Pecos Valley Aquifer, West Texas: Structure and Brackish Groundwater

by John E. Meyer, P.G. • Matthew R. Wise, P.G. • Sanjeev Kalaswad, Ph.D., P.G.

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John E. Meyer
No. 2026

John E. Meyer

John E. Meyer

Matthew R. Wise, P.G. No. 6867

Mr. Wise was responsible for well log interpretation and cross-section preparation. The seal appearing on this document was authorized on June 1, 2012, by

Matthew R. Wise
6867

Matthew R. Wise

Matthew R. Wise

Sanjeev Kalaswad, Ph.D., P.G. No. 478

Dr. Kalaswad was responsible for general oversight of the project and editing the report. The seal appearing on this document was authorized on June 1, 2012, by

Sanjeev Kalaswad
No. 478

S. Kal-

Sanjeev Kalaswad

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1. Executive summary

Estimated at more than 2.7 billion acre-feet (LBG-Guyton, 2003), brackish groundwater (water with total dissolved solids concentration of 1,000 to 10,000 milligrams per liter) constitutes an important desalination water supply option in Texas. However, one of the more challenging issues—and a potential roadblock to more widespread implementation of desalination—is the lack of detailed information on parameters important to desalination for the brackish sections of Texas Water Development Board (TWDB) designated aquifers.

In 2009, TWDB established the Brackish Resources Aquifer Characterization System program to map and characterize brackish groundwater in the state and facilitate the planning of desalination projects. As part of the program, the Pecos Valley Aquifer in Regional Water Planning Area F was selected for a pilot study. In addition to mapping and characterizing brackish water in the aquifer, the goals of the project were to develop techniques of data analysis and build a database management system that could be used in future brackish aquifer mapping projects and other geologic studies.

The Pecos Valley Aquifer underlies an area of about 8,650 square miles in the Trans-Pecos area of West Texas and New Mexico. It is the primary source of water in the area. The underlying Edwards-Trinity (Plateau), Dockum, Rustler, and Capitan Reef Complex aquifers provide smaller volumes.

For the study, we collected, analyzed, and interpreted thousands of water well and geophysical well logs to map the geologic units and establish stratigraphic relationships. We also gathered water chemistry, water level, and aquifer test data from a wide variety of sources to characterize groundwater in the Pecos Valley Aquifer.

The Pecos Valley Aquifer consists of more than 1,700 feet of Tertiary and Quaternary alluvial sediments that are present in two hydrologically separate, approximately north-south trending solution basins known as the Pecos and Monument Draw troughs. Because there are several sub-basins within the two solution troughs that have not been penetrated by water wells, complete water chemistry for the entire aquifer could not be evaluated. Nevertheless, the chemical quality of water in the aquifer appears to be highly variable, changing with location and depth.

In the Pecos Valley Aquifer, the concentration of total dissolved solids ranges from less than 200 to more than 10,000 milligrams per liter; silica from 1 to 83 milligrams per liter; iron from 0.01 to 4.5 milligrams per liter; sulfate from 2 to 4,208 milligrams per liter; and chloride from 3 to 7,280 milligrams per liter. In places, water quality has deteriorated as a result of past irrigation practices and oil and gas activities.

We estimate that the Pecos Valley Aquifer contains about 15 million acre-feet of fresh water (0 to 1,000 milligrams per liter of total dissolved solids), 85 million acre-feet of brackish groundwater (1,000 to 10,000 milligrams per liter of total dissolved solids), and 1 million acre-feet of very saline water (>10,000 milligrams per liter of total dissolved solids). Brackish water is present almost everywhere in the aquifer but appears to be more prevalent in the central and western parts—areas where the saturated thickness of the aquifer is the greatest.

The 2010 approved Region F water plan projects water shortages of about 28,887 acre-feet in 2010 increasing to 35,342 acre-feet in 2060. Desalination of brackish groundwater present in the Pecos Valley Aquifer may be one option to meet at least some of the projected shortages.

While the project report presents important new information about the Pecos Valley Aquifer on a regional scale, the real value of the project is the new database and GIS datasets that were built and raw well records assembled for the project. These data sources—which were hitherto not available to the public—contain a wealth of groundwater data (raw and processed). Water planners can customize and use the data to develop more site-specific information to meet their needs.

The pilot study has helped lay the foundation for future Brackish Resources Aquifer Characterization System projects by developing a database management system in which a variety of data can be stored and processed.

Information contained in the report is not intended to serve as a substitute for site-specific studies that are required to evaluate local aquifer characteristics and groundwater conditions for a desalination plant.

2. Introduction

Estimated at more than 2.7 billion acre-feet (LBG-Guyton, 2003), brackish groundwater constitutes an important desalination water supply option in Texas. However, the more widespread implementation of desalination is being hindered by the lack of detailed information (especially parameters pertinent to desalination) on the brackish sections of TWDB-designated aquifers (henceforth, brackish aquifers).

Groundwater contains dissolved minerals (total dissolved solids) measured in units of milligrams per liter and can be classified as fresh (0–1,000 milligrams per liter), brackish (1,000–10,000 milligrams per liter), and saline (greater than 10,000 milligrams per liter). For comparison, seawater contains approximately 35,000 milligrams per liter of total dissolved solids.

For the purposes of the study, we define brackish groundwater as water that has a total dissolved solids concentration of between 1,000 and 9,999 milligrams per liter.

While a 2003 TWDB-funded study (LBG-Guyton, 2003) helped lay the foundation for estimating brackish groundwater volumes in the state, the study was by design regional in scope, limited in areal extent, and narrow in its assessment of groundwater quality. To improve on the 2003 study, TWDB requested and received funding from the 81st Texas Legislature, 2009, to implement the Brackish Resources Aquifer Characterization System program to more thoroughly characterize the brackish aquifers.

The goals of the Brackish Resources Aquifer Characterization System program are to map and characterize the brackish parts of the major and minor aquifers of the state in greater detail using existing water well reports, geophysical well logs, and available aquifer data; build datasets that can be used in replicable numerical groundwater flow models to estimate aquifer productivity; and develop parameter-screening tools to help communities assess the viability of brackish groundwater supplies.

Initially, for a pilot study, we selected the Pecos Valley Aquifer in West Texas (Figure 2-1). This aquifer is designated as a major aquifer by TWDB and provides water to parts of nine counties in West Texas. More than 80 percent of water pumped from the aquifer is used for irrigation, while the rest is used for municipal and industrial purposes (George and others, 2011).

The selection of the aquifer for a pilot study was based on a number of factors including its inclusion as a water management strategy in a draft version of the 2010 Region F water plan, its geology, and—based on a preliminary assessment—the availability of adequate data. The pilot study provided us an opportunity to gain experience in and become familiar with data sources, procedures, techniques, and equipment. It also brought into sharp focus the challenge of identifying and procuring crucial data such as appropriate geophysical well logs, which have an impact on techniques proposed for the study.

For this study, we used geophysical well logs (spontaneous potential, gamma ray, and neutron), and water well and water quality data from several different sources to map and characterize the Pecos Valley Aquifer. We also mapped the geologic units underlying the Pecos Valley Alluvium but did not analyze water quality information from these formations.

Figure 2-1. Study area in Trans-Pecos, West Texas. Project boundary based on extent of the Pecos Valley Aquifer.

Specifically, the goals of the study were to

- map the geological boundaries of the Pecos Valley Alluvium and the underlying units;
- map the distribution of total dissolved solids in the aquifer;
- map the distribution of key chemical parameters of interest to desalination;
- estimate the volume of brackish water in the aquifer; and
- assemble and make available to the public data collected for the project.

The limited availability of geophysical well logs with resistivity data from appropriate depth intervals precluded us from assessing the different techniques that can be used to estimate the concentration of total dissolved solids in the aquifer. Similarly, we could not determine salinity gradients in the aquifer, because of the lack of discrete water quality analyses from different depth intervals.

3. Study area

A brief description of the study area including its location, topography, climate, and geologic history follows.

3.1 Location, topography, and climate

The description of the study area is largely based on and is a summary of the information presented in Anaya and Jones (2009).

The study area covers about 8,650 square miles of west central Texas and southeastern New Mexico and underlies all or part of nine counties in Texas and two in New Mexico (Figure 2-1). Although we mapped the subsurface geology in the two counties of New Mexico to develop formation datasets, we did not include these counties in the water quality and brackish water resource calculations. The study area is mostly rural, with populations typically concentrated in the county seats. Production of oil and gas in the area began in 1925. Since then more than 61,000 petroleum wells have been drilled in the study area (Figure 3-1).

Prior to 2007, the Pecos Valley Aquifer was known as the Cenozoic Pecos Alluvium Aquifer. Its boundary was modified in the 2007 State Water Plan (TWDB, 2007) to reflect updated knowledge of the aquifer, in part, as a result of the modeling efforts of Anaya and Jones (2009). The Pecos Valley Aquifer hereafter refers to an updated boundary of the former Cenozoic Pecos Alluvium Aquifer.

The study area falls almost entirely within Regional Water Planning Area F (Figure 3-2) and extends over Groundwater Management Areas 2, 3, and 7 (Figure 3-3). Only the Middle Pecos Groundwater Conservation District is present in the study area (Figure 3-4).

Physiographically, the study area lies within the High Plains, Pecos Valley, and Edwards Plateau sections of the Great Plains province (Fenneman and Johnson, 1949). These sections are characterized by broad intervalley remnants of smooth fluviatile plains (High Plains section), mature to old plains (Pecos Valley section), and young plateaus with mature margins of strong to moderate relief (Edwards Plateau section).

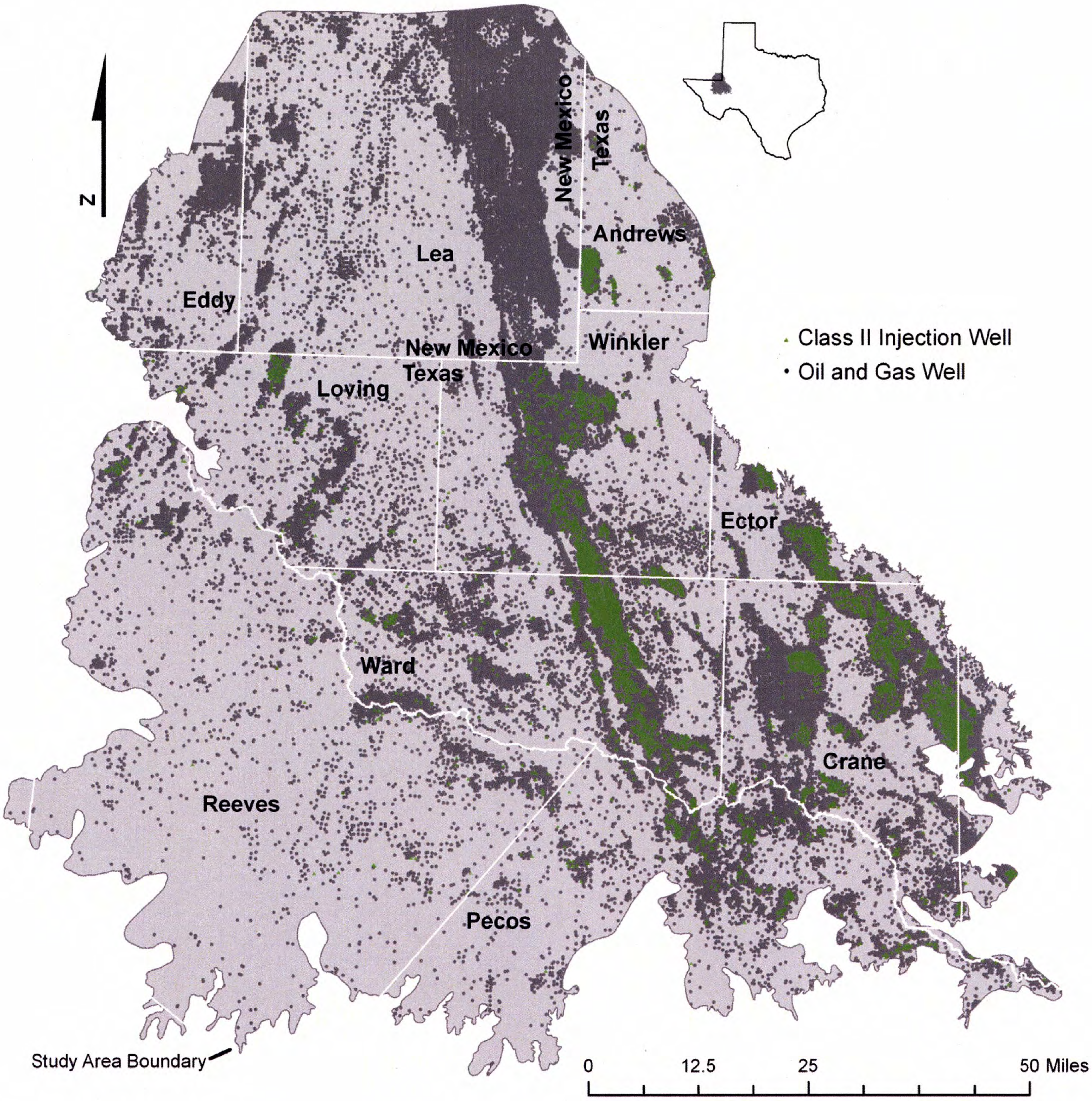


Figure 3-1. **Oil and gas wells in the study area: 46,262 in Texas and 14,944 in New Mexico. Class II injection wells in Texas are used to dispose of produced salt water and for secondary recovery. There are approximately 4,518 Class II wells in the Texas portion of the study area. Source: Railroad Commission of Texas and New Mexico Energy, Minerals, and Natural Resources Department.**

Topographic relief (the difference between the highest and lowest elevations) within the study area is about 1,700 feet: elevations range from about 2,200 feet above sea level along the Pecos River valley to about 3,900 feet above sea level in New Mexico.

The Pecos Valley Aquifer consists of a thick accumulation of alluvial and eolian (windblown) sediments between the westernmost plateau margin and the Mescalero Escarpment (Figure 2-1). Bands of northwest-southeast trending migrating sand dunes approximately five miles wide and rising as much as 50 feet above the surrounding land surface (Ashworth, 1990) occur between the Pecos River (tributary to the Rio Grande) and the Mescalero Escarpment. Alluvial fans emerge from the Trans-Pecos uplands and spread northeastward into the Pecos River Valley, capping the underlying Edwards-Trinity and Paleozoic sediments. The shallow drainage area between the Davis Mountains and the Pecos River is commonly referred to as the Toyah Basin.

The southeast-flowing Pecos River (Figure 2-1) drains the entire southwestern half of the study area. The river drops about 500 feet in elevation along a reach from the Texas-New Mexico border to the entrance of the Pecos Canyon in northwestern Crockett County. It drops another 1,100 feet as it flows through the Pecos Canyon (some canyon walls rise more than 300 feet above the riverbed) to its confluence with the Rio Grande. Except for short and steep arroyos along the Mescalero Escarpment and Landreth Draw in eastern Crane County, drainage features between the Pecos River and the Mescalero Escarpment consist mainly of desert flats, evaporation pans, and small playas.

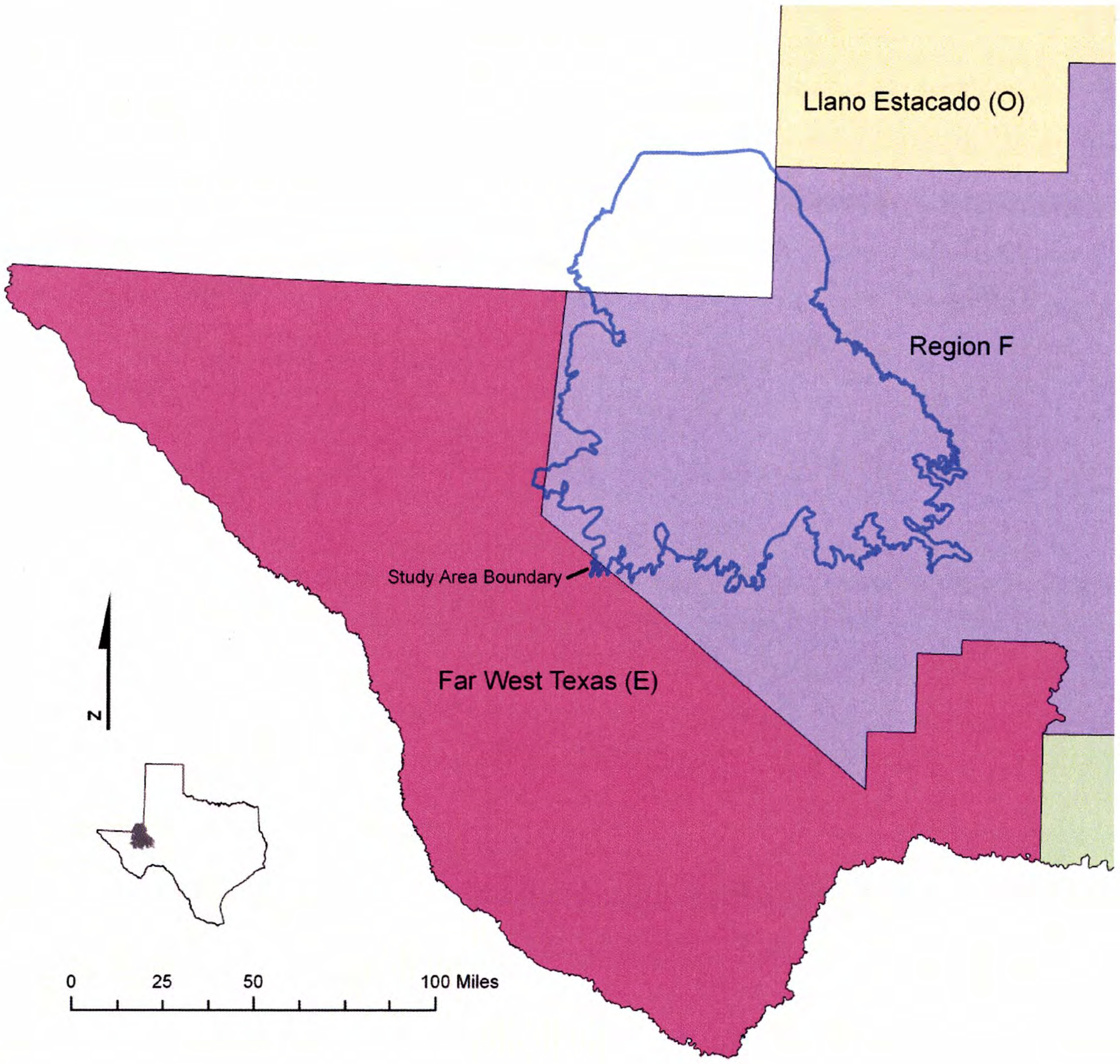


Figure 3-2. **Regional water planning areas in the project area.**

Although surface water flows rarely contribute to the Pecos River flow (Ashworth, 1990), the southwestern half of the Pecos Valley is drained by numerous draws dissecting the alluvial fans that have formed along the Trans-Pecos uplands. Toyah Creek is the primary tributary to the Pecos River. Red Bluff Reservoir in Loving County is located along the northwestern margin of the study area (Figure 2-1).

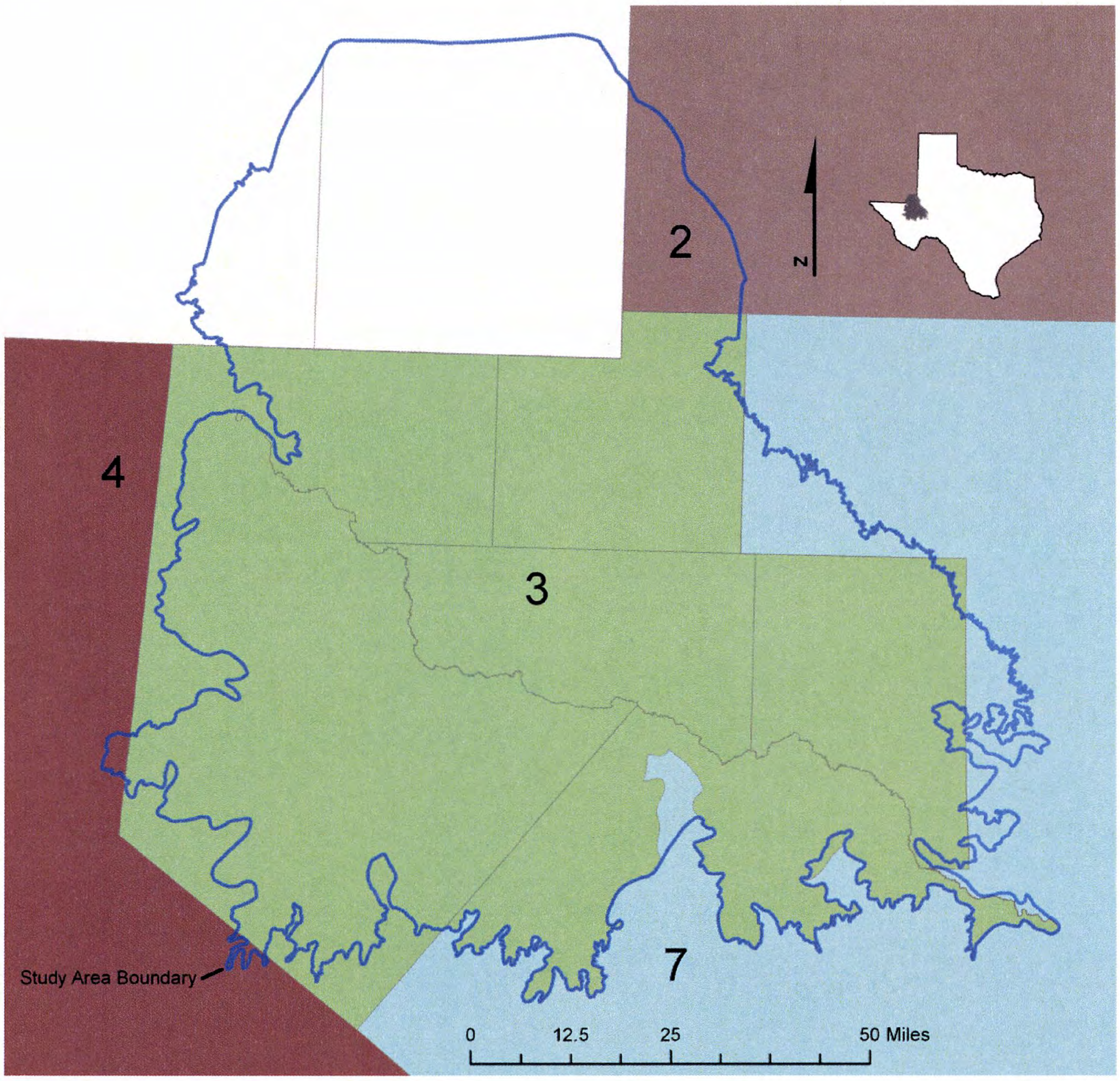


Figure 3-3. **Groundwater management areas in the study area. The numbers on the map refer to Groundwater Management Area number.**

The study area receives about 12 to 16 inches of precipitation annually (Anaya and Jones, 2009). The maximum average annual temperature in the study area ranges from about 76 degrees Fahrenheit to about 78 degrees Fahrenheit. Evaporation rates in the study area are high, with average annual lake evaporation ranging from about 78 to 80 inches (Anaya and Jones, 2009).

3.2 Geologic history

The study area has a complicated geologic history. Because an understanding of the past is important in deciphering present relationships among the five major and minor aquifers in the study area, we summarize next the major tectonic, depositional, and erosional events that have shaped the geology of the region.

3.2.1 *Paleozoic Era*

Deposition of Cambrian through Devonian sediments occurred on a stable, shallow-water marine platform. Extensive deformation of the area began in Mississippian time as a result of the Ouachita orogeny caused by the convergence of the North American continental plate with the European and African-South American continental plates. Thick sequences of Mississippian through early Pennsylvanian sediments were deposited in the foreland basin. Thrust faulting of Paleozoic strata in a northwestern direction is exposed in the Marathon area.

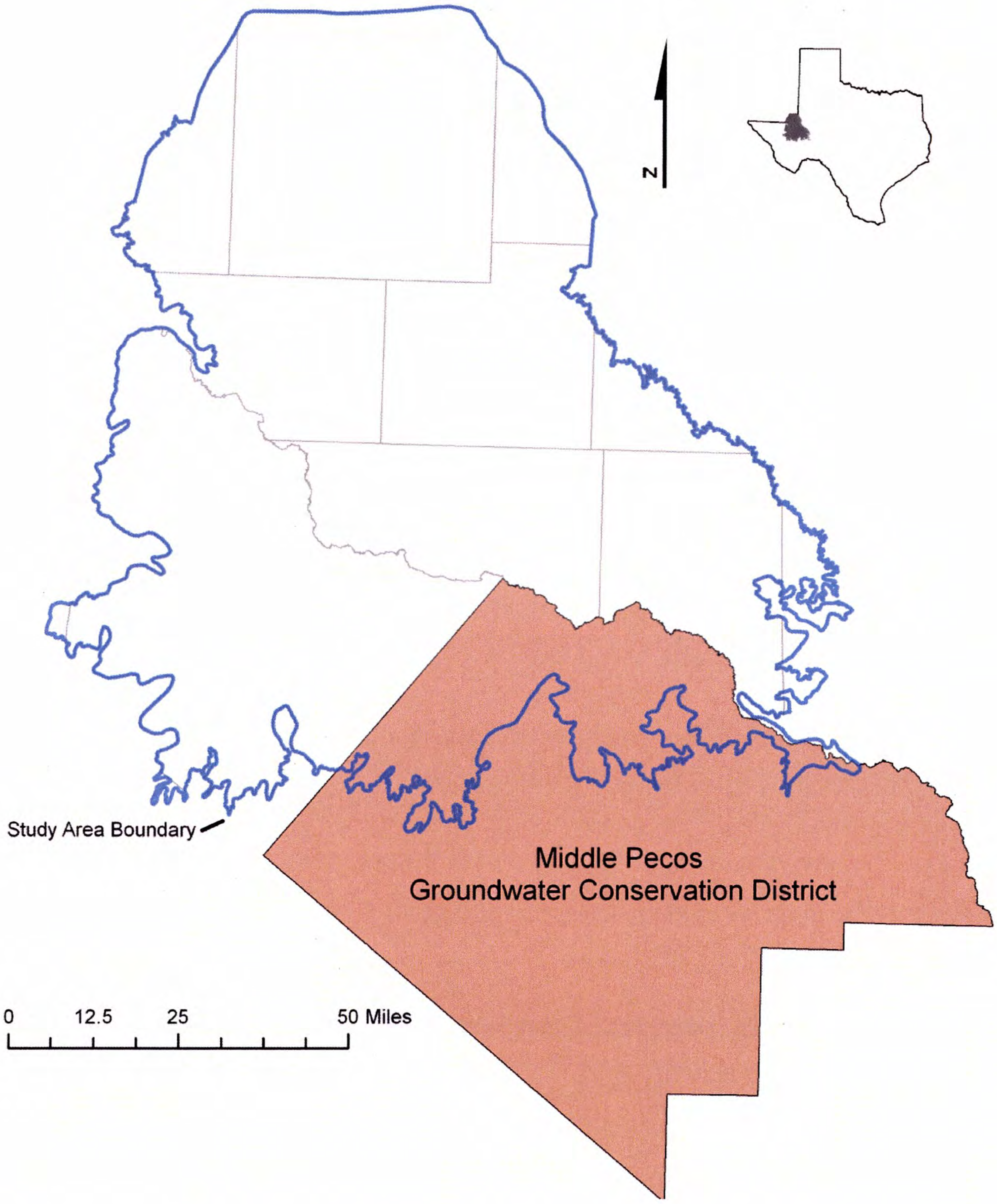


Figure 3-4. Groundwater conservation district in the study area.

The Middle Pennsylvanian to early Permian time was characterized by major subsidence of, and deposition in, the Delaware Basin and contemporaneous uplift and erosion of older rocks on the Central Basin Platform (Figure 3-5). Subsidence of the Delaware Basin continued through middle to late Permian (Ewing, 1991). The Central Basin Platform consists of a structurally complicated chain of uplifts that formed the foundation on which the Permian carbonate shelf was deposited. The Capitan Reef Complex formed along the margin of this platform, on the edge of the Delaware Basin (Standen and others, 2009). Evaporites (primarily gypsum) of the Castile Formation began filling the Delaware Basin and were overlain by evaporites (primarily halite) of the Salado Formation that filled the basin and extended over the top of the Capitan Reef Complex and Artesia Group back-reef deposits. The Rustler Formation, consisting of carbonates, evaporites, and clastic sediments, was deposited on top of the Salado Formation (Jones and others, 2011). The red beds of the Dewey Lake Formation record the final deposition of Paleozoic strata in the study area. Bebout and Meador (1985) present cross-sections across the Central Basin Platform showing the complex stratigraphic and structural relationships of the Paleozoic and later formations in the region.

