Texas Water Development Board

Report 359

The Groundwater Resources of the Dockum Aquifer in Texas

by
Robert G. Bradley, P.G., and
Sanjeev Kalaswad, Ph.D., P.G.

December 2003

Geoscientist Seal

The contents of this report (including figures and tables) document the work of the Following Licensed Texas Geoscientists:

Robert Bradley, P.G. No. 707

> Robert Bradley prepared the original illustrations, data assimilation, and draft reports, all of which were subsequently modified and updated by Sanjeev Kalaswad.

The seal appearing on this document was authorized on May 19, 2009 by

Robert Bradley

Sanjeev Kalaswad, P.G. No. 478

> Sanjeev Kalaswad wrote the report, prepared the illustrations including the geological cross-sections and chemical plots, and helped develop the groundwater estimates in the aquifer.

The seal appearing on this document was authorized on May 19, 2009 by

Sanjeev Kalaswad

Report 359 - The Groundwater Resources of the Dockum Aquifer in Texas, 2003

Texas Water Development Board

Published and distributed
by the
Texas Water Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231

December 2003
Report 359
(Printed on recycled paper)

This page intentionally blank.

Table of Contents

List of Figures

List of Tables

Appendix I

Appendix II

Appendix III

This page intentionally blank.

1.0 Executive Summary

The Dockum aquifer is a minor aquifer that underlies much of the Ogallala Formation in the Texas Panhandle and West Texas. Recoverable groundwater in the Dockum aquifer occurs within the many Upper Triassic sandstone and conglomerate beds that host the aquifer. The hydrogeologic properties of the aquifer vary widely. For example, well yields range from 0.5 to 2,500 gpm and transmissivity from 48 to 4,600 square feet per day. Generally, however, well yields and transmissivities are fairly low throughout much of the aquifer.

Precipitation recharges the aquifer where it is exposed at the land surface around the eastern and southern edges of the aquifer. The confined portions of the aquifer receive some recharge by leakage from overlying and underlying geologic units. We estimate that annual recharge to the aquifer is approximately 31,000 acre-feet. Discharge from the aquifer occurs from pumping wells, small springs, evapotranspiration and cross-formational flow.

Regional groundwater flow in the aquifer is generally to the east. Historical hydrographs of wells show that water levels in the northern and southern parts of the aquifer have declined in some areas and risen in others over the past 20 to 30 years. In the central part of the aquifer, water levels have generally risen over the same time period.

Groundwater in the Dockum aquifer is generally of poor quality. Water quality ranges from fresh in the outcrop areas to brine in the confined parts of the aquifer. It also tends to deteriorate with depth, and total dissolved solids (TDS) concentrations can exceed 60,000 mg/l in the deepest parts of the aquifer. Water in the Dockum aquifer is also typically hard with a mean hardness of about 470 mg/l. Radionuclides naturally derived from uranium minerals in the host rocks occur at concentrations above 5 pCi/l in widespread areas of the aquifer. Most counties in the study area also had at least one groundwater sample that contained sulfate or chloride at concentrations greater than the secondary standard of 250 mg/l. In contrast, fluoride concentrations were higher than the secondary standard in only a few samples collected from five counties. Much of the land overlying the Dockum aquifer is susceptible to salinity problems originating from the high concentrations of sodium in the groundwater. This problem is most prevalent over the confined areas of the aquifer and is less of a concern over the outcrops.

We estimate that the total amount of water in the entire Dockum aquifer in the study area is approximately 185 million acre-feet. Of this amount, approximately 109 million acre-feet contains TDS of less than 5,000 mg/l, about 27 million acre-feet between 5,000 and 10,000 mg/l, and 49 million acre-feet greater than 10,000 mg/l. However, not all of the water in the Dockum is readily available for withdrawal. In fact, measured aquifer parameters suggest that the aquifer can provide only small quantities of water. Furthermore, because the confined part of the aquifer (where water with the highest TDS concentrations is present) receives little recharge, any significant withdrawal of water from these areas will essentially mine or deplete the aquifer.

2.0 Introduction

The Upper Triassic Dockum Group extends over approximately 96,000 square miles in parts of Colorado, Kansas, Oklahoma, New Mexico and Texas (Figure 2-1). In Texas, sands of the Dockum Group produce small to moderate quantities of fresh to saline water and constitute the Dockum aquifer which is classified as a minor aquifer (Ashworth and Hopkins, 1995). As delineated by Ashworth and Hopkins (1995), the Dockum aquifer includes an area of the aquifer containing groundwater with less than 5,000 mg/l total dissolved solids (Figure 2-2). However, for the purposes of this report, we also include other areas of the aquifer that have total dissolved solids concentrations greater than 5,000 mg/l. In this report, the term "Dockum aquifer" is used loosely for all water-bearing strata of the Dockum Group regardless of their dissolved solids content.

Locally, the Dockum aquifer can be an important source of groundwater for irrigation, public supply, oil-field activity, livestock, and manufacturing. However, deep pumping depths, poor water quality, low yields, and declining water levels have discouraged its more widespread use. Nevertheless, the aquifer may become an important secondary source in the future, especially in areas where demand from the overlying Ogallala and Edwards-Trinity (Plateau) aquifers is high. It could also be considered for desalination in the future.

To date, only a few investigations have been conducted on the Dockum aquifer in Texas. One of the first regional studies was conducted by Gould (1907) in west Texas. Later, Galloway (1955) investigated Triassic artesian wells near Hereford, Texas, to evaluate the feasibility of obtaining water from similar types of wells in eastern New Mexico. Other studies of a local nature were conducted by Fink (1963) and Rayner (1965). Several county-level studies on the Dockum aquifer have also been conducted (see, for example, Garza and Wesselman, 1959; Ogilbee and others, 1962; Shamburger, 1967; White, 1971; Duffin, 1984; and Ashworth, 1986).

The aim of this study was to evaluate the groundwater resources of the Dockum aquifer (Figure 2-2). Specific goals of the investigation were to compile and evaluate existing geologic and hydrologic information on the area, determine the quality of groundwater in the Dockum aquifer, and estimate the approximate amount of groundwater in the aquifer. Much of the information presented in this report was obtained from previous literature and Texas Water Development Board (TWDB) records. We collected groundwater samples in 1995 and 1996 from all of the counties in the study area to assess the chemical quality of water in the aquifer.

3.0 Study Area

The study area (Figure 2-2) encompasses the total areal extent of the Dockum Group in Texas (approximately 42,000 square miles). The outcrop area of the Dockum Group is approximately 5,500 square miles, and extends as a north-south-trending belt paralleling the eastern escarpment of the Llano Estacado. The belt is narrow between Armstrong and Dickens counties in the north but broadens south of Dickens County to include most of Scurry and Mitchell counties.

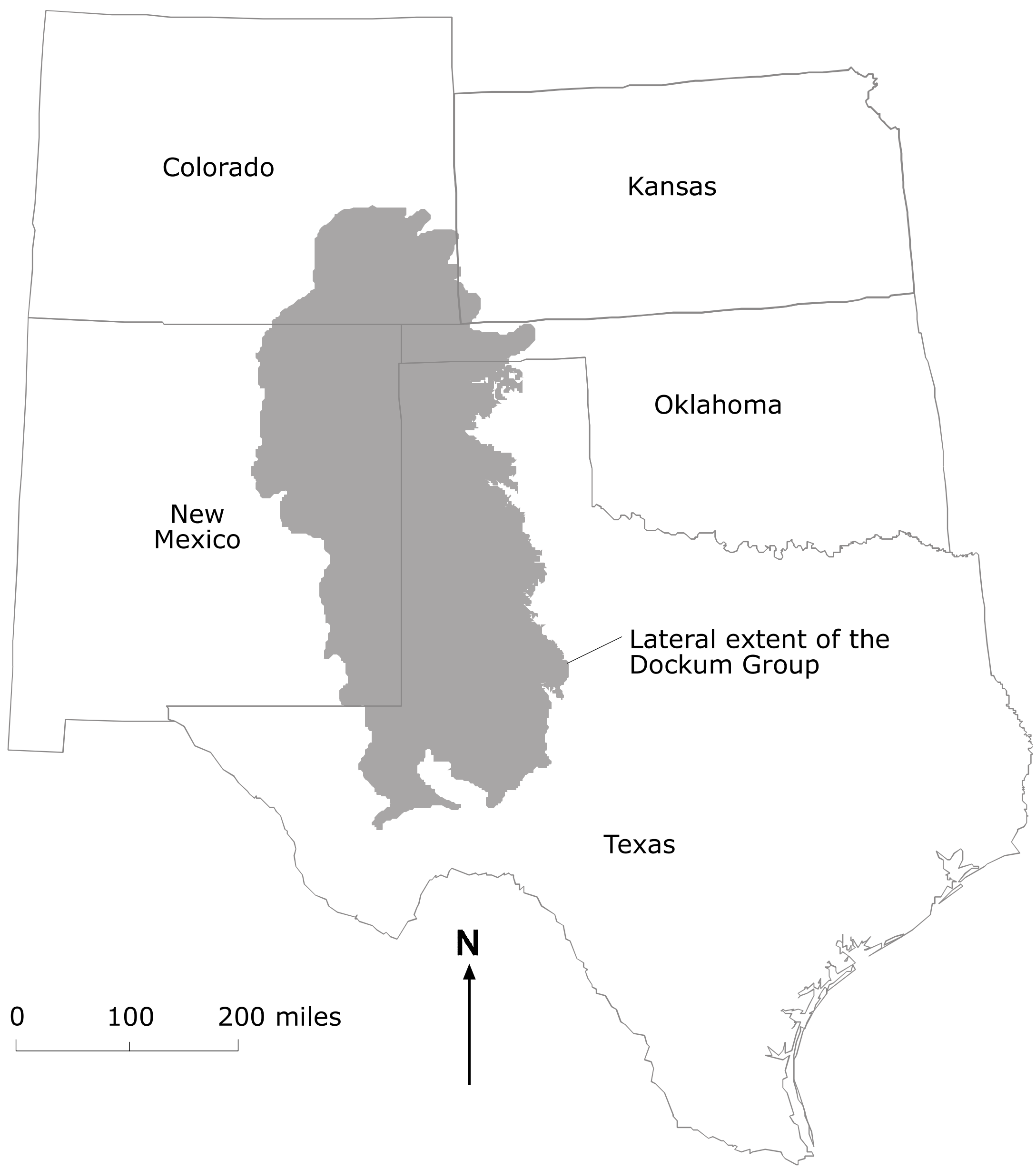

Figure 2-1. Lateral extent of the Dockum Group in southwestern United States (modified from McKee and others, 1959; Bureau of Economic Geology, 1967, 1968, 1969, 1974, and 1983; McGowen and others, 1977).

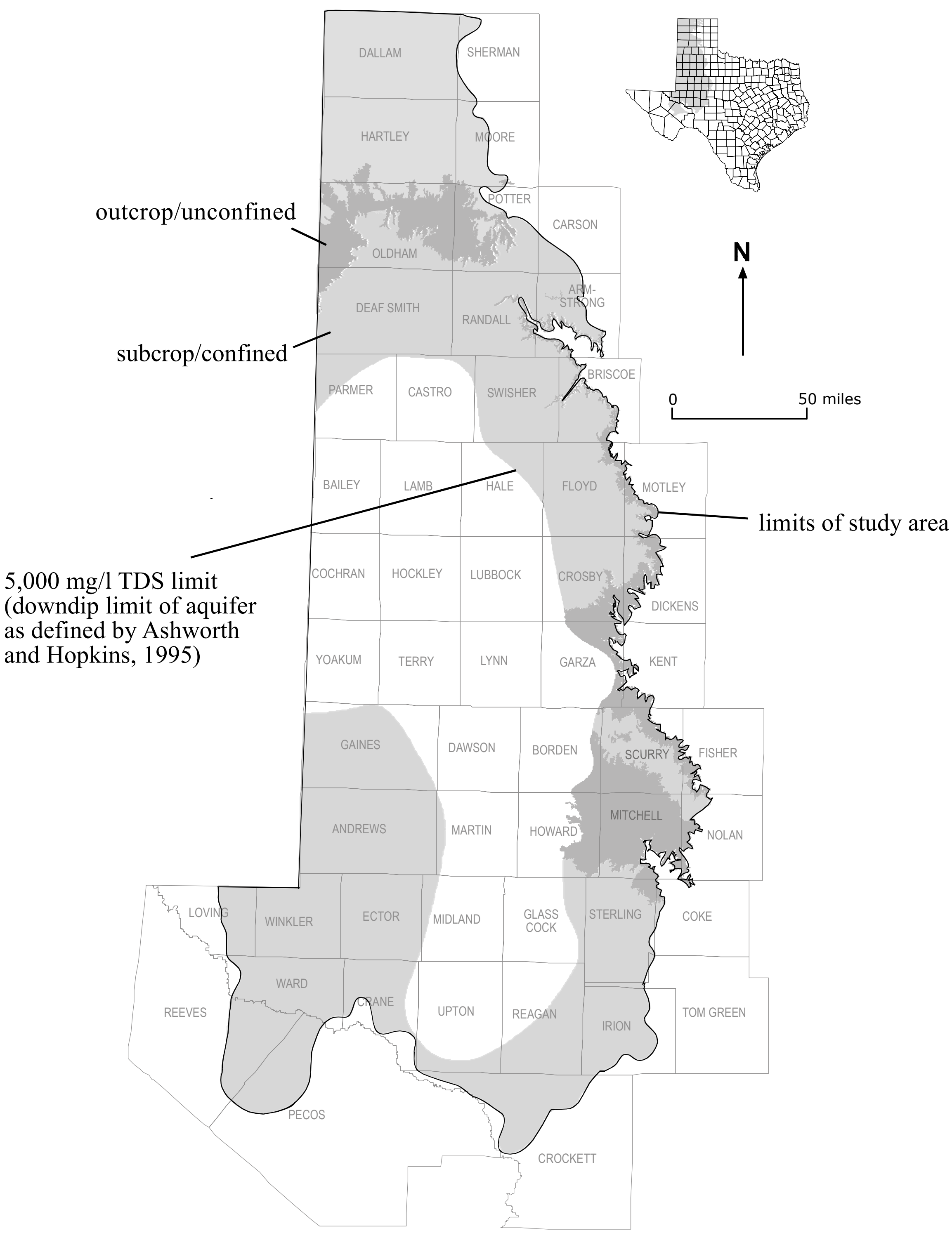

Figure 2-2. Areal extent of the study area and the Dockum aquifer in Texas.

Within the study area, the Dockum aquifer is exposed along the Canadian River in the north, along the east edge of the Caprock Escarpment in the east, and in parts of Borden, Fisher, Garza, Howard, Kent, Mitchell, Nolan, and Scurry counties in the south. Other small exposures are found in Coke, Crane, Ector, Loving, Martin, Sterling, and Ward counties. Covered outliers of the Dockum aquifer are present in Hansford, Hutchinson, and Ochiltree counties.

The Dockum aquifer in the study area overlies Permian-age units and is in turn overlain by Jurassic rocks in the northwest corner of the Texas Panhandle, by Cretaceous sediments in the southern High Plains and Edwards Plateau, and by the Ogallala Formation in the northern High Plains (Table 3-1). In the southwest part of the study area, the aquifer is overlain by the Cenozoic Pecos Alluvium.

3.1 Physiography

Much of the study area lies within the High Plains section of the Great Plains physiographic province which extends from the Pecos River in the south to the latitude of the Great Bear Lake in Canada (Thornbury, 1965). The High Plains section in Texas is a vast, monotonous flat surface underlain primarily by Tertiary sediments. The eastern edge of the section is marked by a pronounced escarpment called the Caprock Escarpment.

Smaller parts of the study area in the south lie within the Pecos Valley and the Edwards Plateau sections of the Great Plains physiographic province. The Pecos Valley section, which lies southwest of the High Plains section, consists of a broad north-south-trending topographic depression underlain by highly soluble Cretaceous rocks. To its east lies the Edwards Plateau section, characterized by low relief (except along major stream channels) in the west and higher relief in the east. The Edwards Plateau is underlain by carbonate rocks of Cretaceous age. A small part of the study area east of the Caprock Escarpment falls within the Osage section of the Central Lowlands province and is underlain by mainly Pennsylvanian or Permian rocks.

Five major river basins drain the study area, including the basins of the Canadian and Red rivers, which drain eastward, and the basins of the Brazos, Colorado, and Pecos rivers, which drain toward the southeast. A significant part of the Dockum Group outcrop is drained by the Canadian and Colorado rivers and their tributaries.

3.2 Climate

The climate over much of the northern and central parts of the study area is of a continental steppe type and is characterized by large variations in daily temperatures, relatively low humidity, and infrequent rainfall events (Larkin and Bomar, 1983). Average annual precipitation in these areas ranges from about 21 inches in the eastern parts of the study area to about 17 inches in the western parts (Figure 3-1). Historically, mean annual precipitation has ranged from 13.89 inches in the southern part of the study area (Figure 3-1c) to 22.23 inches in the central part (Figure 3-1b). Three-fourths of the precipitation in these areas typically occurs between early spring and early fall. May and September are usually the rainiest months. Snowfall is an important source of precipitation in the winter. Temperatures often exceed 100° F in the summer and drop below freezing in the winter.

Table 3-1. Geologic Formations in the Texas Panhandle and West Texas and Their Water-Bearing Characteristics (modified from Knowles and others, 1984; Lehman, 1994a and 1994b).

System	Series	Group	Formation	Physical Characteristics	Water-bearing Characteristics
Quaternary			Cenozoic Pecos Alluvium	Unconsolidated to partially consolidated sand, silt, gravel, clay, and caliche.	Yields small to large amounts of fresh to slightly saline water.
Tertiary	Late Miocene to Pliocene		Ogallala	Tan, yellow, and reddish-brown, silty to coarse-grained sand alternating with yellow to red silty clay and variable sized gravel.	Yields moderate to large amounts of water to well.
Cretaceous		Washita		Massive, fine to coarse grained, white, gray, or yellowish gray limestone and thick, dark greenish gray, gray, or yellow marl.	Yields small to large amounts of water to wells and springs.
		Fredericksburg	Kiamichi	Thinly laminated, sometimes sandy, gray to yellowish-brown shale with beds of thin, gray argillaceous limestone, and, thin, yellow limestone.	Yields small amounts of water locally to wells.
			Edwards	Light-gray to yellowish-gray, thick bedded to massive, fine- to coarse-grained limestone.	Yields small to large amounts of water to wells and springs.
			Comanche Peak	Light gray to yellowish-brown, irregularly bedded, argillaceous limestone, thin beds light-gray shale.	Yields small to large amounts of water to wells.
			Walnut	Light-gray to yellowish-brown, fine to medium-grained, sandstone, thin bedded, gray to grayish-yellow, calcareous shale; and light gray to grayish-yellow, argillaceous limestone.	Not known to yield water to wells.
		Trinity	Antlers	White, gray, yellowish-brown to purple, fine to medium-grained, loosely cemented sandstone and conglomerate, with beds of siltstone and clay.	Yields small to moderate amounts of water to wells.
Jurassic			Morrison	Variegated shale, sandstone, siltstone, and limestone.	Yields small amounts of fresh to slightly saline water.
			Exeter	Light-colored sandstone.	Yields small amounts of fresh to slightly saline water.
Triassic		Dockum	Cooper Canyon	Reddish-brown to orange siltstone and mudstone with lenses of sandstone, and conglomerate.	Yields small to large quantities of fresh to brine water to wells and springs.
			Trujillo	Gray, brown, greenish-gray, fine to coarse-grained sandstone and sandy conglomerate with thin gray and red shale interbeds.	
			Tecovas	Variegated, sometimes sandy mudstone with interbedded fine to medium-grained sandstones.	
			Santa Rosa	Red to reddish-brown sandstone and conglomerate.	
Permian	Ochoa		Dewey Lake	Red siltstone and shale.	Not known to yield water to wells.
			Rustler	Dolomite, anhydrite, sandstone, conglomerate, and variegated shale.	Yields small to large amounts of slightly to moderately saline water.
	Guadalupe	Undifferent-iated		Sandstone, shale, gypsum, anhydrite, dolomite, and selenite.	Yields small to large amounts of fresh to moderately saline water.

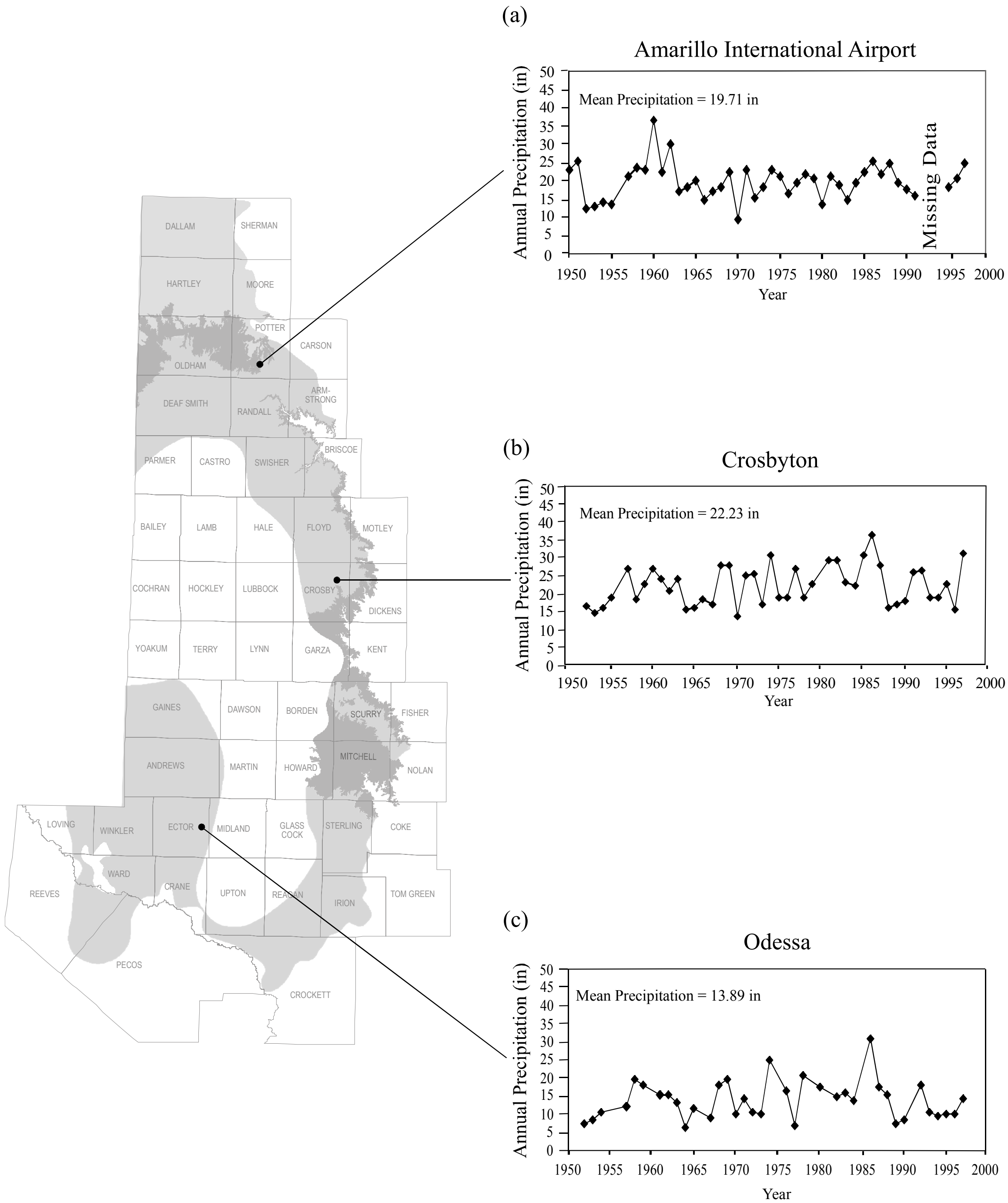

Figure 3-1. Historical annual precipitation recorded at (a) Amarillo International Airport, (b) Crosbyton, and (c) Odessa.

Evaporation in the northern and central parts of the study area is greatest in the summer months. The average annual evaporation potential for an open surface water body in Lubbock County is approximately three-and-half times the average annual precipitation (Knowles and others, 1984).

The southern part of the study area (Trans-Pecos) is semi-arid and is characterized by a wide range of temperatures, low rainfall, and high evaporation rates (Ashworth, 1990). Temperatures typically range from below freezing in winter to over 100° F during the summer. Average annual precipitation in the southern part of the study area ranges from 9 inches in the west to about 14 inches in the east with much of it occurring in April and October. Historical annual precipitation at the Odessa rain gage station has ranged from 6.2 inches to 30.8 inches (Figure 3-1c).

4.0 Geology

The Triassic sediments of the Dockum Group that form the Dockum aquifer consist of a series of alternating sandstones and shales (Cazeau, 1962). Individual sandstone units are light- to dark- or greenish-gray, buff and red, and range in thickness from a few feet to about 50 feet. They are often lens-shaped, partly conglomeratic, poorly sorted, friable, and micaceous. The red and maroon sandy shale units that separate the sandstones range in thickness from about 50 to 100 feet.

Recoverable groundwater in the Dockum aquifer is present within the many sandstone and conglomerate beds that occur throughout the sedimentary sequence. The coarse-grained deposits form the more porous and permeable water-bearing units of the Dockum Group, whereas the fine-grained sediments form impermeable aquitards in the group (Fallin, 1989). The more prolific parts of the aquifer are consequently developed in the lower and middle sections where the coarse-grained sediments predominate (Best Sandstone in Figure 4-1 through 4-10). Locally, any water-bearing sandstone within the Dockum Group is typically referred to as the Santa Rosa aquifer. In the Pecos River valley, the Dockum aquifer is usually known as the Allurosa aquifer (White, 1971).

The geologic setting of the Dockum Group, as well as information on aquifer properties, water levels, chemical quality of water in the aquifer, and recharge to and discharge from the aquifer are presented below.

4.1. Stratigraphy

Recent investigations of the Dockum Group have largely focused on stratigraphic nomenclature, and a fair amount of controversy has arisen over its rank as a group or formation (for an in-depth

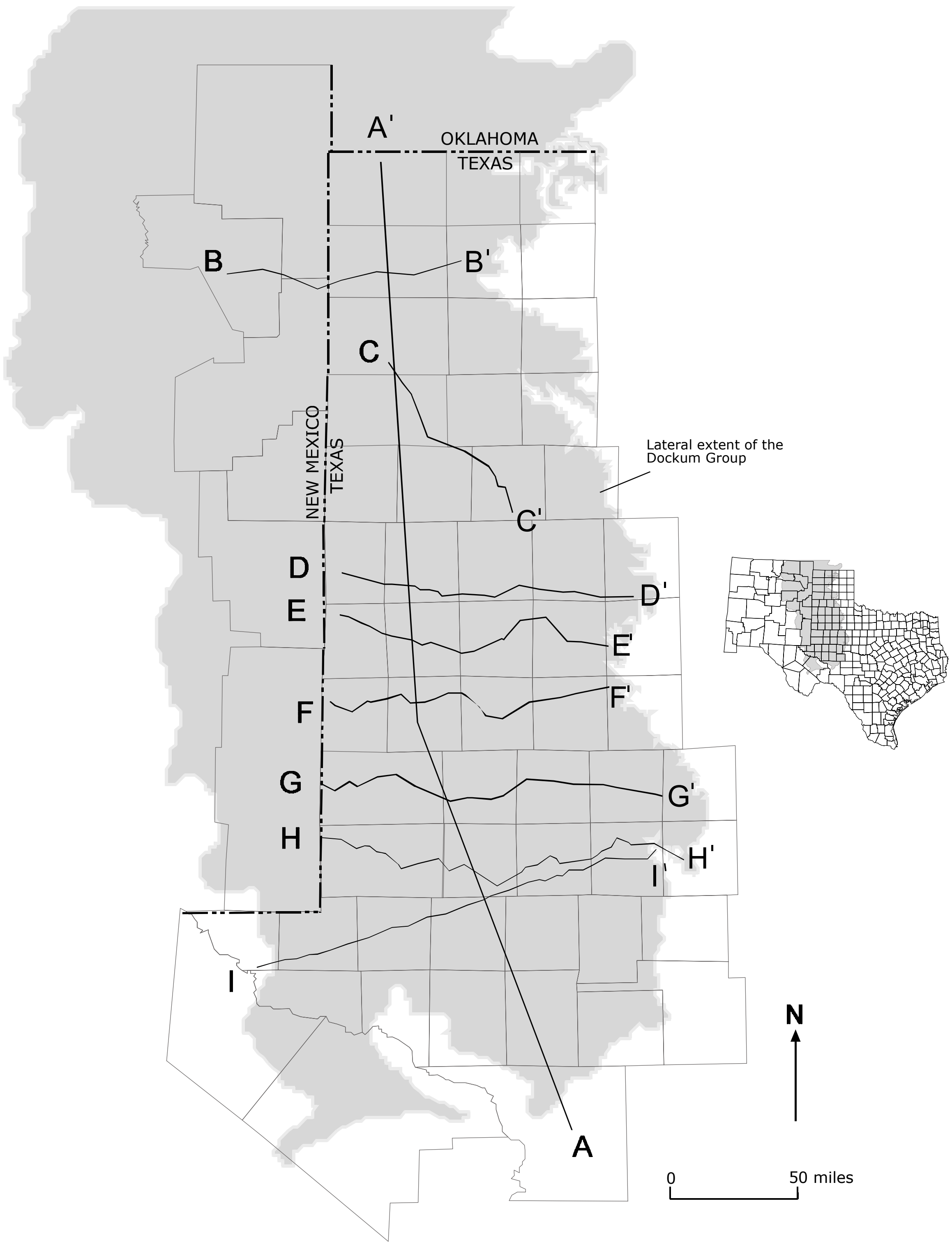

Figure 4-1. Index map of geologic cross-sections.

