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Hydrogeochemistry and Water Resources of the Triassic Lower Dockum Group in the Texas Panhandle and Eastern New Mexico

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and
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CONTENTS

ABSTRACT 1
INTRODUCTION 3
HYDROGEOLOGIC SETTING 3
DATA AND METHODS 10
RESULTS 11
Potentiometric surface 11
Hydrogeochemistry 13
Water resources 21
DISCUSSION 24
Origin of ground water in the Lower Dockum Group 24
Mineralogic controls on chemical composition 26
CONCLUSIONS 32
ACKNOWLEDGMENTS 33
REFERENCES 33
APPENDIX A. Estimated hydraulic properties of the Dockum Group, Texas Panhandle 37
APPENDIX B. Chemical composition of Dockum Group ground water 46

Figures

1. Geologic map of the study area 2
2a. Isopach map of the Lower Dockum Group 4
2b. Isopach map of the Upper Dockum Group 5
3. North-south stratigraphic cross section through the Texas Panhandle showing hydraulic-head profiles of aquifers in the Ogallala Formation, Edwards/Trinity Groups, and Dockum Group 6
4a. Regional map of percent sandstone in the Lower Dockum Group 8
4b. Regional map of percent sandstone in the Upper Dockum Group 9
5. Potentiometric surface map of Lower Dockum Group ground water 12
6. Plot of δD and $\delta^{18}O$ values of Dockum Group ground water along the meteoric water line 14
7. Map of δD values of Lower Dockum Group ground water 15
8. North-south stratigraphic cross section showing inferred profile of $\delta^{18}O$ values of ground water in the Ogallala Formation and Dockum Group 16
9. Piper diagrams of hydrochemical facies 18
10a. Hydrochemical facies of Lower Dockum Group ground water 19
10b. Total dissolved solids in Lower Dockum Group ground water 20
11. Relation between $\delta^{34}S$ and sulfate concentration 21
12. Dockum water wells drilled in the Texas Panhandle, 1950–1978 21
13. Mean value of sodium adsorption ratio by county 23
14. Hypothetical regional flow paths of ground water in the Ogallala Formation and Dockum Group before and after development of the Pecos River valley 27

LES-005015

15. Diagram showing chemical composition of Lower Dockum Group ground water relative to stability fields of minerals in the $NaO-SiO_2-H_2O$ system 28
16. Diagram showing chemical composition of Lower Dockum Group ground water relative to stability fields of minerals in the $NaO-CaO-SiO_2-H_2O-CO_2$ system 28
17. Diagram showing chemical composition of Lower Dockum Group ground water relative to stability fields of minerals in the $MgO-CaO-SiO_2-H_2O-CO_2$ system 29
18. Plot of saturation indices relative to halite and gypsum 29
19. Plot of sodium and chloride concentrations in Lower Dockum Group ground water 30

Tables

1. Mineral reactions and equilibrium reaction constants 11
2. Chemical and isotopic composition of Lower Dockum Group ground water 14
3. Municipal water-supply use of Dockum Group ground water 22
4. Estimation of carbon-14 age of water from the SWEC Mansfield No. 2 well 25

Appendix Figures

A1. Data from pumping test at the City of Hereford No. 18 well 38
A2. Data from pumping test at the City of Tulia No. 13 well 41
A3. Average transmissivity of Lower Dockum Group sandstones by county 45

Appendix Tables

A1. Transmissivity estimates from specific capacity tests 42
A2. Comparison of transmissivity estimates from pumping and specific capacity tests 44

LES-005016

ABSTRACT

Topographically controlled ground-water-basin divides, established during the Pleistocene by erosion of the Pecos and Canadian River valleys, prevent ground-water recharge in the outcrop of the Triassic Dockum Group from entering the confined part of the aquifer in the Dockum Group beneath the Southern High Plains in the Texas Panhandle and eastern New Mexico. Ground water in the confined aquifer was probably recharged from precipitation at higher elevations in eastern New Mexico before thick deposits of Dockum Group sandstones were eroded. The confined aquifer in the Lower Dockum Group is separated from the overlying, heavily pumped High Plains aquifer in the Neogene Ogallala Formation and Cretaceous Edwards/Trinity Groups by thick mudstones in the Upper Dockum Group. Hydrologic separation beneath most of the Southern High Plains is indicated by (1) hydraulic heads of Lower Dockum Group ground water that are 300 to 700 ft (90 to 200 m) lower than the water table of the High Plains aquifer, (2) $\delta^{18}O$ and δD values of Lower Dockum Group ground water that are 2 to 3 ‰ and 15 to 25 ‰ lighter, respectively, than ground water in the Ogallala Formation, and (3) different associations of hydrochemical facies in the two aquifer systems. The significant differences in hydraulic head between the two aquifer systems reflect the Pleistocene cutoff of recharge and the continuation of discharge during the Holocene, which have caused a decrease in ground-water storage. The $\delta^{18}O$ and δD values suggest that Dockum Group ground water was recharged in a cool climate at elevations above approximately 5,900 ft (1,800 m) in eastern New Mexico.

Chemical composition of Dockum Group ground water is controlled by reactions with Dockum Group minerals, including calcite, chalcedony, dolomite, feldspar, kaolinite, opal, pyrite, and smectite. Accounting for salinity greater than 20,000 mg/L in Na-Cl facies are (1) discharge of ground water that dissolved halite in underlying Permian strata or (2) Cretaceous seawater that was incompletely flushed from low-permeability mudstones in the Dockum Group. Spatially variable water quality occurs in unconfined parts of the Dockum Group where ground water from adjacent formations mixes with Dockum Group ground water.

Ground water in the Lower Dockum Group beneath the Southern High Plains in the Texas Panhandle and eastern New Mexico has not proved to be a substitute for Ogallala Formation ground water everywhere. Development of Dockum Group water resources for irrigation and municipal supply will continue to be limited to areas having thick sandstone deposits, moderate head lift of less than 500 ft (150 m), and fresh to slightly brackish salinity as great as 3,000 mg/L. Production of Dockum Group ground water beneath the Southern High Plains will deplete stored water because the recharge rate to the confined Dockum Group is negligible.

Keywords: hydrogeology, hydrogeochemistry, water resources, chemical composition, isotopic composition, specific capacity tests, Dockum Group, Southern High Plains, Texas Panhandle, eastern New Mexico

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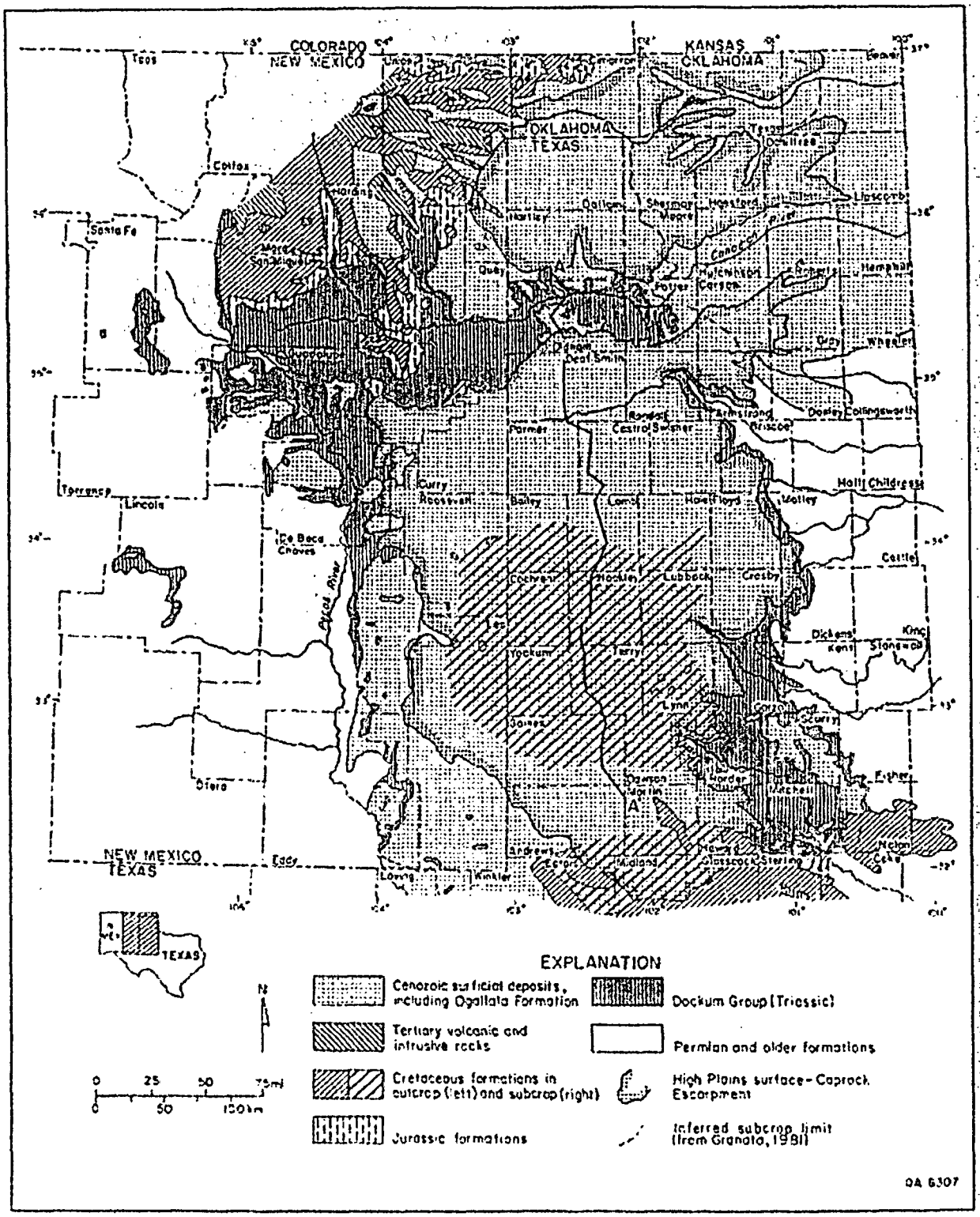

FIGURE 1. Geologic map of the study area, including surficial geology and subcrops of the Edwards/Trinity Groups (modified from American Association of Petroleum Geologists, 1967, 1973).

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INTRODUCTION

This report documents how aquifer lithology, regional ground-water flow patterns, and chemical reactions between ground water and minerals control the quality and location of ground-water resources in the Lower Dockum Group of Triassic age in the Texas Panhandle and eastern New Mexico (fig. 1). Research presented in this paper was part of a program designed to characterize possible sites for a high-level radioactive waste repository in Permian salt deposits in the Texas Panhandle (U.S. Department of Energy, 1984a, 1984b). The aquifer system in the Dockum Group overlies Permian mudstones and evaporites that act as a confining system (Bassett and Bentley, 1982; Kreitler and others, 1985). Dockum Group ground water beneath the Southern High Plains underlies the High Plains aquifer, which is composed of terrigenous sands and gravels of the Neogene Ogallala Formation and marine sandstones and limestones of the Cretaceous Edwards/Trinity Groups (Knowles and others, 1984). Extensive pumping of ground water for irrigation and municipal supply has markedly lowered water levels in the unconfined High Plains aquifer (Knowles and others, 1984). Dockum Group ground water is used locally in place of Ogallala Formation water for irrigation and is mixed with Ogallala Formation water for municipal supply. Where the Dockum Group crops out, it is the primary source of ground water for irrigation, stock, and domestic use.

The hydrogeochemistry and water resources of the Dockum Group were studied throughout the Texas Panhandle and eastern New Mexico to define regional controls on ground-water salinity, hydraulic head, and regional ground-water flow paths. Hydrogeologic studies of the Dockum Group specific to a possible repository site in the Texas Panhandle can be developed from this regional characterization. To determine sources of water and regional ground-water flow paths through the Dockum Group, we studied its potentiometric surface, hydrochemical facies, and stable isotope composition. We reviewed ground-water use, specific capacity tests, and water well records to better predict future use of Dockum Group ground water. We agree with Raynor (1973) and Blair (1976), who concluded that Dockum Group ground water generally will not replace Ogallala Formation ground water as a resource because of a salinity hazard and the high cost of production where the Dockum Group is overlain by the High Plains aquifer. In this paper we discuss hydrogeologic explanations of the salinity distribution and the relation of salinity to well yield.

Data on the hydrogeology of the Lower Dockum Group are sparse for large areas beneath the Southern High Plains, where well depth, well yield, and water salinity limit potable water resources. Our study is limited to the Lower Dockum Group because hydrogeologic data from the Upper Dockum Group are absent in most of the Texas Panhandle. The somewhat more abundant data from the Upper Dockum Group in outcrops in New Mexico are excluded from this report.

HYDROGEOLOGIC SETTING

The Dockum Group, which is less than 100 ft (30 m) to more than 2,000 ft (610 m) thick (figs. 2a and 2b), accumulated during the Triassic Period (230 to 208 m.y. B.P.) in a closed continental basin in fluvial, deltaic, and lacustrine environments (McGowen and others, 1977, 1979). Clastic Dockum deposits overlie shelf deposits of Permian halite, anhydrite, dolomite, mudstone, and sandstone. McGowen and others (1977, 1979) informally divided the Dockum Group into lower and upper sections, called Lower Dockum and Upper Dockum in this report (fig. 3). The Lower Dockum Group is composed of fine- to coarse-grained quartzose sandstone and granule to pebble conglomerate, which were deposited in braided and meandering streams, in alluvial fans and fan deltas, and in high-constructive lobate deltas. Thick, coarse-grained sandstones are concentrated in the northern, east-central, southern, and west-central parts of the Lower Dockum Group (fig. 4a). Mudstone deposited in lacustrine and prodelta environments is common at the base of progradational sequences (McGowen and others, 1979). On a regional scale, sandstone facies show little lateral continuity (McGowen and others, 1977, p. 12).

In the mud-rich Upper Dockum Group, thickest sandstone deposits are in southeastern New Mexico and the south-central part of the Texas Panhandle (fig. 4b). Thick packages of sandstone are not extensive elsewhere in the Upper Dockum because fluvial-deltaic systems were generally small (McGowen and others, 1979). Sandstone beds in the Upper Dockum Group are discontinuous throughout the Texas Panhandle and eastern New Mexico.

South of the Canadian River, Cretaceous, Tertiary, and Quaternary deposits overlie the Dockum Group (figs. 1 and 3). Jurassic deposits are limited to the

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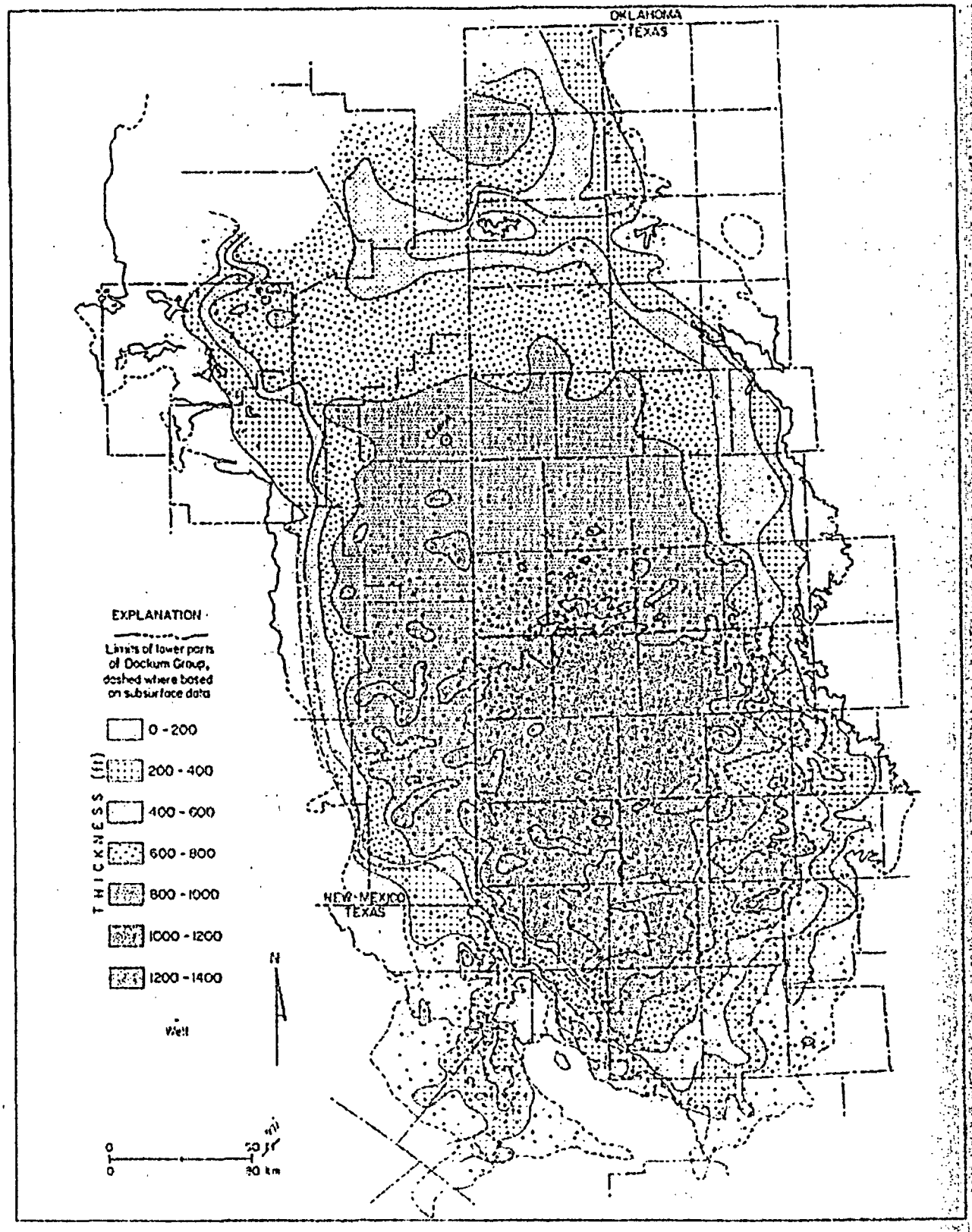

FIGURE 2a. Isopach map of the Lower Dockum Group (McGowen and others, 1977).

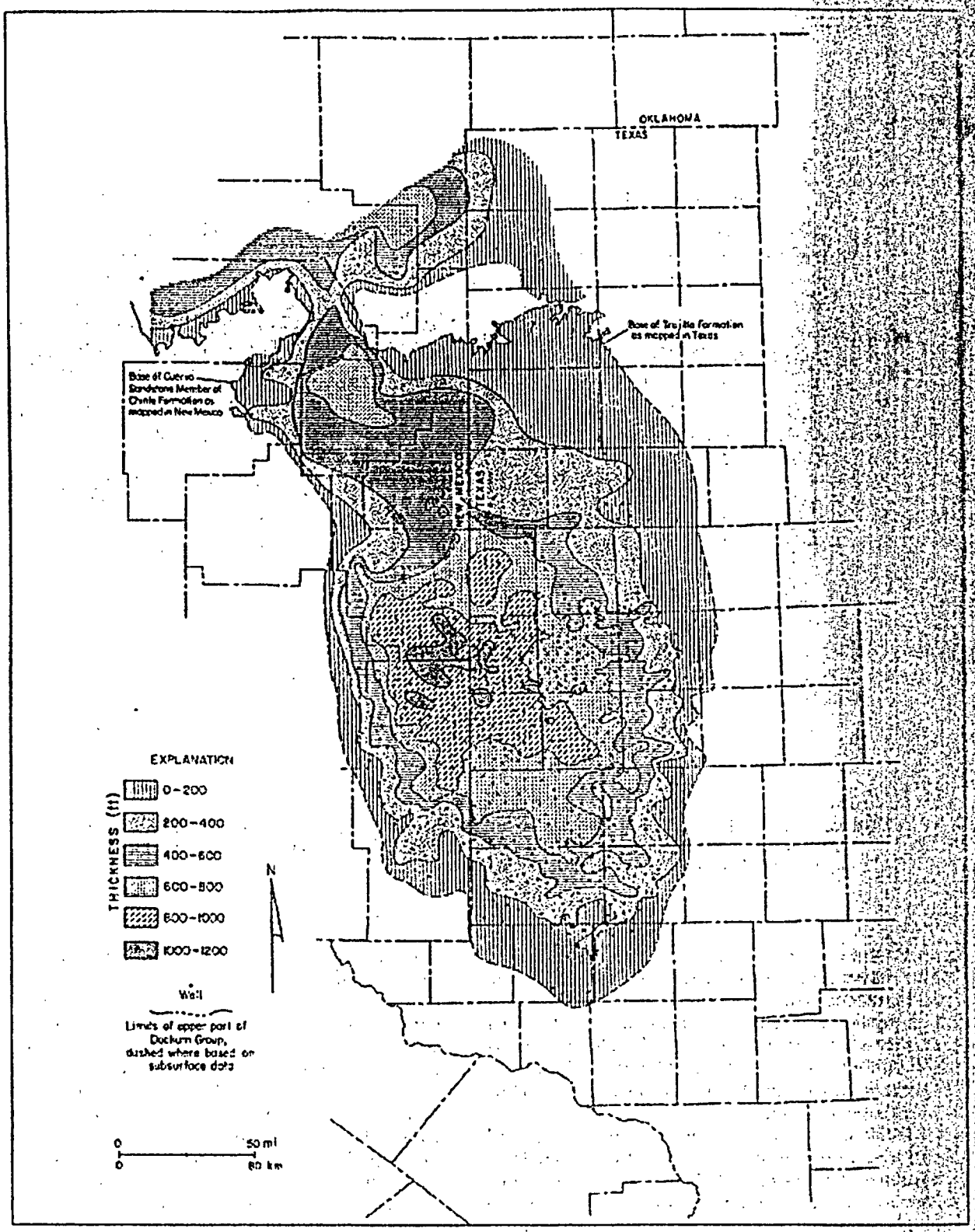

FIGURE 2b. Isopach map of the Upper Dockum Group (McGowen and others, 1977).

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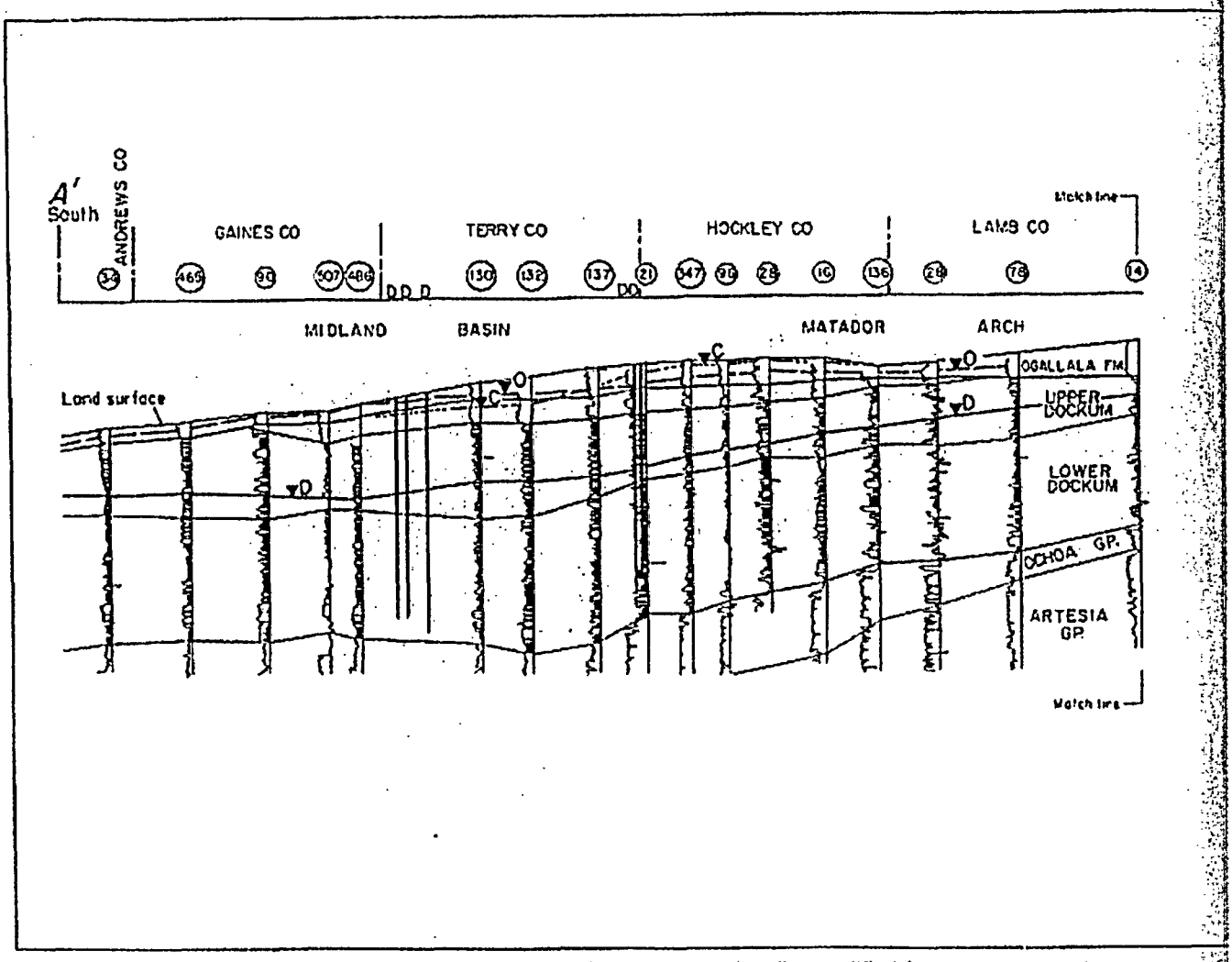

FIGURE 3. North-south stratigraphic cross section through the Texas Panhandle (modified from Granata, 1981) showing hydraulic-head profiles of aquifers in the Ogallala Formation, Edwards/Trinity Groups, and Dockum Group. Line of section A-A' shown in figure 1.

northwestern corner of the Texas Panhandle and to northeastern New Mexico. Some erosion of Triassic and Cretaceous rocks took place before deposition of the Neogene Ogallala Formation. The Ogallala Formation is composed of wet alluvial-fan deposits shed from the southern Rocky Mountains during the Neogene; it caps the High Plains in Texas and New Mexico (Seni, 1980).