3.2.2 Mesozoic Era

The Mesozoic Era began with a period of erosion that may have lasted almost 25 million years (Lucas and Anderson, 1993). Middle Triassic Dockum Group sandstones and red beds record continental deposition in an extensive basin in West Texas. The basin was filled from all directions by fluvial, deltaic, and lacustrine sediments (McGowan and others, 1977, 1979). There is no record of Jurassic strata in the study area, because sediments were not deposited or were deposited but eroded prior to the start of Cretaceous deposition.

The Cretaceous is marked by widespread transgression of marine seas across North America. The Trinity Group sediments represent three cycles of transgressive-regressive sequences in Texas (Barker and Ardis, 1996). Terrigenous and marine sediments unconformably overlie Triassic red beds in the study area. Fredericksburg and Washita strata were deposited in the Fort Stockton Basin consisting of the Finlay and Boracho formations. Gulfian strata, including the Boquillas Formation and the Austin Chalk, were deposited, with remnants found in western Pecos County (Armstrong and McMillion, 1961a). The Mesozoic Era ended with the Laramide orogeny consisting of late Cretaceous to Paleocene uplift and eastward tilting that exposed older strata to erosion (Ewing, 1991).

3.2.3 Cenozoic Era

Substantial erosion of Cretaceous and older formations has exposed Permian strata at ground surface west of the study area and Triassic strata in the middle of the study area, and has produced Cretaceous outcrops along the eastern, southern, and southwestern limits of the area. From 38 to 28 million years before present, volcanism produced ash-flow tuffs and associated volcanic rocks in the Trans-Pecos Texas region (Ewing, 1991). Regional uplift of the western United States in the Miocene and later times raised the area to its present elevation.

The Pecos and Monument Draw troughs contain collapsed post-Salado formations that are overlain by the Pecos Valley Alluvium. The Pecos Trough is present in the central Delaware Basin, between the outcropping Permian formations in the west and a ridge of undissolved Salado halite separating it from the Monument Draw Trough to the east (Figure 3-5). Collapse of the Pecos Trough may have post-dated the volcanism that occurred south of the study area because in central and southern Reeves County, basal Pecos Valley sediments contain eroded volcanic material. The north-south trending Monument Draw Trough lies directly above the central and western portions of the Capitan Reef Complex (Figure 3-5).

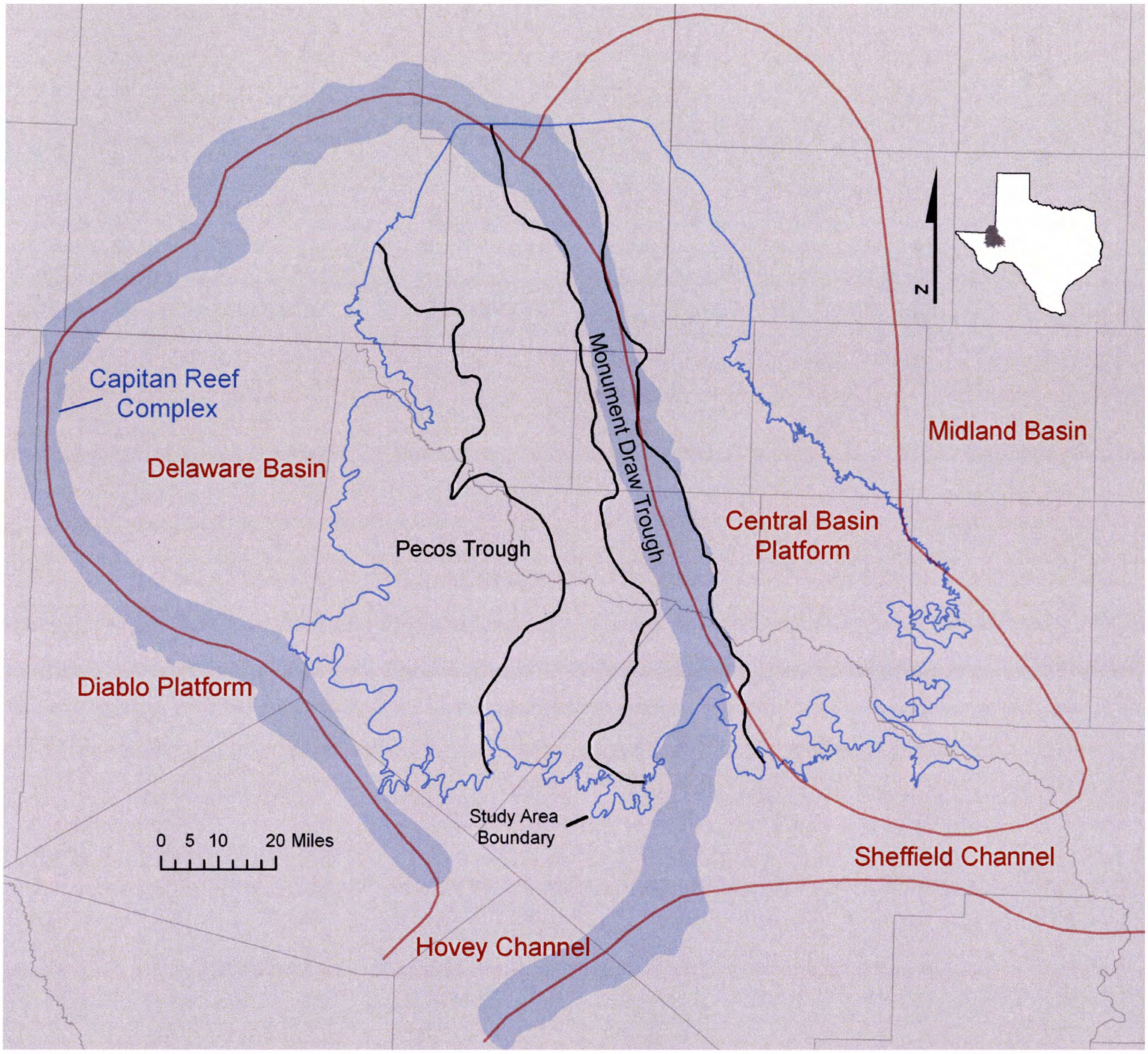


Figure 3-5. **Regional geologic elements of the Trans-Pecos of West Texas. The Capitan Reef Complex (shaded blue, Standen and others, 2009) formed along the margins of the Delaware Basin. The Monument Draw Trough (bounded by black lines) overlies the Capitan Reef Complex along the western margin of the Central Basin Platform. The Pecos Trough (eastern limit represented by black line) lies in the central Delaware Basin. The boundary of the study area is shown by the blue line.**

Uplift, erosion, dissolution of Permian evaporites, and deposition have shaped the present-day landscape, created the structural geometry of the sediments, and influenced groundwater flow patterns within the aquifers.

3.3 Summary of water demands and supplies in the study area

The Pecos Valley Aquifer is the primary source of water in the study area and the second most used aquifer in Regional Water Planning Area F. It represents approximately 31 percent of total groundwater use in the region. Agriculture-related consumption (irrigation and livestock) accounts for approximately 80 percent of the total use of water from the aquifer, while municipal consumption and power generation account for about 15 percent of aquifer use (RWPG F, 2010).

The 2010 Region F Water Plan indicates that demand for water in the nine counties that overlie the Pecos Valley Aquifer will increase by about four percent from the years 2010 to 2060 (Table 3-1). While municipal demand is projected to increase by about 21 percent in the 2010–2060 time period, irrigation demand is projected to decrease by about five percent over the same time period. Although the overall increase in water demand of four percent is not large, the increase will be from manufacturing, steam-electric, and municipal demands, which require water of higher quality delivered consistently throughout the year, compared to irrigation demand, which generally requires water of lower quality delivered seasonally.

Table 3-1. **Water demand projections, by use category, for counties in the Pecos Valley Aquifer, Region F. Data are from the approved Region F Water Plan, 2010.**

Use Category	2010 (acre-feet)	2060 (acre-feet)	Percent change in demand 2010–2060	Percent of overall demand in 2010	Percent change in relative share of overall demand 2010–2060
Municipal	48,111	57,985	+21	15	+2
Manufacturing	3,488	4,325	+24	1	0
Irrigation	245,602	232,490	-5	75	-7
Steam-Electric	11,289	25,799	+129	3	+5
Mining	15,441	17,550	+14	5	0
Livestock	4,755	4,755	0	1	0
Total	328,686	342,904	+4		

Although existing water supplies in Region F are expected to increase by 7,763 acre-feet over the 2010 to 2060 time period, demand is projected to exceed supply and shortages are expected. These shortages will increase from 28,887 acre-feet in 2010 to 35,342 acre-feet in 2060 (RWPG F, 2010).

Because shortages are projected, water management strategies will be required to meet the shortages. For the counties in the study area, the recommended water management strategies include water conservation, water reuse, desalination (Dockum Aquifer), and new groundwater sources (Pecos Valley Aquifer).

4. Previous investigations

Maley and Huffington (1953) published one of the first papers linking the dissolution of Permian evaporites to the deposition of Cenozoic alluvial fill in the Delaware Basin. County-wide hydrological studies by TWDB (and predecessor agencies) and the U.S. Geological Survey began in the late 1950s for Pecos, Reeves, Ward, and Winkler counties and in the Sand Hills region of Crane County (Armstrong and McMillion, 1961a and 1961b; Garza and Wesselman, 1959; Ogilbee and others, 1962a and 1962b; Shafer, 1956; White, 1971). Characterization of the Pecos Valley Aquifer in the multi-county study area includes studies by Ashworth and Hopkins (1990), George and others (2011), and Jones (2001, 2004 and 2008). The TWDB groundwater availability model for the Pecos Valley and Edwards-Trinity (Plateau) aquifers is presented in Anaya and Jones (2009).

Geologic maps prepared by The University of Texas at Austin at a scale of 1:250,000 were subsequently processed into a statewide digital geologic map in a geodatabase format (BEG 1976a, 1976b, 1994).

Brackish resource studies involving the Pecos Valley Aquifer were conducted by Winslow and Kister (1956) and LBG-Guyton (2003). These studies were regional in scope and were not conducted at the level of detail needed to fully characterize the aquifer.

For our study, we conducted an extensive literature review of water quality interpretation using geophysical well logs and regional geology including the underlying aquifers. We entered the references into a relational database and collected paper and digital documents.

5. Data collection and analysis

One of the primary objectives of the project was to gather all available well-control data from existing water well reports, geophysical well logs, water chemistry samples, and aquifer tests. This information augmented existing well information contained in the TWDB Groundwater Database. Because many of the anticipated datasets and analysis features were new to the TWDB and did not fit into the structure or meet the purpose of the existing Groundwater Database, a new relational database named BRACS (after the Brackish Resources Aquifer Characterization System) was designed specifically for this project.

Another equally important objective was to make the information and datasets gathered for the project readily available to the public. The information included raw data such as water well reports and digital geophysical well logs; processed data such as lithology, simplified lithologic descriptions, stratigraphic picks, and water chemistry; and interpreted results in the form of geographic information system (hereafter referred to as GIS) datasets and geological cross-sections.

With these goals in mind, we appended information from 2,639 wells to the BRACS Database that were new records, and from an additional 492 wells that are present in the TWDB Groundwater Database (Figure 5-1). The Groundwater Database has 2,672 existing well records for the study area, some of which contain critical information such as water chemistry, aquifer tests, and static water levels.

All new well records were obtained from publicly available sources that were not subject to copyright restrictions. We attempted to collect at least one well report or geophysical well log from every 2.5-minute grid cell in the study area; where necessary, more than one well was obtained.

We did not verify the location of every well that was obtained from other agency datasets unless there appeared to be a problem, such as a mismatch in the geology. When locations had to be verified or when digital locations were not available, the Original Texas Land Survey GIS data from the Railroad Commission of Texas was used as a base map. The legal descriptions of locations noted on the log header were used to plot the wells in GIS to determine the latitude and longitude coordinates.

5.1 Data sources and processing

A description of the method that we used to identify water wells and geophysical well logs, the various agencies and sources from which these data were obtained, and a brief discussion on the hydraulic properties of the aquifer are provided next.

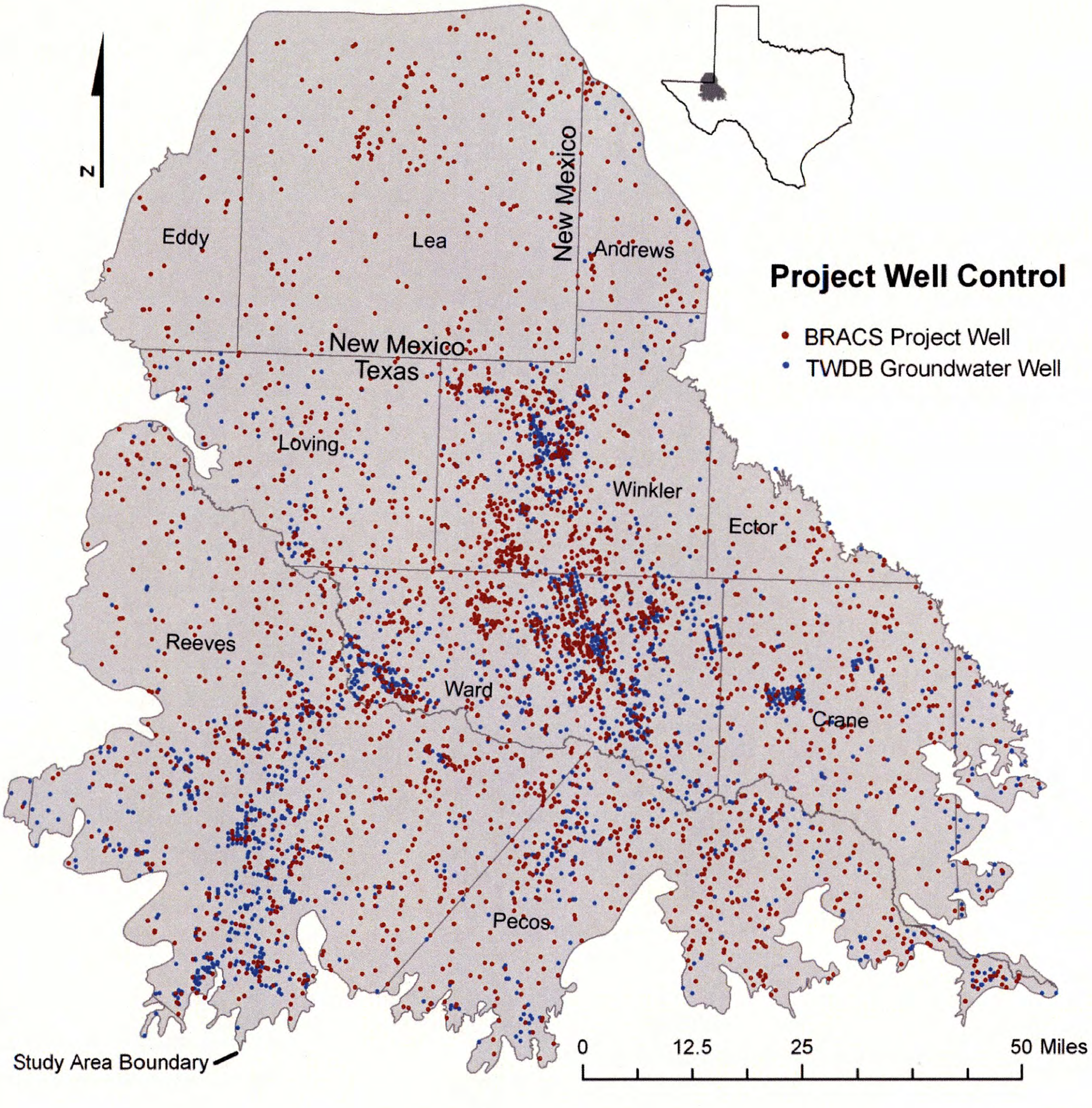


Figure 5-1. **Brackish Resources Aquifer Characterization System project well control included 2,639 new wells collected for this project plus an additional 492 wells from the existing TWDB Groundwater Database. Well control included water wells and oil and gas wells. The study area contained a total of 2,672 wells in the TWDB Groundwater Database.**

5.1.1 Well identification numbers

There is no universal well numbering system in Texas. Each well record may have zero to many unique identification names or numbers assigned to it, referred to as foreign keys. Every effort was made to cross-reference and record these identifiers in a database table. As the project progressed, more and more unique well numbers were discovered from the many agencies that collect and disseminate well information and from entities that collect and process well information into reports.

The unique identifier serves as a link between the BRACS Database and another database. Well information can be loaded into the BRACS Database automatically, saving data entry time. Other agency datasets contained information that is not necessary for our project at the present time. However, the compilation of these unique identifiers provides an opportunity for future data mining and analysis. Table 5-1 lists common well identification numbers used in the BRACS Database.

Table 5-1. Well identification numbers used in the BRACS Database.

Well identification number	Purpose	Agency assigning identification number
American Petroleum Institute number	Each new oil/gas well is assigned this unique number	American Petroleum Institute
Track number	Water well reports loaded digitally	Texas Department of Licensing and Regulation
State well number	Wells in the Groundwater Database	Texas Water Development Board
Water source	Public water supply wells	Texas Commission on Environmental Quality
Q number	Geophysical well logs used in the Surface Casing Program	Texas Commission on Environmental Quality and Railroad Commission of Texas
POD	POD (point of diversion) wells in the State Engineers Database	New Mexico Office of State Engineer
Well number	Owner name/number for well; Previous well number	Well owner; well number assigned in published report by Texas water agencies prior to development of State well number
Well ID	Well records in the BRACS Database	Texas Water Development Board

Note: ID=identification number

5.1.2 Water well reports

A total of 1,694 water well records were obtained and entered into the BRACS Database tables. The primary information obtained from these reports was the driller's description of the geological formations encountered in the borehole. These descriptions were used to make the stratigraphic picks and determine aquifer lithology. Water well information was also appended if it had water chemistry or aquifer test data that did not already exist in the Groundwater Database.

The data entered for each water well included owner information; well identification number(s); depth; location attributes; drill date; well type; and source of well information. Elevations were determined for each well using a seamless statewide 30-meter digital elevation model.

Texas Commission on Environmental Quality

We obtained 325 water well reports from the Texas Commission on Environmental Quality's Water Well Report Viewer, a Web-based portal that contains more than 800,000 scanned well reports in a Portable Document Format (commonly known as PDF). These wells are organized using a numerical system representing a grid cell consisting of 2.5 minutes of latitude and longitude. The five-digit grid cell is equal to the first five digits of the TWDB State Well Number. The Texas Commission on Environmental Quality had all well reports in a grid cell folder as one or more documents. The front and back of each paper water well report was captured on screen. County maps showing well locations as plotted by drillers were also imaged as separate documents.

Every grid cell in the study area (1,130 cells) was searched for potential logs. Obtaining adequate location information on the well report was a significant challenge. The majority of selected wells contained legal descriptions that were used for plotting with the Original Texas Land Survey GIS datasets. Driller locations plotted on county maps and latitude and longitude coordinates were also used. The information contained in these well reports was manually appended into the BRACS Database and the paper well reports filed in a Brackish Resources Aquifer Characterization System program folder.

An additional 24 water well records were obtained from the Texas Commission on Environmental Quality's Public Drinking Water, Source Water Assessment Program Database. Well lithology obtained from the Source Water Assessment Program Database was appended to the BRACS Database along with latitude and longitude coordinates obtained from a variety of methods.

Texas Water Development Board

We copied 311 well records from TWDB's Groundwater Database in order to supplement the well lithology and aquifer test information. The well reports were downloaded from TWDB's Water Information Integration and Dissemination system. All lithologic descriptions were entered manually into the BRACS Database.

An additional 576 well records were obtained from published reports (Armstrong and McMillion, 1961a and 1961b; Garza and Wesselman, 1959; Ogilbee and others, 1962a and 1962b; Shafer, 1956; White, 1971). Because these wells did not have corresponding records in TWDB's Groundwater Database, the well attributes were manually appended to the BRACS Database.

Texas Department of Licensing and Regulation

The Texas Department of Licensing and Regulation's Submitted Drillers Report Database contained 353 digital well reports. The reports can be downloaded individually from TWDB's Water Information Integration and Dissemination Web portal or obtained in a statewide database from the TWDB Web site. The database was redesigned to meet the requirements of the project. Wells were selected from a GIS shape file showing locations relative to the study area. Once selected, the well attributes such as location, depth, and owner information were automatically loaded into the BRACS Database. The driller's description of the geological formations exists in a memo field in the database. These data were reprocessed using a parser technique so that individual lithologic records could be extracted to show the lithologic name, depth to the top and bottom of the lithologic unit, its thickness, and source of data. Well lithologic records were then appended to the BRACS Database.

New Mexico Office of State Engineer

New Mexico Water Rights Reporting System of New Mexico Office of State Engineer provided 23 digital well reports. Some of the digital files contained a simplified lithologic description of the screened portion of the well. This proved to be inadequate for determining stratigraphic picks in the study area.

An additional 78 paper well reports were obtained directly from the New Mexico Office of State Engineer's office and the well attributes loaded manually into the BRACS Database. Four wells from the same agency containing aquifer test index data were also appended to the BRACS Database.

5.1.3 Geophysical well logs

Geophysical well logs are produced when a sensing tool is lowered into a well bore and raised back to the surface recording different types of information as it is brought to the surface. The type of information recorded depends on the type of tool used. The study area has more than 61,000 oil and gas wells that are recorded in the Railroad Commission of Texas' statewide Digital Map Data and in the New Mexico Energy, Minerals and Natural Resources Department database. However, only a fraction of these logs are publicly available, and an even smaller number met project requirements for tool type, and start and bottom depths. The initial objective was to obtain resistivity logs for interpreting total dissolved solids in groundwater. Unfortunately, a majority of the logs were recorded at depths starting from below the base of the Pecos Valley Aquifer and could not be used for this purpose.

A total of 1,437 digital geophysical well logs were obtained and appended to the BRACS Database tables. The digital logs were mainly obtained in a Tagged Image File format (commonly known as TIF) while a few were obtained in a Log ASCII Standard (commonly known as LAS) format. The primary information obtained from the logs was stratigraphic picks and interpreted simplified lithologic descriptions (from gamma ray logs). A small number of logs were used to estimate total dissolved solids concentration using resistivity or spontaneous potential log analysis.

Data entered for each geophysical well log included tool type; start and end depth for each tool; digital file name and type; owner; well number; depth; location attributes; drill date; kelly bushing (rig floor, derrick floor, rotary turntable) height; and source of well information. Elevations for all wells were determined using a seamless statewide 30-meter digital elevation model.

Railroad Commission of Texas

The Railroad Commission of Texas' Web site contained 299 digital geophysical well logs for the study area. The wells can be selected from a map-based interface or by entering an American Petroleum Institute number directly into a search feature. The Railroad Commission of Texas also maintains a spreadsheet of digital logs that are added to the database each month. We downloaded these spreadsheets and appended the well records to one of the BRACS-supporting databases. A GIS map of available logs was maintained in our program for use in selecting project wells.

University Lands, University of Texas System

The University Lands, University of Texas System's Web site provided 188 digital geophysical well logs for the study. The logs are organized by county and by the American Petroleum Institute number. Although the geographic coverage of this dataset is limited, the quality and completeness of the data are excellent. Additionally, many of the well logs already have annotations for stratigraphic picks. A GIS shapefile containing well locations can be downloaded from the University Lands, University of Texas System's Web site. This information was converted into a relational database format for use in selecting project wells for the study area.

Bureau of Economic Geology

The Bureau of Economic Geology maintains an extensive paper log collection of geophysical well logs in the Geophysical Log Facility. We selected 438 paper geophysical well logs from this collection for use in the study area. A contractor then scanned these into digital files. A subset of the Bureau of Economic Geology paper well log collection is also available in its Integrated Core and Log Database. The dataset for each county in the study area was processed and appended to a relational database designed to support the Brackish Resources Aquifer Characterization System program.

Texas Commission on Environmental Quality

The Texas Commission on Environmental Quality's Surface Casing program (transferred to the Railroad Commission of Texas on September 1, 2011) contained 162 digital geophysical well logs that were used in the study. The Bureau of Economic Geology scanned the entire collection of logs available for Reeves and Ward counties and some in Pecos County for the project.

For the Surface Casing program, each well or group of wells is assigned a unique number, termed the Q number. The Q number represents a specific geographic location or area. However, the location of each well must be verified against the legal description on the log header before latitude and longitude coordinates can be assigned. The Q number is often noted on well records in the TWDB Groundwater Database, especially if a water well has been logged and added to the Texas Commission on Environmental Quality's Surface Casing collection.

Texas Water Development Board

We selected 35 water wells with paper geophysical well logs from TWDB's Groundwater Database. A contractor then scanned these into digital files. An additional 137 digital logs were obtained from the Capitan Reef Complex Structure and Stratigraphy project that was completed for TWDB by Daniel B. Stephens and Associates, Inc. (Standen and others, 2009).

We also received more than 1,100 logs from New Mexico and several hundred logs from the Rustler Aquifer groundwater availability model project conducted for TWDB by Intera, Inc. (Jones and others, 2011). Although these logs were acquired late in the project and could not be used in the stratigraphic analysis, they have been added to the TWDB collection of geophysical well logs and are available for use in future studies.

New Mexico Energy, Minerals and Natural Resources Department

We downloaded 178 digital geophysical well logs from the New Mexico Energy, Minerals and Natural Resources Department's Oil Conservation Department Web site. We also downloaded a database of all oil and gas wells from the same Web site and reformatted it to meet our requirements. A GIS file of well locations was created to support the selection of wells.

U.S. Geological Survey

We obtained 61 digital geophysical well logs and supporting files from the U.S. Geological Survey, which is presently conducting a study of the Edwards-Trinity (Plateau) Aquifer in Pecos and adjacent counties. Although these logs were acquired late in the project and could not be used in our study, they have been added to the TWDB collection of geophysical well logs and are available for use in future projects.

5.1.4 Water quality data

Information on 3,509 groundwater chemical samples was compiled from wells in the study area: 1,548 from wells listed in the two main tables in the TWDB Groundwater Database and 389 wells from published reports (Armstrong and others, 1961; Garza and Wesselman, 1959; Ogilbee and Wesselman, 1962; Shafer, 1956; White, 1971). We entered the records into two BRACS Database tables but did not conduct a quality control check.

All records were appended to one master table in the BRACS Database. The source of each record was noted in the table along with all applicable well identification numbers. Information on 561 radionuclide samples was compiled from 187 wells in the TWDB infrequent constituents table and written to a table in the BRACS Database. The samples that were acquired from multiple aquifers in the study area were analyzed for uranium, radium, and alpha and beta particles.

5.1.5 Static water-level data

Static water-level measurements (15,130) were compiled from wells in the study area spanning the years 1927–2011. Information from 2,108 wells was obtained from the TWDB Groundwater Database and the Texas Department of Licensing and Regulation's water well reports. A small number of measurements were also obtained from water well reports from the Texas Commission on Environmental Quality paper well reports and Public Water Supply datasets.

All records were appended to one master table in the BRACS Database. The source of each record and the method of water-level measurement were noted, along with all relevant well identification records.

5.1.6 Hydraulic properties

The hydraulic properties of an aquifer refer to characteristics that allow water to flow through the aquifer. Hydraulic properties include transmissivity, hydraulic conductivity, specific yield, specific capacity, drawdown, pumping rate, and storativity. Lithology, cementation, fracturing, structural framework, and juxtaposition of adjacent formations all influence the flow of water within and between aquifers.

We compiled hydraulic properties for 879 wells from a variety of published sources and database tables. Values from wells consist of transmissivity (49); hydraulic conductivity (28); specific capacity (287); and well yield (875). The sources of information included aquifer tests from a TWDB spreadsheet; the TWDB Groundwater Database remarks table; spreadsheets compiled for the Pecos Valley and Edwards-Trinity (Plateau) groundwater availability model (Anaya and Jones, 2009); published reports (Garza and Wesselman, 1959; Myers, 1969; Ogilbee and Wesselman, 1962; White, 1971); Texas Department of Licensing and Regulation Submitted

Driller Log Database; and the New Mexico Office of State Engineer aquifer test index data spreadsheet. These measurements were appended to a database table.