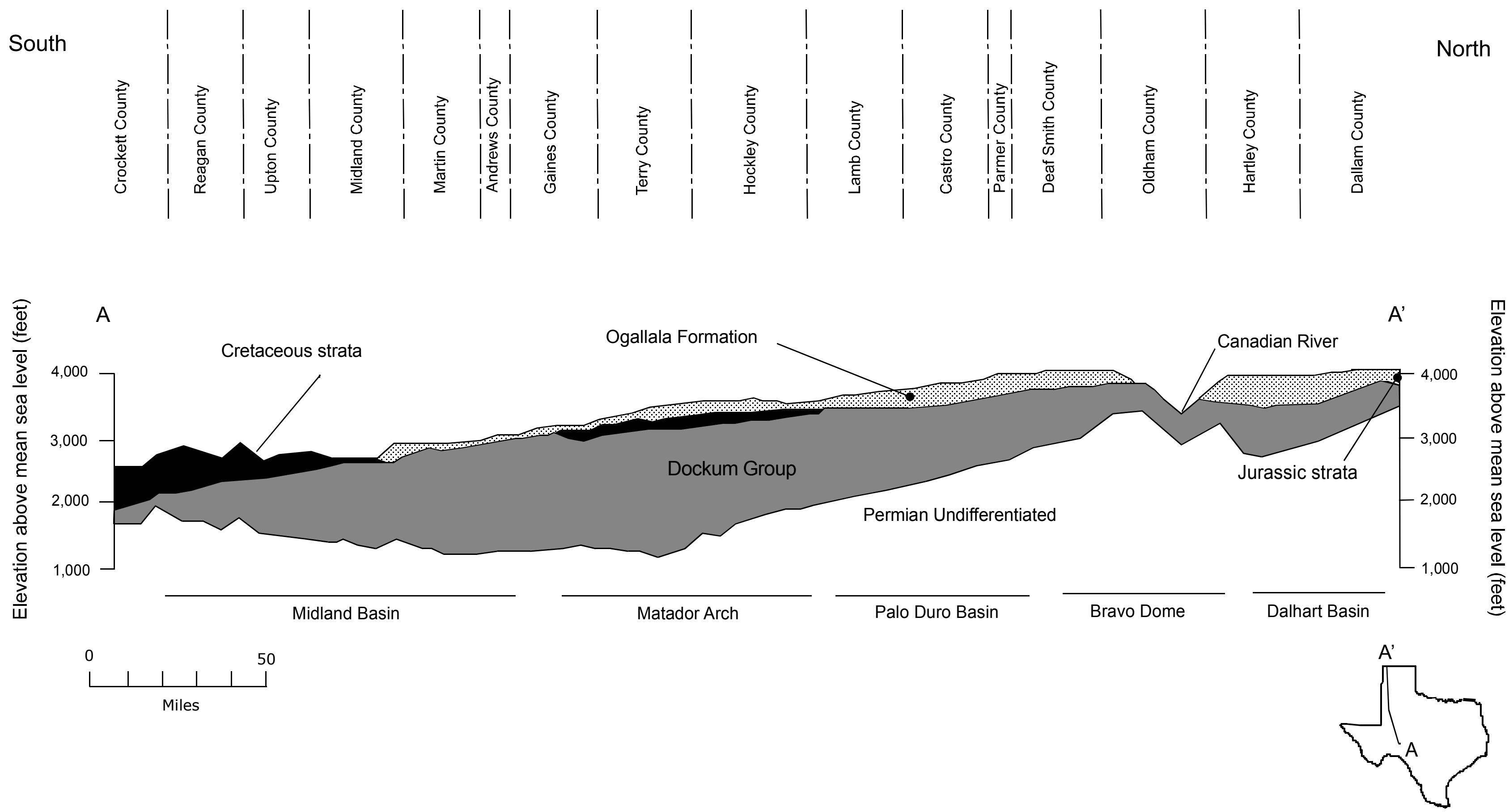

Figure 4-2 Geologic cross-section A-A'.

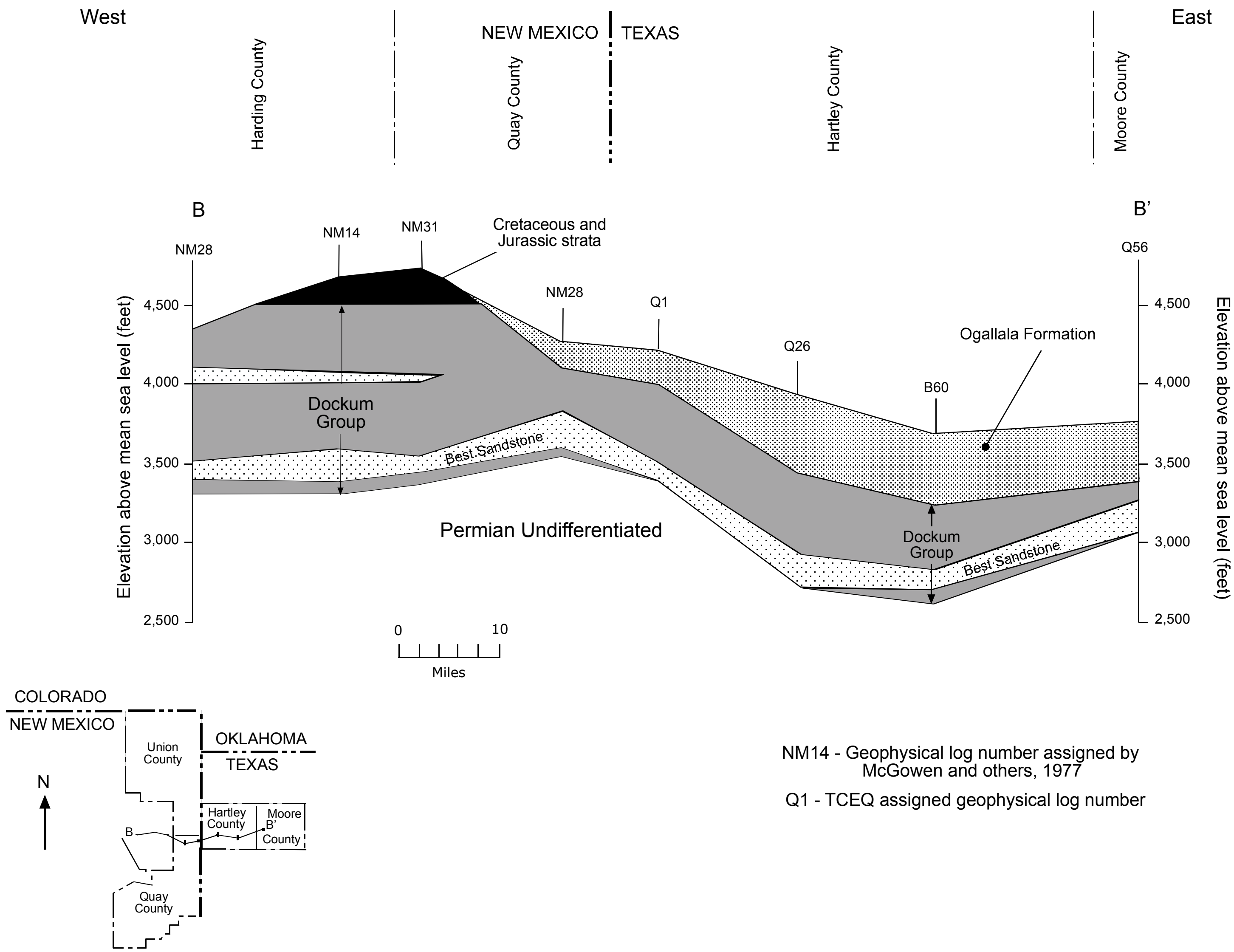

Figure 4-3. Geologic cross-section B-B'.

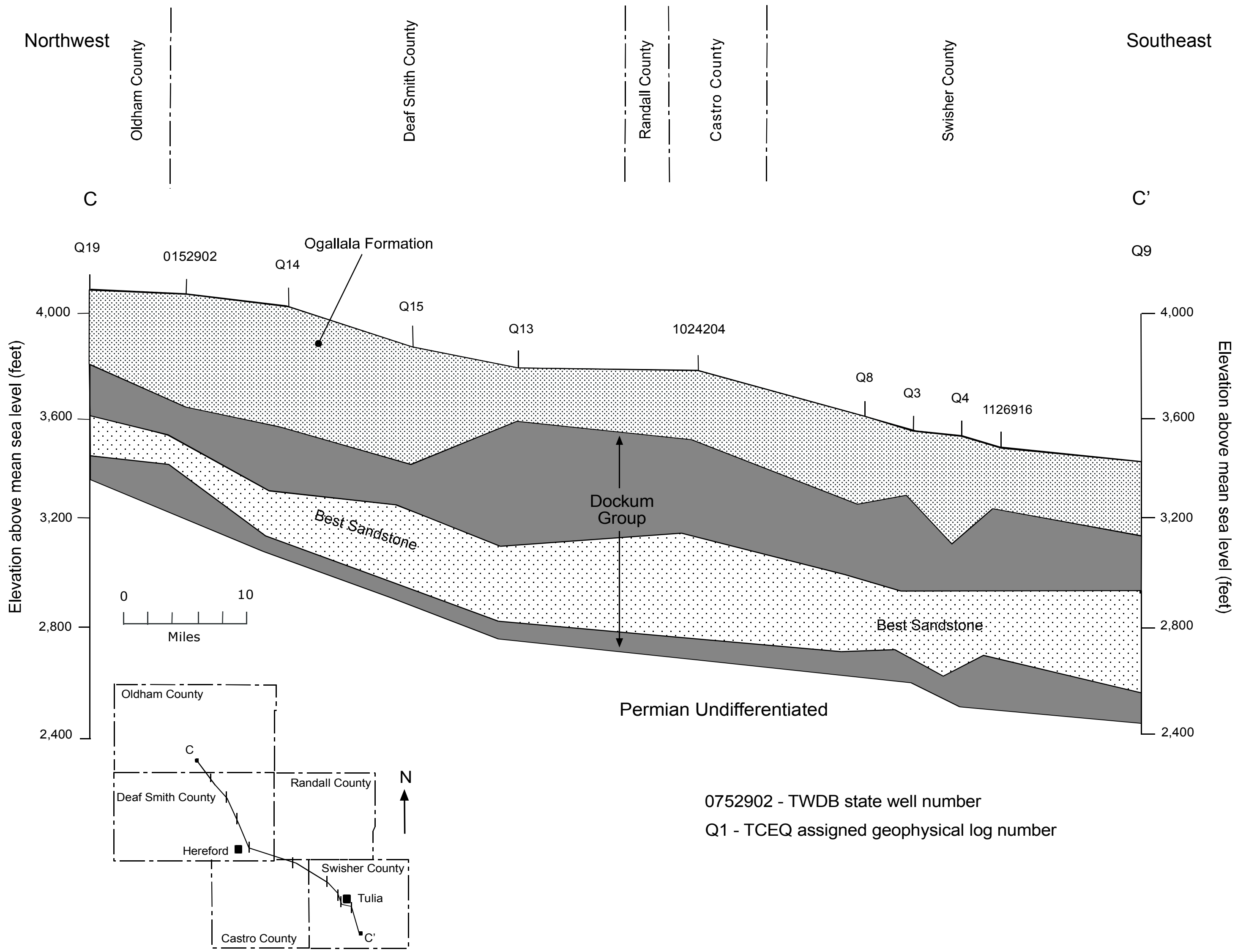

Figure 4-4. Geologic cross-section C-C'.

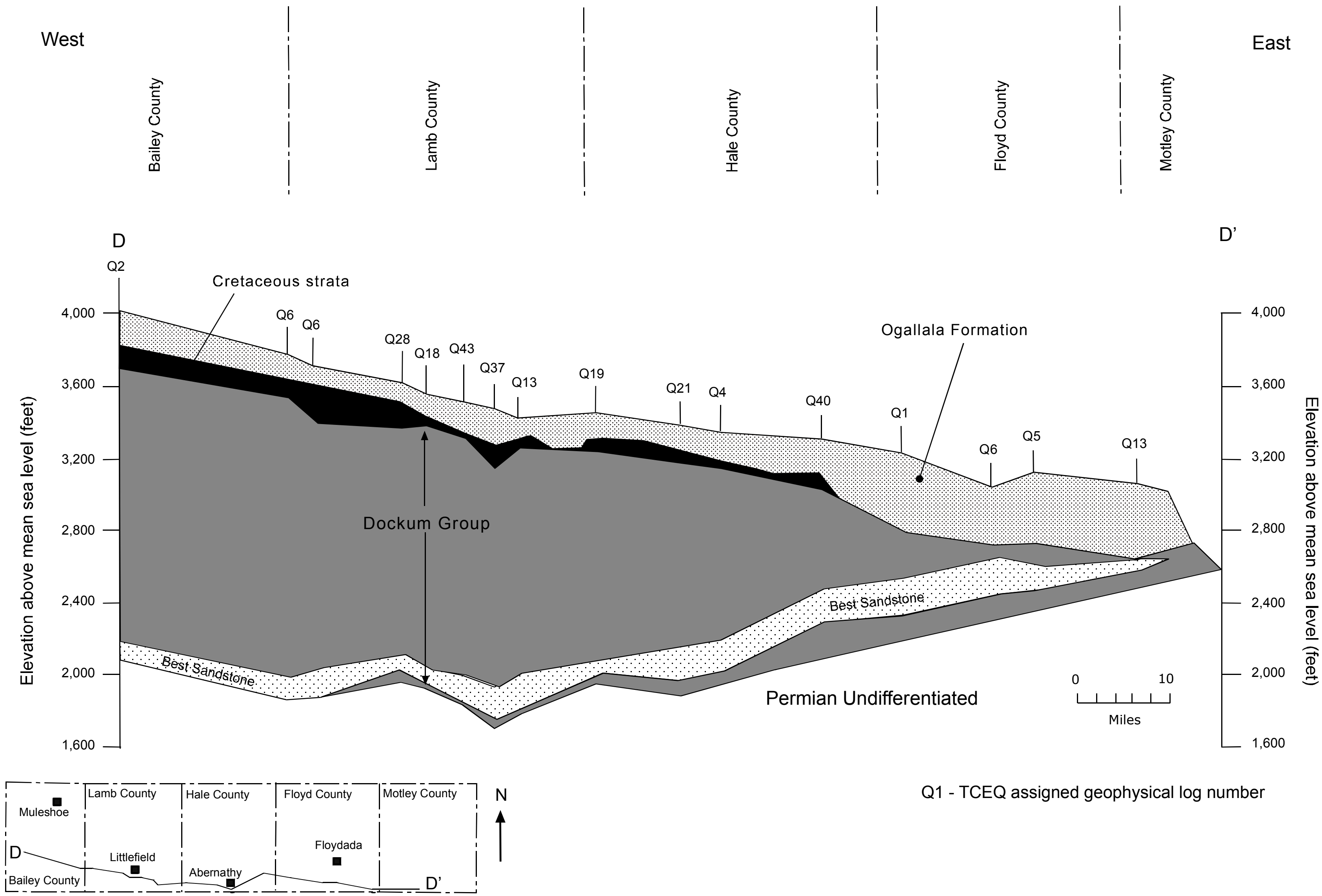

Figure 4-5 Geologic cross-section D-D’.

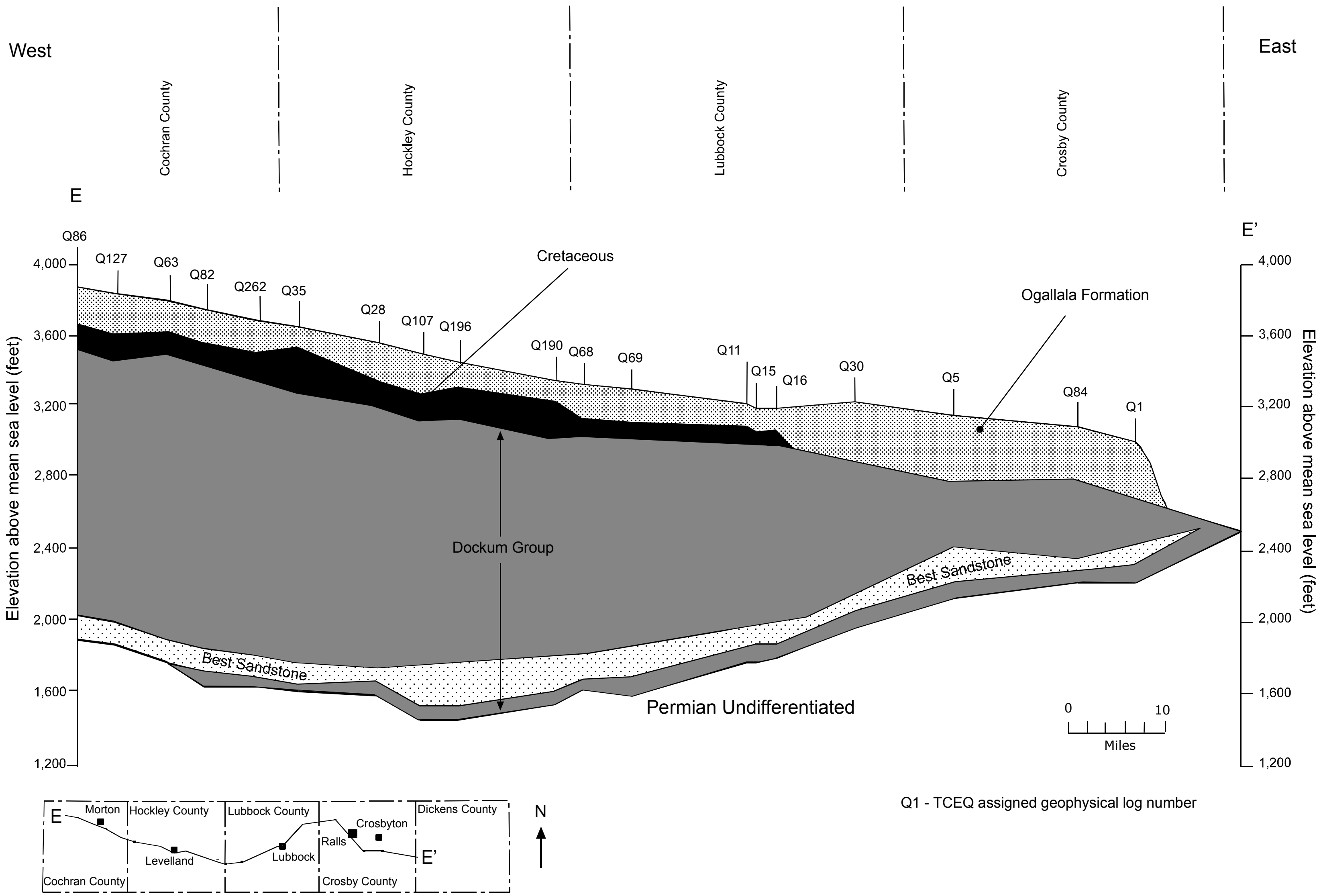

Figure 4-6 Geologic cross-section E-E'.

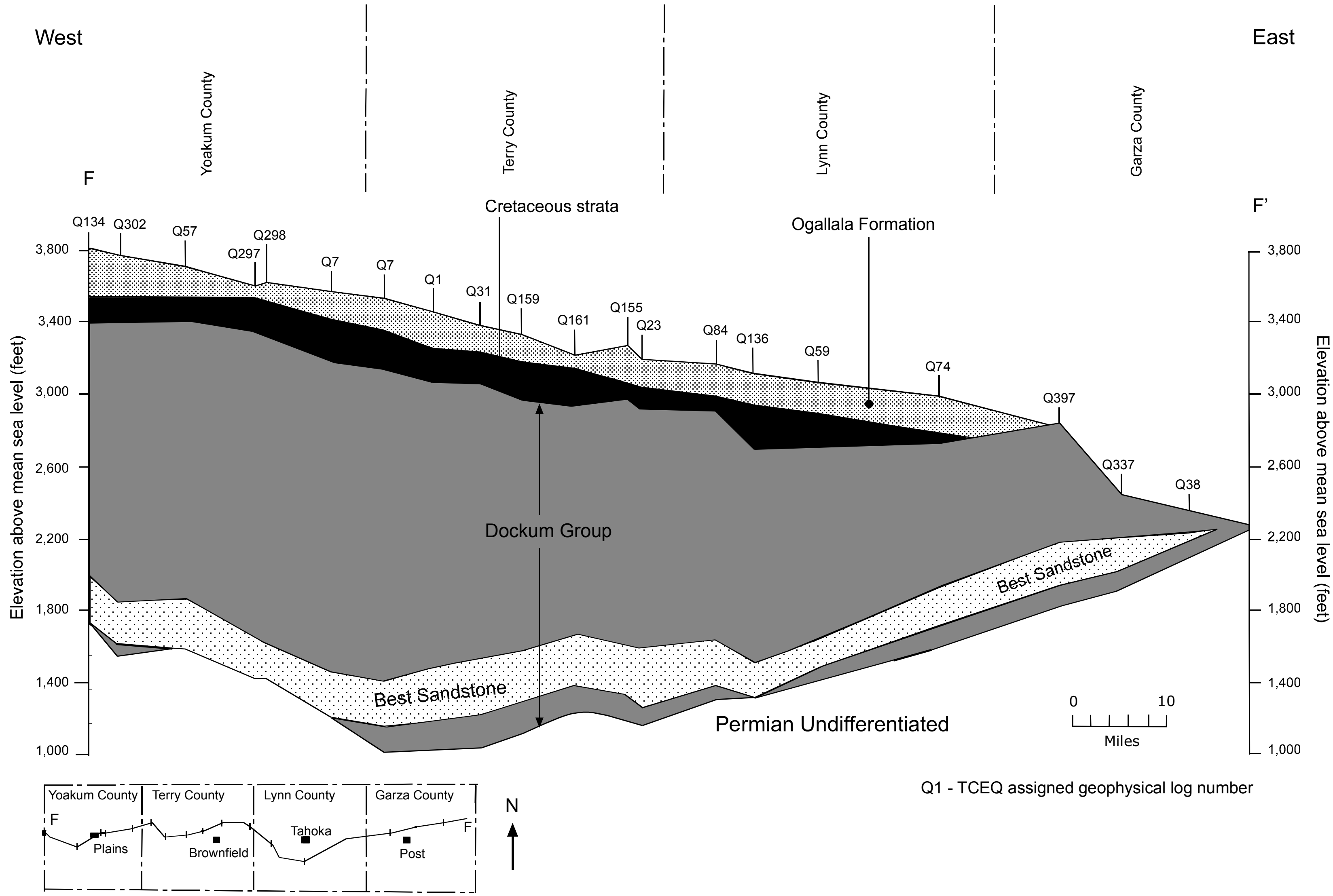

Figure 4-7. Geologic cross-section F-F'.

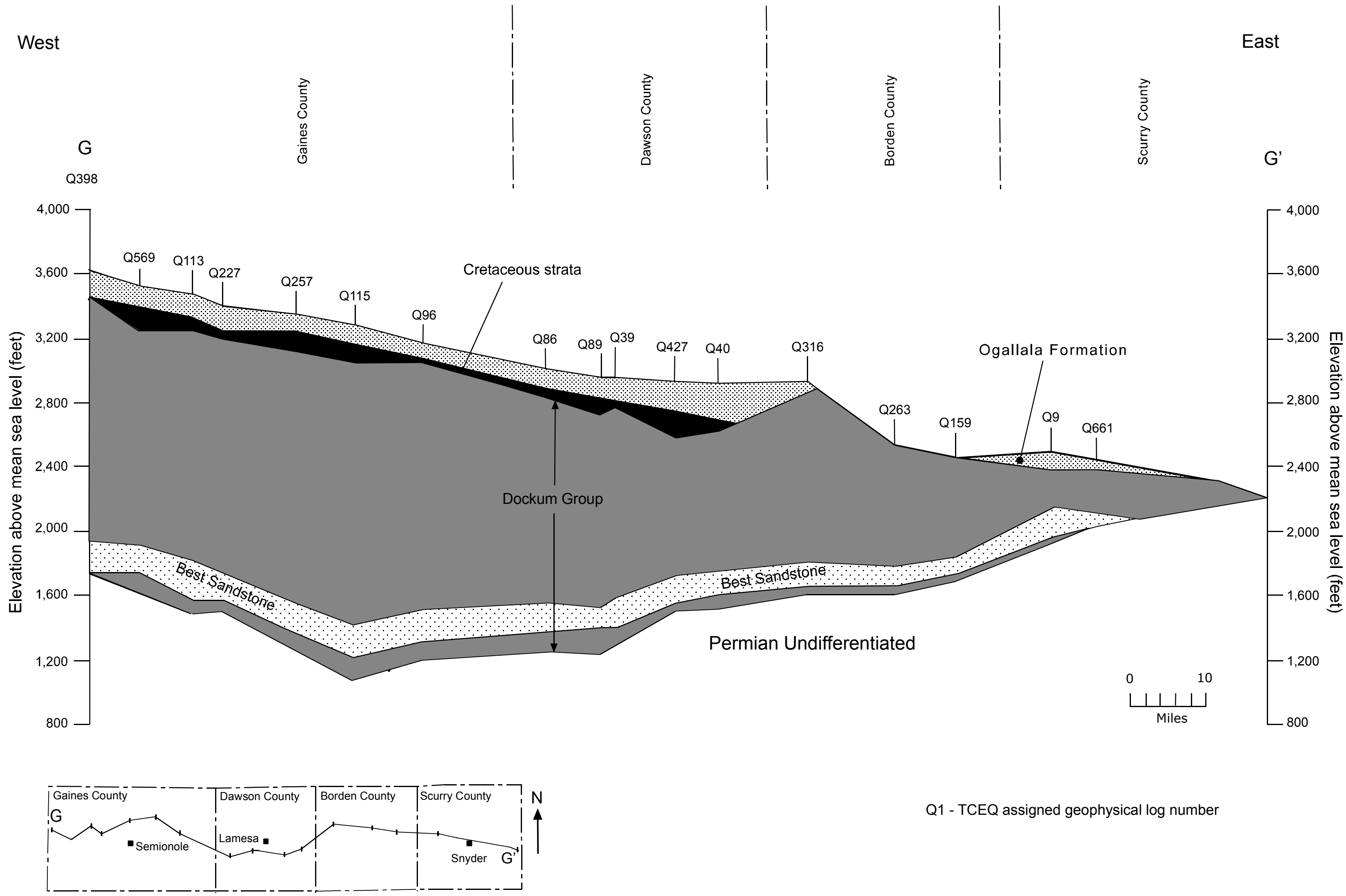

Figure 4-8. Geologic cross-section G-G'.