Dockum Group rocks were exposed at land surface by erosion of the Pecos and Canadian River valleys and by retreat of the High Plains Caprock Escarpment. The broadest exposures are in the headwaters of the Pecos and Canadian Rivers in northeastern New Mexico and in the headwaters of the Colorado River in the southeastern part of the study area. The Dockum Group is also exposed in a narrow band around the base of the Eastern Caprock Escarpment north of Garza County (fig. 1). Erosion of the Canadian River valley began during the late Pliocene, and valley drainage was completely established by the early Pleistocene (Gustavson and Finley, 1985). Pecos River drainage was not fully developed until the middle to late Pleistocene (Morgan, 1941; Gustavson and Finley, 1985). Retreat of the Caprock Escarpment probably took place during the late Pleistocene and Holocene (Gustavson and

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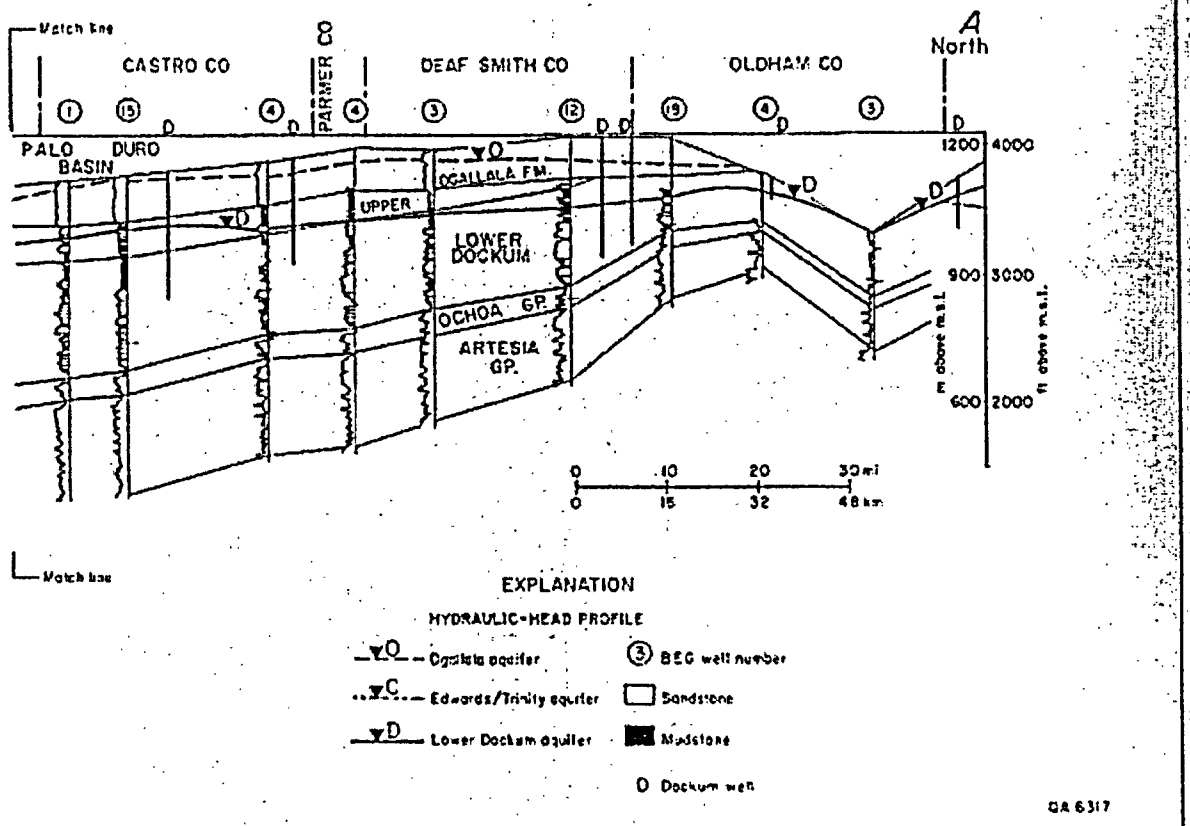

Finley, 1985). The effect of erosion of the major river valleys on Dockum Group hydrogeology is discussed in the section "Origin of ground water in the Lower Dockum Group" (p. 24).

The amount of water available for recharge to shallow aquifers in the Texas Panhandle and eastern New Mexico is limited. The climate ranges from semiarid to subhumid. Mean annual precipitation increases west to east from less than 12 inches (30 cm) across the Pecos Plains to about 24 inches (61 cm) across the Rolling Plains (Larkin and Bomar, 1983). Potential evapotranspiration increases from about 50 inches/yr (127 cm/yr) across the northern end of the Texas Panhandle to about 70 inches/yr (177 cm/yr) across the southern end of the High Plains (Eagleman, 1976). Only during winter and early spring does available moisture in the ground exceed the soil-moisture deficit, allowing ground-water recharge. Most of the annual precipitation falls during intense rainstorms, but because infiltration capacity is generally exceeded, most rainfall is carried away as surface runoff and does not infiltrate the subsurface (Finley and Gustavson, 1980). Warm and subhumid climates have prevailed during the Holocene; cooler and more humid climates may have existed in the Texas Panhandle during the late Pleistocene (Caran and McGookey, 1983).

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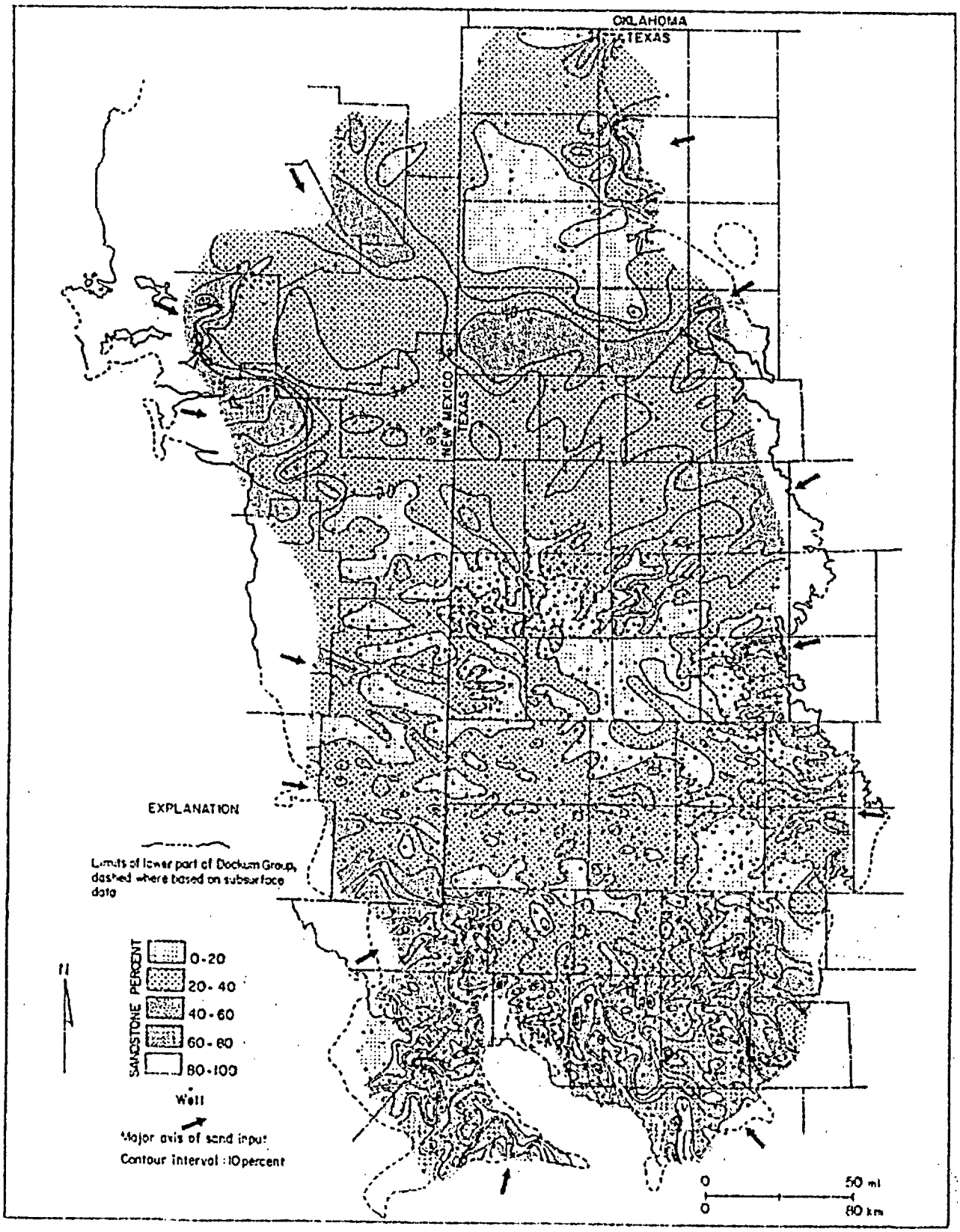

FIGURE 4a. Regional map of percent sandstone in the Lower Dockum Group (McGowen and others, 1977).

DATA AND METHODS

A report by Duffin (1985), computerized data and open-file records of the Texas Department of Water Resources, and records of the High Plains Water Conservation District No. 1, Lubbock, Texas, were the sources for water-level measurements of 258 wells in Texas and records of well drilling in the Dockum Group. We compiled water-level measurements of 798 wells in eastern New Mexico from Theis (1932), Griggs and Hendrickson (1951), Hendrickson and Jones (1952), Long (1957), Smith (1957), Nicholson and Clebsch (1961), Berkstresser and Mourant (1966), Mourant and Shomaker (1970), Dinwiddie and Clebsch (1973), Hudson (1976, 1978), and Hudson and Borton (1983) and from open-file records of the New Mexico State Engineers Office. The water levels were measured in irrigation, stock, and domestic supply wells during several decades. Some measurements were made during the irrigation season and were undoubtedly affected by drawdown. We assume that historic and seasonal changes in ground-water level at any location are small relative to regional variations in the potentiometric surface. Where several measurements were made at one well, we used the highest water level.

Methods and calculations used to estimate transmissivity from specific capacity well tests, following steps described by Brown (1963) and Theis (1963), are detailed in appendix A.

Most chemical analyses of Dockum Group ground water are from wells in the outcrop; data coverage of ground water in the Dockum Group beneath the Southern High Plains is poor. We compiled chemical analyses of 266 Lower Dockum Group ground-water samples from wells in the High Plains and Rolling Plains of the Texas Panhandle and another 88 samples from wells in the Pecos Plains and High Plains in eastern New Mexico (app. B). Several common problems that arise during sampling and laboratory determinations require that caution be used in interpreting the results. Temperature, pH, and alkalinity were not always measured on site and therefore are unreliable estimates of in situ values. Of the 354 analyses, 122 lack pH and temperature measurements. Loss of CO_2 gas during fluid production and sample collection can cause pH to rise (Pearson and others, 1978), accounting for the apparently high saturation indices of calcite and dolomite in most samples. In addition, the charge balance between cations and anions was almost always exact, indicating that sodium and potassium concentrations were computed from the difference between total equivalent charge of anions and equivalent charge of other cations (Hem, 1970, p. 234).

We collected 21 ground-water samples from the Dockum Group throughout the study area to verify previous analyses, to supplement sparse data, and to determine stable isotopes ($\delta^{18}O$, $\delta^{2}H$, and $\delta^{34}S$) useful in interpreting the hydrogeologic system. We measured pH, alkalinity, Eh, and temperature at well sites using standard methods (Barnes, 1964; Wood, 1976). Before sampling, wells were pumped until pH, Eh, and temperature stabilized. Samples for determining $\delta^{18}O$ and $\delta^{2}H$ (δD) were collected in 500-mL glass bottles. Samples for determining $\delta^{34}S$ of sulfate were collected in 500-mL glass bottles and treated first with 6N hydrochloric acid and then with a 5-percent cadmium-acetate solution. Ratios of D/H, $^{18}O/^{16}O$, and $^{34}S/^{32}S$ are reported as differences from arbitrary standards expressed as

$$\delta = (R_{sample} - R_{standard}) \times 1000/R_{standard} \qquad (1)$$

where R is (D/H), ($^{18}O/^{16}O$), or ($^{34}S/^{32}S$). The standard for hydrogen and oxygen is standard mean ocean water (SMOW) (Craig, 1961). The standard for sulfur is based on the Canyon Diablo troilite standard (Thode and others, 1961). Few wells in the Dockum Group in the southern part of the Southern High Plains (app. B) are still available for sampling; they have been plugged and abandoned, used for brine injection, or have had pumping equipment removed.

Chemical composition of the ground water was interpreted with the aid of bivariate plots of ionic concentrations, plots of mineral saturation indices, and plots of data on phase diagrams. We used the program SOLMNEQ (Kharaka and Barnes, 1973) to calculate ionic activities from measured concentrations to (1) determine activity products and mineral saturation indices and (2) plot water samples on the phase diagrams. To run SOLMNEQ, we assigned the average pH of 8.0 and the average temperature of 64.2°F (17.9°C) to water samples that lacked these measurements. Analyses using the assigned pH were not included in estimates of mineral saturation states that vary with pH, nor were they included in plots on phase diagrams. To determine phase boundaries, we used Helgeson's (1969, 1978) thermodynamic data and equilibrium constants for mineral dissociation and hydrolysis reactions; the Helgeson data differ from other data sets (Nordstrom and Munoz, 1985, p. 340). Table 1 lists equilibrium constants for the reactions depicted in the phase diagrams. Activity of water was assumed equal to unity, and temperature was assumed to be 77°F (25°C).

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TABLE 1. Mineral reactions and equilibrium reaction constants (K).*

(1)** K = +0.125; albite - kaolinite
$NaAlSi_3O_8 + H^+ + 4.5H_2O = 0.5Al_2Si_2O_5(OH)_4 + Na^+ + 2H_4SiO_4$

(2) K = −4.02; albite - gibbsite
$NaAlSi_3O_8 + H^+ + 7H_2O = Al(OH)_3 + Na^+ + 3H_4SiO_4$

(3) K = +1.42; albite - Na-smectite
$1.167NaAlSi_3O_8 + H^+ + 3.33H_2O = 0.5Na_{.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + Na^+ + 1.67H_4SiO_4$

(4) K = −7.645; Na-smectite - kaolinite
$3Na_{.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + H^+ + 11.5H_2O = 3.5Al_2Si_2O_5(OH)_4 + Na^+ + 4H_4SiO_4$

(5) K = +8.29; gibbsite - kaolinite
$2Al(OH)_3 + 2H_4SiO_4 = Al_2Si_2O_5(OH)_4 + 5H_2O$

(6) K = −1.02; Ca-smectite - Na-smectite
$6Ca_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 2Na^+ = 6Na_{.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + Ca^{2+}$

(7) K = +0.50; Ca-smectite - Mg-smectite
$Ca_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + Mg^{2+} = 6Mg_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + Ca^{2+}$

(8) K = −16.31; Ca-smectite - kaolinite
$6Ca_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 2H^+ + 23H_2O = 7Al_2Si_2O_5(OH)_4 + Ca^{2+} + 8H_4SiO_4$

(9) K = −16.08; Mg-smectite - kaolinite
$6Mg_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 2H^+ + 23H_2O = 7Al_2Si_2O_5(OH)_4 + Mg^{2+} + 8H_4SiO_4$

(10) K = −475.8; Mg-smectite - chlorite
$6Mg_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 72H_2O + 34Mg^{2+} = 7Mg_5Al_2Si_3O_{10}(OH)_8 + 68H^+ + H_4SiO_4$

(11) K = −475.3; Ca-smectite - chlorite
$6Ca_{.167}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 35Mg^{2+} = 7Mg_5Al_2Si_3O_{10}(OH)_8 + Ca^{2+} + 68H^+ + 58H_2O + H_4SiO_4$

(12) K = −4.00; quartz - silicic acid
$SiO_2 + 2H_2O = H_4SiO_4$

(13) K = −3.73; chalcedony - silicic acid
$SiO_2 + 2H_2O = H_4SiO_4$

(14) K = −2.71; opal - silicic acid
$SiO_2 + 2H_2O = H_4SiO_4$

(15) K = +9.76; calcite solution
$CaCO_3 + 2H^+ = Ca^{2+} + CO_3^{2-} + H_2O$

(16) K = −0.28; dolomite - calcite
$CaMg(CO_3)_2 + Ca^{2+} = 2CaCO_3 + Mg^{2+}$

*The general form of the equations is $aA + bB = cC + dD$; the reaction constant for the general equation equals $[C]^c[D]^d/[A]^a[B]^b$.

**Equation numbers keyed to phase boundaries in figures 15 through 17.

RESULTS

Potentiometric Surface

The shape of the potentiometric surface of Lower Dockum Group ground water (fig. 5) clearly reflects the influence of topography, as is expected in a near-surface aquifer system (Tóth, 1962, 1963, 1978; Hitchon, 1969). A fold, or a reversal in the slope direction, in the potentiometric surface indicates the locations of hydrologic divides between ground-water basins. Ground-water-basin divides lie along the western and northern limits of the Southern High Plains, and they separate Dockum Group ground water beneath the Southern High Plains from ground water in outcropping Dockum rocks in the Pecos and Canadian River valleys (Fink, 1963; Summers, 1981). A narrow ridge in the potentiometric surface, running southeastward from the Dockum outcrop in northeastern New Mexico to the northwesternmost arm of the Southern High Plains, defines the divide between the Pecos and Canadian River valley ground-water basins (fig. 5). Available data do not accurately define the northern boundary of the Canadian River valley ground-water basin.

The shape of the potentiometric surface of Lower Dockum Group ground water appears to be also influenced by stratigraphy of the Dockum Group. In the northern part of the Southern High Plains ground-water basin, the potentiometric surface of ground water (fig. 5) in thick sandstone deposits (fig. 4a) is inclined to the east-southeast at gradients ranging from less than 6 ft/mi (1.1 m/km) to more than 18 ft/mi (3.4 m/km), which are similar to water-table gradients in the High Plains aquifer (Knowles and others, 1984). Hydraulic-head data from the central and southern parts of the Southern High Plains, although sparse, suggest that the lateral hydraulic-head gradient is steeper in Cochran, Yoakum, and Gaines Counties than in Bailey, Parmer, Castro, and Deaf Smith Counties in the northern part of the Southern High

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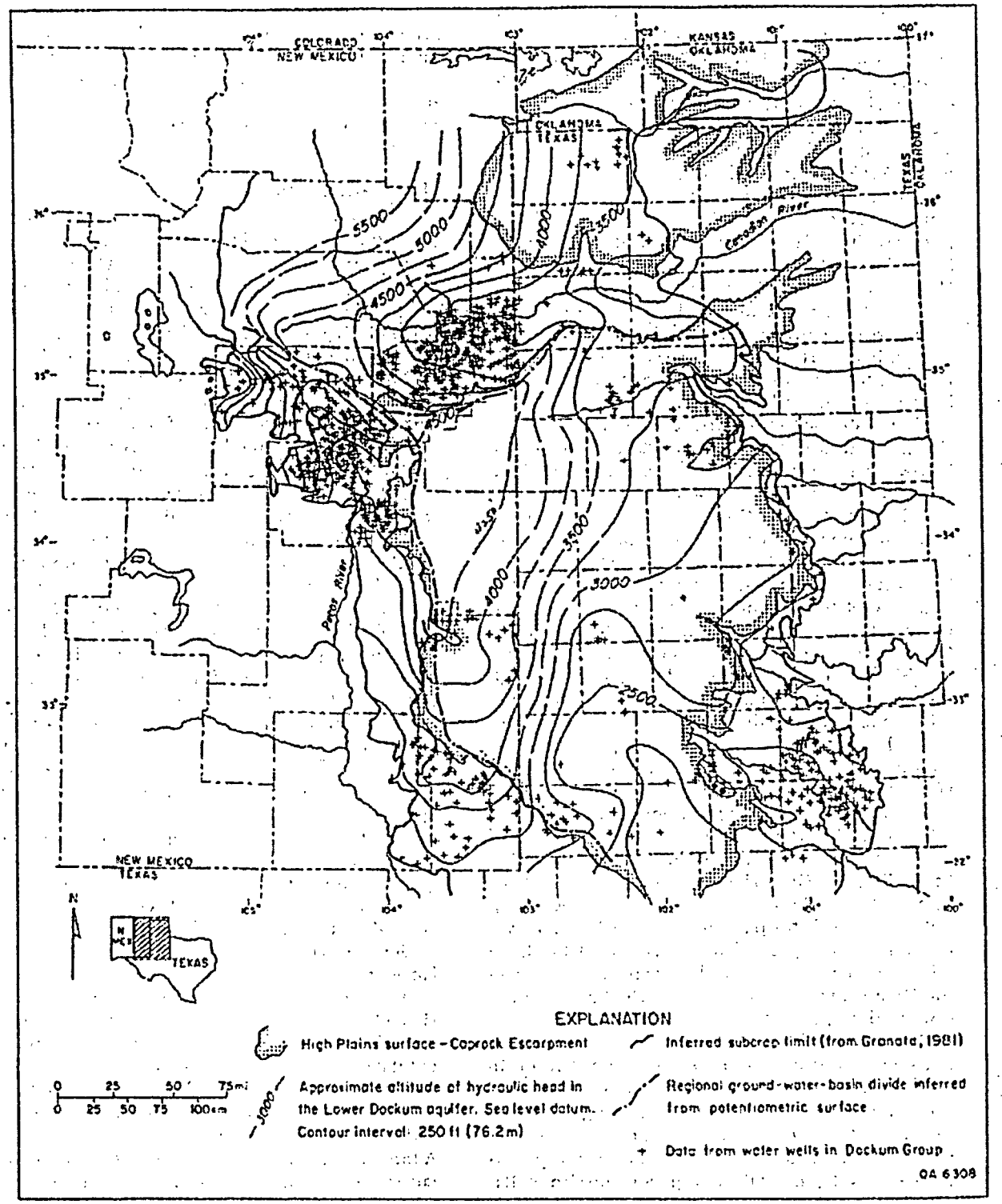

FIGURE 5. Potentiometric surface map of Lower Dockum Group ground water. Regional ground-water-basin divides, inferred from topography and shape of the potentiometric surface, separate regional ground-water basins. See description of data sources in text.

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Plains (fig. 5). The regionally depressed potentiometric surface of the Dockum Group in Cochran, Hockley, Yoakum, Terry, and Gaines Counties, where hydraulic head is less than 2,750 ft (838.2 m), coincides with a large area where sandstone and conglomerate make up less than 30 percent of the Lower and Upper Dockum Group (figs. 4a and 4b) and less than 50 percent of the Ogallala Formation (Seni, 1980, p. 15). A steep hydraulic-head gradient reflects either loss of hydraulic head as Dockum Group ground water moves eastward into an area of lower permeability or lack of vertical flow of ground water from the High Plains aquifer downward through Upper Dockum mudstone into the Lower Dockum Group. Thickness of the Dockum Group does not decrease and structural dip does not increase across the southern part of the Southern High Plains, so these factors probably do not affect the steepness of the hydraulic-head gradient.

The potentiometric surface of Lower Dockum Group ground water is 300 to 700 ft (90 to 210 m) below the water table of the High Plains aquifer (Fink, 1963) and is below the base of the Ogallala Formation and Edwards/Trinity Groups (fig. 3), indicating a regional potential for vertical flow of ground water downward from the High Plains aquifer to the aquifer in the Lower Dockum Group. On the one hand, the similarity of the potentiometric surfaces of ground water in the Ogallala Formation and Edwards/Trinity Groups suggests that the aquifers in these stratigraphic units are interconnected and part of the High Plains aquifer system. On the other hand, the difference between the potentiometric surfaces of ground water in the High Plains aquifer and the aquifer in the Lower Dockum Group suggests that vertical hydrologic connection between the aquifers is poor in most areas of the Southern High Plains. The difference between potentiometric surfaces of ground water in the High Plains aquifer and in the Lower Dockum Group increases toward the southern part of the Southern High Plains, mainly because of the depression in the potentiometric surface of Lower Dockum Group ground water. Origin of the large difference in hydraulic head between ground water in the High Plains aquifer and in the Dockum Group is discussed on page 24.

Potentiometric surfaces of ground water also differ between sandstones within the Dockum Group. In the northern part of the Southern High Plains, along section line A-A′ (fig. 3; Fink, 1963, his figs. 2 and 3), the potentiometric surface of ground water in sandstones at the base of the Dockum Group appears to be below the top of the Lower Dockum Group. It is possible that the potentiometric surface of ground water in the upper part of the Lower Dockum Group is above the top of the Lower Dockum and lies between the water table of the High Plains aquifer and the potentiometric surface of ground water in the lower part of the Lower Dockum Group. The potentiometric surface of ground water in Upper Dockum sandstones is poorly known but is probably also between the altitude of the water table in the High Plains aquifer and the potentiometric surface of the Lower Dockum Group.

Hydrogeochemistry

In hydrogeochemistry, isotopic and chemical compositions are used to interpret sources of ground water and to define chemical reactions between water and minerals that determine ground-water quality. Chemical composition of ground water in the Lower Dockum Group is presented with Piper, or trilinear, diagrams (Piper, 1944; Freeze and Cherry, 1979, p. 249) and bivariate plots of ionic concentrations.

Dockum Group ground water appears to be meteoric in origin, that is, derived from precipitation and not isotopically altered by exchange with rocks or by mixing with nonmeteoric water. The D/H and $^{18}O/^{16}O$ ratios in Lower Dockum Group ground water from the Texas Panhandle and eastern New Mexico (table 2) plot along the meteoric water line (fig. 6), which is typical of worldwide precipitation (Craig, 1961; Dansgaard, 1964). A southeast to northwest trend of increasing depletion of δD and $\delta^{18}O$ values in precipitation across the Texas Panhandle and eastern New Mexico (Taylor, 1974) is generally reflected in the isotopic composition of Dockum Group ground water, but the isotopically lightest water occurs in thick sandstone deposits in the northern part of the Southern High Plains (compare figs. 4a and 7). Values of δD and $\delta^{18}O$ of Dockum Group ground water are 15 to 25 ‰ and 2 to 3 ‰ lighter, respectively, than ground water in the Ogallala Formation throughout the Southern High Plains (fig. 8; Nativ and Smith, 1985). Isotopic composition of Dockum Group ground water resembles the isotopic composition of shallow ground water in the Pecos Plains of eastern New Mexico (Gross and others, 1982).

Several mappable associations of hydrochemical facies are present in the Lower Dockum Group in the northern, central, and southern parts of the Southern High Plains (figs. 9 and 10a). Hydrochemical facies are named for the ions that account for at least 50 percent of total equivalent concentration as depicted in Piper diagrams (Back, 1966); mixed-cation and mixed-anion hydrochemical facies, as defined in this report, are waters in which no one cation or anion is dominant. Although mappable associations of hydrochemical facies vary across the study area, the reactions that appear to control the chemical composition of ground water are common to all hydrochemical facies (see discussion beginning on page 26).

LES-005028

TABLE 2. Chemical and isotopic composition of Lower Dockum Group ground water. Concentrations in mg/L.