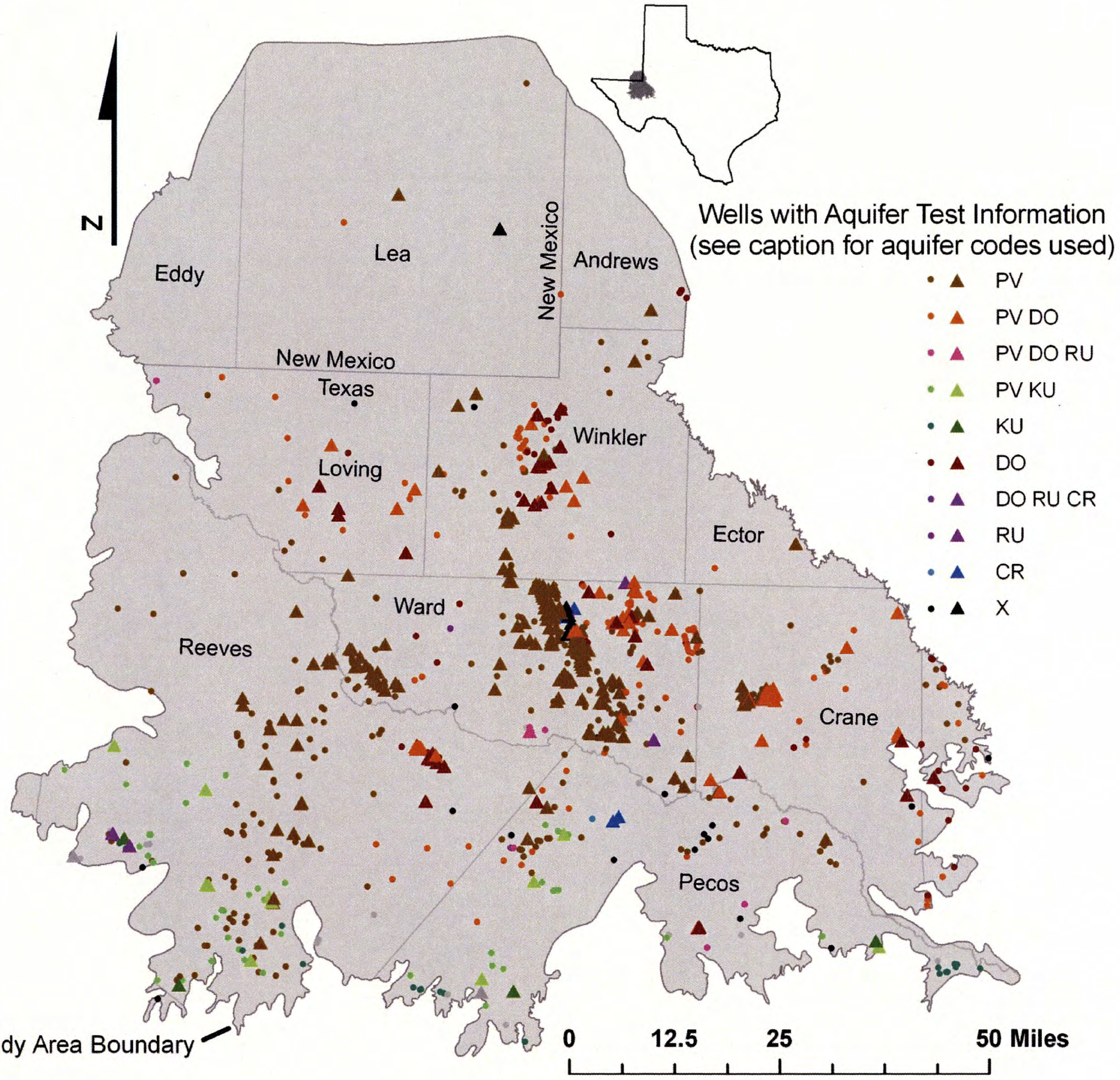


Figure 5-2. **Wells with aquifer test information obtained from written reports and TWDB files. Triangles represent wells with transmissivity, hydraulic conductivity, or specific capacity values. Circles represent wells with well yield values. Wells color-coded based on aquifer encountered (based on well screen or well depth analysis). Aquifer codes used in figure: PV (Pecos Valley Aquifer); KU (Edwards-Trinity (Plateau) Aquifer); DO (Dockum Aquifer); RU (Rustler Aquifer); CR (Capitan Reef Complex Aquifer); X (not a major or minor aquifer).**

Anaya and Jones (2009) reviewed hydraulic property records for the Pecos Valley Groundwater Availability Model and determined a mean hydraulic conductivity of 8.6 feet per day. Based on this value, transmissivity ranged from less than 1 square foot per day to approximately 14,000 square feet per day. Anaya and Jones (2009) reported that specific yield values were not available for the Pecos Valley Aquifer. However, in general, specific yield values for alluvium may range from 0.02 to 0.27 (Johnson, 1967).

Well records with hydraulic property data were assessed using the aquifer determination process (see Section 6-2 and Figure 5-2). We did not process hydraulic properties into GIS grid files because groundwater modeling was outside the scope of the study.

5.2 Availability of project data to customers

One of the primary objectives of our study—and of the Brackish Resources Aquifer Characterization System program—is to develop raw datasets and make them available to the public. The datasets include original well data, database tables, GIS datasets, and supporting documentation such as a database dictionary and project-related technical reports. At the time of writing this report, TWDB was redesigning the Groundwater Database and Web portal for the Water Information Integration and Dissemination system. The future Groundwater Database will include the BRACS Database tables and analysis, and users will have the ability to download digital geophysical well logs from it. However, until these upgrades are completed, users can acquire Pecos Valley Aquifer project data by contacting TWDB.

The original well data include digital geophysical well logs and paper copies of water well reports. A copy of the BRACS Database in Microsoft® Access® 2007 format is available with a supporting data dictionary. The database will include all tables and forms to view the information. The GIS datasets listed in Appendix 13.1 are available with metadata in the Environmental Systems Research Institute, Inc. formats specified in Section 8.2. Project reports in Portable Document Format are also available for download from the TWDB Web site.

6. Hydrogeologic setting

Information about the Pecos Valley Aquifer including its framework, hydraulic properties, and the chemical properties of water in the aquifer is presented next.

6.1 Hydrostratigraphy

The Pecos Valley Aquifer overlies portions of the Edwards-Trinity (Plateau), Dockum, Rustler, and Capitan Reef Complex aquifers. The geographical extent of these aquifers based on the different stratigraphic relationships present in the region is shown in Figure 6-1 and Table 6-1. After reviewing published literature and conducting GIS mapping of the region, we decided that more detailed mapping was required to fully define the lateral and vertical relationships between these aquifers. Because one of the main objectives of our study was to delineate the brackish water resources in the aquifer, we avoided mapping geologic units at the formation level with its inherent stratigraphic complexity and nomenclature controversies.

Accordingly, we mapped the following geologic units: Pecos Valley Alluvium; Cretaceous Undivided; Dockum Group-Dewey Lake Formation; and only the top surface of the Rustler Formation. A groundwater flow model for the Rustler Aquifer is currently being developed by Jones and others (2011). When completed, it will provide information on the bottom surface of the formation. We did not map the Capitan Reef Complex, because it was investigated in another TWDB-funded project (Standen and others, 2009).

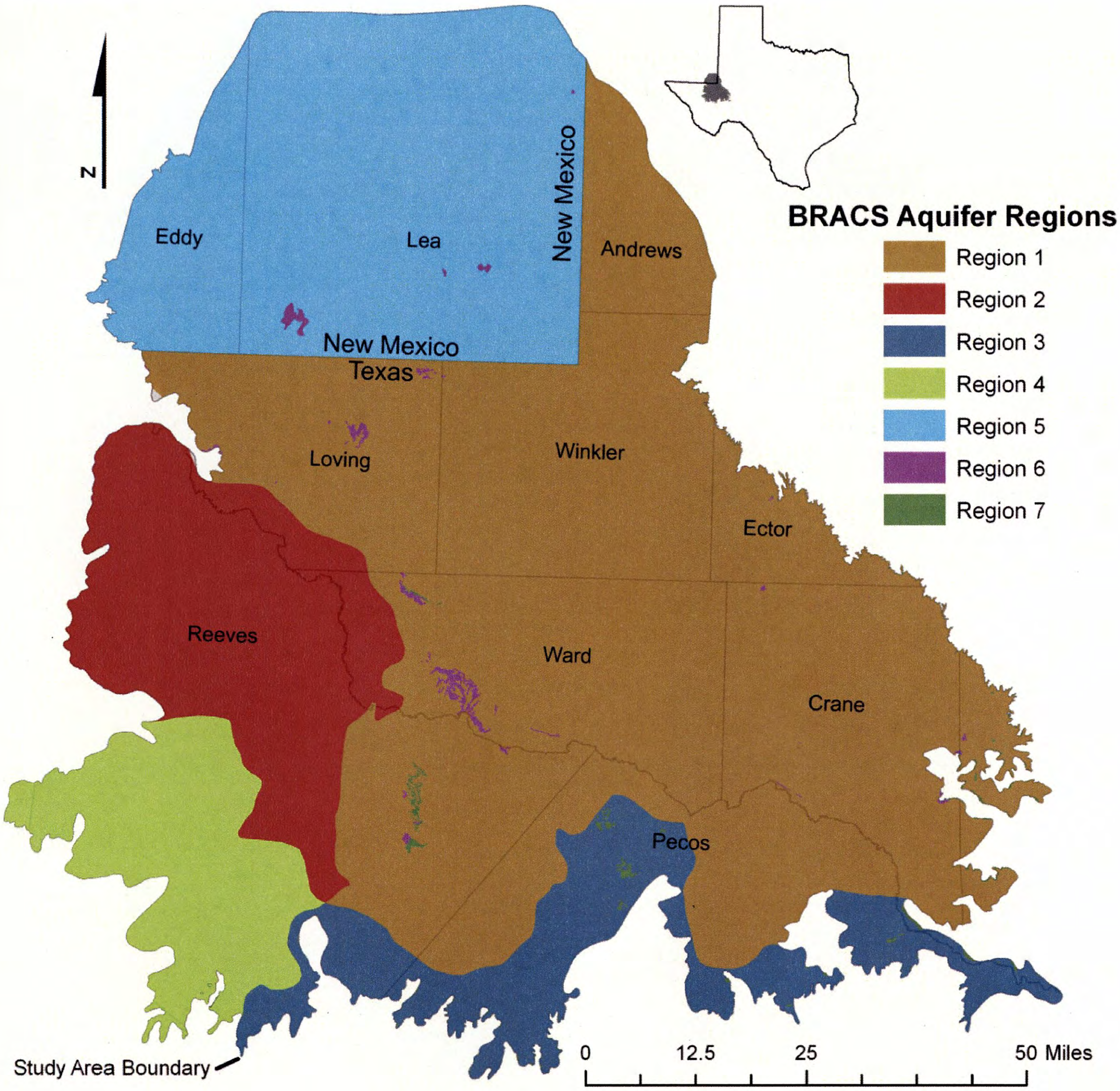


Figure 6-1. Brackish Resources Aquifer Characterization System aquifer regions divide the study area into separate stratigraphic relationships. Refer to Table 6-1 for stratigraphic chart. Regions 6 and 7 represent areas where the Dockum Group and Cretaceous Undivided strata are exposed at the ground surface.

6.1.1 Stratigraphic unit interpretation

Water wells, geophysical well logs, and published reports were the most important data sources that we used to define the stratigraphic top and bottom of each geologic unit. We used an iterative process of correlating logs and defining stratigraphic picks; picks were revised several times as we became more familiar with the area and new wells were added to the project. If a stratigraphic pick was not possible using information presented on a well log, no value was added to the database table. If a water well did not fully penetrate the stratigraphic base of a geologic unit, a value of ">" was inserted into the table field to denote partial penetration of the unit. Lithology and partial depth information proved extremely useful in preparing contour maps.

As the project progressed, we found that no single source of data was perfect for correlation purposes. Limitations on using the descriptions of geological formations on water well driller reports included imprecise and inconsistent lithologic terminology and interpretation; the possibility that drill cuttings from different depths may have become mixed during the drilling process; the likelihood that top/bottom depth values may be inaccurate because of lag time between drilling and retrieving the cuttings; and the presence of water wells that do not fully penetrate the aquifer.

Geophysical well logs were used throughout the study area, with gamma ray logs providing the most information. Gamma ray logs normally reflect the clay content in sedimentary formations (Schlumberger, 1972). Clays, such as illite and mica, which contain the radioactive potassium-40 isotope, produce gamma rays in the shale units. The advantages of using the gamma ray log are that

- it is present on most logging runs;
- it can be recorded in cased holes;
- it is generally started near ground surface; and,
- in many situations, the clay content can be used to recognize the boundaries of geologic units or depositional environments.

The disadvantages include

- attenuation of the overall log signature in cased holes;
- masking of the more subtle changes in log response with transition from uncemented to cemented formations;
- inability to evaluate borehole washouts because of the absence of caliper logs prior to casing the well;
- lack of tool calibration or complete casing records on the log header, which precludes accurate interpretation;
- presence of older gamma tool types where documentation of tool parameters is limited or impossible to acquire; and
- inability to differentiate clay-free sand, silt, and gravel. Additionally, in the study area, the gamma ray track on geophysical well logs often started as much as a few hundred feet below ground surface.

We reviewed published reports in the study area for formation descriptions, maps, and cross-sections (Armstrong and others, 1961; Bebout and Meador, 1985; Garza and Wesselman, 1959; Ogilbee and Wesselman, 1962; Shafer, 1956; Small and Ozuna, 1993; West Texas Geological Society, 1961; White, 1971). Geological cross-section well points and lines (Figure 6-2) were loaded into GIS and used to evaluate stratigraphic picks from project wells. The published reports also served as a reference for interpreting the composition, thickness, and areal distribution of the geological units.

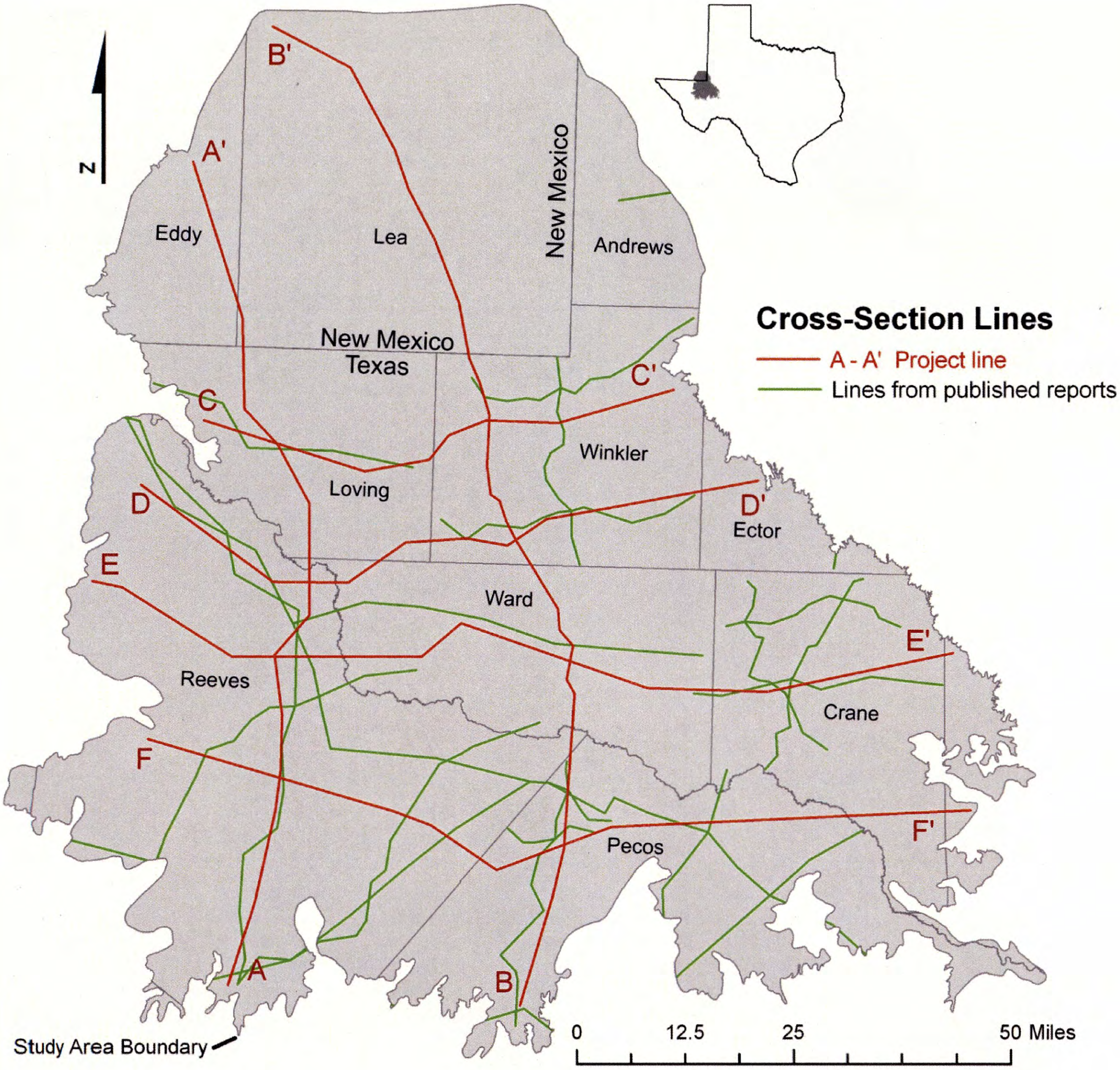
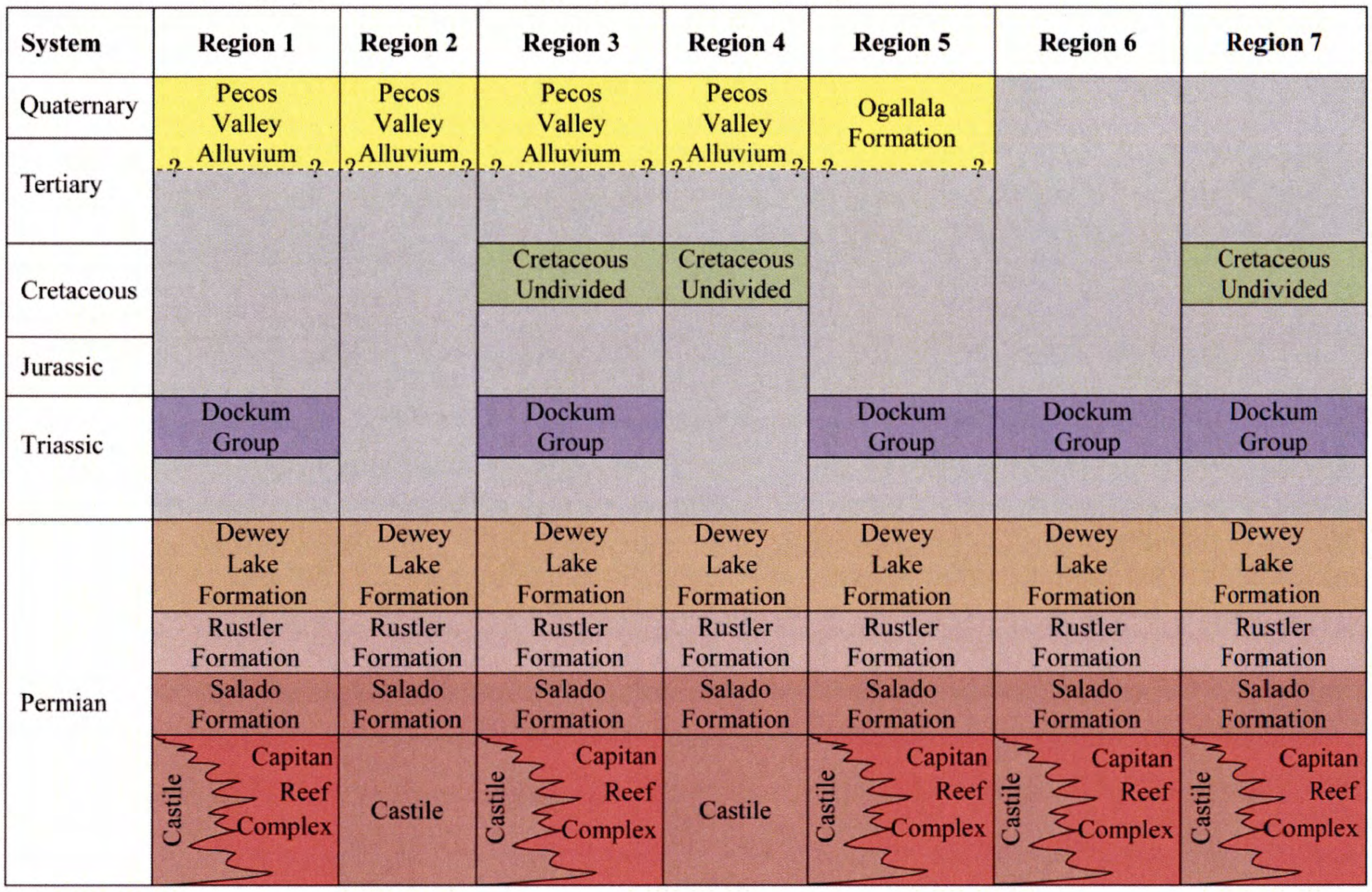


Figure 6-2. **Location of cross-section lines created in this project and those from published reports on the Pecos Valley Alluvium and underlying aquifers. The well point and line shapefiles are available as a GIS dataset.**

Pecos Valley Alluvium, top and bottom

The Pecos Valley Alluvium consists of Tertiary and Quaternary sediments deposited unconformably on older formations (Table 6-1). The sediments consist of caliche, clay, silt, sand, gravel, and boulder-sized material deposited in a variety of continental depositional settings including eolian, lacustrine, fluvial, valley-fill, and solution-collapse environments. These sediments, which we mapped as undifferentiated Pecos Valley Alluvium, constitute the hydrostratigraphic unit for the Pecos Valley Aquifer. In the northeastern study area, the Pecos Valley Aquifer is correlative with the Ogallala Aquifer; the drainage divide of the Rio Grande serves as the boundary between the two aquifers.

Table 6-1. **Stratigraphic relationships within the different regions of the study area. Refer to Figure 6-1 for a map of the study area regions. The formations shown in this table may not occur everywhere in a region. Gray areas represent missing section.**



System	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7
Quaternary	Pecos Valley Alluvium	Pecos Valley Alluvium	Pecos Valley Alluvium	Pecos Valley Alluvium	Ogallala Formation		
Tertiary							
Cretaceous			Cretaceous Undivided	Cretaceous Undivided			Cretaceous Undivided
Jurassic							
Triassic	Dockum Group		Dockum Group		Dockum Group	Dockum Group	Dockum Group
Permian	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation
	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation
	Salado Formation	Salado Formation	Salado Formation	Salado Formation	Salado Formation	Salado Formation	Salado Formation
	Castile Capitan Reef Complex	Castile	Castile Capitan Reef Complex	Castile	Castile Capitan Reef Complex	Castile Capitan Reef Complex	Castile Capitan Reef Complex

Table 6-2. **The number and types of wells used to define the tops and bottoms of the stratigraphic units in the study area.**

Geologic unit	Total number of wells	Number of partially penetrating wells	Number of picks based on geophysical well log	Number of picks based on water well report
Pecos Valley Top	1,851	N/A	849	1,002
Pecos Valley Base	1,851	433	849	1,002
Ogallala Top	206	N/A	114	92
Ogallala Base	206	24	114	92
Cretaceous Undivided Top	188	73	71	117
Cretaceous Undivided Base	171	73	60	111
Dockum Group Top	1,379	467	793	586
Dewey Lake Top	167	18	134	33
Dewey Lake Base	1,343	20	1,256	87
Rustler Top	1,350	15	1,281	69

The Pecos Valley Aquifer, previously known as the Cenozoic Pecos Alluvium, is designated as a major aquifer in Texas (Ashworth and Hopkins, 1995; George and others, 2011). The name and lateral extent of the Pecos Valley Aquifer were modified in 2007 (TWDB, 2007). It is an unconfined aquifer, although deeper sections may have local confining layers.

The stratigraphic top of the Pecos Valley Alluvium consists of post-Cretaceous sediments that are exposed at ground surface in the study area. Mapping the stratigraphic bottom of the geologic unit proved more complicated because the basal sediments consist of reworked Permian and Triassic red beds across much of the study area. The collapse of older consolidated material into solution voids and infilling with younger basin materials has created an extremely complicated stratigraphy that makes it impossible in some cases to accurately define contacts using information on water well and geophysical well logs (Armstrong and McMillion, 1961a; Maley and Huffington, 1953; Shafer, 1956; Snyder and Gard, 1982).

Geological correlations were made using geophysical well logs and lithology from nearby water wells. In order to make stratigraphic picks consistently, the base of the Pecos Valley Alluvium was chosen using, wherever possible, the following criteria: contact between unconsolidated sediments and consolidated red beds as described on water well logs; contact between light colored sediments and predominantly red-colored, lithified red beds; and contact between low gamma ray response and a higher gamma ray response using geophysical well logs (Figures 6-3 and 6-4).

The technique of using geophysical well log correlation was inherently biased toward a signature that indicated a coarse, unconsolidated geological unit overlying a more uniform siltstone or shale unit. This bias may have precluded us from including basal fine-grained deposits in the Pecos Valley Alluvium that are almost indistinguishable from the underlying Triassic and Permian units.

Table 6-2 lists the number and type of wells that were used to define the Pecos Valley Alluvium and the equivalent Ogallala Formation in New Mexico. In all, we interpreted 2,057 wells to define the formations and build the 3-D top and bottom surfaces in GIS. We loaded these picks into a database table with the name of the stratigraphic pick, top depth, bottom depth, and source of information.

The Pecos Valley Alluvium ranges in thickness from 0 to 1,745 feet (Figure 6-5). The most significant controlling factor on sediment accumulation was solution-collapse within the Monument Draw and Pecos troughs. The timing of this solution-collapse played a large role in the distribution and character of the sediment infill and is a subject that has been debated in the literature over the years. It is thought to have occurred anywhere from the Late Permian to the Present (Bachman, 1974; Bachman and Johnson, 1973; Hiss, 1975; Hovorka, 1998; Johnson, 1993). In one scenario, Bachman (1974) using information gathered in New Mexico suggested three significant periods of dissolution: post Triassic and pre-middle Pleistocene, middle Pleistocene, and late Pleistocene. Events during these periods most likely influenced the accumulation of Pecos Valley Alluvium sediments.

Several wells in Reeves County encountered significant thicknesses of eroded volcanic material, ash, and bentonitic clay in basal Pecos Valley Alluvium sediments, the deepest units being present almost more than 1,400 feet below ground surface. The eroded volcanic detritus were identified in wells located more than 25 miles from the nearest igneous outcrop. Volcanism in Trans-Pecos Texas occurred from Eocene through the Miocene (Ewing, 1991). The deposition of these volcanic-rich sediments occurred after the erosion and removal of Cretaceous units and was related to and occurred during the initial subsidence of the Pecos Trough.

Previous authors have grouped aquifers in the study area using the following hydrostratigraphic terminology: Pecos Aquifer (Pecos Valley Aquifer overlying the hydraulically connected

Cretaceous formations in Pecos County; Richey and others, 1985); Allurosa Aquifer (Pecos Valley Aquifer overlying the hydraulically connected Dockum Group Santa Rosa Sandstone; Richey and others, 1985; White, 1971); and Toyah Aquifer (Pecos Valley Aquifer overlying the hydraulically connected Cretaceous formations in Reeves County; LaFave, 1987). While these terms are not used in our report, we mention them to illustrate the complexity of mapping the aquifers in the study area.

Cretaceous Undivided, top and bottom

The unit mapped as Cretaceous Undivided consists of Cretaceous sediments deposited unconformably on the Triassic Dockum Group or the Permian Dewey Lake Formation (Table 6-1). The sediments consist of clay, sand, and limestone deposited in continental to marine depositional settings at the onset of the marine transgression in West Texas. The undifferentiated Cretaceous Undivided unit constitutes the hydrostratigraphic unit for the Edwards-Trinity (Plateau) Aquifer, classified as a major aquifer in Texas (Ashworth and Hopkins, 1995; George and others, 2011).