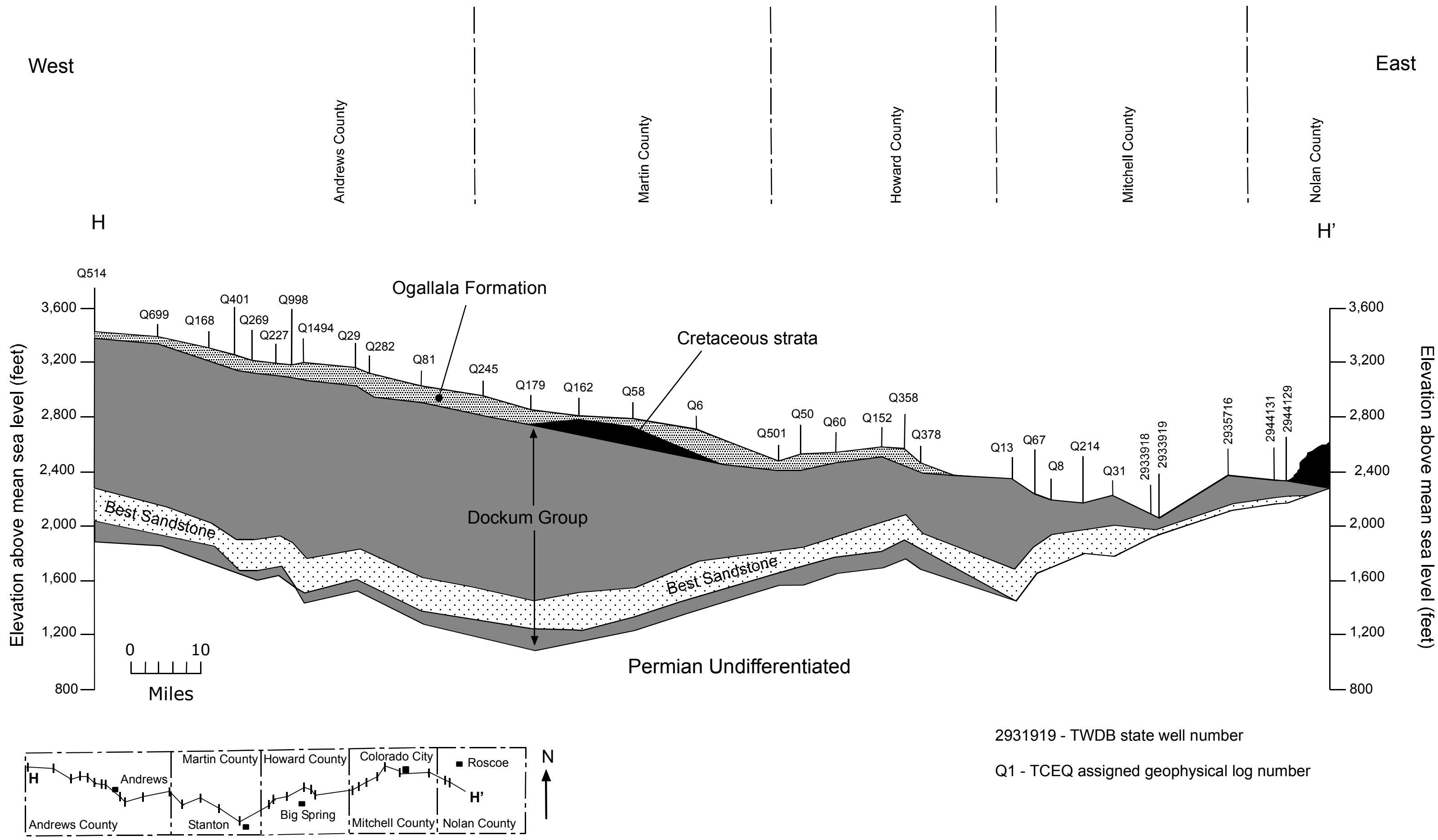

Figure 4-9. Geologic cross-section H-H'.

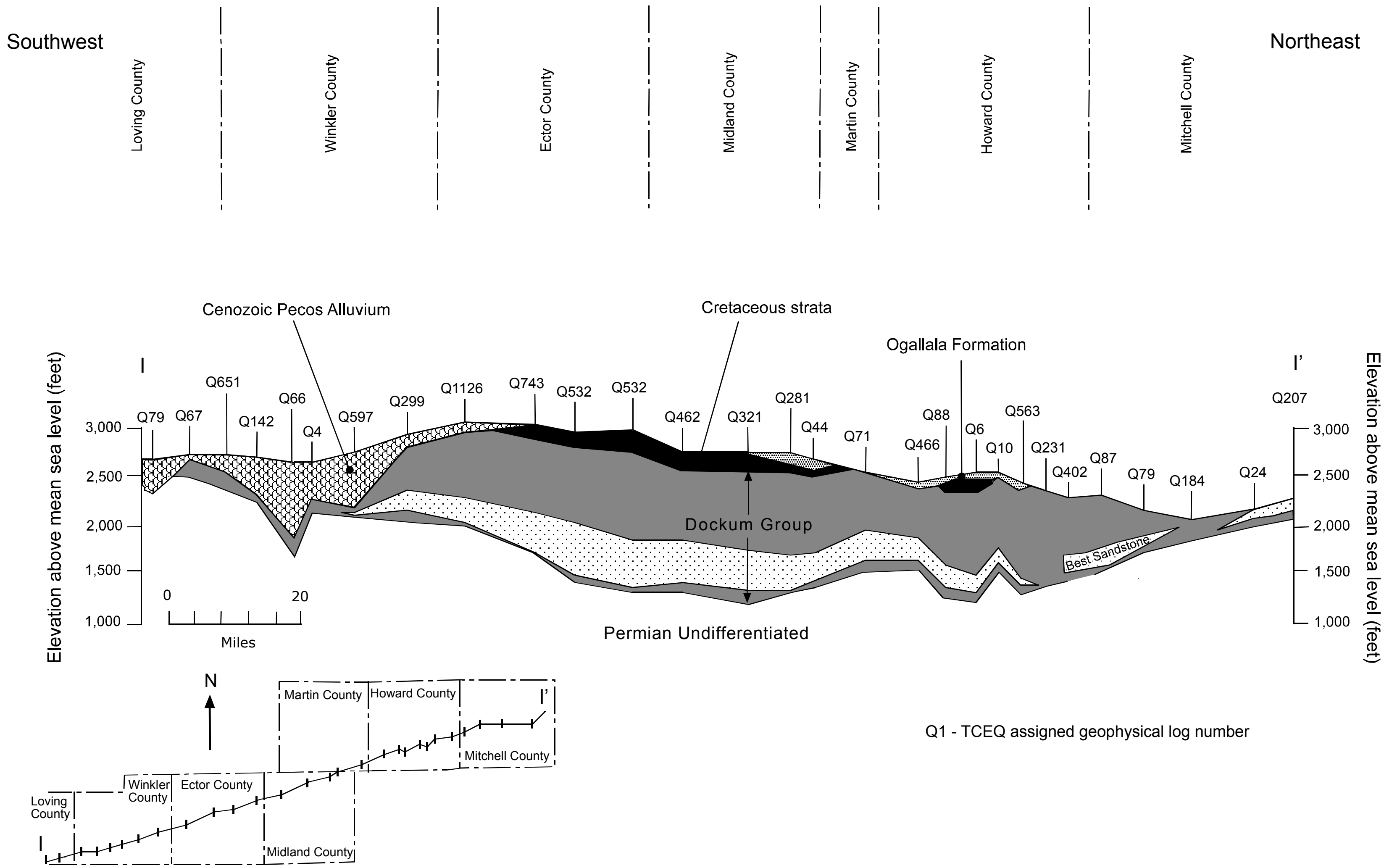

Figure 4-10. Geologic cross-section I-I'.

Table 4-1. Development of Upper Triassic Stratigraphic Nomenclature in Texas (modified from Lucas and Anderson, 1995; McGowen, and others, 1977, 1979).

<table>
<tr><th colspan="2">Cummins (1890)</th><th colspan="2">Gould (1907)</th><th colspan="2">Adams (1929)</th><th>Adkins (1932)</th><th colspan="2">Reeside and others (1957)</th><th colspan="2">McGowen and others (1977, 1979)</th><th colspan="3">Lucas and Anderson (1992, 1993, 1994, 1995)</th><th colspan="2">Lehman (1994a, 1994b)</th></tr>
<tr><td colspan="2">Not Recognized</td><td rowspan="5">Dockum Group</td><td rowspan="2">Trujillo Formation</td><td rowspan="5">Dockum Series</td><td>Chinle Formation</td><td>Chinle Formation</td><td>Not Described</td><td>Chinle Formation</td><td rowspan="5">Dockum Group</td><td rowspan="2">Upper</td><td rowspan="5">Chinle Group</td><td rowspan="5">Dockum Formation</td><td>Bull Canyon Member</td><td rowspan="5">Dockum Group</td><td>Cooper Canyon Formation</td></tr>
<tr><td rowspan="4"></td><td>Sandstone</td><td rowspan="4">Santa Rosa Sandstone</td><td>Trujillo Formation</td><td>Trujillo Formation</td><td>Santa Rosa Formation</td><td>Trujillo Member</td><td>Trujillo Sandstone</td></tr>
<tr><td rowspan="2">Red Clay</td><td rowspan="3">Tecovas Formation</td><td rowspan="2">Tecovas Formation</td><td rowspan="2">Tecovas Formation</td><td rowspan="2">Tecovas Formation</td><td rowspan="3">Lower</td><td>Tecovas Member</td><td rowspan="2">Tecovas Formation</td></tr>
<tr><td>Colorado City Member</td></tr>
<tr><td>Conglomerate</td><td>Camp Springs Conglomerate</td><td>Camp Springs Conglomerate</td><td>Camp Springs Conglomerate</td><td>Camp Springs Member</td><td>Santa Rosa Formation</td></tr>
</table>

discussion, see Lucas and Anderson, 1992, 1993, 1994; Lehman, 1994a, 1994b). Table 4-1 is a summary of the development of the stratigraphic nomenclature of the Dockum Group. Because our study is focused on groundwater resources, we have avoided the stratigraphic controversy and have retained the well established and widely accepted nomenclature of Dockum Group suggested by Lehman (1994a, 1994b) to describe the Triassic-age rocks.

Rocks of the Dockum Group are the only Triassic-age sediments exposed at the land surface in Texas. The formations within the Dockum Group (in ascending stratigraphic order) are: Santa Rosa Formation, Tecovas Formation, Trujillo Sandstone, and Cooper Canyon Formation (Lehman 1994a and 1994b in Table 4-1). Locally, the term "Santa Rosa" has been applied to the lower sandstone zones in the Dockum Group that may include all units of the Dockum Group except the upper mudstone. Traditionally, the base of the Dockum Group has been identified as a mudstone that is difficult to distinguish from older Permian sediments (McGowen and others, 1977, 1979; Granata, 1981). However, some older studies and more recent investigations describe the base of the Dockum Group as an extensive sandstone or conglomerate bed. The basal unit, called the Santa Rosa Formation, rests unconformably on Upper Permian red beds and can be as much as 130 feet thick (Lehman and others, 1992; Lehman, 1994a, 1994b; Riggs and others, 1996).

The Santa Rosa Formation is overlain by variegated mudstones and siltstones of the Tecovas Formation (Gould, 1907), which in turn is disconformably overlain by the 250-foot-thick Trujillo Formation composed of massive crossbedded sandstones and conglomerates (Lehman, 1994a, 1994b). The Trujillo Formation, exposed in some of the outcrop areas, has been mapped along the Canadian River (Bureau of Economic Geology, 1969, 1983).

Gould (1907) recognized an additional mudstone unit above the Trujillo Formation. The upper beds of this unit consist of reddish-brown to orange mudstone, along with some siltstone, sandstone and conglomerate and are now known as the Cooper Canyon Formation (Lehman and others, 1992). Previously, these beds were referred to as the Chinle Formation or the Chinle Equivalent (Table 4-1).

The subsurface mapping of individual beds within the Dockum Group has not been entirely successful. The apparent discontinuity of many beds in the subsurface has precluded an accurate correlation of outcrop units or the mapping of their exact subsurface extent (McGowen and others, 1977; Granata, 1981). Geologic cross-sections (Figure 4-1 through 4-10) illustrate the general stratigraphy of the Dockum Group in the study area. Appendix A contains a list of wells with geophysical logs that we used to construct the cross-sections. The approximate elevations of the base and top of the Dockum Group are shown in figure 4-11 and 4-12, respectively.

4.2 Depositional Environment

McGowen and others (1977, 1979) and Granata (1981) described the Dockum Group as a 2,000-foot-thick sequence of sediments that accumulated in fluvial, deltaic, and lacustrine environments within a closed continental basin. On the basis of paleocurrent analysis, Lucas and Anderson (1992) concluded that sediments of the Dockum Group were mainly fluvial in origin and that the siltstones and mudstones were deposited on floodplains, interfluves, and in small

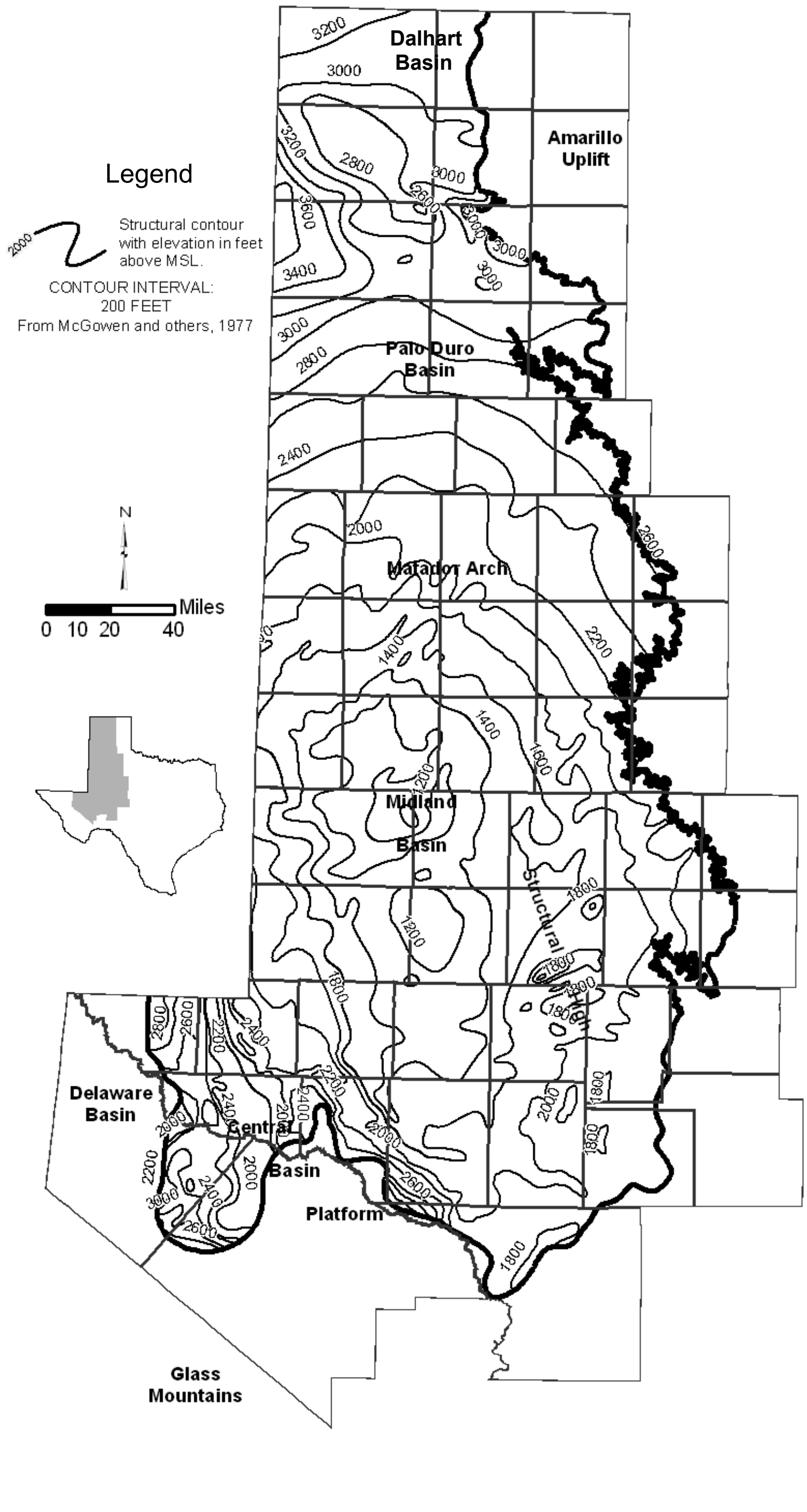

Figure 4-11. Approximate elevation of the bottom of the Dockum Group.

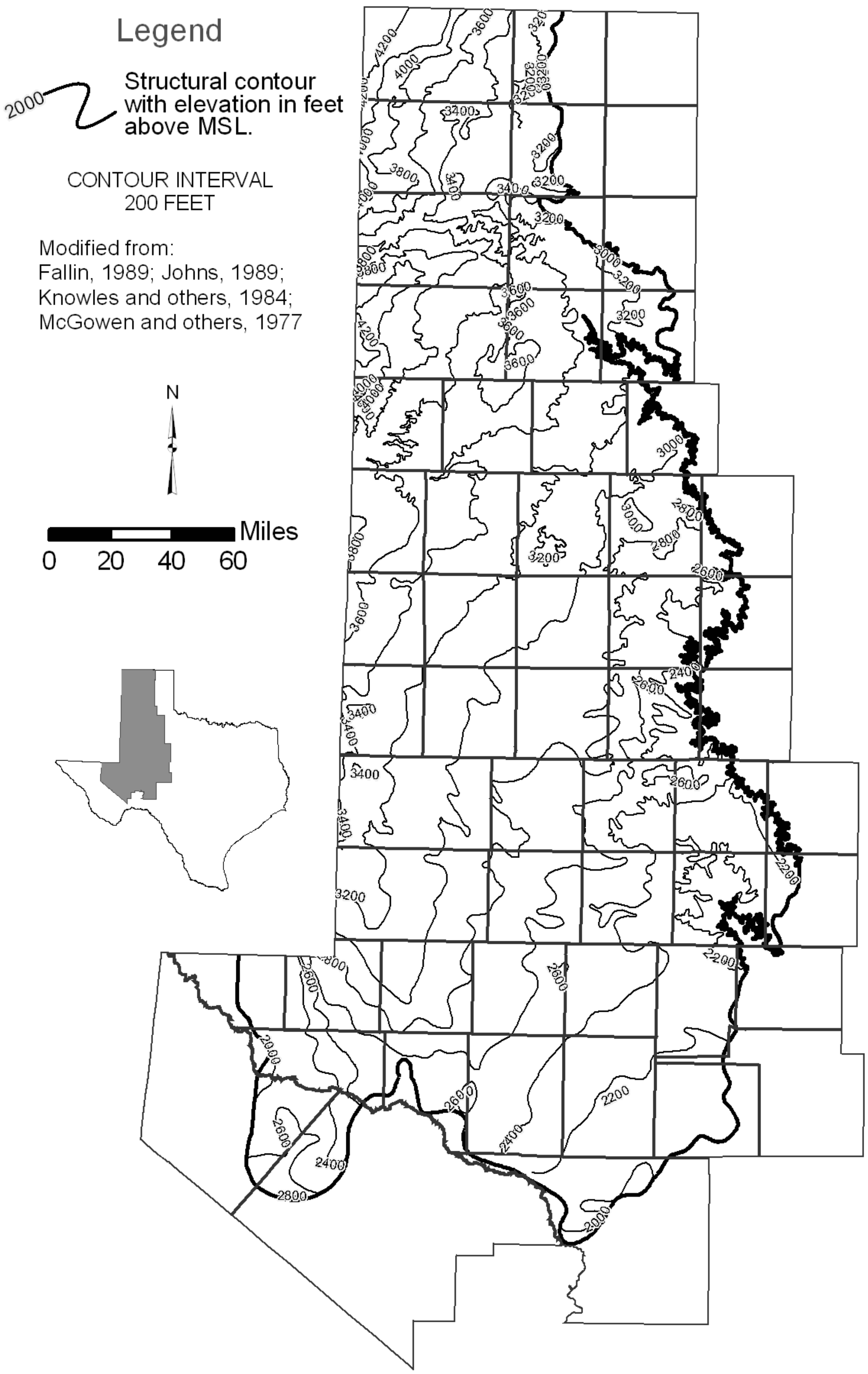

Figure 4-12. Approximate elevation of the top of the Dockum Group.

isolated ponds. The basin received sediments from all directions from the erosion of Paleozoic sedimentary source rocks exposed around the edges of the basin. Meandering, low-gradient streams traversed lowlands to the east and west, and higher gradient streams were present at the north and south ends of the basin.

On the basis of an analysis of detrital zircon grains in northwest Texas, Riggs and others (1996) suggested that early deposition of the Dockum Group (Santa Rosa Formation) was accomplished by a river system that flowed from Texas to Nevada during the Late Triassic.

4.3 Structure

The beds of the Dockum Group are essentially horizontal, with gentle dips toward the center of the structural basin whose axis trends approximately north-south. The dip varies considerably from location to location but is approximately 30 feet per mile (Rayner, 1965). Deposition of the Dockum Group sediments in the Triassic represents the final filling of a number of small adjoining, intracratonic basins that were active mainly in the Paleozoic (Granata, 1981). In Texas, these basins include the Midland basin in the south, the Palo Duro basin in the central region, and the Dalhart basin in the north (Figure 4-11, Fallin, 1989). The basins are separated by structural highs such as the Amarillo Uplift between the Dalhart and Palo Duro basins and the Matador Arch between the Palo Duro and Midland basins (Figure 4-11). The Central Basin Platform present at the southwest end of the Midland Basin separated the Midland Basin from the Delaware Basin to the west. The entire area over which the Dockum Group sediments were deposited has been referred to as the Dockum Basin (Granata, 1981).

The top of the Dockum Group is relatively flat (Figure 4-11) and reflects the final filling of the Dockum Basin and the effects of post-depositional erosion. The opening of the Gulf of Mexico in the Cenozoic tilted the entire region toward the southeast.

5.0 Water Levels and Regional Groundwater Flow

We used water-level information available in the TWDB database and from the USGS New Mexico district to construct an average water-level elevation map for the study area during the 1981 through 1996 time period (Figure 5-1). Water-level information from New Mexico was used primarily to constrain water-level contours in the Texas part of the Dockum aquifer. Groundwater flow in the Dockum aquifer is generally to the east and southeast (Figure 5-1). In Hartley and Oldham counties, groundwater flows locally toward the Canadian River. In Mitchell County, groundwater flows toward the Colorado River. Hydraulic gradients range from about 8 feet per mile in the central part of the aquifer to 37 feet per mile along the Canadian River. A relatively steep gradient of about 14 feet per mile is present in Cochran, Yoakum, and Gaines counties. The rate of groundwater flow ranges from about 0.002 feet per day in Terry County to 0.05 feet per day in Deaf Smith County. We determined these flow rates from hydraulic conductivities derived from aquifer tests, an assumed average aquifer porosity, and regional hydraulic gradients shown on water-level maps.

We also used the water-level information to construct hydrographs for 20 wells in the study area (Figure 5-2, 5-3, and 5-4). For convenience in discussing the hydrographs, we divided the study

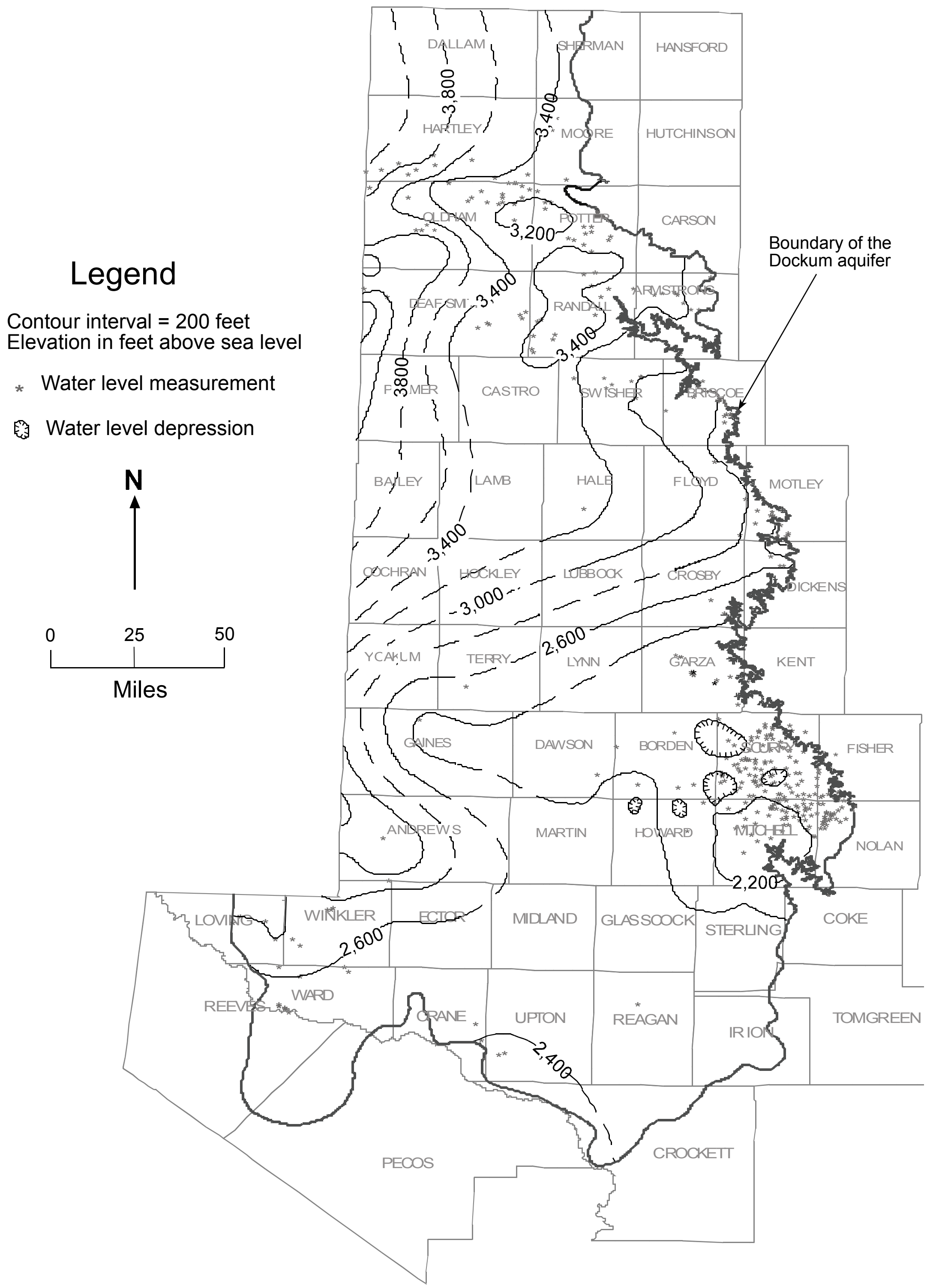

Figure 5-1. Approximate water level elevations in the Dockum aquifer, 1981 through 1996.

