the Midland Basin. The lower lithologic cycle of the Triassic, often referred to as the Santa Rosa Formation, is characterized by a sandy lower segment that becomes increasingly muddy upward. The upper lithologic cycle exhibits similar overall upward fining in the northwestern part of the study area. However, upward fining is not typical of this cycle farther south in the northwestern Midland Basin. In this area, sand from an eastern source was deposited throughout the preserved part of the upper Triassic cycle (McGowen and others, 1977).

The Permian-Triassic contact has been studied using well logs (McGowen and others, 1977; Presley, 1981). In some locations within the study area, such as Deaf Smith and Carson Counties (figs. 8a and 8b), the lithologies on both sides of the contact are permeable and could permit flow from one to another.

The Triassic Dockum Group is overlain in some areas of the High Plains by Jurassic and Cretaceous sediments, the original extent of which is not known because of partial erosion before Ogallala deposition. Study of the Triassic-Cretaceous contact using well

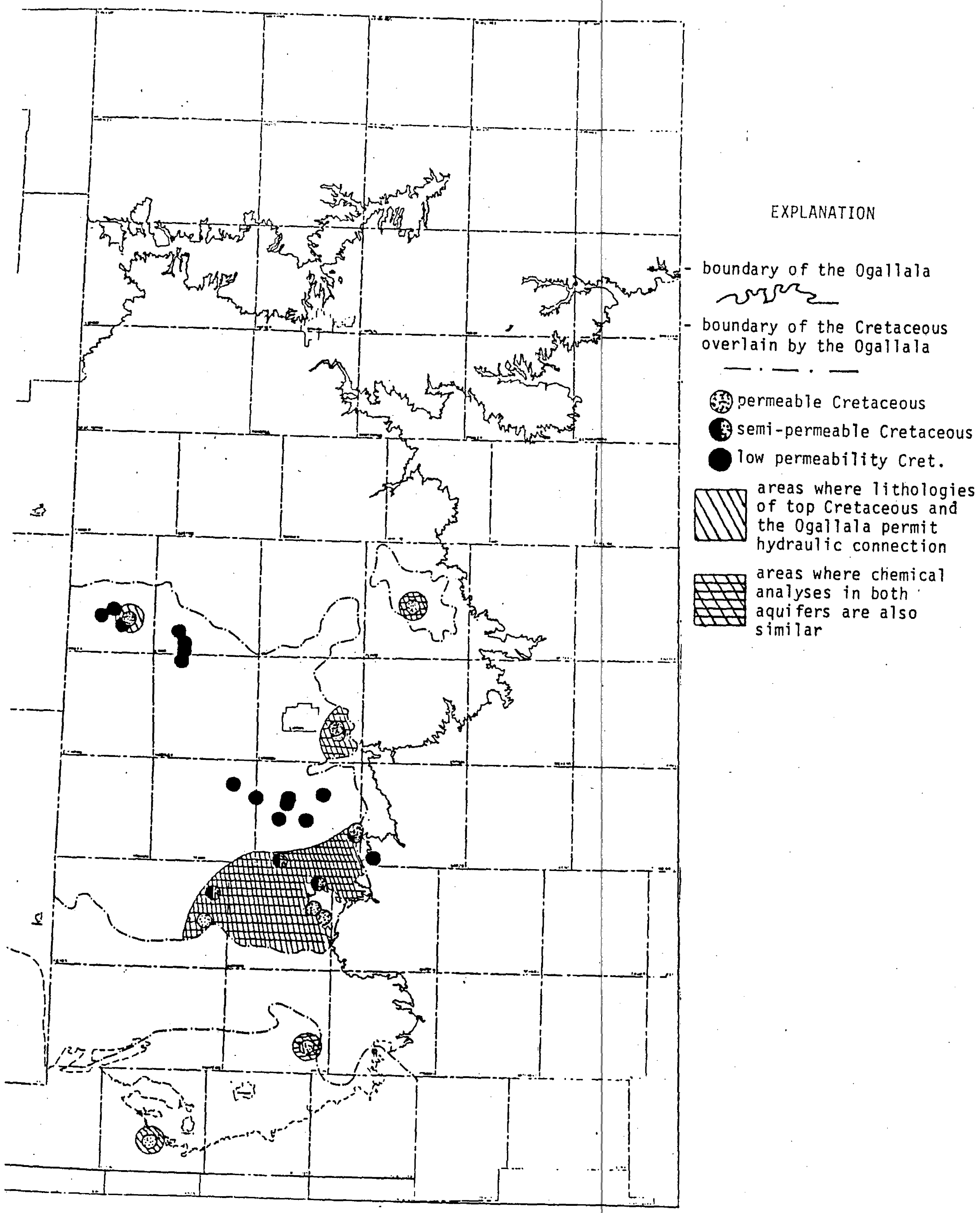

Figure 7. Hydraulic characterization of top Cretaceous at the contact with the Ogallala aquifer (based on Brand, 1953).

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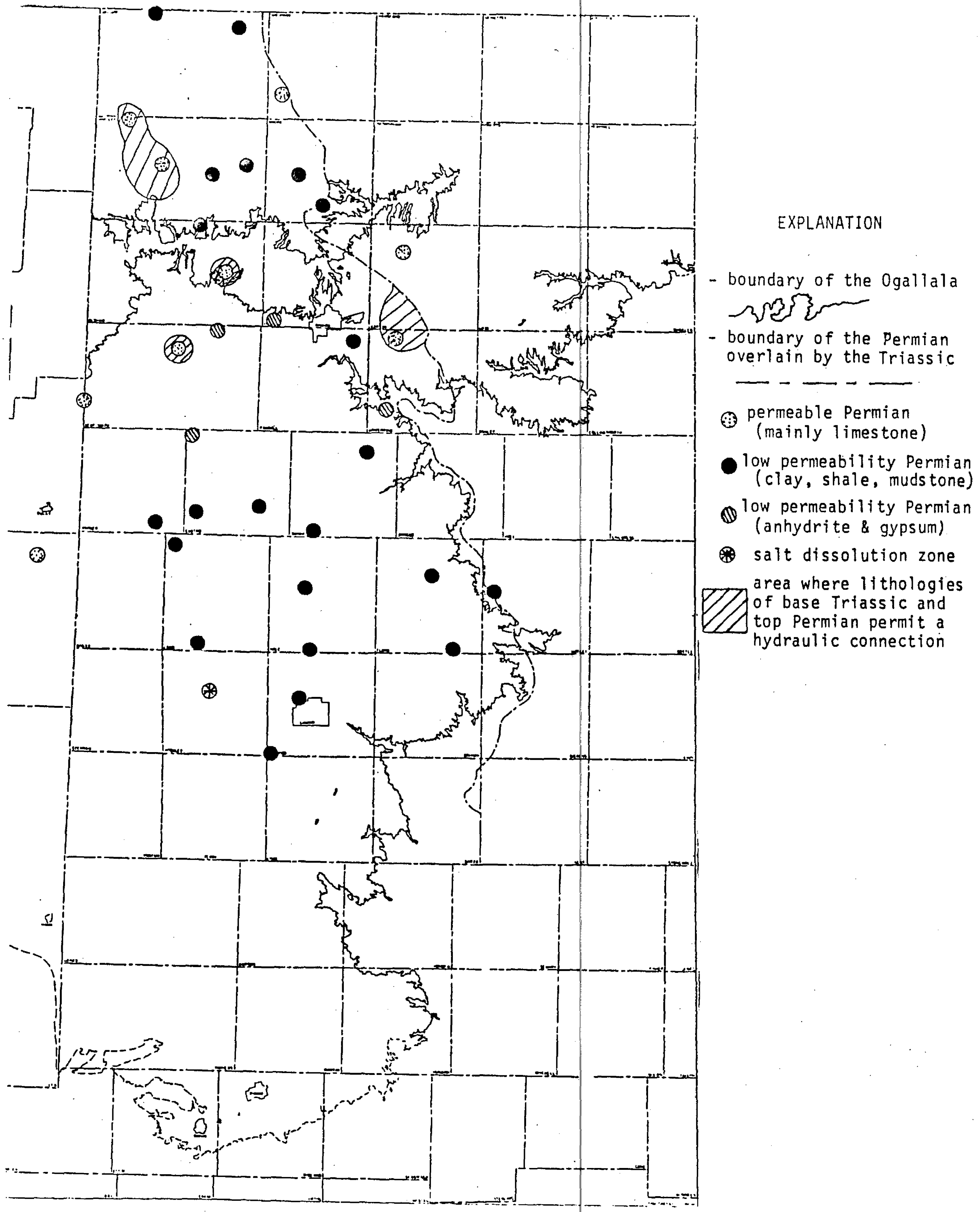

Figure 8a. Hydraulic characterization of top Permian at the Triassic contact (based on Presley, 1981).

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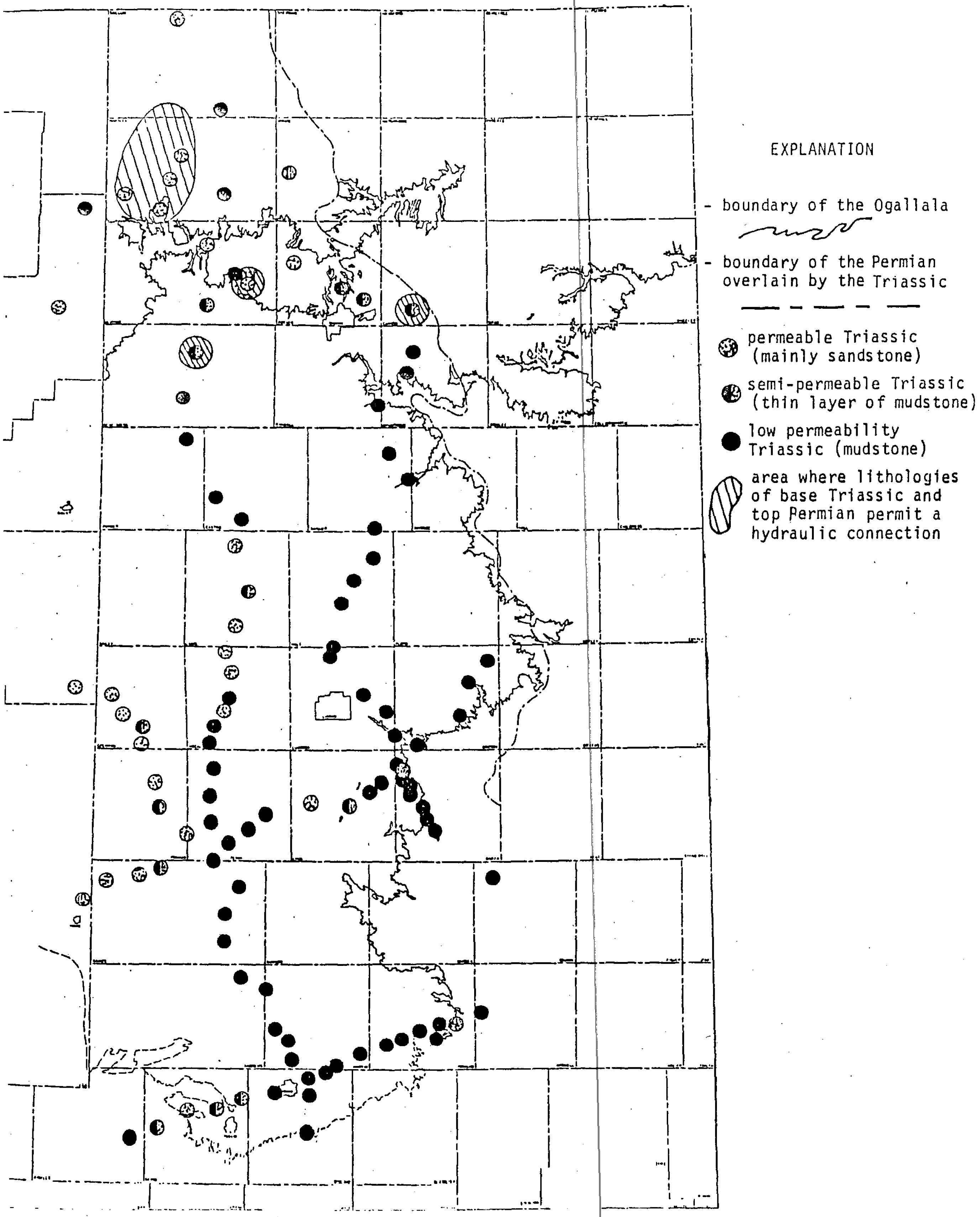

Figure 8b. Hydraulic characterization of basal Triassic at the Permian contact (based on McGowen and others, 1977).

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logs (McGowen and others, 1977) and type-section descriptions (Brand, 1953) suggests that these formations are permeable on both sides of the contact in Lynn, Martin, and Ector Counties (figs. 9a and 9b). Observations are limited to a relatively small amount of outcrops where the base of the Cretaceous is exposed. It is assumed, therefore, that permeable contact between Triassic and Cretaceous rocks can also be found elsewhere.

Study of the Ogallala-Triassic contact based on well logs (McGowen and others, 1977) indicates permeable sequences in both formations in parts of Potter, Swisher, Castro, Crosby, Dickens, Martin, Andrews, and Garza Counties (fig. 10).

Permian Strata

Permian rocks underlie the entire Panhandle and are composed of a wide range of marine to terrestrial sediments. Thick, salt-bearing zones representing evaporitic phases are being considered as possible host rocks for nuclear waste isolation. For a detailed description of these formations refer to Handford (1980a, 1980b), Handford and Dutton (1980), and Presley (1981).

Within the study area, the Ogallala Formation contacts Permian rocks (mainly Whitehorse Group and Blaine Formation) in a relatively limited area along the northeastern Panhandle in parts of Carson, Gray, Wheeler, Armstrong, and Donley Counties (fig. 4). The thickness of the Permian formations that overlie the San Andres/Blaine dolomites and anhydrites ranges from 350 to 500 ft (107 to 152 m) (Presley, 1979). They mainly include mudstones and siltstones that accumulated in a mud-(salt?)-flat facies (Presley, 1981).

The Ogallala-Permian contact is characterized by closed, contoured collapse basins that were formed by solution of Permian evaporites. These basins were later filled with thick Ogallala deposits (Dutton and others, 1979; Gustavson and others, 1980; Seni, 1980). Study of the Ogallala-Permian contact based on well logs (Presley, 1981) indicates that the upper layers of the Permian consist of mudstones, anhydrites, or salt with relatively low

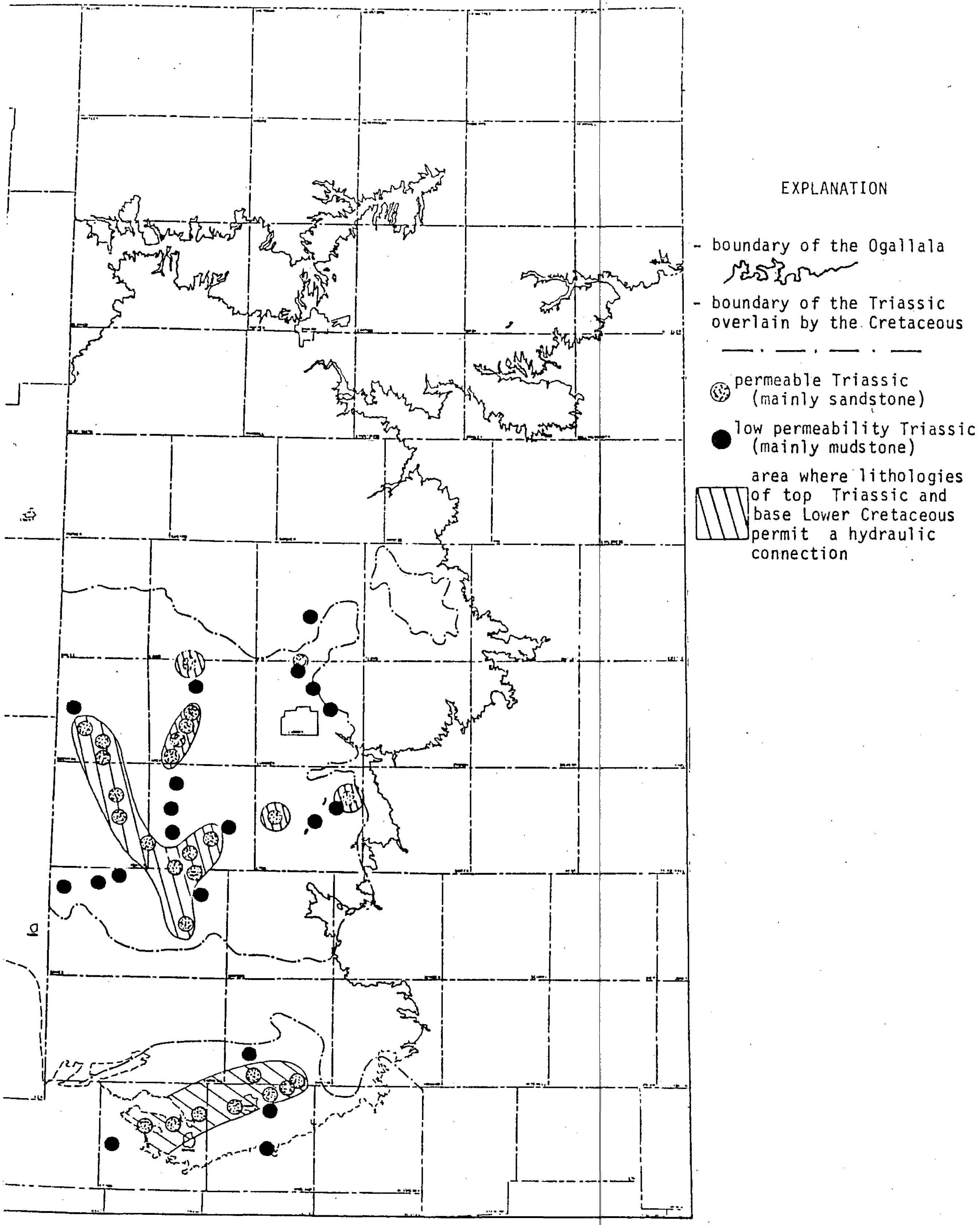
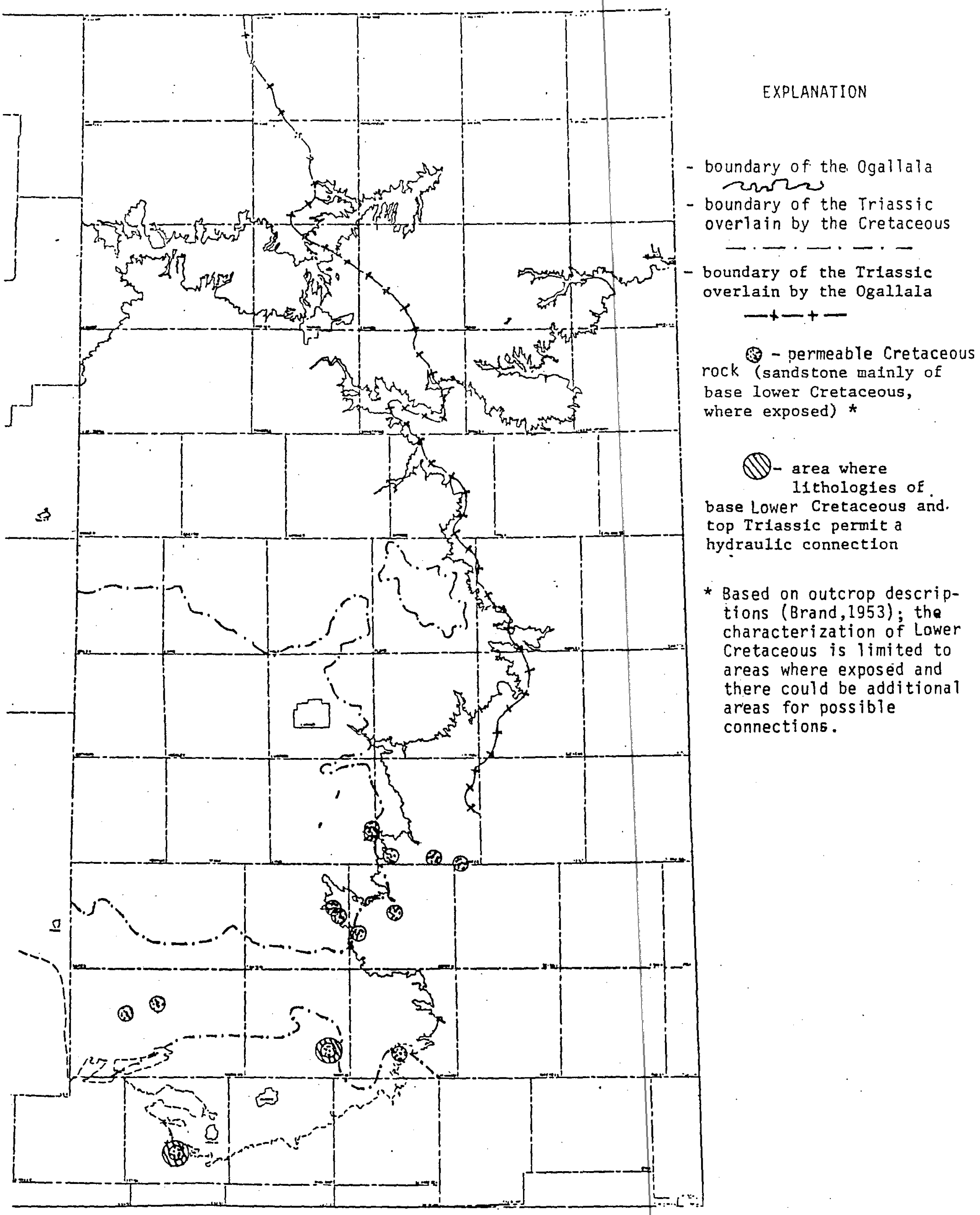


Figure 9a. Hydraulic characterization of top Triassic at the contact with base lower Cretaceous (based on McGowen and others, 1977).