The stratigraphic top of the Cretaceous Undivided is marked by a sharp lithologic change from limestone to siltstone of the overlying Pecos Valley Alluvium. This boundary is clearly represented on water well reports and on geophysical well logs by a distinct low gamma ray profile. Many geophysical well logs obtained from the Texas Commission on Environmental Quality's Surface Casing collection are already annotated with Cretaceous top and bottom picks. This served as an invaluable resource for our study. Where the limestone is missing due to erosion, the contact between Pecos Valley Alluvium and Cretaceous Undivided is not as readily apparent and may be misinterpreted altogether. The TWDB has mapped the Edwards-Trinity (Plateau) Aquifer as a contiguous unit including outcropping Cretaceous sediments in eastern Reeves County. Our mapping indicates that the outcrop in eastern Reeves County may be an isolated erosional remnant, separated from mapped Cretaceous sediments to the south by a southeastern extension of the Pecos Trough.

The stratigraphic bottom of the Cretaceous Undivided unit is marked by significant change in the sediments as seen on geophysical well logs. This pick is subject to misinterpretation along the northwestern limits of the Cretaceous sediments in Reeves County, where the nature of the Cretaceous sediments also changes with the appearance of the Cox Sandstone.

We used 188 wells to interpret the top of the unit and 177 wells for the base (Table 6-2). These were used to develop the 3-D top and bottom surfaces in GIS.

Dockum Group-Dewey Lake Formation, top and bottom

The Dockum Group consists of Upper Triassic sediments deposited unconformably on the Upper Permian Dewey Lake Formation. The unconformity represents approximately 25 million years (Lucas and Anderson, 1993). The Dockum Group represents the filling of the Dockum basin, which received sediments (eroded Paleozoic rocks) from all directions (McGowen and others, 1979). The sediments consist of alternating shale, siltstone, sandstone, and gravel that were deposited in a variety of fluvial, lacustrine, and deltaic environments (Bradley and Kalaswad, 2003).

The Dockum Group constitutes the hydrostratigraphic unit for the Dockum Aquifer which is classified as a minor aquifer in Texas (Ashworth and Hopkins, 1995; George and others, 2011). In the study area, the terms Santa Rosa and Allurosa aquifers have been applied to the Santa

Rosa Sandstone of the Dockum Group and to the Santa Rosa Sandstone plus Pecos Alluvium by previous authors (Richey and others, 1985; White, 1971).

Individual formations within the Dockum Group were not mapped in this project. The lithology was recorded from numerous water well reports and geophysical well logs; sandstone within the lower Dockum Group has been referred to as the Santa Rosa Sandstone or the Camp Springs member, the principal water-bearing unit of the aquifer.

The Dewey Lake Formation consists of Upper Permian continental sediments deposited on the Permian Rustler Formation. The sediments consist of alternating shale, siltstone, and red sandstone (BEG, 1976b) that are believed to have originated from areas to the north, west, and south of the Delaware Basin (Jones and others, 2011). The Dewey Lake Formation, equivalent to the Quartermaster Formation in the Texas Panhandle (Lucas and Anderson, 1993), is not considered an aquifer in the Trans-Pecos region.

The stratigraphic top of the Dockum Group was mapped across the study area where it is unconformably overlain in places by Cretaceous sediments or by the Pecos Valley Alluvium (Figure 6-1; Table 6-1). The Dockum Group is exposed at ground surface in several areas within the study area.

The contact between the Dockum Group and underlying Dewey Lake Formation was not mapped in the study. This unconformity is indistinct on both water well reports and geophysical well logs, and often confusing in outcrop exposures. Some previous authors have attempted to map this contact in the subsurface (for example, Garza and Wesselman, 1959), but we could not replicate their interpretation in the study area using geophysical well logs. McGowen and others (1979, Figure 33 on p. 37) indicated that the contact was clearly distinguished on geophysical well logs within the Midland Basin to the east of the study area and in only a small portion of northeastern Winkler and part of Ward counties. Lucas and Anderson (1993) provide a detailed discussion of this contact including the ages of the formations.

We mapped the stratigraphic top of the Dewey Lake Formation in Reeves County, west of the western extent of the Dockum Group, and the bottom across the entire study area. The bottom of the formation rests on the stratigraphic top of the underlying Rustler Formation.

The western extent of the Dockum Group is represented by the western limit of Region 1 in Figure 6-1. The western limit is problematic, in part because the contact between the Dockum Group and Dewey Lake Formation cannot be clearly delineated. The Pecos geologic atlas map (BEG, 1976b) shows Dockum Group sediments in the northwestern corner of Loving County with exposed Dewey Lake sediments immediately to the west. It is possible that these Dockum Group outcrops are erosional remnants or, as Lucas and Anderson (1993) suggest, Dewey Lake sediments, or even Cenozoic alluvium. We chose to include this area as the western limit for the Dockum Group and extended this line to the southeast along the eastern margin of the Pecos Trough.

We analyzed more than 1,300 wells to define the formations and to build the 3-D top and bottom surfaces in GIS (Table 6-2).

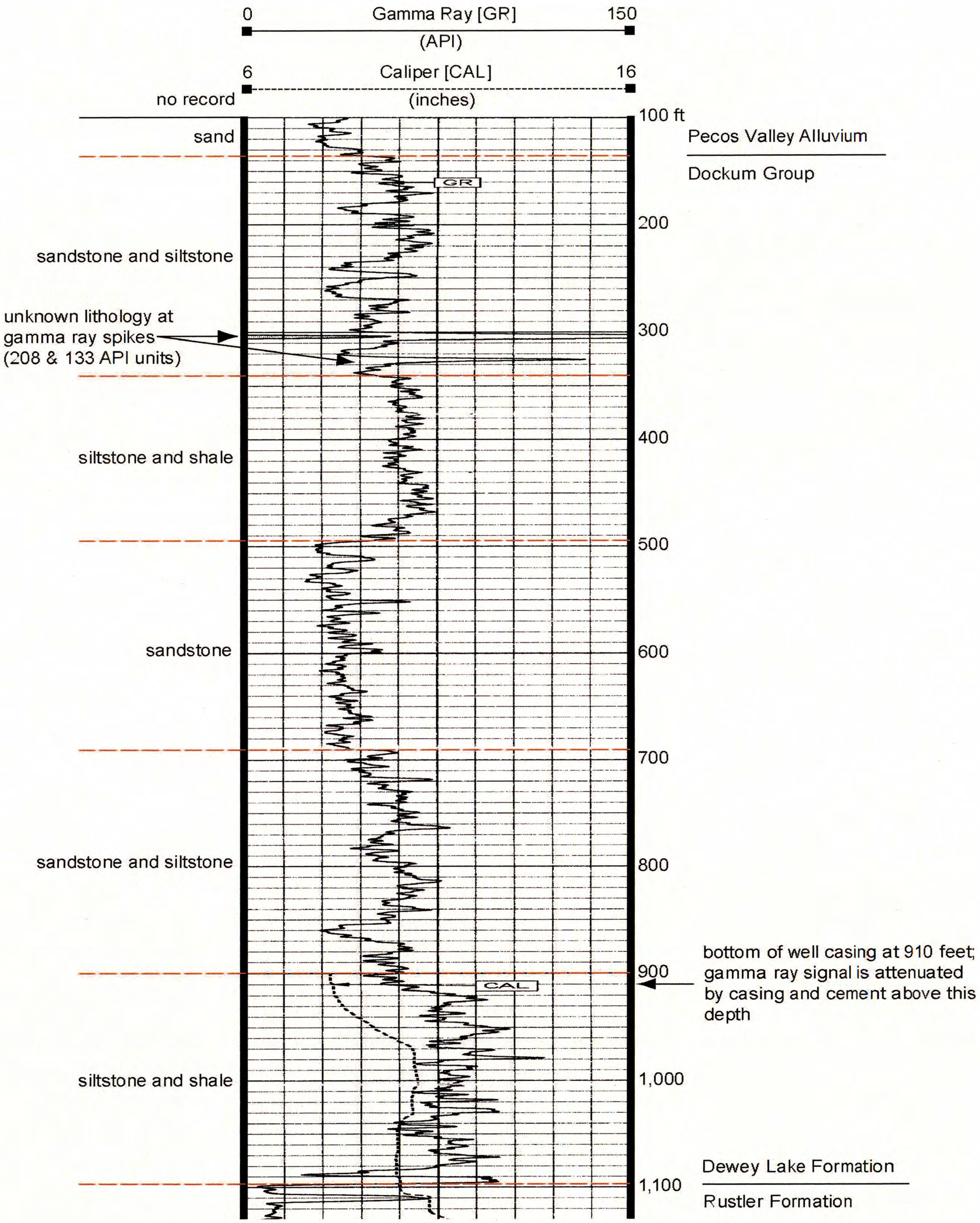


Figure 6-3. BRACS Well 1258 showing stratigraphic picks for the Pecos Valley Alluvium, Dockum Group, and Dewey Lake Formation and simplified lithologic units interpreted from the gamma ray log.

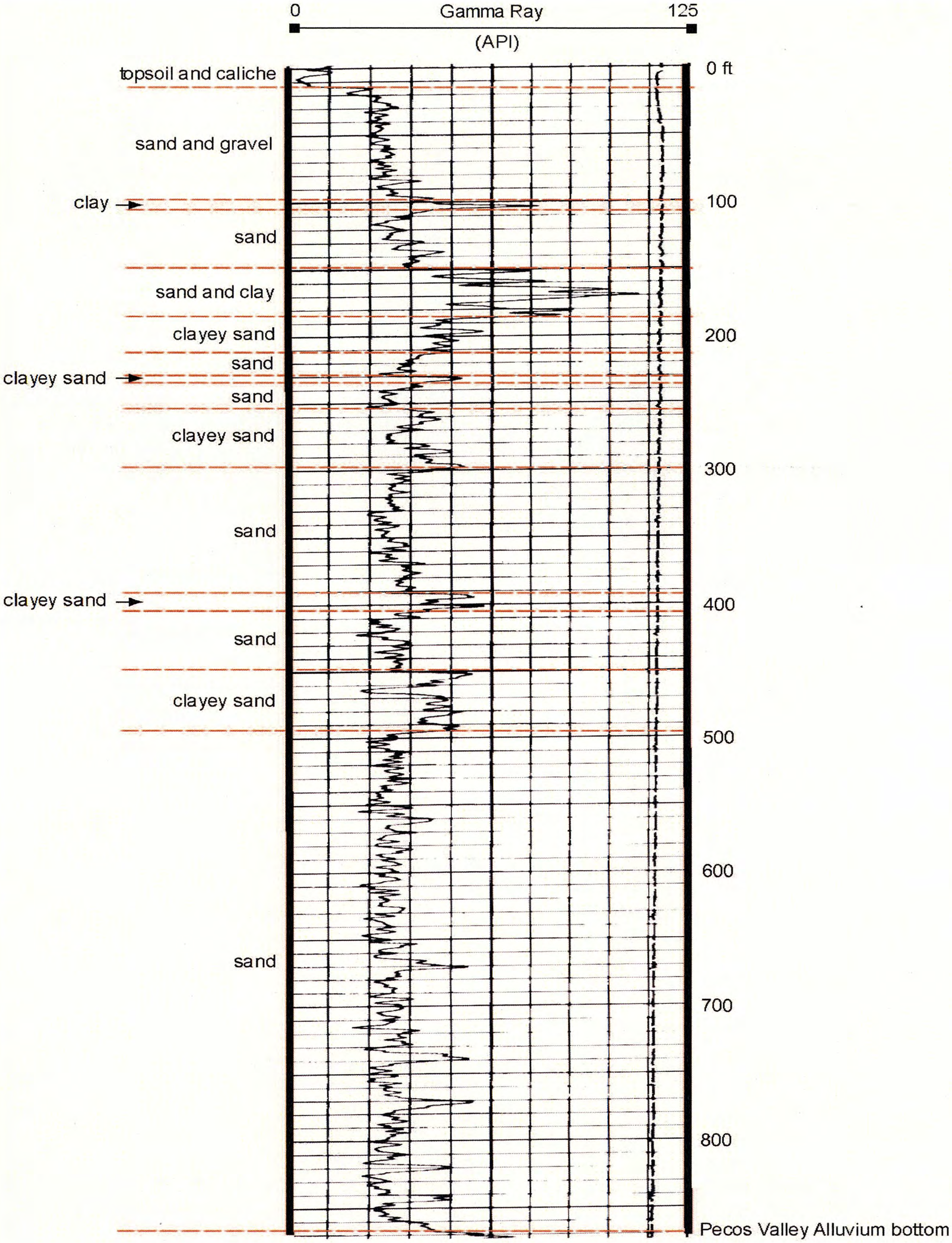


Figure 6-4. **BRACS Well 2079 showing simplified lithologic units and the Pecos Valley Alluvium bottom stratigraphic pick.**

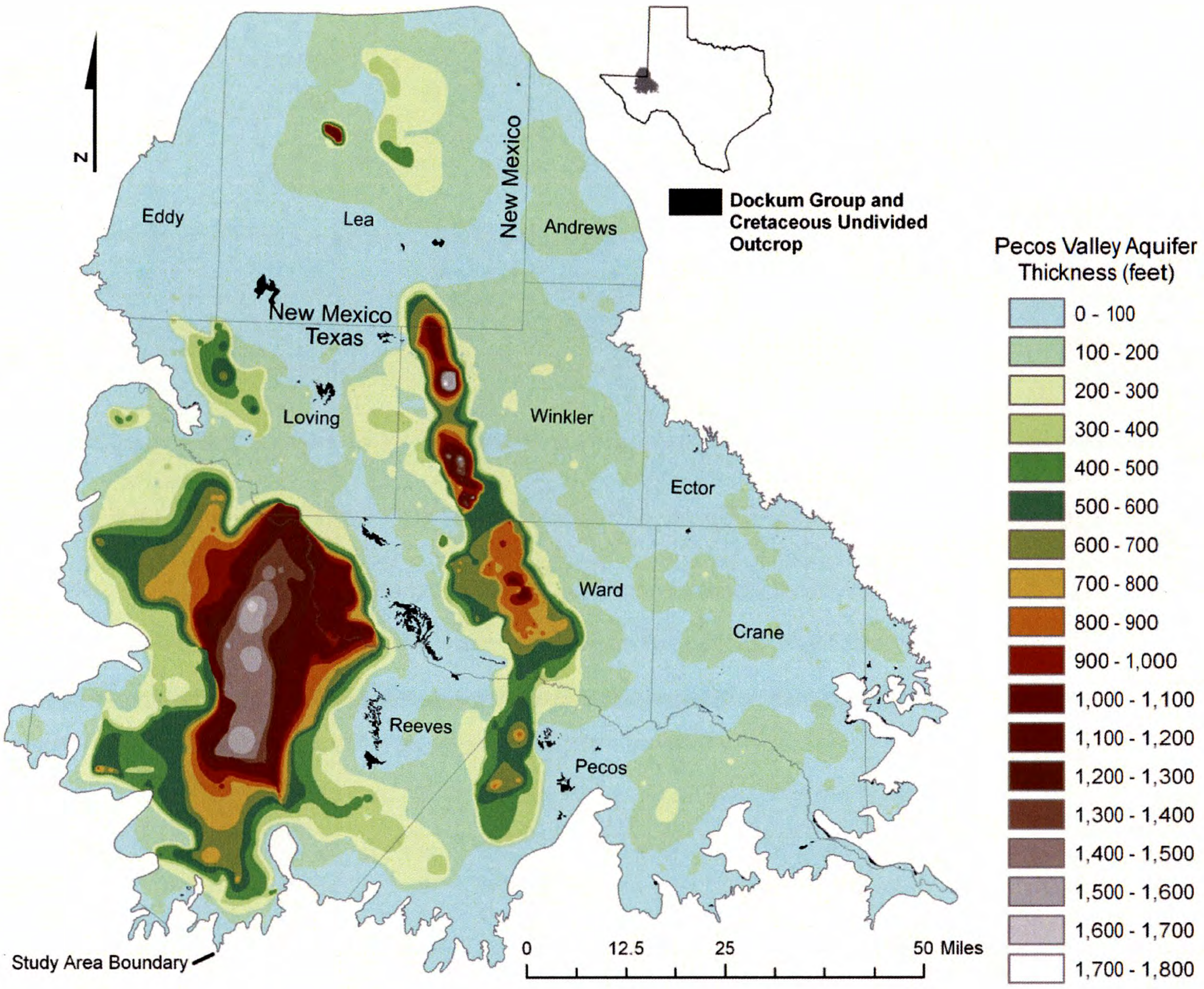


Figure 6-5. **Thickness of the Pecos Valley Aquifer. Well control included 2,057 sites in Texas and New Mexico.**

Rustler Formation, top

The Rustler Formation consists of Upper Permian sediments deposited unconformably on the Permian Salado Formation. The sediments consist of shale, silt, sandstone, dolomite, and the evaporites, halite and gypsum (anhydrite at depth). The Rustler Formation constitutes the hydrostratigraphic unit for the Rustler Aquifer, although the areal extent of the formation is much larger than the mapped limits of the aquifer. The Rustler Aquifer is considered a minor aquifer in Texas with the subsurface boundary defined on the basis of a total dissolved solids content of 5,000 milligrams per liter (Ashworth and Hopkins, 1995; George and others, 2011).

Only the top of the formation was mapped for this study because the surface is critical in understanding the location, extent, and magnitude of solution collapse into the underlying Salado Formation. This is the only formation in the study area that can be used as a regional marker (Maley and Huffington, 1953). It also provided the needed control for correlating the 3-D extent of the overlying Pecos Valley Alluvium. We did not map below the top surface of the formation, because this work is being completed as part of a groundwater flow model for the Rustler Aquifer (Jones and others, 2011).

The stratigraphic top of the Rustler Formation is easily recognized on geophysical well logs across and beyond the entire study area with the following exceptions. In southern Pecos County, the Rustler Formation is equivalent to the Tessey Limestone (Jones and others, 2011); the contact in this region is difficult to interpret because of local structures and lithologic changes. In southwestern Loving County, northwestern Reeves County, and in other localized areas, the top of the Rustler Formation is difficult to interpret because of possible evaporite dissolution and possible chaotic mixing of strata resulting from solution collapse.

The typical geophysical well log response for the Rustler Formation in New Mexico was described by Snyder (1985) and in Ward County by White (1971). We compared our top of Rustler stratigraphic picks with those of Hiss (1976) and traded datasets with Jones and others (2011) to ensure that our interpretations were consistent. Additionally, many digital geophysical well logs that we used in the project were already annotated with picks for the top of the Rustler Formation.

We used 1,350 wells to define the top of the Rustler surface in the study area, while many more were correlated outside of the study area to help build the 3-D top surface in GIS (Table 6-2).

6.1.2 Lithologic descriptions

The descriptions of rocks recorded by water well drillers on well reports were appended to the well geology table in the BRACS Database either manually or by digital parsing techniques if a digital well report was available from the Texas Department of Licensing and Regulation. The database table includes the top and bottom depths, thickness of each unique lithologic unit, a description of the lithologic unit as presented by the driller, and the source of information. Although it would be beneficial to parse the lithologic description into additional fields such as color, texture, rock type, relative hardness, fossils, and presence of water, we chose to keep the entire lithologic description in one database field. While this limited our ability to process the information into net sand maps and display more detailed lithologies on geological cross-sections, it allowed us to enter data faster.

Because well drillers frequently use non-geological terms (for example, gumbo), misapply terms (for example, talc in an alluvial deposit), and almost never describe the formations in a uniform and systematic manner, we developed a process to convert the drillers' descriptions of rocks into a simplified lithologic description. Our description consists of a short list of terms based on mineralogy and grain size. Simplifying drillers' descriptions of lithologies is not new and has been used by others (for example, Seni, 1980; Young and others, 2010).

A database lookup table relating the described lithologic name to the simplified lithologic description was prepared to accommodate the numerous variations present on well reports. Presently, the database lookup table contains more than 4,300 records and 89 simplified lithologic names.

The simplified lithologic names represent either one predominant type of material (for example, sand), or a mixture of two (for example, sand and gravel). Each term representing a mixture assumes that each component of the mixture approximates a 50-50 mix. The creation of the database table relating lithologic name to simplified lithologic name both presented challenges and necessitated some simplifications. Formation descriptions that contained more than two terms as part of a mixture (for example, sand, clay, and limestone) were converted to only the first two terms or the two most important terms based on percentage (if provided by the driller). Formation descriptions that included percentages of material within the 35–65 percent range were categorized as 50-50 mixtures. Formation descriptions that included non-geological terms (for example, cut hard) were listed as unknown. Units that were listed as lost circulation, hole-deepened, or variations thereof were listed as no record.

We interpreted 470 digital gamma ray logs for simplified lithologic description. This represents about 36 percent of the 1,300 geophysical well logs in the study area that contain a gamma ray tool. Many logs could not be used because the logged interval was too deep, attenuation of the gamma ray log was unacceptable, or well density in the area was so high that interpreting all logs proved impractical. The simplified lithologic description was only applied from ground surface to the top of the Rustler Formation. Simplified lithologic names, top and bottom depths, and source of information were entered into the BRACS Database using a custom data entry form.

Within clastic sequences, a low gamma ray response was interpreted as sand and a sand line established on the log. A high gamma ray response was interpreted as clay or shale and a shale line established on the log. An intermediate response was interpreted as a mixture of sand and clay. Two exceptions were the presence of very low gamma ray response near the ground surface that was interpreted as caliche and extremely high gamma ray response in very thin beds that was attributed to naturally occurring uranium or thorium minerals (Figure 6-3). There were 46 wells that showed lithologic units with an elevated gamma ray response: 22 in the Pecos Valley Alluvium, 32 in the Dockum Group-Dewey Lake Formation, and one in the Cretaceous Undivided. Caliche and high gamma ray kicks were recorded in the simplified lithology description field, with the latter indicating "unknown" and a lithologic description indicating the highest American Petroleum Institute unit reading. The gamma ray response does not indicate grain size within shale-free sands and gravels. When the simplified lithologic description for a record in the geology table shows a grain size other than sand or clay, it is based on adjacent water well lithologic descriptions.

The gamma ray response was evaluated after reviewing lithologic descriptions on nearby water well logs. The boundaries of the geologic units were generally interpreted as the mid-point between high and low gamma ray response. As recommended by Collier (1993a, 1993b), units thicker than 20 feet were recorded as separate lithologic units. Thick sequences of interbedded sand and clay, where the relative thickness of each unit was approximately the same, were recorded as 50-50 mixtures: for example, sand and clay. The transition from basal Pecos Valley Alluvium to Dockum Group-Dewey Lake Formation required a change in lithologic terminology from unlithified to lithified forms (for example, sand to sandstone). Dockum and Dewey Lake red beds were generally interpreted as siltstones unless very low gamma ray response indicated sandstone or high gamma ray response indicated shale (Figures 6-3 and 6-4).

Figures 6-3 and 6-4 provide examples of gamma ray log interpretation using simplified lithologic descriptions for classifying the geologic units.

6.1.3 Net sand and sand percent maps

Net sand and sand percent values for wells penetrating the Pecos Valley Alluvium and the Dockum Group sediments were generated from the simplified lithologic description. If a well only partially penetrated a formation, a net sand value was calculated, but not the sand percent.

The sand percent values for the Dockum Group-Dewey Lake Formation would likely have been lower had we been able to map the base of the Dockum Group.

The top and bottom depths of formations encountered at each well site in the study area were determined using GIS analysis. This technique is described in Section 6.2 (Aquifer determination analysis).

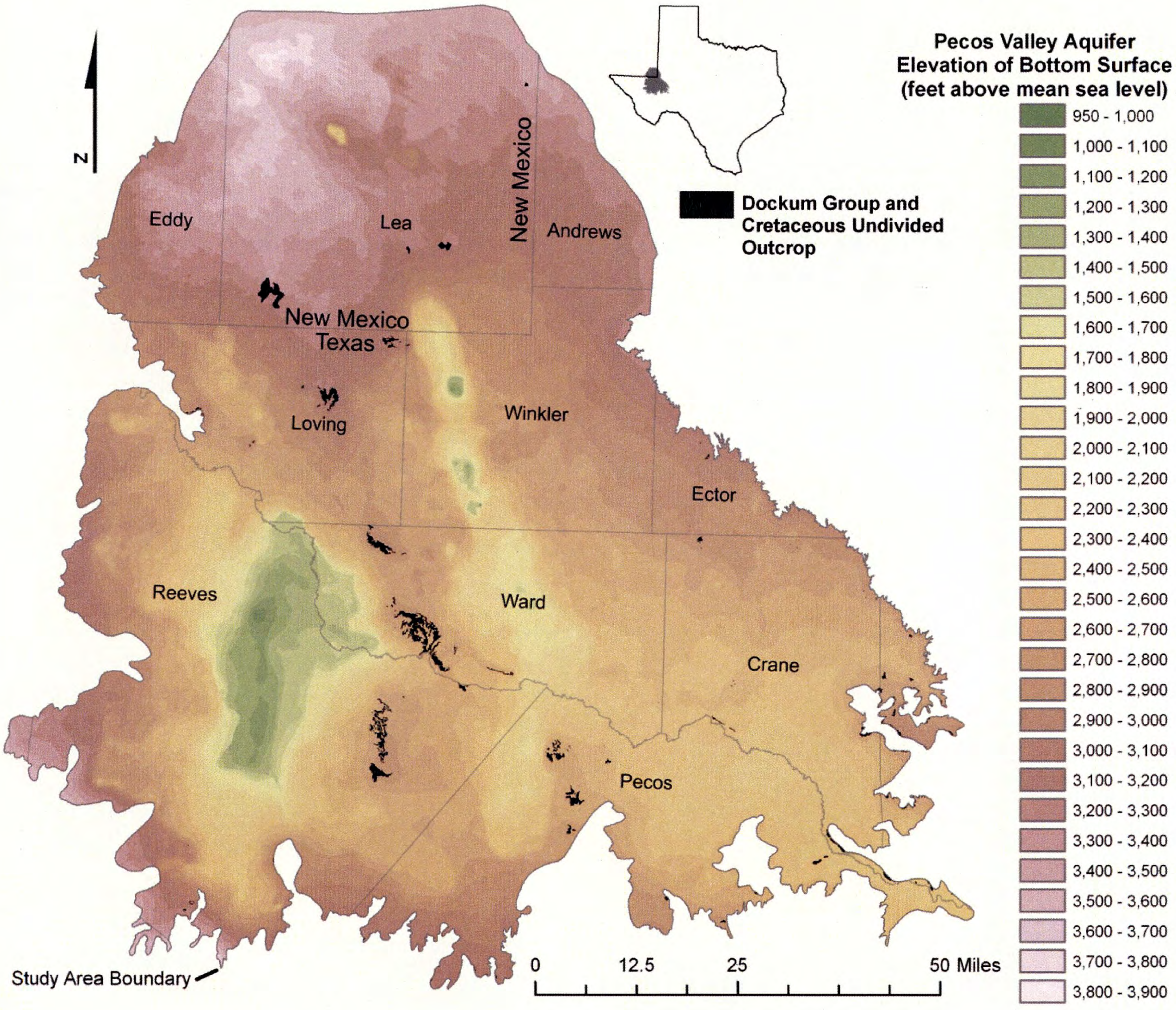


Figure 6-6. **Elevation of the bottom surface of the Pecos Valley Aquifer.**

The table listing all simplified lithologic names contains a field for sand percent. Values of 0, 50, or 100 were chosen based on the presence of sand or coarser material. For example, a value of 50 would be applied to a lithologic unit containing a mixture of sand and clay. This table is used in subsequent database queries to process well records.