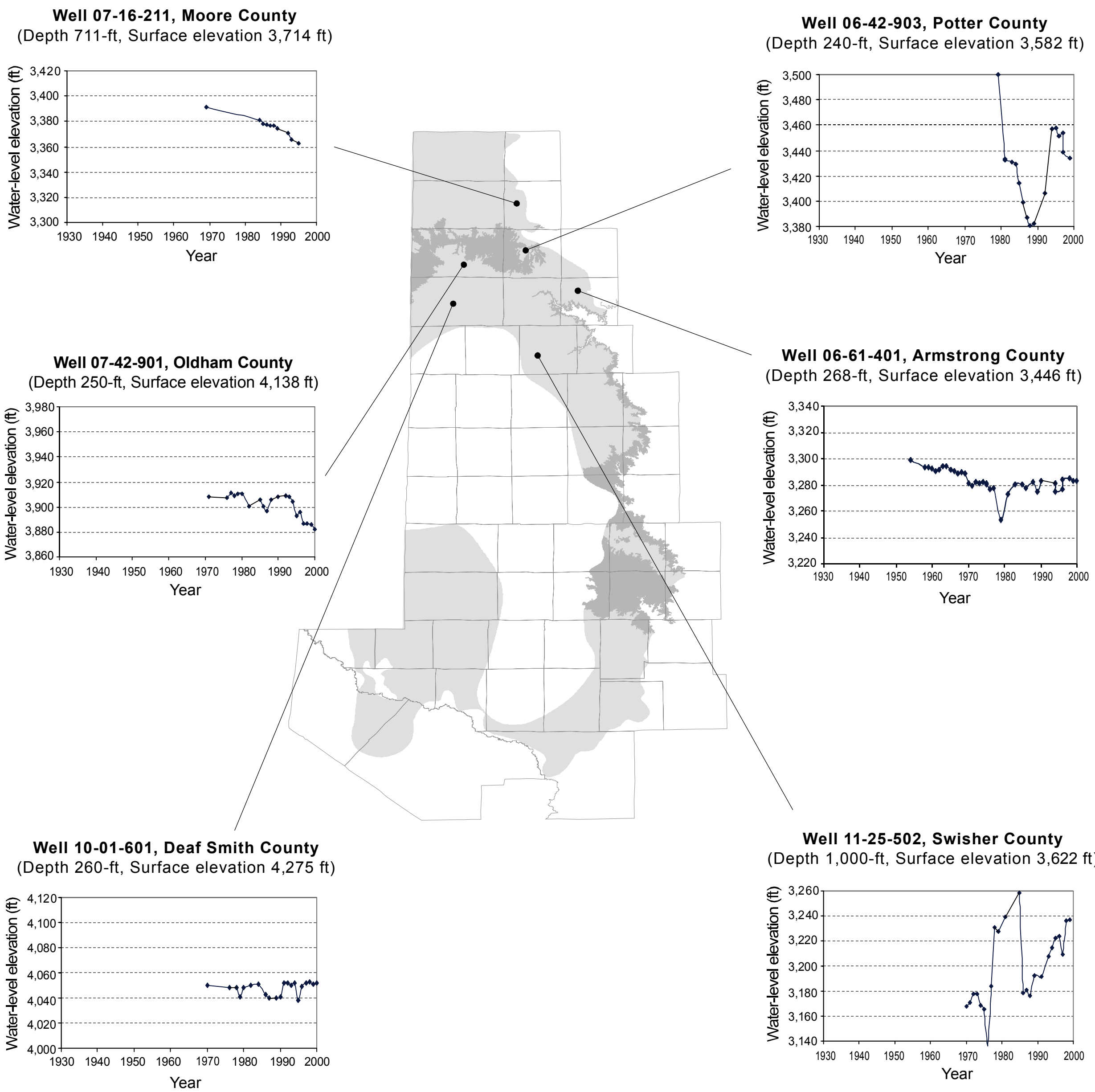

Figure 5-2. Selected hydrographs from the northern part of the study area.

area into three areas: a northern area (Figure 5-2), a central area (Figure 5-3), and a southern area (Figure 5-4).

Overall, the hydrographs show that water levels in many parts of the aquifer have fluctuated over time. The fluctuations were not uniform everywhere. For example, in the northern part of the study area, water levels in Moore, Potter, and Armstrong counties generally declined from 1981 through 1996. The largest recorded decline (110 feet) was in well 06-42-903 in Potter County (Figure 5-2). In other areas, the water level remained relatively stable (Deaf Smith County),

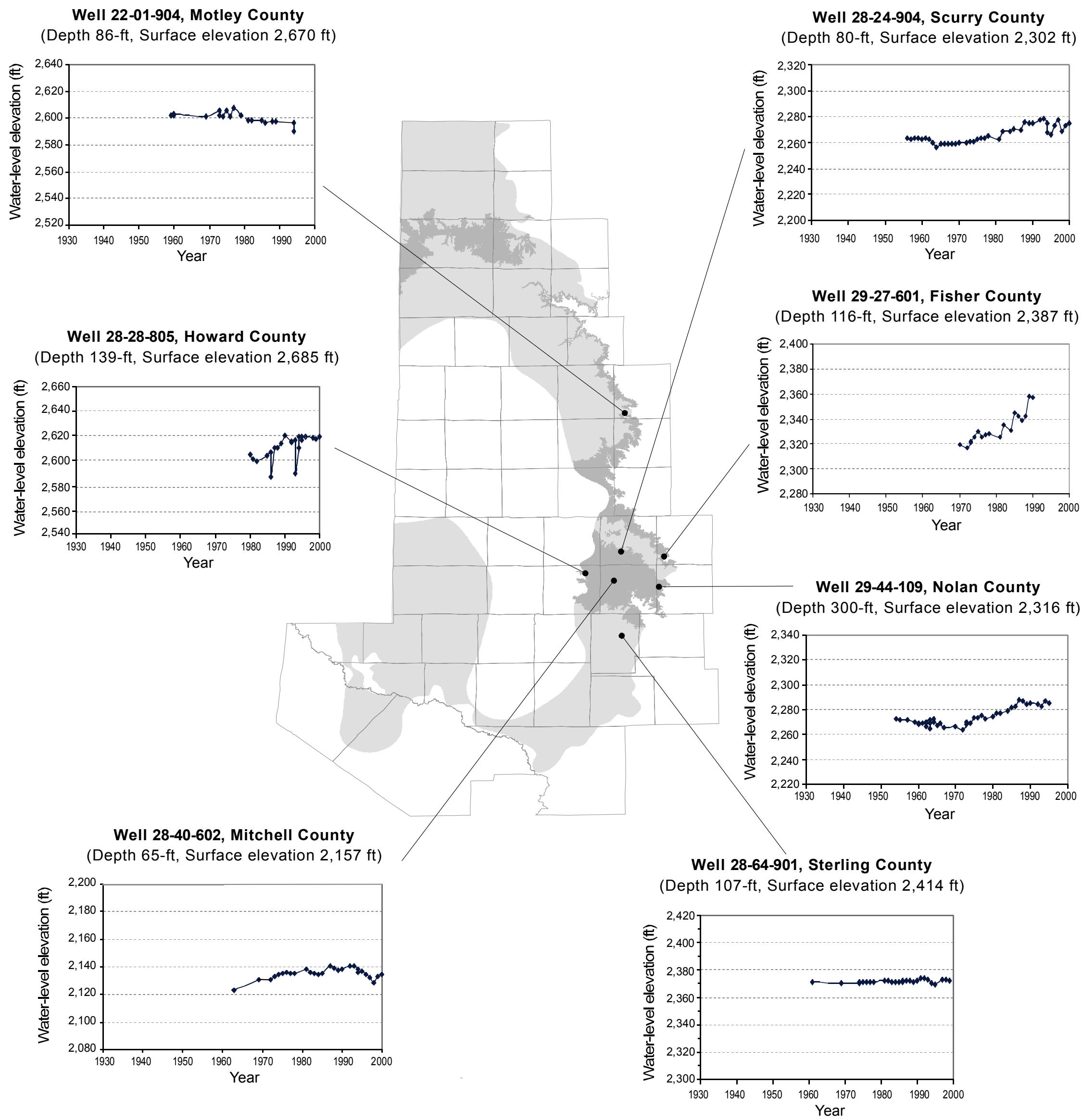

Figure 5-3. Selected hydrographs from the central part of the study area.

declined slightly (Oldham County), or even rose (Swisher County).In the central part of the study area (Howard, Mitchell, Scurry, Nolan, Fisher, and Sterling counties) the hydrographs generally show an increase in water levels over much of the area (Figure 5-3). The largest increase (almost 45 feet) was recorded in well 29-27-601 in Fisher County (Figure 5-3). This well and others that had a rise in water level are located on or near the outcrop of the Dockum aquifer and reflect increased recharge, reduced pumpage, or both. The Sterling County hydrograph (well 28-64-901) is flat, suggesting that the aquifer was not being used much or that it was receiving recharge from the overlying Cretaceous aquifer. The drought of the late 1950s is clearly evident in the Nolan County hydrograph (Figure 5-3), which shows a fall in water level in the late 1960's and early 1970's presumably in response to increased pumpage from irrigation wells or decreased recharge

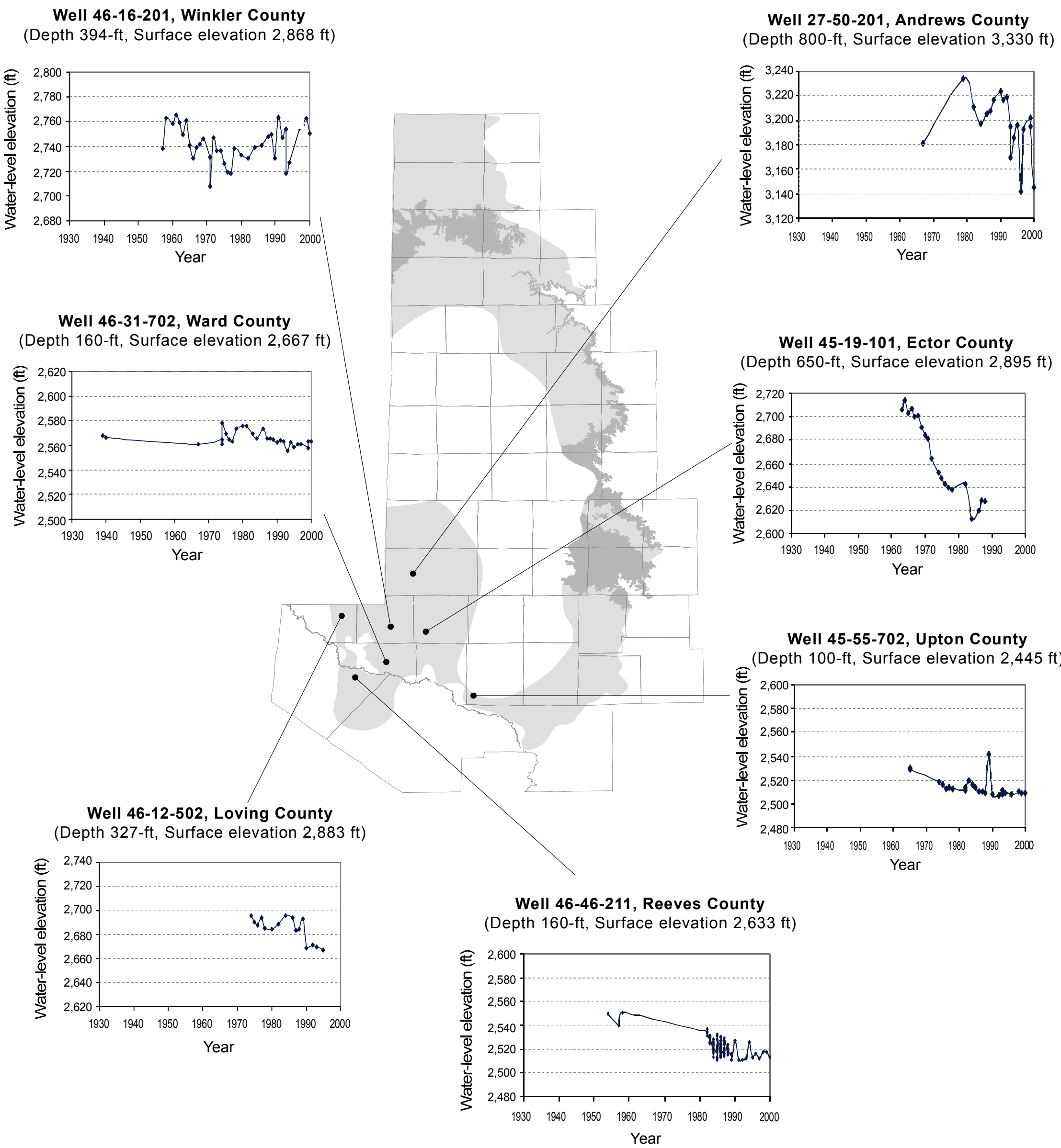

Figure 5-4. Selected hydrographs from the southern part of the study area.

to the aquifer. Hydrographs of wells in the south part of the study area (Andrews, Ector, Upton, Loving, Reeves, Ward, and Winkler counties) show a variety of water-level fluctuations (Figure 5-4). Hydrographs of wells in Loving, Ector, and Reeves counties show a distinct decline in the water table, whereas that from Ward County shows relatively stable water levels or only small declines. The most significant water-level decline (almost 85 feet) occurred in well 28-39-401 in Ector County (Figure 5-4). This decline was most likely the result of pumping from a nearby municipal water-supply well.

Where overlain by younger formations, the Dockum aquifer is typically under confined conditions. Within the Dockum Group itself, mudstone units (especially the thick upper sequence within the center of the aquifer basin) also act as confining beds. The aquifer is partially confined in areas where the Dockum Group sediments are exposed at the surface. The aquifer is also partially confined in parts of the Pecos River valley (Loving, Reeves, Ward and Winkler counties) where Dockum Group sandstones are in contact with the Cenozoic Pecos Alluvium. Where exposed at land surface, the Dockum aquifer is typically under unconfined conditions.

5.1 Recharge

The Dockum aquifer is recharged by precipitation over areas where Dockum Group sediments are exposed at the land surface (Figure 2-2). Shamburger (1967) suggested that substantial recharge also occurred along stream channels and tributaries of several creeks, such as Champion Creek and the South Fork Champion Creek in Nolan County, where the basal conglomerate and sandstone units are exposed (Lucas and Anderson, 1993). Shamburger (1967) reported that one well in Nolan County was capable of producing 15 to 20 percent more water after sustained heavy runoff into the South Fork Champion Creek.

Groundwater in the confined parts of the Dockum aquifer in Texas most likely originated as precipitation that fell on outcrops in eastern New Mexico. This recharge ceased when the Pecos River and Canadian River valleys were incised during the Pleistocene between the present-day Dockum aquifer in Texas and the paleo-recharge areas to the west (Dutton and Simpkins, 1986; Figure 5-5).

Soils on the outcrop of the Dockum aquifer have a major effect on recharge to the aquifer. Soils that have formed on the outcrop of the Dockum Group sediments belong to hydrologic groups B, C, and D (soils that are classified on the basis of their water intake at the end of long-duration storms). A vast majority of the soils are included in Group B, which is characterized by moderate infiltration rates when saturated. Some soils on the outcrop belong to Group C which is characterized by slow infiltration rates when saturated. The Group D soils, which have the second-largest areal extent on the outcrop, are typically heavy clay soils exhibiting a high shrink-swell potential and a very slow infiltration rate when saturated. Areas that have Group B soils near subsurface sandstone units provide the greatest recharge potential to the aquifer.

The Dockum aquifer is also recharged by upward leakage from the underlying Permian rocks, although in the Palo Duro Basin the water movement is downward because the hydraulic head in the Dockum aquifer is almost 1,800 feet higher than it is in the underlying Permian brine aquifer (Bassett and others, 1981; Bentley, 1981; Wirojanagud and others, 1984; Orr and others, 1985).

Downward leakage into the Dockum aquifer occurs from the overlying Ogallala Formation, Cretaceous rocks, and Cenozoic Pecos Alluvium as a result of hydraulic-head differences between the aquifers (Dutton and Simpkins, 1986; Nativ and Gutierrez, 1988).

In parts of Crockett, Irion, Reagan, Sterling, Tom Green and Upton counties the Santa Rosa Sandstone is in hydrologic contact with the overlying Edwards-Trinity (Plateau) aquifer (Walker, 1979; Ashworth and Christian, 1989). Groundwater samples obtained from wells completed in the Dockum aquifer in Sterling County are dominated by calcium bicarbonate-type (Ca-HCO_3)

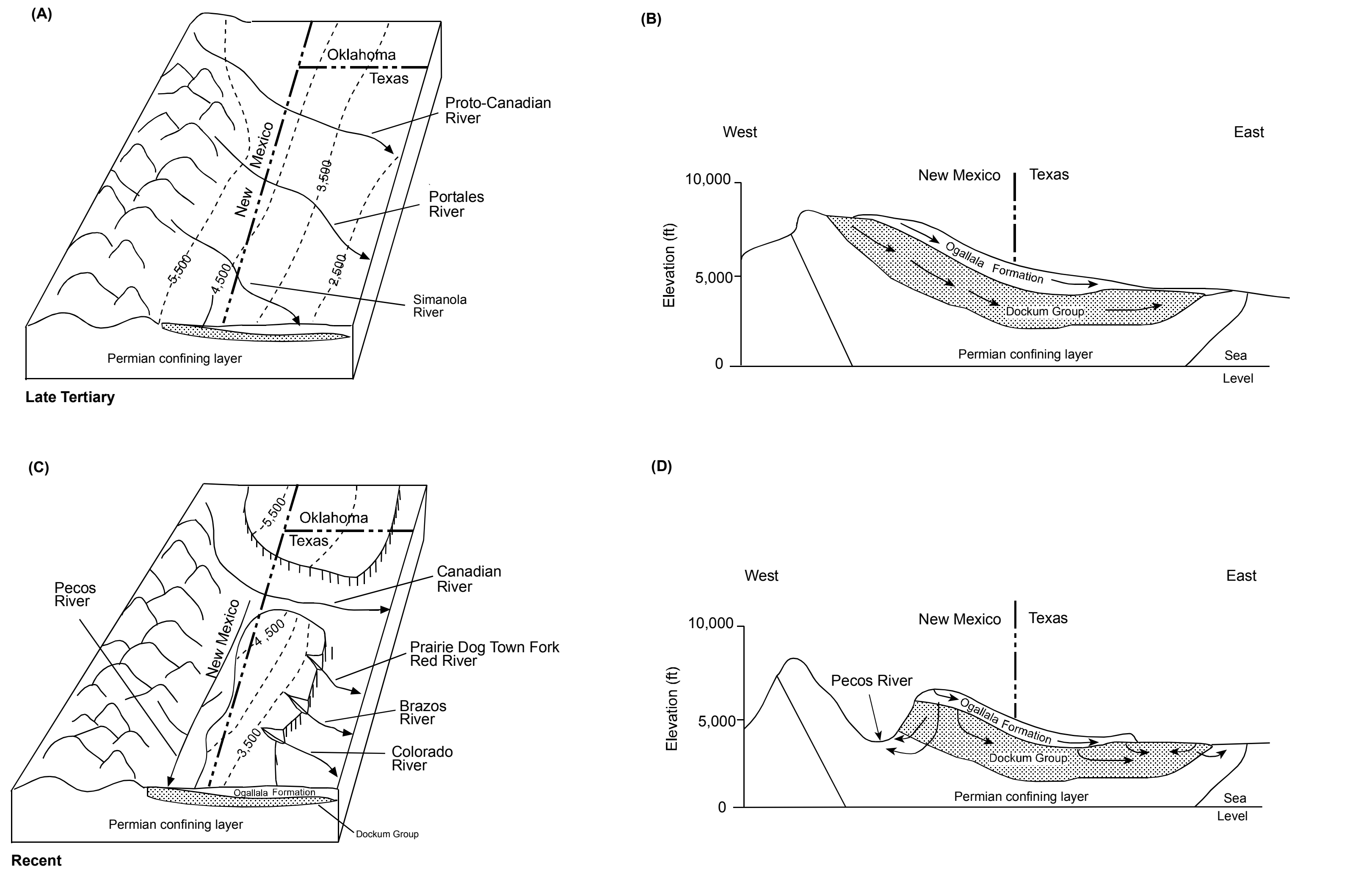

Figure 5-5. Hypothetical regional flow paths of groundwater in the Dockum aquifer. Before hydrologic divides developed, groundwater flowed from an area in eastern New Mexico downdip into the confined portions of the aquifer in Texas (A and B). After divides formed by incision of rivers (C and D), groundwater flow into Texas from New Mexico was essentially cut off(modified from Gustavson and Finley, 1985; Dutton and Simpkins, 1986). Contours are in feet above mean sea level.

water that is characteristic of groundwater in the Edwards-Trinity (Plateau) aquifer. The presence of $CaHCO_3$ in Dockum groundwater suggests that there is some groundwater movement from the limestone-dominated Edwards-Trinity (Plateau) aquifer into the Dockum aquifer.

A combination of groundwater divides and thick, relatively impermeable mudstones (Cooper Canyon Formation) above the sandstone layers in the center of the basin prevents the aquifer from receiving direct recharge from surface precipitation. We estimate that the annual recharge to the entire aquifer is approximately 31,000 acre-feet. This estimate was derived for outcrops and other areas in contact with overlying aquifers.

5.2 Aquifer Properties

The properties of an aquifer are typically described using terms such as well yield, specific capacity, transmissivity, hydraulic conductivity and storativity (Driscoll, 1986). Well yield is defined as the volume of water discharged per unit time from a well either by pumping or from free flow. It is typically measured in gallons per minute (gpm). Specific capacity is the well yield per unit drawdown in the water level when the well is pumped. The specific capacity of a well, expressed as gallons of water per minute per foot of drawdown, can be a good indicator of the water-producing ability of an aquifer. Aquifers with high specific capacities are generally productive aquifers whereas those that have low specific capacities are not as productive.

Transmissivity is a term that describes the ease with which water can move through an aquifer. Transmissivity specifically describes the volume of water that will move through a vertical strip of the aquifer one unit wide, under a unit hydraulic gradient, for a unit time. Storativity (or storage coefficient) represents the volume of water released from or taken into storage per unit of aquifer storage area per unit change in head. The storativity of an unconfined aquifer corresponds to its specific yield which is the fraction of water that can be drained by gravity for a unit volume of aquifer. In confined aquifers, storativity is the result of compression of the aquifer and expansion of the confined water when pressure is reduced during pumping.

Table 5-1 is a compilation of Dockum aquifer properties from various sources including the TWDB Well Information/Ground Water Data database and published literature. Mean well yields by county ranged from 6 gpm in Howard County to 770 gpm in Moore County with individual yields ranging from 0.5 gpm in Mitchell County to 2,500 gpm in Winkler County (Table 5-1, Figure 5-6, and Appendix III).

Specific capacity tests performed on 86 wells completed in the Dockum aquifer indicate that mean specific capacities by county ranged from 0.14 gallons per minute per foot (gpm/ft) in Garza County to 25 gpm/ft in Reeves County (Table 5-2). The mean specific capacity from all tests was 3.84 gpm/ft. The highest specific capacity within a county ranged from 0.19 gpm/ft in Garza County to 37 gpm/ft in Reeves County (Table 5-2).

We also performed 21 pumping tests in nine counties to determine aquifer properties including transmissivity which was calculated using standard techniques (i.e., Theis, 1935; Cooper and Jacob, 1946). Transmissivity ranged from about 48 square feet per day (ft^2/d) in Upton County to 4,600 ft^2/d in Winkler County (Table 5-1). The mean transmissivity from all tests was

Table 5-1. Summary of Dockum aquifer properties.

County	TWDB Well No.	Test Date	Screened Interval(s) (feet bgs)	Yield (gpm)	Transmissivity (gpd/ft)	Transmissivity (ft^2/d)	Storage Coefficient	Type of Test	Source of Data
Deaf Smith	10-13-503	12/01/1966	683-944	1,400	14,800	1,978	--	D	1
		12/04/1966			10,700	1,430		R	1
	10-14-202	01/16/1959	600-776	788	22,000	2,941	1.0×10^{-4}	M	2,4
Mitchell	29-34-709	03/1963	--	--	7,900	1,056	4.5×10^{-5}	D	8
		11/05/1963			7,000	936	5.5×10^{-5}	D	8
	29-34-714	03/1963	--	75	4,400	588	--	D	8
		11/05/1963		66	4,700	628		D	8
	29-34-716	03/1963	--	--	7,700	1,029	6.5×10^{-5}	D	8
		03/1963			6,100	815	9.6×10^{-5}	R	8
		11/05/1963			6,500	869	4.4×10^{-5}	D	8
	29-35-437[A]	11/21/1963	120-195 205-273	170	11,270	1,506	1.3×10^{-4}	D	6,8
	29-35-712	01/09/1964	--	--	5,856	783	4.4×10^{-4}	D	7,9
		01/10/1964			7,760	1,037	4.4×10^{-4}	R	7,9
	29-35-713	01/09/1964	--	245	3,680	492	--	D	8
	29-43-403	--	--	70	12,300	1,644	1.2×10^{-4}		6,8
Motley	22-01-201	10/26/1968	200-282 287-300	321	11,700	1,564	--	R	7,8
Potter	06-42-601	07/25/1958	140-170	--	480	64	--	R	8
Scurry	28-31-301	07/22/1970	440-450		8,000	1,069		D	8
		07/23/1970	500-510 520-530 545-555	608	5,900	789	--	R	8

NOTES: * = Open hole
- Well numbers used in previous reports and subsequently renumbered: **A**. 29-35-106, **B**. D-291, **C**. D-293, **E**. D-299, **F**. D-279.
- Types of tests: **D** = Drawdown, **M** = Average Value, **R** = Recovery, **SD** = Step Drawdown.
- Sources of data: **1**. Dutton and Simpkins, 1986; **2**. Fink, 1963; **3**. Garza and Wesselman, 1959; **4**. Rayner, 1963; **5**. Robotham et al., 1985; **6**. Shamburger, 1967; **7**. Smith, 1973; **8**. TWDB Central Records; **9**. White, 1968.

gpm = gallons per minute
bgs = below ground surface
gpd/ft = gallons per day per foot

Table 5-1. Summary of Dockum aquifer properties (continued).