County	Lat. °N	Long. °W	T°C	pH	Ca	Mg	Na	K	Sr	Cl	SO_4	HCO_3	Br	SiO_2	δD ‰	$\delta^{18}O$ ‰	$\delta^{34}S$ ‰	Sample no.
Andrews	32.240	102.650	27.1	8.05	15.9	26.5	860	12.6	0.44	518	760	537	3.3	11	-47;-49	-7.5;-7.3	2.3;2.4	85-607
Deaf Smith	34.854	102.347	19	8.2	4.59	1.4	326	2.39	0.12	56	251	503	0.45	10.4	-67;-70	-9.6;-9.6	-	84-887
	34.800	102.431	19	5.7	5.95	2.03	917	3.41	0.2	510	360	1,074	0.52	12.1	-54;-55	-7.4;-7.4	-2.4;-2.2	84-885[a]
	35.122	102.502	19	8.15	15.4	6.13	239	2.34	0.31	54.5	116	428	0.24	10.6	-76	-10.8	-6.1	85-600[b]
	35.121	103.021	18	7.6	15.6	13.1	335	2.34	0.25	58.4	177	633	0.64	13.3	-48;-46	-6.8;-6.9	-2.7	85-601
	34.803	102.317	17.9	8.43	5.14	1.82	283	2.02	-	48	189	475	-	10.8	-80	-11.2	-	84-446[a]
	34.904	102.317	17.9	8.5	7.3	3.52	227	2.44	-	31.3	104	447	-	11.1	-83	-11.8	-	84-445[a]
	34.896	102.181	17.9	8.95	3.11	1.96	230	2.37	-	29	94.2	464	-	7.63	-85	-12.7	-	84-438[a]
	34.833	102.344	17.9	8.58	3.41	.89	380	1.63	-	84.5	201	630	-	10.6	-71	-9.9	-	84-443[a]
	34.793	102.331	17.9	8.6	3.24	.65	449	1.42	-	104.5	220	720	-	10.8	-67	-9.1	-	84-444[a]
Garza	33.279	101.419	17	6.7	751	275	16,930	36.1	4.4	25,160	2,805	226	7.88	11.2	-61;-59	-8.9;-8.6	9.5	85-605
	33.074	101.098	20.5	7.8	34.9	18.6	2,020	5.2	1.29	2,170	972	377	0.73	10.4	-47;-48	-6.9	-7.4;-7.5	85-606
Howard	32.476	101.361	26	7.8	47.1	21.9	2,050	6.49	1.6	1,571	1,656	531	4.29	11.1	-45;-45	-6.7	9.7	85-608
	32.417	101.238	19	7.8	43.1	21.5	1,320	5.82	1.88	1,183	840	491	4.21	10.1	-42;-40	-6.2;-5.9	11.2;11.1	85-609
Oldham	35.538	102.289	18	7.2	28	21.7	498	6	0.53	58.1	279	1,090	0.28	-	-66;-68	-9.1;-9.3	9.7	85-007
Randall	34.775	101.869	17.9	8.18	25.4	15.9	153	4.13	-	49.5	101	362	-	27.8	-62	-9.1	-	84-447[a]
	35.015	101.752	17.5	8.1	12	11.7	110	3.88	0.73	8.25	25	359	0.19	11.8	-55;-55	-7.5;-7.5	-1.9	84-888[c]
Swisher	34.439	101.881	17.9	8.14	35.6	23.6	46.9	7	-	24.8	22.5	283	-	45	-50	-6.6	-	84-440[a]
	34.734	101.864	20.5	8.1	4.69	2.6	318	2.99	0.12	71.1	194	529	0.58	10.9	-74;-75	-10.7;-10.8	2.5;2.5	84-886[d]
	34.546	101.769	15	8.4	4.7	1.94	391	1.85	0.16	126	232	510	0.47	10.2	-73;-71	-10.4	-3.8	85-603
	34.558	101.774	13	8.25	3.13	1.75	301	2.86	0.1	54.9	161	486	0.42	10	-75;-73	-10.6	-1.8;-1.7	85-604
De Baca	34.523	104.225	17	7.85	22.4	17.1	239	1.31	1.01	71.9	214	367	0.37	-	-52;-54	-7;-6.8	8.7	85-011
Quay	35.358	103.458	18	7.25	86.6	31.9	42.9	2.48	0.64	46.1	133	314	0.4	-	-50;-48	-6.3;-6.5	-7.1;-7.2	85-008
	35.142	103.350	13.5	8.9	2.75	2.11	480	1.41	0.14	129	266	753	1.04	-	-57;-58	-7.7;-7.5	6	85-010
	34.983	103.367	20	9.7	1.66	0.41	278	1.01	0.04	135	188	-	0.54	5.76	-73;-72	-10.7;-10.7	10.1	85-611
San Miguel	35.467	104.417	13.5	7.4	70.6	144	135	9.6	2	90	378	691	0.55	-	-50;-52	-6.8;-6.6	-5.8	85-009

[a]Samples collected by Texas Department of Water Resources.

Eh measurements: [a] -0.19 V; [b] -0.13 V; [c] -0.09 V; [d] -0.12 V.

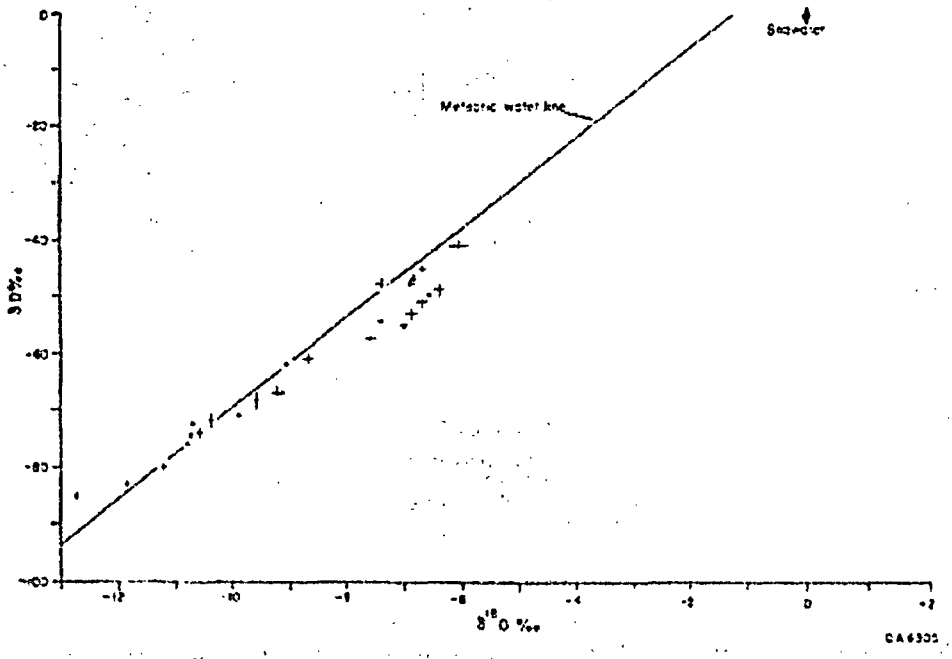

FIGURE 6. Plot of δD and $\delta^{18}O$ values of Dockum Group ground water along the meteoric water line. Meteoric water line defined by Craig (1961). Oxygen isotopes defined relative to SMOW.

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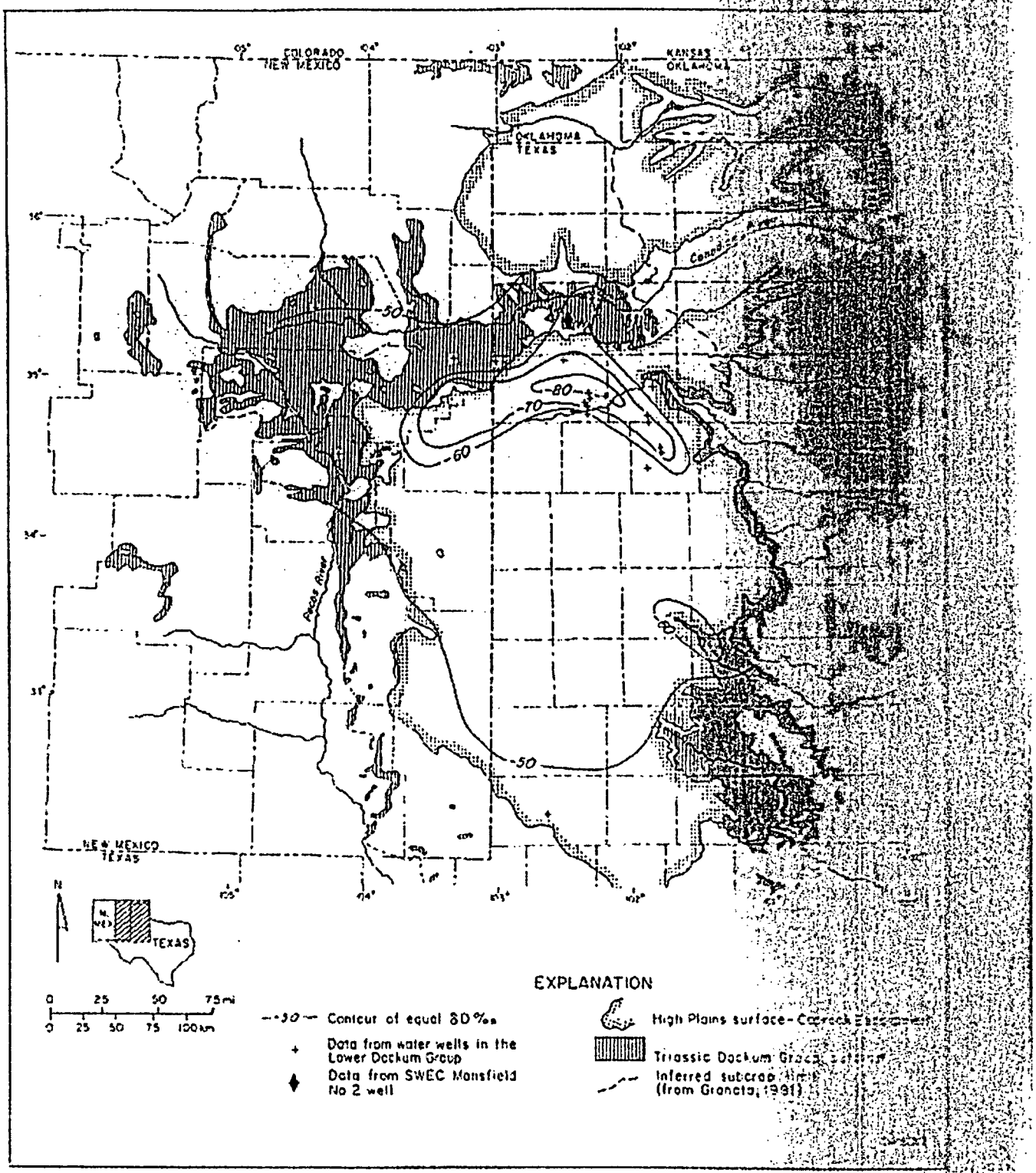

FIGURE 7. Map of δD values of Lower Dockum Group ground water. Ground water sampled at the SWEC Mansfield No. 2 well is from the lower part of the Seven Rivers Formation in a salt-dissolution zone (see [illegible] text).

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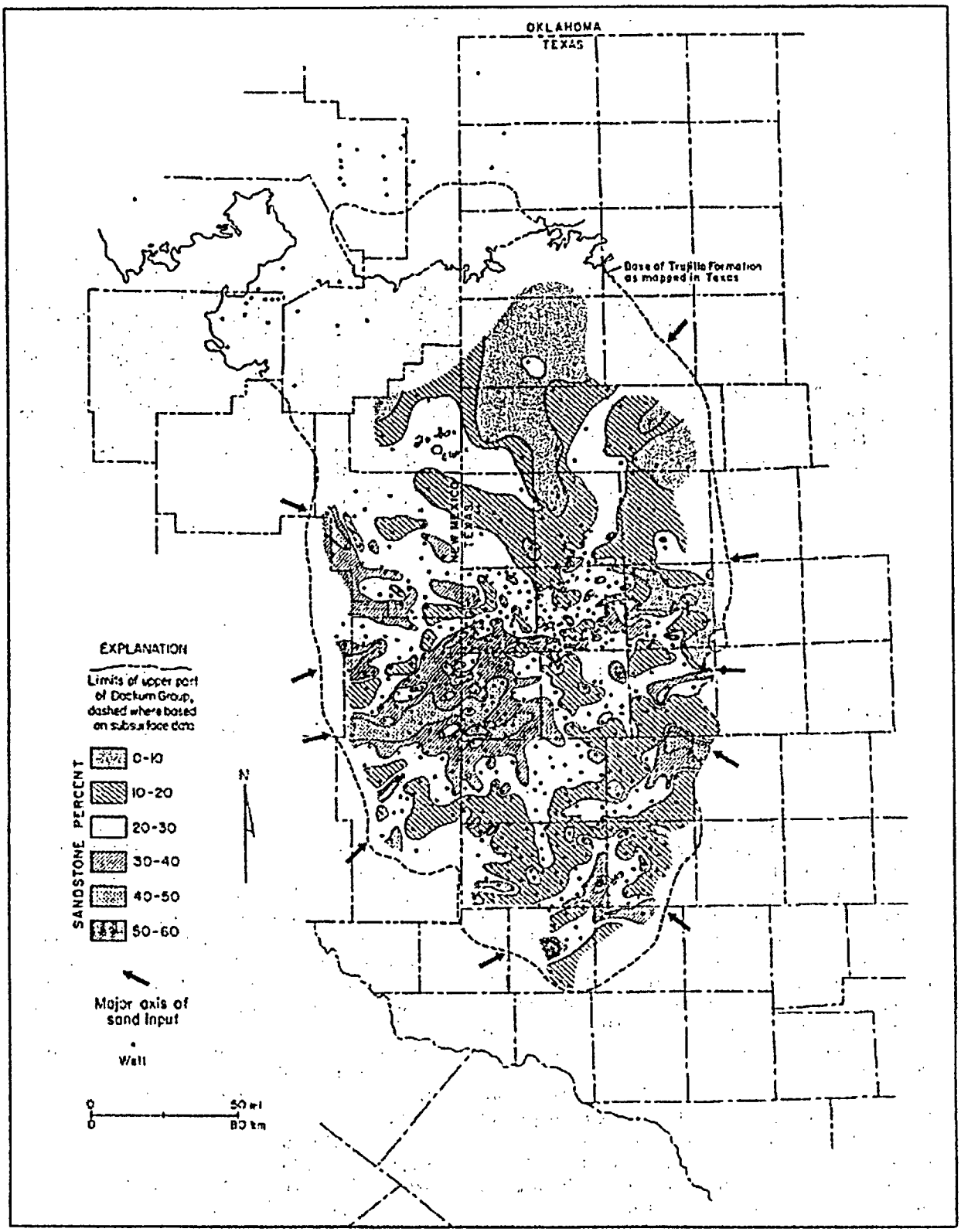

FIGURE 4b. Regional map of percent sandstone in the Upper Dockum Group (McGowen and others, 1977).

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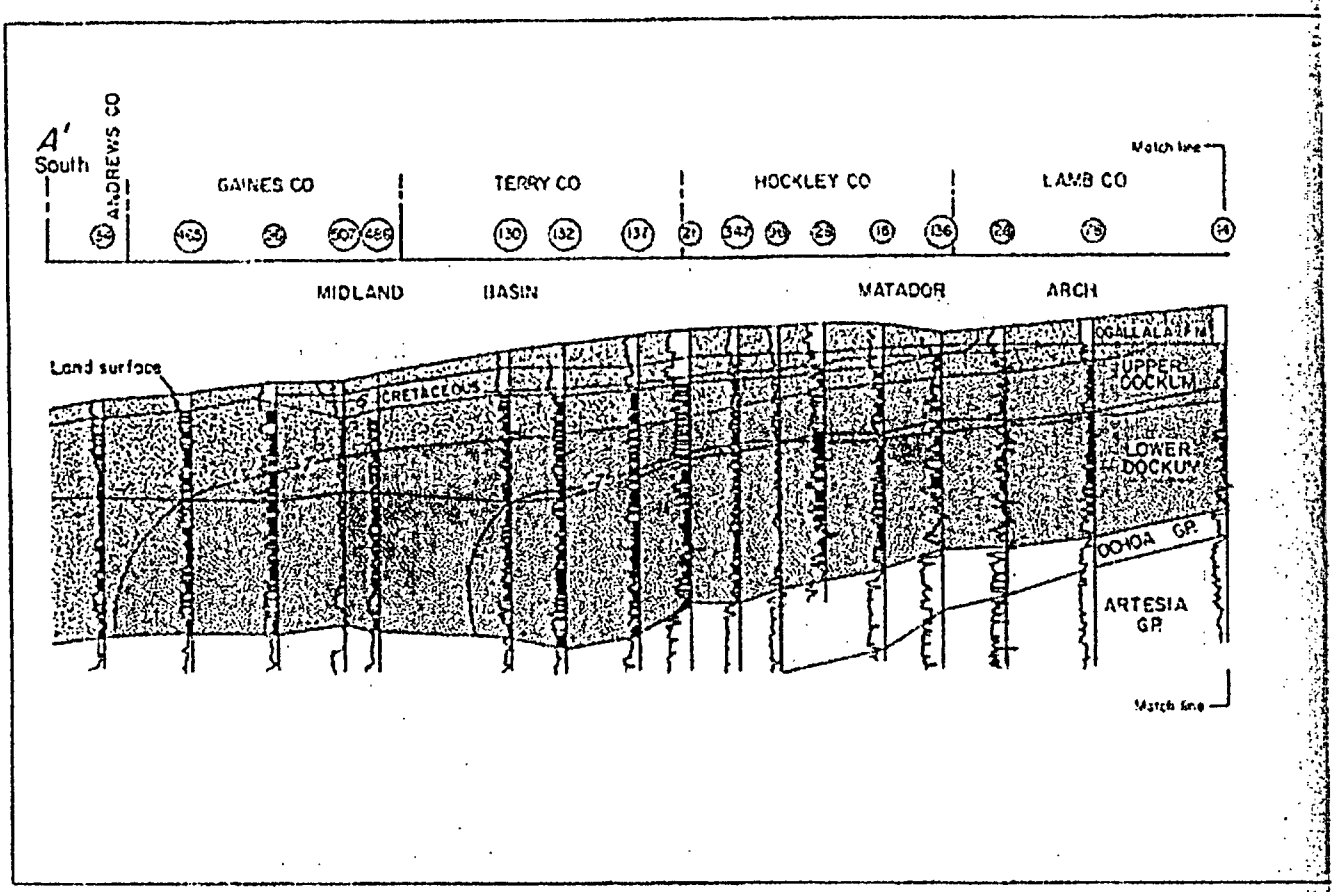

FIGURE 8. North-south stratigraphic cross section showing inferred profile of $\delta^{18}O$ values of ground water in the Ogallala Formation and Dockum Group. Sample locations of Dockum Group ground waters shown in figure 7. Line of section A-A' shown in figure 1. The SWEC Mansfield No. 2 well in Oldham County

In the northern part of the Southern High Plains, along the southern side of the Canadian River valley, the total dissolved solids (TDS) of Na-HCO_3, mixed-cation-HCO_3, and Na-mixed-anion hydrochemical facies is generally less than 3,000 mg/L (figs. 10a and 10b). This good quality water occurs in the thicker deposits of Lower Dockum Group sandstone (fig. 4a). In comparison, ground water in the Ogallala Formation in the northern part of the Southern High Plains is a predominantly Ca-HCO_3, mixed-cation-HCO_3, or mixed-cation-mixed-anion type (Nativ and Smith, 1985).

A Na-Cl hydrochemical facies having TDS of more than 20,000 mg/L dominates Dockum Group ground water in the central part of the Southern High Plains ground-water basin (figs. 10a and 10b); this area has often been a disappointment in the search for good quality water in the Dockum Group (Broadhurst, 1957; *The Lockney Beacon*, 1964). The saline ground water occurs in a sand-poor area of the Dockum Group that is partly overlain by the Cretaceous Edwards/Trinity Groups (figs. 1 and 3). The transition from fresh to saline water in the lower Dockum is poorly defined because of sparse data.

Characteristics of Dockum Group ground water in the southern part of the Southern High Plains include Na-mixed-anion and Na-SO_4 hydrochemical facies and salinities of less than 5,000 mg/L (figs. 9, 10a, and 10b). The two hydrochemical facies are not truly distinct, and the degree of dominance of sulfate among anions varies gradually across the area.

Ground water from the confined aquifer in the Dockum Group appears to mix with less saline, locally recharged water in the unconfined aquifer in the outcrop of Dockum Group rocks east of the Southern High Plains. Hydrochemical facies in the outcrop belt are variable, including Na-HCO_3, Ca-HCO_3, Na-Cl, Na-SO_4, and mixed-ion types (fig. 9e).

Total dissolved solids in the Dockum Group in the Pecos River valley ground-water basin range from less

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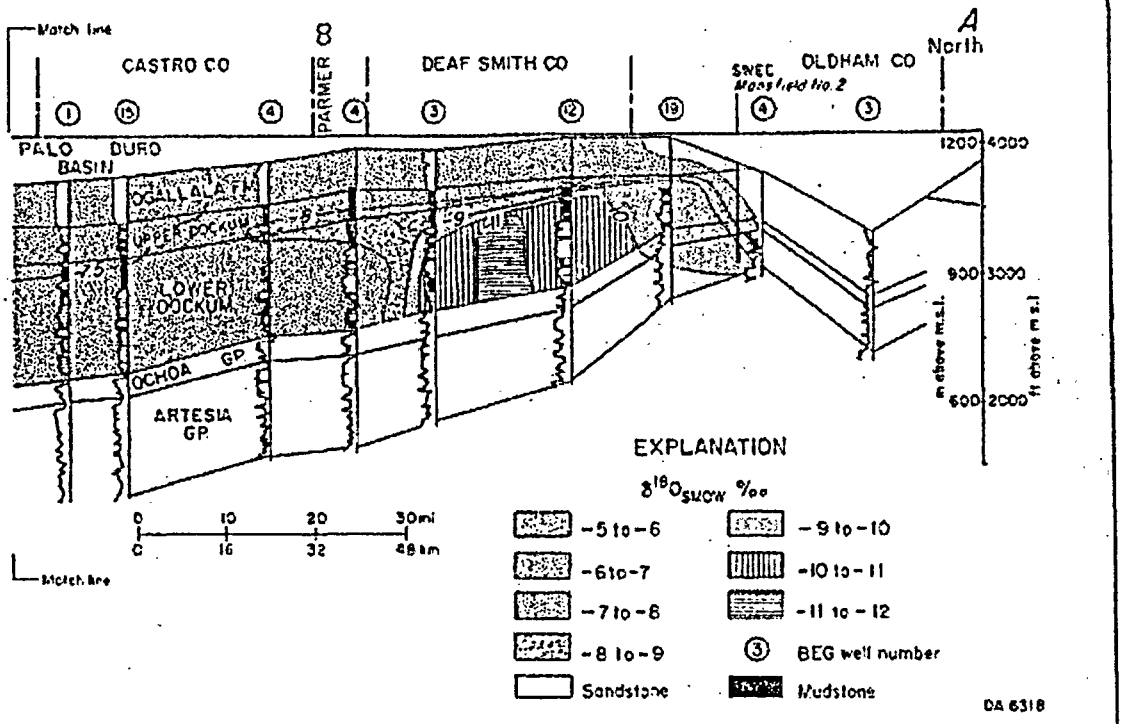

penetrates the Seven Rivers Formation and yields water similar in isotopic composition to Dockum Group water. Isotope data on Ogallala Formation water from Nativ and Smith (1985).

than 400 mg/L to more than 7,000 mg/L (fig. 10b). Sixty-one percent of the ground-water samples from that basin consist of Na-HCO_3, Na-mixed-anion, Ca-SO_4, and mixed-cation-HCO_3 hydrochemical facies (fig. 9d).

The sulfur isotopic composition of dissolved sulfate in Lower Dockum Group ground water ranges from -7.5 to +11.4 ‰ (fig. 11). The $\delta^{34}S$ value of dissolved sulfate reflects the $\delta^{34}S$ value of sulfur-bearing minerals that react with ground water. For example, a $\delta^{34}S$ value of dissolved sulfate greater than +5 ‰ in Dockum Group ground water most likely reflects solution of Permian anhydrite along some flow path leading to the Dockum Group; a $\delta^{34}S$ value of Permian anhydrite is typically +11 to +12 ‰, less positive than most marine sulfate deposits (Holser, 1979, p. 331-332). Sulfate with $\delta^{34}S$ values of less than -5 ‰ probably comes from oxidation of pyrite, which is common in Dockum rocks. Dockum Group ground waters with the greatest concentrations of dissolved sulfate tend to have $\delta^{34}S$ values greater than +5 ‰, but the correlation between $\delta^{34}S$ and sulfate concentration among all samples is not statistically significant. Some Na-Cl waters in outcropping Dockum rocks have a positive $\delta^{34}S$ value (samples 85-605, 85-608, and 85-609); sample 85-606 has a negative $\delta^{34}S$ value (table 2). Sample 85-011 (table 2) in the Pecos River valley has a $\delta^{34}S$ value of +8.7 ‰, suggesting that ground water in the Lower Dockum Group has contacted Permian anhydrite or gypsum along some flow path.

Dockum Group ground water has also contacted Upper Permian anhydrite or gypsum deposits in parts of the Canadian River valley ground-water basin. The Ca-HCO_3, Na-HCO_3, and mixed-cation-HCO_3 hydrochemical facies are predominant, and salinity is generally less than 1,000 mg/L (figs. 10a and 10b). In the part of the ground-water basin where salinity exceeds 1,000 mg/L, however, $\delta^{34}S$ is more positive than +5 ‰.