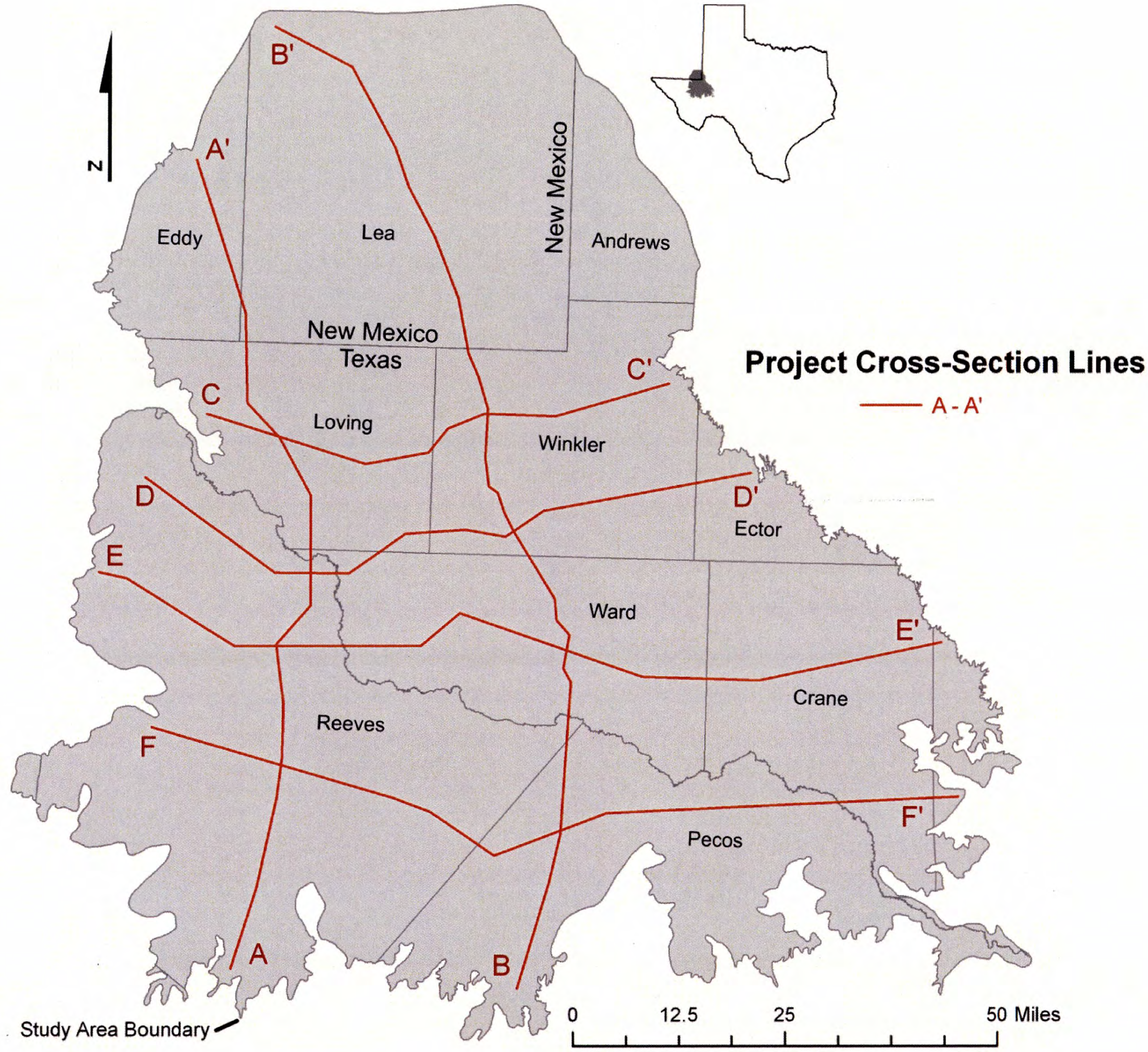


Figure 6-7. **Locations of geologic cross-section lines.**

Because database queries must address lithologic units that are not completely contained within one formation (the unit may straddle the formation top, bottom, or both), we wrote specific queries to evaluate each of these scenarios and to assign the correct thickness of a lithologic unit to the correct formation. We performed more than 40 separate queries to create a final dataset for both the Pecos Valley Alluvium and Dockum Group sediments. We loaded these queries into Microsoft® Visual Basic® for Applications and linked them to a form to systematically process the information. We performed a separate query to assemble the information into a table for export into GIS for spatial display.

6.1.4 Structural geometry

The structural geometries of the hydrostratigraphic units in the study are presented next.

Pecos Valley Aquifer hydrostratigraphic unit structural top and bottom

A significant thickness (up to 1,800 feet) of saturated Pecos Valley Aquifer is present in the solution troughs (Figure 6-5). Areas outside the troughs generally contain less than 200 feet of alluvial material, thinning to zero where Triassic Dockum Group or Cretaceous strata are exposed at the ground surface. The Pecos Trough is a broad area of significant sediment accumulation that lies directly on the unconformity above the Dewey Lake or Rustler formations. The northeastern extent of the Pecos Trough terminates abruptly against a ridge of Permian Salado and Castile evaporites that are capped by Dockum Group strata. This faulted margin of the basin juxtaposes Pecos Valley Alluvium against Permian evaporites draped with relatively thin, fractured Dewey Lake and Dockum Group red beds (Figures 6-8 and 6-11).

The Monument Draw Trough consists of a linear system of narrow, elongate, and deep collapse features where the basal part of the Pecos Valley Alluvium is isolated from adjacent alluvial-filled collapse features. The trough broadens in central Ward County and becomes narrow in northwestern Pecos County (Figure 6-14). There is no groundwater flow between the Monument Draw and Pecos troughs mainly because of the intervening structural ridge in Loving and eastern Reeves counties (Figure 6-11). The two troughs act like separate groundwater systems (Ashworth, 1990).

A distribution of water wells showing percent penetration into the Pecos Valley Aquifer is shown in Figure 6-15. The Monument Draw Trough in Winkler and south-central Ward counties has very few water wells that penetrate the full thickness of the aquifer. The Pecos Trough in northern Reeves and northwestern Loving counties is similarly underrepresented by water wells. The implication is that there is not enough lithologic and water chemistry data in the thicker sections of the Pecos Valley Alluvium to map water quality. Information about the geological formations was based solely on interpretations of gamma ray geophysical well logs.

The complex nature of solution trough development in the Pecos and Monument Draw troughs has led to complex sediment infill patterns and differences in the nature of the sediments in the two troughs. In the Monument Draw Trough, basal Pecos Valley sediments typically consist of eroded red Dockum Group sediments or solution collapse material from the Dockum Group. The base of the formation is often difficult, if not impossible, to determine. As the solution troughs deepened and alluvial material started to accumulate, a distinct package of sediments consisting primarily of sand began to form in the depressions. The sediment packages—a few hundred feet thick—are recognizable in wells located in the same general geographic area, suggesting that they are not laterally continuous over large distances. Furthermore, the sediment packages are not always present at the same depth, suggesting that sections of the trough may have collapsed at different rates.

It is also not uncommon to encounter a significant accumulation of clay in some wells. However, correlation of individual lithologic units over large distances is, at best, tenuous. This complex pattern of sediment infill has profound implications for groundwater development because the present-day aquifer exhibits anisotropic properties. In summary, it appears that each "sub-basin" within the Monument Draw trough acts somewhat independently of adjacent sub-basins, and wells within a sub-basin record solution collapse at different rates.

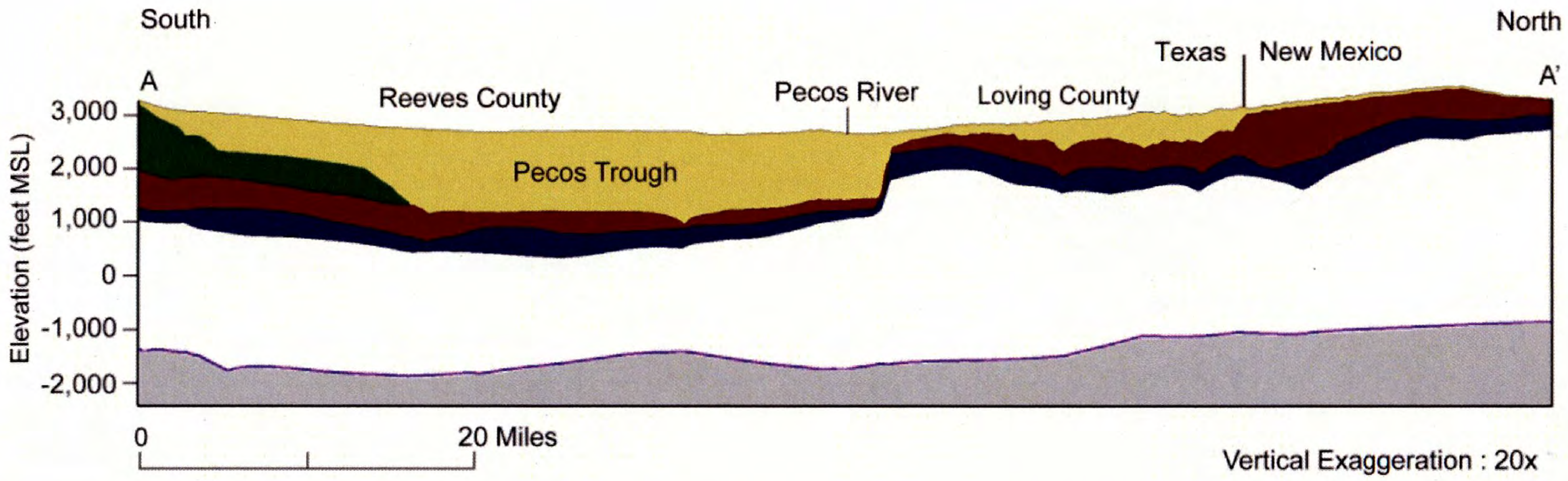


Figure 6-8. The south to north section crosses the Pecos Trough in Reeves County and solution collapse features in Loving County. Refer to Figure 6-7 for cross-section location. The bottom of the Rustler Formation was determined using data from Jones and others (2011).

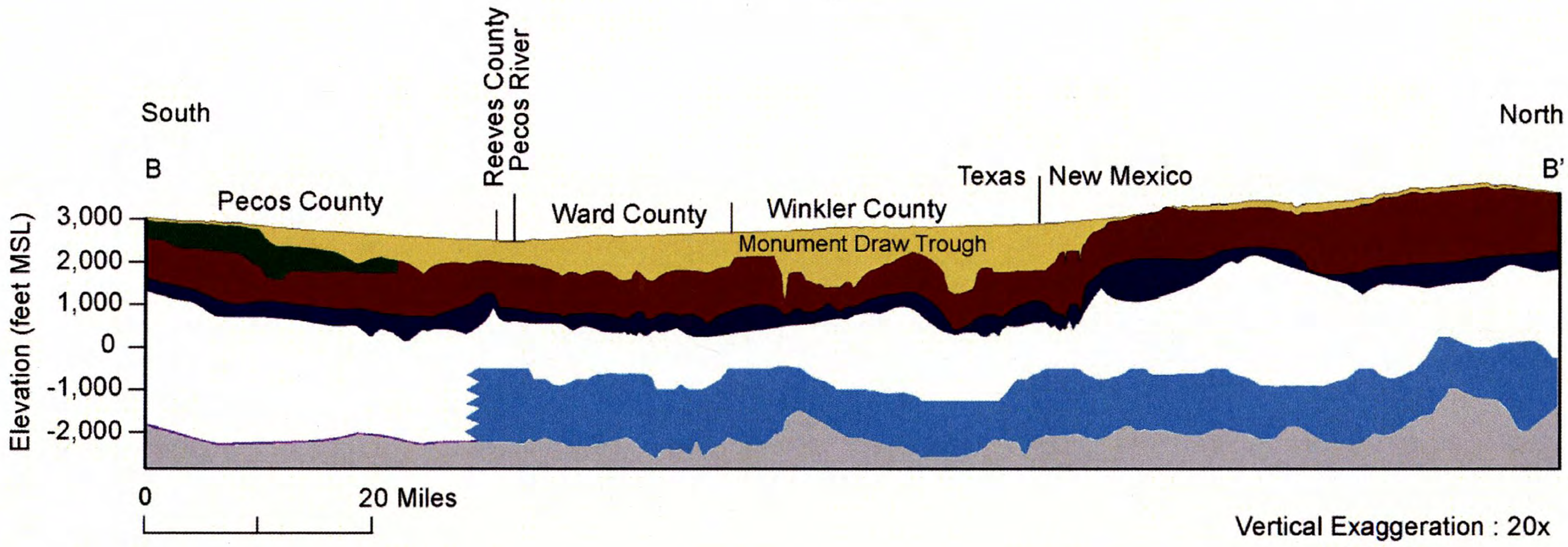


Figure 6-9. The south to north section crosses the Monument Draw Trough. Note the complexity of the bottom Pecos Valley Alluvium. Refer to Figure 6-7 for cross-section location. The bottom of the Rustler Formation was determined by data from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

🟨 Pecos Valley Alluvium
■ Cretaceous Undivided
🟥 Dockum Group and Dewey Lake Formation
■ Rustler Formation

□ Salado and Castile Formations
🟦 Capitan Reef Complex
▨ Pre-Salado beds east of Capitan Reef Complex and Pre-Castile beds west of Capitan Reef Complex

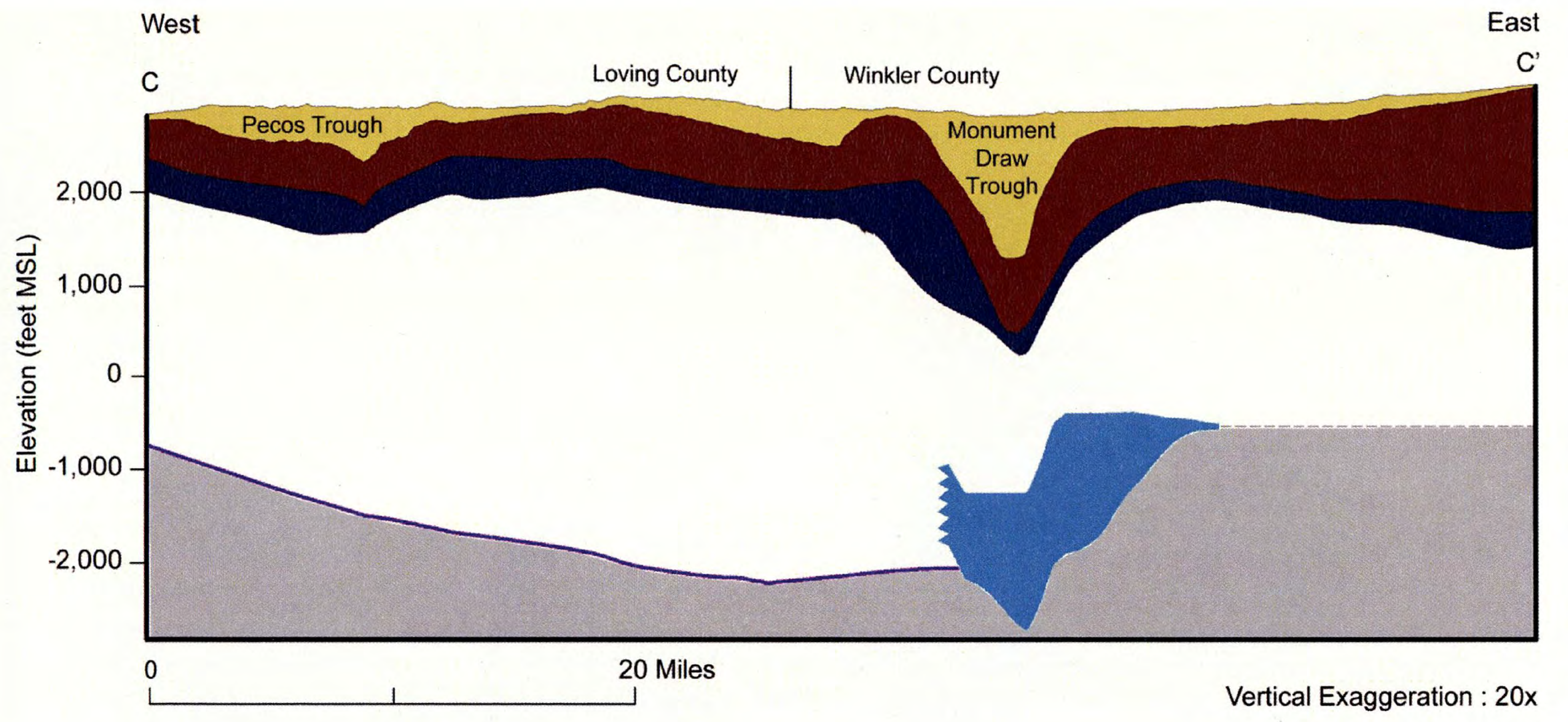


Figure 6-10. The section crosses the solution collapse features in Loving County and the Monument Draw Trough in Winkler County. Refer to Figure 6-7 for cross-section location. The pre-Salado contact east of the Capitan Reef Complex is diagrammatic. The Rustler bottom was calculated from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

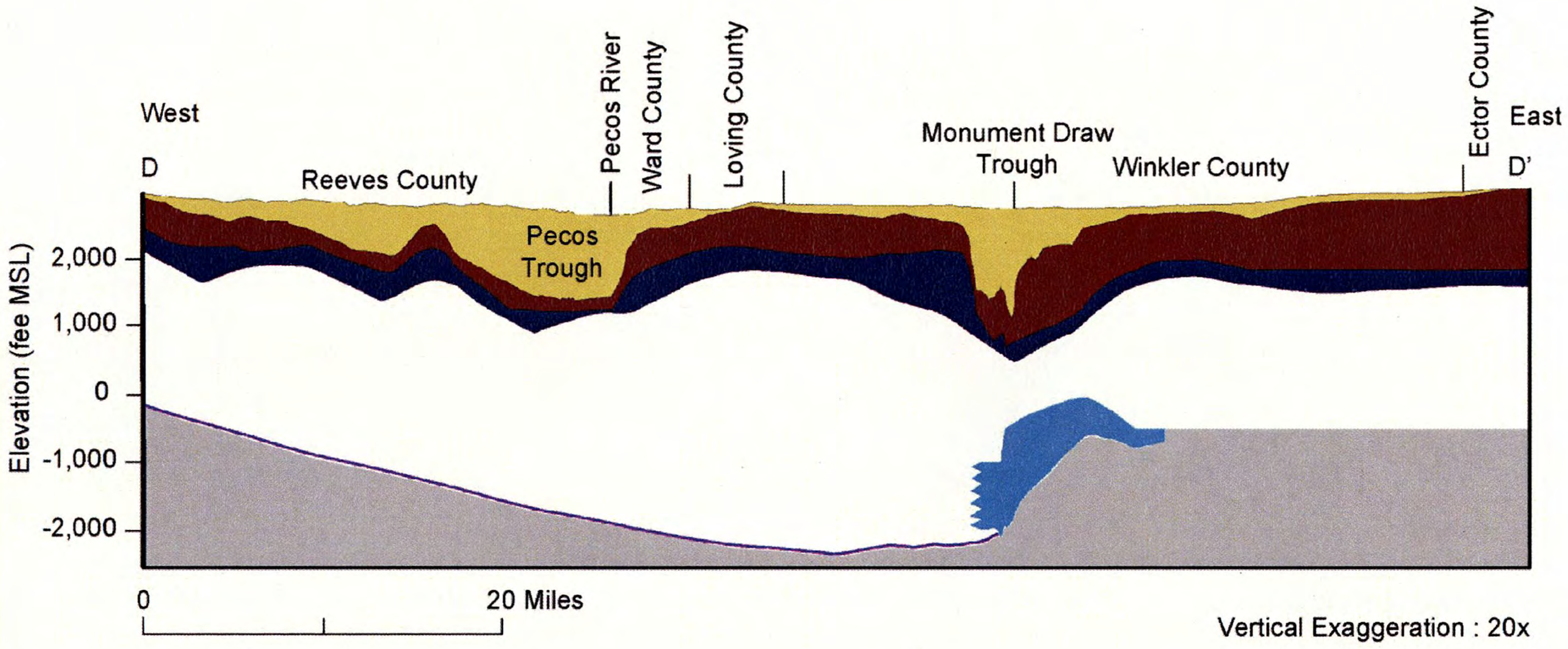


Figure 6-11. The section crosses the Pecos Trough in Reeves County and the Monument Draw Trough in Winkler County. Refer to Figure 6-7 for cross-section location. The pre-Salado contact east of the Capitan Reef Complex, is diagrammatic. The Rustler bottom was calculated from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

🟨 Pecos Valley Alluvium

▨ Cretaceous Undivided

🟫 Dockum Group and Dewey Lake Formation

■ Rustler Formation

☐ Salado and Castile Formations

🟦 Capitan Reef Complex

▨ Pre-Salado beds east of Capitan Reef Complex and Pre-Castile beds west of Capitan Reef Complex

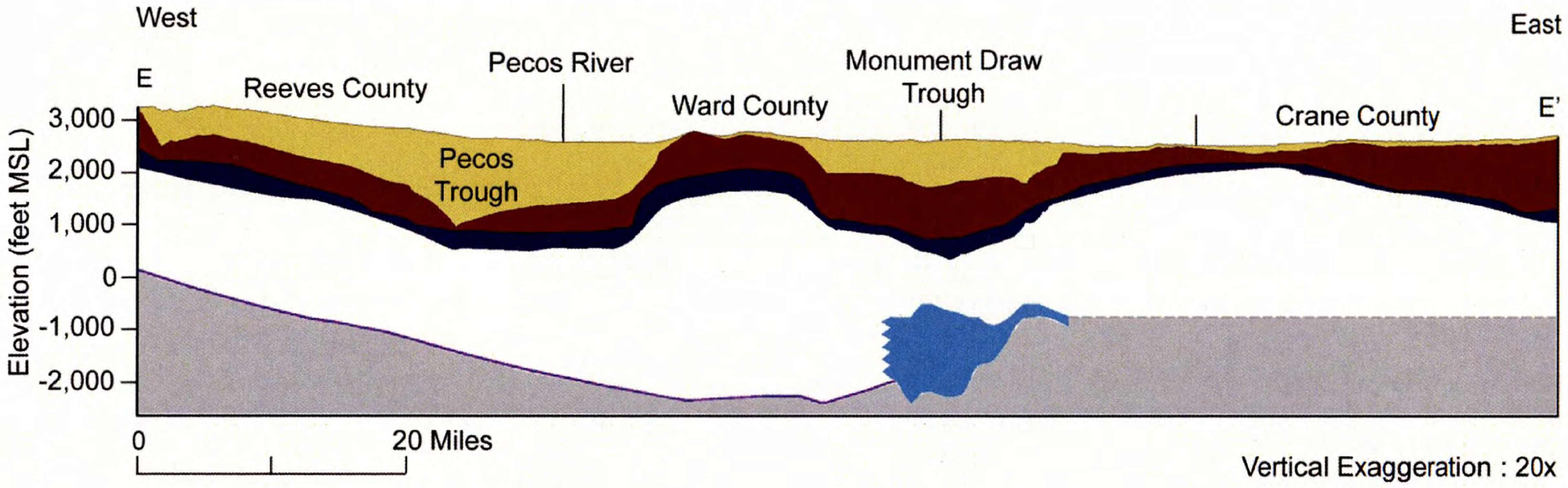


Figure 6-12. The west to east section crosses the Pecos Trough in Reeves County and the Monument Draw Trough in Ward County. Refer to Figure 6-7 for cross-section location. We did not map the pre-Salado contact east of the Capitan Reef Complex, so this boundary is diagrammatic. The bottom of the Rustler Formation was determined by data from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

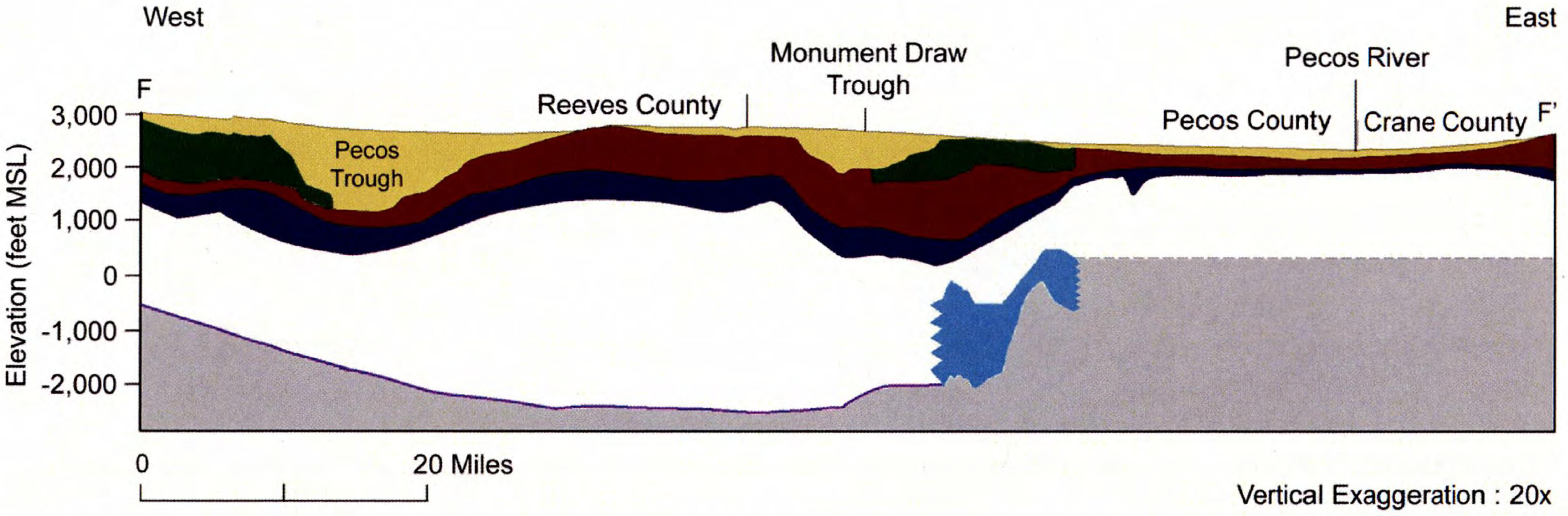


Figure 6-13. The west to east section crosses the Pecos Trough in Reeves County and the Monument Draw Trough in Pecos County. Refer to Figure 6-7 for cross-section location. We did not map the pre-Salado contact east of the Capitan Reef Complex. This boundary is diagrammatic. The bottom of the Rustler Formation was determined by data from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

■	Pecos Valley Alluvium	□	Salado and Castile Formations
■	Cretaceous Undivided	■	Capitan Reef Complex
■	Dockum Group and Dewey Lake Formation	■	Pre-Salado beds east of Capitan Reef Complex and Pre-Castile beds west of Capitan Reef Complex
■	Rustler Formation		

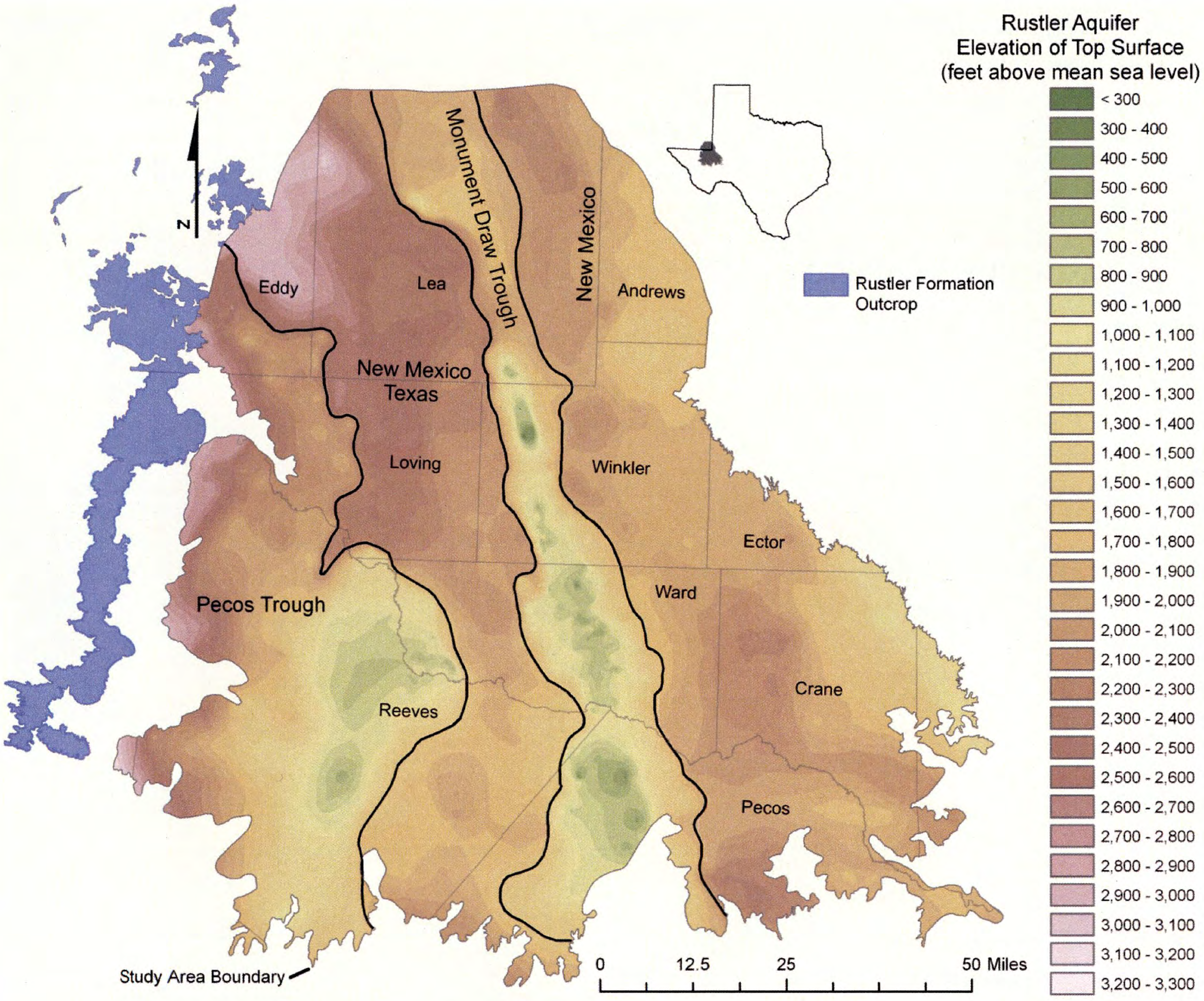


Figure 6-14. **Rustler Formation top elevation surface. Solid black lines show approximate boundaries of the Monument Draw and Pecos Troughs.**

An examination of the thickness and bottom elevation maps of the Pecos Valley Aquifer (Figures 6-5 and 6-6) and geological cross-sections (Figures 6-7 through 6-13) shows significant differences in geometry between the Pecos and Monument Draw troughs, suggesting different mechanisms of solution collapse.