County	TWDB Well No.	Test Date	Screened Interval (s) (feet bgs)	Yield (gpm)	Transmissivity (gpd/ft)	Transmissivity (ft^2/d)	Storage Coefficient	Type of Test	Source of Data
Swisher	11-26-611	07/24/1967	620-820	2,000	15,600	2,085	--	D	1
		07/24/1967			28,800	3,850		SD	
Terry	27-05-204	02/19/1985	1833-1853	74.9	1,533	205	--	D	5
		02/19/1985	1873-1893 1903-1993		1,081			R	
	27-05-205	02/26/1985	1733-1793	72.2	866	116	--	D	5
		02/26/1985	1813-1833 1853-1903		1,199			R	
Upton	45-46-603	03/08/1966	428-490	36	360	48	--	D	9
Winkler	46-16-104[B]	04/27/1957	--	305	25,000	3,342	--	R	3
		07/26/1957		--	24,000	3,208		D	
		07/27/1957		--	24,000	3,208		R	
	46-16-130[C]	07/26/1957	--	--	25,000	3,342	2.9×10^{-4}	D	3
		07/27/1957			24,000	3,208	2.5×10^{-4}	R	
	46-16-201[D]	07/26/1957	265-364*	1,875	37,000	4,646	--	R	3
	46-16-101[E]	08/18/1957	230-405*	1,200	12,000	1,604	--	R	3
	46-16-120[F]	08/17/1957	274-700*	--	13,000	1,738	2.5×10^{-4}	D	3
		08/18/1957			13,000	1,738	2.4×10^{-4}	R	

NOTES: * = Open hole

- Well numbers used in previous reports and subsequently renumbered: **A**. 29-35-106, **B**. D-291, **C**. D-293, **E**. D-299, **F**. D-279.
- Types of tests: **D** = Drawdown, **M** = Average Value, **R** = Recovery, **SD** = Step Drawdown.
- Sources of data: **1**. Dutton and Simpkins, 1986; **2**. Fink, 1963; **3**. Garza and Wesselman, 1959; **4**. Rayner, 1963; **5**. Robotham et al., 1985; **6**. Shamburger, 1967; **7**. Smith, 1973; **8**. TWDB Central Records; **9**. White, 1968.

gpm = gallons per minute
bgs = below ground surface
gpd/ft = gallons per day per foot

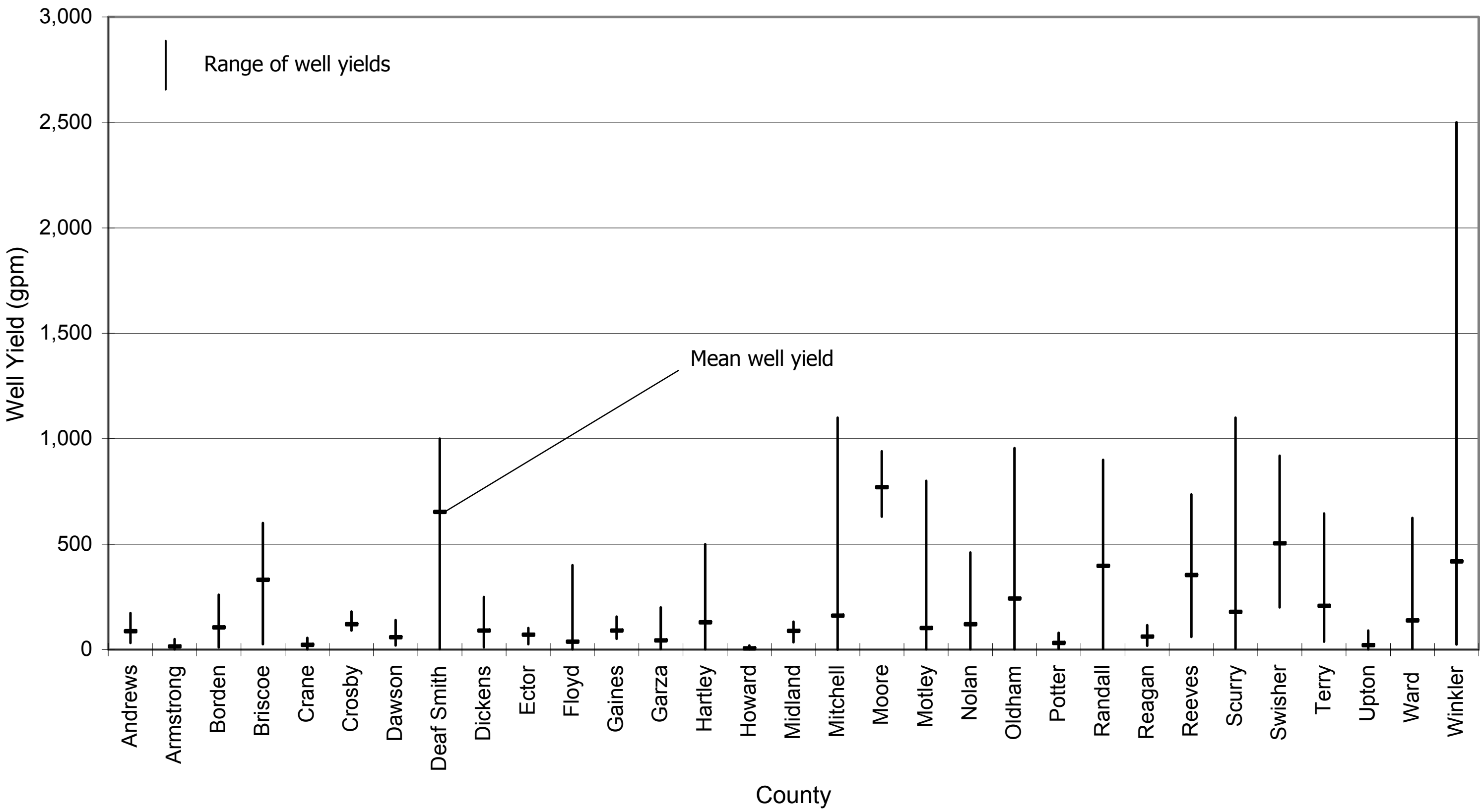

Figure 5-6. Range of well yields in the Dockum aquifer by county.

Table 5-2. Summary of Specific Capacities of Wells in the Dockum Aquifer (from TWDB Reports).

County	Specific Capacity (gpm/ft) Maximum	Minimum	Mean	Number of Records
Andrews	0.76	0.76	0.76	1
Armstrong	2.8	0.60	1.7	2
Borden	2.6	0.203	0.82	7
Crosby	2.3	1.8	2.0	2
Deaf Smith	12.4	0.02	8	3
Dickens	7.0	1.3	4.2	4
Gaines	0.579	0.442	0.511	2
Garza	0.19	0.055	0.14	3
Martin	0.42	0.42	0.42	1
Mitchell	3.6	0.30	1.2	14
Moore	11	7.7	9.5	2
Motley	8.2	1.8	5.5	3
Nolan	2.0	0.38	1.0	6
Oldham	3.5	0.3	2	7
Potter	0.78	0.78	0.78	1
Randall	9.00	4.32	6.66	2
Reeves	37	13	25	2
Scurry	6.1	0.33	2.8	18
Swisher	1.93	1.93	1.93	1
Upton	0.307	0.307	0.307	1
Winkler	17.1	.13	5.3	4

NOTE: gpm/ft = gallons per minute per foot

approximately 1,500 ft^2/d. The Winkler County pumping test was performed on the City of Kermit's municipal wells, which are completed in the Santa Rosa Formation that was described by Garza and Wesselman (1959) as a massive sandstone unit of limited areal extent. Storativity values ranged from 4.4×10^{-5} in Mitchell County to 2.9×10^{-4} in Winkler County (Table 5-1). The mean storativity from all aquifer tests conducted in the study area was 1.9×10^{-4}. The low storativities suggest that the Dockum aquifer is confined to partly confined in the test areas. The above parameters suggest that the aquifer may not be able to provide large quantities of water.

5.3 Chemical Quality

Groundwater in the Dockum aquifer is generally of poor quality. Over most of the study area, it is characterized by decreasing quality with depth, mixed types of water, high concentrations of total dissolved solids (TDS) and other constituents that exceed secondary drinking water standards, and high sodium levels that may be damaging to irrigated land.

The chemical quality of water in the Dockum aquifer ranges from fresh (TDS of less than 1,000 mg/l) in outcrop areas that are present around the fringes of the aquifer to brine (TDS greater than 10,000 mg/l) in the confined parts of the aquifer (Figure 5-7). TDS concentrations also tend to increase with depth and range from 5,000 mg/l to more than 60,000 mg/l (Figure 5-8 and Appendix IV) in the deepest parts of the aquifer. Groundwater in the Dockum aquifer is also typically hard with hardness ranging from less than 25 mg/l in Swisher County to more than 3,600 mg/l in Reagan County (Figure 5-9 and Appendix VII). The mean hardness value for the entire study area is approximately 470 mg/l.

In the northern and northeastern counties of the study area, the groundwater is composed of mixed cations and HCO_3^- type water (Figure 5-10a and 5-10b). In the central part of the study area (Andrews, Dawson, Gaines, Hockley, and Terry counties), the groundwater is dominated by $Na^+ + K^+$ and $Cl^- + SO_4^{2+}$ (Figure 5-10). The eastern outcrop area consists of $Ca^{2+} + Mg^{2+}$ and mixed-anion-type water (Figure 5-10d). The seven groundwater samples that we collected from an area near the Edwards-Trinity (Plateau) aquifer in 1995 and 1996 do not show a characteristic signature (Figure 5-10e). Where overlain by the Cenozoic Pecos Alluvium, groundwater in the Dockum aquifer is characterized by $Ca^{2+} + Mg^{2+}$ and $SO_4^{2-} + Cl^-$ rich waters (Figure 5-10f). A more detailed listing of the major cations and anions detected in the groundwater samples is available in Appendices V and VI, respectively.

One of the primary contaminants of concern in the study area is nitrate. The maximum contaminant level (MCL) for nitrate (measured as nitrogen) is 10 mg/l. Groundwater samples obtained from the study area between 1981 and 1996 indicate that nitrate concentrations were higher than their MCL in counties where the Dockum aquifer is either exposed at the surface or is in hydrologic communication with an overlying aquifer such as the Cenozoic Pecos Alluvium or the Edwards-Trinity (Plateau) aquifer. In these areas, the likely sources of nitrate are livestock waste, agricultural fertilizers, and old cesspools.

The radiological constituents for which we tested groundwater samples included gross alpha, gross beta, radium-226, and radium-228 (Table 5-3). The MCL established by the EPA for gross-alpha particle activity limit is 15 picoCuries per liter (piC/l). The MCL for combined radium-226 and radium-228 is 5 piC/l. Some areas of the Dockum aquifer contained radium-226 and radium-228 in concentrations greater than 5 piC/l (Table 5-4). The occurrence of uranium minerals in the Dockum Group has been recognized for years (McGowen and others, 1977) and is the source of the high concentrations of radium-226 and radium-228 detected in groundwater samples. Radium-226 and radium-228 are daughter products of the various uranium decay series.

Other constituents that we tested for in the groundwater samples included antimony, arsenic, barium, beryllium, cadmium, chromium, lead, mercury, nickel, selenium, and thallium. The concentrations of arsenic, barium, chromium, and nickel were below their respective MCLs in all of the samples that were analyzed. However, the detection limit for some of the analyses was higher than the MCL. Therefore, it is possible that some elements could have been present at concentrations above their MCLs but were not detected because of the elevated detection limits. The concentrations of antimony, beryllium, cadmium, lead, mercury, selenium, and thallium exceeded their respective MCLs in several counties (Table 5-4).

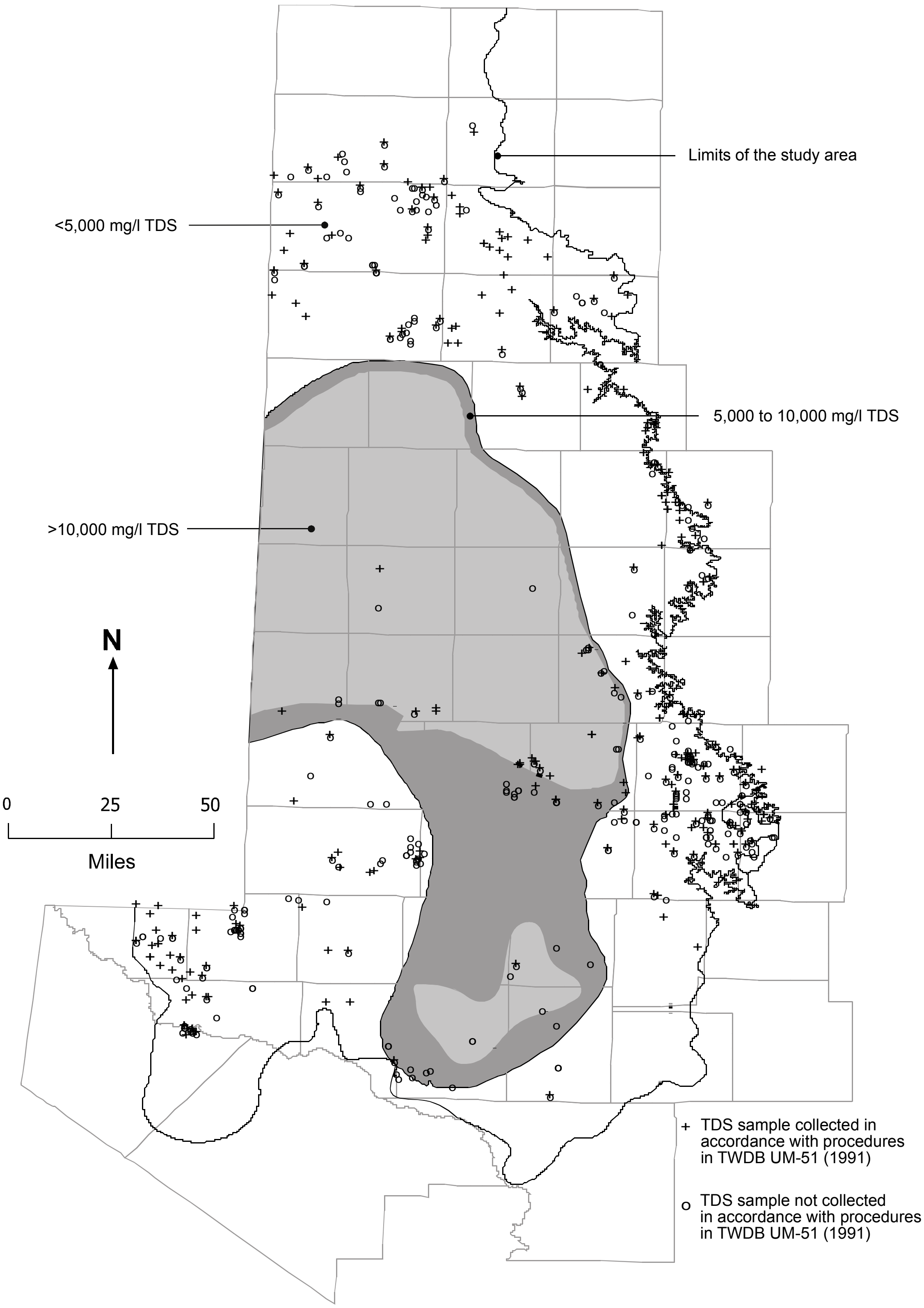

Figure 5-7. Distribution of total dissolved solids (TDS) in the Dockum aquifer, 1981 through 1996 (TWDB, 1997)

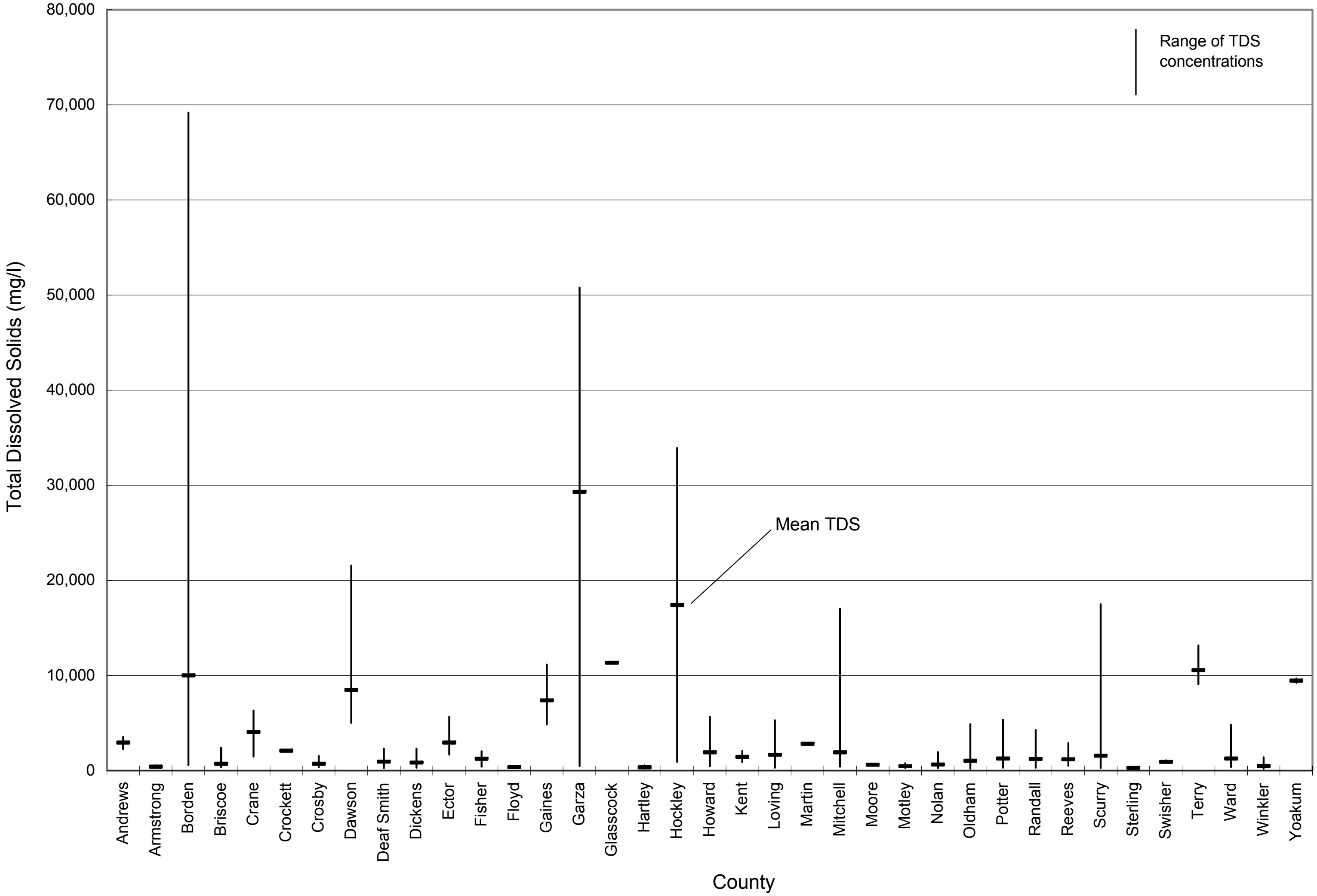

Figure 5-8. Concentrations of total dissolved solids (TDS) detected in the Dockum aquifer water samples 1981 through 1996.

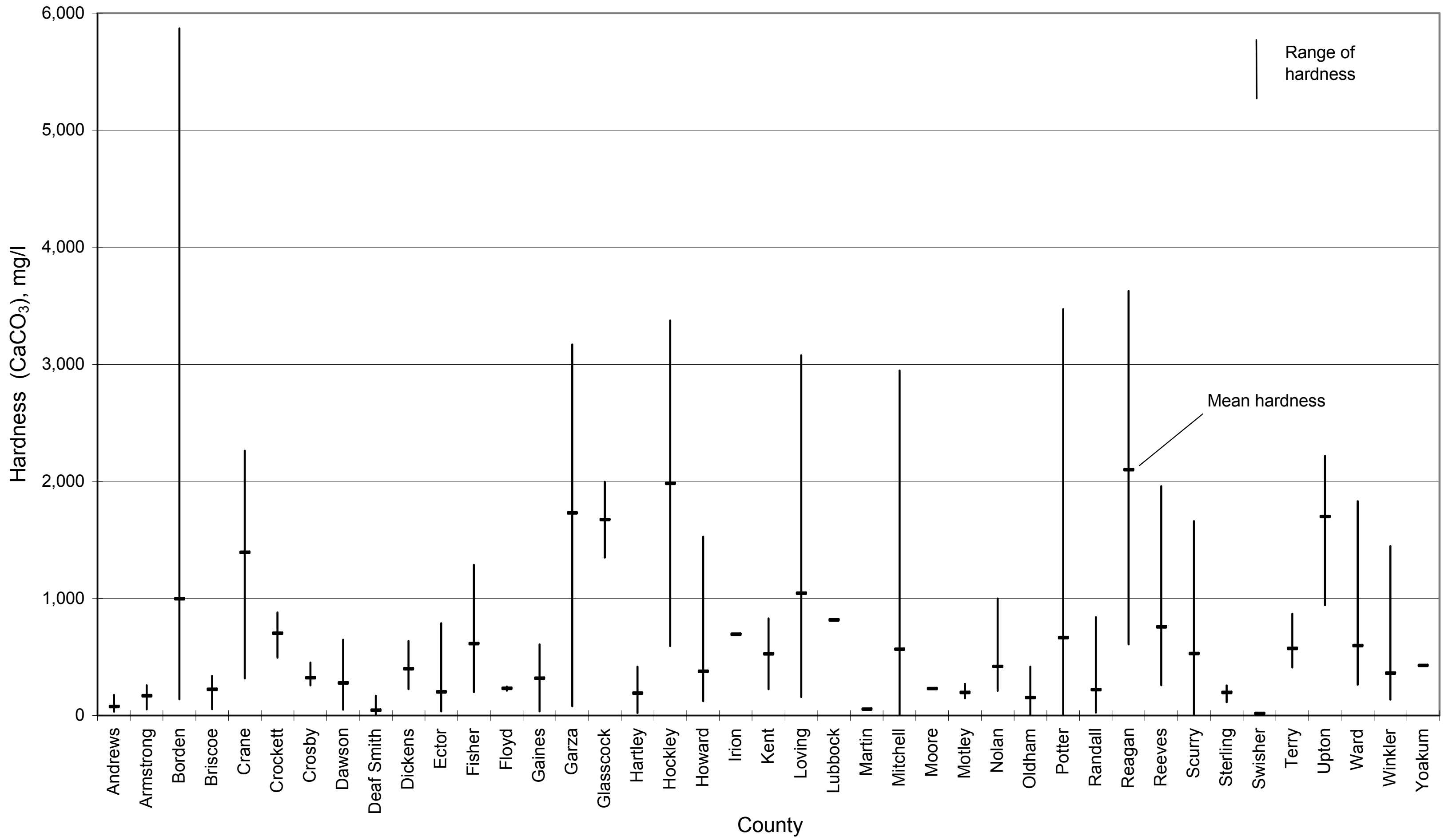

Figure 5-9. Range of hardness in groundwater samples obtained from the Dockum aquifer, 1981through1996.

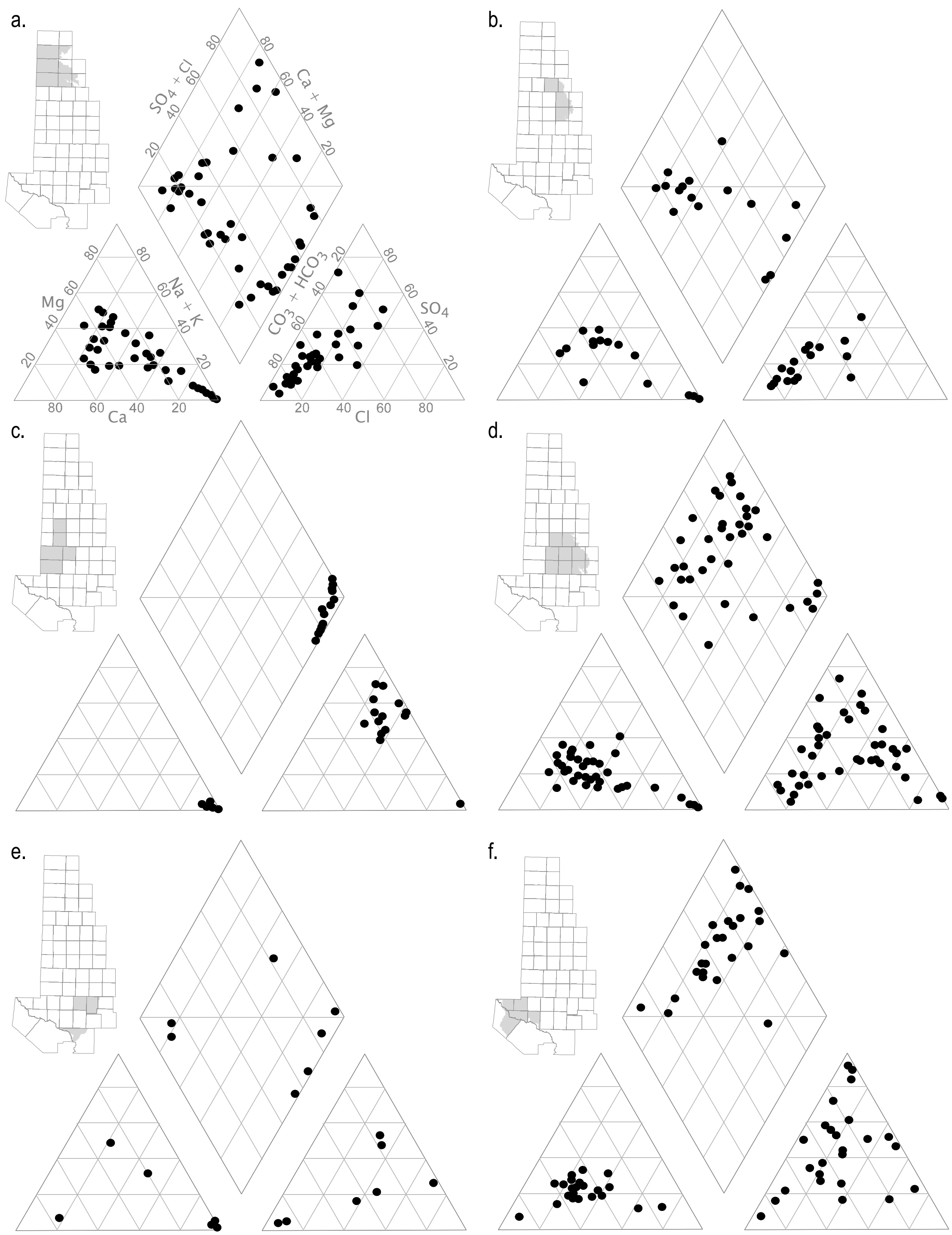

Figure 5-10. Trilinear diagrams for the northern (a, b) and central (c, d) parts of the study area, and for areas overlying the Edwards Plateau region (e) and Pecos River valley (f).

Table 5-3. Gross Alpha, Gross Beta, and Radium Isotope concentrations detected in groundwater samples obtained from the Dockum aquifer, 1981 through 1996.

County	Gross Alpha pCi/l		Gross Beta pCi/l		Radium-226 pCi/l		Radium-228 pCi/l	
	No. of samples	Range	No. of samples	Range	No. of samples	Range	No. of samples	Range
Andrews	9	<3 - 19	9	<4 - 16	9	0.2 - 6.1	9	<0.1 - 7
Armstrong	7	<2 - 24	7	1 - 13	7	0.5 - 0.6	7	1 - 6
Borden	9	3 - <72	9	4.5 - 60	9	<0.2 - 3.1	9	<1 - 25
Briscoe	9	5.5 - 21	9	<3 -13	9	0.2 - 3.1	9	<1 - 4
Crane	3	9 - <13	3	<7 - <11	3	<0.6 - 6.8	3	1 - 5
Crockett	3	7 - 19	3	10 - 16	3	1.4 - 4.9	3	2 - 4
Crosby	2	9.1 - 12	2	9 - 9.3	2	<0.6 - 6.6	2	1 - 13
Dawson	5	7.3 - 29	5	<4 - 36	5	1.1 - 3.9	5	1.5 - 19
Deaf Smith	12	<5 - 519	13	<3 - 183	13	<0.2 - 1.4	13	<1 - 4
Dickens	9	<2 - 28	10	4.7 - 12	10	0.2 - 0.6	10	<1 - 8
Ector	3	<6 - 23	3	<4 - 11	1	<0.6	1	3
Fisher	5	3.3 - 20	5	<4 - 18	2	0.2 - 0.9	2	<1
Floyd	7	<3 - 7.2	7	5 - 10	7	<0.2 - 0.5	7	<1 - 1.6
Gaines	3	<13 - 81	3	<9 - 21	3	<0.6 -	3	<2 - <3
Garza	9	2.9 - 244	9	<4 - 193	9	1.4 - 59	9	<1 - 47
Glasscock	1	90	1	40	1	<0.6	1	3
Hartley	5	2 - 11	5	<3 - 8	5	<0.6	5	<1 - 5
Hockley	1	<197	1	<57	1	17.6	1	52
Howard	10	3 - 30	10	<3 -	10	<0.6 - 3.4	10	<1 - 5
Irion	2	<4 - 20	2	<4 - 31	2	2 - 2.4	2	3.2 - 11
Kent	4	3.5 -35	4	<4 - 23	4	<0.6 - 3.5	4	1.8 - 3
Loving	3	3 - 7	3	<3 - 5.4	3	0.3 - 0.7	3	1.1 - <2
Mitchell	23	<2.2 - 50	23	<4 - 64	22	<0.2 - 8.4	22	<1 - 3.3
Motley	10	<2 - 25	10	4 - 15	10	0.4 - 2.7	10	<1 - 3
Nolan	16	<2 - 27	16	<4 - 34	6	0.3 - 3	6	<1
Oldham	17	4 - 42	17	<3 - <30	17	<0.2 -	17	<1 - 6
Potter	12	<4 -47	12	<3 - <12	12	<0.2 - 3.2	12	<1 - 4
Randall	4	10 - 42	4	7 - 30	3	<0.6 - 2	3	<3 - 5
Reagan	2	10 - 29	2	21 - 43	2	0.7 - 4	2	<1 - 8.2
Reeves	5	4.8 - 13	5	<5 - 13	3	<0.2	3	<1
Scurry	28	3.6 - 43	28	<4 - 30	27	<0.2 - 7.3	27	<1 - 3.6
Sterling	5	2.4 - 4.5	4	<4	4	0.4 - 8	3	<1 - 3
Swisher	3	<2 - <3	3	<3 - 10	3	<0.6	3	<2 - 5
Terry	1	<33	1	<23	1	4.6	1	9
Upton	2	14 - 25	2	24 - 28	2	0.2 - 3.3	2	<1 - 4.5
Ward	8	<2 - 13	8	4 - 13	6	<0.2	6	<1 - 1.5
Winkler	6	4 - 5.6	7	0.6 - 10	4	<0.2 -	5	<0.1 - 2

NOTE: pCi/l = pico Curies per liter

Table 5-4. Elements detected at concentrations above their maximum contaminant levels (MCLs) in groundwater samples collected from the Dockum aquifer, 1981 through 1996.