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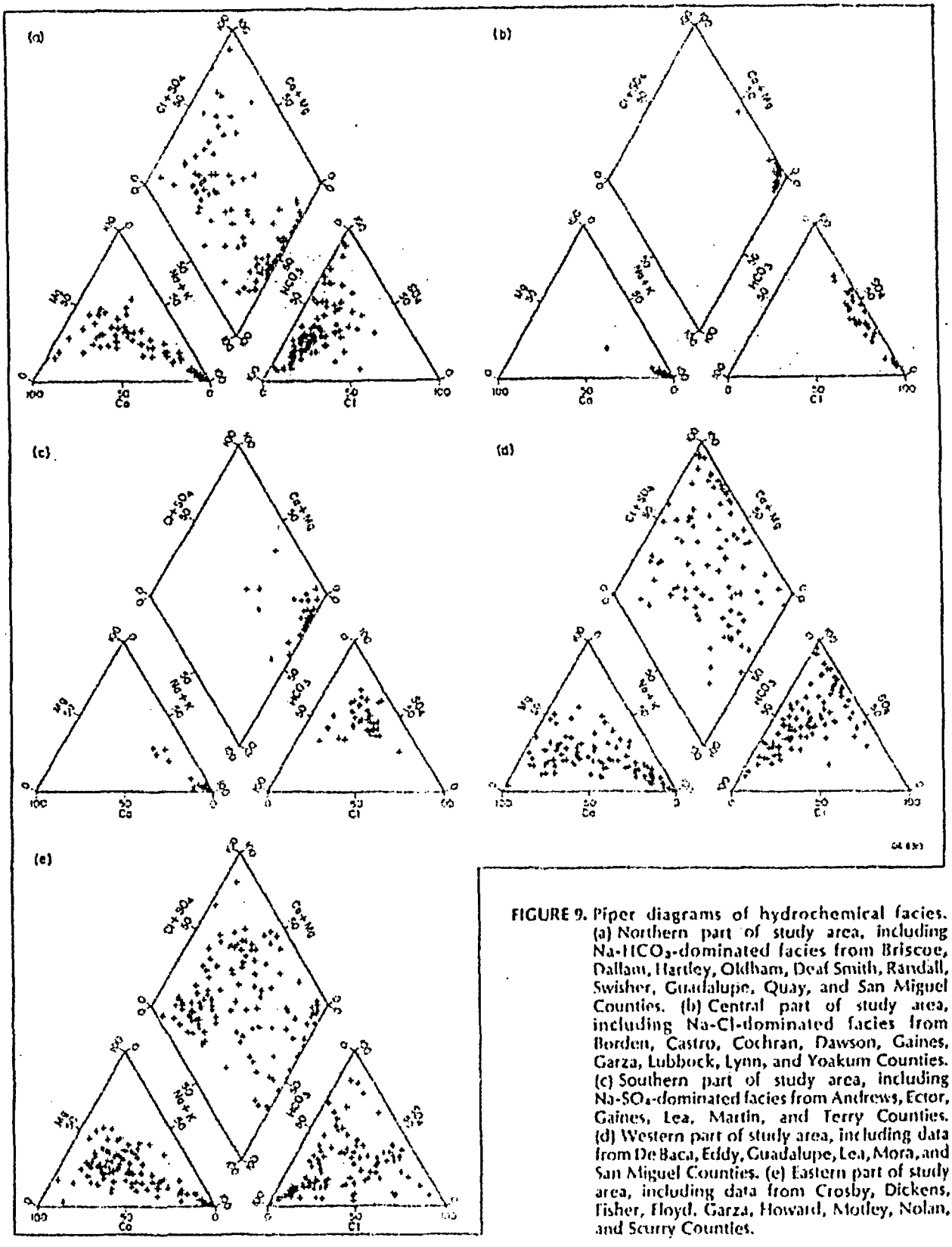

FIGURE 9. Piper diagrams of hydrochemical facies. (a) Northern part of study area, including Na-HCO_3-dominated facies from Briscoe, Dallam, Hartley, Oldham, Deaf Smith, Randall, Swisher, Guadalupe, Quay, and San Miguel Counties. (b) Central part of study area, including Na-Cl-dominated facies from Borden, Castro, Cochran, Dawson, Gaines, Garza, Lubbock, Lynn, and Yoakum Counties. (c) Southern part of study area, including Na-SO_4-dominated facies from Andrews, Ector, Gaines, Lea, Martin, and Terry Counties. (d) Western part of study area, including data from De Baca, Eddy, Guadalupe, Lea, Mora, and San Miguel Counties. (e) Eastern part of study area, including data from Crosby, Dickens, Fisher, Floyd, Garza, Howard, Motley, Nolan, and Scurry Counties.

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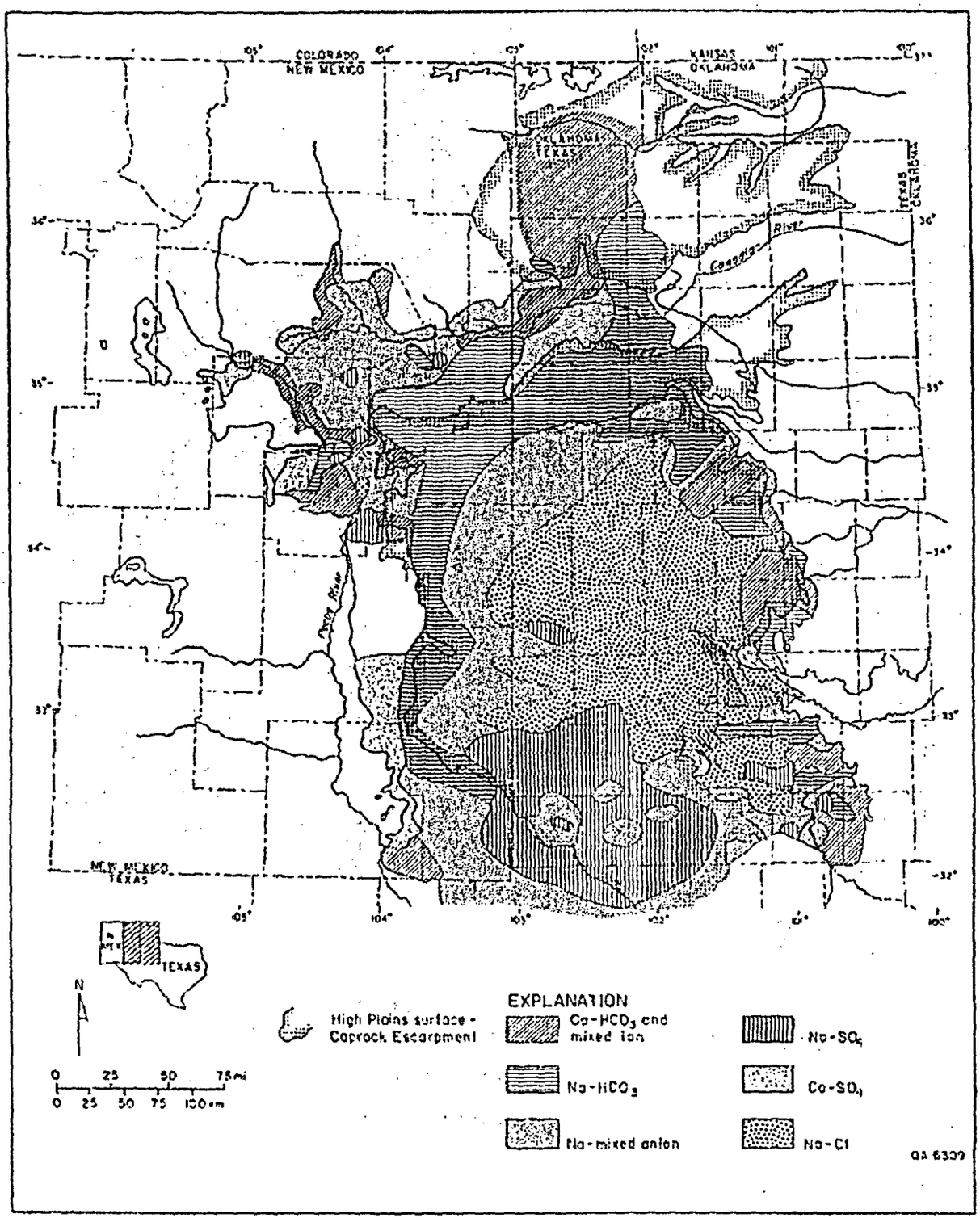

FIGURE 10a. Hydrochemical facies of Lower Dockum Group ground water. Hydrochemical types inferred from Piper diagrams (fig. 9; see discussion in text). Data locations shown in figure 10b.

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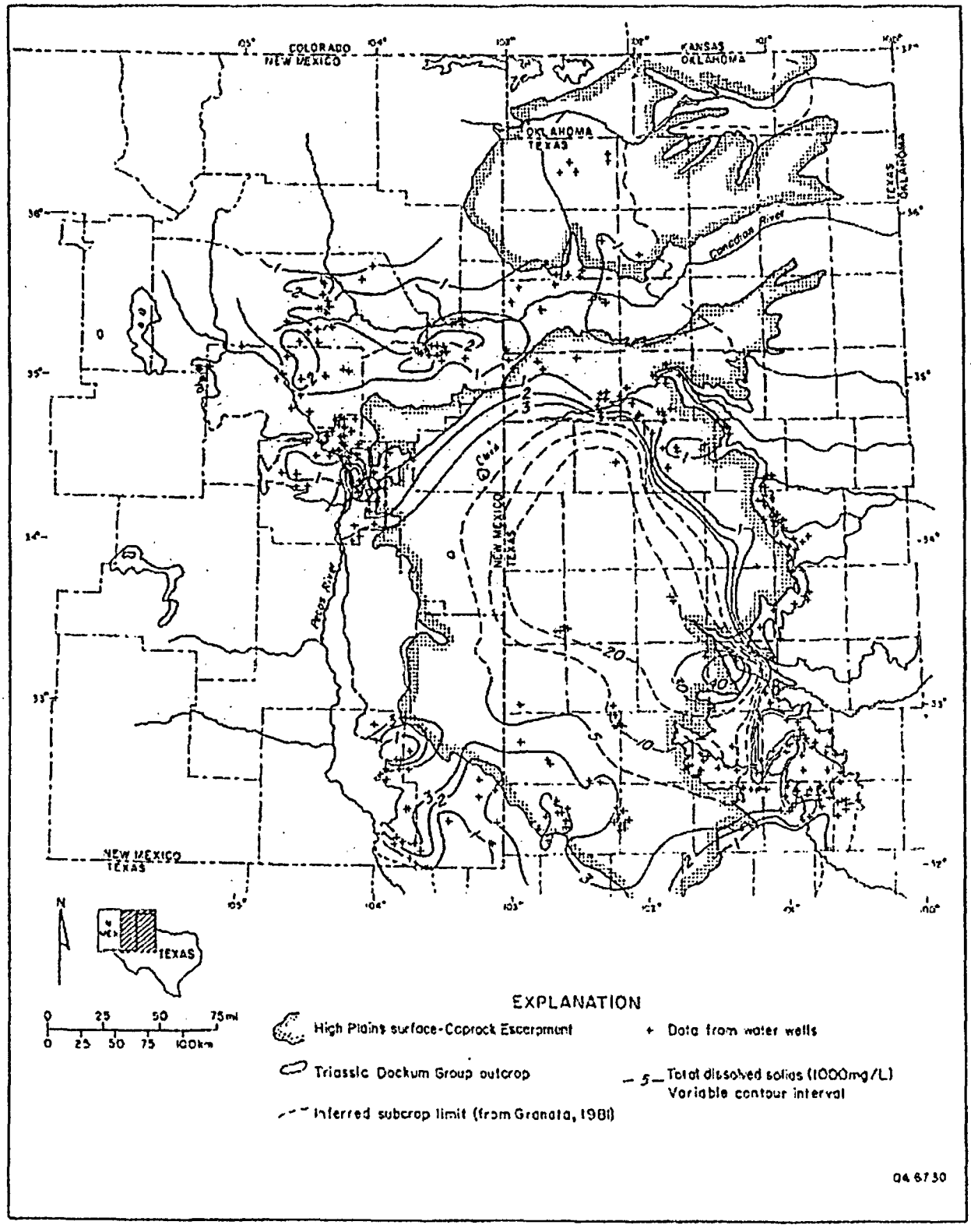

FIGURE 10b. Total dissolved solids in Lower Dockum Group ground water.

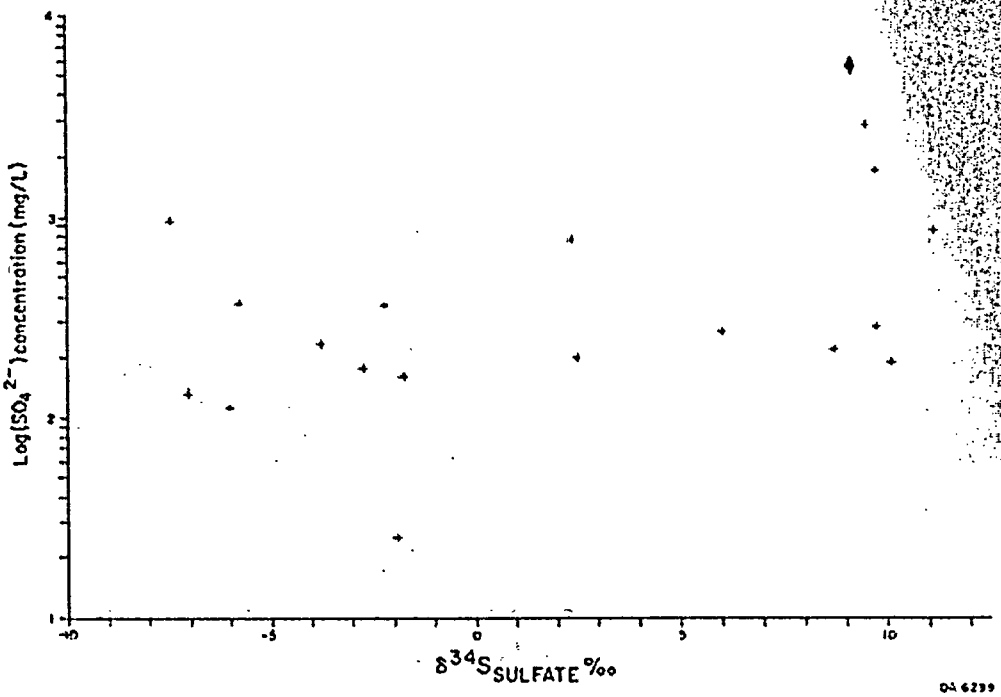

FIGURE 11. Relation between $\delta^{34}S$ and sulfate concentration. Diamond represents water from SWEC Mansfield No. 2 well (see discussion in text).

Water Resources

Principal uses of the aquifer in the Lower Dockum Group include irrigation, livestock watering, brine and industrial waste injection, and domestic, municipal, and oil field water supply. Most irrigation and municipal wells were drilled in the early 1960's (fig. 12) and were equipped with natural-gas-driven turbine pumps. Ground-water resources were discovered in Deaf Smith, Randall, and Swisher Counties in thick sections of fluvial and deltaic sandstones in the Lower Dockum Group (fig. 4a). Transmissivities, estimated from drawdown and specific capacity tests, range from 10 to 3,180 ft^2/d (1 to 300 m^2/d) in these counties (app. A). Outside the major trend of thick sandstones, well yield and aquifer transmissivity are much less, and wells commonly tap saline water or produce an insufficient quantity of water for irrigation or municipal supply.

Raynor (1973) and Blair (1976) discouraged continued exploration of the Lower Dockum Group for irrigation water because of a salinity hazard to soils and because the production cost was more than that of Ogallala water owing to greater head lift and generally lower transmissivity of the aquifer in the Dockum Group. Long-term irrigation with sodium-rich Dockum Group ground water may pose a salinity hazard and affect soil tilth and permeability. The sodium concentration in Dockum Group ground water in the northern part of the Southern High Plains is as much as 1,500 mg/L. Fink (1963, p. 28) suggested

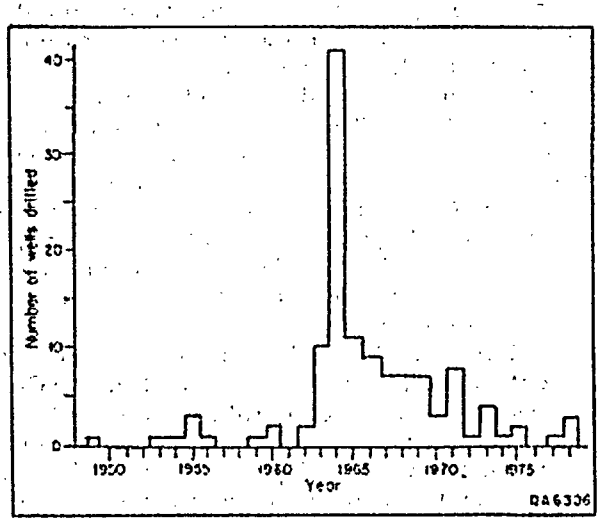

FIGURE 12. Dockum water wells drilled in the Texas Panhandle, 1950–1978.

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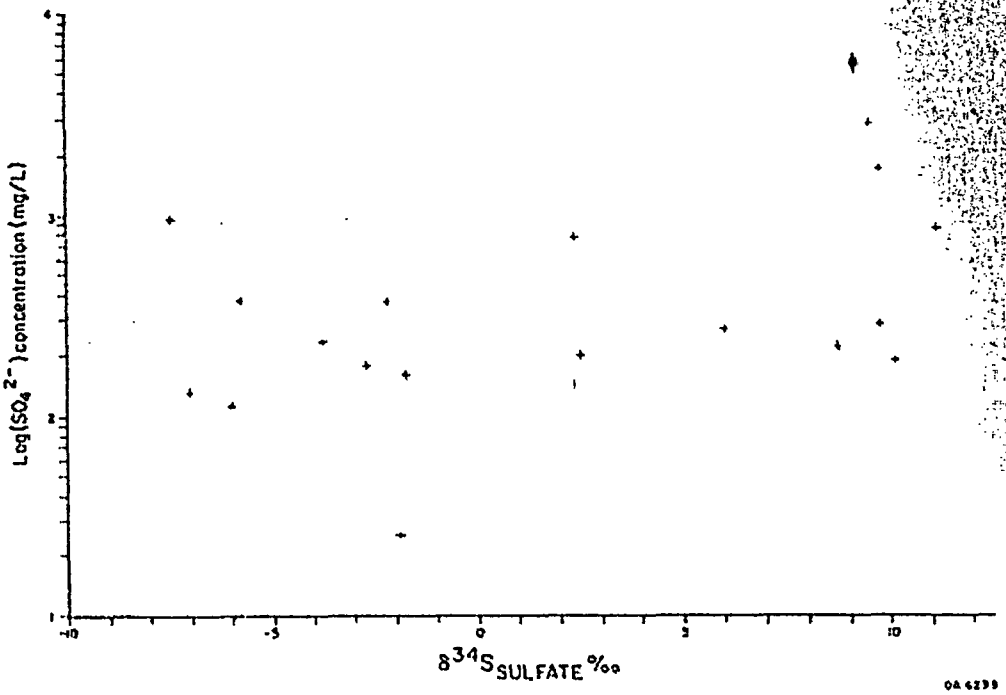

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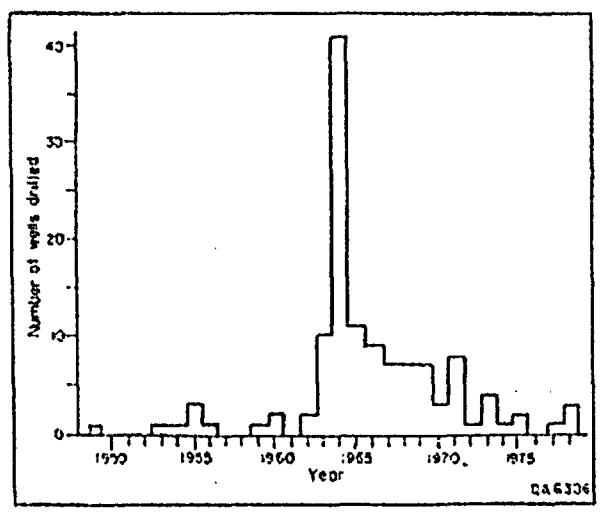

FIGURE 12. Dockum water wells drilled in the Texas Panhandle, 1950–1978.

LES-005038

mixing Dockum Group ground water with the more calcium-rich water from the Ogallala Formation to reduce the salinity hazard.

The sodium adsorption ratio (SAR) is widely used to characterize salinity hazard of water (Sposito and Mattigod, 1977) and is defined as

$$SAR = \frac{Na}{\sqrt{\frac{(Ca + Mg)}{2}}} \qquad (2)$$

(concentrations in equivalents/L). SAR values of Dockum Group ground water are largest in Na-HCO_3, Na-SO_4, and Na-mixed-anion hydrochemical facies in Quay, Union, Deaf Smith, Swisher, Andrews, Martin, Ector, Borden, and Garza Counties (compare figs. 10a and 13). For example, the SAR of Dockum Group ground water in Deaf Smith County ranges from 13 to 65 and in seven wells is greater than 18, the low limit for waters of high salinity hazard (U.S. Salinity Laboratory, 1954). In comparison, SAR values for water from 110 irrigation wells in the Ogallala Formation in Deaf Smith County range from 0.2 to 8 and average 1.5. Where fields are irrigated with Dockum Group ground water, the addition of large amounts of gypsum to the soil may be needed to replenish calcium and reduce SAR, but this practice is expensive and apparently not used on farmland in the Southern High Plains.

The cost of well construction, maintenance, and pumping will probably be a major limitation on future drilling and use of Dockum Group ground water for irrigation, even in the northern part of the Southern High Plains, where sandstones are thick (figs. 4a and 4b) and transmissivities fairly high (fig. A3). Because wells in the Dockum Group are 200 to 650 ft (61 to 200 m) deeper than wells in the Ogallala Formation, drilling and casing costs for irrigation wells are about three times greater (approximately $100,000). Dockum Group irrigation wells have head lifts of 300 to 500 ft (90 to 150 m) and commonly need 200-hp (150-kW) pumps. In contrast, 30- to 50-hp (22- to 37-kW) pumps are used in Ogallala Formation water wells. The larger pumps require more maintenance and use more energy per volume of ground water produced.

Many irrigators have abandoned wells in the Dockum Group, and municipalities have converted pump motors from natural gas to less expensive electrical power in Deaf Smith, Randall, Swisher, and Castro Counties. Production cost of Dockum Group ground water ($45 to $82/acre-ft, or $0.04 to $0.07/$m^3$) is generally greater than production cost of Ogallala water ($23 to $60/acre-ft, or $0.02 to $0.05/$m^3$). Blair (1976) estimated that farmers in the area could afford to pay up to $22/acre-ft ($0.02/m^3) (1976 basis) for irrigating grains such as milo, corn, or wheat. Since 1976, the cost of Dockum Group ground water has risen and profit margins on many crops have fallen; only farmers growing crops with high profit margins, such as seed crops, still irrigate with Dockum Group ground water. Although the supply of Ogallala Formation water is declining and pumping cost is increasing as water levels drop, the water-table aquifer in the Ogallala Formation continues to provide a better quality and less expensive source of irrigation water than does the confined aquifer in the Lower Dockum Group in the northern part of the Southern High Plains.

The aquifer in the Lower Dockum Group supplies water to the Texas cities of Happy, Hereford, and Tulia (table 3). Lower Dockum Group ground water is the only developed water supply for the City of Happy in northern Swisher County. In Hereford, Deaf Smith County, and Tulia, Swisher County, Lower Dockum Group ground water supplements other water supplies during summertime peak demand periods. The City of Hereford mixes Dockum Group ground water with water from the Ogallala Formation because of an objectionable taste and in order to dilute total dissolved solids. Small amounts of ground water are used for domestic supply and stock watering in the Dockum Group outcrop areas. Water quality in the outcrop belt is related to local hydrogeology and varies from place to place.

TABLE 3. Municipal water-supply use of Dockum Group ground water, northern part of the Southern High Plains.

Location	1983 gal	1983 m^3	1984 gal	1984 m^3
Happy, Texas	33,609,000	127,200	36,650,000	138,840
Hereford, Texas	72,750,000	275,600	49,800,000	188,658
Tulia, Texas*	250,000,000	1,022,714	87,909,000	333,027

*Includes ground water from Ogallala Formation in well field.

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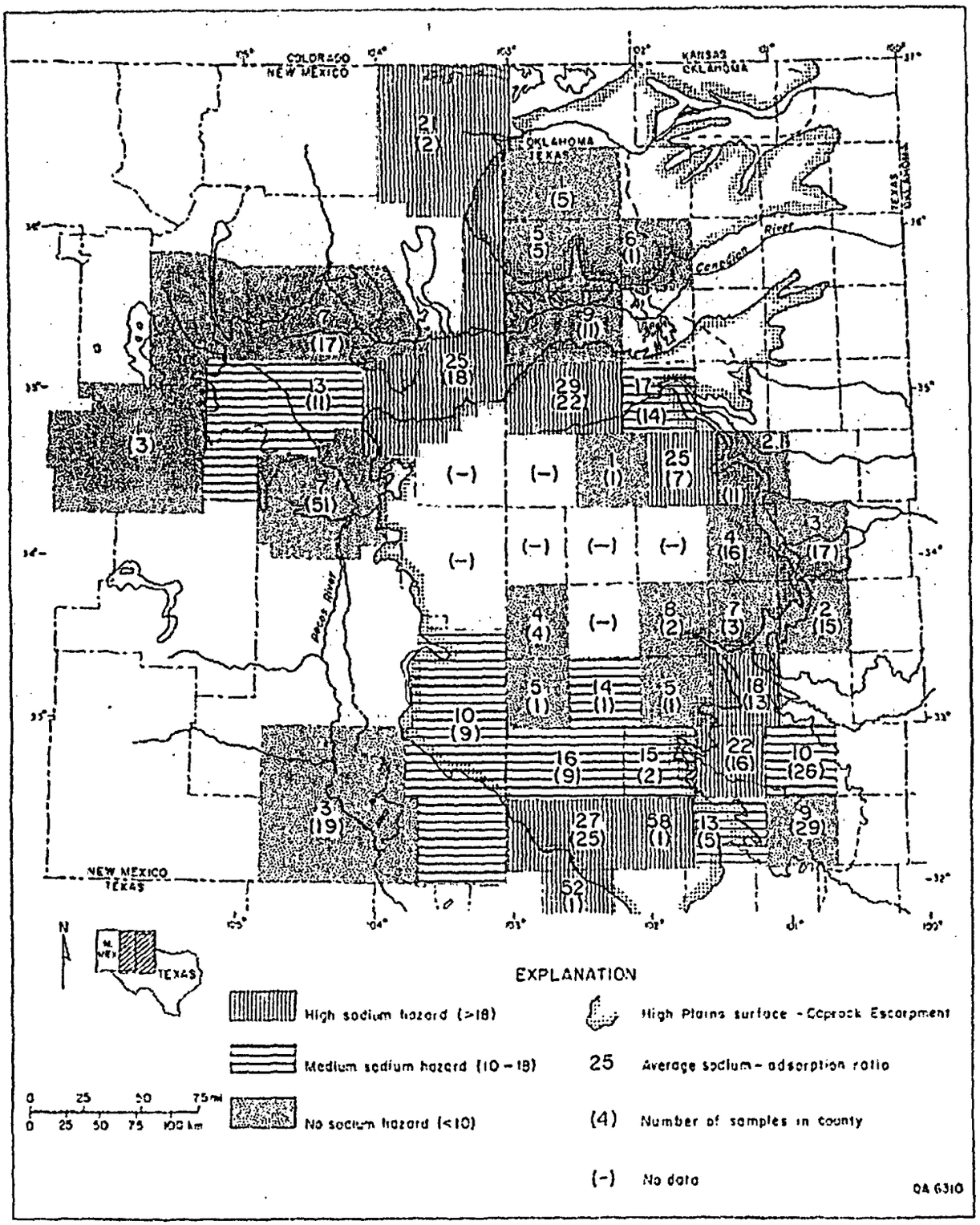

FIGURE 13. Mean value of sodium adsorption ratio by county. Definition of salinity hazard due to sodium from U.S. Salinity Laboratory (1954).