The Pecos Trough in Reeves County records a different pattern of infill than the Monument Draw Trough. The base of the Pecos Valley Alluvium in this trough is much easier to distinguish on both water well and geophysical well logs. The presence of eroded volcanic material in basal Pecos Valley sediments (as described in Section 6.1.1) provides evidence of source rock to the south of the study area. Drillers have reported boulders in many of the boreholes drilled in this region. The Pecos Valley thickness map (Figure 6-5) shows a central north-south trending section of thick sediment with narrower, thicker sediment channels feeding the main trough from all directions. This same pattern is also reflected in the elevation map of the top of the Rustler Formation (Figure 6-14).

Recharge to the Pecos Valley Aquifer occurs through infiltration of rainfall, seepage from ephemeral streams, cross-formational flow, and irrigation return flow (Ashworth, 1990; LaFave, 1987). Recharge was not evaluated for this project, but Jones (2001, 2004, and 2008) and Anaya and Jones (2009) provide an excellent discussion on the topic.

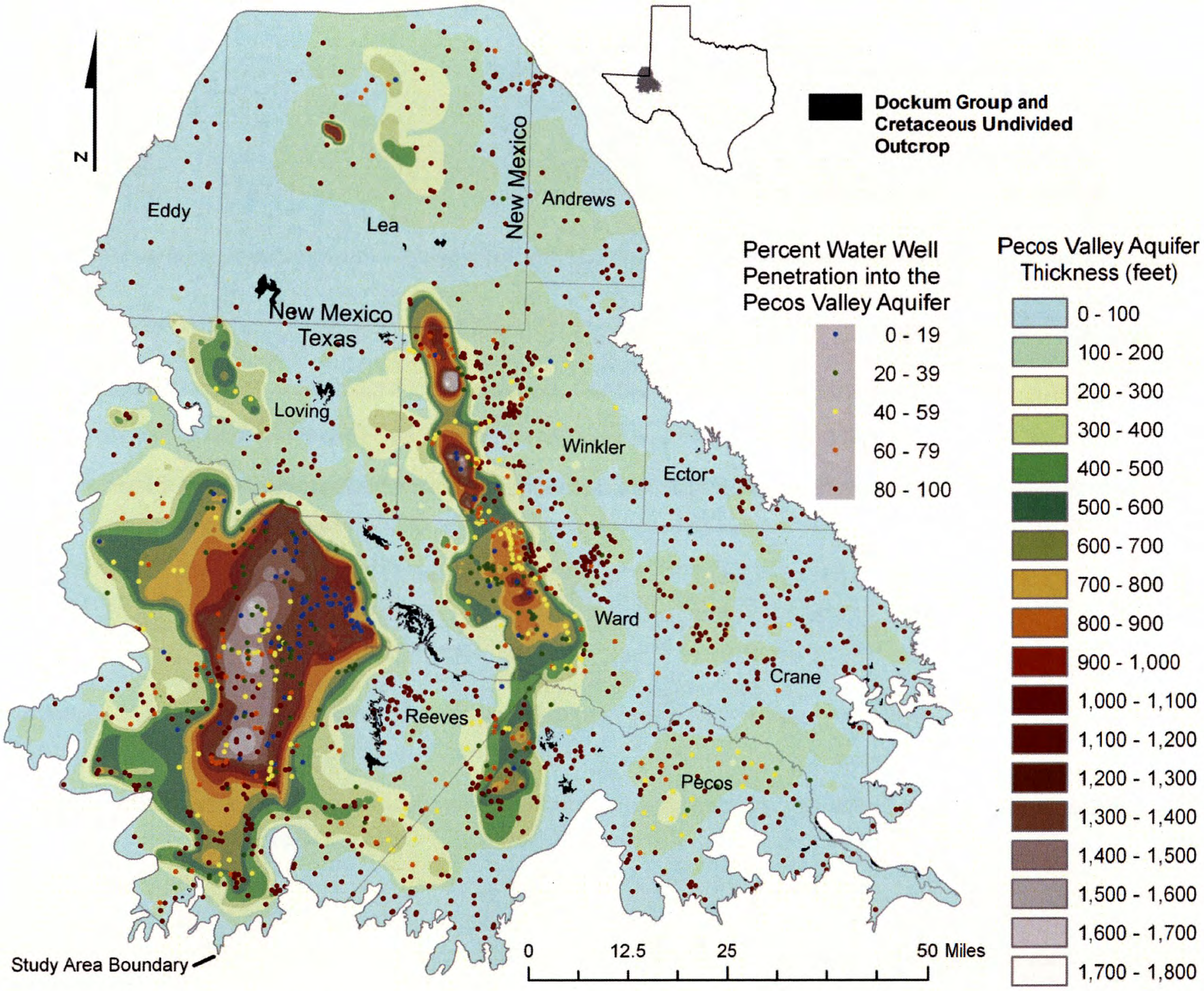


Figure 6-15. **Water wells showing percent of penetration into the Pecos Valley Aquifer. Base map shows Pecos Valley thickness. The water wells in the northern portion of the Pecos Trough in Reeves County penetrate less than half the thickness of the Pecos Valley Aquifer. Deep sections of the Monument Draw Trough in Winkler and Ward counties are also relatively unexplored for water resources.**

Dockum Group-Dewey Lake hydrostratigraphic unit structural top and bottom

Sands within the Dockum Group are an important source of groundwater in parts of the study area. There are many wells installed in the Dockum Aquifer or in both the Pecos Valley and Dockum aquifers. We performed net sand calculations for both of these aquifers (Figures 6-16 and 6-17). The net sand dataset for the Dockum Group is incomplete because many wells penetrate the Dockum Aquifer only partially. Also, there are many more gamma ray logs available in the project collection that could have been used to gain a more complete understanding of the 3-D extent of Dockum Group sands, but we could not use them because of time constraints.

Dockum sands are overlain by fine-grained red beds and shale, especially in the eastern part of the study area where the formation begins to thicken. Figure 6-18 shows well locations where erosion has removed the overlying fine-grained red beds in the upper Dockum Group, allowing sediments of the Pecos Valley Alluvium to be deposited directly on the Dockum sands. In these locations, the two aquifers are interconnected. The Dockum sands are underlain by fine-grained sediments across the entire study area.

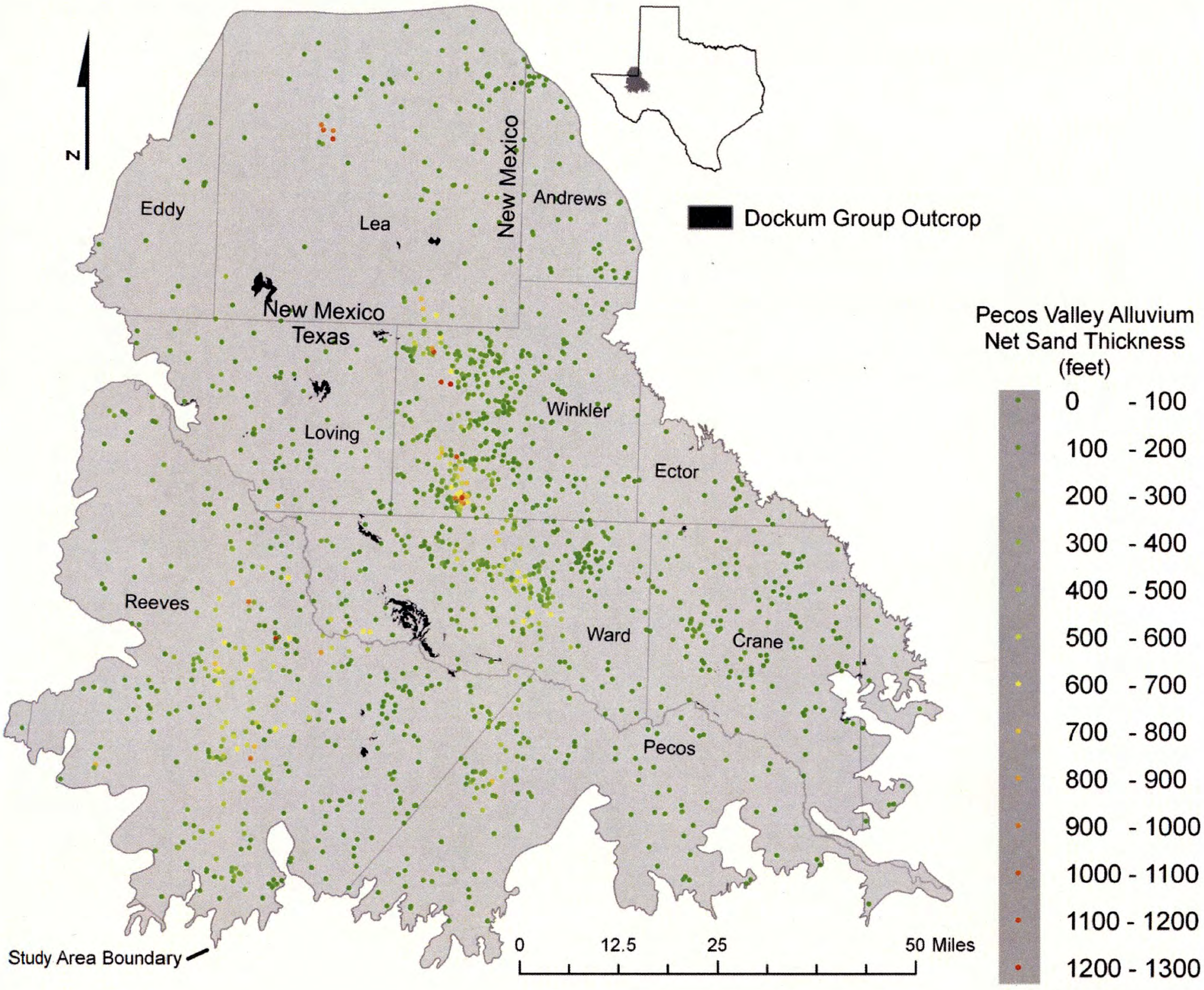


Figure 6-16. Pecos Valley Aquifer net sand map.

Localized fracturing of the Dockum sands allows higher well production such as in the cities of Kermit (Garza and Wesselman, 1959) and Pecos (Richey and others, 1985) well fields. An examination of the top of the Rustler Formation in the City of Pecos well field indicates slight anticlinal/synclinal folding with maximum downwarp in the well field. Similarly, the Rustler Formation in the area around Kermit shows a synclinal structure with maximum downwarp in the well field. Based on this observation, the top surface of the Rustler Formation, in conjunction with Dockum net sand maps, can be used to discern areas favorable to the formation of fractured sands.

Cretaceous Undivided hydrostratigraphic unit structural top and bottom

The Cretaceous Undivided strata in the study area were mapped for the purpose of understanding the relationship with the overlying Pecos Valley Alluvium (Figure 6-19). The Cretaceous units represent a small fraction of the Edwards-Trinity (Plateau) Aquifer in Texas (Anaya and Jones, 2009). The lateral extent of the Cretaceous Undivided sediments in the study area is still problematic.

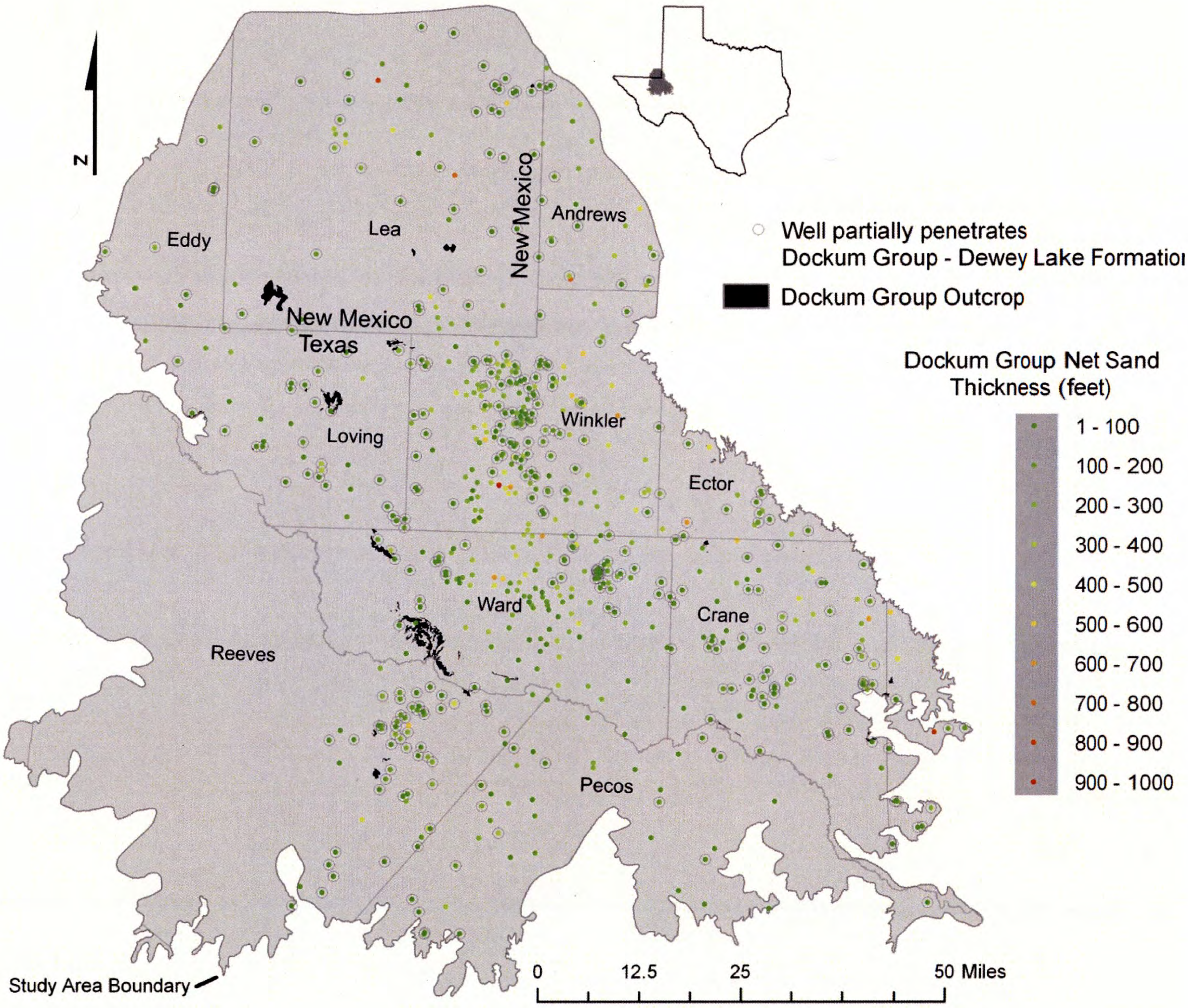


Figure 6-17. **Wells with Dockum Group net sand thickness values. Wells with superimposed open circle symbol indicate well did not fully penetrate the Dockum Group-Dewey Lake Formation interval, so net sand values may be less than total.**

We mapped the Cretaceous Undivided in Reeves County as an escarpment along its northeastern edge based on limited well control data in the area (Figure 6-19). Ogilbee and others (1962a;

Plate 7) have mapped this as a wedge, but we could not confirm the interpretation, because wells in this area do not reach the Cretaceous sediments. Additional work needs to be done to better understand the stratigraphy in the area.

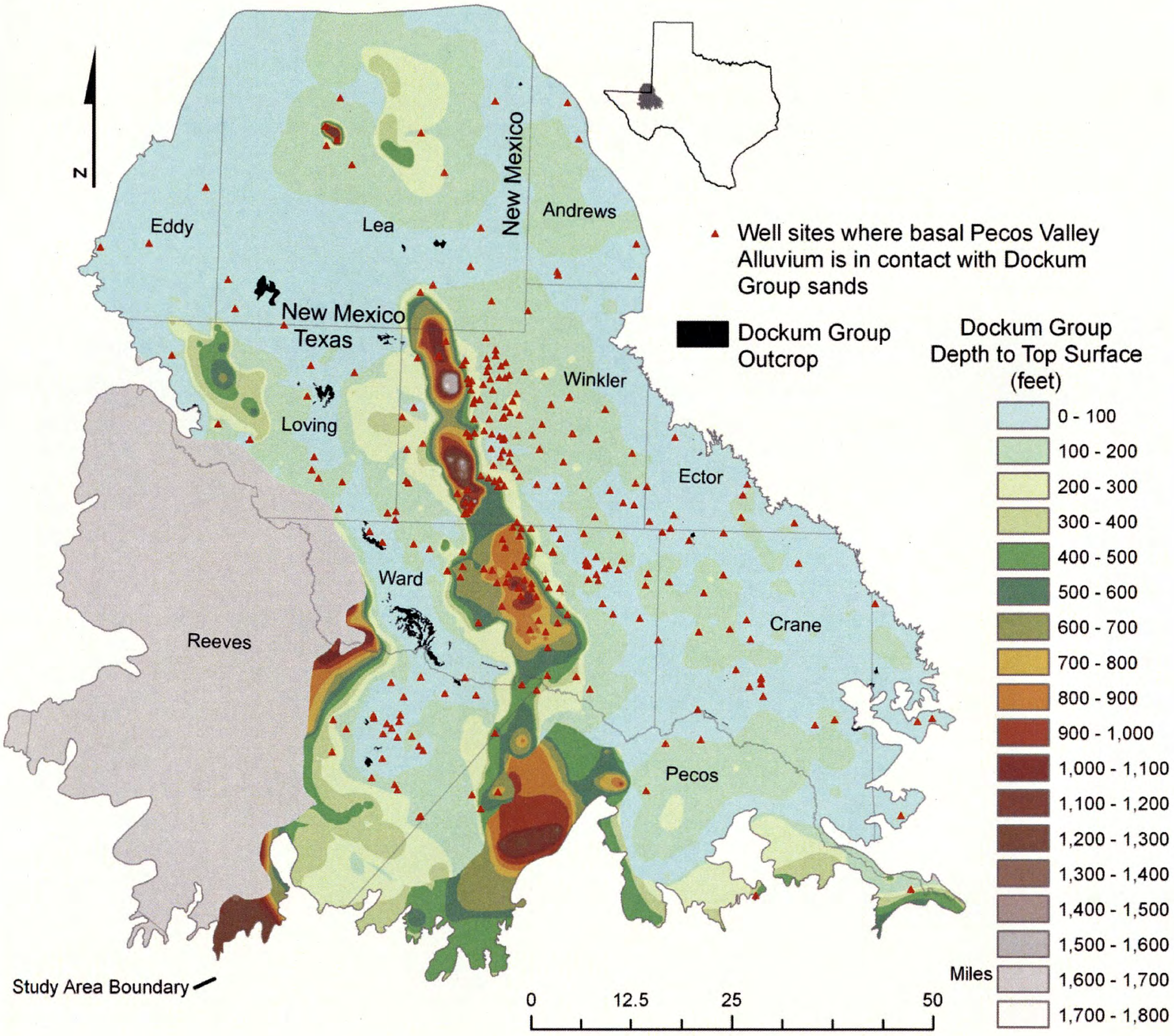


Figure 6-18. **Map showing areas where the basal Pecos Valley Alluvium lies directly over sands in the Dockum Group. The two aquifers are interconnected at these locations. The Dockum Group is missing in the western study area, represented by gray color.**

In the Coyanosa area of northwestern Pecos County, Cretaceous Undivided strata appear to have collapsed into a solution feature (Figures 6-9 and 6-13). The edge of Cretaceous sediments could be bounded by faults in this area, although more work needs to be done to define the relationships.

Cretaceous strata that collapsed into the solution features probably fractured, thereby increasing the transmissivity of the sediments. An examination of the top surface of the Rustler Formation in areas with overlying Cretaceous strata shows areas and magnitudes of collapse (Figure 6-14).

Armstrong and McMillion (1961a) mapped the Pecos Valley and Edwards Trinity (Plateau) aquifers as the Pecos Aquifer in Pecos County. They indicate that the individual formations are hydraulically connected in the county.

Rustler hydrostratigraphic unit structural top

An examination of the top surface of the Rustler Formation (Figure 6-14) reveals several prominent features: an east-sloping surface from the Rustler Formation outcrop in Culberson and Eddy counties eastward into the Pecos Trough; a prominent structurally elevated ridge essentially north-south between the Pecos and Monument Draw troughs; the Monument Draw Trough trending north-northwest; and an eastward sloping surface on the east side of the study area dipping into the Midland Basin.

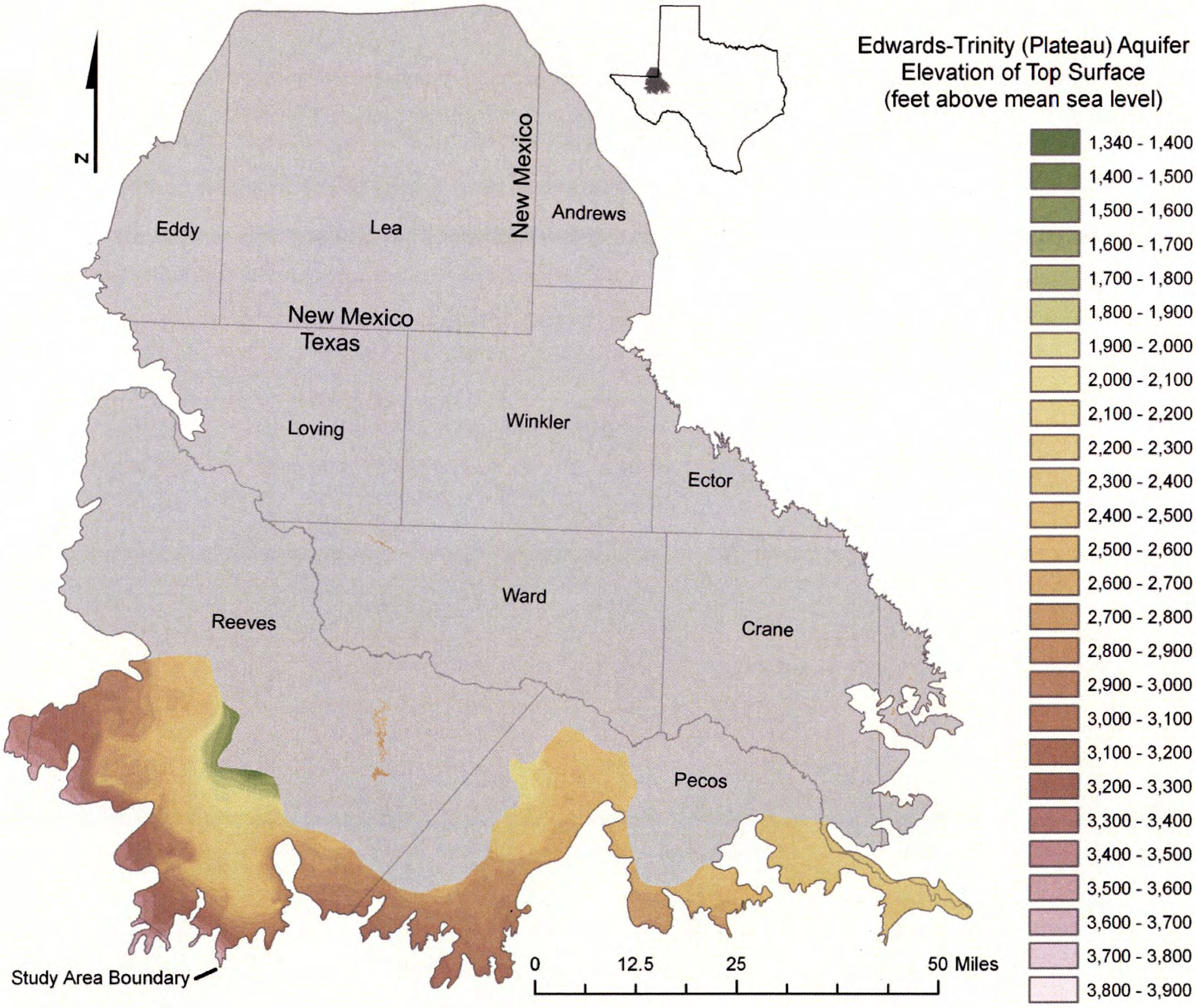


Figure 6-19. Top surface elevation of the Edwards-Trinity (Plateau) Aquifer.

The Pecos Trough is most prominent in Reeves County where the top surface is more than 2,100 feet below ground surface and there is a near-vertical fault margin with more than 1,000 feet of displacement along the northeastern edge. The Pecos Trough has a slight topographic expression in the form of a low, broad depression (Figures 6-11 and 6-12). In Reeves County, the trough is a broad collapse structure that terminates abruptly against Permian evaporites in the northeastern part of the county. Dean and Anderson (1982) characterize the Permian evaporite section as having breccia beds (known as blanket solution breccias) instead of halite within the Castile and Salado formations in this area.

The structurally elevated ridge separating the Pecos and Monument Draw troughs is underlain by the thickest sections of evaporites of the Salado and Castile formations (Figures 6-11 and 6-12) (Dean and Anderson, 1982; Maley and Huffington, 1953). The ridge is capped by a thin veneer of Pecos Valley Alluvium that is underlain by Triassic Dockum Group sediments. This suggests that the Dockum Group sediments played a role in protecting the underlying evaporites from solution. The ridge also restricts groundwater flow between the two solution troughs within the Rustler, Dockum Group, and Pecos Valley aquifers (Ashworth, 1990; Jones and others, 2011).

The Monument Draw Trough consists of a series of coalesced collapse features with the top of the Rustler Formation occurring more than 2,500 feet deep in northwest Winkler County. The lower portion of the trough consists of separate basins of different geometries (Figure 6-9, cross-section B-B'). The Monument Draw Trough overlies the western and central extent of the Permian Capitan Reef Complex along the western margin of the Central Basin Platform (Hiss, 1976; Figure 3-3). Several authors have suggested that the Capitan Reef Complex influenced development of the solution collapse (Hiss, 1976; Maley and Huffington, 1953).

Some of the solution collapse features along the Monument Draw Trough are of small areal extent, with the deepest part of the collapse visible in only one well (for example, BRACS Well IDs 2594 and 2612). These features may represent breccia pipes that appear similar in size to features studied in New Mexico (Snyder and Gard, 1982) and to modern features in Winkler County (Baumgardner and others, 1982; Paine and others, 2009). Other features have the appearance of coalesced individual breccia pipes amongst a number of wells in the area, each showing differences of several hundred feet of displacement to the top of the Rustler Formation. Evaluation of the Pecos Valley Alluvium in some of these wells suggests a complex pattern of collapse, timing, deposition, and, in some cases, erosion.

The approximate boundaries of the solution troughs are shown in Figure 6-14. Jones and others (2011) referred to the solution troughs as grabens. We continue to use the term solution trough where the trough boundary is characterized by downwarping of overlying formations in some places and clearly faulted in other areas. A system of concentric ring faults analogous to modern collapse features in the Wink Sink region (Paine and others, 2009) likely surround small-diameter, deep, individual breccia pipes and areas where several breccias pipes have coalesced into a larger structure. The nature of the trough boundary is important with respect to fracturing or faulting of overlying, lithified formations and juxtaposition of one formation against another.

Several authors have prepared contour maps of the top of the Rustler Formation for part or all of the study area (Garza and Wesselman, 1959; Hiss, 1976; Johnson, 1993; Jones and others, 2011; Maley and Huffington, 1953; Ogilbee and Wesselman, 1962a; White, 1971). We reviewed these maps but could not use them for stratigraphic picks, because the majority of well logs used by those authors were unavailable. The exception was the well logs used by Jones and others (2011).