* Based on outcrop descriptions (Brand,1953); the characterization of Lower Cretaceous is limited to areas where exposed and there could be additional areas for possible connections.

Figure 9b. Hydraulic characterization of base lower Cretaceous at the contact with top Triassic (based on Brand, 1953).

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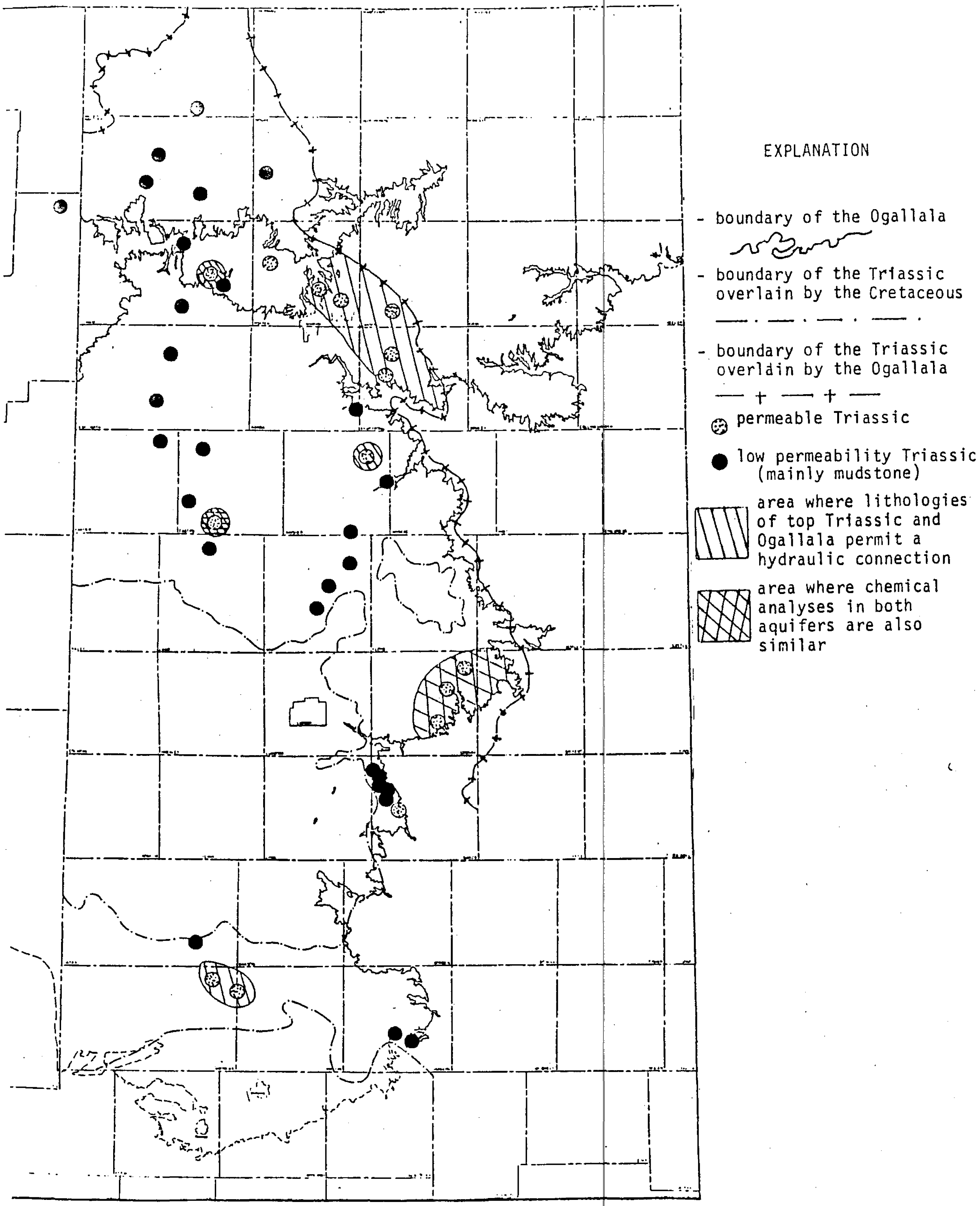

Figure 10. Hydraulic characterization of top Triassic at the contact with the Ogallala aquifer (based on McGowen and others, 1977).

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permeabilities. Therefore, the chances for hydraulic connection on a regional basis between the Ogallala and the Permian are limited (fig. 11).

HYDROLOGY

In this section the hydraulic features of the Ogallala and the underlying aquifers are discussed. Distribution of porosity and hydraulic conductivity that affect flow rates and residence time of water in the Ogallala aquifer are presented. Recharge sources into the Ogallala and points of discharge from the aquifer are outlined and their relative importance discussed. Both issues are crucial for the study of the flow paths of potential spills. Water levels in the Ogallala aquifer and the underlying aquifers are discussed for the purpose of tracing vertical flows between them. The relations between the saturated and unsaturated thickness of the Ogallala in various locations are outlined as a major factor that controls the vertical movement of various contaminants from the surface to water level.

Distribution of Porosity and Hydraulic Conductivity

Specific yield (effective porosity) and permeability maps were published by Knowles and others (1984) in their regional study of the Ogallala aquifer. These maps are based on lithologic descriptions taken from driller's logs, and the correlated specific yields and permeabilities are based on previous studies (Johnson, 1967; Morris and Johnson, 1967). Patterns of high specific yield follow areas of high sand and gravel percentages (fig. 6) along major channels (fig. 12).

In addition, cores retrieved from 41 test holes (Knowles and others, 1984) were analyzed for their porosities and permeabilities and provide a cross-check for the permeability and porosity maps. Also, hydraulic conductivity values calculated from pumping tests (Myers, 1969) performed in 19 wells in six counties can be used for the same

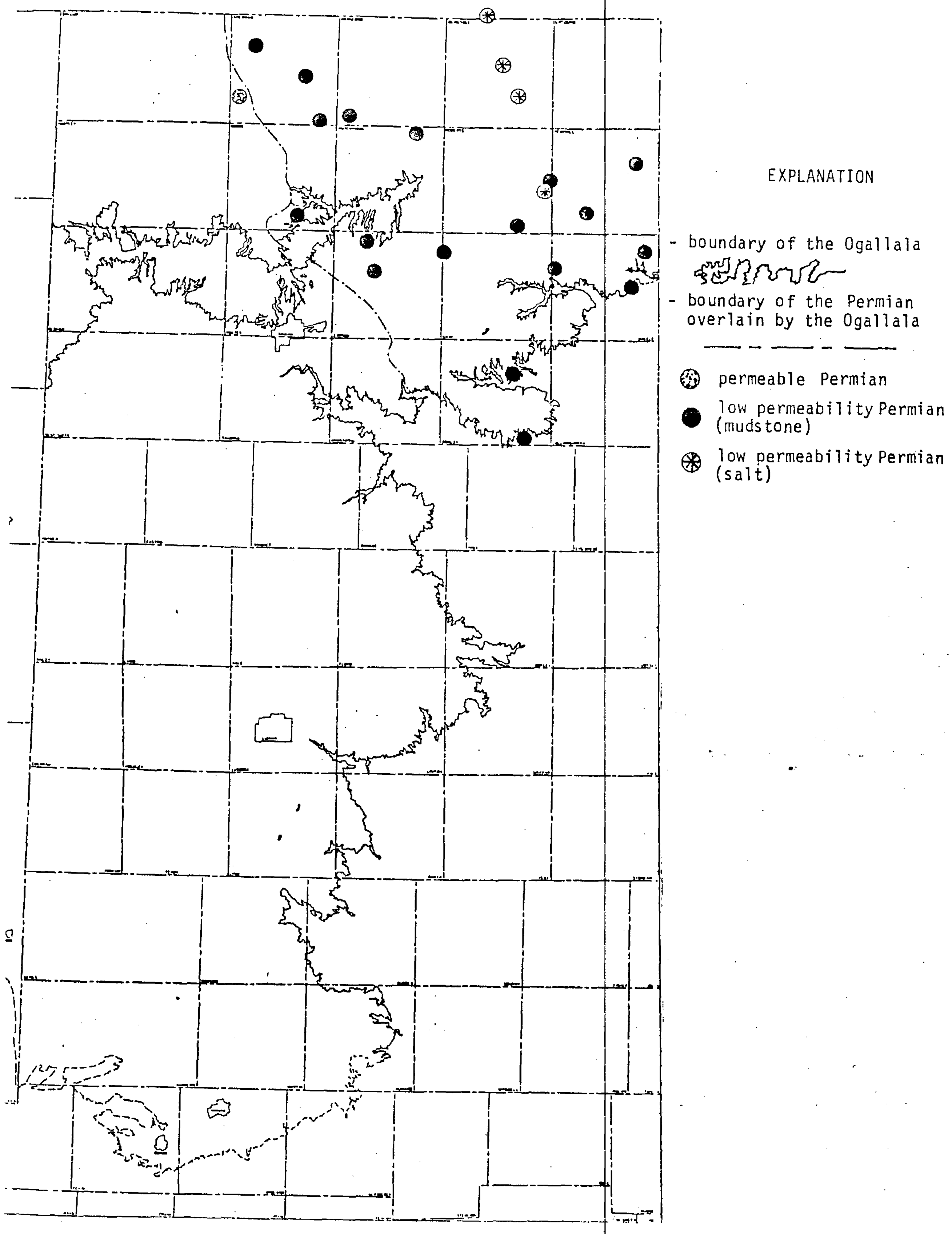


Figure 11. Hydraulic characterization of top Permian at the contact with the Ogallala aquifer (based on Presley, 1981, and Jordan and Vosburg, 1963).

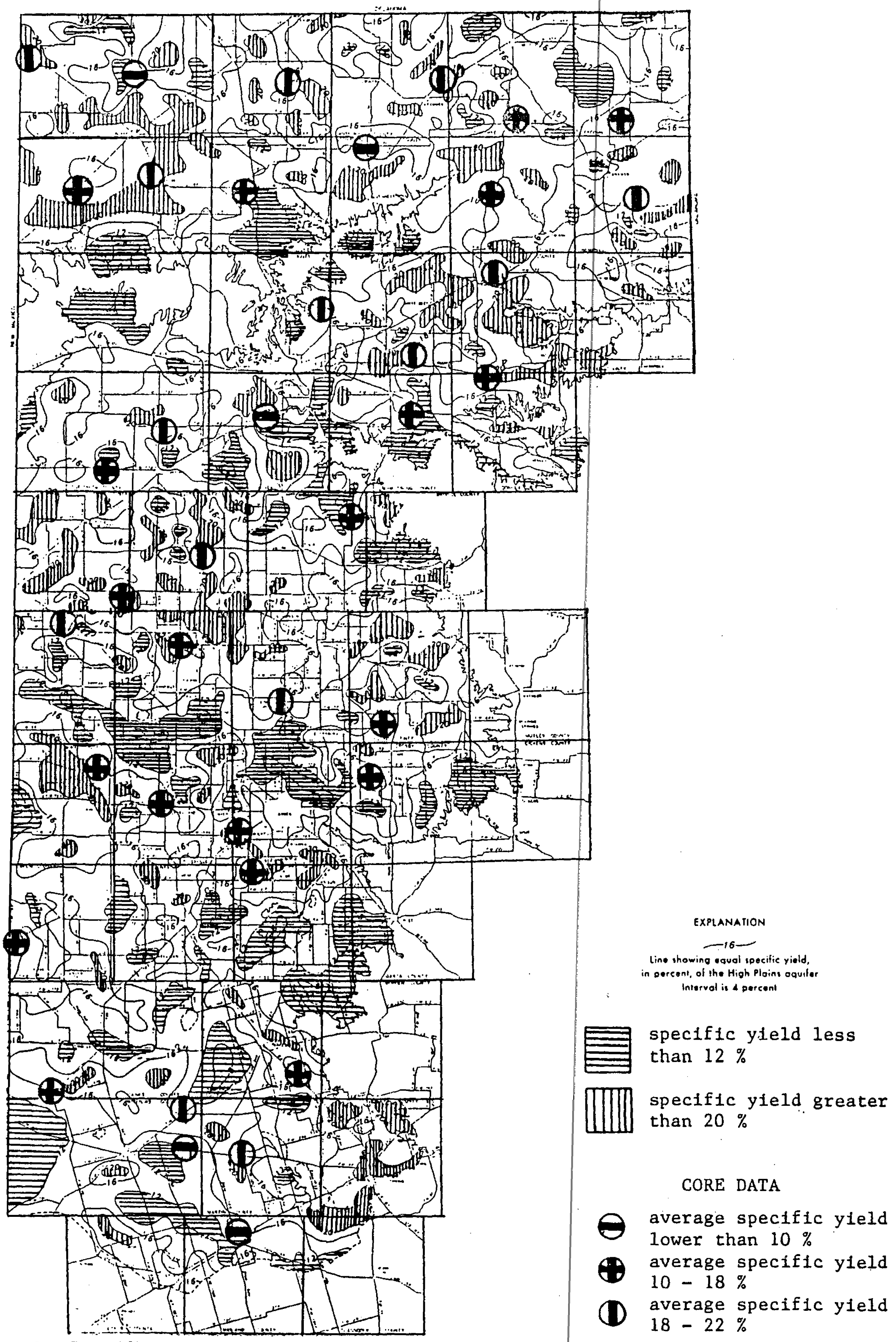


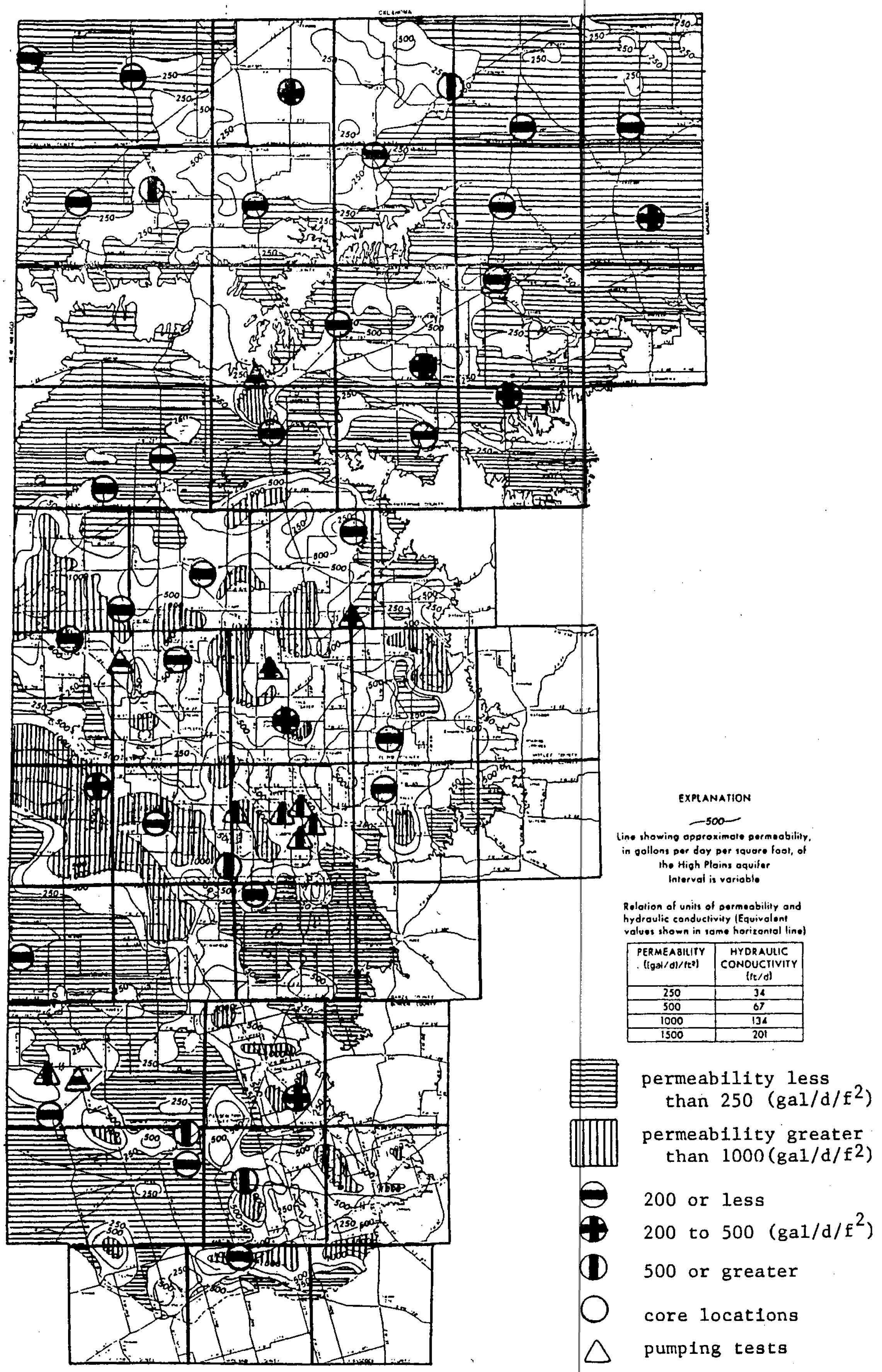
Figure 12. Specific yield map of the Ogallala aquifer (modified from Knowles and others, 1984).

purpose. They range from 70.4 to 1,680.6 gal/d/ft with a mean value of 423 gal/d/ft. Core porosities range between 7.23 and 19.54 percent with an overall average of 16.06 percent, and hydraulic conductivities range from 22 to 1,934 gal/d/ft^2 with an overall average of 232 gal/d/ft^2.

The core results, when overlaid on the specific yield map, confirm the suggested pattern of the map: High core-porosity values (greater than 18 percent) fall along the main clastics flow channels and the suggested contour of 20 percent specific yield. Low core-porosity values (7 to 10 percent) are found next to 12 percent or less contours in the interfan areas. The specific yield map, therefore, correlates well with effective porosity distribution.

The permeability map (fig. 13) does not agree with either the isopach or the percent of sand and gravel maps (figs. 5 and 6). Although the central and southern alluvial fans can be recognized by relatively high permeabilities (1,000 to 1,500 gal/d/ft^2), the northern fan is not clearly differentiated by higher permeability. Also, large discrepancies exist between the measured core or pumping test values and the map (fig. 13). Generally, the map provides higher values than the direct measurements. It is of interest to note that the higher values of these measurements are also arranged along the main flow channels. However, they are much more scattered and less consistent compared to the porosity map. No clear relationship was observed between permeability and depth, even though sediments are coarser toward the base of the aquifer (Knowles and others, 1984). Hydraulic conductivity values range from 30 to 200 ft/d (10 to 60 m/d) (Knowles and others, 1984).