LES-005040

Slightly saline Na-HCO_3 and Na-mixed-anion hydrochemical facies in the southern part of the Southern High Plains ground-water basin are used extensively to water flood oil fields in the Permian Basin. The dissolved salt content is incompatible with formation waters in some oil fields. Regulatory statutes encourage use of the slightly saline Dockum Group water so that fresh water is reserved for other purposes; therefore, oil companies develop Dockum Group ground water for water-flood operations even though the production cost is greater than that of other sources of water.

At least 47 wells inject oil field brine into the Dockum Group. Most of the wells are in Borden (injection zone depth = 500 to 1,900 ft, or 152.4 to 579.1 m), Garza (300 to 1,000 ft, or 152.4 to 579.1 m), Hockley (1,500 to 2,000 ft, or 457.2 to 609.6 m), and Lubbock (1,100 to 1,425 ft, or 335.3 to 434.3 m) Counties. Brine injection in the Dockum Group outcrop areas of Garza, Crosby (injection zone depth = 394 to 1,300 ft, or 120.1 to 396.2 m), and Mitchell (500 to 700 ft, or 152.4 to 213.4 m) Counties is a potential hazard to fresh-water supplies in the Dockum Group and Ogallala Formation. Fresh-water supplies in these counties have already undergone some brine contamination from now-abandoned brine-disposal pits (Burnitt and Crouch, 1964; Crouch and Burnitt, 1965).

DISCUSSION

Origin of Ground Water in the Lower Dockum Group

The presence of ground-water-basin divides around the northern and western perimeters of the Southern High Plains suggests that currently no deep recharge of ground water comes from Dockum Group outcrops in the Pecos and Canadian River valleys (fig. 5). Precipitation that falls on the Dockum Group outcrop in these valleys moves away from the Southern High Plains ground-water basin. After the ground-water-basin divides formed between the Pecos River valley and the Southern High Plains, Dockum Group ground water could have been recharged only by ground water percolating downward from the Ogallala Formation or Edwards/Trinity Groups. Because hydraulic head of ground water in the High Plains aquifer is above the hydraulic head of ground water in the Lower Dockum Group (fig. 3), a potential for downward percolation of ground water exists. The several-hundred-foot difference in hydraulic heads suggests that the volume of cross-formational recharge to the Dockum Group is much less than 0.188 inch/yr (0.5 cm/yr), approximately the present rate of recharge to the High Plains aquifer (Knowles and others, 1984; Nativ and Smith, 1985). The difference in hydraulic heads might reflect either a loss of head because of resistance to ground-water flow downward through low-permeability mudstones or a decrease of ground water stored in the Dockum Group due to the present lack of substantial recharge and the continuation of discharge in springs and seeps along the Eastern Caprock Escarpment and western part of the Rolling Plains. Low-permeability mudstone in the Upper Dockum and at the top of the Lower Dockum retards recharge. The regional depression in the potentiometric surface of Lower Dockum Group ground water in the southern part of the Southern High Plains (fig. 5) may be at least partly due to the lack of cross-formational recharge, as previously suggested.

Low volume of cross-formational recharge to the Lower Dockum Group is also suggested by the fact that Dockum Group ground water is in general isotopically and chemically distinct from ground water in the High Plains aquifer. The volume of cross-formational recharge from the High Plains aquifer under present conditions is too low to modify the chemical and isotopic composition of Dockum Group ground water.

Isotopic and chemical differences between ground waters in the Lower Dockum Group and in the Ogallala Formation probably indicate that Lower Dockum Group ground water was recharged by precipitation during the Pleistocene at elevations of 6,000 to greater than 7,000 ft (1,830 to greater than 2,130 m) in Dockum Group sandstones that were later eroded from the Pecos Plains and Pecos River valley. Before the Pecos River valley was fully incised during the late Pleistocene (Gustavson and Finley, 1985), the prominent ground-water-basin divide along the western side of the Southern High Plains (fig. 5) may have been absent. Precise timing of development of the ground-water-basin divide has not been established because it depends on the timing and history of erosion in the Pecos River valley. Recharge of Dockum Group ground water from the west may explain $\delta^{18}O$ and δD values because elevation of the recharge area could have been several thousand feet higher than that of the northern part of the Southern High Plains. The $\delta^{18}O$ and δD values of precipitation decrease with increasing elevation because of the effect of cooling on the isotopic fractionation between vapor and

LES-005041

precipitation. Isotopic composition of Dockum Group ground water below the Southern High Plains is generally similar to isotopic composition of modern ground water in rocks of the Permian San Andres Formation that crop out in the Pecos Plains (Gross and others, 1982). The oxygen and hydrogen isotopes of Dockum Group ground water were probably not depleted by reaction with rock or by evaporation, which would have enriched the heavy isotopes in water, and they probably did not mix with other, nonmeteoric, ground waters, which would have yielded waters that plot away from the meteoric water line.

Effects of continental glaciation during the middle to late Pleistocene on local air temperature and on isotopic composition of recharge water may have been superimposed on the elevation effect. Clayton and others (1966), Gat and Issar (1974), Perry and others (1982), and Friedman (1984) described so-called "fossil waters" or "paleowaters" that were recharged during Pleistocene glacial episodes when cool, humid climates existed. In these studies, $\delta^{18}O$ and δD values of Pleistocene-age ground water were found to be depleted, relative to both modern precipitation and ground water at shallow depths, by approximately the same amount as the differences in $\delta^{18}O$ and δD values between ground waters in the Ogallala Formation and Lower Dockum Group. The primary cause of isotopic depletion appears to be cooler mean annual temperature across the recharge area during glacial periods. Temperature and humidity at the source of the precipitable water, storm trajectories, differences between summer and winter precipitation, and duration and intensity of rainfall also influence isotopic composition of recharge water (Gat, 1983). Precipitable water reaching the Texas Panhandle and eastern New Mexico during the Pleistocene could have been more depleted in $\delta^{18}O$ and δD than modern precipitation, relative to SMOW, because the Gulf of Mexico coastline was approximately 100 mi (160 km) farther from the Texas Panhandle owing to episodic lowering of Pleistocene sea level (Stuart and Caughey, 1979). Precipitation becomes progressively depleted in heavy isotopes with distance from the source because of fractionation between condensed water and remaining vapor during successive precipitation events. Elevation of the Southern High Plains probably did not change greatly during the Quaternary, so no tectonic effect on isotopic composition (Coplen and Davis, 1984; Winograd and others, 1985) occurred.

The age of Dockum Group ground water in the Southern High Plains ground-water basin must be determined to verify the origin of the water. If Dockum Group ground water was recharged primarily by intrastratal flow from the west before late Pleistocene development of ground-water-basin divides, much of the ground water in the Dockum Group beneath the Southern High Plains may be older than 600,000 yr, the age of incision of the Pecos River into the Diamond A-Mescalero Plain near Fort Sumner, New Mexico (Gustavson and Finley, 1985). Younger ground water could enter the Dockum Group below the Southern High Plains only by cross-formational flow where the aquifer in the Dockum Group is hydrologically connected to the High Plains aquifer or to aquifers in Upper Permian rocks.

Although the age of Lower Dockum Group ground water has not been determined, a water sample from a well in the Lower Seven Rivers Formation (Upper Permian) in the northern part of the Southern High Plains was dated at roughly 19,000 to 34,000 yr B.P. (table 4). The ground-water sample

TABLE 4. Estimation of carbon-14 age of water from the SWEC Mansfield No. 2 well.

Data:	[^{14}C] activity	1.7% ± 0.13%
	$\delta^{13}C_{sm}$	-3.1 ‰ PDB
	[HCO_3]	41.53 mg/L
	pH	7.2
Approach:	$Age = -k \ln\left[\frac{^{14}C\ \%Mdn}{100\ P}\right]$	(Pearson and White, 1967)
	$k = 5{,}730\ yr/\ln 2$	
	$P = \delta^{13}C_{sm}/\delta^{13}C_t$	Estimates ratio of atmospheric-derived carbon to total carbon in system
	$\delta^{13}C_t$	Typical value of recharge water
Assumption:	$\delta^{13}C_t$ is -17.9 ‰ PDB based on CO_2 in unsaturated zone of Ogallala Formation below playa lakes (Wood and Petraitis, 1984).	
Result:	Age is 19,200 ± 600 yr; P = 0.173.	
	Age is 33,700 ± 600 yr; P = 1.0 (no correction).	

LES-005042

from the Stone and Webster Engineering Corporation (SWEC) Mansfield No. 2 well is assumed to have flowed from the Lower Dockum Group into Upper Permian rocks because oxygen and deuterium isotopic compositions of the water sample are similar to isotopic compositions of Dockum Group ground water in the area (figs. 7 and 8). The SWEC Mansfield No. 2 well is located in the Canadian River valley in Oldham County, Texas, where erosion has removed the Ogallala Formation and Upper Dockum Group (Dutton, 1985). The test well produces from a depth of 723 to 778 ft (220.4 to 237.1 m) below land surface (fig. 8). The sample age (table 4) suggests that the isotopically depleted water in the Lower Dockum Group was recharged during late Wisconsinan time (Johnson, 1982) of the late Pleistocene. The range in estimated age reflects uncertainty in the correction of absolute carbon-14 activity for the amount of non-atmospheric carbon present in the sample (Pearson and White, 1967). The widespread Wisconsinan deposits across the Southern High Plains indicate that the climate during late Wisconsinan time was cooler and more humid than the modern climate (Caran and McGookey, 1983). Oxygen and deuterium isotopic composition of ground-water recharge during late Wisconsinan time may have been depleted relative to modern precipitation in the northern part of the Southern High Plains. By late Wisconsinan time, the regional ground-water-basin divides were probably fully developed (Gustavson and Finley, 1985) and limiting recharge to the Dockum Group in the Southern High Plains to cross-formational flow.

Figure 14 illustrates how regional ground-water flow paths may have been changed by the erosion of the Pecos River valley. From the late Tertiary to early Quaternary, ground-water recharge to the Ogallala and Dockum Group aquifers could have taken place at elevations above 6,000 ft (1.8 km) in eastern New Mexico. Hydraulic head in the Dockum Group may have been similar to the water-table elevation in the Ogallala Formation, and cross-formational flow of ground water may have been minimal. Excavation of the Pecos River valley isolated Dockum Group ground water beneath the Southern High Plains from recharge areas at higher elevations. The timing of development of ground-water-basin divides relative to the lateral inflow of recharge water from the west is at present imprecise. Volume of recharge from the west before the ground-water-basin divides were established is assumed to have been large, in part because the sandstone-distribution maps (figs. 4a and 4b) suggest that the sandstone section thickened to the west in the location of the present Pecos River valley. Some deep percolation of ground water from the Ogallala Formation may now slowly take place in areas where the two hydrostratigraphic units are somewhat connected by sandstone deposits.

Mineralogic Controls on Chemical Composition

Because samples indicate a meteoric origin for Lower Dockum Group ground water, reactions with minerals affect the chemical composition of the ground water, including the Na-HCO_3 hydrochemical facies in the northern part of the Southern High Plains, the saline, Na-Cl hydrochemical facies in the central part, and the Na-SO_4 hydrochemical facies in the southern part. Calcite, chalcedony, dolomite, feldspar, kaolinite, pyrite, opal, and smectite appear to exert significant control on all the hydrochemical facies. Other possible influences include oxidation of pyrite and organic matter, inflow and mixing of ground water that dissolved anhydrite and halite from Permian strata, and diffusion of connate Cretaceous seawater from low-permeability Dockum mudstones.

Almost all ground-water samples from the Lower Dockum Group plot within the fields of stability of kaolinite and smectite (figs. 15 through 17). Kaolinite and smectite, common authigenic cements in Dockum Group sandstones (Johns, 1985), readily form as weathering products from feldspar and other silicate minerals (Garrels, 1976). Both potassium- and sodium-rich feldspars are present in Dockum Group sandstones (Johns, 1985). The chemical composition of water suggests that calcium-rich smectite is more prevalent than sodium-rich smectite in the Dockum Group (fig. 16). Kaolinite and smectite appear to be in thermodynamic equilibrium with dissolved ions in some samples of Dockum Group ground water (figs. 15 and 16). However, in interpreting position of data on phase diagrams, it is important to remember that phase boundaries were calculated assuming that activity of water is equal to unity, and temperature is 77°F (25°C). Activity of water and temperature of samples were ignored in plotting data. Errors in these assumptions may affect the scatter of data relative to the phase boundaries.

In almost all samples the concentration of monosilicic acid (H_4SiO_4) is greater than 18 mg/L and less than 186 mg/L (fig. 15). Data distribution suggests that low concentrations of dissolved silica are limited by solution equilibrium with chalcedony (log K = -3.73) and with kaolinite and that high concentrations are limited by solution equilibrium with amorphous silica or opal (log K = -2.71) and with smectite. The abundant detrital chert in the Dockum Group must buffer silica concentrations, but authigenic silica cements such as chalcedony and opal within sandstones also buffer silica concentrations. A preliminary petrographic study noted that scattered examples of quartz cement

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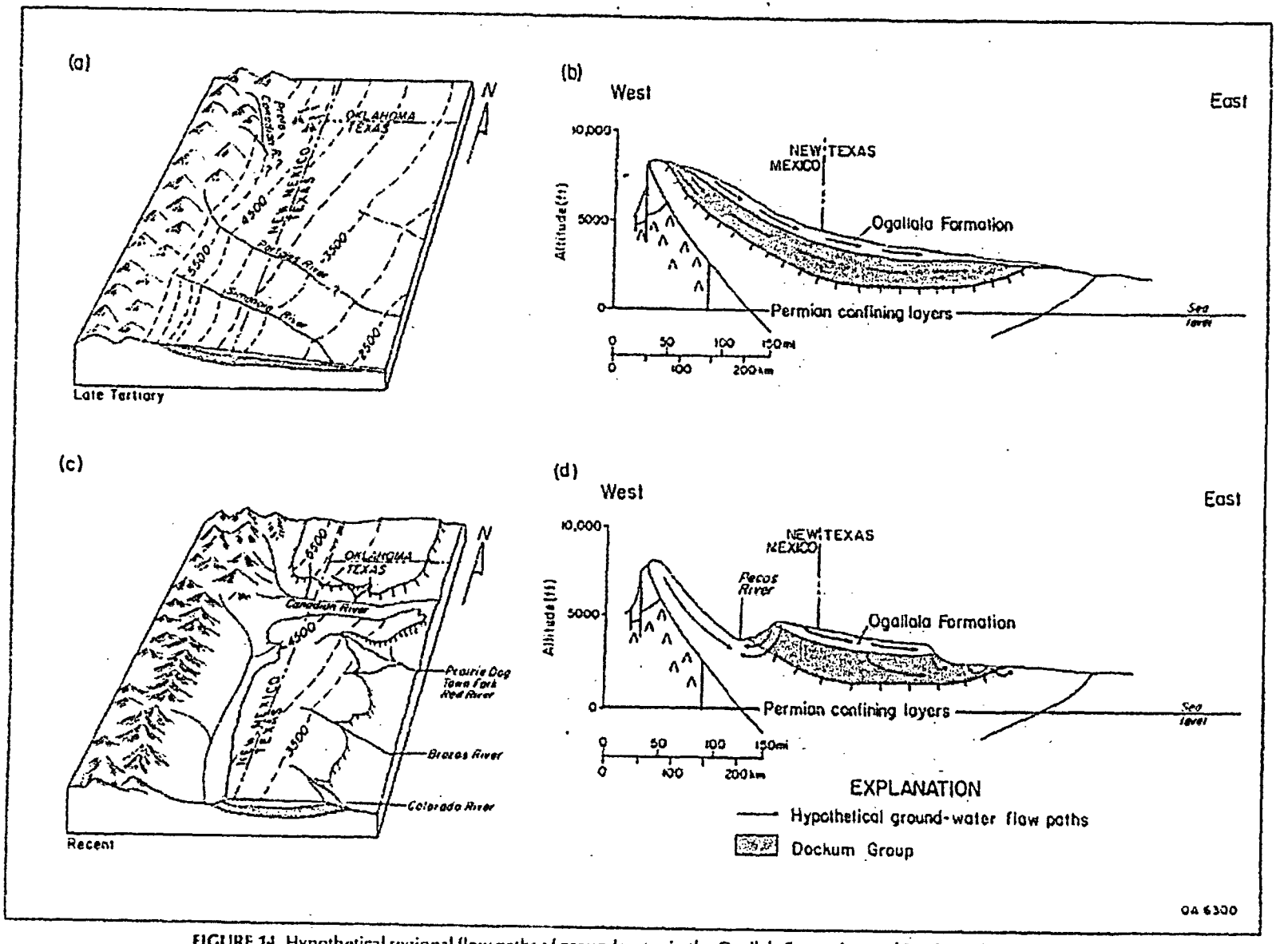

FIGURE 14. Hypothetical regional flow paths of ground water in the Ogallala Formation and Dockum Group before (b) and after (d) development of the Pecos River valley. Block diagrams (a and c) modified from Gustavson and Finley (1985).

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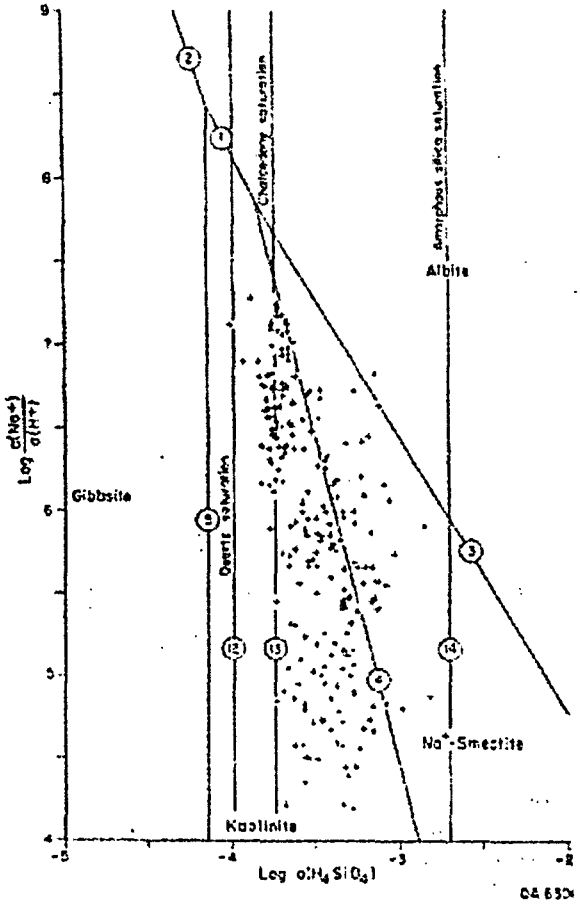

FIGURE 15. Diagram showing chemical composition of Lower Dockum Group ground water relative to stability fields of minerals in the NaO-SiO_2-H_2O system at 77°F (25°C), based on data from Helgeson (1969, 1978). Equilibrium reactions between minerals and dissolved ions are numerically keyed to table 1.

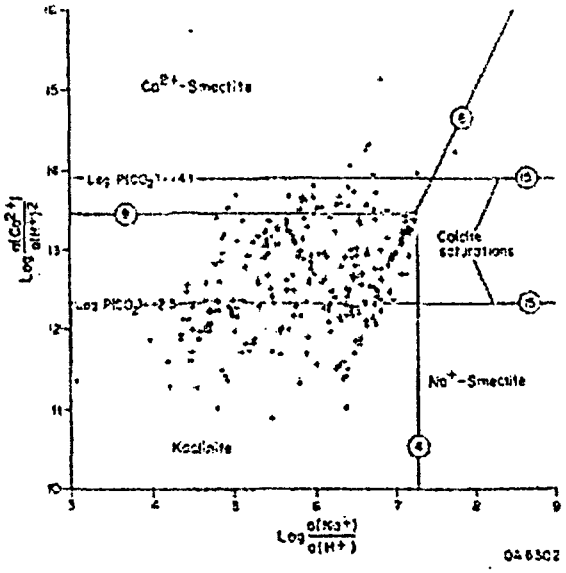

FIGURE 16. Diagram showing chemical composition of Lower Dockum Group ground water relative to stability fields of minerals in the NaO-CaO-SiO_2-H_2O-CO_2 system at 77°F (25°C), based on data from Helgeson (1969, 1978) and assuming $\log[H_4SiO_4]$ activity of -3.64. Equilibrium reactions between minerals and dissolved ions are numerically keyed to table 1.

formed as overgrowths on detrital quartz grains (Johns, 1985), but chalcedony and opal cements have not been described. Iler (1979, p. 79) stated that amorphous silica is deposited from the greatest concentrations of dissolved silica, then chalcedony is deposited from a lower concentration, and finally macroscopic quartz crystals are deposited from the lowest concentrations just exceeding the saturation level of quartz. Iler noted that through millions of years most amorphous silica in the presence of water is eventually transformed to chalcedony or chert and quartz.

Partial pressures of dissolved CO_2 gas in Dockum Group ground water, calculated by the program SOLMNEQ (Kharaka and Barnes, 1973) from pH and alkalinity measurements, range from a low of $10^{-4.1}$ atm to a high of $10^{-0.3}$ atm. Calculated partial pressures are greater than true partial pressures because of loss of CO_2 gas and rise in pH during sample collection and storage. Figure 17 shows the equilibrium boundary between dolomite and calcite fields of stability (line 16) superimposed on the phase diagram for the MgO-CaO-SiO_2-H_2O-CO_2 system. Carbon dioxide outgassing does not affect the Ca^{2+}/Mg^{2+} ratio as long as calcite does not precipitate during sample collection. Dockum Group ground waters cluster more tightly along this equilibrium boundary than along other phase boundaries shown in figures 15 and 16, and they extend along this boundary from the kaolinite to the chlorite stability fields, suggesting that concentrations of dissolved calcium and magnesium are controlled more closely by calcite and dolomite than by equilibration with smectite. Coarse, sparry calcite is the most common authigenic cement in the Dockum Group at one well in the northern part of the Southern High Plains (Johns, 1985). Euhedral rhombs of dolomite were also

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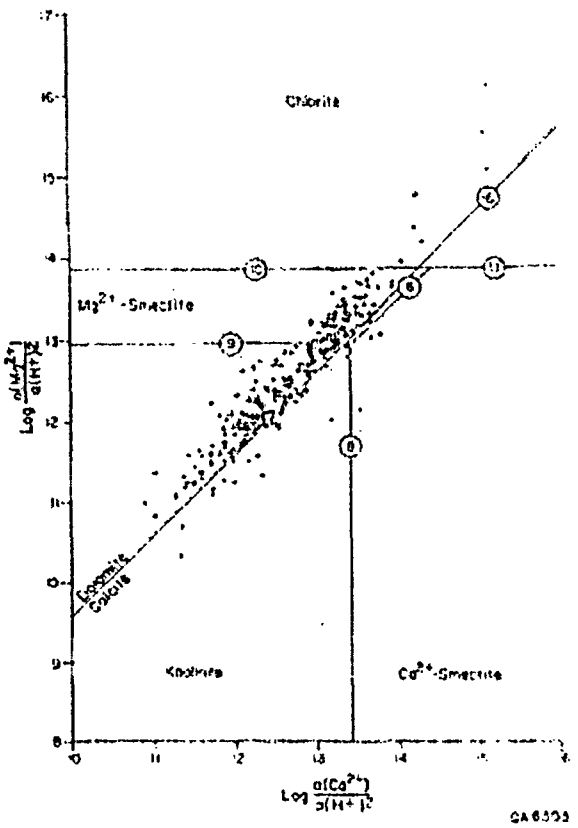

FIGURE 17. Diagram showing chemical composition of Lower Dockum Group ground water relative to stability fields of minerals in the MgO-CaO-SiO_2-H_2O-CO_2 system at 77°F (25°C), based on data from Helgeson (1969, 1978) and assuming log[H_4SiO_4] activity of -3.64. Equilibrium reactions between minerals and dissolved ions are numerically keyed to table 1.

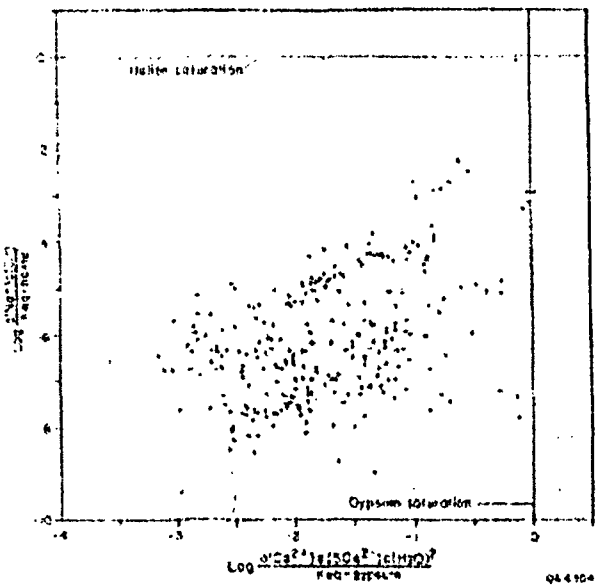

FIGURE 18. Plot of saturation indices relative to halite and gypsum calculated for Lower Dockum Group ground waters using the computer program SOLMNEQ.

found in Dockum Group sandstones (D. A. Johns, written communication, 1986).

Chemical compositions of water from different geographic regions plot in overlapping fields as shown in figures 15 through 19, suggesting that the various hydrochemical facies are controlled by the same set of mineralogic reactions. The main differences are correlated with salinity; the brackish to saline waters from the central part of the Southern High Plains form one end member, and the fresh ground waters from the northern part of the Southern High Plains form the other.

Chemical composition of Dockum Group ground water in the northern part of the Southern High Plains could have developed as a result of fresh recharge water reacting in the Dockum Group with calcite, chalcedony, dolomite, feldspar, kaolinite, opal, pyrite, and smectite. Ground water in most of the northern part of the study area is dominated by Na-HCO_3 hydrochemical facies, but locally Ca-HCO_3 hydrochemical facies occur in the Lower Dockum Group (fig. 10a). The Na-HCO_3 facies tend to be at greater depth or to occur farther along a flow path away from a recharge source compared with the distribution of Ca-HCO_3 hydrochemical facies. The Na-HCO_3 facies may reflect weathering of sodium-rich feldspars or exchange of dissolved calcium with sodium adsorbed on clays. Foster (1950), Back (1966), Kreitler and others (1977), Thorstenson and others (1979), and Fogg and Kreitler (1982) suggested that Na-HCO_3 facies originates with solution of calcite and exchange of dissolved calcium for adsorbed sodium. Dissolved bicarbonate probably derives from solution of calcite and dolomite; high concentrations of bicarbonate, such as those found in the Dockum Group, can develop when calcium and magnesium are removed from solution by ion exchange, which allows more solution of calcite and dolomite (Fogg and Kreitler, 1982). The Na-mixed-anion and mixed-cation-HCO_3 ground waters reflect additional reactions or sources of water. The mineralogic controls mentioned previously apply regardless of whether Dockum Group ground water was recharged by intrastratal flow from pre-Holocene outcrops or by cross-formational flow from the High Plains aquifer.