	Concentration in micrograms per liter (mg/l)						
	Antimony	**Beryllium**	**Cadmium**	**Lead**	**Mercury**	**Selenium**	**Thallium**
County	**0.006**	**0.004**	**0.005**	**0.0015**	**0.002**	**0.05**	**0.002**
Andrews	---	---	---	---	---	0.0588	---
Borden	---	---	<0.01	<0.05	---	0.0822	<0.005
Crane	---	---	---	<0.05	0.0113	0.0565	<0.004
Crosby	---	---	<0.01	---	---	---	---
Dawson	<0.01	<0.005	<0.01	<0.05	---	0.0992	<0.01
Deaf Smith	---	---	---	---	0.0028	---	---
Dickens	---	---	<0.01	<0.05	---	---	---
Fisher	---	---	<0.01	<0.05	---	0.0507	---
Gaines	---	---	---	---	---	0.1121	<0.005
Garza	<0.05	<12.5	0.025	<0.05	---	0.093.7	<0.05
Glasscock	<0.01	<0.005	---	---	---	0.2406	<0.01
Hockley	<0.05	---	0.025	<0.05	---	---	<0.05
Howard	---	---	<0.01	<0.05	---	0.0833	---
Kent	---	---	<0.01	<0.05	---	---	---
Loving	---	---	<0.01	<0.05	---	0.050	---
Mitchell	---	---	<0.01	<0.05	---	0.1031	---
Nolan	---	---	<0.01	<0.05	---	---	---
Potter	---	---	<0.01	<0.05	---	---	---
Randall	---	---	---	<0.05	---	0.0647	---
Reeves	---	---	<0.01	<0.05	---	---	---
Scurry	---	---	<0.01	<0.05	---	---	---
Sterling	---	---	<0.01	<0.05	---	---	---
Terry	<0.01	<0.005	<0.005	---	---	0.1136	<0.01
Winkler	---	---	<0.01	<0.05	---	---	---
Yoakum	---	---	---	---	---	4.9	---

NOTES: The concentrations listed above are the highest concentrations detected in samples collected in each county. Only detected concentrations higher than the MCLs are listed in the table. The detection limit for some samples was greater than the MCL, and these results are also included in the table. Other elements that were analyzed but were not detected above their MCLs are arsenic, barium, chromium, and nickel. The MCL for lead is the action level as outlined in TAC 290.120. If a county is not listed above, then all constituents tested for in the groundwater samples obtained from that county were below their MCLs.

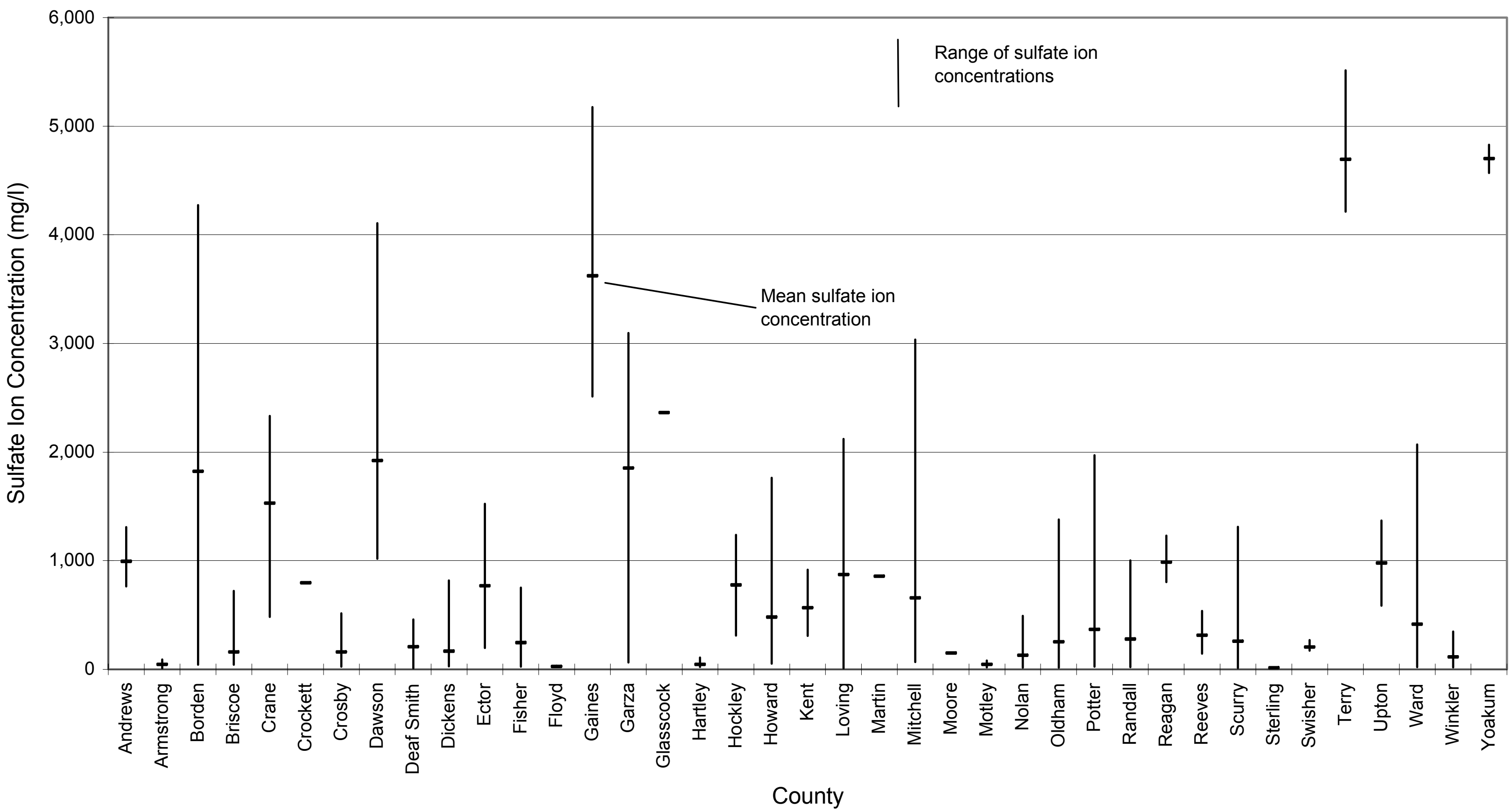

Figure 5-11. Range of sulfate ion concentrations in groundwater samples obtained from the Dockum aquifer, 1981through 1996.

We also analyzed the groundwater samples collected from the study area for TDS, fluoride, chloride, and sulfate. Groundwater in most counties contained TDS at concentrations higher than the secondary standard of 1,000 mg/l (Figure 5-8). TDS concentrations were below the secondary standard in samples collected from Armstrong, Floyd, Hartley, Moore, Motley, and Sterling counties. Most counties had at least one groundwater sample that contained sulfate (Figure 5-11) or chloride at concentrations higher than the secondary standard of 250 mg/l. These two constituents were the dominant anions over much of the study area.

Fluoride concentrations were higher than the secondary standard of 4.0 mg/l in only a few samples that were obtained from Briscoe, Dawson, Deaf Smith, Ector, and Scurry counties (Appendix V). The fluoride in the groundwater is derived from the fluorite grains that occur as heavy minerals in the Dockum sediments.

Sodium in groundwater is a constituent that has neither an MCL nor a secondary standard but that is still a concern where the water is used for irrigation purposes. If sodium exceeds 60 percent of the total cations in water, the water may be unsuitable for irrigation. To determine the hazard of sodium in groundwater, we calculated sodium adsorption ratio (*SAR*), residual sodium carbonate (*RSC*) and percent-sodium. In many counties the percent-sodium values were above 60 percent (Figure 5-12).

The potential effect of sodium on irrigated land can also be determined by *SAR* proposed in 1954 by the United States Salinity Laboratory (USSL, 1954). This indicator is calculated from

$$SAR = \frac{Na}{\frac{\sqrt{Ca + Mg}}{2}},$$

where sodium, calcium, and magnesium concentrations are expressed in milliequivalents per liter (meq/l). *SAR* values lower than 10 suggest that sodium does not pose a threat to the irrigated land, whereas values higher than 18 typically result in excess sodium in the soils. In the central part of the Dockum aquifer, the *SAR* values of groundwater samples were generally higher than 18 (Figure 5-13).

Another indicator of sodium hazard is *RSC*. As calcium and magnesium precipitate out of the groundwater in the unsaturated zone and onto soils, the relative proportion of sodium in irrigation water increases. *RSC* is calculated by

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

or

$$RSC = 0.02 \times (\text{total alkalinity} - \text{hardness})$$

where carbonate, bicarbonate, calcium, and magnesium concentrations are expressed in meq/l. Water with *RSC* values greater than 2.5 meq/l is not suitable for irrigation (Figure 5-14).

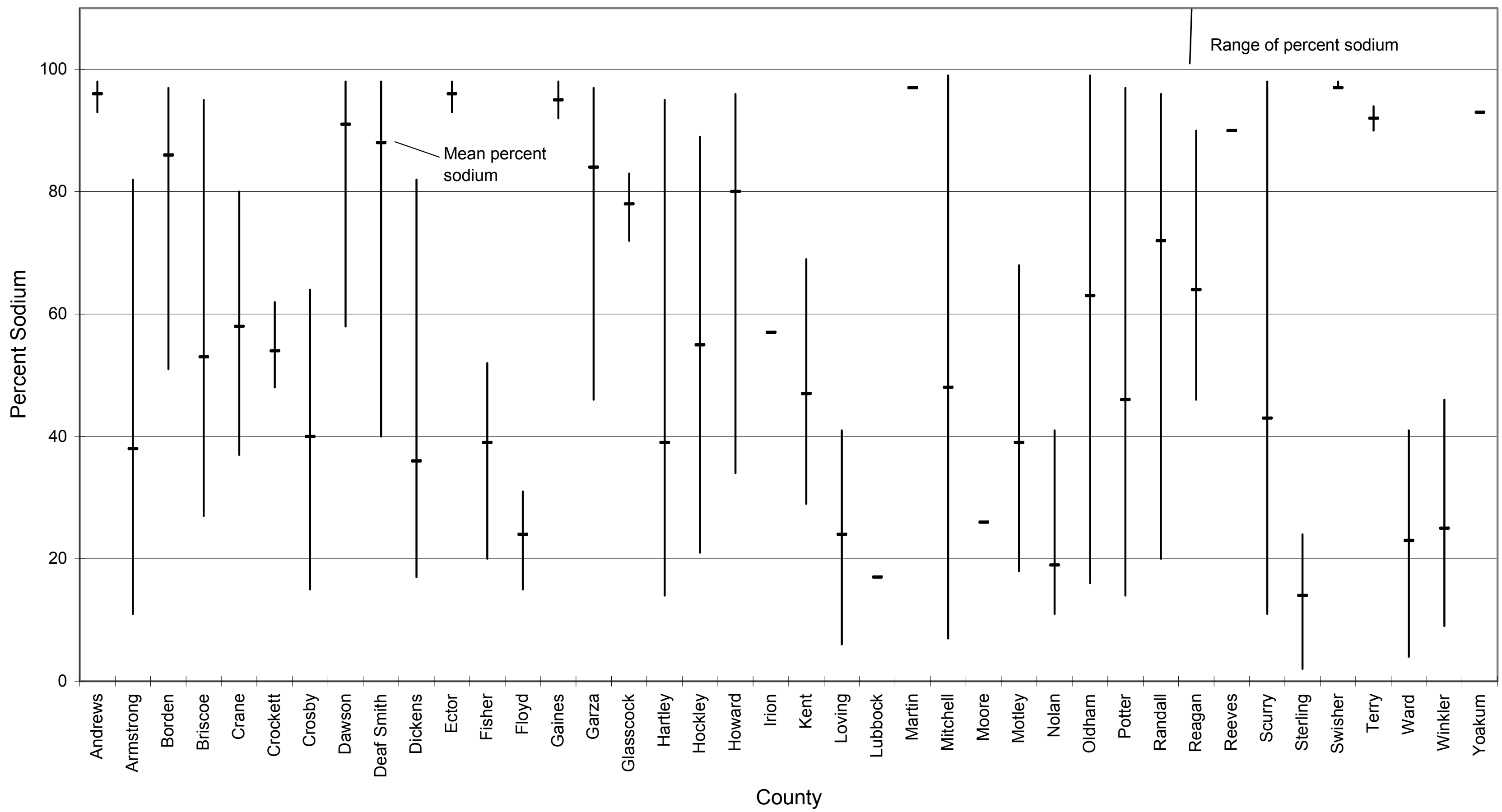

Figure 5-12. Percent sodium in groundwater samples obtained from the Dockum aquifer, 1981 through 1996.

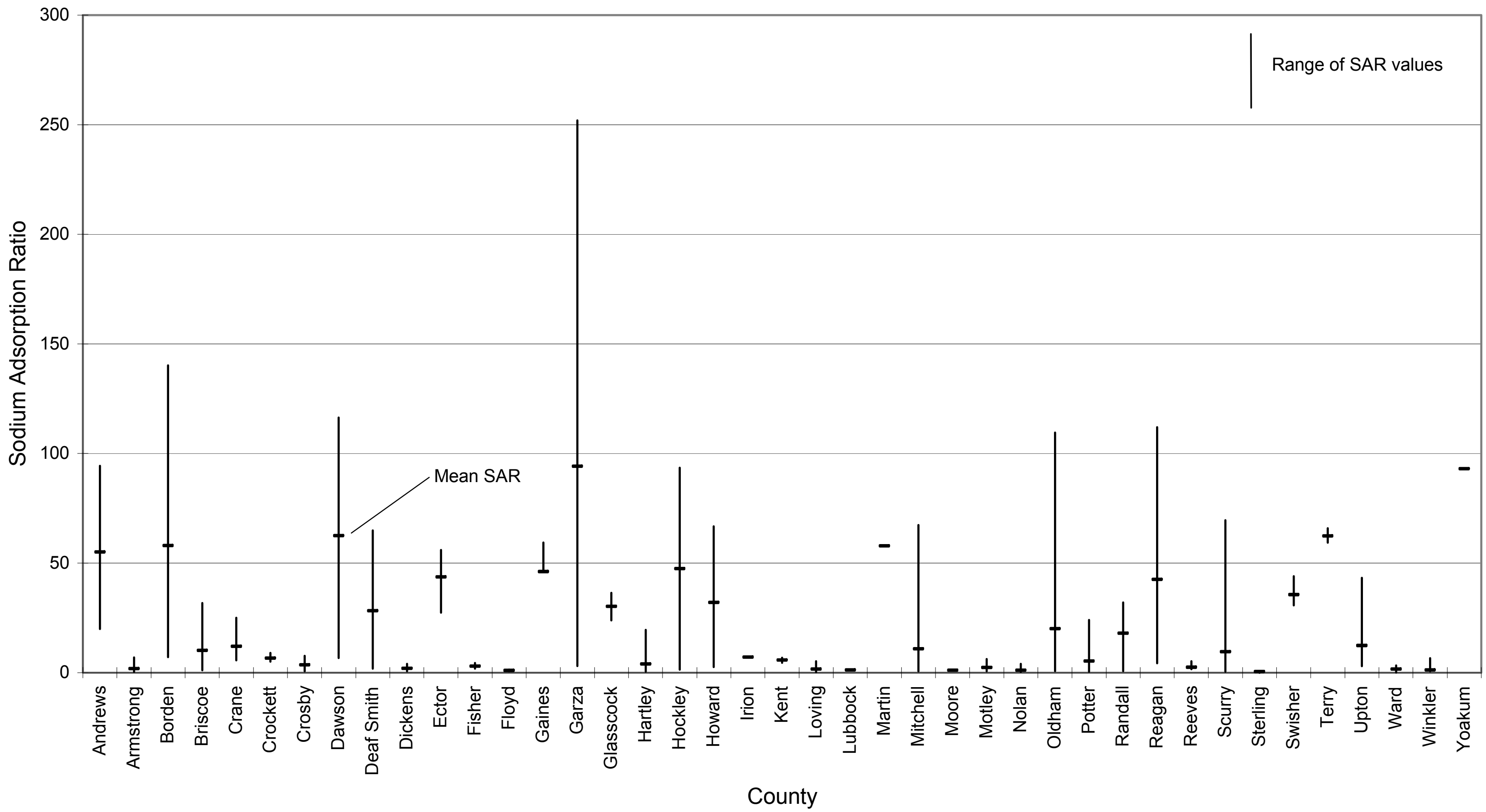

Figure 5-13. Range of Sodium Adsorption Ratio (SAR) values in groundwater samples from the Dockum aquifer, 1981 through 1996.

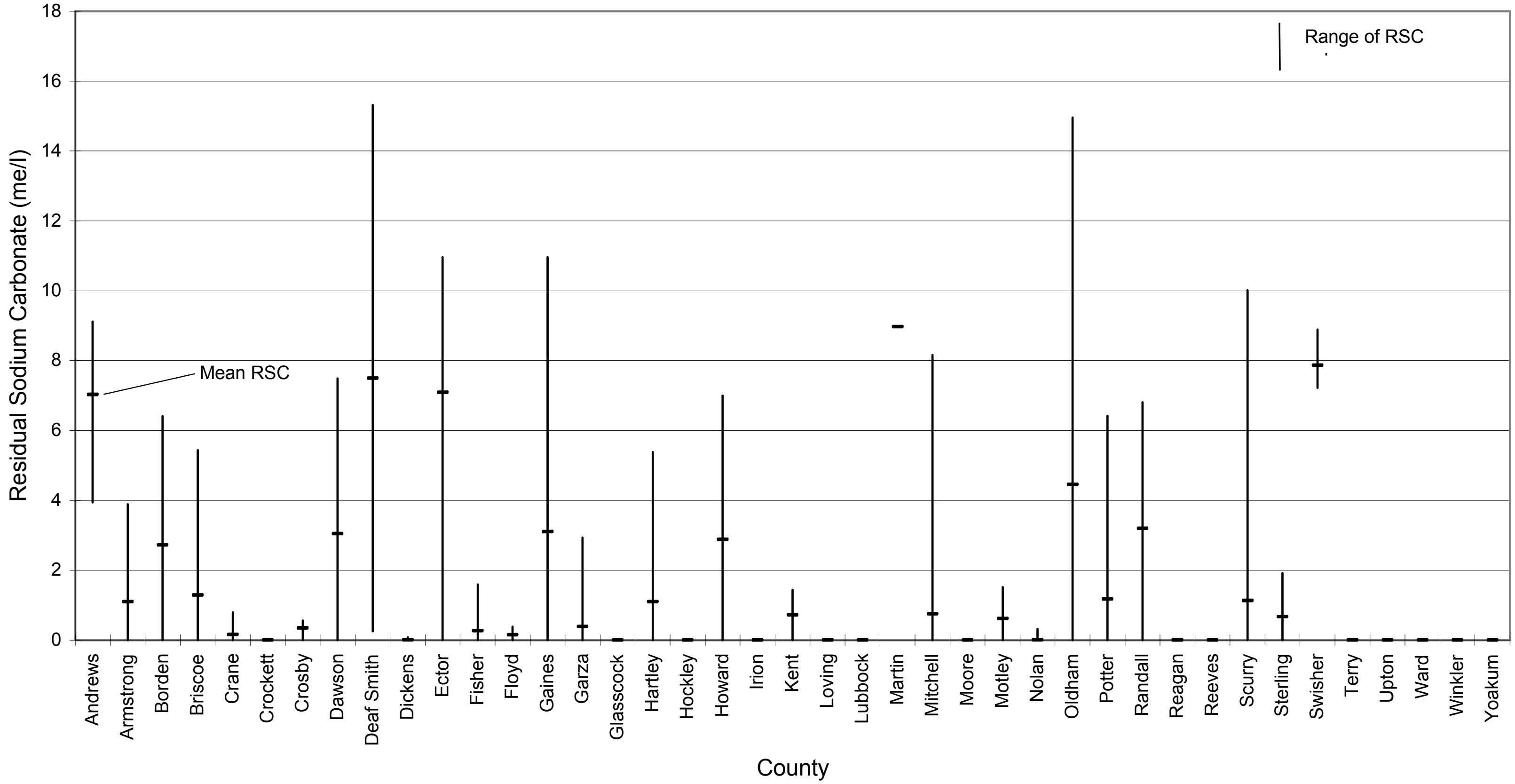

Figure 5-14. Residual Sodium Carbonate (RSC) values in groundwater samples obtained from the Dockum aquifer, 1981 through 1996.

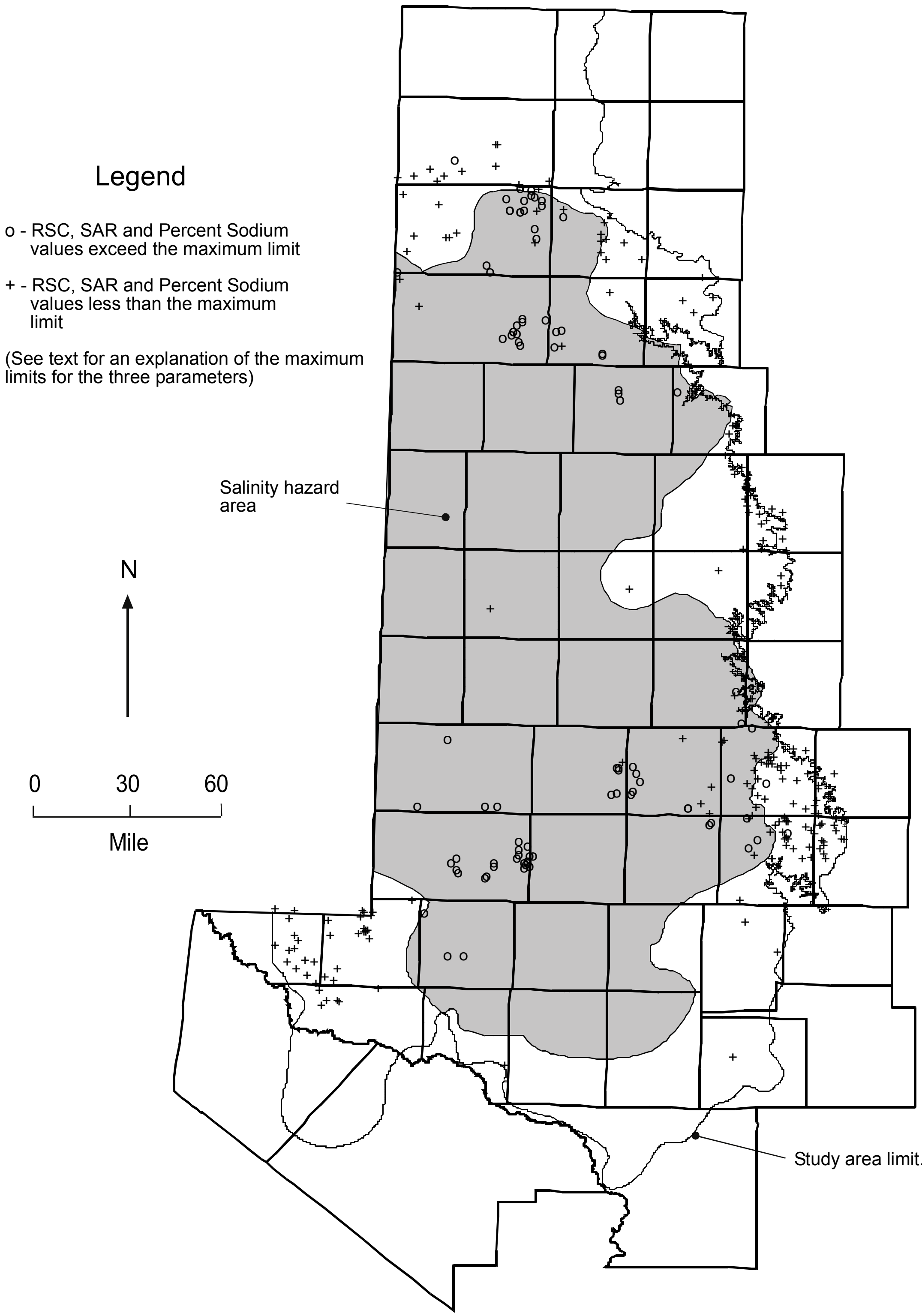

Figure 5-15. Salinity hazard for areas overlying the Dockum aquifer.

Except for parts of the study area that overlie the aquifer where the Dockum sediments outcrop, much of the study area is susceptible to salinity hazard (Figure 5-15). More detailed information about percent sodium, *SAR,* and *RSC* values that were calculated for the study area is presented in Appendix VII.

Only three groundwater samples from the study area had boron concentrations of more than 3 mg/l (Appendix VII). The highest concentration (55.5 mg/l) was detected in a sample from a deep well in Yoakum County that is probably influenced by brine from underlying Permian rocks. Boron, an element that is essential for healthy plant growth, can be toxic to crops at high concentrations. The maximum range of boron concentration that crops can typically tolerate is between 0.67 and 3 mg/l (Scofield, 1936).

5.4 Discharge

Discharge of groundwater from the Dockum aquifer occurs due to pumping, small springs that contribute to stream baseflow in the outcrop (Brune, 1981), evapotranspiration, and cross-formational flow. Most current discharge occurs from the pumping of wells installed in the aquifer.

In the central part of the basin, wells are typically completed in the basal sandstone-dominated zone. However, many wells in the High Plains are completed in both the Dockum and in the overlying Ogallala aquifer. Such dual completion wells can be found in Armstrong, Briscoe, Carson, Crosby, Dallam, Deaf Smith, Floyd, Garza, Hale, Hartley, Hutchinson, Lamb, Moore, Oldham, Potter, Randall, Sherman, and Swisher counties. The primary reason for completing wells in both the Dockum and Ogallala aquifers is to increase well yield. Wells completed in the Edwards-Trinity (Plateau) and Dockum aquifers are present in Bailey, Ector, Hale, Irion, Reagan, Sterling, and Upton counties and in the Cretaceous outlier in Nolan County. In outcrop areas along the Canadian River (primarily in Oldham and Potter counties), wells are completed in both the Dockum and older Permian aquifers.

Irrigation and public-supply uses are limited to areas of the Dockum aquifer in which the water quality is acceptable (TDS generally less than 1,000 mg/l), depth to water is shallow, and a sufficient thickness of sandstone exists to make the aquifer productive. Past and present municipal users of Dockum aquifer water include the cities of Barstow, Canyon, Colorado City, Dickens, Happy, Hereford, Hermleigh, Kermit, Loraine, Pecos, and Snyder. The Colorado River Municipal Water Authority also uses water from this aquifer.

Figure 5-16 illustrates historical water use from the Dockum aquifer between 1994 and 2000. The estimated total pumpage increased from 40,035 acre-feet in 1994 to 50,682 acre-feet in 2000. Irrigation accounted for 58 percent of total water use in 1994 and 66 percent in 2000. While irrigation use increased during the 1994 to 2000 time period, municipal, manufacturing, mining, and livestock water use remained relatively constant (Figure 5-16).