Minimal permeability data are available for the underlying aquifers. Eight well tests are available for the Triassic aquifer in Deaf Smith and Swisher Counties where the aquifer's permeability ranges from 33 to 282 gal/d/ft^2 (Dutton and Simpkins, 1985). Eight pumping tests are also available for the Cretaceous aquifer; all of the tests were made in Midland County in Trinity Sandstone. Aquifer permeability at the test sites ranges from



EXPLANATION

—500—
Line showing approximate permeability, in gallons per day per square foot, of the High Plains aquifer
Interval is variable

Relation of units of permeability and hydraulic conductivity (Equivalent values shown in same horizontal line)

PERMEABILITY ((gal/d)/ft²)	HYDRAULIC CONDUCTIVITY (ft/d)
250	34
500	67
1000	134
1500	201

▤ permeability less than 250 (gal/d/f²)

▥ permeability greater than 1000 (gal/d/f²)

⊖ 200 or less

⊕ 200 to 500 (gal/d/f²)

◐ 500 or greater

○ core locations

△ pumping tests

Figure 13. Permeability map of the Ogallala aquifer (modified from Knowles and others, 1984, and Myers, 1969).

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116 to 511 gal/d/ft^2 and the thickness of the aquifer there is about 70 to 90 ft (21 to 27 m) (Myers, 1969). No pumping tests are available for the Permian aquifer in the area where it underlies the Ogallala.

Recharge

Recharge into the Ogallala aquifer can take place through direct infiltration into the outcrops, through the sand dunes that overlie it in some locations, and through local intake areas such as playa lakes or riverbeds. Because annual precipitation is relatively small and most of the rain falls between April and October when evapotranspiration is at its peak, only a small percentage is available for recharge.

Direct recharge into the Ogallala has been studied extensively. It was assumed (Barnes, 1949) that recharge is reduced in areas where soil cover has finer grain size in the northern Panhandle (fig. 3). Caliche that overlies the surface of the Ogallala is regarded as a severe barrier to recharge, since its permeability is considered to be very low (Broadhurst, 1942; Ries, 1981; Knowles and others, 1984). Indeed, deep percolation in 19 out of 22 sites that were studied across the Panhandle using neutron log measurements did not exceed 20 to 30 ft (6 to 9 m) (Klemt, 1981). Under a separate study during the years 1970 to 1972 (Wood and Osterkamp, 1984) no change in moisture was observed below 6 ft (2 m) despite some significant rain events. Because caliche was observed to be forming there, it was suggested that evaporation from the soil is higher than recharge.

Recharge probably takes place along riverbeds, since flowing rivers at the western and central High Plains carry little water to the Rolling Plains. But the poorly developed drainage system indicates that the annual recharge from this source is relatively insignificant.

Recharge from playa lakes is a controversial issue. The large number of playa lakes, 20,000 to 30,000 (Ward and Huddlestone, 1979), or one lake per 510 to 3,160 acres (Dvoracek and Black, 1973), has attracted the attention of everyone that has studied the hydrology of the High Plains. The large areas that are being drained into the playa lakes are estimated to total between 30,000 mi^2 (Ward and Huddlestone, 1979) and 78,000 mi^2 (Wood and Osterkamp, 1984), or up to 89 percent of the entire High Plains (Dvoracek and Black, 1973). The amount of water that is accumulated in the playa lakes is estimated to be 2 to 3 million acre-ft (Templer, 1978 in U.S. Bureau of Reclamation, 1982). It was noted (Lotspeich and others, 1971; Dvoracek and Black, 1973) that areas with finer soil cover in the northern High Plains (fig. 3) have larger but fewer lakes compared to the south, which has soils with coarser grain-size distribution.

The two major mechanisms that control water loss from playa lakes are evaporation and infiltration. Clay-rich soils in the bottom of the playa lakes may be impervious, at least shortly after they are filled with water (Harris and others, 1972; Knowles and others, 1984). The underlying caliche is considered to be a second impermeable barrier (Knowles and others, 1984). Because of these seals, significant recharge is prevented and most of the water eventually evaporates. Various estimates for evaporation range from 55 percent to 60 percent of the available water (Reddell, 1965; Ward and Huddlestone, 1979; U.S. Bureau of Reclamation, 1982).

Other studies have suggested that the playa lakes are a major source of recharge into the Ogallala aquifer (Texas Department of Water Resources, 1980; Kier and others, 1984; Stone, 1984; Wood and Osterkamp, 1984). In 1937 and 1938 several hundred test holes were drilled in the beds of many playa lakes. Under almost every playa some caliche was encountered, but commonly the material formed a relatively permeable sandy caliche. Shrinkage cracks in the playa-floor clays, in conjunction with solution channels that were commonly observed in the underlying caliche, provided passageways for downward movement of water (White and others, 1946). It was also suggested (Lotspeich and others, 1971) that the caliche under playa lakes was partially dissolved, thus permitting leakage. Wood and Osterkamp (1984) pointed to the area of more permeable soil that immediately surrounds the basin floor as being the main recharge zone in the playa. The lack of evaporites among the playa-floor materials (Harris and others, 1972) and lack of hallophytic flora also suggest that these basins are being well flushed, rather than accumulating salts as a result of evaporation. Low water salinities in playa lakes (Wells and others, 1970; Felthy and others, 1972; Lehman, 1972) also support this assumption. Studies conducted in the unsaturated zone below playa lakes, as well as in other areas (Stone, 1984; Wood and Osterkamp, 1984), have indicated significantly lower dissolved solutes in soil samples below the playas compared to other areas. Presence of tritium in some ground-water samples in New Mexico at the end of the 1950's also suggests rapid recharge mechanisms other than regional, slow, diffuse percolation (Wood and Osterkamp, 1984).

A program for sampling rainfall on a daily basis for one year, as well as playa lakes and ground water from wells surrounding playas, was established to further study the importance of recharge in playas. All samples were analyzed for deuterium, oxygen-18, and tritium. If significant evaporation takes place and water does not infiltrate, then playa water should reflect enriched values for deuterium and oxygen-18. On the other hand, if rapid recharge occurs, the isotope composition of playa water should remain constant and similar to the precipitation values. Preliminary results show some shift from the meteoric water line for Ogallala water, including playa water (figs. 14 and 37), indicating that some evaporation took place prior to recharge. Comparison of tritium values in current rainfall, playa lakes, and ground water may also indicate recharge rates. Based on preliminary results (fig. 14), the Ogallala aquifer may be recharged by water accumulating in playa lakes that undergoes some evaporation prior to its percolation. Recharge on a regional basis is considered, therefore, relatively less significant.

Some of the estimates of recharge that were provided by various studies under different conditions follow:

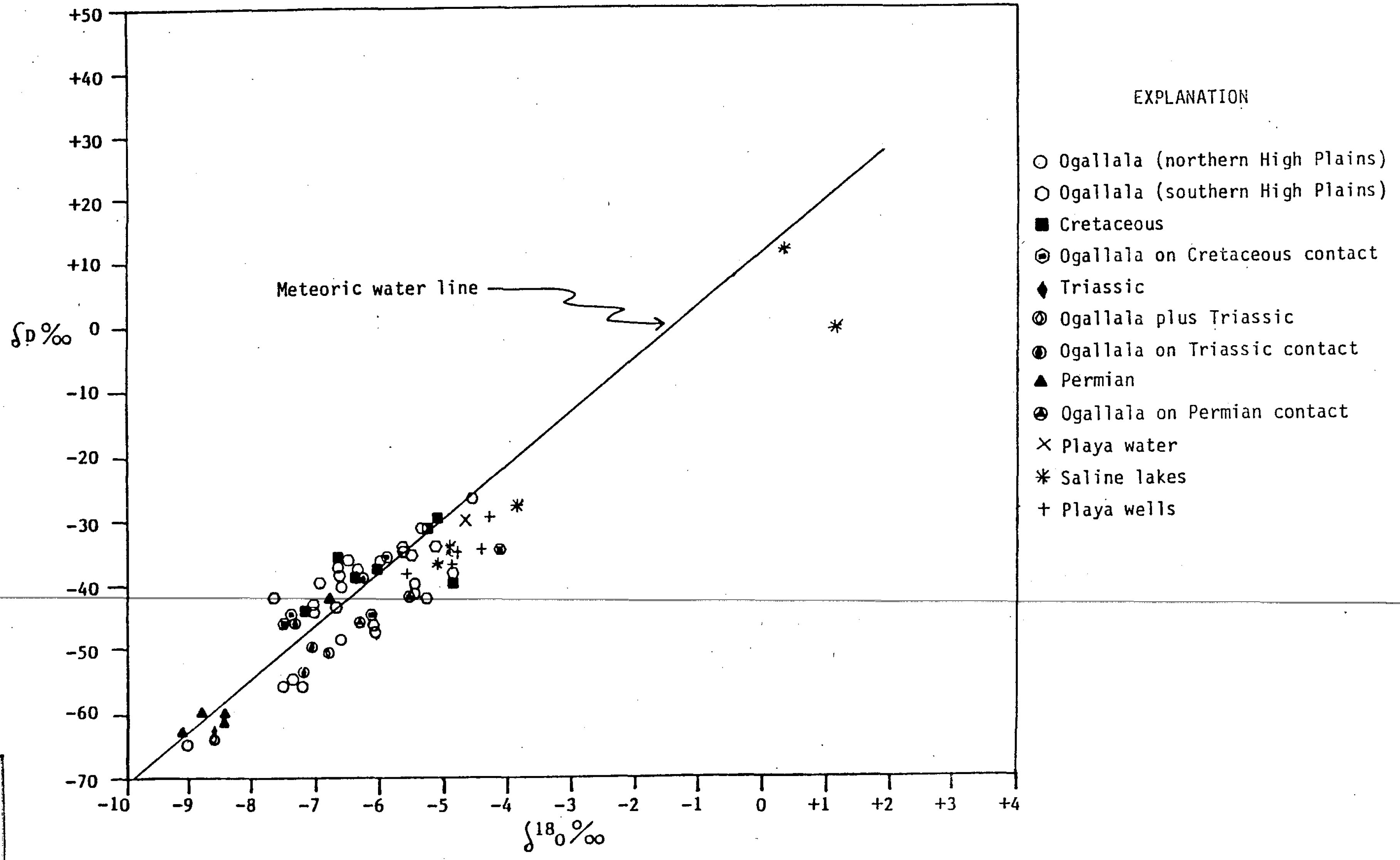

Figure 14. Isotopic composition of water in the High Plains.

	Recharge from playa lakes	Recharge from diffused percolation	Recharge from sand dunes
Stone, 1984	0.11 inches (0.28 cm)	0.01 inches (0.025 cm)	0.05 inches (0.13 cm)
Wood and Osterkamp,1984	1.60 inches (4.1 cm)	~0.00 inches	
U.S. Bureau of Reclamation, 1982	1.00 inches (2.54 cm)		
Klemt, 1981	0.2 inches (0.51 cm)		
Knowles and others, 1984	0.058-0.571 inches (0.15-1.45 cm)	0.833 inches	
Barnes, 1949	0.10 inches (0.25 cm)		

The variety of recharge values is partially a result of different approaches to the study of the recharge mechanism. Stone (1984) based his estimates of recharge in various areas on chloride concentrations in soil profiles. Wood and Osterkamp (1984) based their values on calculations made with data taken from other works. Wood and Petraitis (1984) based their values on CO_2 emission in the unsaturated zone. They suggested that the organic carbon that infiltrates the aquifer with clay particles is oxidized and emits CO_2. The rate of CO_2 flux is correlated to infiltration rates. The U.S. Bureau of Reclamation (1982) used remote sensing data in addition to playa monitoring for water levels and evaporation rates. Klemt (1981) based his values on soil moisture measurements by neutron logs. Knowles and others (1984) divided the High Plains into recharge areas based on soil types.

An additional source of recharge into the Ogallala aquifer is upwelling water from the underlying formations. It was previously indicated that areas where hydraulic connection is lithologically possible between the Ogallala and the Triassic and the Cretaceous exist in some sections of the High Plains. The feasibility of such flow will be discussed later in the report.

Lithologic and Structural Effects on Ogallala Water Chemistry

Three major alluvial fan systems in the Panhandle have higher percentages of sands and gravels than the rest of the area (fig. 6; Seni, 1980). The aquifer is thicker in these major flow areas (figs. 5 and 23) and higher permeabilities and porosities were measured along these channels (figs. 12 and 13). Ground-water flow lines follow their dip orientation (fig. 17). Water chemistry and isotope values are also consistent within these major flow elements. Water in the alluvial fans has mainly Mixed-HCO_3 and Ca-HCO_3 facies and relatively depleted $\delta^{18}O$ and $\delta^{2}H$ values. The southern and northern alluvial fans (zones 1, 4, and 19, fig. 27) also have higher $\delta^{34}S$ values than the central fan (zone 7, fig. 27).

Between these major flow areas (zone 14, fig. 27), the percentage of sand and gravel is smaller, permeabilities are lower, and the aquifer is thinner. Water types vary and consist of Mixed-Mixed, Na-Mixed, Mg-Mixed, and even Mixed-SO_4, Mixed-Cl, Na-SO_4, Na-Cl, and Ca-SO_4 facies. $\delta^{18}O$ and $\delta^{2}H$ values are "heavier."

Figure 35 presents water-facies distribution versus saturated thickness in 412 Ogallala wells. The plot supports the assumption that wherever the Ogallala is thicker, prevailing water types are mainly Ca-HCO_3 and Mixed-HCO_3. Other water types are limited to 0 to 90 ft (0 to 30 m) saturated thickness.

Effects of Water-Level Altitudes on Ogallala Water Chemistry

An aquifer with shallow ground water is more susceptible to surface contamination because of its thin unsaturated section. Various chemicals and fertilizers, commonly applied for agricultural purposes, can be quickly located to the ground water. In order to determine if there is a positive correlation between contamination and the depth to ground water, water analyses with very high nitrates (above 90 ppm) and potassium (above 40 ppm) values were screened out of 4,400 chemical analyses of Ogallala water and checked for the

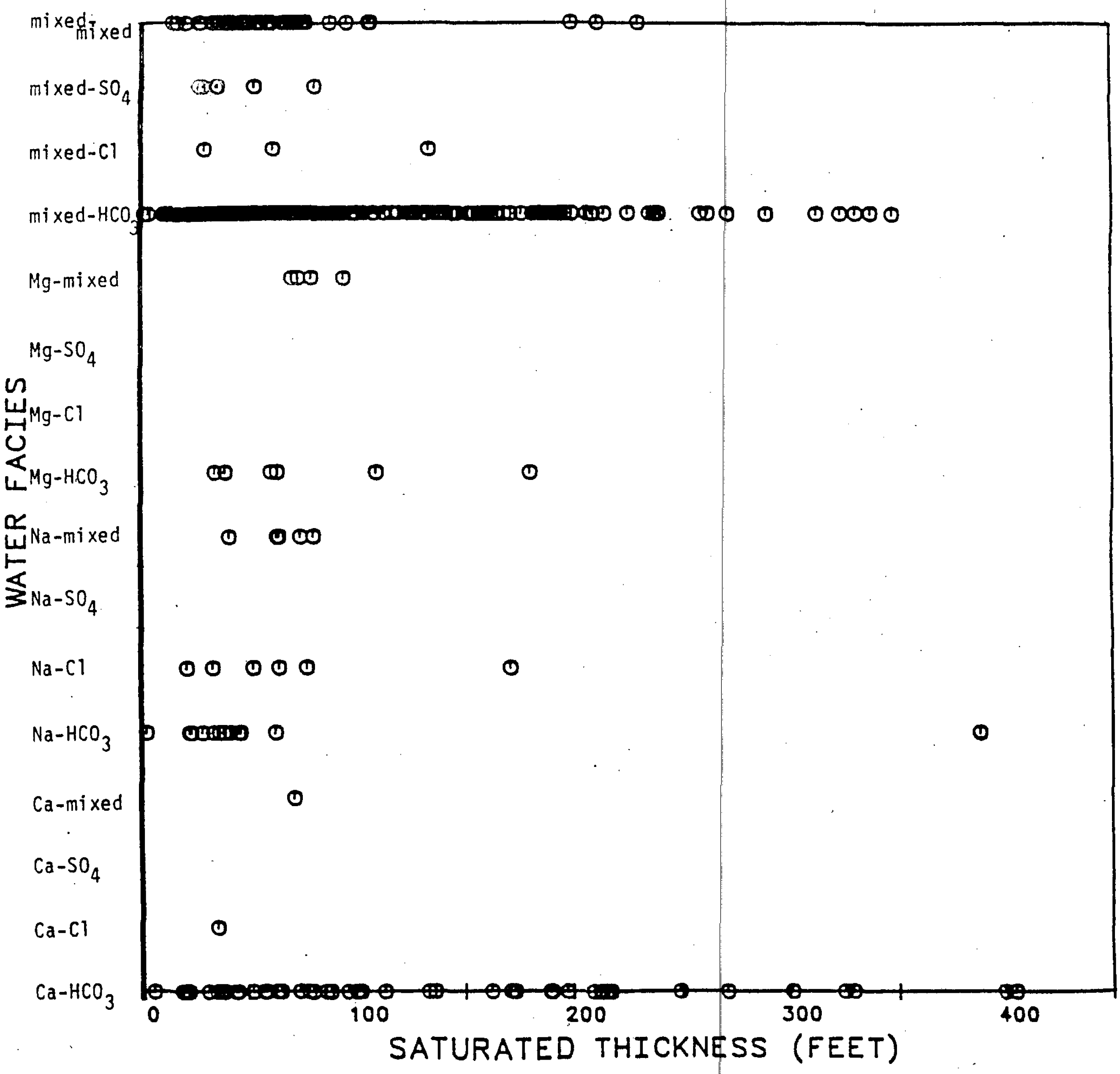

Figure 35. Water facies versus saturated thickness of the Ogallala aquifer.

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thickness of the unsaturated zone. Out of 11 cases, 10 were found to have a very shallow water table (less than 60 ft or 20 m from ground level) and 5 had less than 30 ft (7 m) thickness of the unsaturated zone. Leakage from the surface may be the reason for the unusual concentrations.

Arsenic is another potential hazard. In many areas in the High Plains calcium-arsenate and arsenate acid have been used since 1925 as a cotton defoliator and insecticide. It was observed that in some areas (fig. 36) in the south values approach or are higher than the limits permitted for potable water (0.05 mg/l). In Howard and Martin Counties cattle are reported to have died as a result of this hazardous contamination. High arsenic values are found in the ground water where water levels are generally less than 40 ft (12 m) below land surface. Through more detailed sampling, arsenic may be found in other locations that have a shallow ground-water table and a sandy unsaturated zone, and thus a small capability to adsorb arsenic.

Extremely shallow water levels (0 to 5 ft) can lead to direct evaporation from ground water. Saline lakes in the southern High Plains are possible end products of ground-water exposure to direct evaporation. Out of 22 saline lakes reported by Reeves (1970), 18 were found to be located where water levels range from 5 to 50 ft (1.5 to 15 m) below land surface. Lake waters are characterized by an unusual Na-SO_4 and Na-Cl water facies (calculated from Reeves' [1970] data) that can also be found in some wells near the lakes. This is true in Mound Lake (wells 23-42-601, 24-56-403, 24-64-101), Bull Lake (well 24-06-201), Cedar Lake (wells 27-20-801, 24-16-401, 27-22-602, 24-16-701), Shaffer Lake (wells 27-38-201, 27-52, 201, 27-53-402), and Frost Lake (wells 28-01-801, 28-01-902). For case studies see figure 47. A few isotope analyses from Gooch Lake in Lynn County and from Rich and Mound Lakes in Terry County (W. Wood, U.S. Geological Survey, Reston, VA, unpublished data) show enriched values and in some a shift from the meteoric line, which may indicate evaporation (fig. 14).