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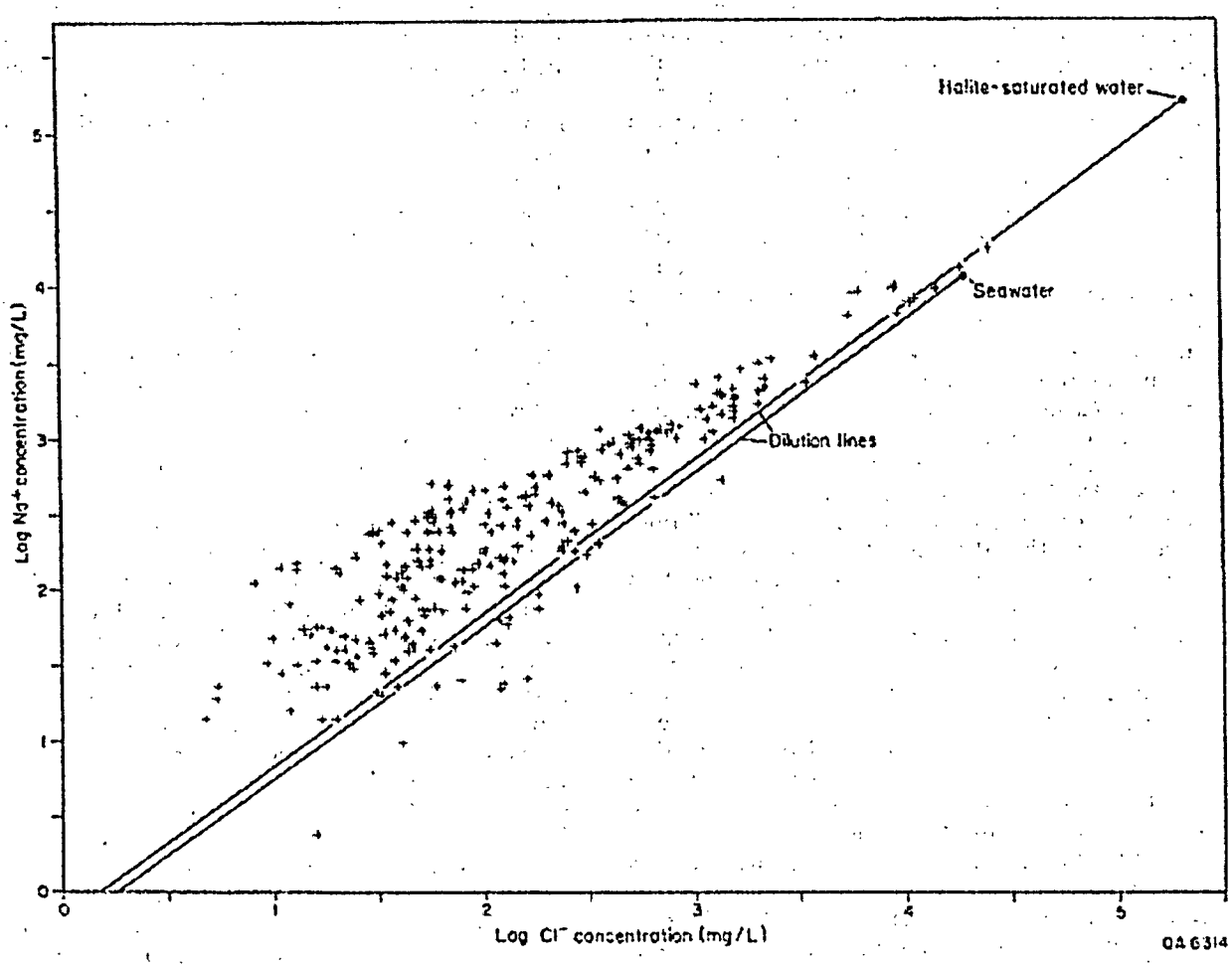

FIGURE 19. Plot of sodium and chloride concentrations in Lower Dockum Group ground water with lines representing fresh-water dilution of seawater and halite-saturated water. Halite-saturated water is assumed to contain 6.2 mol of halite/kg of solution. Concentrations along dilution lines are not corrected for density changes.

Two possible sources of large concentrations of dissolved chloride in Na-Cl hydrochemical facies and in other Dockum Group waters are (1) ground-water flow that dissolved Permian halite from Permian strata and carried it into the Lower Dockum Group and (2) preservation of diluted connate seawater that could have flushed through the Dockum Group during the protracted marine transgression in the Cretaceous, represented by the marine deposits of the Edwards/Trinity Groups. For chlorinity to have been caused by dissolution of Permian halite, an upward-directed component of ground-water flow must have existed at the top of the Permian section below the central part of the Southern High Plains; however, this supposition cannot be tested because the potentiometric surface of ground water in the Upper Permian section is generally unknown. In the northern part of the Southern High Plains, hydraulic head of ground water in Upper Permian rocks is now lower than hydraulic head of Lower Dockum Group ground water, and chlorinity and salinity of Dockum Group ground water are low (Dutton, 1985), which together indicate that ground water flows downward into Permian rocks. During the Late Tertiary, after the western side of the Permian Basin was uplifted by Basin and Range tectonism, a potential for upward flow of ground water from the Upper Permian section into the base of the Dockum Group may have existed (Senger, 1984).

If chloride and other salts remain in Dockum Group ground water from seawater that percolated downward into Dockum Group rocks during the

LES-005047

Cretaceous transgression, recharge of meteoric ground water and displacement of Cretaceous ground water must have been negligible during the Cenozoic. Modified seawater most likely remains in low-permeability mudstones and diffuses into ground water in sandstones in the central part of the Southern High Plains ground-water basin. Regionally, both Cretaceous seawater and solution of Permian evaporites may have contributed to salinity levels. However, reported analyses of saline Na-Cl ground water (app. B) lack diagnostic ions such as bromide and iodide, which have been used in other studies to interpret the origin of salinity (Whittemore, 1984).

The most saline ground waters in the Lower Dockum Group are only two orders of magnitude undersaturated with respect to halite (fig. 18). Figure 19 shows sodium and chloride concentrations of Lower Dockum Group ground water and dilution lines of modern seawater and of brine in equilibrium with halite. The data points with the greatest concentrations of chloride are near the halite dilution line and have a Na^+/Cl^- weight ratio of about 0.65, the Na^+/Cl^- ratio in halite. At smaller chloride concentrations the range of Na^+/Cl^- ratios is wide, from less than 0.55 (seawater) to greater than 8.0. Regardless of whether the dissolved chloride derives from halite or seawater, the increase in sodium relative to chloride probably reflects addition of sodium from the weathering of silicate minerals and formation of clays, as suggested in figures 15 and 16.

The Na-Cl hydrochemical facies (fig. 10a) occurs in mudstones and thin sandstones at the center of the Dockum Group depositional basin (fig. 4a). Diffusion of chloride in ground water from mudstones into sandstones is slow and can continue indefinitely where low-permeability sandstones are poorly interconnected hydrologically (Domenico and Robbins, 1985), such as at the basin center. It is likely that seawater invaded the Triassic sediments during the Cretaceous, but whether significant volumes of that water or of the dissolved ions remain has not been proved. Ground water in the Cretaceous Edwards/Trinity Groups now is less saline than Dockum Group ground water, but sodium and chloride are still predominant (Nativ and Smith, 1985).

Origin of sulfate ions in Dockum Group ground water also is poorly understood. Dissolved sulfate could originate from Permian gypsum, from oxidation of sulfide minerals such as pyrite, which is common in the Dockum Group, and from Cretaceous seawater.

The $Na\text{-}SO_4$ hydrochemical facies in the southern area of the Southern High Plains may derive from ionic exchange of (1) sodium adsorbed on clay minerals and (2) calcium dissolved in ground water discharged from Upper Permian strata bearing gypsum or anhydrite. This process is similar to the generation of $Na\text{-}HCO_3$ water by ion exchange, but gypsum or anhydrite is dissolved instead of calcite. The most saline ground waters in the Dockum Group approach saturation with respect to gypsum (fig. 18). As previously mentioned, large positive $\delta^{34}S$ values indicate that dissolved sulfate of several ground-water samples from the Dockum Group outcrop derived from solution of Permian gypsum or anhydrite (fig. 11, table 2).

The $Na\text{-}SO_4$ water in the southern part of the Southern High Plains may also originate as $Ca\text{-}HCO_3$ or $Na\text{-}HCO_3$ water, to which dissolved sulfate is added from oxidation of pyrite and from which calcium is exchanged for sodium adsorbed on clays. The $Na\text{-}SO_4$ hydrochemical facies contains several hundred milligrams of bicarbonate per liter. Negative $\delta^{34}S$ values of some samples reflect pyrite oxidation.

No water samples collected in this study had $\delta^{34}S$ values in the +14 to +16 ‰ range typical of marine sulfate during Cretaceous time (Holser, 1979), and in a few samples the sulfate concentration exceeds the concentration in seawater. This indicates that Cretaceous seawater is not everywhere the source of high concentrations of dissolved sulfate, which weakens the argument that Cretaceous seawater is a source of dissolved chloride ions.

Sodium-sulfate deposits occur around saline lakes in the southern part of the Southern High Plains (Reeves, 1963; Bluntzer, 1984) and are associated with the remains of Pleistocene lakes in the Northern Great Plains of Canada and the United States (Grossman, 1968). These deposits probably result from dissolution of evaporites and changes in water composition during subsequent evaporation. Sodium-sulfate deposits are unknown in Dockum Group lacustrine sediments.

LES-005048

CONCLUSIONS

The shape of the potentiometric surface and the location of ground-water-basin divides in the Lower Dockum Group are controlled by Dockum Group stratigraphy and by topographic positions of the Dockum Group outcrops and the Caprock Escarpment. Ground-water-basin divides along the western and northern limits of the Southern High Plains reflect truncations of the Dockum Group potentiometric surface by the Pleistocene erosion of the Pecos and Canadian River valleys. The ground-water-basin divides prevent modern recharge in the Dockum Group outcrops from reaching confined parts of the Dockum Group aquifer. Dockum Group ground water in the Southern High Plains ground-water basin was probably recharged in eastern New Mexico before the Pecos River excavated its valley and eroded thick Dockum Group sandstones. Throughout the Southern High Plains ground-water basin, $\delta^{18}O$ and δD values of Dockum Group ground water are depleted relative to ground water in the Ogallala Formation, suggesting that Dockum Group ground water was recharged in a cool climate, most likely at higher elevations in eastern New Mexico during the Pleistocene. Present ground water in the Pecos Plains, where Dockum Group ground water may have been recharged, has $\delta^{18}O$ and δD values similar to that of Dockum Group ground water beneath the Southern High Plains.

The chemical composition of Dockum Group ground water is derived largely from reactions of recharged ground water with minerals. Chemical weathering of silicate minerals, equilibration with calcite and dolomite, and ion exchange determine major features of ground-water composition in the Dockum Group in the northern part of the Southern High Plains. Potable ground water occurs in thick sandstone deposits in the Dockum Group across the northern part of the Southern High Plains, but it may pose a salinity hazard to soil. Brackish to saline Na-Cl hydrochemical facies in the central part of the Southern High Plains indicates that either (1) ground water that dissolved halite in Permian rocks discharged into the Dockum Group or (2) Cretaceous seawater was flushed from marine formations of the Edwards/Trinity Groups but not from the Dockum Group in areas of low transmissivity and poorly connected sandstone deposits. Chemical compositions of waters that either discharged into the Dockum Group from Permian rocks or invaded the Dockum Group during the Cretaceous have been modified by reactions with silicate and carbonate minerals. Fresh to brackish Na-SO_4 water in the southern part of the Southern High Plains most likely originated from dissolution of Permian gypsum, ion exchange of dissolved calcium for adsorbed sodium, and oxidation of pyrite in the Dockum Group. In the Pecos and Canadian River valley ground-water basins, ground waters from the Ogallala Formation, Edwards/Trinity Groups, and Permian formations flow into the Dockum Group.

Current recharge rate to the aquifer in the Lower Dockum Group in the Southern High Plains is low, as indicated by ground water that is possibly 20,000 to 33,000 yr old. Accepting this age for Dockum Group ground water, and given the presence of ground-water divides and of low-permeability mudstones above the aquifer in the Lower Dockum Group, ground water in the Dockum Group appears to be less renewable than ground water in the Ogallala Formation. Wells completed in thin sandstone deposits in the Lower Dockum Group will probably encounter brackish to saline water below the Southern High Plains. High head lift and generally poor quality water with a high sodium adsorption ratio will continue to discourage development of Dockum Group ground water.

LES-005049

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LES-005050

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LES-005053

APPENDIX A. Estimated hydraulic properties of the Dockum Group, Texas Panhandle.

SUMMARY

In contrast to the large amount of information pertaining to hydraulic conductivity, storativity, and porosity of the Ogallala aquifer (Knowles and others, 1984), little is known about the hydraulic properties of the Dockum Group, which underlies the Ogallala Formation across much of the Texas Panhandle. An exhaustive search of the literature and of document files at the offices of the Texas Department of Water Resources and the High Plains Water Conservation District No. 1 yielded data from 4 pumping tests and specific capacity, or well performance, test data from another 62 wells. Storativity was reported for two tests. The hydrologic tests were performed around the perimeter of the Southern High Plains and along the outcrop of the Dockum Group east of the Southern High Plains, where sandstones in the Lower Dockum are fairly thick and yield good quality water.

Transmissivities are highest in Deaf Smith, Randall, and Swisher Counties, where Lower Dockum sandstones are most extensive and thick (fig. 4a). Average transmissivities by county range from 2,060 ± 860 ft^2/d (191 ± 80 m^2/d) in Deaf Smith County to about 30 ± 10 ft^2/d (3 ± 1 m^2/d) in Garza County. The two storativity values, 1×10^{-4} and 2×10^{-3}, reflect confined to partly unconfined aquifer conditions.

PUMPING TEST DATA

Myers (1969) presented results of two pumping tests in Lower Dockum sandstone, one at irrigation wells owned by V. J. Owens in Deaf Smith County and the other at City of Snyder municipal supply wells in Scurry County. F. A. Raynor (Interoffice Memorandum to Texas Water Commission files, February 24, 1963) discussed the Deaf Smith County test in detail and concluded that the best transmissivity estimate is approximately 2,940 ft^2/d (273 m^2/d). Myers (1969) reported that storativity was 1×10^{-4} at the V. J. Owens wells and 2×10^{-3} at the City of Snyder wells. These values are typical of confined to partly unconfined aquifers and are reasonable for the Dockum Group at these two sites.

Akin and others (1962) discussed pumping tests of Lower Dockum sandstones that crop out near Fort Sumner in De Baca County, New Mexico. They estimated that transmissivity in the test area is less than 270 ft^2/d (25 m^2/d).

Variable-rate or step-drawdown pumping tests were performed by drilling contractors at the City of Hereford No. 18 well and City of Tulia No. 13 well in 1966 and 1967, respectively. Transmissivity estimates from these tests follow. No observation wells were available to determine storativity.

Hereford No. 18 Well Pumping Test

An aquifer test at the City of Hereford No. 18 well was conducted from December 1 to December 4, 1966, by McDonald Drilling Company to characterize the production zone in Lower Dockum sandstones and to test well efficiency. The 16-inch O.D. well casing was cemented from land surface to a depth of 650 ft (198 m). The well screen consisted of a 16-inch O.D. pipe perforated with 12 rows of slots (3/8 inch × 10 inches) per foot of pipe between 682.8 and 944.0 ft (208.1 and 287.7 m) below land surface. Total depth of the well is 954 ft (290 m).

Test records indicated that static water level was at a depth of 450 ft (137.2 m) but that water level at the start of the test was 219.45 ft (66.8 m) deeper, suggesting there was residual drawdown from a preceding pumping period. The reported static water level was used in calculations of drawdown and residual recovery, but the earlier conditions that caused the initial drawdown were ignored. The test began at 1:00 p.m. on December 1 by pumping the well at 1,421 gal/min (5.4 m^3/min). The pump was shut down to repair a fuel leak at 11:03 a.m. on December 2 with the water level at 727.2 ft (221.7 m). When pumping was resumed at 12:45 p.m., the water level had recovered to 496.9 ft (151.5 m) below land surface. Figures A1a and A1b show the history of discharge rate and water-level change, respectively, during drawdown and subsequent recovery.

Drawdown data from the period before the pump shutdown were analyzed using the Jacob semilogarithmic approximation, assuming a constant discharge rate (fig. A1c). The Jacob approximation is valid because pseudosteady-state conditions were quickly reached near the pumping well, perhaps within 100 min after the test began (fig. A1c). Step-drawdown data were analyzed using the Cooper-Jacob method (Kruseman and De Ridder, 1976,

LES-005054

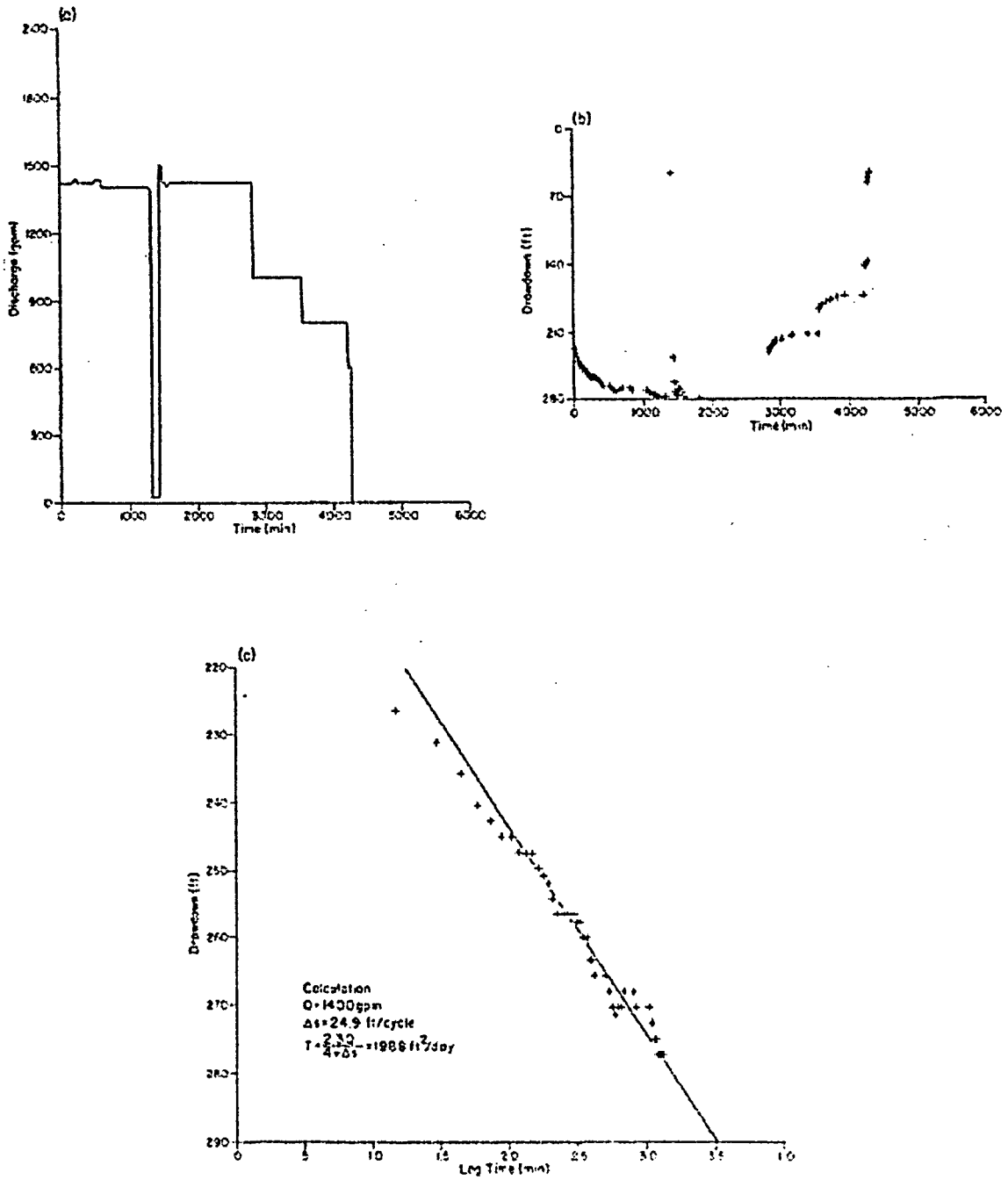
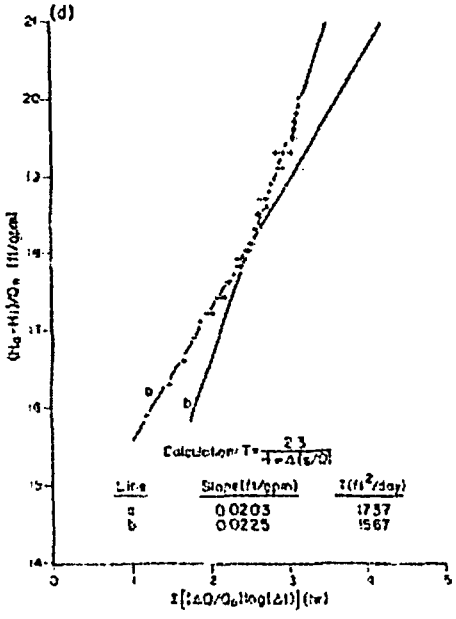
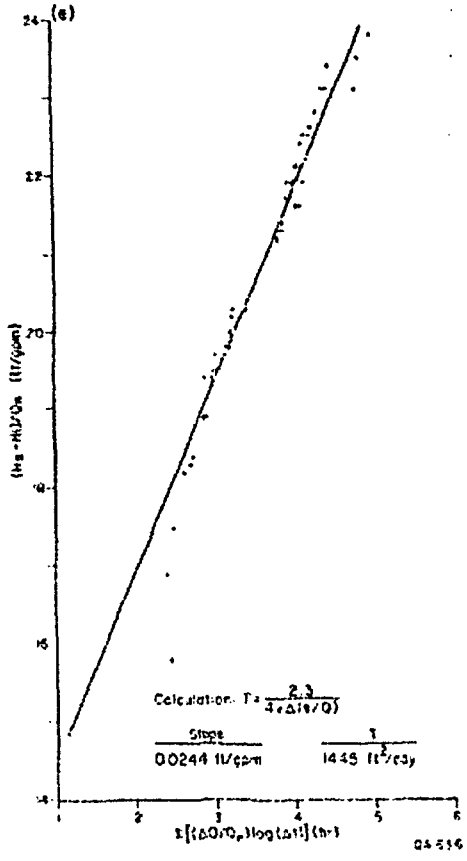


FIGURE A1. Data from pumping test at the City of Hereford No. 18 well. (a) Discharge rate. (b) Drawdown. (c) Drawdown from static water level plotted against logarithm of test

LES-005055





duration. (d) Step-drawdown test data for period before pump shutdown. (e) Step-drawdown test data for period after pump shutdown.

LES-005056

p. 138–140; Earlougher, 1977, p. 31–33), which assumes that the pseudosteady-state condition of constant rate of change of water level was reached. Figures A1d and A1e show data from the pumping periods that preceded and followed the pump shutdown, respectively. Increase in slope of the trend from line a to line b in the first period (fig. A1d) possibly indicates faulting, a transition to pseudosteady-state condition of constant rate of change of water level, or a decrease in hydraulic conductivity away from the well (Earlougher, 1977, p. 33). The three graphical analyses give similar values of transmissivity, ranging from 1,430 ft^2/d to 1,980 ft^2/d (134 m^2/d to 184 m^2/d).

Tulia No. 13 Well Pumping Test

An aquifer test at the City of Tulia No. 13 well was conducted from July 24 to July 28, 1967, by McDonald Drilling Company to characterize the production zone in Lower Dockum sandstones and to test well efficiency. The 16-inch O.D. well was cemented in a 20-inch borehole from land surface to a 600-ft (182-m) depth. The well screen consisted of a 16-inch O.D. pipe perforated with 12 rows of slots (5/16 inch × 8 inches, 4 inches apart) between 620 and 820 ft (189.0 and 249.9 m) below land surface. Total depth of the well was 828 ft (252.4 m).

Test records indicated that static water level was 364 ft (110.9 m) below land surface but that at the start of the test the water level was 85 ft (25.9 m) deeper, suggesting residual drawdown from a preceding pumping period. The reported static water level was used in calculations of drawdown and residual recovery, but the earlier conditions that caused the initial drawdown were ignored. The test began at 9:00 a.m. on July 24 by pumping the well at 2,000 gal/min (7.6 m^3/min). Figures A2a and A2b show the history of discharge rate and of water-level change, respectively, during drawdown and subsequent recovery.

Drawdown data from the long period during which pumping rate was constant were analyzed using the Jacob semilogarithmic approximation (fig. A2c). Step-drawdown data were analyzed using the Cooper-Jacob method (fig. A2d). The straight-line solutions are appropriate because pseudosteady-state conditions were quickly reached near the pumping well, perhaps within 500 min after the test began (fig. A2c). The best-fit line for the step-drawdown test is difficult to determine because of data variability; three possible lines are shown in figure A2d. Transmissivity values from the constant-rate and step-production-rate analyses range from 2,080 ft^2/d to 3,860 ft^2/d (193 m^2/d to 358 m^2/d).

Specific Capacity Data

Specific capacity, or well performance, tests are sometimes performed in new wells to determine well yield and size of a suitable pump. Specific capacity (discharge rate per unit drawdown, Q/s) is a tool used in reconnaissance studies to estimate transmissivity (Brown, 1963; Theis, 1963; Walton, 1970, p. 311–321; Macpherson, 1983). During a test, drawdown in a pumping well is measured while discharge is held constant, ideally until the change in drawdown with time is small. Tests in municipal wells generally last at least 24 hr. Tests in irrigation wells usually last 6 to 8 hr; 2-hr tests are also common (table A1). The pumping rate is decreased during the test to keep the water level in the well above the pump intake. In such cases, the final pumping rate is typically reported as well yield (Heath, 1983). Accuracy of estimates by this method are affected by partial penetration of wells and by well losses. Most wells in the Dockum Group appeared to completely penetrate productive sandstone deposits. Wells that are inefficient because of turbulent flow in or adjacent to the well or because of drilling damage to permeability around the wellbore show a well loss that is an extra amount of drawdown per given discharge rate. Well loss decreases the apparent specific capacity and results in underestimates of transmissivity. Data from the two variable-rate pumping tests were inadequate for characterizing well-loss coefficients for typical Dockum wells, and well loss was assumed to be zero in all wells used in this study.