The solution troughs have been referred to by different names in other studies. For example, the Pecos Trough was called the Balmorhea-Pecos-Loving Trough (Hiss, 1976) and the Toyah Basin (LaFave, 1987) and the Monument Draw Trough was called the Belding-San Simon Trough (Hiss, 1976) or the Belding-Coyanosa Trough (Boghici, 1997).

Solution collapse of Permian evaporites has also affected the Ogallala Formation in the Texas Panhandle which may be temporally equivalent to the Pecos Valley Alluvium sediments. Similar styles of solution collapse, spatial relationships of overlying formations, and timing of collapse and sediment input have been documented in this region (Gustavson and others, 1980; Paine, 1995). Shallow geophysical techniques addressing the present solute input to surface water are addressed in Paine and others (1994), and those techniques could be applied to the study area in future studies.

Jones and others (2011) present a comprehensive analysis of the Rustler Formation and its behavior as an aquifer. We added additional well control from their project to the BRACS Database, but obtained the data after we had generated our GIS datasets.

Structural cross-sections

We constructed six geologic cross-sections to illustrate the geologic structure and stratigraphic relationships of the Pecos Valley Aquifer and underlying formations in the study area. Cross-section locations are shown in Figure 6-7, and the cross-sections are presented in Figure 6-8 through Figure 6-13. The cross-section lines were positioned to highlight salient features of the Pecos Valley Aquifer and the underlying geologic units across the study area.

ViewLog, a software package from EarthFX Incorporated, was used to generate the cross-sections. Raster files of stratigraphic surfaces created in GIS were imported into ViewLog to produce the cross-sections. A vertical exaggeration of 20 was applied to all cross-sections to aid in the visual interpretation of the images.

6.2 Aquifer determination analysis

A detailed analysis of each well site, well depth (depths of tops and bottoms of screens), and aquifer surface (depth of top and bottom) is necessary to determine which aquifers are being used by a well in the study area. Water wells in the TWDB Groundwater Database have aquifer codes assigned to them. Over the 25 years that the database has been in existence, different staff using a variety of information has been assigning aquifer codes in the database. In particular, for the Pecos Valley Aquifer, the aquifer codes have been applied inconsistently because of the complex stratigraphy and solution trough structures present in the aquifer. In order to create a uniform dataset that would allow us to compare water quality, static water level, and aquifer test within an individual aquifer or across a group of aquifers, we analyzed the data and compiled it into a table in Microsoft® Access®. We used GIS data analysis and database queries utilizing many different tables of information for this purpose.

Each aquifer in the study area (the Pecos Valley, Edwards-Trinity (Plateau), Dockum, Rustler, and Capitan Reef Complex aquifers) was included in the analysis. The top and bottom surfaces representing the Capitan Reef Complex were obtained from the geodatabase created by Standen and others (2009). We received information for the bottom of the Rustler Formation from Jones and others (2011) after the initial aquifer determination was run. For the initial analysis, data for Rustler Formation wells was updated manually. The first step was to extract all TWDB groundwater wells and Brackish Resources Aquifer Characterization System project wells that are contained within the study area into one table. There are 5,312 wells in this table: 2,672 with a state well number; 3,132 with a BRACS Database well number; and 492 that have both numbers.

The next step was to extract the depth-to-surface value for each mapped geologic unit (for example, Pecos Valley Alluvium bottom depth) at each well site using the ArcGIS® tool (Spatial Analyst, Extraction, Extract Value to Point) and then updating the data table in Microsoft® Access®. The next step was to create a region map in ArcGIS® showing areas with different stratigraphic relationships (Figure 6-1; Table 6-1). A region code was then assigned to each well record. The combination of spatial intersection of the top of a well screen, bottom of a well screen, well depth, or total depth of hole with the top and bottom surfaces of the geologic unit was made for each well site. The intersection precedence, if present, was well screen, well depth, and total depth of hole. Well screens that straddled more than one aquifer had each aquifer assigned to it. If well screen information was not available, the well depth or total depth of the hole was used. In these cases, all aquifers were selected based on the depth and formation top/bottom depths.

Queries were written in Structured Query Language and the analysis was organized in Visual Basic for Applications in Microsoft® Access®. All of the wells were processed in one step. Results were checked with the raw data and the queries for consistency and accuracy and the Visual Basic for Applications code was corrected accordingly. The selection process recorded the aquifer(s) for each well, the Structured Query Language code sequence used for the selection (for quality control), and the aquifer decision with each well record. We did not select aquifers for the oil and gas wells.

We developed a database data entry form to allow staff to review all well information and the automated aquifer selection results. Information for all water wells in which a selection was not made by the software was verified manually. Staff has the ability to overwrite the computer analysis and assign an aquifer decision of "Geologist, best professional judgment." This occurred, for example, if a well had multiple screens—the software only uses the shallowest top screen depth and the deepest bottom screen depth. Thus, all wells with multiple screens were checked manually.

The well information stored in the Microsoft® Access® database was extracted and geo-referenced in ArcGIS® to spatially display the information. This step was used to verify the logic of the Structured Query Language and to identify and correct errors. The patterns of aquifer usage across the study area can thus be evaluated, although care needs to be exercised when using wells whose aquifer(s) were assigned only on the basis of well depth or total depth of hole.

Wells with aquifer test information were assessed using the aquifer determination results and then compared with the source of the data in published reports. In several cases, the aquifer assigned to a well in the published report was different from the aquifer determination result. After reexamining the water well report lithology, well screen, and formation surface datasets, we concluded that errors in past reports have persisted and been carried over into more recent studies.

While the analysis tool was written specifically for this study area, the methodology can be applied anywhere in the state. However, the dataset and series of custom queries must be developed for each specific study area.

6.3 Water levels and saturated thickness

We developed a static water level grid map from water wells completed in the Pecos Valley Aquifer. The map was created for the purpose of generating the Pecos Valley Aquifer saturated thickness map and to estimate brackish water volumes (Section 6.5.3).

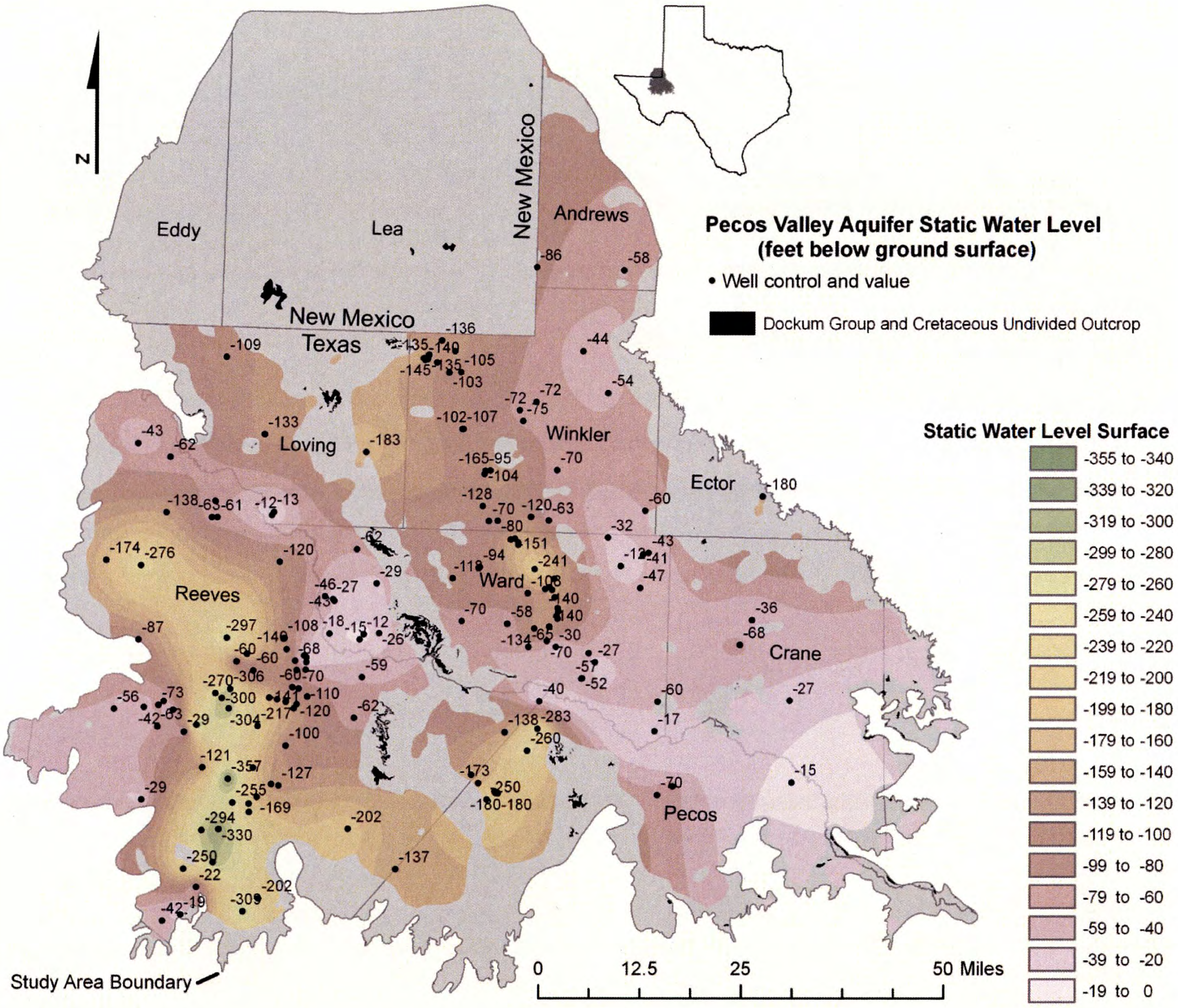


Figure 6-20. **Pecos Valley Aquifer static water level surface and well control. New Mexico was not processed. Gray areas in Texas represent unsaturated Pecos Valley Alluvium. This map was created for the generation of brackish water volume calculations. Static water level measurements compiled from records in 2000 through 2009.**

A significant challenge in creating the static water level map was the small number of well records and the spatial distribution of the wells. A typical static water level map is created using data from one winter season, producing a water level surface that reflects minimum influence from seasonal irrigation pumping. While the database contains 15,130 water level records from 2,108 wells, winter-season water levels from wells completed in the Pecos Valley Aquifer are typically less than 80 measurements in any given season during the last 6 years. The wells are clustered in small areas and created significant problems for developing a grid map.

Because the purpose of developing a water level surface was to estimate brackish water volume, we decided to average all water levels within the 2000-2009 time period to create one water level for the well. This dataset consisted of 332 water wells, with 163 completed in the Pecos Valley Aquifer with a relatively good spatial distribution. We did not collect and analyze water level data for New Mexico.

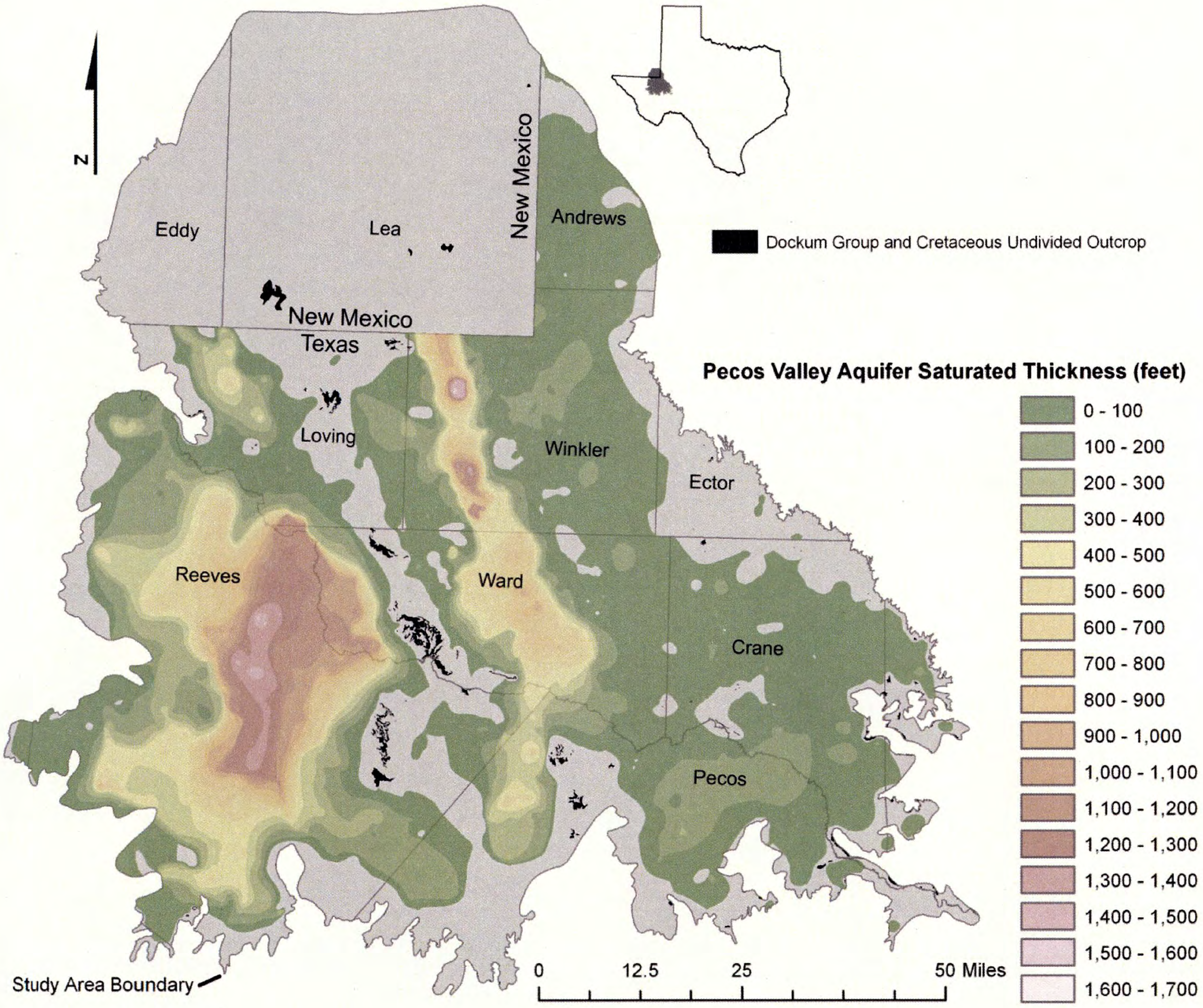


Figure 6-21. **Pecos Valley Aquifer saturated thickness.**

The well points were extracted from Microsoft® Access® and imported into ArcGIS® and georeferenced. The points were interpolated using the ArcGIS® Spatial Analyst and Topo to Raster tools. The resulting grid map was compared with input points (Figure 6-20). Some counties have few data points, resulting in a rough approximation of the static water table surface. Major pumping centers in central Reeves, northwestern Pecos, north-central Ward, and northwestern Winkler counties are clearly visible on Figure 6-20.

The static water-level grid was subtracted from the Pecos Valley thickness map using the ArcGIS® Spatial Analyst Raster Calculator tool to produce a saturated thickness grid map (Figure 6-21). The unsaturated regions and all of the study area in New Mexico were converted to no-data cells.

6.4 Water quality

A description of water quality in the Pecos Valley Aquifer with an emphasis on parameters that are important to and a concern for desalination is provided next.

6.4.1 Aquifers

The master water quality data and the aquifer determination table were combined into one table and georeferenced in ArcGIS®, allowing us to spatially display water quality for a specific aquifer or combination of aquifers. The ability to discretely select water quality based on an aquifer is an important advancement in the study of brackish aquifers in Texas and is an improvement over previous studies such as the one completed by LBG-Guyton (2003). The estimation of brackish water reserves for the Pecos Valley Aquifer depended on the ability to select data using this technique and is one of the reasons that the volumes of brackish groundwater estimated in this study are different from those presented in LBG-Guyton (2003).

6.4.2 Parameters of concern for desalination

If used for potable purposes, brackish groundwater needs to be treated (desalinated). Without treatment, brackish water can cause scaling and corrosion problems in water wells and treatment equipment and cannot be used in many industrial processes. The Texas Commission on Environmental Quality has established a primary standard of 500 milligrams per liter of total dissolved solids and a secondary standard of 1,000 milligrams per liter of total dissolved solids for public water supply systems (TCEQ, 2011). Groundwater containing total dissolved solids at concentrations greater than 3,000 milligrams per liter is not usable for irrigation without dilution or desalination and, although considered satisfactory for most poultry and livestock watering, can cause health problems at increasingly higher concentrations (Kalaswad and Arroyo, 2006).

The physical and chemical parameters of concern to desalination facilities that use reverse osmosis—the predominant desalination technology in Texas—are listed in Table 6-3. While the TWDB Groundwater Database contains sample results in two tables for most of these parameters, the amount of information available from a well can vary greatly. For example, TWDB does not maintain information on silt density index or turbidity from groundwater samples. If the turbidity or silt density index is high, feedwater pre-treatment is required to avoid plugging membranes in a reverse osmosis treatment system.

Groundwater quality in an aquifer can vary greatly due to factors such as mineral composition of aquifer materials; recharge rates, spatial distribution, chemical composition of recharge waters, and historical changes with time; geochemical processes; natural and man-made discharge rates and spatial distribution; residence time; and groundwater flow velocity. A review of published literature and comparison with GIS mapping of chemical parameters show that groundwater geochemistry in the Pecos Valley Aquifer is extremely complex.

Mapping groundwater quality data also depends on the number and spatial distribution of samples, types of samples collected, and the dates the samples were collected. We present a series of maps for the Pecos Valley Aquifer showing the distribution of some of the parameters of concern to desalination. The lack of significant numbers of samples in any one recent sampling year meant that we had to extract data from a multi-year period. The most recent sample for a well since 1960 was queried from the database to create the maps. While these maps display the spatial distribution of chemical parameters, they do not necessarily show current water quality conditions. Users interested in a specific region are encouraged to use the available database, GIS datasets, and GIS software to construct site-specific maps to meet project needs.

Table 6-3. Parameters of concern for desalination.

Physical Parameters	Chemical Parameters			
	Cations		**Anions**	**Other**
Conductivity	Al^{+3}	K^{+}	Cl^{-}	Alkalinity
pH	As^{+3}	Mg^{+2}	CO_3^{-2}	Boron
Silt Density Index	As^{+5}	Mn^{+2}	F^{-}	Dissolved Oxygen
Temperature	Ba^{+2}	Na^{+}	HCO_3^{-}	H_2S
Turbidity	Ca^{+2}	NH_4^{+}	NO_2^{-}	Hardness
	Cu^{+2}	Ni^{+2}	NO_3^{-}	Pesticides
	Fe^{+2}	Sr^{+2}	OH^{-}	Radionuclides
	Fe^{+3}	Zn^{+2}	SO_4^{-2}	Silica
				Total dissolved solids

Total dissolved solids is a measure of the mineral content in water and is an important parameter for designing a reverse osmosis plant. Figure 6-22 shows the spatial distribution of total dissolved solids in 527 samples in the study area. The total dissolved solids content ranged from 116 to almost 15,000 milligrams per liter. Three wells showed concentrations of 9,295 milligrams per liter (probable oil field contamination from produced salt water); 71,118 milligrams per liter (probable contamination from brine mining of Salado Formation halite); and 223,000 milligrams per liter (well adjacent to Ozark Lake in Ward County where groundwater containing sodium sulfate was pumped to the surface and allowed to evaporate (White, 1971). Wells sampled prior to 1960 indicate additional elevated total dissolved solids concentration likely associated with oil field contamination (Garza and Wesselman, 1959).

Silica is an important desalination parameter because at elevated concentrations, it can foul reverse osmosis membranes. The term silica is widely used to refer to dissolved silicon in natural water, but the actual form is hydrated and should be represented as H_4SiO_4 (Hem, 1985). The SiO_4^{4-} tetrahedron is the building block of most igneous and metamorphic rocks and is present in some form in most soils and groundwater. Figure 6-23 shows the spatial distribution of silica in 478 well samples obtained from the Pecos Valley Aquifer. In these samples, silica content ranged from 1 to 83 milligrams per liter.

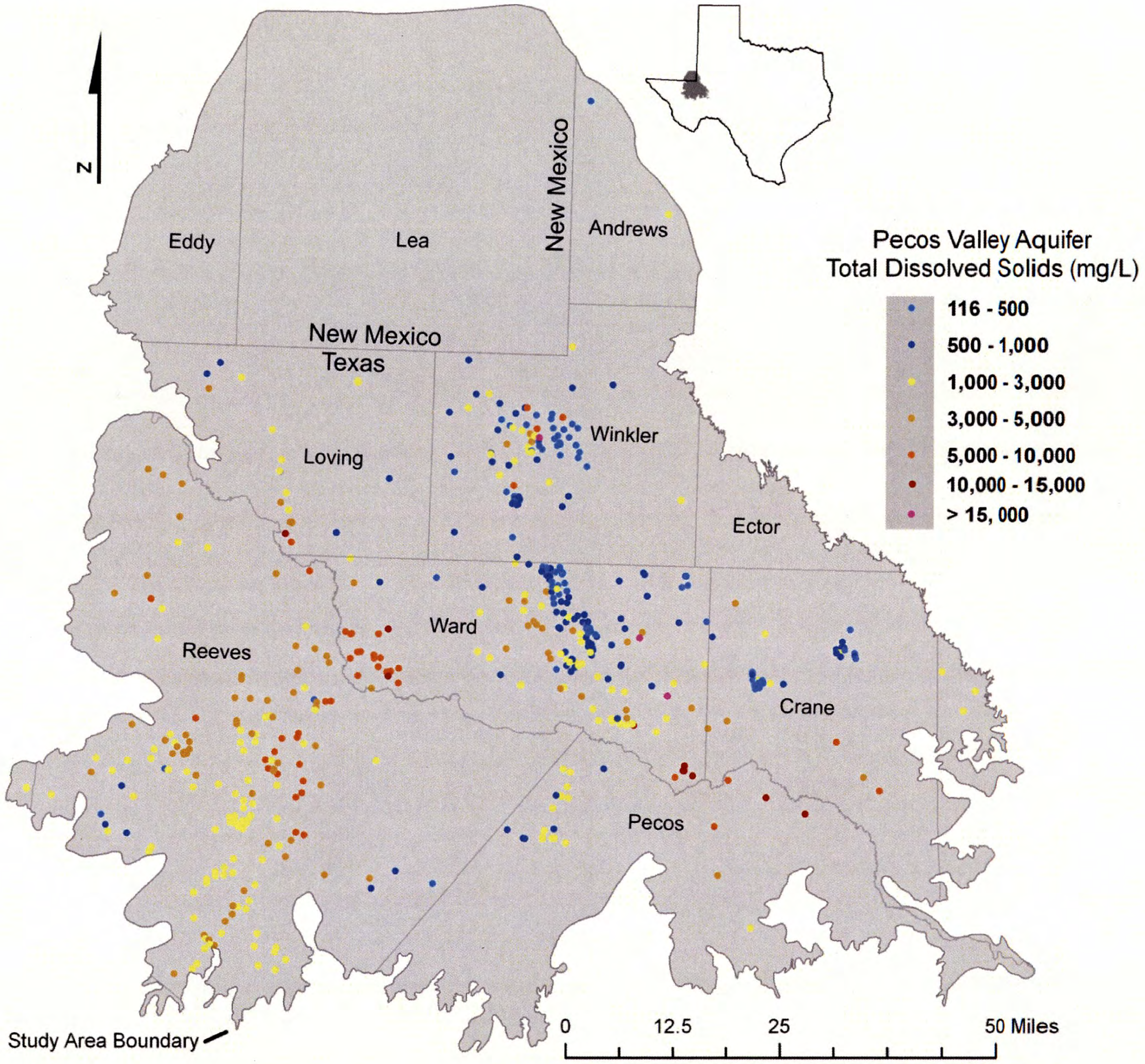


Figure 6-22. **Total dissolved solids concentration in wells completed in the Pecos Valley Aquifer. Wells are colored based on range of total dissolved solids values. The three pink-colored wells exceed 15,000 milligrams per liter total dissolved solids and are probably the result of contamination as explained in the text.**

Iron in groundwater can become oxidized and will precipitate when it reaches ground surface. To avoid fouling reverse osmosis membranes, water with elevated levels of iron must be pre-treated. Unfortunately, there was not enough data for iron in the database to adequately map and characterize the element over much of the study area. Nevertheless, data obtained from 69 wells show iron concentrations ranging from 0.01 to 4.5 milligrams per liter (Figure 6-24).

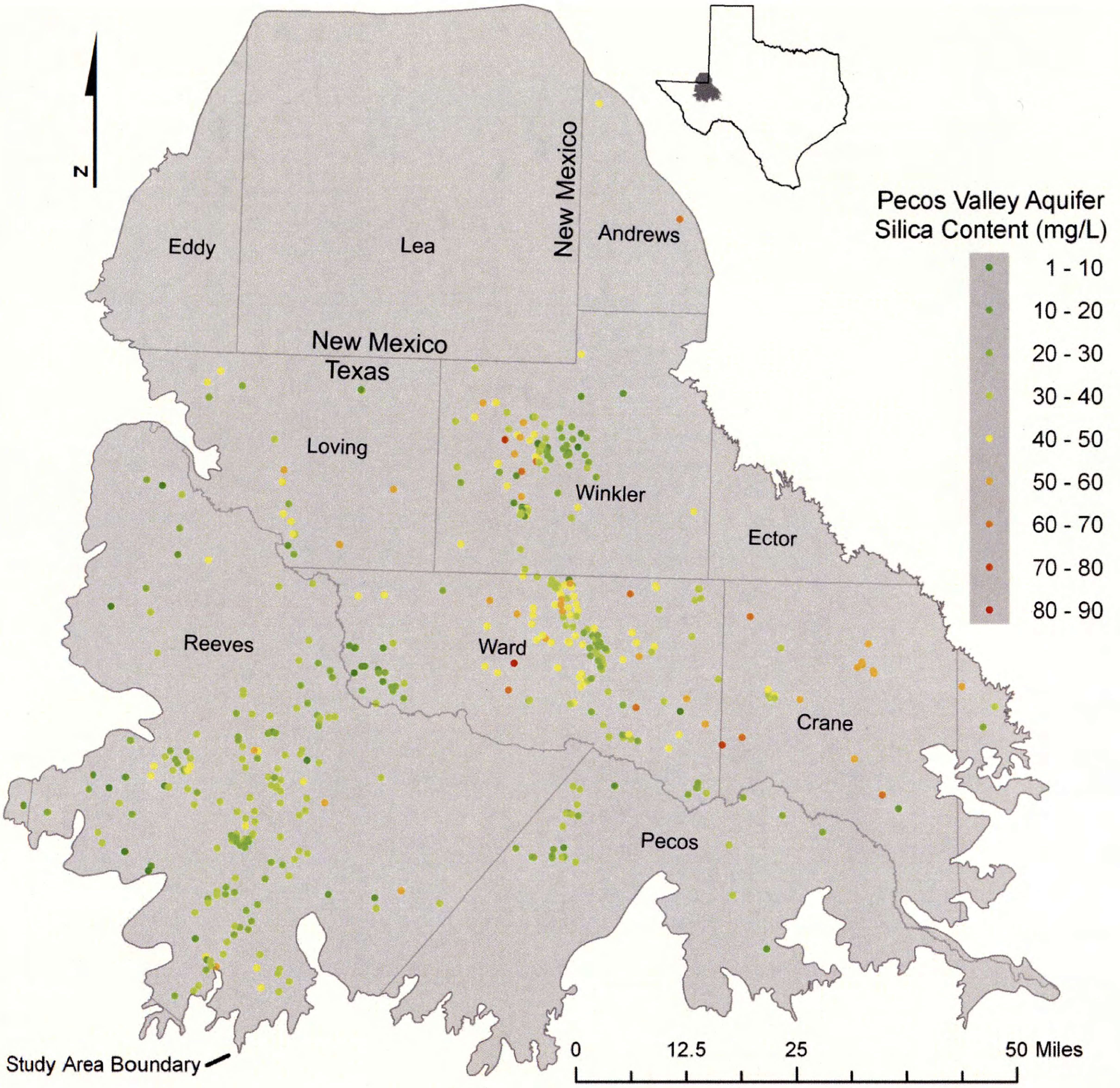


Figure 6-23. **Silica concentration in wells completed in the Pecos Valley Aquifer.**

The TWDB groundwater database includes 79 Pecos Aquifer Valley wells that have radionuclide analyses for a total of 188 sample results. Samples include a mixture of uranium, radium, and alpha and beta particles. Gamma ray logs were interpreted for high gamma ray response during the process of assigning simplified lithologies to the geologic units. Elevated gamma ray readings were detected in 46 samples, some with more than one depth interval affected. Twenty-two wells in the Pecos Valley Alluvium had high gamma ray responses, 32 in the Dockum Group-Dewey Lake Formation, and 1 in the Cretaceous Undivided (Figure 6-25). The presence of radionuclides is important when considering disposal of concentrate. Elevated, naturally occurring radioactive material waste in the concentrate will impact the method of waste disposal and, thus, cost. The source of natural radionuclides was not examined in this study, but McGowen and others (1977) provide a discussion of the subject for the Dockum Group.