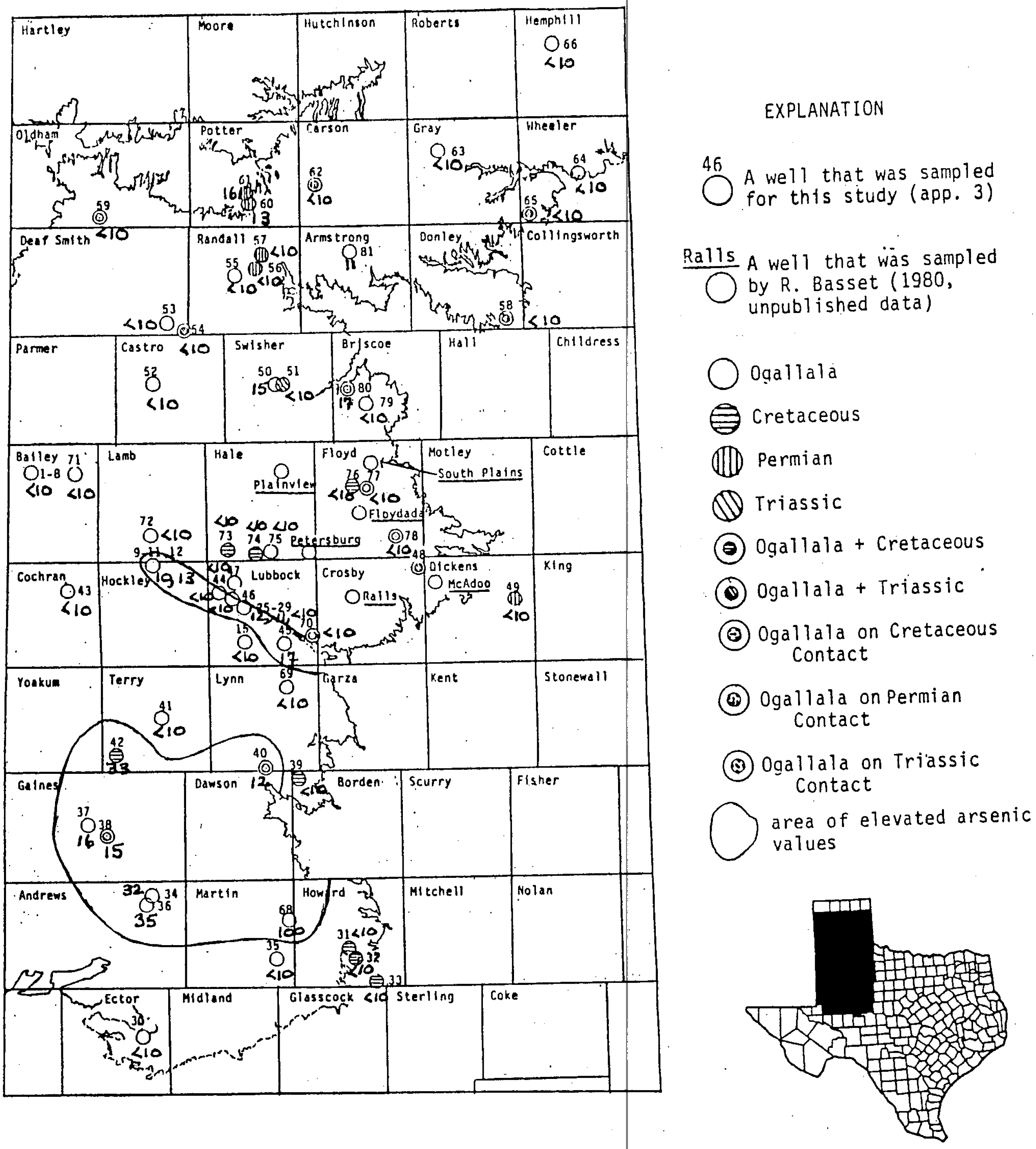


Figure 36. Arsenic concentration (µgs) in the High Plains (50 µgs are the limit for potable water).

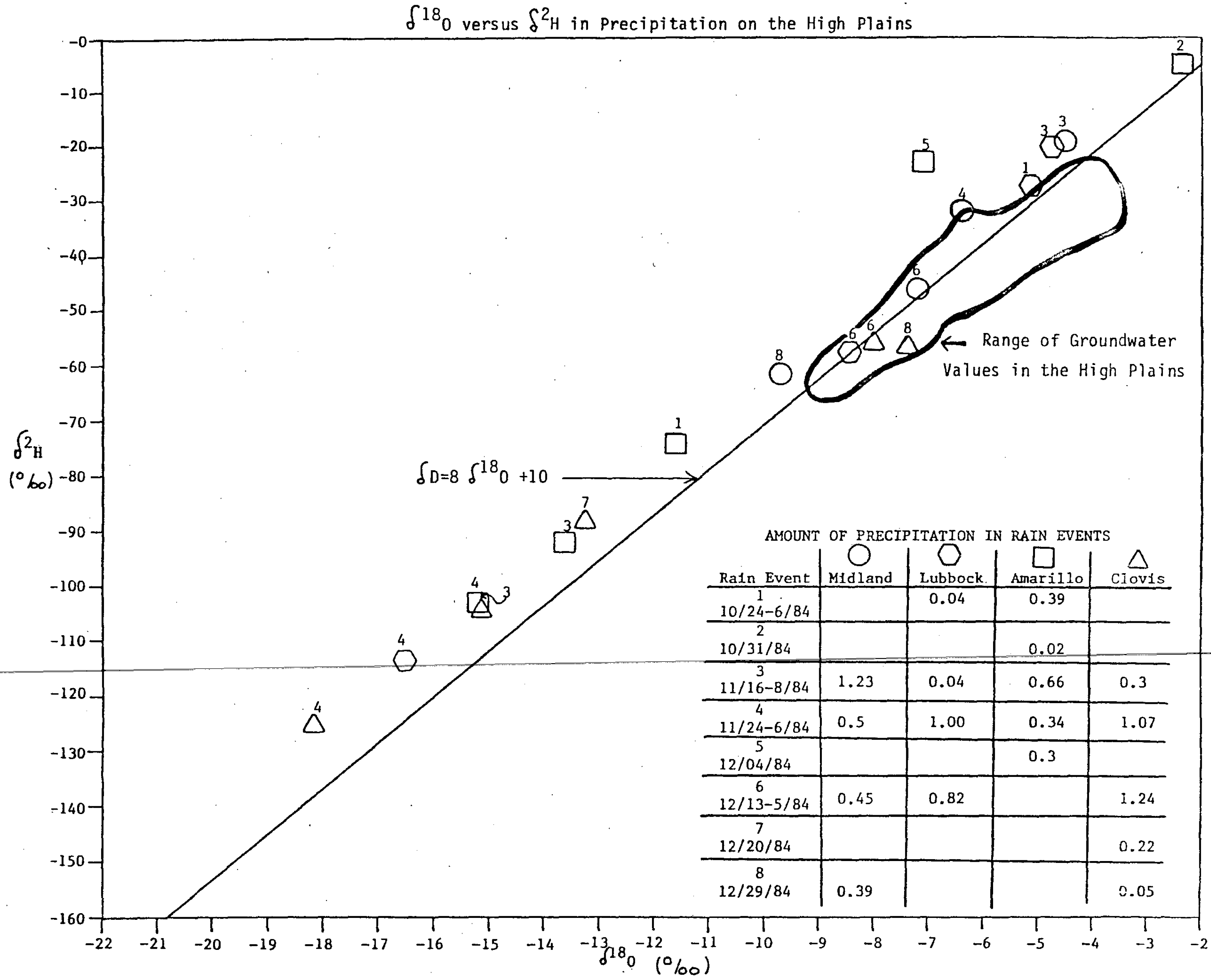
Effects of Natural Recharge from Precipitation on Ogallala Water Chemistry

Rainfall has been collected on a daily basis in five stations in the High Plains and the Rolling Plains. Rain samples were analyzed for $\delta^{18}O$, $\delta^{2}H$, and occasionally for tritium. $\delta^{18}O$ and $\delta^{2}H$ values of rain plot on a line parallel to the meteoric line, but slightly above it (fig. 37). They show a large range (-21.8 to 2.3 for $\delta^{18}O$ and -154 to 5 for $\delta^{2}H$). Weighted mean value for $\delta^{18}O$ is -11.1 and for $\delta^{2}H$ is -72.8, based on rain samples collected between October 1984 and January 1985.

During each rain event, rainfall becomes isotopically lighter (more negative) with time, because when water in a cloud condenses, the first rain is preferentially enriched with heavier molecules. Values shown in figure 37 are weighted means for each rain event for each station. It is possible, therefore, that rainwaters that cause runoff, and which eventually recharge the aquifer, have different compositions.

The northern and western stations have lighter isotopic compositions for some events, such as event no. 3 (fig. 37). The higher altitude of these stations and a later arrival of the contributing air masses from the main source of the moisture--the Gulf of Mexico--may account for the difference. However, isotopic composition for other events (nos. 4 and 6, fig. 37) may be additionally controlled by the rain quantity; that is, the larger the rain amount, the lighter the isotopic composition of the rainfall.

Figure 14 presents $\delta^{18}O$ versus $\delta^{2}H$ in the Ogallala and the underlying aquifers. Ground-water values are scattered along the meteoric water line, but have heavier values compared to rainwater (fig. 37). Only a few rain events, primarily from the southern stations, fit into the range of ground-water values from all aquifers. It should be again noted that rainfall data in figure 37 represent only three months of the late fall and early winter of 1984-85 (rain samples are still being collected to complete a full sampling year). Spring and summer rains may be heavier and provide most of the recharge to the aquifer, and if this happens, ground-water values would be closer to rainwater values. Another



AMOUNT OF PRECIPITATION IN RAIN EVENTS

Rain Event	○ Midland	⬡ Lubbock	□ Amarillo	△ Clovis
1 10/24-6/84		0.04	0.39	
2 10/31/84			0.02	
3 11/16-8/84	1.23	0.04	0.66	0.3
4 11/24-6/84	0.5	1.00	0.34	1.07
5 12/04/84			0.3	
6 12/13-5/84	0.45	0.82		1.24
7 12/20/84				0.22
8 12/29/84	0.39			0.05

Figure 37. δ^{18}O versus δ^{2}H (°/oo) in precipitation in the High Plains.

reason for the difference in $\delta^{18}O$ and $\delta^{2}H$ values between rainwater and ground water could result from evaporation from playa lakes, where runoff is being accumulated prior to infiltration. Faster recharge rates in the south, owing to more permeable soil (fig. 3) compared to the north, could also help minimize the difference in isotope values between rainwater and ground water in the south. In the north, runoff water may be retained longer in playa lakes prior to percolation and thus undergo more evaporation. As a result, the recharging water would exhibit a greater isotopic difference between rainwater and ground water. One playa lake in the south (in Lubbock County) did show some shift from the meteoric water line and had relatively heavy values ($\delta^{18}O = -4.7$, $\delta^{2}H = -30$, fig. 14). A similar shift could be observed in water samples taken from a well (No. 15) near the playa lake in Lubbock County and from five wells (Nos. 25 through 29) next to another playa in Lubbock County (fig. 1, app. 2). However, since no pronounced shift from the meteoric line can be observed for most of the ground-water samples, it is suggested that evaporation is carried out under equilibration conditions and is not a kinetic process.

Tritium values for rainwater from October 1984 through January 1985 ranged from 2.4 to 14.7 TU with a weighted mean of 8.28 TU. No correlation could be observed between tritium values and the station's altitude, geographical location, or rainwater quantity. Tritium in Ogallala water ranges from 0.0 to 73 TU. High values were observed in the southern Panhandle in Hockley, Lamb, Lubbock, and Terry Counties, whereas values in the rest of the area approached zero.

Comparison of tritium values in rainwater and ground water may indicate the rate of recharge. However, in the unsaturated zone and in ground water, tritium decays and its concentration decreases to a half after 12.3 yr, to a quarter after another 12.3 yr, and so on. As a result, comparison of tritium values in a ground-water sample that has been recently collected with tritium values in current precipitation is not valid. A decay curve of the tritium should be used to reconstruct from past tritium values in rainwater the tritium values of current ground water. The sets of reconstructed "ground-water" values (each set can be attributed to a different year of precipitation) are the ones to be compared and matched with tritium values in current ground-water samples. As a result, based on current tritium values in ground water, the year when the water was recharged from precipitation may be traced back. However, back records of tritium values in precipitation are not available for the Panhandle. Therefore, two other stations located in Waco, Texas and in Albuquerque, New Mexico, where rainfall has been analyzed for tritium for the last 25 years, were used for this purpose (app. 3).

High tritium values in the southern Panhandle were reconstructed using the tritium decay curve and then compared with tritium values in past precipitation (app. 3). The current high tritium values can be attributed to 1966-67 rainfall. Based on a time period of 18 to 19 years (1966-67 to 1985), and taking into account a short vertical path of 25 ft (7 m) in the unsaturated zone that can represent a large area in the high-tritium zone, the annual flux can be calculated (app. 3). The recharge rate ranges from 0.5 inches to 3.24 inches/yr (1.3 to 8 cm/yr), depending on the moisture content of the soil profile. These values are within the range of annual recharge previously mentioned in the hydrology section of this report. However, a thin unsaturated zone is encountered in other areas, in Bailey, Gaines, and Andrews Counties, where tritium values are very low. Therefore, another or an additional source for tritium should be sought in order to address this problem.

Effects of Underlying Aquifers on Ogallala Water Chemistry

A brief chemical characterization of waters in the aquifers below the Ogallala aquifer is needed in order to detect possible interaction effects. Previous sections have indicated cross flows of ground water from the Ogallala aquifer into the Triassic aquifer and from the Cretaceous aquifer into the Ogallala aquifer. These relationships have been based on prescreening of permeable contacts between these aquifers as well as on comparisons of their potentiometric surfaces. A third approach to identify leakage between formations is through water chemistry.

The Cretaceous Aquifer

Mean values (calculated from 87 Cretaceous water analyses) for major ions are given in appendix 1 and show that Na > Ca > Mg and Cl > HCO_3 > SO_4. Water salinity is not much higher than in Ogallala water in the southern High Plains. Piper diagrams (fig. 38) reflect these patterns. Bivariate plots (fig. 39) show an increase of Ca, Mg, Na, SO_4, and Cl with TDI and a good correlation between Cl and Na, Ca, and Mg and between SO_4 and Na, Ca, and Mg. $\delta^{18}O$ and $\delta^{2}H$ values range from -7.2 to -4.9°/oo for $\delta^{18}O$ and from -45 to -30°/oo for $\delta^{2}H$ (based on seven Cretaceous wells sampled during 1985). Heavier values exist along the eastern escarpment and more depleted values are found to the west (fig. 14, app. 2). Tritium values are surprisingly high and range from 14.7 to 68.2 TU (app. 2), which indicates a recent recharge (post-1954). $\delta^{34}S$ ranges from +2.7 to -7.6 and $\delta^{13}C$ ranges from -6.9 to -10.8. No spatial pattern was observed for the last two isotopes (app. 2).

In the southern Panhandle some chemical and isotopic similarities exist between Ogallala water and underlying Cretaceous water. It was previously suggested that Cretaceous water moves upward into the Ogallala aquifer (based on permeable contacts between the aquifers and on comparisons of their potentiometric surfaces). This hypothesis will also be studied geochemically.

As was previously mentioned, Na and Cl increase in Ogallala water in the southern High Plains. Na and Cl are also the major ions of the Cretaceous aquifer and could contribute to this increase. In both aquifers Na is in strong correlation with Cl, but since in many cases Na and Cl do not exceed 50 percent, both aquifers have mixed-water facies (app. 1). Piper diagrams of both aquifers (figs. 32 and 38) reflect this chemical similarity.

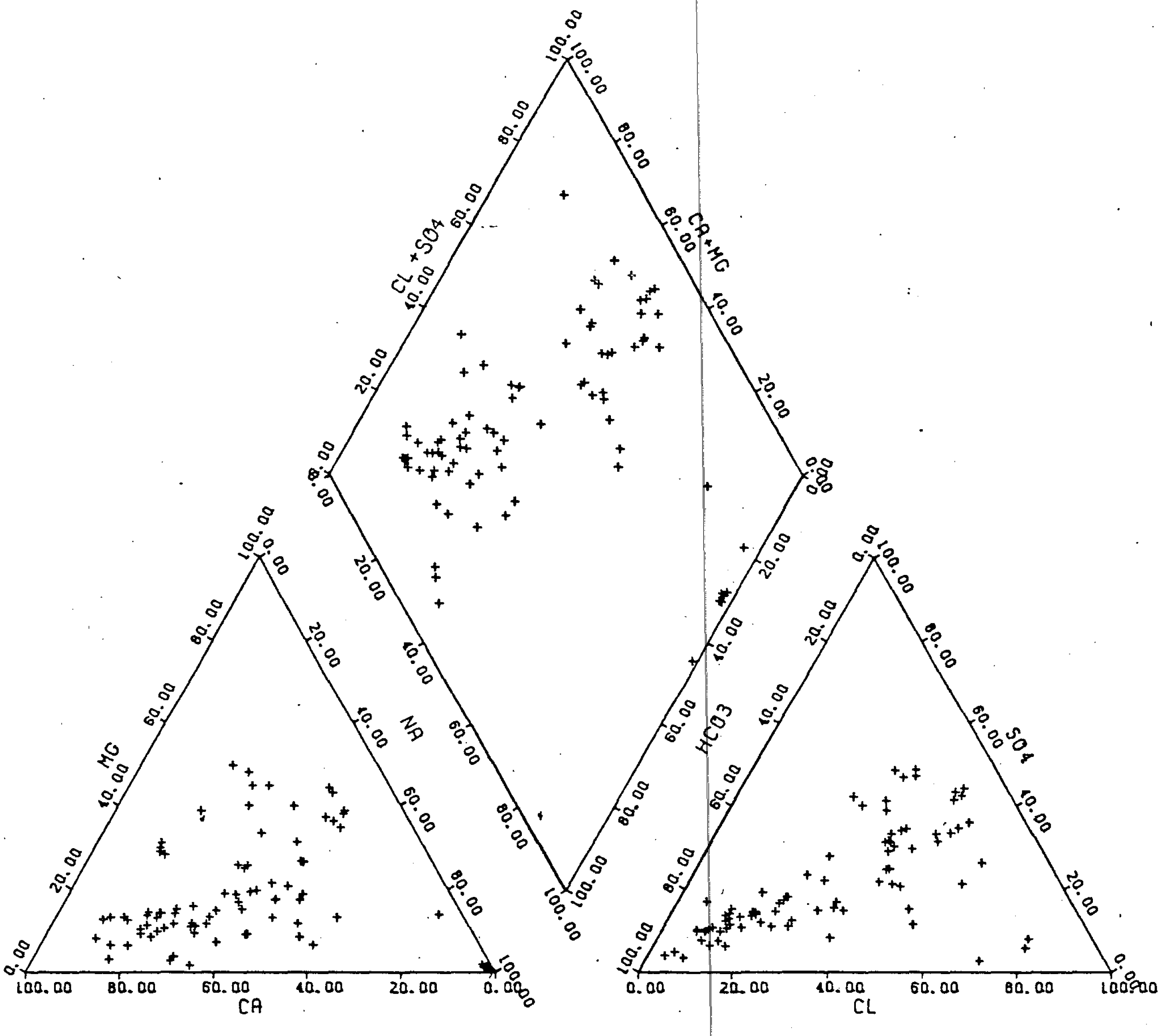


Figure 38. Piper diagram of southern High Plains Cretaceous water.