Brown (1963) and Theis (1963) derived general formulas for estimating transmissivity from specific capacity tests by assuming typical values of transmissivity and storativity for unconfined and confined aquifers. Transmissivity estimated from these formulas is more sensitive to an error in the assumed storativity value than to an error in the assumed transmissivity value. To increase the accuracy of Dockum Group transmissivity estimates, the formulas were rederived using transmissivity and storativity values from pumping tests that were assumed to be typical of Dockum Group sandstones. Transmissivity estimates from specific capacity data were similar to those calculated from the four available pumping test records (table A2).

Derivation of Transmissivity Formulas from Specific Capacity Tests

Derivation of formulas for estimating transmissivity from specific capacity test data follows the steps presented by Brown (1963) and Theis (1963) for

LES-005057

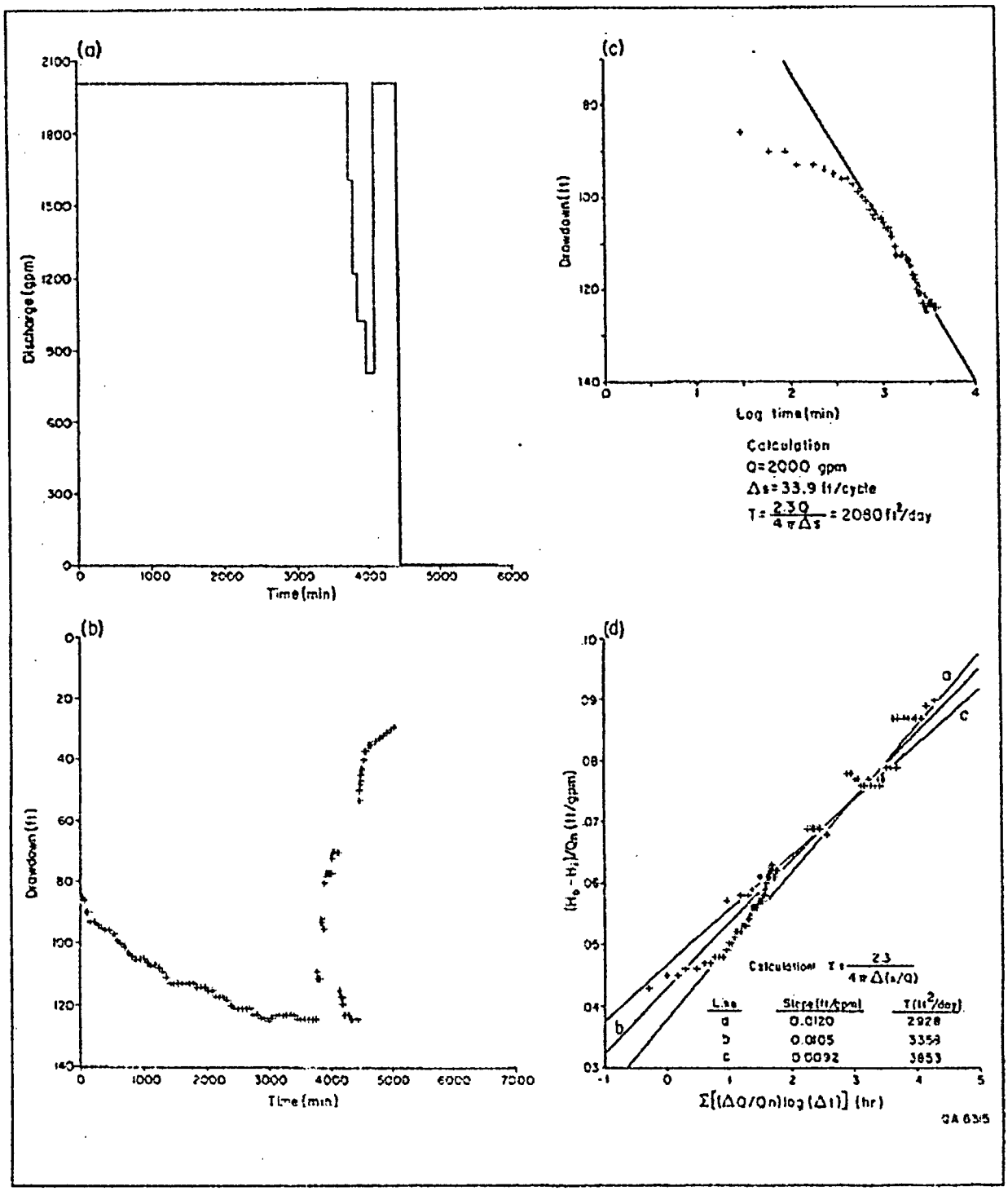


FIGURE A2. Data from pumping test at the City of Tulia No. 13 well. (a) Discharge rate. (b) Drawdown. (c) Drawdown from static water level plotted against logarithm of test duration. (d) Step-drawdown test.

LES-005058

TABLE A1. Transmissivity estimates from specific capacity tests.
(Q - discharge, s - drawdown, Q/h - specific capacity, d - well diameter, t - test duration, T - estimated transmissivity, σ - standard deviation of transmissivity estimates)

County	Well no.	Owner	Use[1]	Depth interval screened (ft)	Q gal/min	s (ft)	Q/h (gal/ft·min)	d (inch)[2]	t (hr)[3]	T (ft²/d)	2σ (ft²/d)	Data source[4]
				Confined Aquifer Setting[5]								
Andrews	(A-9)	Univ. Texas	IN	1,150-1,250	117	130	0.9	-	-	220	70	3
	(A-31)	O. Fasken	IN	?-1,605	132	325	0.4	8⅝	-	90	30	3
	27-55-403	Texaco	WF	1,750 open	152	200	0.8	7⅝	24	210	60	3
Deaf Smith	10-14-202	V. J. Owens	IR	658-762	788	84	9.4	16	96	2,900	700	1,7
	07-52-902	Richardson Seeds	IR	606-862	900	79	11.4	13	8	3,180	660	1
	10-06-837	F. W. Hill	IR	627-807	1,000	91	11.0	16	8	2,980	820	1
	10-06-832	F. W. Hill	IR	592-768	1,000	210	4.8	16	8	1,230	360	1
	10-13-503	City of Hereford	M	683-944	1,400	270.3	5.2	20	22	1,400	390	1
	10-14-107	H. Brorman	IR	600-820	900	140	6.4	16	8	1,690	480	1
	10-14-024	J. H. Fish	IR	670-770	750	98	7.7	13	8	2,090	570	2
	10-07-804	L. Miller	IR	642-760	700	180	3.9	12⅝	8	1,020	290	1
Gaines	KD2706501	-	M	1,418-1,608	157	271	0.6	-	2	130	40	3
Hockley	WSW#1	A. A. Slaughter Est.	WF	1,950-2,100	227	150	1.5	8⅝	-	380	110	3
	Frazier #25	Honolulu Oil	SU	?	140	60	2.3	-	-	620	170	3
Martin	27-55-202	Texaco	WF	1,600 open	83	200	0.4	7⅝	24	110	30	3
Randall	11-01-606	LLL Land & Cattle	IR	520-662	900	100	9.0	-	-	2,580	660	3
	-	City of Canyon No. 1	M	357-493	163	55	3.0	12½	-	820	220	2
	11-01-205	City of Canyon No. 5	M	250-550	760	176	4.3	16	12	1,140	320	2
	-	City of Canyon No. 6	M	?-537	500	135	3.7	16	14	970	280	2
	-	City of Canyon No. 7	M	400-545	335	50	6.7	-	2	1,610	510	2
	11-01-2P	A. W. Lair	IR	270-470	325	120	2.7	15	12	700	200	3
	11-02-?	Arkla Exploration	SU	408-528	15	40	0.4	10	12	90	30	3
	11-03-1A	A. M. Standefer	D	308-410	4.5	60	0.1	12¼	8	10	10	3
Swisher	11-25-302	O. V. Morris	IR	700-1,000	800	163	4.9	13	8	1,300	370	1
	11-26-611	City of Tulia No. 13	M	620-820	2,000	124	16.1	20	62	4,900	1,200	1
	11-26-916	City of Tulia No. 14	M	636-816	960	285.5	3.4	16	24	910	250	1
	11-26-612	City of Tulia No. 15	M	625-820	600	311	1.9	14	24	510	140	1
Terry	ABO-WD#1	Gulf Energy & Minerals	WF	?-1,961	189	651	0.3	-	8	70	20	3
				Partly Unconfined Aquifer Setting[6]								
Crosby	23-39-502	E. H. Williams	IR	60	90	30	3.0	10	12	670	230	3
Garza	23-45-801	Conoco	WF	557-750	62	332	0.2	8⅝	7	30	10	3
	23-54-701	Am. Petrofina	WF	566-662	40	223	0.2	-	3	20	10	3
Mitchell	29-26-907	Rogers & Baker	IR/S	170-230	86	60	1.4	-	6	300	110	3
	29-34-214	H. Hoyle	S	200	110	160	0.7	-	0.5	110	50	3
	29-34-434	Pace	IR/S	235	70	192	0.4	-	1	60	30	3
	29-34-524	O. B. Trulock	IR/S	177	180	145	1.2	-	2	240	90	3
	29-35-704	City of Loraine	IR/D	198-268	60	38	1.6	-	0.5	270	120	3
	29-35-721	B. Preston	IR	150-258	350	170	2.1	-	4	430	150	3
	29-42-210	Mrs. O. Gale	IR	165	207	28	7.4	-	1	1,540	540	3
	29-42-211	Mrs. O. Gale	IR	190	110	20	5.5	-	0.5	1,050	410	3

LES-005059

TABLE A1 (cont.)

County	Well no.	Owner	Use[1]	Depth interval screened (ft)	Q gal/min	s (ft)	Q/h (gal/ft·min)	d (inch)[2]	t (hr)[3]	T (ft^2/d)	2σ (ft^2/d)	Data source[4]
				Partly Unconfined Aquifer Setting (cont.)								
Mitchell (cont.)	29-42-212	Mrs. O. Gale	IR	169	250	75	3.3	-	4	720	240	3
	29-33-919	Browne Bros.	IR	125	50	20	2.5	-	1	470	180	3
	29-42-213	Browne Bros.	IR	183	80	120	0.7	-	2	120	50	3
	29-42-214	Browne Bros.	IR	200	100	112	0.9	-	2	160	70	3
Scurry	28-15-603	A. Beaver	D/S/IR	200	40	40	1.0	-	4	200	70	3
	28-23-601	R. E. Smith	IN	381-883	575	353	1.6	-	7	430	120	3
	28-23-902	R. E. Smith	IN	338-665	475	203	2.3	-	7	640	170	3
	28-24-401	Chevron Oil Co.	IN	400-632 (intermittent)	350	188	0.3	-	24	60	20	3
	28-24-403	Chevron Oil Co.	IN	350-640 (intermittent)	400	78	5.1	-	7	1,200	370	3
	28-24-706	Chevron Oil Co.	IN	342-644 (intermittent)	521	123	4.2	-	6	970	310	3
	28-24-707	Chevron Oil Co.	IN	358-550 595-625	400	75	5.3	-	6	1,240	390	3
	28-24-801	Chevron Oil Co.	IN	350-450 480-570 595-630	400	66	6.1	-	6	1,420	440	3
	28-24-802	Chevron Oil Co.	IN	360-490 604-650	400	100	4.0	-	6	910	290	3
	28-24-803	Chevron Oil Co.	IN	340-400 434-540 595-625	360	110	3.3	-	7	740	240	3
	28-24-804	Chevron Oil Co.	IN	360-648	448	82	5.5	-	24	1,390	390	3
	28-31-301	Colorado River Municipal Water Dist.	IN	421-556 (intermittent)	608	162	3.8	-	37.5	960	270	3
	28-32-205	Mabee Petrol. Co.	IN	356-470	250	79	3.2	-	24	780	230	3
	29-09-905	N. Falks	IN	80-230	60	160	0.3	-	4	60	20	3
	29-17-207	Amor and Crenwelge	IN	125-297	350	170	2.1	-	24	490	150	3
	-	City of Snyder	M	98-229	150	64	2.3	-	24	570	170	3,7
	29-17-703	Lion Oil Co.	IN/IR	330-396 406-448	326	58	5.6	-	24	1,440	410	3
	29-18-702	J. Walker	IN/IR	97-160	85	142	0.6	-	3	110	40	3
	29-19-401	T. A. Thompson	?	147-397	140	209	0.7	-	3	120	50	3
	29-25-401	New Mont Oil Co.	IN	357-470	150	220	0.7	-	24	150	50	3
Motley	22-01-201	Herring Sand & Gravel	IN	200-282 287-300	350	125	2.8	-	-	610	210	5
Floyd	-	test well	-	500-800	75	190	0.4	-	-	70	30	6

[1]IN - industrial, Wf - water flood, IR - irrigation, M - municipal, SU - supply, D - domestic, S - stock
[2]Unknown well diameter indicated by -; 4, 8, and 12 inch assumed in iteration.
[3]Unknown test duration indicated by -; 2, 6, and 12 hr assumed in iteration.
[4]1 - Duffin (1985); 2 - Fink (1963); 3 - Texas Department of Water Resources, Central Records; 4 - Long (1957); 5 - Smith (1973); 6 - Broadhurst (1957); 7 - Myers (1969).
[5]Confined aquifer setting. Storativities of 10^{-3}, 10^{-4}, and 10^{-5} assumed in iteration.
[6]Partly unconfined aquifer setting. Storativities of 10^{-1}, 10^{-2}, and 10^{-4} assumed in iteration.

LES-005060

TABLE A2. Comparison of transmissivity estimates (ft^2/d) from pumping and specific capacity tests ($1\ ft^2/d = 0.134\ m^2/d$).

Owner/Well	Pumping test	Specific capacity test
City of Hereford No. 18	1,430 to 1,980	1,400 ± 90
City of Tulia No. 13	2,080 to 3,860	4,900 ± 1,200
City of Snyder, municipal supply well	460 to 483	570 ± 170
V. J. Owens, irrigation well	~2,940	2,900 ± 700

unconfined and confined aquifers, with characteristic values of transmissivity and storativity substituted into the Theis formula

$$T = (15.3\ Q/s)\ [-0.577 - \ln(1.87\ r^2\ S/(T\ t))] \quad (1)$$

where T is transmissivity (ft^2/d), Q is discharge rate (gal/min), s is drawdown (ft), r is distance from the pumping well to the observation well (ft), S is storativity (dimensionless), and t is duration of test (d). Well radius is substituted for distance to the observation well. Transmissivity and storativity of typical confined sections of the Lower Dockum Group are assumed to be 2,940 ft^2/d (273 m^2/d) and 1×10^{-4}, respectively, based on the tests at V. J. Owens' wells in Deaf Smith County (F. A. Raynor, Interoffice Memorandum to Texas Water Commission files, February 24, 1963; Myers, 1969, p. 120). For typical partly confined or unconfined sections of the Lower Dockum, transmissivity and storativity are assumed to be 485 ft^2/d (45 m^2/d) and 2×10^{-3}, respectively, based on results of tests at the City of Snyder wells in Scurry County (Myers, 1969, p. 440–441).

For confined parts of the Dockum

$$T' = (Q/s)\ [F - 35.3 \log(2{,}200\ S) + 35.3 \log(t)] \quad (2)$$

where

$$F = -8.8 - 35.3 \log(8.5\ 10^{-9}\ r^2). \quad (3)$$

For partly confined and partly unconfined parts of the Dockum

$$T' = (Q/s)\ [F - 35.3 \log(18.15\ S) + 35.3 \log(t)] \quad (4)$$

where

$$F = -8.8 - 35.3 \log(1.03\ 10^{-6}\ r^2). \quad (5)$$

Theis (1963) suggested reading T from a graph of T' (T, T' in gal/d ft) versus Q/h based on

$$T' = T - 264\ (Q/s) \log(T\ 10^{-5}). \quad (6)$$

Transmissivity was solved from equation 6 by successive approximation using a computer program.

Almost two-thirds of the test records lack data on well diameter, and one-seventh do not specify test duration. To maximize the amount of information available from these specific capacity tests, a range of typical values of well diameter (4, 8, and 12 inches) and of test duration (2, 6, and 12 hr) were iteratively substituted into equations 2 and 3 or equations 4 and 5 to calculate an expected transmissivity value. A range of storativity values also was iteratively substituted into the equations; a range from 10^{-3} to 10^{-6} was used for wells in confined settings and a range of 10^{-2} to 10^{-4} was used for wells in partly unconfined settings. Table A1 lists the mean value of transmissivity from the iterative estimates and two standard deviations of the estimates around that mean value. Two standard deviations include 97.7 percent of expected values, assuming that errors in transmissivity calculations were normally distributed.

RESULTS

Variations in quality and completeness of hydrologic test data from Dockum Group water wells limit the accuracy of transmissivity estimates from specific capacity tests. Transmissivities estimated from wells in Deaf Smith, Randall, Swisher, and Floyd Counties range from 10 ± 10 ft^2/d (1 ± 1 m^2/d) to 3,180 ± 860 ft^2/d (295 ± 80 m^2/d). In these counties, Lower Dockum sandstones reach maximum thickness for the Texas Panhandle but still make up less than 50 percent of the Lower Dockum stratigraphic column (fig. 4a). In areas without thick sandstone sections, well yields are less than 100 gal/min (0.38 m^3/min) and most specific capacities calculated from discharge and drawdown measurements are less than 0.5 gal ft^{-1} min^{-1} (0.3 m^3 m^{-1} min^{-1}) (table A1). Transmissivities estimated from specific capacity tests in thin and discontinuous sandstones range from about 20 ± 10 ft^2/d (2 ± 1 m^2/d) in Garza County to about 1,540 ± 540 ft^2/d (143 ± 50 m^2/d) in Scurry County. Average transmissivities by county throughout the Texas Panhandle range from 2,060 ± 860 ft^2/d (191 ± 80 m^2/d) in Deaf Smith County to about 30 ± 10 ft^2/d (3 ± 1 m^2/d) in Garza County and are summarized in figure A3. Storativity values of 2×10^{-3} to 1×10^{-4} from two tests suggest that ground water in Lower Dockum sandstones is confined to partly unconfined, probably by mudstones in the Upper Dockum and top of the Lower Dockum.

LES-005061

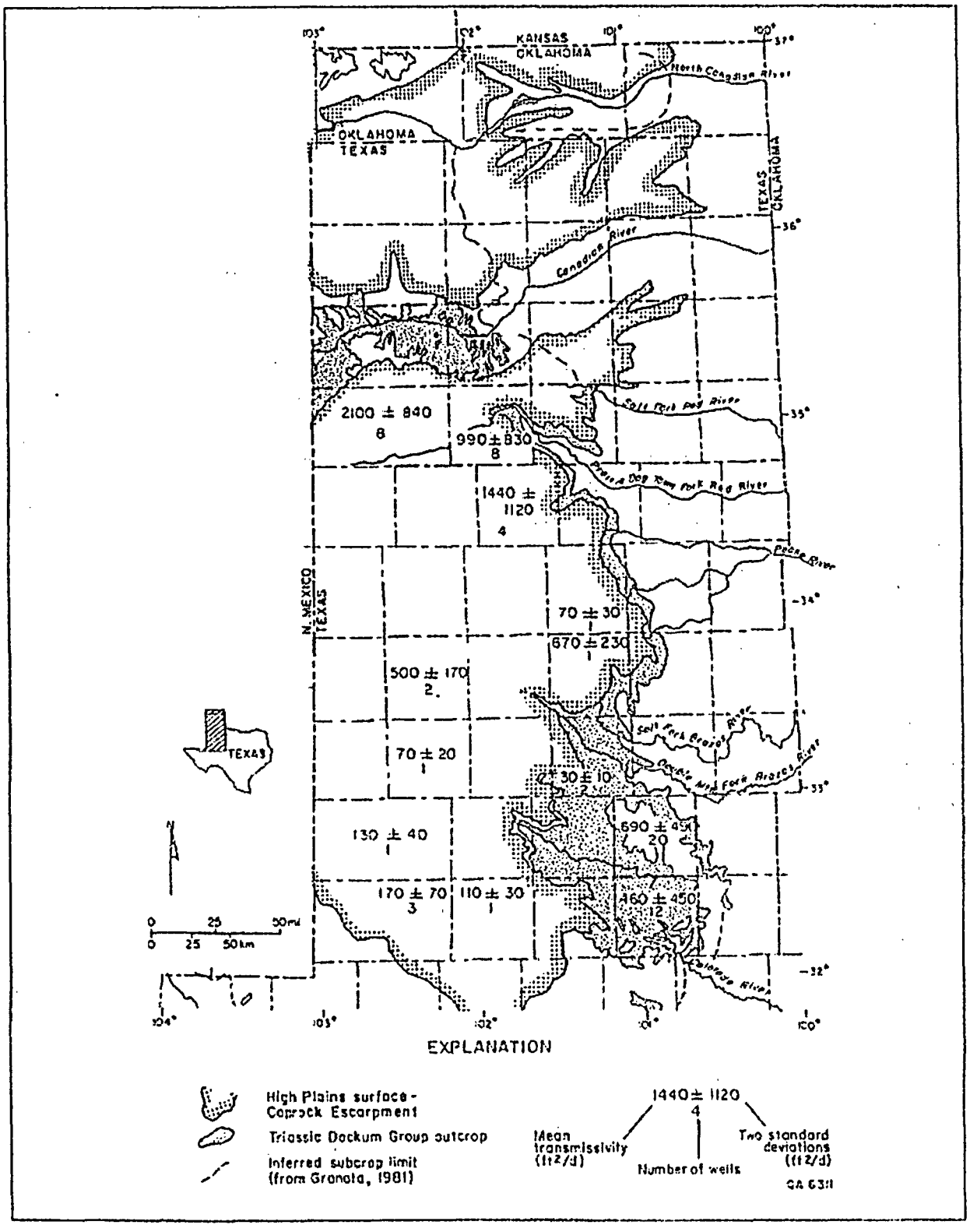


FIGURE A3. Average transmissivity of Lower Dockum Group sandstones by county derived from data in table A1.

LES-005062

APPENDIX B. Chemical composition of Dockum Group ground water.

County	Lat.	Long.	Temp.	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	Source[1]
Andrews	33.240	102.650	27.2	8.05	15.9	26.5	860	12.6	518	760	537	11	18
	32.367	102.717	-	8.2	15	6.8	969	-	630	838	498	12	4
	32.275	102.783	-	8.3	9.2	3.4	685	-	300	625	538	12	4
	32.317	102.642	-	8.1	11	4.9	755	-	310	793	512	13	4
	32.250	102.645	-	8.2	9.4	4.2	703	-	300	668	549	9.4	4
	32.306	102.695	-	8.3	9	4	825	-	286	920	536	12	12
	32.190	102.842	-	7.8	73	16	780	-	458	940	390	-	12
	32.235	102.895	-	8.1	33	15	741	-	300	960	405	13	12
	32.318	102.269	-	8.6	13	4	1,005	.4	617	764	587	13	13
	32.280	102.269	-	8.6	12	.5	958	8	559	846	593	13	13
	32.300	102.225	-	8.4	18	8	1,176	-	868	938	566	14	13
	32.291	102.670	-	-	90	39	1,966	-	1,176	2,721	260	7	13
	32.134	102.788	-	7.5	47	19	927	-	420	1,300	338	-	13
	32.207	102.639	-	8.4	16	11	981	-	526	1,011	506	12	13
	32.178	102.666	-	8.4	12	6	893	-	403	860	511	13	13
	32.238	102.283	-	8.4	16	5	1,087	.5	674	913	564	13	13
	32.213	102.239	-	8.5	21	30	1,117	11	804	1,052	536	13	13
	32.225	102.224	-	8.5	16	8	1,115	.5	685	972	560	13	13
	32.205	102.233	-	8.5	18	9	1,120	5	702	1,098	525	13	13
	32.191	102.239	-	8.5	21	10	1,218	6	798	1,226	481	13	13
	32.258	102.267	-	8.6	15	6	1,062	.5	755	855	584	12	13
	32.207	102.639	-	7.1	160	10	1,472	-	1,600	925	517	-	13
	32.199	102.215	-	8.5	17	6	1,076	.4	624	1,053	529	13	13
	32.492	102.463	-	8.5	15	6	1,046	.5	502	1,191	447	12	13
	32.491	102.388	-	8.5	9	3	834	.3	375	796	540	12	13
Borden	32.865	101.215	-	-	78	28	1,310	-	1,860	349	204	11	12
	32.694	101.419	-	-	185	94	3,660	-	4,300	2,410	279	7.2	12
	32.559	101.516	-	-	80	36	1,980	-	1,980	1,560	278	10	12
	32.568	101.452	-	-	41	24	1,860	-	1,680	1,460	405	14	12
	32.550	101.387	-	-	26	28	2,300	-	2,080	1,730	476	5	12
	32.638	101.638	-	8.4	40	13	1,915	-	1,434	1,814	458	11	13
	32.674	101.652	-	8.4	43	13	1,921	-	1,372	1,901	474	11	13
	32.657	101.653	-	8.4	42	13	1,915	-	1,372	1,904	466	11	13
	32.631	101.639	-	8.4	46	16	1,938	-	1,322	2,016	482	11	13
	32.645	101.660	-	8.2	147	32	3,371	-	3,892	1,988	468	11	13
	32.631	101.615	-	8.4	37	15	1,842	-	1,397	1,761	521	12	13
	32.613	101.632	-	8.5	33	10	1,508	-	1,254	1,268	509	11	13
	32.519	101.668	-	8.3	41	15	1,831	-	1,652	1,366	506	11	13
	32.536	101.659	-	8.3	60	31	1,982	-	2,066	1,554	261	10	13
	32.575	101.261	-	8.3	45	16	1,859	-	1,568	1,501	494	10	13
	32.598	101.230	-	-	589	256	1,277	-	1,450	2,803	336	15	13
Briscoe	34.691	101.341	-	-	45	24	19	-	26	34	221	-	12
	34.660	101.330	-	-	61	42	30	-	22	28	391	-	12
	34.391	101.154	-	-	51	41	25	-	35	50	304	-	12
	34.735	101.399	-	-	40	26	43	-	15	55	270	-	13
	34.690	101.380	-	8.2	42	27	40	6	22	44	273	44	13
	34.730	101.143	-	7.1	570	92	51	-	15	1,660	198	-	13
	34.527	101.392	-	8.2	42	25	87	6	48	122	242	56	13
	34.386	101.134	-	8.1	77	26	74	6	52	117	322	36	13
	34.364	101.133	-	-	60	39	297	-	232	113	608	36	13
	34.328	101.193	-	-	42	25	91	-	22	65	372	-	13
	34.314	101.133	-	8.2	36	24	114	-	64	78	322	-	13
Castro	34.483	102.250	-	7.7	308	120	9,100	-	14,200	1,360	332	9	12
Cochran	33.455	102.691	-	7.1	530	170	6,100	-	5,600	6,950	197	11	13
	33.473	102.633	-	7.4	610	207	9,200	-	9,000	9,130	220	-	17
	33.475	102.620	31.6	7.5	704	149	9,558	-	9,223	9,580	204	-	16
	33.470	102.670	27.2	7.7	519	200	8,682	-	6,249	11,530	225	-	16
Crosby	33.564	101.082	-	7.9	25	1.5	254	2.8	71	133	396	10	12
	33.818	101.254	-	8.3	39	27	57	9	17	34	332	41	13
	33.441	101.204	-	8.1	27	24	184	7	49	146	439	19	13