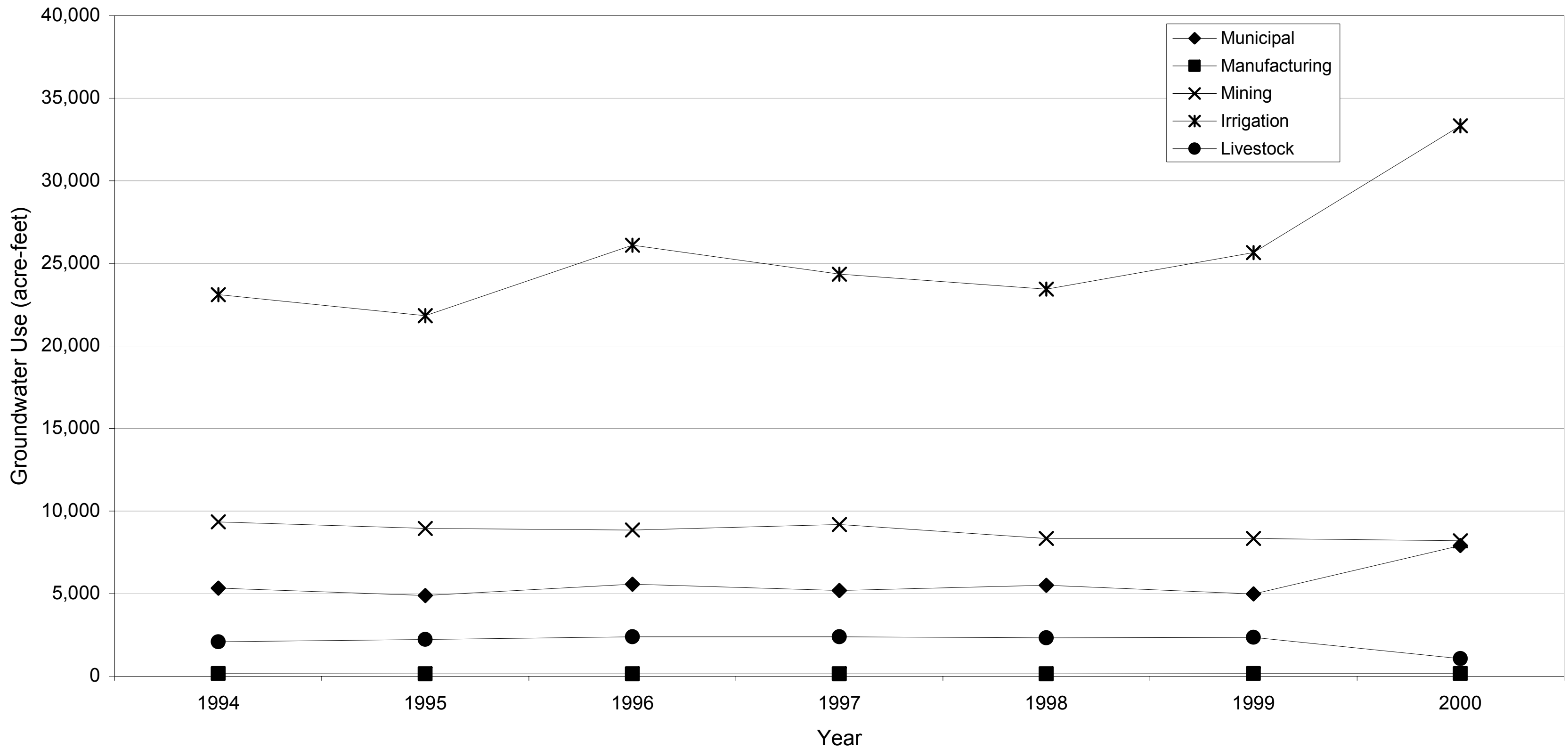

Figure 5-16. Historical water use from the Dockum aquifer, 1994 through 2000.

6.0 Estimate of Groundwater in the Dockum Aquifer

The amount of water in an aquifer that is available for withdrawal can generally be determined by multiplying the saturated volume of the aquifer by its specific yield (the fraction of water that will drain from a saturated porous medium under the influence of gravity). However, estimating this volume for the Dockum aquifer is difficult. Interbedded mudstones, sandstones and other rock types; confined to partly confined conditions; and the very low recharge rates combine to make the aquifer a complex hydrologic system. We estimated the amount of water of different chemical quality (TDS) in the aquifer on a county-by-county basis using the procedure and assumptions outlined below.

For the purpose of representing the saturated volume of the aquifer, we selected the "Best Sandstone" unit (Figure 4-2 to 4-10) because it is the most productive and widely used portion of the aquifer. To estimate the volume of water of different TDS concentrations (<5,000 mg/l, 5,000 to 10,000 mg/l, and >10,000 mg/l) within the Dockum aquifer, we used the TDS map (Figure 5-7) to measure aquifer areas within a county (Appendix VIII) and multiplied these areas by the average thickness of the Best Sandstone unit (125 feet). We determined the average thickness of the Best Sandstone unit from available geologic cross-sections (Figure 4-2 to 4-10). For specific yield of the Best Sandstone unit, we chose a value of 0.065 which is a weighted average derived by adding the minimum specific yields of fine-grained sandstone and silt (0.1 and 0.03, respectively; Johnson, 1967 as cited in Fetter, 1980) in a sandstone unit that is composed of 35 percent sand and 65 percent silt. The aquifer parameters used here are generalized and can be improved by using site-specific aquifer properties where available to produce more accurate volume estimates.

A total of 185 million acre-feet of water is present in the Dockum aquifer in Texas (Table 5-5). The total volume of water with TDS less than 5,000 mg/l is approximately 109 million acre-feet and that with TDS between 5,000 and 10,000 mg/l is about 27 million acre-feet. In parts of the aquifer where the water has very high TDS (>10,000 mg/l), we estimate the volume of water at approximately 49 million acre-feet.

The largest volume of water (>6 million acre-feet) of all TDS concentrations is present in Andrews, Dallam, Deaf Smith, Gaines, Hartley and Oldham counties. With the exception of Hartley County, these same counties also have the largest volume of water with TDS concentrations less than 5,000 mg/l. Bailey, Cochran, Hockley, Lamb, Lubbock, Lynn, and Terry counties contain the largest volume of water (>3,000 acre-feet) with TDS concentrations greater than 10,000 mg/l.

It must be reiterated that not all of the water estimated here is available for withdrawal. Aquifer properties determined during this study (Chapter 5.2) clearly suggest that well yields and transmissivities are low over much of the aquifer, and the aquifer is generally not productive. Furthermore, the chemical quality of water in the aquifer precludes its use for many purposes. Because the confined parts of the aquifer receive little recharge, water withdrawn from these areas will essentially mine or deplete the aquifer.

Table 5-5 Estimated volume of water in the Dockum aquifer

	Volume of Water (acre-feet)			
County	**<5,000 mg/l TDS**	**5,000 to 10,000 mg/l TDS**	**>10,000 mg/l TDS**	**Total**
Andrews	6,544,360	0	0	6,544,360
Armstrong	1,948,573	0	0	1,948,573
Bailey	0	0	3,605,720	3,605,720
Borden	440,360	1,146,680	2,332,600	3,919,640
Briscoe	2,012,801	0	0	2,012,801
Carson	566,664	0	0	566,664
Castro	294,089	1,395,200	2,225,991	3,915,280
Cochran	0	0	3,379,000	3,379,000
Coke	126,706	0	0	126,706
Crane	2,283,863	431,640	0	2,715,503
Crockett	3,332,178	0	0	3,332,178
Crosby	688,819	2,442,990	792,192	3,924,001
Dallam	6,561,800	0	0	6,561,800
Dawson	0	2,881,960	1,050,760	3,932,720
Deaf Smith	6,526,920	0	0	6,526,920
Dickens	1,159,849	0	0	1,159,849
Ector	3,928,360	0	0	3,928,360
Fisher	308,048	0	0	308,048
Floyd	4,122,680	202,440	0	4,325,120
Gaines	5,025,677	1,353,003	170,040	6,548,720
Garza	892,506	514,480	2,498,280	3,905,266
Glasscock	684,520	2,062,280	1,181,560	3,928,360
Hale	1,124,880	553,720	2,703,200	4,381,800
Hartley	6,374,320	0	0	6,374,320
Hockley	0	0	3,958,880	3,958,880
Howard	1,303,313	2,633,767	0	3,937,080
Irion	2,902,030	0	0	2,902,030
Kent	306,120	0	0	306,120
Lamb	0	0	4,429,760	4,429,760
Loving	1,228,164	0	0	1,228,164
Lubbock	0	0	3,924,000	3,924,000
Lynn	0	0	3,889,120	3,889,120
Martin	297,992	3,691,408	0	3,989,400
Midland	353,160	3,562,120	8,720	3,924,000
Mitchell	3,552,889	0	0	3,552,889
Moore	1,588,314	0	0	1,588,314
Motley	669,553	0	0	669,553
Nolan	569,920	0	0	569,920
Oldham	6,544,360	0	0	6,544,360
Parmer	1,020,240	845,840	1,979,440	3,845,520
Pecos	2,563,278	0	0	2,563,278
Potter	3,051,550	0	0	3,051,550
Randall	3,974,774	0	0	3,974,774
Reagan	2,995,320	941,760	1,185,920	5,123,000
Reeves	2,344,140	0	0	2,344,140
Scurry	3,466,602	0	0	3,466,602
Sherman	413,212	0	0	413,212
Sterling	3,955,862	0	0	3,955,862
Swisher	3,883,622	40,378	0	3,924,000
Terry	0	361,880	3,518,520	3,880,400
Tom Green	234,466	0	0	234,466
Upton	802,240	1,639,360	2,973,520	5,415,120
Ward	2,685,426	0	0	2,685,426
Winkler	3,515,897	0	0	3,515,897
Yoakum	0	741,200	2,746,800	3,488,000
TOTAL	**109,170,417**	**27,442,106**	**48,554,023**	**185,166,546**

7.0 Summary and Conclusions

Although not widely used at present, the Upper Triassic Dockum aquifer in the Texas Panhandle and West Texas could become an important source of groundwater in the future, especially in areas where there is high demand from the Ogallala and Edwards-Trinity (Plateau) aquifers. This report documents a comprehensive regional hydrogeologic study of the Dockum aquifer.

Recoverable groundwater in the Dockum aquifer occurs within the many sandstone and conglomerate beds that are present throughout the 2,000-foot-thick sedimentary sequence, but mainly in the lower sections of the sequence (Best Sandstone unit). The hydrogeologic properties of the aquifer vary widely. Well yields range from 0.5 gpm in Mitchell County to 2,500 gpm in Winkler County, and specific capacities from 0.19 gpm/ft (Garza County) to 37 gpm/ft (Reeves County). Transmissivity values range from about 48 ft^2/day in Upton County to 4,600 ft^2/day in Winkler County while storage coefficients range from 4.4×10^{-5} in Mitchell County to 2.9×10^{-4} in Winkler County.

Where exposed at the land surface, the Dockum aquifer is recharged by precipitation, and the confined portions by upward leakage from the underlying Permian rocks and downward leakage from the overlying Ogallala, Edwards-Trinity (Plateau) and Cenozoic Pecos Alluvium aquifers. We estimate that annual recharge to the aquifer is approximately 31,000 acre-feet. Discharge from the aquifer occurs from pumping wells and small springs, and through evapotranspiration and cross-formational flow.

Regional groundwater flow maps suggest that flow is generally to the east. Hydrographs of wells installed in the aquifer show that water levels have fluctuated variably over time in different parts of the aquifer. For example, in the northern and southern parts of the aquifer, water levels have both declined (by more than 80 feet) in some wells and risen in others over the past 20 to 30 years, while in the central part of the aquifer, they have generally risen over the same time period.

Groundwater in the Dockum aquifer is generally of poor quality. Water quality ranges from fresh in the outcrop areas, in the east, to brine in the confined western part of the aquifer. It also tends to deteriorate with depth, and TDS concentrations can exceed 60,000 mg/l in the deepest parts of the aquifer. Dockum aquifer water is also typically hard with a mean hardness of about 470 mg/l. A mixed-cation and HCO_3^- type water characterizes groundwater in the northern and northeastern counties of the study area whereas in the counties in the central area the groundwater typically contains Na^+, K^+, Cl^- and SO_4^{2-} in the west and Ca^{2+}, Mg^{2+} and mixed-anions in the east. Dockum groundwater from near the Edwards-Trinity (Plateau) aquifer is not characterized by a specific suite of chemical constituents, but where overlain by the Cenozoic Pecos Alluvium aquifer, contains Ca^{+2}, Mg^{+2}, SO_4^{2-} and Cl^- rich water.

Radium-226 and radium-228 were detected at concentrations greater than 5 pCi/l in samples collected from widespread areas of the aquifer. The source of the radionuclides in the groundwater is uranium that has long been known to be present in the Dockum sediments. Most counties in the study area also had at least one groundwater sample that contained sulfate or chloride at concentrations greater than the secondary standard of 250 mg/l. In contrast, fluoride concentrations were higher than the secondary standard in only a few samples collected from Briscoe, Dawson, Deaf Smith, Ector, and Scurry counties.

Much of the area overlying the Dockum aquifer is susceptible to salinity problems originating from the high concentrations of sodium present in Dockum groundwater. This type of water is most prevalent in the confined portions of the aquifer, and salinity is less of a concern along the outcrop areas. High boron concentrations did not appear to be widespread, and only three samples contained boron at concentrations greater than 3 mg/l.

Estimating the total amount of usable groundwater in the Dockum aquifer is difficult because of the interbedded nature of the geologic units, the confined to partially confined conditions of the aquifer, and low recharge rates. We estimate that the total amount of water available in the entire Dockum aquifer in Texas is approximately 185 million acre-feet. Of this amount, approximately 109 million acre-feet contain TDS of less than 5,000 mg/l. However, not all of this water is readily available for withdrawal. In fact, the measured aquifer parameters suggest that the aquifer cannot provide large quantities of water. The confined parts of the aquifer receive little recharge, and any water withdrawn from these areas will essentially mine the aquifer.

8.0 Acknowledgements

We thank property owners in the study area for granting us access to their water wells to obtain water-level measurements, and water samples for chemical analysis. Field personnel of the TWDB's Hydrologic Monitoring Section obtained the water levels and water samples reported in this study. Steve Hutton, Steve Gifford, Mark Hayes, Robert E. Mace, and Brent Christian assisted in preparing the illustrations for the report. The database was managed by John Derton, Frank Bilberry, and Paul McElhaney. Robert E. Mace, Bill Mullican, Richard Smith, and Shirley Wade reviewed the report and suggested changes that greatly improved its quality. Edward S. Angle edited and prepared the report for publication.

9.0 References

Adams, J. E., 1929, Triassic of West Texas: Bulletin of the American Association of Petroleum Geologists, v. 13, no. 8, p. 1045-1055.

Adkins, W. S., 1932, The Mesozoic systems in Texas: The University of Texas at Austin Bulletin 3232, p. 239-518.

Ashworth, J. B., 1986, Evaluation of the Santa Rosa aquifer in Glasscock County: Texas Water Development Board, Report LP-203, 26 p.

________________________, 1990, Evaluation of groundwater resources in parts of Loving, Pecos, Reeves, Ward and Winkler counties, Texas: Texas Water Development Board, Report 317, 26 p.

Ashworth, J. B., and Christian, P. C., 1989, Evaluation of groundwater resources in parts of Midland, Reagan, and Upton Counties, Texas: Texas Water Development Board, Report 312, 52 p.

Ashworth, J.B., and Hopkins, J., 1995, Aquifers of Texas: Texas Water Development Board, Report 345, 69 p.

Bassett, R. L., Bentley, M. E., and Simpkins, W. W., 1981, Regional groundwater flow in the Panhandle of Texas—A conceptual model: *in* Gustavson, T. C., Bassett, R. L., Finley, R. J., Goldstein, A. G., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle; a report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 81-3, p. 102-107.

Bentley, M. E., 1981, Regional hydraulics of brine aquifers, Palo Duro and Dalhart Basins, Texas: *in* Gustavson, T. C., Bassett, R. L., Finley, R. J., Goldstein, A. G., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle; a report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-3, p. 93-101.

Brune, G., 1981, Springs of Texas: Branch-Smith, Fort Worth, Texas, 566 p.

Bureau of Economic Geology, 1967, Geologic atlas of Texas, Lubbock sheet: The University of Texas at Austin, Bureau of Economic Geology, plate.

________________________, 1968, Geologic atlas of Texas, Plainview sheet: The University of Texas at Austin, Bureau of Economic Geology, plate.

________________________, 1969, Geologic atlas of Texas, Amarillo sheet: The University of Texas at Austin, Bureau of Economic Geology, plate.

_______________________, 1974, Geologic atlas of Texas, Big Spring sheet: The University of Texas at Austin, Bureau of Economic Geology, plate.

_______________________, 1983, Geologic atlas of Texas, Tucumcari sheet: The University of Texas at Austin, Bureau of Economic Geology, plate.

Cazeau, C, J., 1962, Upper Triassic deposits of West Texas and northeastern New Mexico: The University of North Carolina, Chapel Hill, North Carolina, Master's thesis, 94 p.

Cooper, H. H., Jr., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: American Geophysical Union Transactions, v. 27, p. 526-534.

Cummins, W. F., 1890, The Permian of Texas and its overlying beds: Geological Survey of Texas, First Annual Report, p. 183-197.

Driscoll, F. G., 1986, Groundwater and wells, second edition: Johnson Division, St. Paul, Minnesota, 1,089 p.

Duffin, G. L., 1984, Groundwater conditions in the Triassic aquifer in Deaf Smith and Swisher counties: Texas Department of Water Resources, Report No. LP-196, 95 p.

Dutton, A. R., and Simpkins, W. W., 1986, Hydrogeochemistry and water resources of the Triassic Lower Dockum Group in the Texas Panhandle and Eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 161, 51 p.

Fallin, J. A., 1989, Geohydrology of the Dockum Formation (late Triassic) under the High Plains of Texas: Texas Water Development Board, Unpublished Report.

Fetter, C. W., Jr., 1980, Applied hydrogeology: Charles E. Merrill Publishing Company, Columbus, Ohio, 488 p.

Fink, B. E., 1963, Groundwater geology of Triassic deposits in the northern part of the southern High Plains of Texas: High Plains Underground Water Conservation District No. 1, Report No. 163, 76 p.

Galloway, S. E., 1955, Feasibility report on the possibility of obtaining artesian irrigation water from the Triassic "red beds" Curry County, New Mexico: New Mexico State Engineer, miscellaneous report, not paginated.

Garza, S., and Wesselman, J. B., 1959, Geology and groundwater resources of Winkler County, Texas: Texas Board of Water Engineers, Bulletin No. 5916, 200 p.

Gould, C. N., 1906, The geology and water resources of the eastern portion of the Panhandle of Texas: United States Geological Survey, Water-Supply and Irrigation Paper No. 154, 64 p.

_________, 1907, The geology and water resources of the western portion of the Panhandle of Texas: United States Geological Survey, Water-Supply and Irrigation Paper No. 191, 70 p.

Granata, G. E., 1981, Regional sedimentation of the late Triassic Dockum Group, West Texas and eastern New Mexico: The University of Texas at Austin, Master's thesis, 199 p.

Gustavson, T. C., and Finley, R. J., 1985, Late Cenozoic geomorphic evolution of the Texas Panhandle and northeastern New Mexico – Case studies of structural controls on regional drainage development, The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 148, --- p.

Johns, D. A., 1989, Lithogenetic stratigraphy of the Triassic Dockum Formation, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 182, 71 p.

Knowles, T., Nordstrom, P., and Klemt, W. B., 1984, Evaluating the groundwater resources of the High Plains of Texas, vol. 1: Texas Department of Water Resources, Report 288, 113 p.

Larkin, T. J., and Bomar, G. W., 1983, Climatic atlas of Texas: Texas Department of Water Resources, Report LP-192, 151 p.

Lehman, T. M., 1994a, The saga of the Dockum Group and the case of the Texas/New Mexico boundary fault: New Mexico Bureau of Mines and Mineral Resources, Bulletin No. 150, p. 37-51.

___________, 1994b, Save the Dockum Group!: West Texas Geological Society Bulletin, v. 34, No. 4., p. 5-10.

Lehman, T., Chatterjee, S., and Schnable, J., 1992, The Cooper Canyon Formation (late Triassic) of western Texas: The Texas Journal of Science, v. 44, no. 3, p. 349-355.

Lucas, S. G., and Anderson, O. J., 1992, Triassic stratigraphy and correlation, West Texas and eastern New Mexico: American Association of Petroleum Geologists, Southwest Section, Transactions, West Texas Geological Society Publication SWS 92-90, p. 201-207.

___________________________, 1993, Lithostratigraphy, sedimentation, and sequence stratigraphy of upper Triassic Dockum Formation, West Texas: American Association of Petroleum Geologists, Southwest Section Transactions, Fort Worth Geological Society, p. 55-65.

___________________________, 1994, The Camp Springs Member, base of the late Triassic Dockum Formation in West Texas: West Texas Geological Society Bulletin, v. 34, no. 2, p. 5-15.

___________________________, 1995, Dockum (Upper Triassic) stratigraphy and nomenclature: West Texas Geological Society Bulletin, v. 34, no. 7, p. 5-11.

McGowen, J. H., Granata, G. E., and Seni, S. J., 1977, Depositional systems, uranium occurrence and postulated groundwater history of the Triassic Dockum Group, Texas Panhandle–eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for the United States Geological Survey.

____, 1979, Depositional framework of the Lower Dockum Group (Triassic) Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 97, 60 p.

McKee, E. D., Oriel, S. S., Ketner, K. B., MacLachlan, M. E., Goldsmith, J. W., MacLachlan, J. C., and Mudge, M. R., 1959, Triassic System: U. S. Geological Survey, Miscellaneous Geological Investigation Map I-300.

Nativ, R., and Gutierrez, G. N., 1988, Hydrogeology and hydrochemistry of Cretaceous aquifers, Texas Panhandle and eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 88-3, 32 p.

Ogilbee, W., Wesselman, J. B., and Irelan, B., 1962, Geology and groundwater resources of Reeves County, Texas: Texas Water Commission, Bulletin 6214, v. 1, 193 p.

Orr, E. D., Kreitler, C. W., and Senger, R. K, 1985, Investigation of underpressuring in the deep-basin brine aquifer, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 85-1, 44 p.

Rayner, F. A., 1963, Pumping test of the V. J. Owens Santa Rosa irrigation wells, 10-16-802 and 10-14-202, Section 5, Block K-3, Deaf Smith County, Texas: Texas Water Commission, interoffice memo, 1 p.

___________, 1965, The ground-water supplies of the Southern High Plains: Unpublished paper presented at the Third Annual West Texas Water Conference, 23 p.

Reeside, J. B., Jr., Applin, P. L., Colbert, E. H., Gregory, J. T., Halley, H. D., Kummel, B., Lewis, P. J., Maldonado-Koerdell, M., McKee, E. D., McLaughlin, D. B., Muller, S. W., Reinemund, J. A., Rodgers, J., Sanders, J., Siberling, N. J., and Waage, K., 1957, Correlation of the Triassic formations of North America exclusive of Canada: Geologic Society of America Bulletin, v. 68, p. 1451-1514.

Riggs, N. R., Lehman, T. M., Gehrels, G. E., and Dickenson, W. R., 1996, Detrital zircon link between headwaters and terminus of the upper Triassic Chinle-Dockum paleoriver system: Science, v. 272, p. 97-100.

Robotham, H. B., Skrabacz, C. F., and Reed, J. A., 1985, Construction, development, testing and equipping with submersible pumps of two Santa Rosa supply wells in the Wellman oil field, Terry County, Texas: Report prepared for NRM Petroleum Corporation, Ed. L. Reed and Associates, Inc., Midland, Texas, 6 p.

Scofield, C. S., 1936, The salinity of irrigation water: Smithsonian Institution Annual Report, 1934-1935, p. 275-287.

Shamburger, V. M. Jr., 1967, Groundwater resources of Mitchell and western Nolan counties, Texas: Texas Water Development Board, Report 50, 175 p.

Smith, J. T., 1973, Groundwater resources of Motley and northeastern Floyd Counties, Texas: Texas Water Development Board Report 165, 66 p.

Texas Administrative Code, 1997, Title 30, Part 1, Chapter 290 (Public Drinking Water).

Texas Water Development Board, 1991, A field manual for ground-water sampling: TWDB User-Manual UM-51, Revised.

Texas Water Development Board, 1997, Groundwater database: Texas Water Development Board, Water Resources Planning Division.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, p. 519-524.

Thornbury, W. D., 1965, Regional geomorphology of the United States: John Wiley & Sons, Inc., New York, 609 p.

United States Salinity Laboratory, 1954, Diagnosis and improvement of saline and alkali soils: United States Department of Agriculture, Agricultural Handbook No. 60, 160 p.

Walker, L. E., 1979, Occurrence, availability, and chemical quality of groundwater in the Edwards Plateau region of Texas: Texas Department of Water Resources Report 235, 336 p.

White, D. E., 1968, Water resources of Upton County, Texas: Texas Water Development Board, Report 78, 32 p.

_________, 1971, Water resources of Ward County, Texas: Texas Water Development Board, Report 125, 136 p.

Wirojanagud, P., Kreitler, C. W., and Smith, D. A., 1984, Numerical modeling of regional groundwater flow in the deep-basin brine aquifers of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Open-File Report OF-WTWI-1984-8, 39 p

Appendix I

List of wells with geophysical well logs used for the cross-sections in this report.

County	Q Number	Operator	Lease & Well Number	Date Drilled
Andrews	29	Honolulu Oil Corp.	Parker D-6	1957
	81	Anderson -Prichard Oil Corp.	Faskin J #1	1951
	168	Mid-Cont. Petr. Corp.	Un. 8 #8	1948
	227	Stanolind O & G Co.	Un B-EH #1	1948
	245	The Texas Co.	J.E. Mabee A #1 Tract 3	1948
	269	Gulf Oil Corp.	Tex. QQ#2	1948
	282	James G. Brown & Assoc.	Eastman #1	1962
	401	Ashmun & Hilliard	Un. #1-15A	1960
	514	Great Western Drilling Co.	Scratch Royalty #1	1958
	699	Stanolind O & G Co.	Chesley #1	1951
	998	Midwest Oil Corp.	J. L. Bennett #3	1954
	1494	Mobil Oil Co.	Elizabeth Armstrong #17	1962
Bailey	2	Phillips Petroleum Co.	Stephens A #1	1951
	6	Shell Oil Co.	Nichols #1	1951
Borden	159	Shell Oil Co.	Miller #1-A	1957
	263	Shell Oil Co.	W.T. Long #1	1951
	316	Southland Royalty Co.	J. Dorward #1	1956
Cochran	63	J.D. Baker	M.E. Hancock No. 1	11/10/1956
	82	Amerada Petr. Corp.	Elma Slaughter No. 1	07/30/1958
	86	Geochemical Surveys	F.O. Masten "I" No. 1	06/15/1960
	127	Shell Oil Co.	Tanner-Enochs No. 1	01/16/1960
	262	Pan American Pet. Corp.	H.H. Kern "A" No. 1	06/10/1967
Crosby	1	Cities Service Oil Co.	Jones "C" No. 1	1957
	5	Humble Oil & Ref. Co	R.N. Irvin #1	1953
	84	Safari Drilling Co.	Jordan #1	1973
Dawson	39	Amerada Petr. Corp.	Dunlop Est. #1	1961
	40	The Texas Co.	Anna R. Nowell #1	1958
	86	Blackwood & Nichols Co.	Richards #1	1955
	89	The Texas Co.	B.E. Miller #1	1957
	427	Texas Crude	Berry #39	
Deaf Smith	13	Hereford Salt Inc.	No. 1 Sharp	
	14	Stone and Webster Engineering Corp.	No. 1 J. Friemel	
	15	Stone and Webster Engineering Corp.	No. 1 Detten	
Floyd	1	Poff-Brinsmere	Krause #1	1952
	5	Standard Oil Co. of Texas	Minnie Adams #1	1952
	6	Standard of Texas	L.M. Daniels #1	1948
	13	Kern Co. Land Co.	W.J. Ross #1	1966
Gaines	96	McDaniel & Beecher	Radford Groc. Co. #1	1947
	113	Mobil Oil Co.	H&J #2	1959
	115	Kelley Bell	Cornett #1	1957
	227	Sinclair O&G Co.	P.W. DuBose #2	1952
	257	Luling Oil & Gas Co. et.al.	Folk #1	1958
	398	Blackwood Nichols	Granberry 1-7	1953
Garza	38	R.L. Turley	C.A. Bird #1-A	1954
	337	Alamo Corp.	Neff #1	1952
	397	D.J. Stone Oil & Gas Operations	Post Est. #5-1	1966

List of wells with geophysical well logs used for the cross-sections in this report.