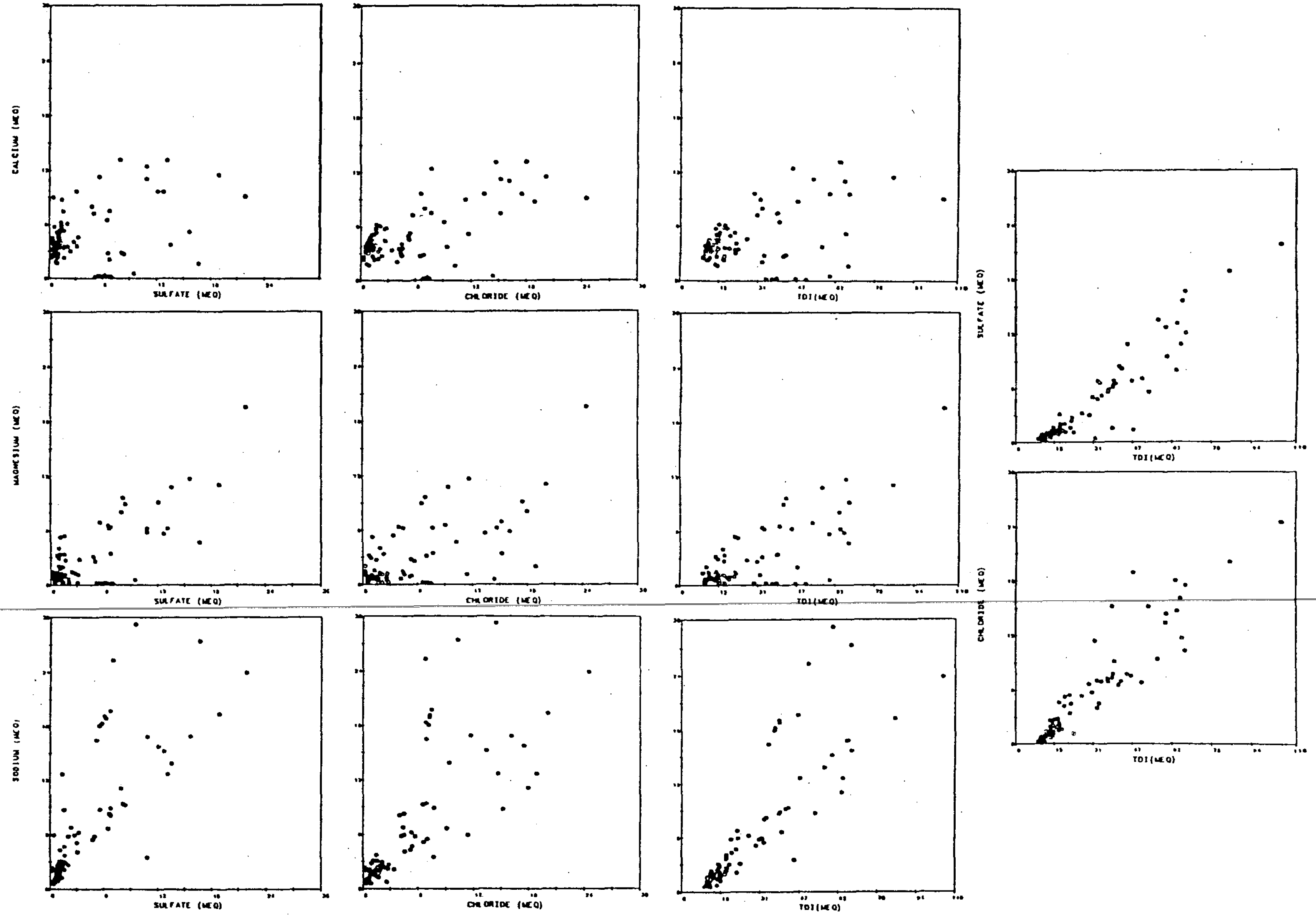


Figure 39. Bivariate plots of Cretaceous water in the High Plains.

Isotopically, waters in the Cretaceous and Ogallala aquifers in the southern High Plains are very similar. Both are heavy with regard to $\delta^{18}O$ and $\delta^{2}H$ when compared to Ogallala water in the northern High Plains (fig. 14). Both have high tritium values, whereas Ogallala water in the north has hardly any tritium (fig. 29, app. 2). The $\delta^{34}S$ and $\delta^{13}C$ values of Cretaceous and Ogallala waters fall within the same range. Several locations were pointed out for potential upwelling of Cretaceous water based on lithologic considerations and water levels (figs. 7 and 21). Two of these locations in Gaines and Lubbock Counties were chosen to present the chemical similarity between waters in the Ogallala and Cretaceous aquifers (fig. 40). Water types seem to fit into one another and demonstrate that mixing, probably owing to upward movement of Cretaceous water, does take place. It is important to note that the suggested movement of Cretaceous water into the Ogallala is restricted to specific areas within the southern Panhandle (most parts of zone 14, fig. 27).

There are other areas where water levels of the Ogallala aquifer are higher than those of the Cretaceous aquifer. In these areas (zone 19, fig. 27), Ogallala water has a Mixed-HCO_3 facies, water isotope values are less enriched, and tritium values drop to nearly zero. Their chemical characteristics are similar to the Ogallala water in the northern Panhandle (zone 7, fig. 27). The areas of higher Ogallala water levels follow the central and southern major alluvial fans, are characterized by thick saturated zones, have higher percentages of sand and gravel, and, as a result, also have higher permeabilities. Upward movement of Cretaceous water can be located within the interfan areas where the saturated thickness of the Ogallala is smaller, where the aquifer consists of larger amounts of fine-grained materials, and where permeability values are lower.

The Triassic Aquifer

Salinities of Triassic water are higher than those of Ogallala water in the northern High Plains. The water becomes more saline in the south and its chemical facies changes

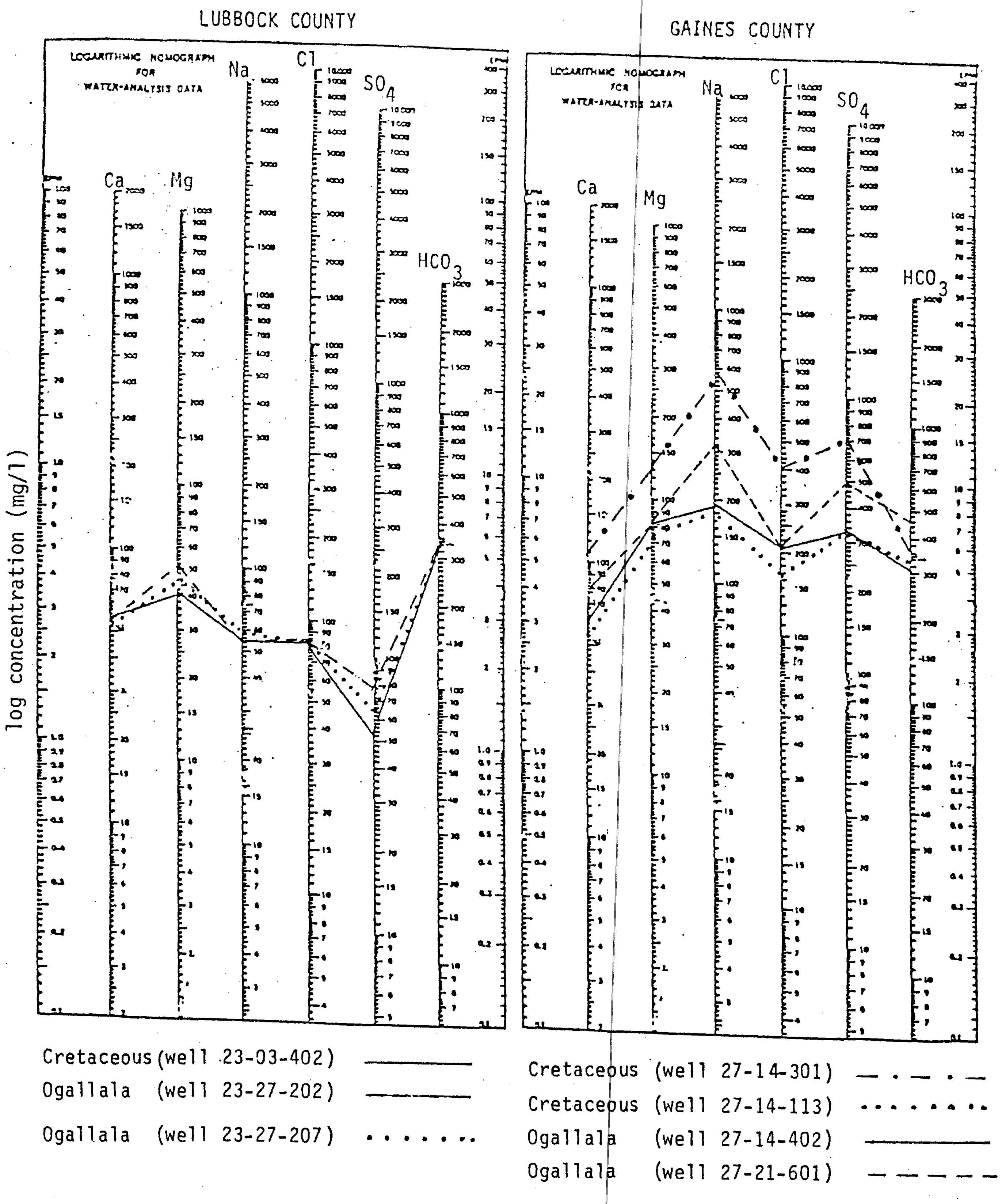


Figure 40. Salinity diagrams of Ogallala and Cretaceous water in Gaines and Lubbock Counties.

(Dutton and Simpkins, 1985). Therefore, the chemical features of the northern and the southern parts of the High Plains will be described separately. Mean values for the major ions in Triassic water in the north and in the south were calculated from 187 chemical analyses and are provided in appendix 1. Sodium is the prevailing cation in Triassic water, whereas Ca and Mg concentrations are very low (less than 10 ppm) in the north and relatively low in the south. HCO_3 is the major anion in the north; however, concentrations of other anions are also high when compared to Ogallala water. In the south, SO_4 and Cl concentrations increase considerably, changing chemical facies from Na-HCO_3 and Na-Mixed in the north to either Na-Cl or Na-SO_4 type in the south (Dutton and Simpkins, 1985). Bivariate plots (fig. 41) indicate an increase of Na, HCO_3, SO_4, and Cl with TDI and good correlation between Na and HCO_3 in the north. An increase of Na and Cl with TDI and a strong correlation between Cl and Na and between SO_4 and Na is indicated for the south. Isotopically, Triassic water is more depleted than Ogallala water with regard to $\delta^{18}O$ and $\delta^{2}H$ wherever data allowed comparison (fig. 27, app. 2) (Dutton and Simpkins, 1985).

The lithology of the Triassic-Ogallala contact indicates few locations for potential cross-formational flow (fig. 10). According to the water-level head difference map between the Ogallala and Triassic aquifers (fig. 22), it seems for the most part that if vertical flow is possible, flow should be from the Ogallala downward because heads of the Ogallala are higher (by 300 ft [91 m] in the north and by 700 ft [213 m] in the south) than the heads of the Triassic. However, when comparing the water chemistry and isotopic composition of both aquifers, it is not easy to locate areas of similar water geochemistry.

In the north, Ogallala water has high Ca and Mg concentrations, in contrast to the typical Na-dominated water of the Triassic. Isotopic composition of Triassic water is more depleted than Ogallala water with regard to $\delta^{18}O$, $\delta^{2}H$, and $\delta^{13}C$ (figs. 1, 14, and 27 through 31, app. 2). In the south, Ogallala water has higher concentrations of Na and Cl, but not as high as Triassic water. In the same area, the Cretaceous aquifer has higher

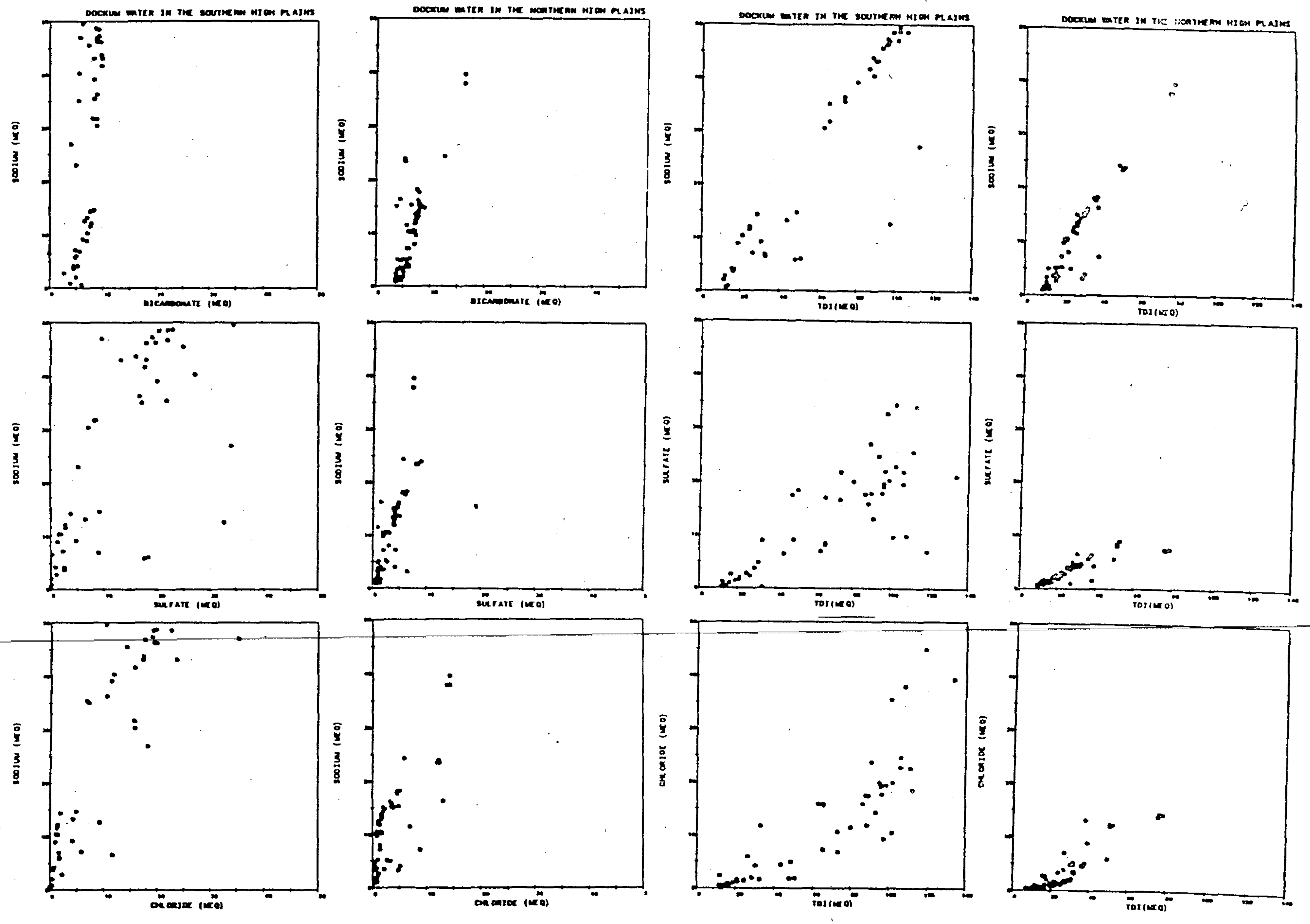


Figure 41. Bivariate plots of the northern and southern Triassic Dockum aquifer.

water levels than the Ogallala, and it is unlikely that downward flow can take place from the Ogallala through the Cretaceous into the Triassic.

In some locations along the escarpment Triassic water levels are higher than those of the Ogallala (fig. 22) and upward flow from the Triassic to the Ogallala is possible. Chemical similarities in these places support that possibility. In Deaf Smith and northwestern Parmer Counties, Ogallala water changes from the Mixed-HCO_3 facies typical in this area, to Na-HCO_3 water similar to the Triassic facies. A similar change takes place in Dickens County (zones 8 and 15, fig. 27). In Howard and Garza Counties the Ogallala facies is also Na-Cl type, similar to the underlying Triassic water (zones 16 and 18, fig. 27).

In other parts of the escarpment, where the potentiometric surface of the Triassic aquifer is not known, upward movement of Triassic water into the Ogallala is also possible. A case study from Dickens County, where no head difference data are available, was chosen to demonstrate the similarity between Ogallala and Triassic waters (fig. 42). It appears that where the saturated thickness of the Ogallala is thin and Triassic water levels are sufficiently high, there is a possibility of upwelling of water from the Triassic into the Ogallala, even away from the escarpment. One example of this situation is in southeastern Deaf Smith County. Due to a local structural high of top Triassic, the Ogallala section is very thin and the saturated zone is less than 20 ft (7 m). The water-level difference, which ranges typically in this area from 350 to 410 ft, drops to only 25 ft. Figure 22 presents the chemical similarity between the Ogallala and Triassic water in that area. Because Na-HCO_3 facies is unusual for Ogallala water but typical for Triassic water, vertical flow from the Triassic into the Ogallala appears possible in this case.

The Permian Aquifer

The upper section of the Permian aquifer is considered to have low permeability because of the presence of halite and other evaporite beds. The head difference map does

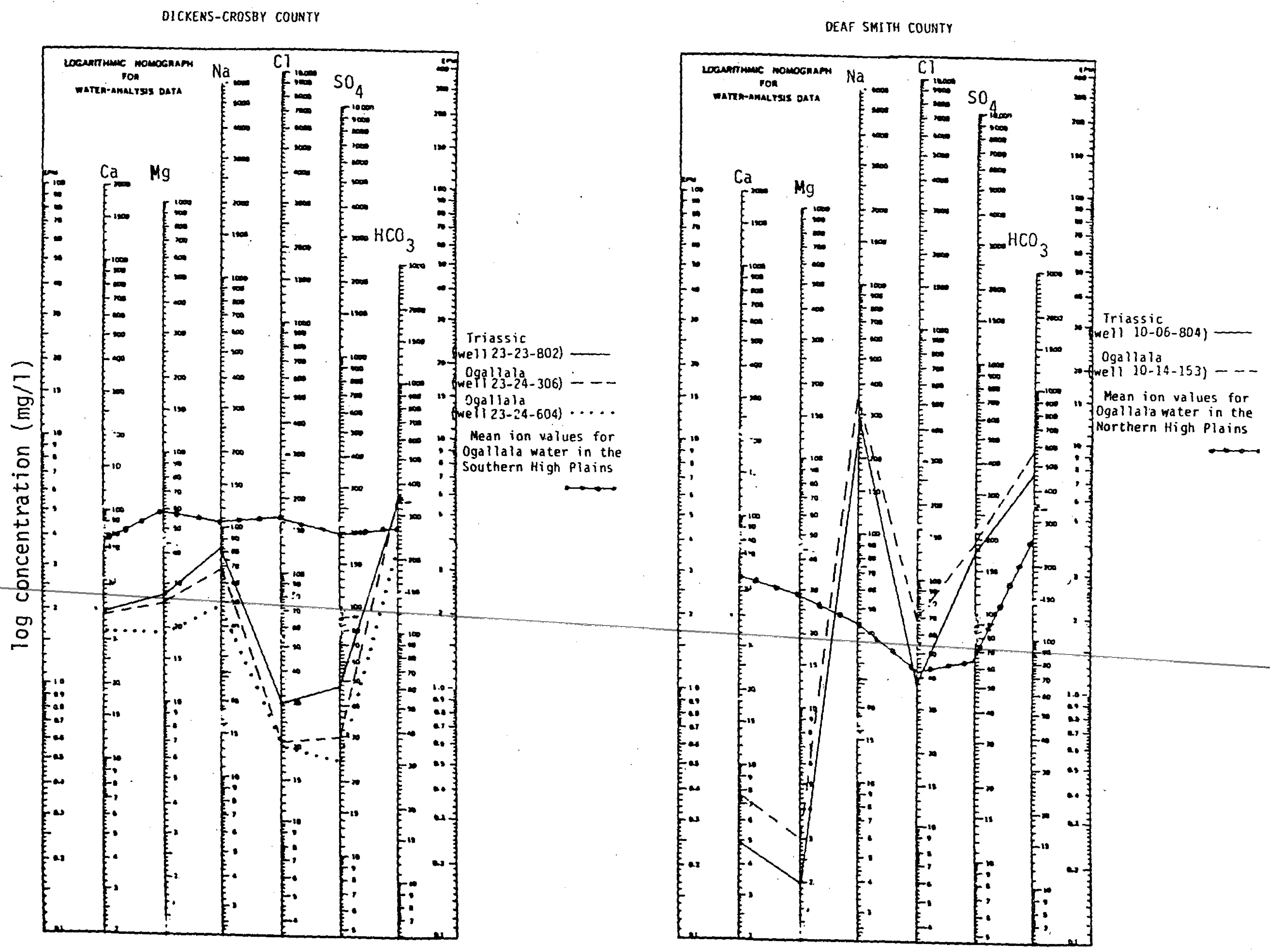


Figure 42. Salinity diagrams of Ogallala and Triassic water.

not indicate any possible areas for upward movement of Permian water into the Ogallala (fig. 21). However, a brief description of its water chemistry is provided.

Three uppermost formations--the Quartermaster, Whitehorse, and Blaine--are considered here. Water in the Permian is more mineralized than water in the Ogallala. The Blaine has the most saline water of the three formations. Mean values for major ions of waters in the Quartermaster, Whitehorse, and Blaine Formations were calculated (based on 22, 109, and 26 chemical analyses, respectively), and are provided in appendix 1.