LES-005063

County	Lat.	Long.	Temp.	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	Source[1]
Dallam	36.395	102.233	-	8.3	34	26	56	6	19	84	245	28	13
	36.349	102.516	-	-	41	40	92	8	51	156	290	33	13
	36.301	102.599	-	-	46	19	42	6	22	52	231	27	13
	36.290	102.476	-	8.2	37	31	33	6	23	58	229	31	13
	36.353	102.230	-	8.4	22	25	28	5	11	39	189	28	13
Dawson	32.555	101.771	-	8.4	47	42	2,125	11	2,268	1,294	508	11	13
	32.565	101.746	-	8.4	38	15	1,770	-	1,585	1,352	470	11	13
Deaf Smith	35.122	102.502	19	8.15	15.4	6.13	239	2.34	54.5	116	428	10.6	18
	35.121	103.021	18	7.8	15.6	13.1	335	2.34	58.4	177	633	13.3	18
	35.080	103.020	-	8.1	33	20	54	5	38	51	222	28	13
	35.100	102.791	-	-	22	16	102	-	18	53	317	-	12
	35.869	102.293	-	8.6	4.4	2.2	275	4.2	37	177	456	12	19
	34.905	102.289	-	8.2	6	3	243	-	32	146	442	12	13
	34.870	102.342	-	8.5	4	1	313	2	56	240	449	11	13
	34.780	102.330	-	8.5	4	1	560	3	208	269	777	10	13
	34.883	102.317	-	8.43	5.14	1.82	203	2.02	48	189	475	10.8	18
	34.904	102.317	-	8.5	7.3	3.52	227	2.44	31.3	104	447	11.1	18
	34.896	102.181	-	8.95	3.11	1.96	230	2.37	29	94.2	464	7.63	18
	34.800	102.431	19	5.7	5.95	2.03	917	3.41	510	360	1,074	12.1	18
	34.854	102.347	19	8.2	4.59	1.4	326	2.39	56	251	503	10.4	18
	34.833	102.344	-	8.58	3.41	.89	380	1.63	84.5	201	630	10.6	18
	34.793	102.331	-	8.6	3.24	.65	449	1.42	104.5	220	720	10.8	18
	35.148	102.865	17	8.4	15	9	345	3	133	460	206	12	11
	35.166	103.523	-	8.2	5	5	202	-	33	58	444	-	11
	35.062	102.755	-	-	13	8	279	-	55	191	493	9	11
	34.879	102.298	-	8.6	4.4	2.2	275	4.2	37	177	440	12	11
	34.894	102.307	-	8.2	6	3	243	-	32	146	442	12	11
	34.895	102.183	-	8.2	5	3	231	-	30	90	479	10	11
	34.896	102.181	-	8.3	3	6	570	-	213	280	840	10	11
Dickens	33.624	100.860	-	7.5	76	20	41	3.5	47	61	282	18	12
	33.620	100.840	-	7.4	74	20	38	4.6	30	49	303	14	13
	33.767	100.921	-	8.2	56	17	21	5	31	32	229	29	13
	33.874	100.850	-	8.2	208	23	166	-	314	203	356	32	13
	33.780	100.830	-	7.9	144	58	92	-	186	202	345	40	13
	33.679	100.930	-	-	78	12	42	-	41	44	281	-	13
	33.646	100.857	-	-	208	29	160	8	342	277	297	27	13
	33.627	100.829	-	-	69	15	42	-	34	39	293	22	13
	33.626	100.818	-	7.5	137	36	74	3	186	142	280	21	13
	33.585	100.931	-	8.2	53	15	134	6	81	67	377	23	13
	33.585	100.926	-	7.5	50	20	147	-	96	73	374	21	13
	33.621	100.854	-	7.4	86	25	23	3.8	60	55	246	16	13
	33.619	100.850	-	7.6	68	17	39	3.1	44	47	258	16	13
	33.605	100.806	-	7.9	157	59	200	-	358	285	295	23	13
Ector	31.748	102.563	-	7.9	5.8	4.5	682	6.9	255	508	760	10	12
Fisher	32.721	100.585	-	-	80	77	51	-	69	193	393	-	12
	32.622	100.661	-	-	42	12	115	-	25	46	367	-	12
	32.850	100.460	-	7.8	65	34	28	2.8	34	61	304	11	12
	32.850	100.460	-	7.1	96	13	2.4	2	16	179	118	8	12
Floyd	34.209	101.175	-	-	51	27	52	-	23	36	342	-	12
	34.127	101.152	-	-	17	1	238	-	55	72	500	-	12
	34.268	101.178	-	-	42	33	35	-	17	39	305	-	13
	34.253	101.156	-	8.2	50	43	57	7.7	16	35	444	50	13
	34.224	101.198	-	7.7	43	38	34	6.9	16	36	348	49	13
	34.224	101.199	-	-	48	41	19	-	15	36	336	-	13
	34.225	101.108	-	7.7	37	28	50	7.7	22	34	312	30	13
	34.180	101.082	-	-	64	18	22	-	16	25	287	-	13
	34.144	101.123	-	-	50	26	29	-	21	35	268	-	13
	34.150	101.117	-	-	45	31	41	8	25	34	311	47	13
	34.138	101.082	-	7.6	44	24	34	6	20	28	276	39	13
	34.091	101.055	-	-	37	19	40	-	16	26	256	-	13
	34.090	101.053	-	-	47	23	111	6.3	145	33	274	32	13

LES-005064

County	Lat.	Long.	Temp.	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	Source[1]
Floyd (cont.)	34.095	101.061	-	-	48	18	296	-	390	69	256	-	13
	34.098	101.048	-	-	89	31	1,873	-	2,720	327	293	-	13
	34.110	101.076	-	-	40	16	233	-	260	2	293	-	13
Gaines	32.946	102.298	-	-	112	74	3,500	-	2,660	4,220	334	12	12
	32.739	102.974	-	7.9	16	8.2	1,140	-	368	1,650	375	10	13
	32.847	102.233	-	7.5	94	46	3,030	-	2,090	3,700	417	17	13
	32.624	102.774	-	9.3	6	5	807	-	256	817	332	-	13
	32.954	102.293	-	7.7	100	44	3,242	-	2,415	3,506	395	16	13
	32.832	102.244	-	-	381	186	4,261	-	4,964	3,347	598	-	13
	32.824	102.232	-	7.7	53	32	2,230	-	1,050	2,990	468	19	13
Garza	33.279	101.419	17	6.7	751	275	16,930	36.1	25,160	2,805	226	11.2	18
	33.074	101.098	20.5	7.8	34.9	18.6	2,020	5.2	2,170	972	377	10.4	18
	33.355	101.091	-	7.7	95	34	239	4	278	138	374	33	12
	33.282	101.108	-	7.5	63	33	23	8.3	18	30	316	32	12
	33.318	101.173	-	7.2	180	30	266	4.5	332	306	280	24	12
	33.205	101.097	-	8.4	3.5	1.1	620	1.9	500	224	442	9.3	12
	33.100	101.119	-	7.4	95	110	184	5.9	104	541	462	16	12
	32.982	101.151	-	8.3	5.8	1.4	894	2.2	650	342	794	8.7	12
	33.267	101.217	21.1	7.3	496	189	9,220	25	14,500	1,850	255	9.8	12
	33.300	101.250	22.2	7.1	247	98	6,280	18	9,420	1,290	371	11	12
	33.042	101.170	-	8.6	25	19	375	-	464	74	276	13	13
	33.352	101.298	-	7.9	45	30	550	-	345	402	520	35	13
	32.841	102.225	-	7.6	71	30	2,780	-	1,720	3,150	224	15	13
Hartley	35.729	102.726	-	8.3	15	17	142	7	43	80	323	16	13
	35.673	102.636	-	8.4	33	19	372	6	216	338	404	11	13
	35.661	102.583	-	8.2	30	21	40	5	20	28	240	27	13
	35.677	102.470	-	8.2	39	30	45	5	10	113	240	30	13
	35.648	102.483	-	8.2	33	23	42	5	10	45	249	27	13
Howard	32.476	101.361	26	7.8	47.1	21.9	2,050	6.49	1,571	1,656	531	11.1	18
	32.417	101.238	19	7.8	43.1	21.5	1,320	5.82	1,183	840	491	10.1	18
	32.518	101.280	-	-	178	263	526	10	219	2,054	301	60	13
	32.418	101.278	-	7.7	72	25	1,410	-	1,390	1,010	403	11	13
	32.424	101.225	-	7.9	33	12	990	-	840	630	500	11	13
Lubbock	33.649	101.855	-	7.4	284	122	7,420	-	10,800	1,850	230	8.4	12
	33.642	101.842	-	7.8	332	114	7,832	-	11,375	1,942	264	-	15
Lynn	33.288	101.600	-	7.4	646	425	12,660	-	18,532	2,995	384	-	12
Martin	32.245	102.192	-	8.4	14	5	991	7	612	857	600	13	13
Mitchell	32.295	101.040	-	7.6	341	145	620	-	650	1,630	244	14	13
	32.304	101.010	-	7.6	218	377	1,150	-	570	3,170	510	24	13
	32.378	101.037	-	8.1	86	37	2,396	9	2,240	1,932	428	10	13
	32.453	101.031	-	8.7	11	5	731	-	554	409	492	6	13
	32.411	100.974	-	7.3	131	49	188	-	242	263	283	27	13
	32.426	100.854	-	8.3	67	24	160	2	130	202	243	37	13
	32.382	100.805	-	8.5	2	1	447	-	91	490	417	18	13
	32.343	100.978	-	8.5	24	14	475	5	183	521	449	13	13
	32.347	100.832	-	-	615	344	114	-	150	2,520	478	19	13
	32.342	100.666	-	-	161	50	83	-	163	288	278	17	13
	32.246	100.731	-	7.5	123	53	44	-	116	205	293	20	13
	32.288	101.107	-	8.1	55	40	15	-	1	7	366	92	13
	32.414	101.168	-	8.2	148	75	964	-	1,150	885	329	20	13
	32.247	100.889	-	7.6	220	48	139	-	11	655	397	13	13
	32.253	100.674	-	8.1	117	82	59	6	131	258	376	11	13
	32.470	100.661	-	8.1	79	40	103	8	128	176	259	18	13
	32.403	100.799	-	-	82	42	54	-	35	193	314	16	13
	32.234	100.952	-	7.6	111	61	397	-	447	440	282	14	13
	32.364	100.724	-	8.5	33	9	163	3	25	110	292	22	13
	32.310	100.821	-	8.2	119	32	178	4	64	443	315	21	13
	32.452	100.821	-	8.4	53	33	100	5	42	168	309	16	13
	32.431	100.810	-	8.1	119	59	96	-	85	357	320	19	13
	32.396	100.883	-	7.9	58	26	175	-	103	206	317	13	13
	32.515	100.662	-	8.2	113	106	195	8	300	276	338	52	13
Moore	35.791	102.008	-	8.5	26	14	149	-	13	110	366	20	13

LES-005065

County	Lat.	Long.	Temp.	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	Source[1]
Motley	34.108	101.023	-	7.6	68	9	358	1.9	480	62	304	-	13
	34.080	101.006	-	8.1	33	12	126	-	127	33	227	24	13
	34.070	101.037	-	-	54	19	50	-	63	17	256	-	13
	34.025	101.011	-	-	47	16	29	-	27	14	238	-	13
	33.987	100.926	-	-	48	7	116	6	99	51	245	19	13
	33.967	100.875	-	8.2	18	8	142	1.9	56	64	304	17	13
	33.948	100.975	-	-	20	15	284	-	190	100	427	-	13
	33.923	100.977	-	-	48	26	40	-	20	24	305	-	13
	33.887	100.970	-	8.1	48	14	23	3	16	18	232	32	13
	33.917	100.935	-	-	54	15	20	-	13	18	246	33	13
	33.875	100.900	-	8.3	81	17	62	6	44	59	314	32	13
	33.997	100.837	-	8.1	56	12	112	-	80	53	325	19	13
	33.873	100.885	-	7.6	72	31	62	8	121	82	244	-	13
	33.865	100.885	-	-	78	24	60	4	110	173	146	-	13
	33.850	100.865	-	7.1	79	30	74	-	83	77	315	34	13
	33.952	101.025	-	8.1	59	18	16	-	12	16	265	32	13.
	33.950	101.017	-	-	48	16	17	-	6	9	244	-	13
Nolan	32.295	100.632	-	7.7	296	59	401	-	660	540	278	19	13
	32.296	100.633	-	-	220	86	284	-	538	501	254	10	13
	32.350	100.598	-	-	94	15	40	-	64	57	265	18	13
	32.334	100.621	-	7.9	71	14	23	2	39	62	203	14	13
	32.345	100.511	-	8.2	81	2	14	1	17	15	243	15	13
	32.330	100.612	-	8.3	76	10	14	2	17	20	272	13	13
Oldham	35.621	102.676	-	8.4	50	30	71	3	36	77	331	21	13
	35.595	102.953	-	8.2	45	23	41	4	30	59	239	29	13
	35.538	102.289	18	7.2	28	21.7	498	6	58.1	279	1,090	-	18
	35.517	102.325	-	8.2	93	39	260	4	125	420	417	26	13
	35.546	102.339	-	8.2	28	17	396	8	70	269	786	16	13
	35.538	102.352	-	7.8	45	27	121	-	35	119	302	30	13
	35.555	102.357	-	7.5	46	20	30	-	24	47	220	27	13
	35.504	102.263	-	8.4	14	9	478	3	69	304	856	14	13
	35.515	102.287	-	8.4	13	15	490	6	70	278	944	14	13
	35.457	102.804	-	7.6	101	29	65	-	134	167	187	20	13
	35.497	103.007	-	8.1	49	16	36	4	25	48	226	29	13
Randall	35.005	101.939	-	-	6	6	150	-	24	36	334	-	12
	35.077	101.862	-	7.4	25.6	22.3	80.8	-	12	23.1	353.8	12	12
	34.764	101.022	-	8.4	10	4	298	-	60	195	483	14	12
	34.764	102.043	-	8.4	11	3	310	-	81	201	555	14	12
	34.800	101.820	-	-	7.7	5.8	135	3.2	17	29	341	11	1
	34.848	102.099	-	8.2	23	10	539	-	441	306	337	11	13
	34.768	102.041	-	8.3	4	2	312	-	58	203	486	10	13
	34.758	102.056	-	8.6	10	4	239	-	62	150	367	10	13
	34.662	101.953	-	-	16	15	265	-	250	48	348	13	13
	34.775	101.869	-	8.18	25.4	15.9	153	4.13	49.5	101	362	27.8	13
	34.793	101.899	-	8.2	9	5	419	-	181	302	465	9	13
	34.790	101.881	-	8.2	11	5	406	-	163	289	492	9	13
	34.935	102.133	-	8.2	5	3	237	-	30	90	475	9	13
	35.015	101.752	17.5	8.1	12	11.7	110	3.88	8.25	25	359	11.8	13
Scurry	32.676	101.011	-	8.3	3.2	1.1	357	1.2	232	116	410	11	12
	32.838	100.936	-	7.9	9.8	4.2	146	1.1	35	46	322	13	12
	32.730	100.936	-	7.7	54	18	23	3.9	5.5	16	287	41	12
	32.685	100.749	-	7.7	52	17	13	3.7	9.4	17	298	16	12
	32.060	100.760	-	8.1	84	21	94	4.2	32	222	274	17	5
	32.644	101.019	-	8.5	3	3	238	1.1	57	78	433	11	13
	32.710	101.019	-	7.5	35	18	1,650	-	2,080	494	358	11	13
	32.784	100.718	-	8.1	92	64	103	6	91	352	279	17	13
	32.533	100.731	-	8.4	87	39	277	-	202	403	329	36	13
	32.636	100.763	-	8.4	51	39	72	-	55	164	244	17	13
	32.694	100.869	-	7.8	151	42	102	7	279	164	267	33	13
	32.743	100.897	-	7.7	57	19	67	-	53	43	305	23	13
	32.789	100.947	-	7.6	56	19	72	-	64	22	315	21	13
	32.753	100.993	-	-	59	19	48	-	55	38	259	33	13

LES-005066

County	Lat.	Long.	Temp.	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	Source[1]
Scurry (cont.)	32.756	100.959	-	7.7	44	16	35	-	14	25	306	27	13
	32.609	101.094	-	7.5	63	15	85	1	26	124	273	18	13
	32.869	101.009	-	8.7	1	1	240	-	44	94	427	10	13
	32.897	101.216	-	8.8	3	1	328	-	72	182	465	9	13
	32.649	101.116	-	7.6	18	7	1,590	-	1,600	750	592	-	13
	32.649	101.118	-	8.7	38	13	1,081	-	1,257	462	346	8	13
	32.790	100.786	-	8.2	90	25	162	-	122	231	285	22	13
	32.626	100.922	-	8.3	12	5	277	-	59	192	443	12	13
	32.694	100.869	-	7.8	151	42	102	7	279	164	267	33	13
	32.707	100.822	-	7.7	96	23	24	-	126	16	231	36	13
	32.538	100.933	-	8.1	200	84	142	6	109	734	332	20	13
	32.533	100.731	-	8.4	87	39	277	-	202	403	329	36	13
Swisher	34.546	101.769	15	8.4	4.7	1.94	391	1.85	126	232	510	10.2	18
	34.558	101.774	13	8.25	3.13	1.75	301	2.86	54.9	161	486	10	18
	34.558	101.591	-	8.3	4	1.5	414	1.6	163.3	264.5	474	-	14
	34.572	101.581	-	8.3	6.2	3	351.9	1.9	169	217.4	402	-	14
	34.439	101.881	-	8.14	35.6	23.6	46.9	7	24.8	22.5	283	45	18
	34.562	101.929	17.7	-	46	28	40	17.7	20	49	284	62	14
	34.734	101.864	20.5	8.1	4.69	2.6	318	2.99	71.1	194	529	10.9	18
Terry	33.020	102.317	-	7.5	57	20	2,470	-	1,350	3,170	485	12	12
Yoakum	32.973	102.974	-	5.7	144	52	2,250	-	3,520	407	99	-	12
De Baca	34.523	104.225	17	7.85	22.4	17.1	239	1.31	71.9	214	367		18
	34.342	104.619	-	7.7	73	20	14	-	20	57	232	33	8
	34.418	104.620	17	7.9	452	100	22	-	121	1,270	106	61	8
	34.350	104.541	-	7.9	102	36	25	-	79	151	214	32	8
	34.357	104.331	19	7.2	120	71	26	-	162	281	150	31	8
	34.442	104.730	18	7.6	44	54	30	-	24	100	279	23	8
	34.518	104.220	18	7.9	51	41	279	-	148	354	384	32	8
	34.481	104.247	17	7.9	51	14	86	-	37	123	222	-	8
	34.603	104.552	18	7.4	108	23	40	-	56	221	168	25	8
	34.540	104.475	18	7.6	72	20	34	-	38	127	177	21	8
	34.531	104.373	18	7.5	90	25	20	-	33	168	176	29	8
	34.597	104.293	18	7.2	91	30	119	-	39	174	450	23	8
	34.568	104.321	18	7.9	106	52	51	-	34	330	240	19	8
	34.550	104.355	-	7.8	39	17	129	-	41	230	178	19	8
	34.529	104.273	16	8.1	56	27	117	-	44	138	356	25	8
	34.600	104.167	-	8.4	74	23	323	-	242	318	336	18	8
	34.552	104.212	-	8.2	25	14	234	-	74	206	376	24	8
	34.549	104.207	17	8.4	48	28	268	-	103	322	307	29	8
	34.612	104.425	22	7.6	107	36	42	-	73	230	192	41	8
	34.192	104.804	18	7.7	90	13	74	-	4.8	89	230	28	8
Eddy	32.841	104.040	-	-	660	161	393	-	815	1,810	150	-	3
	32.732	104.031	-	-	397	58	43	-	110	911	167	25	3
	32.658	104.026	-	-	628	104	171	-	240	1,820	151	-	3
	32.628	103.875	-	-	139	54	56	-	55	398	219	23	3
	32.621	103.878	-	-	504	303	46	-	60	2,160	191	40	3
	32.602	104.061	-	-	656	20	7.6	-	18	1,490	155	53	3
	32.571	103.968	-	-	636	108	260	-	380	1,860	114	38	3
	32.538	103.997	-	-	680	68	177	-	388	1,590	166	36	3
	32.525	103.966	-	-	662	152	348	-	620	1,960	108	33	3
	32.570	103.813	-	-	400	626	931	-	635	4,280	248	-	3
	32.576	103.864	-	-	132	190	707	-	785	1,190	301	-	3
	32.329	103.840	-	-	604	146	437	-	510	2,150	114	-	3
	32.326	103.804	-	-	554	199	201	-	410	1,560	266	-	3
	32.100	103.912	-	-	86	31	47	-	78	177	175	-	3
	32.147	103.885	-	-	536	102	59	-	22	1,710	89	-	3
	32.110	103.888	-	-	132	46	220	-	360	339	160	-	3
	32.112	103.777	-	-	205	67	161	-	106	837	137	-	3
	32.070	103.726	-	-	410	121	366	-	470	1,500	109	-	3
	32.008	103.803	-	-	51	18	58	-	17	135	188	-	3

LES-005067

County	Lat.	Long.	Temp.	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	Source[1]
Guadalupe	34.824	104.693	17.2	7.4	81	57	9.7	-	41	174	263	26	9
	34.802	104.550	-	-	128	89	57	-	44	494	283	20	9
	35.031	104.760	-	-	72	57	45	-	39	253	235	-	9
	35.001	104.769	-	-	80	24	30	-	29	142	194	-	9
	34.964	104.677	16.7	7.3	572	71	45	-	46	1,540	181	16	9
	35.212	105.060	14.4	7.4	60	22	129	-	21	253	272	15	9
	35.153	104.716	16.7	7.2	189	115	53	-	19	542	569	19	9
Lea	32.678	103.779	-	-	10	13	131	-	21	74	306	19	6
	32.680	103.569	-	7.1	430	65	675	-	560	1,680	189	41	6
	32.504	103.257	-	-	17	7.8	280	-	65	216	434	-	6
	32.444	103.162	-	-	50	31	563	-	208	855	360	16	6
	32.401	103.276	-	-	18	6	425	-	200	340	477	-	6
	32.252	103.509	-	-	32	26	163	-	52	219	287	-	6
	32.235	103.152	-	-	121	93	402	-	252	934	277	13	6
	32.118	103.202	-	-	55	49	170	-	71	280	376	12	6
	32.111	103.190	-	-	34	43	175	-	54	286	264	9.3	6
Mora	36.049	105.140	17	7.9	62	12	19	-	5.4	22	246	26	14
	35.942	105.235	-	7.7	130	40	105	3.3	41	288	412	14	14
Quay	34.983	103.367	20	9.7	1.66	.41	278	1.01	135	188	-	5.76	18
	35.358	103.458	18	7.25	86.6	31.9	42.9	2.48	46.1	133	314	-	18
	35.142	103.350	13.5	8.9	2.75	2.11	480	1.41	129	266	753	-	18
	35.205	103.738	-	-	25	29	136	-	26	126	372	-	7
	35.208	103.597	-	-	3	2.4	518	-	92	494	504	1.9	7
	35.184	103.624	-	-	13	6.3	1,200	-	510	1,100	824	-	7
	35.166	103.688	-	-	29	43	307	-	116	249	572	-	7
	35.159	103.662	-	-	9.5	4.5	1,370	-	300	1,760	824	-	7
	35.160	103.626	-	-	5	5	970	-	238	968	852	-	7
	35.200	103.575	-	-	8	4.8	1,060	-	26	1,450	816	-	7
	35.200	103.517	-	-	7.5	6.3	564	-	308	501	340	-	7
	35.175	103.526	-	-	332	141	342	-	80	1,670	356	-	7
	35.164	103.557	-	-	2.5	1.3	453	-	71	348	528	-	7
	35.131	103.526	-	-	1.5	.5	285	-	50	121	420	-	7
	35.180	103.038	-	7.6	45	38	239	-	111	215	496	15	7
	35.365	103.403	17.2	7.4	109	32	54	-	51	170	314	27	7
	35.383	103.392	18	6.96	210	85	49	4.9	42.5	600	355	27	10
	35.345	103.400	18	6.93	140	190	205	7.1	255	548	761	16	10
San Miguel	35.467	104.417	13.5	7.4	70.6	144	135	9.6	90	378	691	-	18
	35.054	105.340	-	-	286	34	4	-	15	620	264	-	2
	35.259	104.604	-	-	125	184	379	-	70	1,030	880	-	2
	35.246	104.483	-	-	172	97	230	-	168	788	313	24	2
	35.385	104.685	-	-	135	48	5	-	37	385	350	-	2
	35.330	104.481	-	-	60	50	133	-	60	211	404	19	2
	35.312	104.510	-	-	51	71	200	-	90	278	521	19	2
	35.337	104.353	-	-	26	16	485	-	118	458	658	13	2
	35.438	104.375	-	-	53	25	126	-	30	153	372	-	2
	35.470	104.423	-	-	60	103	127	-	45	228	658	16	2
	35.550	104.410	-	-	33	19	343	-	52	425	473	10	2
	35.505	104.381	-	-	5.2	4.3	513	-	62	416	759	12	2
	35.629	104.424	-	-	98	39	419	-	53	600	750	7.2	2

[1] 1 - Broadhurst and others (1951); 2 - Griggs and Hendrickson (1951); 3 - Hendrickson and Jones (1952); 4 - Long (1957); 5 - Smith (1957); 6 - Nicholson and Clebsch (1961); 7 - Berkstresser and Mourant (1966); 8 - Mourant and Shomaker (1970); 9 - Dinwiddie and Clebsch (1973); 10 - Hydro Geo Chem, Inc. (1984); 11 - Duffin (1985); 12 - Stevens (1974); 13 - Texas Department of Water Resources (open-file documents and computerized data); 14 - Mercer and Lappala (1972); 15 - R. A. Taylor (written report to City of Lubbock, Texas, 1949); 16 - Martin Water Laboratories (written reports to Gulf Energy & Minerals and to Gulf Oil Corporation, variously dated); 17 - ARCO Oil and Gas Company (Internal Report, 1960); 18 - Bureau of Economic Geology (see table 2, p. 14); 19 - Fink (1963).

LES-005068