County	Q Number	Operator	Lease & Well Number	Date Drilled
Hale	4	Chambers & Kennedy	Hix #1	1961
	19	Sinclair O & G Co.	J.N. Teauge #1	1964
	21	Western Drilling. Co.	E.M. Jones #1	1954
	40	Plymouth Oil Co.	Daly & Hulburt	1958
Hockley	28	Stanolind Oil And Gas Co.	W.J. Powell No. 1	08/19/1946
	35	T&P Coal and Oil Co.	Bailey No. 1	07/28/1947
	107	Feldmont Oil Corp.	C.M. Phillips No. 1	10/22/1957
	190	G.P. Livermore Inc.	Wells-Hassell No. 1	02/04/1951
	196	Pierce and Dehlinger	Humphries No. 1	10/20/1973
Howard	50	Glen H. McCarthy & S& W Drlg. Co.	Doyle Vaughn #1	1953
	60	Tidwell & Cowder	J.F. Selers #1	1955
	152	SunRay Oil Corp.	R. Harper #1	1951
	358	Gulf Oil Corp.	Maedelle Roley #1	1960
	378	Amerada Petroleum Corp.	G.G. White #1	1969
	501	R.S. Anderson	Mullie Anderson #1	1955
Lamb	6	Cities Service Oil Co.	Stanley #1	1960
	13	Midwest Oil Co.	Duane Moser #1	1957
	18	Amerada Petroleum Corp.	Mary Hagler #1	1957
	28	L.C. Hewett	Cunningham #1	1957
	37	Big Spring Exploration. Co.	Sybert #1	1960
	43	Sharples Oil Corp.	Sharples #1	1954
Lubbock	11	Leland Fikes	J.W. Lemon #2	1956
	15	James G. Brown & Assoc.	Charles Lundell Est. #2	1956
	16	Leland Fikes	Ida S. Collins B#1	1957
	30	Amerada Pet. Corp.	Stribling #1	1948
	68	Continental Oil Co.	E.A. Marquis #1	1955
	69	MFC Corp.	J. Clark #1	1950
Lynn	59	Barnsdall Oil Co.	B. Williams #1	1949
	74	Dalton H. Cobb & Kern Co. Land Co.	Camp & Norman #1	1961
	94	McAlester Fuel	Edwards #1	1949
	136	Apache Corp.	Franklin #1	1969
Martin	6	G.M. McGarr & G.T. Trusler	Billington #1	1959
	58	Sinclair Oil & Gas Co.	-Dickenson #1	1951
	162	Cities Service Oil Co.	Orson #1	1953
	179	Leland Davidson	Guy Mabee #1	1965
Mitchell	8	Standard Oil Co. of Texas	Z.F. Morrison #1	1955
	13	Standard Oil Co.of Texas	Foster #3B	1957
	31	Kay Kimbell et. al.	T.L. Holman #1	1956
	67	R.S. Anderson	Mobil #1	1962
	214	Blue Danube Oil Co.	May #1	1955
Oldham	19	Pan American Petroleum Co.	No. 1 D. Whaley	
Scurry	9	Sun Oil Co.	Randals # B-4	1956
	661	Chevron Oil Co.	Sacroc Unit #176-5	1975
Swisher	3	Frankfort Oil Co.	No. 1 Bradford	
	4	H.L. Hunt Oil Co.	No. 1 Bivins	
	8	Frankfort Oil Co.	No. 1 Culton	
Terry	1	Coroco Drilling Co.	Atlas Life #1	1952
	7	Great Western Drilling Co.	Brit Clare "C" #1	1960
	23	Champlin Ref. Co.	Linsley #1	1950

List of wells with geophysical well logs used for the cross-sections in this report.

County	Q Number	Operator	Lease & Well Number	Date Drilled
Terry	131	Bert Field	Beckham #1	1955
	155	Seaboard Oil Co.	Hinson #1	
	159	Shell Oil Co.	Loyce Floyd #1	1957
	161	Gulf Oil Corp.	T.L. Lowe #1	1951
Yoakum	7	Honolulu Oil Corp.	Cobb #2	1950
	57	Honolulu Oil Corp.	Davis #2	1954
	134	Amerada Pet. Corp.	Weems #1	1952
	297	The Texas Co.	Fitzgerald #1	1953
	298	Texaco Inc.	Fitzgerald #1	1973
	302	Sinclair Oil & Gas Co.	R.N. McGinty #1	1952

Appendix II

Details of well yields in the Dockum aquifer.

County	Well Yield (gpm)			Number of Records
	Mean	Maximum	Minimum	
Andrews	87	173	32	35
Armstrong	15	0	1	17
Borden	105	260	10	16
Briscoe	331	600	25	4
Crane	23	55	1	6
Crosby	120	180	90	3
Dawson	59	140	19	16
Deaf Smith	653	1,000	3	17
Dickens	90	250	10	10
Ector	70	103	26	4
Floyd	38	400	2	12
Gaines	91	157	50.8	3
Garza	43	200	3	24
Hartley	130	500	1	4
Howard	6	20	1	4
Midland	89	133	35	3
Mitchell	161	1,100	0.5	358
Moore	770	940	630	3
Motley	102	800	2	44
Nolan	120	460	2	187
Oldham	242	955	1.5	24
Potter	32	80	5	16
Randall	397	900	5	26
Swisher	504	920	200	5
Reagan	61	116	17.5	3
Reeves	353	736	60	20
Scurry	179	1,100	6	108
Terry	207	645	37	4
Upton	21	90.5	1.2	21
Ward	139	625	5	7
Winkler	418	2,500	24	17

Appendix III

Details of specific capacity tests in the Dockum aquifer.

County	TWDB Well Number	Discharge (gpm)	Drawdown (feet)	Duration of Test (hours)	Specific Capacity (gpm/ft.)
Andrews	2755403	152	200	24	0.76
Armstrong	0662203	12	20	3	0.60
	0663402	34	12	8	2.8
Borden	2806601	150	280	6	0.535
	2819601	130	639	4.5	0.203
	2819602	125	254	6	0.492
	2827301	125	248	6	0.504
	2827302	125	160	6	0.781
	2830601	160	244	6	0.655
	2930602	260	100	8	2.6
Crosby	2339501	90	40	40	2.3
	2339502	90	50	12	1.8
Deaf Smith	0750702	5	240	5	0.02
	0752902	900	79	6.75	11
	1014443	556	44.8	48	12.4
Dickens	2210829	250	40	2	6.3
	2210830	175	25	2	7.0
	2210831	100	75	6	1.3
	2218103	75	35	3	2.1
Gaines	2706501	50.8	115	3	0.442
	2706502	157	271	2	0.579
Garza	2345801	62	332	7	0.19
	2354701	40	223	3	0.18
	2362614	18	325	24	0.055
Martin	2755202	83	200	24	0.42
Mitchell	2840718	250	401	1	0.623
	2840808	60	100	1	0.60
	2926907	86	60	6	1.4
	2934434	71	192	1	0.37
	2934523	75	250	24	0.30
	2934524	180	145	2	1.24
	2934926	100	138	3	0.725
	2935211	175	103	2	1.70
	2935721	350	240	4	1.46
	2942211	207	100	1	2.07
	2942212	250	70	4	3.6
	2942213	80	120	2	0.67

Details of specific capacity tests in the Dockum aquifer.

County	TWDB Well Number	Discharge (gpm)	Drawdown (feet)	Duration of Test (hours)	Specific Capacity (gpm/ft.)
Mitchell (cont.)	2942214	100	112	2	0.893
	2942215	60	112	2	0.54
Moore	0716506	740	96	18	7.7
	0716507	630	56	17	11
Motley	2201201	800	125	6	6.40
	2210915	450	55	24	8.2
	2936524	150	83	1	1.8
Nolan	2936525	75	80	3	0.94
	2936824	75	200	3	0.38
	2944211	91.3	110	2	0.830
	2944505	130	113	24	1.15
	2944707	60	30	1	2.0
	2944708	100	115	3	0.87
Oldham	0730401	880	272	24	3.24
	0738202	20	74	24	0.27
	0738401	150	90	69	1.7
	0738402	180	132	48	1.36
	0738403	175	50	3	3.5
	0738404	40	70	3	0.57
	0738501	5	20	24	0.3
Potter	0642601	50	64	52	0.78
Randall	1101205	760	176	12	4.32
	1101606	900	100	3	9.00
Reeves	4646217	400	30	12	13
	4646602	736	20	213	37
Scurry	2815603	40	40	4	1.0
	2823902	475	203	168	2.34
	2824401	350	188	24	1.86
	2824403	400	78	7	5.1
	2824706	521	123	6	4.24
	2824707	400	75	6	5.3
	2824801	400	66	6	6.1
	2824802	400	100	6	4.00
	2824803	360	110	7	3.23
	2909905	60	180	4	0.33
	2917207	350	170	24	2.06
	2917403	254	89	24	2.9
	2917703	326	58	24	5.6
	2918603	130	40	12	3.3

Details of specific capacity tests in the Dockum aquifer.

County	TWDB Well Number	Discharge (gpm)	Drawdown (feet)	Duration of Test (hours)	Specific Capacity (gpm/ft.)
Scurry	2918702	85	142	3	0.60
	2919401	140	209	3	0.670
	2925401	150	220	24	0.682
	2925602	30	70	1	0.43
Swisher	1126612	600	311	24	1.93
Upton	4546603	36.4	118.4	3	0.307
Winkler	4608516	40	320	48	0.13
	4616213	1,800	105	24	17.1
	4616703	150	44	21	3.4
	4616705	86	187	24	0.46

Appendix IV

Total dissolved solids in groundwater samples from the Dockum aquifer, 1981 through 1996.

County	Total Dissolved Solids (mg/l)			Number of Samples
	Mean	Maximum	Minimum	
Andrews	2,939	3,540	2,252	25
Armstrong	390	551	280	11
Borden	10,000	69,170	588	14
Briscoe	700	2,397	360	11
Crane	4,040	6,316	1,443	3
Crockett	2,082	2,082	2,082	1
Crosby	712	1,528	351	4
Dawson	8,474	21,547	5,018	7
Deaf Smith	926	2,307	263	32
Dickens	824	2,302	303	16
Ector	2,932	5,665	1,688	4
Fisher	1,230	2,038	393	5
Floyd	345	389	307	9
Gaines	7,370	11,159	4,847	3
Garza	29,300	50,784	471	16
Glasscock	11,338	11,338	11,338	1
Hartley	323	553	212	7
Hockley	17,400	33,920	905	2
Howard	1,900	5,658	454	13
Kent	1,420	2,043	885	5
Loving	1,650	5,291	290	20
Martin	2,805	2,805	2,805	1
Mitchell	1,900	17,007	405	52
Moore	593	593	593	1
Motley	460	776	278	14
Nolan	632	1,951	273	28
Oldham	1,030	4,887	209	40
Potter	1,243	5,348	305	14
Randall	1,210	4,262	305	8
Reeves	1,180	2,911	513	5
Scurry	1,560	17,496	286	55
Sterling	282	361	249	5
Swisher	897	1,066	805	6
Terry	10,540	13,164	9,084	3
Ward	1,250	4,819	371	13
Winkler	473	1,408	206	22
Yoakum	9,454	9,675	9,232	2

NOTES: Reliable samples could not be obtained from Carson, Castro, Coke, Dallam, Hale, Irion, Midland, Parmer, Pecos, Reagan, Sherman, Tom Green and Upton counties.

Appendix V

Major cations detected in groundwater samples collected from the Dockum aquifer, 1981 through 1996.

County	Sodium (mg/l)			Potassium (mg/l)			Calcium (mg/l)			Magnesium (mg/l)		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Andrews	1,070	1,754.97	778.9	6	11	3	16	23.62	9	9	30	3
Armstrong	124	124	12.36	6	7	3.02	39	57	10.59	28	39	6.39
Borden	3,430	24,696	178	13	59	2.3	210	1,601	32.22	71	456	10
Briscoe	200	1,023	40	7	10	1.86	50	77	11.08	27	37.33	6.93
Crane	790	1,374	393.5	19	26.4	14.09	336	500.2	65.36	152	278.9	36.88
Crockett	400	562.8	253.8	13	16.09	10.25	117	133.7	86.29	100	132.1	67.45
Crosby	140	374	21	9	9.63	8.6	51	70	40	41	67	27
Dawson	2,920	7,476	1,770	26	101	11	109	397	34	49	186	14
Deaf Smith	330	909	16.33	4	9.1	1.78	14	67.83	2	8	48.37	0.77
Dickens	120	334	21	6	8.3	3.12	118	211	52	35	144	15
Ector	1,000	1,767	680.9	7	8.86	6.34	40	120	7.29	35	119	4.56
Fisher	160	316	67	7	11.37	3.5	185	416.44	43	49	103	21
Floyd	40	50	21	6	8.5	4.18	50	68.12	36	24	35	15
Gaines	2,250	3,294	1,559	8	10.77	5.59	79	145.6	40.55	29	53.35	15.38
Garza	10,650	19,216	127	36	69	2.9	448	798	20	165	287	10
Glasscock	4,015	4,015	4,015	36	35.5	35.5	63	63.04	63.04	96	95.71	95.71
Hartley	60	207.2	14.9	4	5.31	1.83	29	43.66	4.23	20	29.37	2.58
Hockley	6,240	12,397	73	19	25.29	12	496	907.6	85	176	258.7	93
Howard	610	1,949	84	6	10	1	49	140	31	21	63	10
Irion	423.8	423.8	423.8	12.02	12.02	12.02	131.6	131.6	131.6	87.28	87.28	87.28
Kent	240	299	181	5	6	3.62	146	297.7	44	69	114.6	22
Loving	140	499	7.9	5	12	0.4	257	830	41	83	245	8.1
Martin	991	991	991	7	7	7	14	14	14	5	5	5
Mitchell	410	5,779	26	6	30	1.44	140	615	9	79	565	4
Moore	127	127	127	10	9.7	9.7	52	52.3	52.3	23	22.7	22.7
Motley	90	217	20	6	8.1	3.3	51	81	33	17	26.07	7
Nolan	60	263.12	14	5	13.59	1	114	309.5	50	30	112	2

Major Cations Detected in Groundwater Samples Collected from the Dockum Aquifer, 1981 through 1996.

County	Sodium (mg/l)			Potassium (mg/l)			Calcium (mg/l)			Magnesium (mg/l)		
	Mean	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**
Oldham	320	1,781	19	4	10	1	34	101	1.8	17	45	0.12
Potter	220	952	16.99	6	18.86	1	114	566	2.4	65	525.2	1.26
Randall	370	1,240	20.1	5	16	1.32	36	158	3.31	26	106	2.01
Reeves	160	463	66.7	6	11.9	3.8	176	398	73	45	117	18.6
Scurry	380	6,132	18	6	15	1.42	124	416	1.7	41	150.16	0.57
Sterling	20	29.2	6.1	1	1.85	1	61	75.39	37.04	14	37.26	3.7
Swisher	340	396.5	303.1	2	2.91	2	4	5	3.58	2	2.26	1
Terry	3,350	4,006	2,965	14	14.39	14.39	144	231	97	51	70.24	41
Ward	130	381	6.1	4	7	2.14	210	940	62	56	230	5.9
Winkler	40	110.4	15	4	9.87	1.59	90	356	41	16	39	6.03
Yoakum	3,090	3,140	3,035	16	22.6	9	113	122	103	47	52	42

Appendix VI

Major Anion Concentrations Detected in Samples from the Dockum Aquifer, 1981 through 1996.

County	Chloride (mg/l)			Sulfate (mg/l)			Bicarbonate (mg/l)			Carbonate (mg/l)			Number of Samples
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	
Andrews	572	302	868	994	764	1,309	512	378.31	596.75	6	0	16.8	25
Armstrong	28	13	45	46	9	91	293	248.95	423.46	1	0	7.2	11
Borden	4,177	34	38,022	1,821	44	4,273	428	113.49	578.44	1	0	8.4	14
Briscoe	99	20	387	159	44	723.2	337	257.49	436.88	0	0	0	11
Crane	1,060	224	1,849	1,528	483.1	2,333	233	123.25	433.22	0	0	0	3
Crockett	421	421	421	797	796.8	796.8	353	323.39	380.75	0	0	0	3
Crosby	70	17	170	160	26	516	398	303.87	567	2	0	8	4
Dawson	3,196	1,313	11,962	1,921	1,019	4,107	436	324.61	507.66	25	0	163.2	7
Deaf Smith	106	3	508	206	9	460.8	474	198.92	999.46	9	0	37.2	32
Dickens	160	20	410	167	27.9	819	324	229.43	390.51	0	0	0	16
Ector	795	339	1,900	769	196	1,525	549	380.75	706.58	1	0	2.4	4
Fisher	333	33	826	245	26	752	314	216	402.71	0	0	0	5
Floyd	22	16	41	25	19	34	282	253.83	313.63	0	0	3.6	9
Gaines	1,196	510	2,284	3,622	2,512	5,177	361	322.17	389.29	0	0	0	3
Garza	16,010	80	28,000	1,853	63	3,095	227	124	383.19	1	0	8	16
Glasscock	4,575	4,575	4,575	2,362	2,362	2,362	349	349.02	349.02	0	0	0	1
Hartley	19	14	40	46	23	107.5	224	84.2	336.82	6	0	30	7
Hockley	9,584	169	18,999	775	311	1,239	165	87.86	241.63	0	0	0	2
Howard	503	49	1,593	480	54	1,764	351	223	602.85	1	0	8	13
Irion	-	-	-	-	-	-	315	314.85	314.85	0	0	0	1
Loving	149	10	1,608	873	10	2,120	203	54.92	550.38	0	0	0	20
Martin	612	612	612	857	857	857	600	600.41	600.41	7	7.2	7.2	1
Mitchell	411	25	7,774	657	69	3,035	324	200.14	545.49	0	0	7.2	52
Moore	16	15.6	15.6	149	149.3	149.3	391	390.51	390.51	0	0	0	1

Major Anion Concentrations Detected in Samples from the Dockum Aquifer, 1981 through 1996.

County	Chloride (mg/l)			Sulfate (mg/l)			Bicarbonate (mg/l)			Carbonate (mg/l)			Number of Samples
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	
Motley	78	13	226	45	18	80.5	282	220.88	336.82	0	0	1.2	14
Nolan	108	17	479	128	15	494	276	202.58	385.63	0	0	0	28
Oldham	161	4	1,498	252	14.1	1,381	421	80.54	1,036.07	8	0	39.6	40
Potter	276	16	1,879	367	24.2	1,971	283	201.36	374.65	3	0	38.4	14
Randall	311	9	1,664	277	20.9	1,004	314	125.7	449.09	1	0	1.2	8
Reagan	474	221	914	986	804	1,230	274	211.12	338.04	0	0	0	3
Reeves	333	55	1,250	314	143	538	187	156.2	211.12	0	0	0	5
Scurry	547	14	9,339	259	13	1,312	306	186.71	621.16	1	0	28.8	55
Sterling	13	7	18	12	11	14	272	231.87	385.63	0	0	0	5
Swisher	89	65	116	205	172.5	269.8	487	456.41	558.92	6	1.2	12	6
Terry	2,101	1,546	3,177	4,694	4,212	5,514	362	275.8	407.6	0	0	0	3
Upton	440	216	663	978	586	1370	232	178.17	286.78	0	0	0	2
Ward	286	9	2,145	415	20	2,069	198	53.7	303.87	0	0	0	13
Winkler	90	6	465	113	18	350	157	100.07	256.27	0	0	0	22
Yoakum	1,260	1,232	1,288	4,700	4,570	4,830	374	348	399	0	0	0	2

Appendix VII

Percent Sodium, Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Boron, and Hardness Values in Groundwater Samples from the Dockum Aquifer, 1981 through 1996.

County	Percent Sodium				SAR				RSC (me/l)				Boron (mg/l)				Hardness (as CaCO3) mg/l			
	No. of Samples	Mean	Max	Min	No. of Samples	Mean	Max	Min	No. of Samples	Mean	Max	Min	No. of Samples	Mean	Max	Min	No. of Samples	Mean	Max	Min
Andrews	23	96	98	93	23	55.07	94.38	19.87	23	7.03	9.12	3.94	9	1.064	1.316	0.9102	23	76.13	175	34
Armstrong	6	38	82	11	6	1.8	7	0.36	7	1.1	3.89	0	6	0.237	0.511	0.1107	7	170	260	53
Borden	10	86	97	51	10	57.9	140.21	7.04	10	2.72	6.41	0	9	1.245	1.83	0.2683	11	998.36	5870	138
Briscoe	7	53	95	27	7	10.12	31.73	1.14	7	1.29	5.44	0	5	0.819	2.184	0.2333	7	224.14	338	56
Crane	5	58	80	37	5	12	25.07	5.63	5	0.16	0.8	0	3	0.664	1.177	0.1284	5	1394.4	2263	317
Crockett	3	54	62	48	2	6.55	9.04	4.97	3	0	0	0	3	1.286	1.374	1.177	3	704	881	495
Crosby	3	40	64	15	3	3.51	7.67	0.57	3	0.35	0.56	0	2	0.3419	0.3838	0.3	3	322.67	452	256
Dawson	9	91	98	58	9	62.5	116.41	6.74	9	3.05	7.49	0	4	1.109	1.657	0.58	9	278.1	649	50
Deaf Smith	19	88	98	40	19	28.2	64.89	1.8	20	7.5	15.32	0.25	10	1.041	3.193	0.0746	20	46.7	170	10
Dickens	8	36	82	17	7	1.92	4.03	0.61	7	0.01	0.08	0	9	0.306	0.59	0.0806	7	399.86	638	226
Ector	4	96	98	93	5	43.66	56.01	27.36	5	7.09	10.96	0	3	1.14	1.433	0.7428	5	203	789	36
Fisher	6	39	52	20	6	2.94	4.44	1.87	6	0.27	1.59	0	6	0.408	0.63	0.1937	6	614.67	1288	199
Floyd	6	24	31	15	6	1.02	1.35	0.6	6	0.15	0.39	0	3	0.1992	0.2458	0.1529	6	232.17	249	213
Gaines	4	95	98	92	4	46.07	59.36	52.88	5	3.1	10.96	0	3	1.717	1.926	1.583	5	318.2	609	35
Garza	14	84	97	46	14	94.1	252.01	3.08	15	0.39	2.94	0	9	2.028	2.94	0.35	15	1731	3171	78
Glasscock	2	78	83	72	2	30.16	36.44	23.88	2	0	0	0	1	1.531	1.531	1.531	2	1673.5	1998	1349
Hartley	5	39	95	14	5	3.89	19.59	0.46	5	1.1	5.38	0	5	0.428	1.669	0.0869	6	192	418	21
Hockley	2	55	89	21	2	47.4	93.47	1.3	2	0	0	0	1	1.539	1.539	1.539	2	1984.5	3375	594
Howard	9	80	96	34	9	32	66.69	2.61	9	2.88	7	0	10	1.25413	2.17	0.3893	9	377.22	1526	123
Irion	1	57	57	57	1	7.03	7	7	1	0	0	0	1	0.6261	0.6261	0.6261	1	694	694	694
Kent	3	47	69	29	2	5.7	6.88	4.51	2	0.72	1.44	0	4	0.556	0.78	0.1549	2	526.5	830	223
Loving	12	24	41	6	12	1.65	5.25	0.22	14	0	0	0	3	0.292	0.527	0.1361	14	1045.9	3078	159
Lubbock	1	17	17	17	17	1.25	1.25	1.25	1	0	0	0	0	0	0	0	1	818	818	818
Martin	1	97	97	97	1	57.86	57.86	57.86	1	8.97	8.97	8.97	0	0	0	0	1	55	55	55
Mitchell	41	48	99	7	41	10.9	67.41	0.65	41	0.75	8.16	0	31	0.486	2.1	0.05	41	566.7	2949	9
Moore	1	26	26	26	1	1.12	1.1	1.1	1	0	0	0	1	0.57	0.57	0.57	1	230	230	230

County	Percent Sodium				SAR				RSC (me/l)				Boron (mg/l)				Hardness (as CaCO3) mg/l			
Motley	10	39	68	18	10	2.3	6.26	0.62	10	0.62	1.52	0	10	0.27	0.45	0.0987	10	196.8	271	148
Nolan	23	19	41	11	23	1.1	4.01	0.4	23	0.01	0.32	0	18	0.438	0.75	0.0911	23	418.83	999	210
Oldham	33	63	99	16	34	20	109.54	0.68	34	4.46	14.96	0	10	0.66	2.712	0.0618	35	154	418	4
Potter	13	46	97	14	13	5.2	24.12	0.5	13	1.18	6.42	0	7	0.35	0.6695	0.1512	14	664.6	3472	11
Randall	6	72	96	20	6	18	31.99	0.72	6	3.2	6.81	0	5	1.84	3.361	0.176	6	222.3	842	27
Reagan	3	64	90	46	3	42.6	111.93	4.31	3	0	0	0	0	0	0	0	3	2100	3628	608
Reeves	1	90	90	90	13	2.5	5.25	1.55	13	0	0	0	1	0.2277	0.2277	0.2277	13	758	1960	260
Scurry	45	43	98	11	45	9.57	69.61	0.5	46	1.13	10.01	0	30	0.45	2.04	0.0814	46	528.8	1662	11
Sterling	5	14	24	2	5	0.51	0.89	0.05	5	0.67	1.92	0	6	0.119	0.15	0.055	5	196.8	257	115
Swisher	5	97	98	97	5	35.56	44	30.69	5	7.87	8.89	7.22	3	0.89	1.037	0.7587	5	17.6	20	15
Terry	3	92	94	90	3	62.3	65.92	59.24	3	0	0	0	1	1.675	1.675	1.675	3	572.33	871	410
Upton	0	0	0	0	7	12.4	43.26	2.94	7	0	0	0	0	0	0	0	7	1700	2218	943
Ward	10	23	41	4	10	1.6	3.25	0.15	10	0	0	0	6	0.268	0.4032	0.1541	10	598	1831	263
Winkler	17	25	46	9	17	1.2	6.61	0.61	20	0	0	0	7	0.227	0.3789	0.0609	20	361.6	1448	136
Yoakum	1	93	93	93	1	63.68	63.68	63.68	1	0	0	0	1	55.5	55.5	55.5	1	429	429	429

Appendix VIII

Areas in each County underlain by the Dockum Aquifer with Different TDS Consentrations.

		Area of Aquifer (Acres)		
County	**<5,000 mg/l TDS**	**5,000 to 10,000 mg/l TDS**	**>10,000 mg/l TDS**	**Total**
Andrews	960,640	0	0	960,640
Armstrong	286,029	0	0	286,029
Bailey	0	0	529,280	529,280
Borden	64,640	168,320	342,400	575,360
Briscoe	295,457	0	0	295,457
Carson	83,180	0	0	83,180
Castro	43,169	204,800	326,751	574,720
Cochran	0	0	496,000	496,000
Coke	18,599	0	0	18,599
Crane	335,246	63,360	0	398,606
Crockett	489,127	0	0	489,127
Crosby	101,111	358,604	116,285	576,000
Dallam	963,200	0	0	963,200
Dawson	0	423,040	154,240	577,280
Deaf Smith	958,080	0	0	958,080
Dickens	170,253	0	0	170,253
Ector	576,640	0	0	576,640
Fisher	45,218	0	0	45,218
Floyd	605,164	29,716	0	634,880
Gaines	737,714	198,606	24,960	961,280
Garza	131,010	75,520	366,720	573,250
Glasscock	100,480	302,720	173,440	576,640
Hale	165,120	81,280	396,800	643,200
Hartley	935,680	0	0	935,680
Hockley	0	0	581,120	581,120
Howard	191,312	386,608	0	577,920
Irion	425,986	0	0	425,986
Kent	44,935	0	0	44,935
Lamb	0	0	650,240	650,240
Loving	180,281	0	0	180,281
Lubbock	0	0	576,000	576,000
Lynn	0	0	570,880	570,880
Martin	43,742	541,858	0	585,600
Midland	51,840	522,880	1,280	576,000
Mitchell	521,525	0	0	521,525
Moore	233,147	0	0	233,147
Motley	98,283	0	0	98,283
Nolan	83,658	0	0	83,658
Oldham	960,640	0	0	960,640
Parmer	149,760	124,160	290,560	564,480
Pecos	376,261	0	0	376,261
Potter	447,934	0	0	447,934
Randall	583,453	0	0	583,453
Reagan	439,680	138,240	174,080	752,000
Reeves	344,094	0	0	344,094
Scurry	508,859	0	0	508,859
Sherman	60,655	0	0	60,655
Sterling	580,677	0	0	580,677
Swisher	570,073	5,927		576,000
Terry	0	53,120	516,480	569,600
Tom Green	34,417	0	0	34,417
Upton	117,760	240,640	436,480	794,880
Ward	394,191	0	0	394,191
Winkler	516,095	0	0	516,095
Yoakum	0	108,800	403,200	512,000
	16,025,015	**4,028,199**	**7,127,196**	**27,180,410**

NOTES: TDS-total dissolved solids.