Water in all three aquifers is of Ca-SO_4 to Mixed-SO_4 facies. These waters have exceptionally low HCO_3/Cl ratios compared to the overlying Ogallala water. High Na/Cl and SO_4/Cl ratios relative to the Ogallala are also typical of Permian water. Bivariate plots show increase of Ca, Na, and Cl with TDI and a good correlation between Ca and Cl and between SO_4 and Ca, Na, and Mg (fig. 43). Five Permian wells that were sampled for this study are all depleted with respect to $\delta^{18}O$ (-6.3 to -9.1^o/oo), δ^2H (-33 to -63^o/oo), and $\delta^{13}C$ (-6.9 to -18.3) (figs. 1, 14, and 30, app. 2). $\delta^{34}S$ values are relatively high (-1.4 to +10.1^o/oo). Water in the Ogallala aquifer, wherever underlain by Permian, is usually of Ca-HCO_3 or Mixed-HCO_3 facies. Only three cases of typically Permian Mixed-SO_4 or Ca-SO_4 facies were encountered in the Ogallala (along the escarpment at Donley and Wheeler Counties). However, $\delta^{34}S$ of Ogallala water from some wells within this area is relatively enriched. $\delta^{34}S$ values of Ogallala water range between -12.7 and +9.5^o/oo (fig. 31). Permian rocks usually have $\delta^{34}S$ values of +11^o/oo (Hoefs, 1973) and in this area they range from 10.4 to 14.2 percent (Posey, 1985). Water sampled from Permian wells in this area (samples 49, 60, and 61, app. 2; Dutton and others, 1985) ranges from +9.0 to +11.92^o/oo. Samples taken from the Ogallala aquifer in this area had similar $\delta^{34}S$ values of +8.6 and +9.5 (fig. 31). These are the highest $\delta^{34}S$ values that were encountered in the Ogallala water and they may indicate some local upward diffusion from the Permian. Because the values for $\delta^{18}O$, δ^2H, and $\delta^{13}C$ are at the same range as those in the Ogallala (figs. 28 through 30), they can neither support nor eliminate this assumption.

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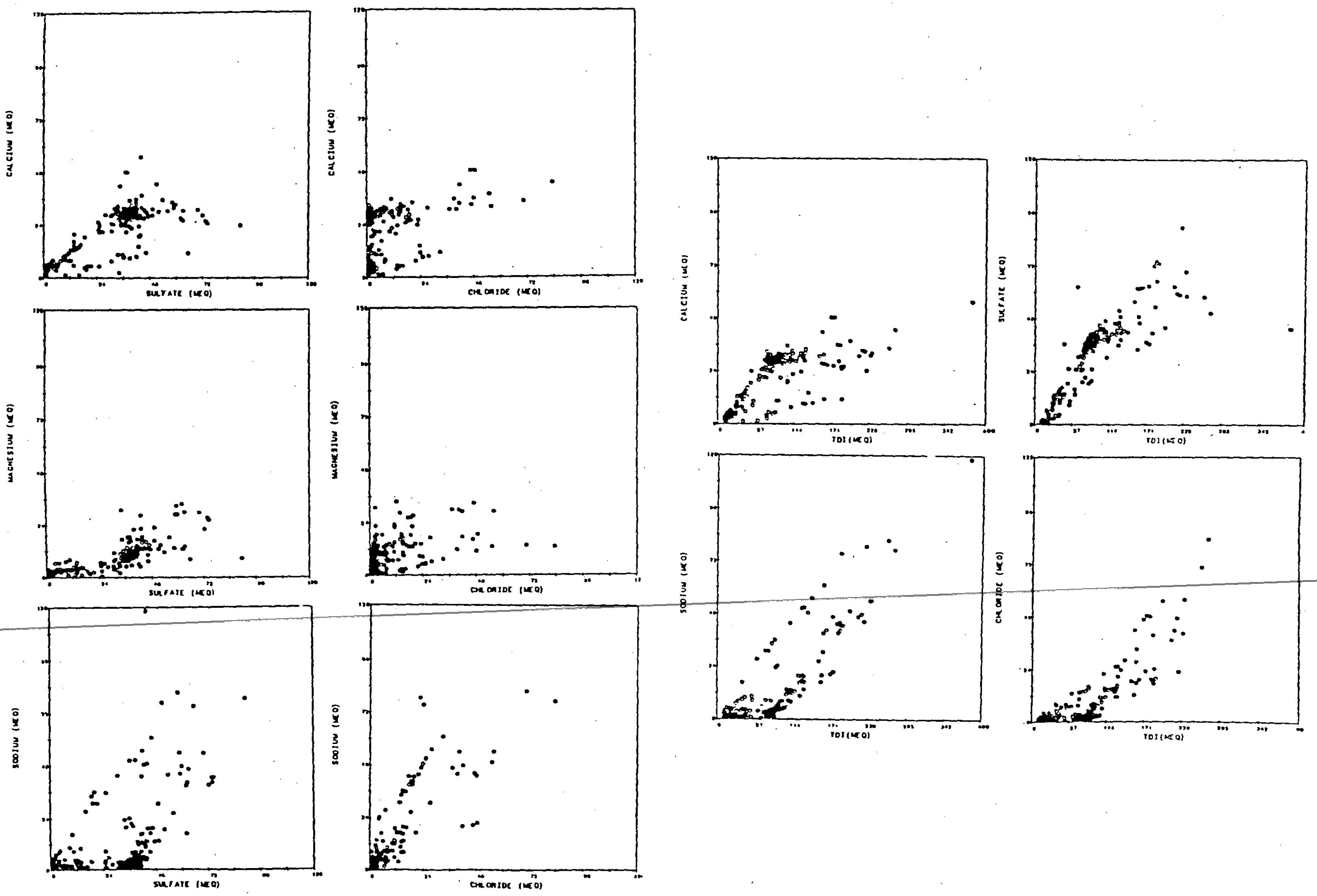

Figure 43. Bivariate plots of the Permian aquifer in the High Plains.

Effects of Oil Field Brine Contamination on Ogallala Water Chemistry

Contamination of ground water by disposal of oil field brines is presumed to be chiefly by infiltration from unlined disposal pits used in the past and by leakage from deep abandoned or injection wells. The southern Panhandle and the Amarillo Uplift are the areas where oil production is concentrated and where ground-water contamination may be found.

To identify brine contamination, approximately 530 chemical analyses of oil field brines from 16 formations in the Panhandle were studied. Data were taken from Burnitt and others (1963), Reed (1963), Burnitt (1964), McAdoo (1964), and Crouch (1965). Mean values were calculated for the major ions in each of the formations and are presented in appendix 4. Brine waters are very saline and TDI range from 1,891 to 5,726 meq/l. The chemical characteristics of all brines are similar: Na > Ca > Mg and Cl >> SO_4 > HCO_3, and water has Na-Cl facies. These patterns are reflected in the Piper diagram for these brines (fig. 44). All brines show an increase in Na and Cl with TDI and good correlation between Na and Cl (fig. 45). In the Permian brines, strong correlation also exists between Ca and Cl. Brines always seem to have very low ratios (in meq/l) of HCO_3/Cl (0.001 to 0.020) and SO_4/Cl (0.006 to 0.06). High ratios of Ca/(HCO_3+SO_4) (4.87 to 48.1) are encountered for all brines. The Na/Cl ratio generally ranges from 0.698 to 0.938, but extremely low values (0.15 to 0.22) are encountered in the Permian brines, which may suggest that halite precipitation took place in these brines. It seems, therefore, that several criteria could serve for the identification of brine contamination of Ogallala water: high salinities, low ratios of HCO_3/Cl, and SO_4/Cl, and high ratios of Ca/(HCO_3+SO_4).

Cases of high salinity were screened from 4,400 Ogallala chemical analyses examined for this study. These exceptional salinities were compared with adjacent oil field brines in order to detect the salinity source. It seems that in several cases at Andrews, Howard, Gaines, and Hockley Counties, salinities originated from a nearby oil field (for

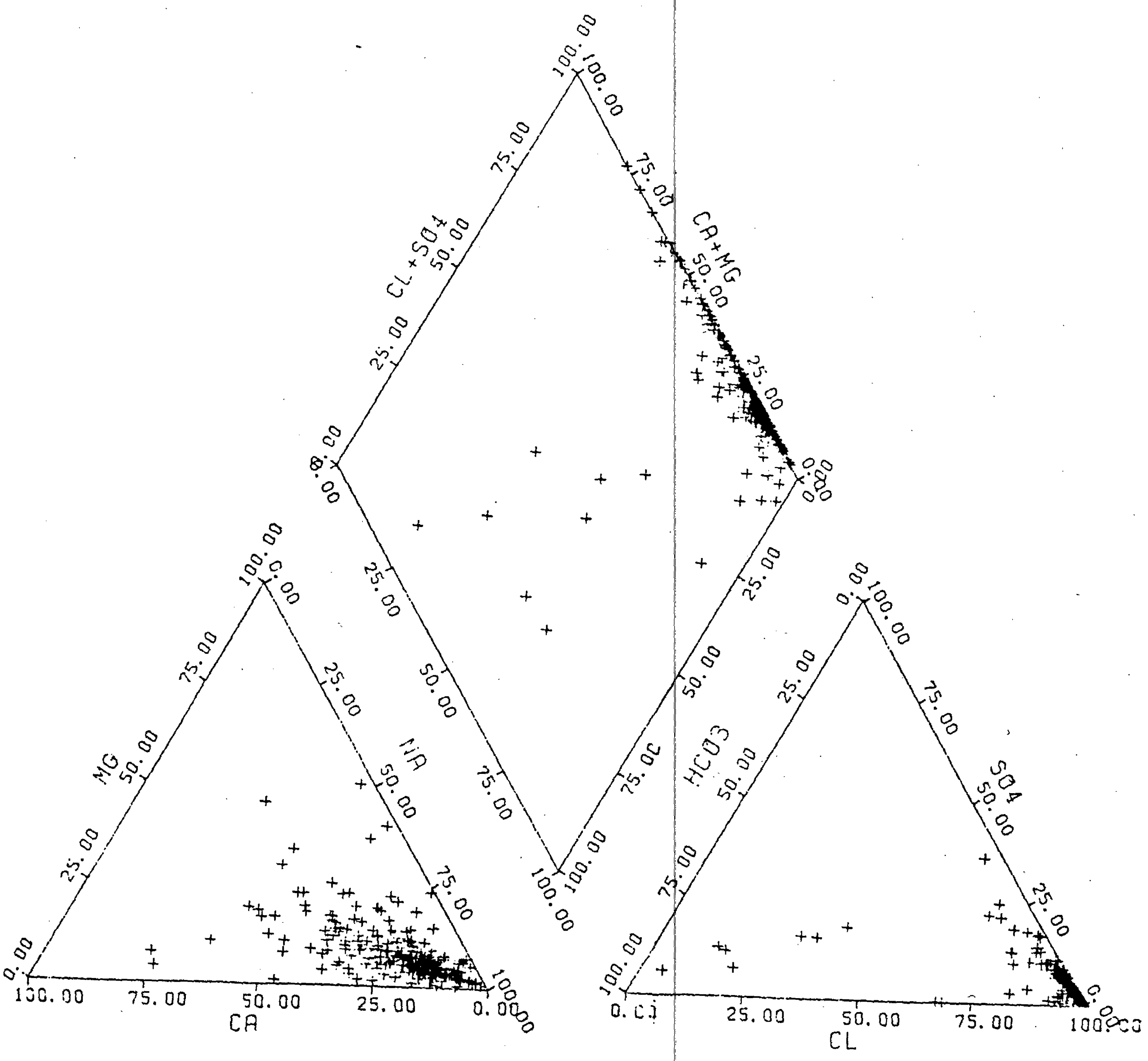

Figure 44. Piper diagram of oil field brines from various High Plains formations (app. 4).

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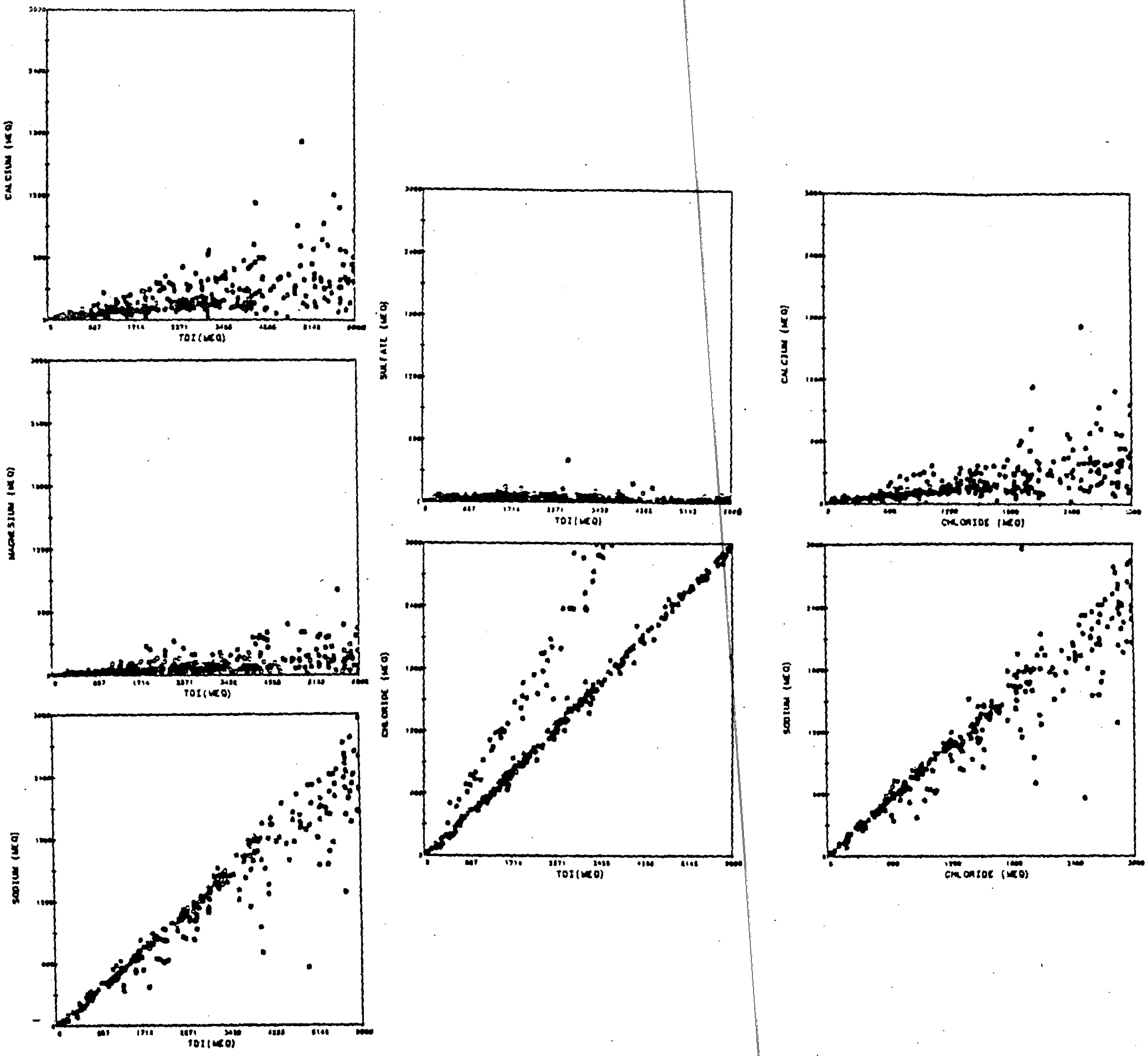


Figure 45. Bivariate plots of brines in various formations in the High Plains.

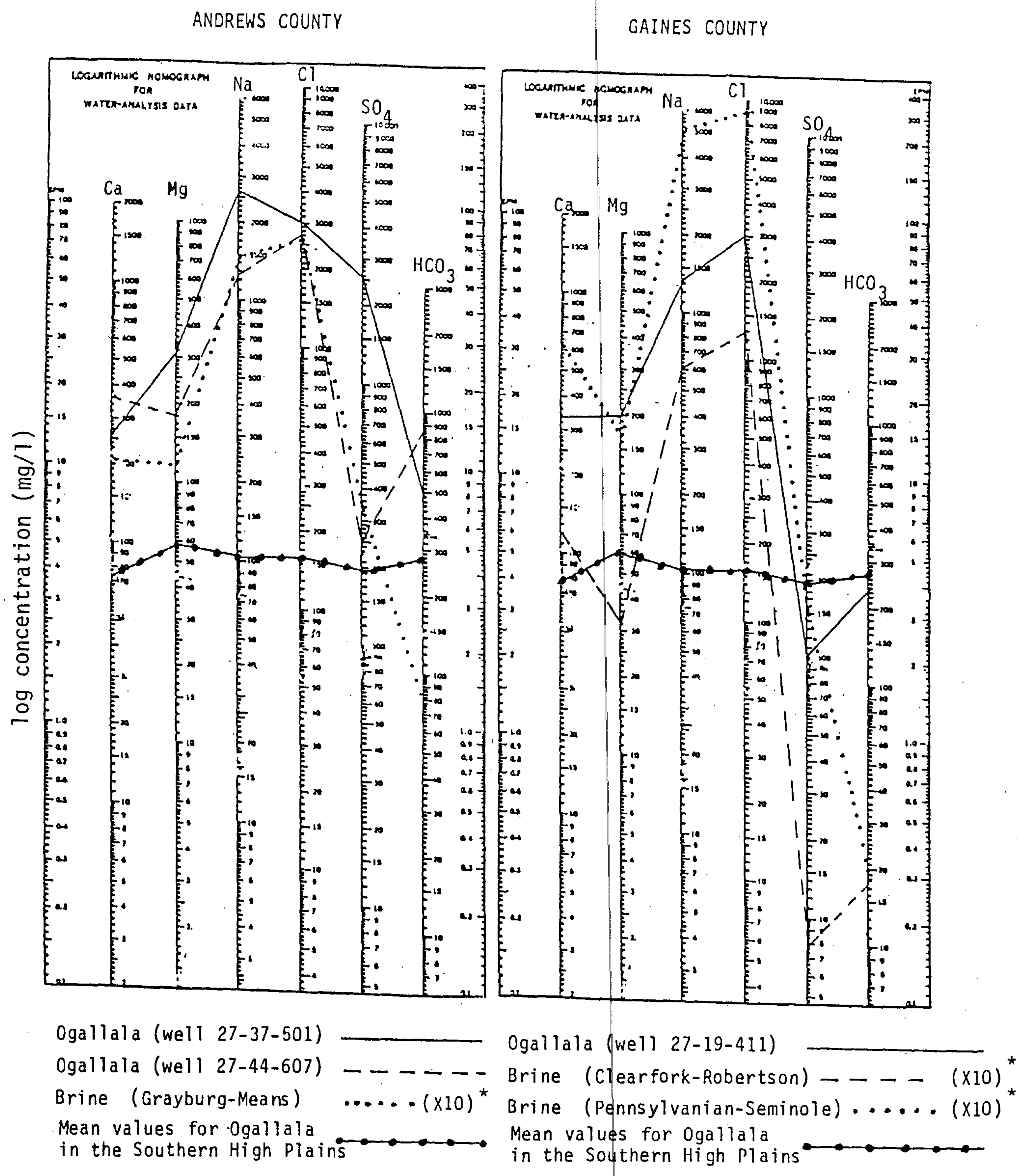
examples see fig. 46). However, saline water of $Na-SO_4$ facies does not resemble any of the adjacent brines; therefore, a different source for its salinity has to be found. Much of the brine may still be in the unsaturated zone. The rate of surface contamination is controlled by the distribution of the aquifer's vertical permeabilities and recharge rates. It is anticipated, therefore, that past activities of brine disposal will have an increasing effect on Ogallala water chemistry in the future.

FLOW MODEL OF THE OGALLALA AQUIFER

The Ogallala aquifer in the study area underlies most of the Texas Panhandle and is only a southern end of a very large aquifer that stretches from South Dakota to Texas. Its varying hydrologic and hydrochemical features are basically controlled by the geology of the underlying formations and its own depositional environment, and by the degree of erosion and superimposed geomorphologic processes. The thickness of the Ogallala aquifer is governed by the topography of the underlying formations and by the location of the main channels that received clastics from the Rocky Mountains.

Three major areas consisting of alluvial fan deposits stretch from northwest to southeast and are characterized by increased thickness and permeability. The saturated section there is thick and the chemical composition relatively constant ($Ca-HCO_3$ to $Mixed-HCO_3$ water, depleted in $\delta^{18}O$, δ^2H, and tritium). External effects on the chemical composition are less pronounced (fig. 27).

In areas between these major channels and along the caprock escarpment the thickness of the Ogallala Formation is smaller and the aquifer is thinner and less permeable. As a result, upwelling of water from the underlying formation is possible. Combined effects of water from other sources and reduced permeabilities result in heterogeneity in water facies and in isotopic compositions different from those of the major flow areas (fig. 27).



*(X10) - the actual concentration of brine was divided by 10 in order to include it on the same plot with the Ogallala wells

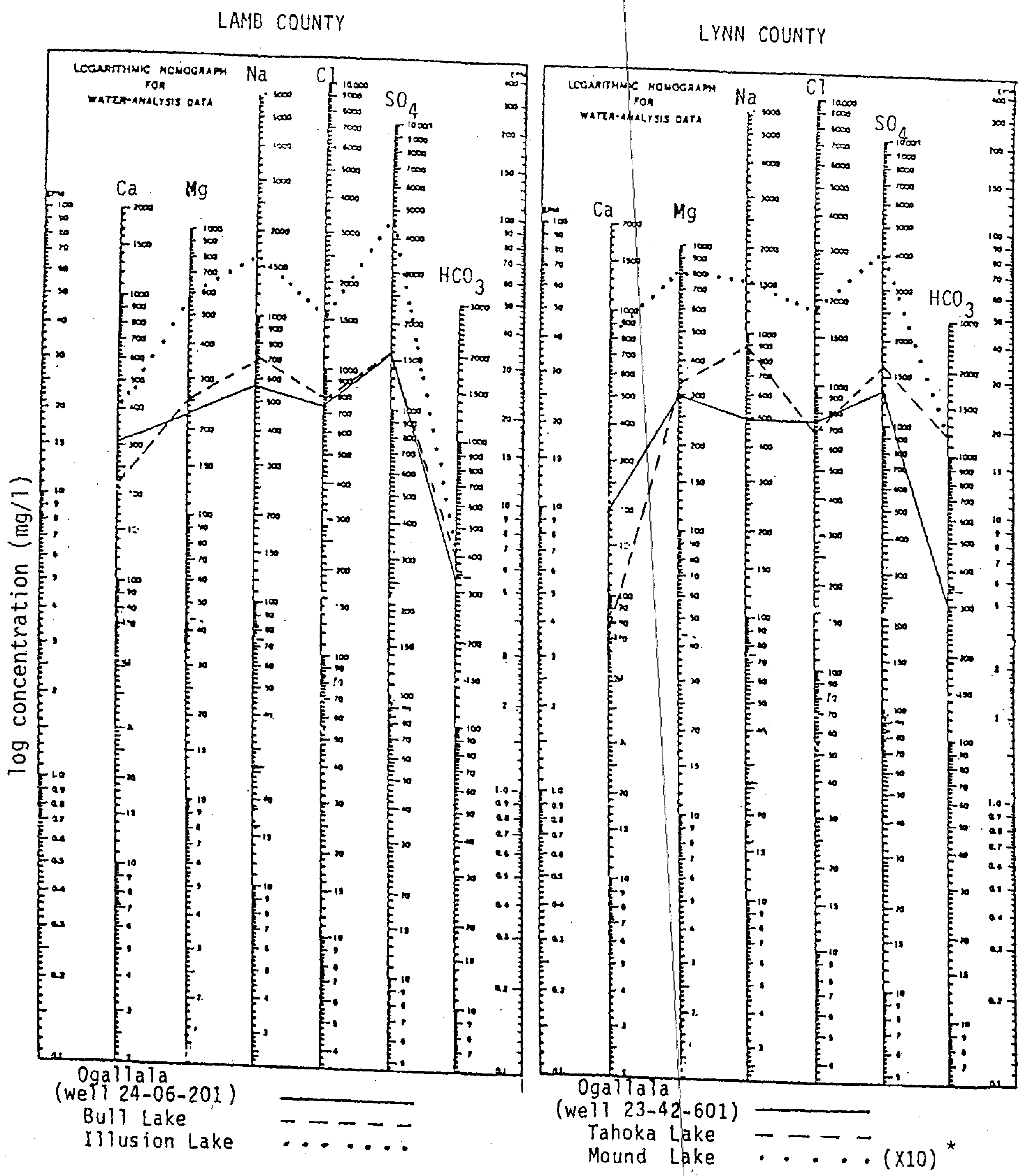
Figure 46. Salinity diagrams of contaminated Ogallala water and oil field brines.

Permeable contacts of the Cretaceous and Ogallala aquifers, higher potentiometric surface of the Cretaceous aquifer, and chemical similarities of water in both aquifers suggest there is cross-formational flow from the Cretaceous to the Ogallala in the southern Panhandle (in parts of Bailey, Lamb, Hale, Cochran, Hockley, Lubbock, Crosby, Yoakum, Terry, and Lynn Counties). Upwelling of water from the Triassic probably takes place along the escarpments and in Deaf Smith County. Possible upward movement of water from the Permian may also occur along the northeastern escarpment (Donley and Wheeler Counties). Changes in water chemistry as a result of vertical flow from the underlying aquifers is well defined in salinity cross sections along the relevant areas (fig. 48). Secondary factors that affect the chemistry of the Ogallala water on a local basis are contaminations from evaporating saline lakes and oil field brines (figs. 46 and 47). The main recharge source to the aquifer is precipitation. Playa lakes may provide the principal pathways for infiltration. The role of sand dunes in the regional recharge needs to be investigated.

The ongoing decline of water levels in the Ogallala owing to heavy pumpage (1 to 6 times the annual recharge) may impoverish the natural resource and make future pumpage uneconomic. The quality of Ogallala water may deteriorate in the future because brines are expected to reach the water table.

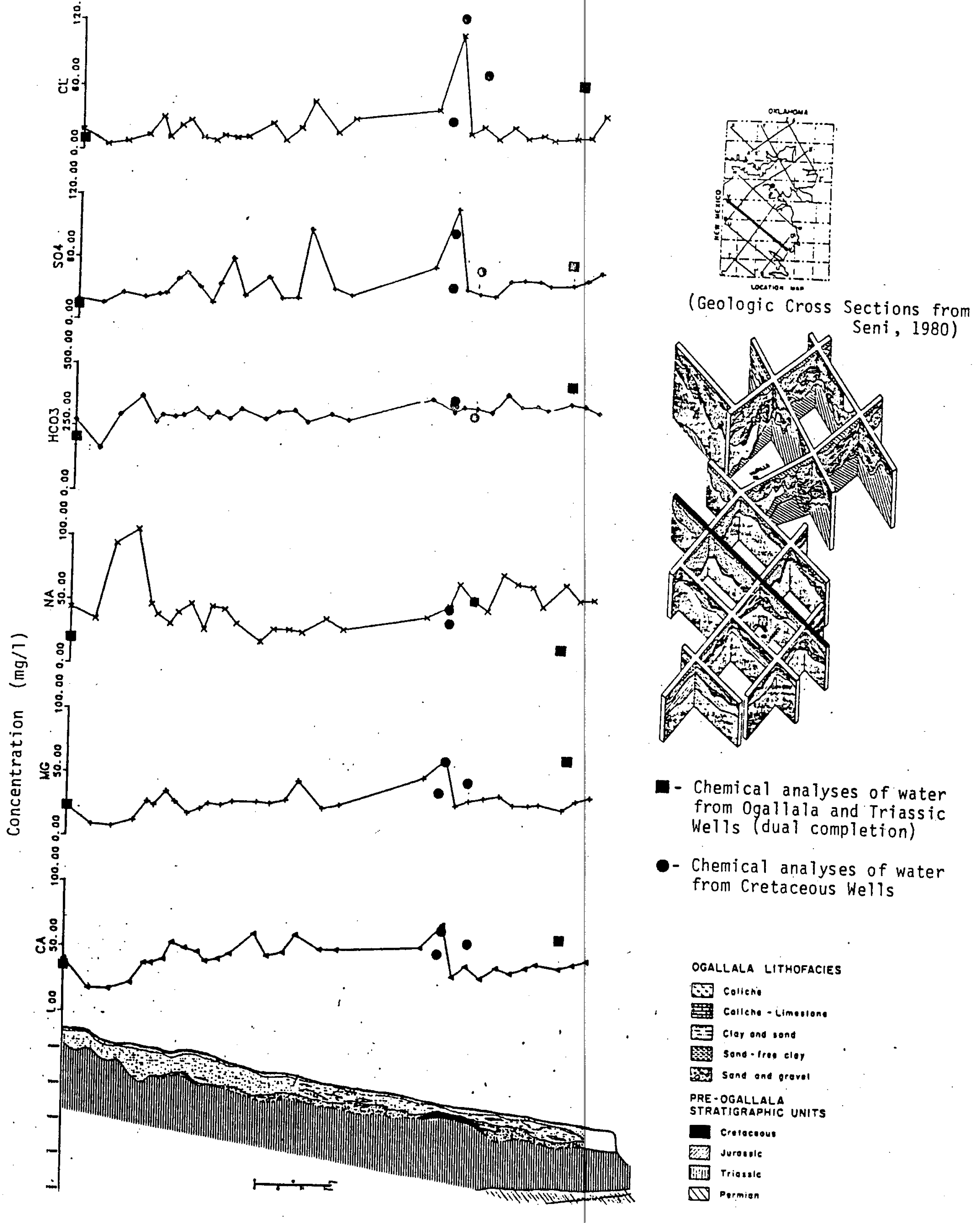
PRELIMINARY OBSERVATIONS RELATED TO A POSSIBLE NUCLEAR WASTE REPOSITORY AND THE OGALLALA AQUIFER

Several issues have been addressed in this study concerning the hypothetical scenario of an accidental nuclear waste spill in the surface or in the subsurface of the Texas Panhandle and its effect on the Ogallala aquifer. The issues include transport rates into ground water, ground-water flow directions, residence time of water in the aquifer, points



*(X10) - the actual concentration of brine was divided by 10 in order to include it on the same plot with the Ogallala wells

Figure 47. Salinity diagrams of contaminated Ogallala water and saline lake water.



(Geologic Cross Sections from Seni, 1980)

Figure 48. Salinity cross section of the Ogallala and underlying aquifers.

of discharge from the aquifer, and possibilities of cross-formational flows between the Ogallala and underlying aquifers.

Although this study is ongoing, some preliminary conclusions can be drawn:

(1) It appears that recharge rates in the northern High Plains are smaller than in the south, caused by different grain-size distribution in the soil cover. Also, large differences in the isotopic composition between rainwater and ground water in the north indicate that evaporation prior to downward percolation is greater in the north than in the south and, consequently, less recharge is estimated for the northern part of the Panhandle. Based on several cases where high concentrations of nitrates and arsenic were observed, it seems that in areas where water levels are high and the unsaturated zone is thin, chances for faster movement of contaminants to ground water are better. Areas of high water levels in the vicinity of Deaf Smith County exist in Randall County. Recharge rates based on tritium values were calculated for areas south of Deaf Smith County and range from 0.5 to 3.24 inches/yr (1.3 to 8.6 cm/yr), assuming all tritium contribution is derived from precipitation.

(2) Flow directions within the aquifer are mainly from northwest to southeast and follow preferential zones of increased permeability with similar directions. The rate of water movement in the aquifer is approximately 7 inches (18 cm) per day.

(3) Residence time of water in the aquifer is still being studied. It is likely that ground water flows faster along high permeability zones, such as the southeastern part of Deaf Smith County.

(4) Discharge locations were indicated on a spring location map (fig. 15). However, it is thought that owing to heavy pumpage in Castro, Swisher, Randall and other adjacent counties, most of the discharge water flowing below Deaf Smith County is in wells in the vicinity of the proposed site and not along the eastern escarpment.

(5) Cross-formational flow from underlying formations appears possible at various areas across the Panhandle. Although the Permian-Ogallala contact is of low permeability,

examples of chemical facies typical for water from the Permian were encountered in Ogallala water in Donley and Wheeler Counties. Also, $\delta^{34}S$ values of Ogallala water underlain by Permian rocks are relatively high and approach Permian water values, suggesting a possibility of diffusion from the Permian into the Ogallala.

Triassic water flows into the Ogallala along the eastern and western escarpment. In Deaf Smith County, upward flow was suggested along the escarpment, but also near Tierra Blanca Creek away from the escarpment. Because the Permian-Triassic contact in this area was indicated to be permeable, a detailed study of the vertical flow direction across this contact is required in order to estimate the possibility of water moving upward from the Permian into the Triassic and then into the Ogallala. Other locations where permeable contact is suggested for the Triassic and the Ogallala, and where downward flow is indicated by head differences, did not show chemical or isotopic similarities between waters.

Based on geologic, hydrologic, and geochemical considerations, flow from Cretaceous rocks into the Ogallala aquifer seems to be possible in large areas in the southern High Plains. Information about water heads in the Triassic in the area overlain by the Cretaceous is scarce, but indicates that water levels are lower than those of the Cretaceous. Therefore, it is unlikely that contamination of Ogallala water by Triassic or Permian water will occur in the south, because water heads of the Cretaceous are higher than those of the Ogallala or Triassic.

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The manuscript was word processed by Rosanne M. Wilson under the supervision of Lucille C. Harrell. The Ogallala base map used in this study was drafted by Dan F. Scranton under the supervision of Richard L. Dillon. Figures were drafted by Gay Gutierrez. Bernd C. Richter, Alan R. Dutton, and Charles W. Kreitler critically reviewed the manuscript, and in doing so greatly improved it. Technical editing was by Jules R. DuBar, and editing was by Mary Ellen Johansen.

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Appendix 1. Mean values ($\frac{mg/l}{meq}$) for chemical parameters of water in the major aquifers in the High Plains.

	Ogallala North	Ogallala South	Cretaceous	Triassic North	Triassic South	Permian (Quartermaster)	Permian (Whitehorse)	Permian (Blaine)
Ca^{+2}	$\frac{57}{2.84}$	$\frac{76}{3.79}$	$\frac{91}{4.54}$	$\frac{30}{1.49}$	$\frac{86}{4.29}$	$\frac{295}{14.7}$	$\frac{427}{21.11}$	$\frac{531}{25.49}$
Mg^{+2}	$\frac{30}{2.47}$	$\frac{60}{4.94}$	$\frac{33.5}{2.76}$	$\frac{16}{1.31}$	$\frac{44}{3.55}$	$\frac{145}{11.95}$	$\frac{101}{8.26}$	$\frac{140}{11.06}$
Na^{+}	$\frac{45}{1.96}$	$\frac{108}{4.70}$	$\frac{151}{6.58}$	$\frac{245}{10.64}$	$\frac{1174}{51.1}$	$\frac{423}{18.38}$	$\frac{210}{9.07}$	$\frac{292}{12.69}$
K^{+}	$\frac{8}{0.2}$	$\frac{13}{0.33}$	$\frac{8}{0.19}$	$\frac{2.3}{0.06}$	$\frac{0.8}{0.02}$	$\frac{10}{0.25}$	$\frac{4}{0.09}$	$\frac{4}{0.10}$
HCO_3^-	$\frac{278}{4.56}$	$\frac{275}{4.51}$	$\frac{292}{4.78}$	$\frac{387}{6.34}$	$\frac{443}{6.97}$	$\frac{279}{4.57}$	$\frac{142}{2.33}$	$\frac{22.5}{3.69}$
SO_4^{-2}	$\frac{66}{1.37}$	$\frac{196}{4.08}$	$\frac{185}{3.87}$	$\frac{161}{3.05}$	$\frac{1145}{23.81}$	$\frac{1509}{31.41}$	$\frac{1347}{28.04}$	$\frac{1716}{35.73}$
Cl^-	$\frac{43}{1.21}$	$\frac{160}{4.51}$	$\frac{170}{5.07}$	$\frac{128}{3.61}$	$\frac{988}{27.86}$	$\frac{310}{8.76}$	$\frac{300}{8.45}$	$\frac{392}{11.05}$
TDI	$\frac{429}{14.74}$	$\frac{800}{27.04}$	$\frac{830}{27.88}$	$\frac{961}{26.98}$	$\frac{3881}{117.9}$	$\frac{2857}{90.16}$	$\frac{2493}{77.65}$	$\frac{3197}{100.08}$
Ion ratios								
HCO_3^-/Cl^-	3.77	1.00	0.95	1.76	0.25	0.52	0.28	0.33
Na^+/Cl^-	1.62	1.04	1.30	2.95	1.83	2.10	1.07	1.15
SO_4^{-2}/Cl^-	1.13	0.9	0.76	0.84	0.85	3.59	3.32	3.23
Water type	Mixed-HCO_3	Mixed-Mixed	Mixed-Mixed	Na-Mixed	Na-Mixed	Mixed-SO_4	Ca-SO_4	Ca-SO_4
no. of analyses	2179	1383	87	73	81	22	109	26

Appendix 2. Analytical data for water samples from the High Plains aquifers 1984-1985[a].

BEG #	TDWR #	County	aquifer[b]	date	Na^+	K^+	Mg^{+2}	Ca^{+2}	Fe^{+2}	Sr^{+2}	Ba^{+2}	Cl^-	SO_4^{-2}	HCO_3^-	Br^-	NO_3^-	F^-	As^{+3}	pH	$\delta^{18}O$	δD	^3H	$\delta^{13}C$	$\delta^{34}S$
001	10-51-RN4b	Bailey	1	12-18-84	32.7	3.8	13.6	65.8		0.54	0.09	8.7	36	236	<0.24		0.46	<10		-6.8	-42	1.1	-6.4	
002	10-51-RN4a	Bailey	1	12-18-84	20.7	3.1	9.7	78.7		0.34	0.13	6.2	27.6	290	<0.24		0.31	<10		-6.0	-36	1.7	-7.1	
003	10-50-RN6a	Bailey	1	12-18-84	44.1	3.4	1.98	69.3		0.51	0.11	10.8	35.7	305	<0.24		0.41	<10		-6.4	-39	2.3	-6.4	
004	10-50-RN8a	Bailey	1	12-18-84	12.7	6.0	22.4	37.9		0.89	0.14	6.0	23.4	232	<0.24		1.5	<10		-6.1	-37	1.3	-4.0	
005	10-50-RN4a	Bailey	1	12-18-84	32.3	2.3	8.7	75.6		0.47	0.05	15.1	48.6	279	0.29		0.39	<10		-6.4	-39	0.6	-4.6	
006	10-49-RN6a	Bailey	1	12-18-84	54.1	5.4	23.4	41.5		0.80	0.04	11.0	97.8	280	0.35		1.8	<10		-6.6	-39	0.7	-2.9	
007	10-50-RN8b	Bailey	1	12-18-84	11.3	7.4	25.6	39.1		0.91	0.16	9.1	24.6	232	0.28		1.8	<6		-6.2	-40	0.5	-4.3	
008	10-57-302	Bailey	1	12-18-84	76.1	7.4	39.9	67.9		0.90	0.05	48.7	221.0	250	0.44		0.94	<10		-6.5	-40	0.7	-4.2	
009	24-14-RN6a	Hockley	1	12-20-84	239.0	25.3	160.0	89.9		7.96	0.05	332.0	600.0	341	2.31		4.4	10		-6.7	-39	8.9	-1.9	
011	24-14-RN6b	Hockley	1	12-20-84	93.0	12.0	63.0	39.9		3.19	0.08	128.0	95.4	331	0.79		4.7	13		-5.2	-36	6.0	-1.5	
012	24-14-RN6c	Hockley	10	12-21-84	475.0	31.3	597.0	498.0		31.8	2.93	3110	53.0	321	8.69		3.1	12		-5.4	-32	8.0	-5.8	
013	24-14-RN6d	Hockley	4	12-21-84	30900	792	1100	4500		106	<0.26	57300	2390	694	155		2.5	<10		-6.8	-43	0.0	+3.5	
014	24-14-RN6e	Hockley	2	12-21-84	13800	47.1	1940	4060		229	<0.26	33600	1114	232	91.3		0.46	<10		-6.8	-42	0.0	-8.9	
015	23-33-RN3a	Lubbock	1	12-22-84	26.8	10.2	62.1	43.4		2.63	0.14	7.8	35.4	447	0.23		4.20	<10		-5.0	-35	33.8		
016	23-33-RN3b	Lubbock	11	12-22-84	4.2	6.9	7.7	52.9		0.42	0.18	5.5	3.6	200	<0.24		0.58	12		-4.7	-30	8.1		
017	24-14-RN6f	Hockley	1	8-16-84																-5.8	-42	0.8		
018	24-14-RN6f	Hockley	1	8-20-84																-5.5	-38	4.7		
019	24-14-RN6b	Hockley	1	8-16-84																-4.9	-29	6.0		
020	24-14-RN6e	Hockley	2	8-17-84																-6.1	-46	1.5		
021	24-14-RN6a	Hockley	1	8-17-84																-5.2	-33	2.4		
022	24-14-RN6a	Hockley	1	8-17-84																-5.6	-37	2.8		
023	24-14-RN6b	Hockely	1	8-20-84																-5.3	-31	1.1		
024	24-14-RN6c	Hockley	10	12-6-84	335	27.6	490	393		27.5	3.16	2250	42.6	339	<0.24		3.2	12		-5.0	-32	5.3		
025	23-25-RN3a	Lubbock	1	1-9-85	220.0	18.0	120.0	94.0	0.5	6.6	0.05	280.0	510.0	380.0	2.1	<0.3	4.6	12		-5.7	-39	27.0		
026	23-25-RN3b	Lubbock	1	1-15-85	130.0	18.0	110.0	91.0	0.3	6.4	0.06	260.0	260.0	410.0	1.3	<0.3	4.1	<10		-4.5	-29	11.3		
027	23-25-RN3c	Lubbock	1	1-16-85	190.0	19.0	140.0	120.0	0.6	6.9	0.06	355.0	530.0	340.0	1.7	<0.3	4.5	<10		-4.5	-36	12.2		
028	23-25-Rn3d	Lubbock	1	1-15-85	90.0	14.0	66.0	55.0	0.3	3.4	0.07	110.0	145.0	360.0	0.9	<0.3	3.7	11		-5.0	-35	23.7		
029	23-25-RN3e	Lubbock	1	1-9-85	265.0	24.0	210.0	190.0	0.2	9.6	0.05	440.0	980.0	340.0	2.9	<0.3	3.6	<10		-5.0	-38	8.9		
030	45-05-514	Ector	1	2-19-85	27	3.0	8.1	84.0	0.50	0.6	0.02	24.0	45.0	230	<0.4	15.0	1.5	<10	8.1	-6.6	-36	0.9	-8.5	+3.6
031	28-53-103	Howard	2	2-19-85	134	4.0	19.0	194.0	0.05	1.4	0.10	260.0	185.0	280	0.9	16.0	0.5	<10	8.2	-5.2	-30	24.6	-10.8	+4.9
032	28-53-712	Howard	2	2-19-85	173	6.9	18.0	277.0	0.10	0.9	0.03	260.0	400.0	410	0.7	9.5	0.2	<10	7.9	-5.4	-31	14.2	-7.2	+6.9
033	28-62-104	Howard	2	2-19-85	61	3.0	11.0	105.0	0.30	0.8	0.10	120.0	48.0	230	0.5	11.0	1.0	<10	8.3	-6.2	-34	1.1	-7.3	+8.5
034	27-37-RN4a	Andrews	1	2-19-85	223	20.0	105.0	108.0	<0.01	6.6	0.02	340.0	480.0	290	2.5	7.7	4.6	32	8.2	-7.7	-42	0.3	-8.7	+6.6
035	28-50-601	Martin	7	2-19-85	515	14.0	148.0	376.0	<0.01	7.7	0.02	980.0	1040.0	220	6.5	13.0	3.0	<10	7.9	-5.6	-43	2.8	-8.8	+7.5
036	27-37-RN2a	Andrews	1	2-20-85	103	8.4	72.0	55.0	<0.01	3.5	0.04	130.0	230.0	280	0.9	5.7	4.8	35	8.1	-6.1	-48	0.7	-7.3	-0.7
037	27-19-117	Gaines	1	2-20-85	63	5.0	45.0	55.0	<0.01	1.5	0.08	81.0	100.0	260	0.7	9.8	4.2	16	8.2	-6.2	-47	1.7	-6.6	+6.7
038	27-19-117	Gaines	7	2-20-85	80	4.6	38.0	55.0	0.80	1.1	0.07	76.0	99.0	280	0.6	11.5	5.1	15	8.2	-6.2	-45	1.4	-7.6	+6.5
039	28-03-901	Borden	2	2-21-85	298	5.6	63.0	185.0	0.04	3.3	0.07	400.0	440.0	280	1.7	78.0	2.8	<10	8.2	-4.9	-40	20.1	-9 4	+7.6
040	28-02-205	Lynn	7	2-20-85	235	30.0	119.0	184.0	7.10	5.7	0.04	360.0	490.0	460	3.2	75.0	4.2	12	8.1	-4.2	-35	55.4	-7.4	+6.0
041	24-54-605	Terry	1	2-22-85	124	13.0	74.0	82.0	0.10	2.9	0.07	220.0	220.0	260	0.7	8.1	3.3	<10	8.3	-4.9	-39	17.7	-6.5	+2.7
042	24-61-RN5d	Terry	2	2-21-85	153	17.0	80.0	63.0	0.20	4.6	0.05	150.0	320.0	300	1.1	22.0	5.6	33	8.2	-6.7	-36	68.2	-6.9	+6.1

[a] All ions except As and Ph are in mg/l. As is in microgram/l. $\delta^{18}O$, δD, $\delta^{13}C$, and $\delta^{34}S$ are in °/₀₀. ^3H is in tritium units.

[b] Aquifer codes: 1) Ogallala 2) Cretaceous 3) Triassic 4) Permian 5) Ogallala + Cretaceous 6) Ogallala + Triassic 7) Ogallala on Cretaceous contact
8) Ogallala on Triassic contact 9) Ogallala on Permian contact 10) Ogallala, possibly contaminated 11) Playa water

Appendix 2. (cont.)

BEG #	TDWR #	County	aquifer^b	date	Na$^+$	K$^+$	Mg^{+2}	Ca^{+2}	Fe^{+2}	Sr^{+2}	Ba^{+2}	Cl$^-$	SO$_4^{-2}$	HCO$_3^-$	Br$^-$	NO$_3^-$	F$^-$	As^{+3}	pH	$\delta^{18}O$	δD	^3H	$\delta^{13}C$	$\delta^{34}S$
043	24-18-303	Cochran	1	2-21-85	173	16.0	93.0	85.0	<0.01	3.3	0.02	210.0	445.0	230	1.5	14.8	3.8	<10	7.9	-7.0	-40	0.0	-10.9	+4.0
044	23-17-RN4a	Lubbock	1	2-18-85	118	28.0	63.0	54.0	<0.01	2.6	0.03	84.0	200.0	390	0.5	17.0	4.8	<10	8.3	-6.2	-39	73.0	-6.9	-1.7
045	23-35-101	Lubbock	10	2-20-85	790	26.0	340.0	380.0	0.70	150.0	0.10	2560.0	200.0	240	13.0	44.0	4.4	17	8.0	-5.3	-43	14.2	-6.3	+6.6
046	23-18-RN7a	Lubbock	10	2-21-85	123	18.0	77.0	94.0	0.20	3.0	0.02	140.0	320.0	330	0.6	18.0	2.8	10	8.2	-6.2	-46	24.3	-5.5	-5.9
047	23-17-RN2a	Lubbock	1	2-21-85	73	15.0	73.0	96.0	0.20	2.7	0.04	200.0	165.0	260	1.1	28.0	1.8	<10	8.0	-7.4	-55	9.5	-5.9	+1.2
048	23-16-503	Crosby	6	2-20-85	42	10.0	39.0	50.0	<0.01	1.4	0.11	29.0	31.0	350	<0.4	3.2	2.0	<10	8.3	-6.9	-51	1.4	-7.5	-1.8
049	22-28-RN1a	Crosby	4	2-21-85	16	2.5	63.0	635.0	0.80	4.2	<0.01	12.7	1620.0	180	<0.4	3.4	0.5	<10	7.9	-6.3	-33	32.0	-10.7	+10.0
050	11-26-RN9a	Swisher	1	2-21-85	234	4.0	3.3	8.2	0.10	0.2	0.02	44.0	105.0	430	<0.4	13.0	2.8	15	8.6	-5.5	-42	27.5	-7.8	-3.9
051	11-26-RN9b	Swisher	3	2-21-85	420	2.6	1.5	4.1	0.30	0.1	0.02	110.0	270.0	590	<0.4	<0.5	2.5	<10	8.6	-8.6	-64	0.2	-8.7	-5.0
052	10-30-RN5a	Castro	1	2-21-85	64	7.4	28.0	38.0	0.20	0.9	0.06	21.0	45.0	320	<0.4	0.9	2.7	<10	8.1	-7.6	-53	0.2	-8.3	-2.1
053	11-13-604	Deaf Smith	1	2-21-85	70	8.6	58.0	50.0	0.10	1.4	0.60	29.0	160.0	350	<0.4	3.0	3.3	<10	8.2	-7.3	-56	0.8	-6.3	-12.7
054	11-15-804	Deaf Smith	6	2-23-85	467	2.8	6.1	12.0	0.80	0.6	0.02	230.0	330.0	450	1.4	<0.5	3.0	<10	8.7	-8.7	-65	0.8	-7.9	+7.6
055	11-01-RN4a	Randall	1	2-18-85	158	2.9	4.3	7.2	0.60	0.3	0.10	23.0	33.0	350	<0.4	<0.5	2.5	<10	8.7	-9.1	-65	0.1	-9.7	+1.7
056	06-57-905	Randall	4	2-18-85	82	5.7	24.0	27.0	0.10	0.9	0.08	11.0	23.0	330	<0.4	4.0	3.6	<10	8.7	-9.1	-63	0.8	-8.5	-1.4
057	06-58-402	Randall	4	2-18-85	35	6.1	33.0	36.0	0.10	1.3	0.09	17.0	45.0	280	<0.4	2.8	2.9	<10	8.5	-8.9	-60	1.0	-6.9	+2.8
058	12-12-405	Donley	9	2-18-85	18	2.0	7.3	81.0	<0.01	0.3	1.80	21.0	12.0	250	<0.4	11.0	0.4	<10	8.4	-6.4	-39	2.0	-6.1	+6.3
059	07-44-RN8a	Oldham	8	2-20-85	32	5.8	32.0	36.0	<0.01	1.1	0.12	12.8	51.0	250	<0.4	1.5	1.7	<10	8.6	-7.1	-50	0.5	-5.6	-0.7
060	06-42-601	Potter	4	2-21-85	1280	7.2	85.0	210.0	<0.01	5.0	0.01	1000.0	2230.0	120	1.4	2.0	0.5	13	8.2	-8.5	-62	1.4	-18.3	+9.0
061	06-41-203	Potter	4	2-20-85	1560	8.1	122.0	280.0	<0.01	7.2	<0.01	1200.0	3300.0	95	1.3	<0.4	0.5	16	8.0	-8.5	-60	0.1	-14.3	+9.2
062	06-44-207	Carson	8	2-20-85	26	6.2	25.0	42.0	0.03	0.9	0.18	16.0	17.0	250	<0.4	5.2	1.5	<10	8.2	-7.3	-54	0.7	-6.6	+3.4
063	05-25-RN8a	Gray	1	2-19-85	110	5.8	21.0	70.0	1.20	0.8	0.08	64.0	110.0	270	<0.4	6.0	0.9	<10	8.5	-8.3	-53	1.1	-7.8	+8.6
064	05-39-RN7a	Wheeler	1	2-19-85	17	1.3	7.7	120.0	<0.01	0.3	1.50	120.0	8.2	180	<0.4	20.0	0.2	<10	8.4	-6.7	-41	55.0	-7.0	+5.4
065	05-52-303	Wheeler	9	2-18-85	23	2.3	7.2	86.0	<0.01	0.2	0.53	4.1	9.3	290	<0.4	17.0	0.3	<10	8.6	-6.4	-46	16.5	-8.2	+6.0
066	05-05-RN9a	Hemphill	1	2-19-85	79	4.3	24.0	65.0	1.30	1.0	0.41	104.0	32.0	290	<0.4	<0.5	1.3	<10	8.1	-6.7	-49	0.0	-7.2	+9.5
068	28-43-RN4a	Martin	10	3-5-85	303.0	40.8	178.0	68.2	0.17	20.9	0.15	434.0	472.0	427	3.4	47.0	6.1	100	7.8	-5.7	-34	31.2	-8.1	+8.3
069	23-43-RN4a	Lynn	1	3-6-85	62.0	9.3	51.6	56.0	<0.02	2.1	0.10	22.6	65.9	396	<0.3	19.0	4.5	<10	8.0	-4.6	-27	35.8	-12.5	+5.3
070	23-28-701	Lubbock	7	3-6-85	31.7	7.4	38.1	47.0	0.27	1.2	0.14	6.0	24.6	288	<0.3	27.0	3.6	<10	8.0	-5.9	-36	31.7	-8.5	+7.1
071	10-51-RN1a	Bailey	1	3-7-85	50.2	3.8	12.2	86.0	0.22	0.4	0.07	15.0	52.2	314	<0.3	3.5	0.5	<10	8.0	-7.1	-44	2.5	-12.5	
072	24-06-501	Lamb	1	3-7-85	75.8	14.4	47.3	80.6	0.17	1.8	0.07	34.6	110.0	351	0.6	9.8	1.5	<10	8.0	-6.8	-43	7.1	-9.3	-2.8
073	23-09-202	Hale	2	3-6-85	69.5	13.6	48.3	64.8	0.14	1.7	0.08	52.4	81.0	326	0.3	15.0	3.1	<10	8.0	-7.2	-45	5.9	-7.5	
074	23-10-110	Hale	2	3-6-85	50.6	12.5	60.7	86.8	0.02	2.1	0.16	88.0	44.0	295	0.6	18.0	1.6	<10	8.0	-6.4	-39	9.2	-8.0	+5.0
075	23-11-RN2a	Hale	1	3-6-85	57.2	9.2	35.7	45.4	<0.02	1.1	0.11	11.5	27.1	357	<0.3	3.8	2.1	<10	8.0	-7.1	-44	4.2	-7.2	+2.3
076	11-54-803	Floyd	2	3-7-85	49.8	7.6	43.0	46.9	0.79	1.2	0.11	21.9	32.4	357	<0.3	3.5	2.1	<10	7.8	-6.1	-38	5.3	-6.7	
077	11-54-804	Floyd	7	3-7-85	41.9	7.9	47.2	46.2	<0.02	1.3	0.10	26.4	31.1	344	<0.3	3.8	2.5	<10	7.9	-7.6	-47	0.7	-7.8	
078	23-07-502	Floyd	7	3-7-85	44.1	8.3	39.0	46.1	0.02	1.1	0.09	12.9	29.2	323	<0.3	2.4	2.6	<10	7.9	-7.5	-45	0.1	-8.0	+1.4
079	11-38-224	Briscoe	1	3-8-85	32.5	6.7	38.1	53.5	7.81	1.1	0.17	5.3	16.1	335	<0.3	2.2	2.8	<10	8.0	-5.7	-35	1.6	-9.9	
080	11-29-901	Briscoe	8	3-8-85	84.6	5.7	33.4	44.2	3.79	2.0	0.07	40.6	52.7	248	0.4	4.5	2.7	17	8.0	-7.4	-46	1.6	-4.7	-0.2
081	06-62-103	Armstrong	1	3-8-85	27.7	6.3	39.1	53.0	0.02	1.3	0.09	11.2	34.1	303	<0.3	5.3	1.7	11	7.9	-6.0	-37	6.9	-9.2	

[a] All ions except As and Ph are in mg/l. As is in microgram/l. $\delta^{18}O$, δD, $\delta^{13}C$, and $\delta^{34}S$ are in °/₀₀. ^3H is in tritium units.

[b] Aquifer codes: 1) Ogallala 2) Cretaceous 3) Triassic 4) Permian 5) Ogallala + Cretaceous 6) Ogallala + Triassic 7) Ogallala on Cretaceous contact 8) Ogallala on Triassic contact 9) Ogallala on Permian contact 10) Ogallala, possibly contaminated 11) Playa water

Appendix 3. Tritium values in precipitation and calculated residual tritium in ground water.

Year	weighted annual mean at Waco, TX	weighted annual mean at Albuquerque, NM	mean calculated from both stations for the High Plains	no. of years elapsed till 1985	percent of residual tritium	calculated residual tritium (TU)
1961	400	/	400	24	26	100
1962	421	/	421	23	28	118
1963	1129	1529	1329	22	29	385
1964	372	1688	844	21	31	262
1965	205	481	343	20	33	113
1966	152	282	217	19	35	76
1967	78	240	159	18	36	57
1968	73	188	131	17	39	51
1969	72	196	134	16	40	53.6
1970	61	200	130	15	42	55
1971	44	203	123	14	45	55

It is possible to attribute the high values of tritium in Ogallala water in the southern Panhandle to the thinness of the unsaturated zone, which results in a shorter leakage path into the aquifer. The feasibility of the assumption can be checked by comparing current tritium in Ogallala ground water to tritium values in precipitation during the last 30 years. However, back records of tritium need to be corrected for radioactive decay. Records from Waco, Texas, and Albuquerque, New Mexico, were used for this purpose. According to the table above, which corrects tritium in precipitation for their radioactive decay, it seems that rainfall of 1966 or 1967 (18.5 yr in equation below), when corrected, provides similar tritium values as those currently observed in Ogallala water in the southern High Plains. By assuming a thin unsaturated section of 25 ft (7 m) and soil moisture content of 10 percent in this zone, the calculated annual recharge flux is 1.62 inches/yr (4.1 cm/yr):

$$\frac{25' \times 0.1}{18.5y} = 0.13'/y = 1.62''/y$$

dry or wet conditions are assumed for the unsaturated zone (3 percent of moisture content or 20 percent, respectively), the annual recharge ranges from 0.5 inches to 3.24 inches/yr (1.3 to 8 cm/yr). These values are in the range of annual recharge mentioned in this study. It appears, therefore, that shorter leakage paths at the southern Panhandle permit fast recharge flux, which is reflected by high tritium values.

Appendix 4. Mean values (mg/l) for chemical parameters of brines in various formations in the High Plains.

	Ellenburger	Fusselman	Devonian	Pennsylvanian	Morrow (Penn)	Strawn	Canyon	Cisco	Wolfcamp	Clear Fork	Glorieta	Spraberry	San Andres	Grayburg	Queen
Ca^{+2}	217	462	156	356	30	669	163	437	323	526	318	202	253	239	312
Mg^{+2}	81	218	59	117	11	187	74	78	128	274	163	70	208	102	382
Na^+	1135	1127	759	1986	245	1947	1346	2265	1861	1599	1786	2062	1432	1522	1979
HCO_3^-	10	7	10	3	7	9	4	13	11	7	10	4	12	9	3
$SO_4^{=}$	33	13	36	15	4	16	23	13	30	35	52	9	55	57	39
Cl^-	1453	1674	958	2500	256	2785	1559	2432	2290	2480	2212	2462	1824	1760	3010
TDI	2503	3075	1891	4898	553	5354	3169	3977	4297	4722	4460	4507	3584	3439	5726
Mean ion ratios															
HCO_3^-/Cl^-	0.01	0.003	0.017	0.002	1.1	0.01	0.003	0.03	0.006	0.009	0.010	0.003	0.020	0.08	0.001
Na^+/Cl^-	0.85	0.793	0.85	0.804	1.25	0.098	0.868	0.938	0.824	0.752	0.875	0.896	0.845	0.870	0.710
$Ca^{+2}/(SO_4^{-2} + HCO_3^-)$	11.0	48.1	24.58	30.8	3.16	75.3	9.86	35.22	15.65	18.35	13.47	35.00	9.32	4.87	10.36
SO_4^{-2}/Cl^-	0.04	0.10	0.06	0.007	0.111	0.016	0.020	0.006	0.055	0.043	0.066	0.006	0.008	0.045	0.016
No. of analyses	22	8	53	25	24	15	13	4	39	65	23	22	103	19	12