Sulfate in groundwater can cause scaling and fouling of reverse osmosis membranes, requiring the source water to be pre-treated. Sulfate concentrations in water samples collected from the Pecos Valley Aquifer ranged from 2 to 4,208 milligrams per liter, with one site in southeastern Ward County recording concentrations as high as 81,700 milligrams per liter (Figure 6-25). It is likely that this site has been impacted by sodium sulfate mining in the area.

Chloride concentration in the Pecos Valley Aquifer ranged from 3 to 7,280 milligrams per liter with five sites showing elevated chloride concentrations of between 13,000 and 70,000 milligrams per liter (Figure 6-27).

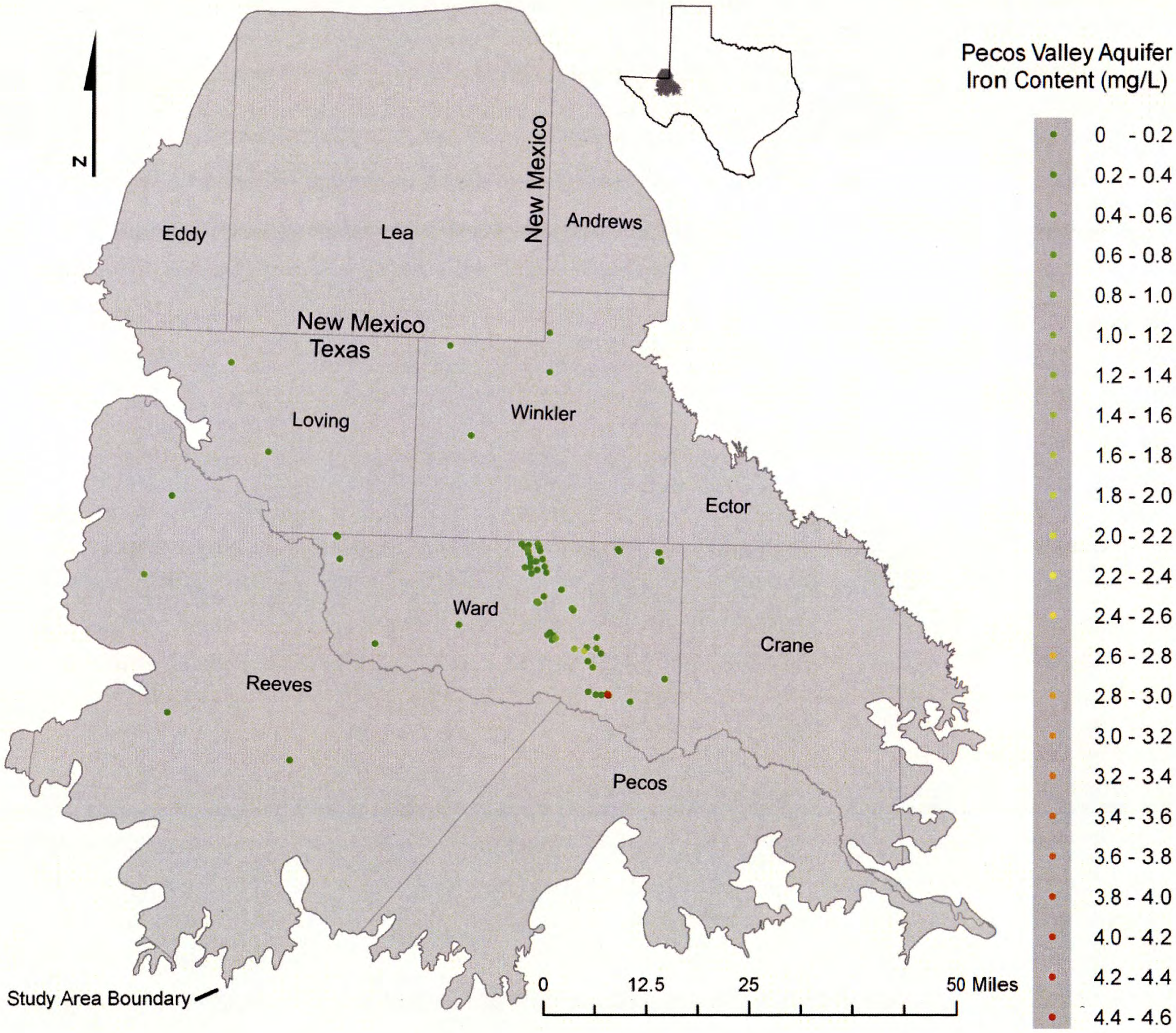


Figure 6-24. **Iron concentration in wells completed in the Pecos Valley Aquifer.**

Operators of desalination facilities need to dispose the waste (concentrate) produced from their operations. A Class I underground injection well general permit issued by the Texas Commission on Environmental Quality's Underground Injection Control Program can be used for disposal of nonhazardous concentrate from desalination of groundwater and seawater, and for nonhazardous drinking water treatment residuals. A Class II underground injection well (regulated by the Railroad Commission of Texas) for oil- and gas-related use can also be dual permitted as a Class I well under the general permit and used for disposal of these wastes. Mace and others (2006) have discussed the use of Class II injection wells to dispose of concentrate in oil fields. More than 4,500 Class II injection wells are present in the study area (Figure 3-1).

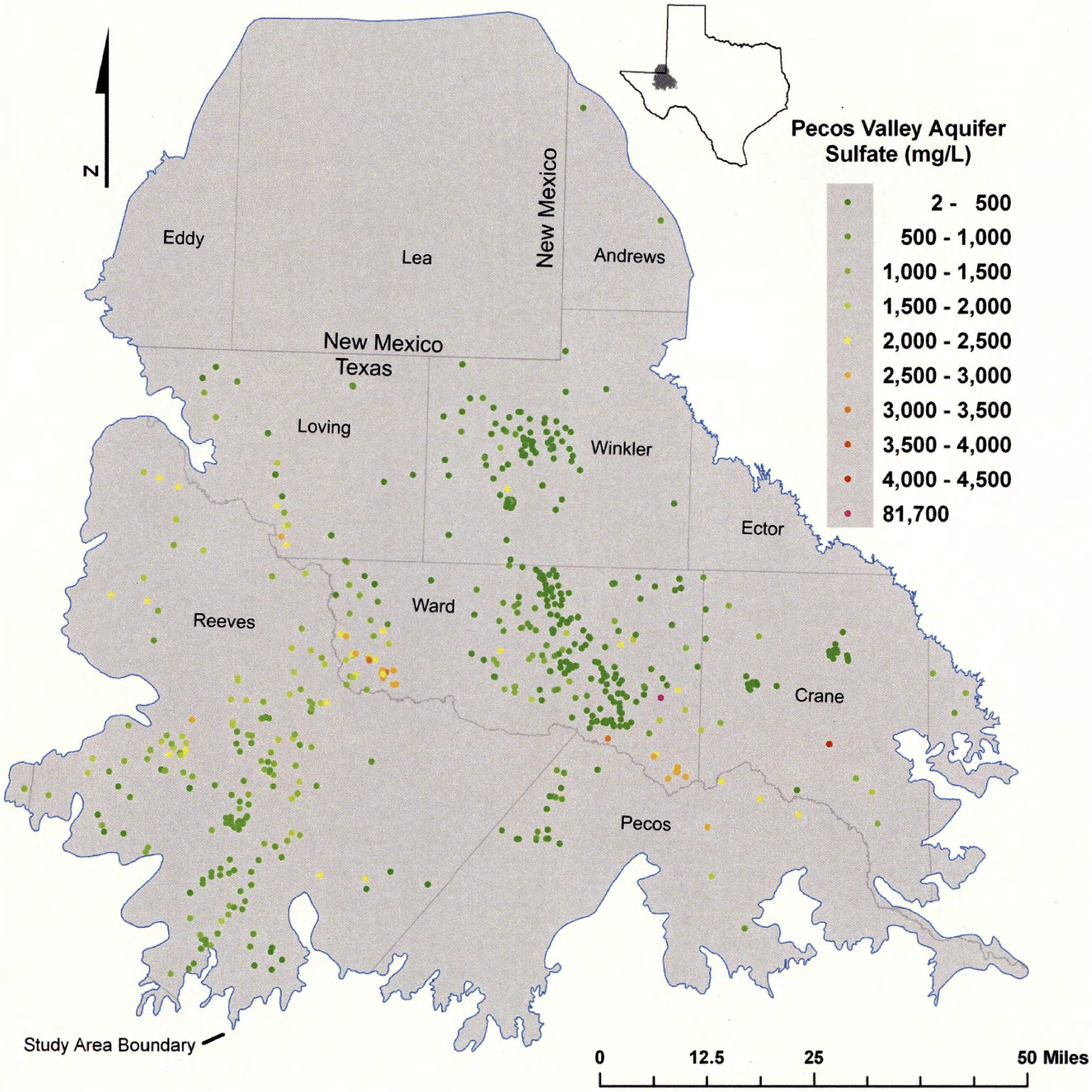


Figure 6-25. **Sulfate concentrations in wells completed in the Pecos Valley Aquifer. The one pink-colored well has a value of 81,700 milligrams per liter.**

Owners of injection wells are not permitted to inject a waste if the fluids being injected into an underground source of drinking water contain contaminants that can cause a violation of any primary drinking water regulation or may adversely affect public health (Mace and others, 2006).

Most of the desalination facilities in Texas do not treat concentrate prior to disposal. While many disposal methods are available, such as discharge to a sanitary sewer or to a surface water body, evaporation, land application, deep well injection, and zero discharge desalination, most desalination facilities in Texas use only one method of disposal (Shirazi and Arroyo, 2011).

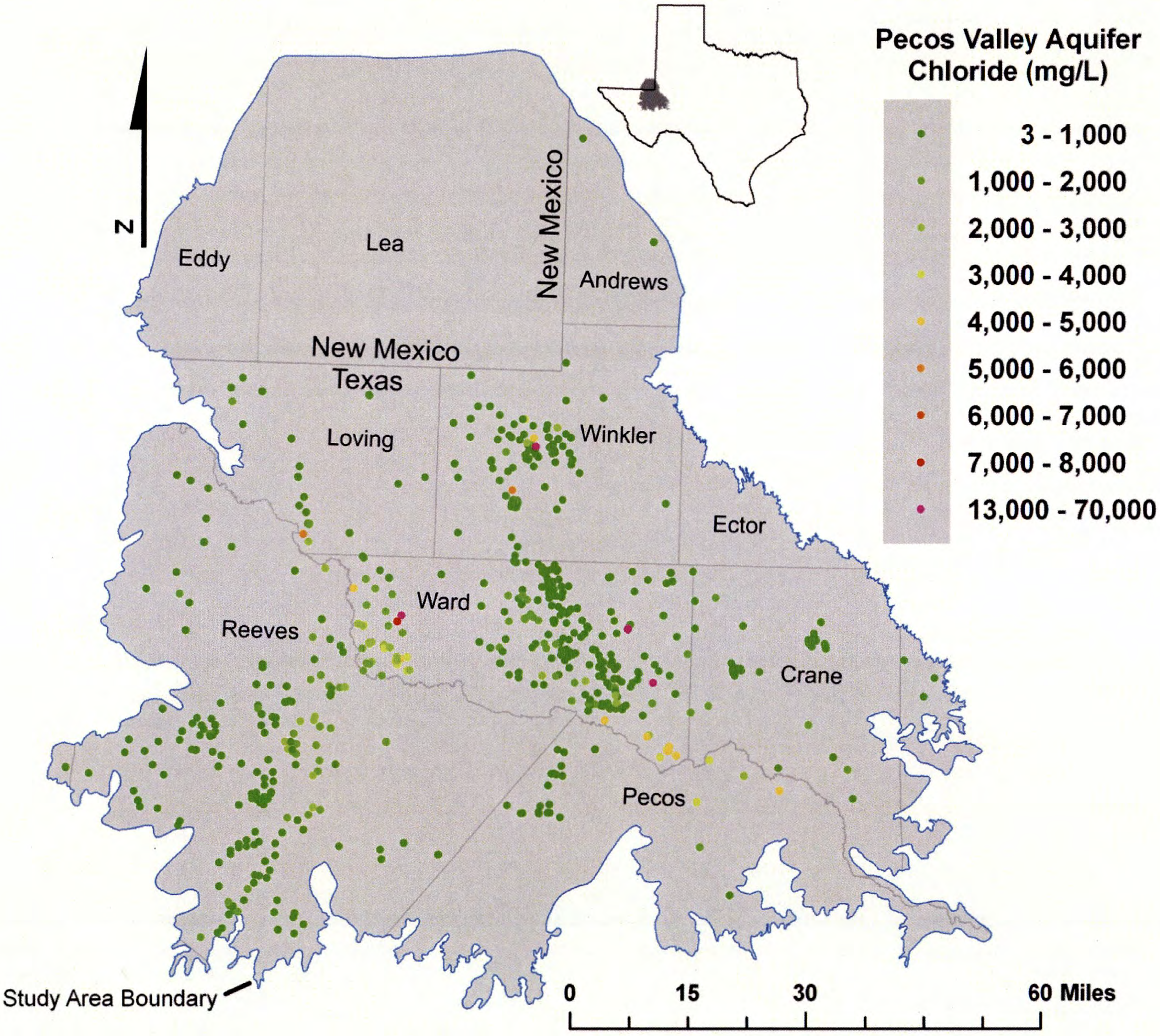


Figure 6-26. **Chloride concentration in wells completed in the Pecos Valley Aquifer. The five pink-colored wells have values ranging from 13,000 to 70,000 milligrams per liter.**

In Texas, a majority of the desalination facilities discharge their concentrate either to a sanitary sewer or to a surface water body. Thirteen facilities use desalination concentrate for land application, seven use evaporation ponds to treat desalination concentrate, and one uses zero discharge desalination. The City of El Paso’s Kay Bailey Hutchison Brackish Groundwater Desalination Plant uses three deep Class V injection wells for concentrate disposal (Shirazi and Arroyo, 2011).

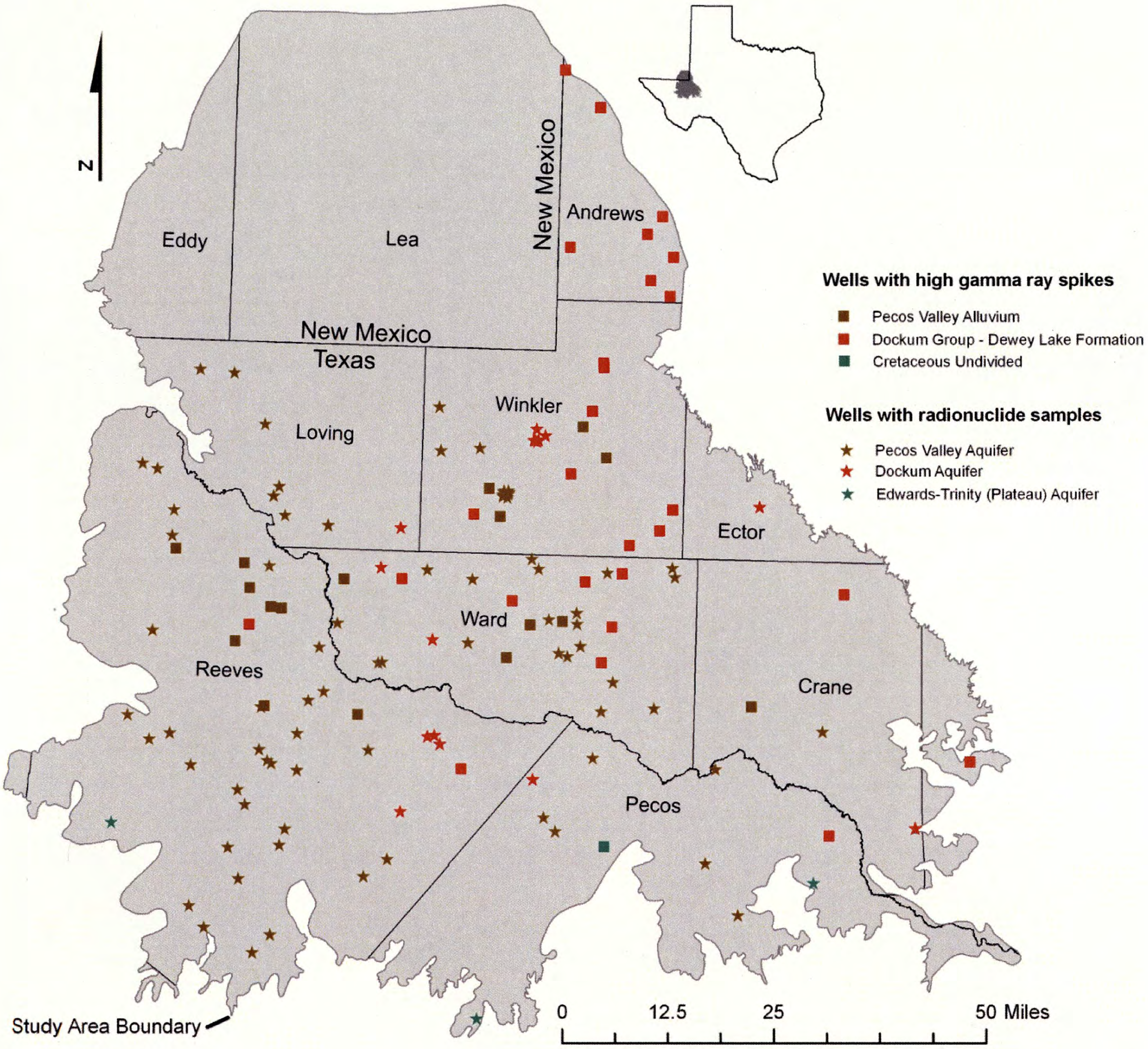


Figure 6-27. **Wells with high gamma ray spikes interpreted from geophysical well logs indicating a possible radionuclide source in the sediments. Wells sampled for radionuclide constituents.**

6.4.3 Brackish water volume estimates

The TWDB defines water quality in terms of total dissolved solids. Water quality based on total dissolved solids has been divided into five categories: fresh (0–999 milligrams per liter); slightly saline (1,000–2,999 milligrams per liter); moderately saline (3,000–9,999 milligrams per liter); very saline (10,000–35,000 milligrams per liter); and brine (> 35,000 milligrams per liter) (Winslow and Kister, 1956). Brackish water includes slightly to moderately saline waters (1,000–9,999 milligrams per liter of total dissolved solids).

Brackish groundwater in the Pecos Valley Aquifer was mapped according to TWDB's classification system, with the exception that all water with total dissolved solids concentration greater than 10,000 milligrams per liter was grouped into one category. This is consistent with the system used by LBG-Guyton (2003). The most recent total dissolved solids analysis available for all water wells completed in the Pecos Valley Aquifer was queried from the BRACS Database. It resulted in 929 water wells that spanned the years 1930 to 2008. Because this information was used to estimate brackish water volumes, the most complete dataset possible was necessary for analysis. Use of more recent total dissolved solids data severely reduced the number of well sites available, leading to additional uncertainty during the interpolation steps.

The total dissolved solids concentration data were loaded into ArcGIS® as a point shapefile and georeferenced. The water quality data contain a field with an integer value representing each total dissolved solids range listed previously. This value was interpolated using the ArcGIS® Spatial Analyst Inverse-Distance Weighted tool. A number of trial runs were performed to fine-tune the tool parameters with the input dataset. The final grid was processed with the saturated thickness map created for this purpose (see Section 6.3) to produce a map showing gridded total dissolved solids range values for only the saturated thickness of the Pecos Valley Aquifer (Figure 6-28). The equivalent aquifer in New Mexico was not processed, because static water level and water quality data from that area were not obtained for this project.

A separate saturated thickness grid file was created for each range of total dissolved solids concentration. Data outside of the total dissolved solids range were converted to no-data cells. Volumes were calculated using the Cut and Fill tool in ArcGIS® Spatial Analyst. The data table from each Cut and Fill grid file was imported into Microsoft® Excel®, and the volume field of each individual record was summed and converted into acre-feet.

The storage term for unconfined aquifers is known as specific yield. It is the volume of water that is released as drainage under gravity from aquifer storage per unit volume of aquifer sediments per unit decline in water level. Not all water in the saturated zone can be removed by drainage or pumping. Retained water is that portion which adheres to the aquifer matrix by surface tension in the void spaces and is known as specific retention. Site-based specific yield data for the Pecos Valley Aquifer are not available (Anaya and Jones 2009). Instead, Anaya and Jones (2009) used a range of values of 0.02 to 0.27 that is representative of alluvial sediments (Johnson, 1967). As a comparison, LBG-Guyton (2003) used a value of 0.12 for the Pecos Valley Aquifer.

For this study, we used a specific yield value of 0.12 to determine the volume of water. We did not attempt to use different specific yield values in the vertical dimension, although it is reasonable to assume that the value may change with depth. Our estimates indicate that the Pecos Valley Aquifer contains about 85 million acre-feet of brackish water (Figure 6-4). LBG-Guyton (2003; Table 5, p. 144) reported about 116 million acre-feet of brackish water for the same aquifer.

Limitations in the amount of available information used to determine volume estimates create a level of uncertainty; hence, the term "estimates" is used. Some of the limitations of the volumetric estimates (depth stratification, well density, water quality data, static water level data, and specific yield values) are discussed next. The latter three limitations have been discussed previously.

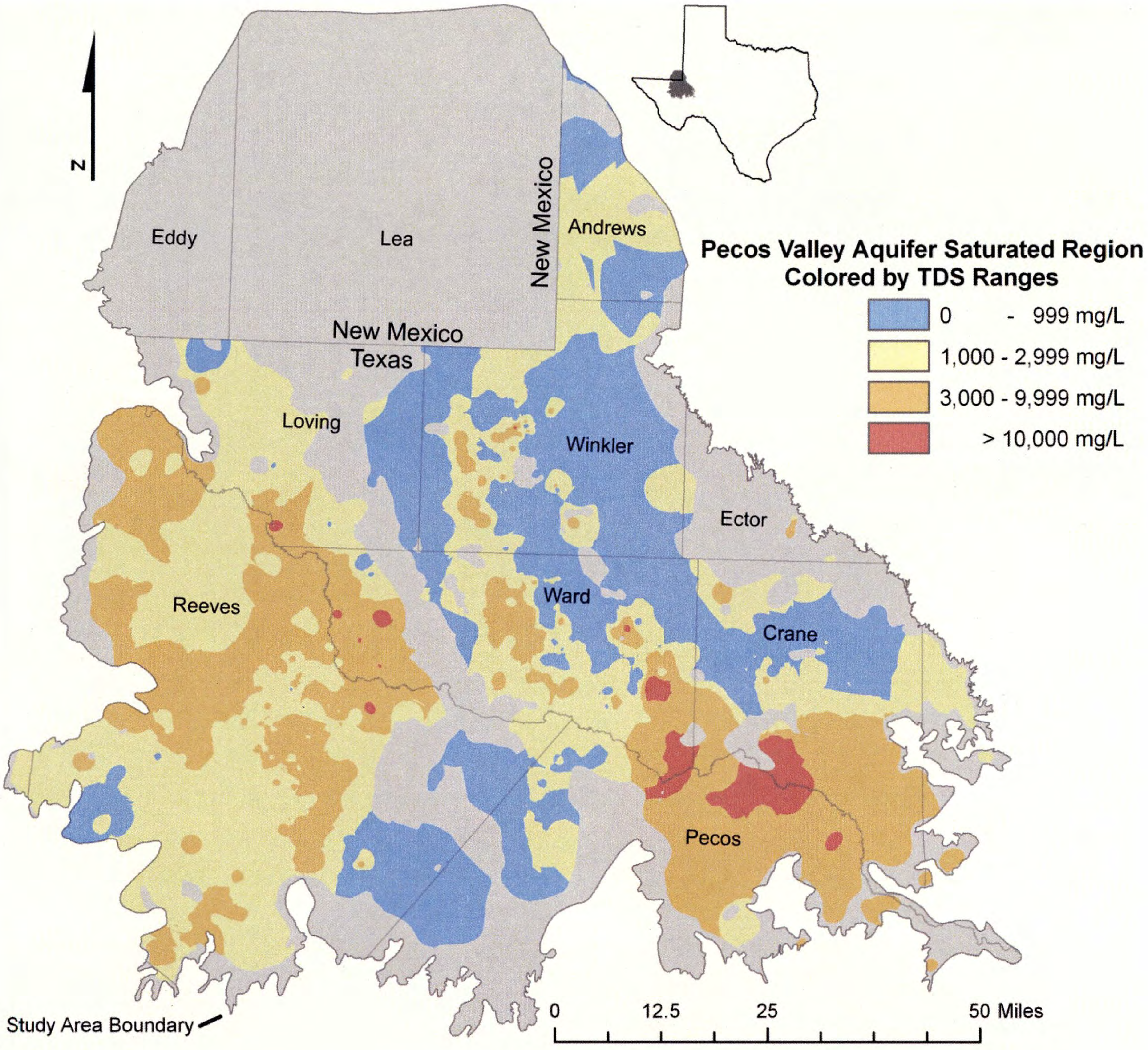


Figure 6-28. **Pecos Valley Aquifer saturated thickness colored according to range of total dissolved solids concentration. This gridded map was created for the generation of brackish water volume calculations using ArcGIS®.**

The volume estimate was derived from a simple 2-dimensional mapping of the distribution of total dissolved solids. No attempt was made to define stratification of waters in the vertical dimension. This is primarily because we did not have sufficient depth-based water quality data from water wells. Furthermore, there were not enough resistivity or spontaneous potential geophysical well logs in the study area to prepare interpreted total dissolved solids concentration vs. depth profiles. It is also possible that there may be no clear or consistent layering of brackish and saline waters in the study area. An indication of this is available in well 994 in central Reeves County and wells 46-32-206 and 46-40-203 in Ward County (White, 1971). Using the spontaneous potential log, we estimated an interpreted total dissolved solids concentration of 3,275 milligrams per liter at a depth of 665 feet below ground surface. At the same location, the total dissolved solids progressively increased to an interpreted concentration of 7,400 milligrams per liter at a depth of 1,295 feet below ground surface. The shallow interpreted total dissolved solids concentration is similar to that recorded in samples of equivalent depths located within two miles of well 994.

Another limitation of the volume estimates is a lack of water quality data in several areas of the study area. Lack of sufficient well density and use of the inverse-distance weighted interpolation technique created extrapolations into areas of low well density and, in some cases (Andrews County), processing artifacts.

Table 6-4. Pecos Valley Aquifer brackish water volumes.

Water classification (milligrams per liter of total dissolved solids)	**Volume of aquifer matrix (cubic feet)**	**Volume of groundwater (acre-feet)**
Fresh water (0–999)	5,345,270,000,000	14,725,000
Brackish water		
(1,000–2,999)	16,784,642,000,000	46,239,000
(3,000–9,999)	14,151,901,000,000	38,986,000
Total: (1,000–9,999)	30,936,543,000,000	85,225,000
Very saline water (> 10,000)	331,737,000,000	914,000
Total volume Pecos Valley Aquifer (Saturated thickness)	36,613,551,000,000	100,864,000

6.4.4 Sources of salinity

Salinity within the Pecos Valley Aquifer is the result of both natural and anthropogenic causes. Ashworth (1990) provides a detailed description of the anthropogenic sources of contamination that have occurred or could occur in the study area.

Natural sources of salinity include the dissolution of Permian evaporites (primarily halite and anhydrite-gypsum) and evaporative concentration of water. Anthropogenic sources include past disposal practices of oil- and gas-related salt water; spills and leaks from oil fields; abandoned water, oil, and gas wells; irrigation return-flow; and well pumping allowing recharge from higher salinity water.

Garza and Wesselman (1959) and White (1971) provide a compelling description of oil-field salt water disposal practices and contamination in Winkler and Ward counties, respectively. Salt water produced from oil wells contains total dissolved solids ranging from 5,400 to 180,000 milligrams per liter. An area in west-central Winkler County (west of Kermit and north of Wink) shows elevated total dissolved solids values that can be attributed to oil field salt water disposal (Figure 6-22). Improper placement of surface casing in oil and gas wells, corroded well casings, improper plugging and abandonment of oil and gas wells, brine injection well operation, and leaking oil field pipelines may all lead to high salinity in the Pecos Valley Aquifer.

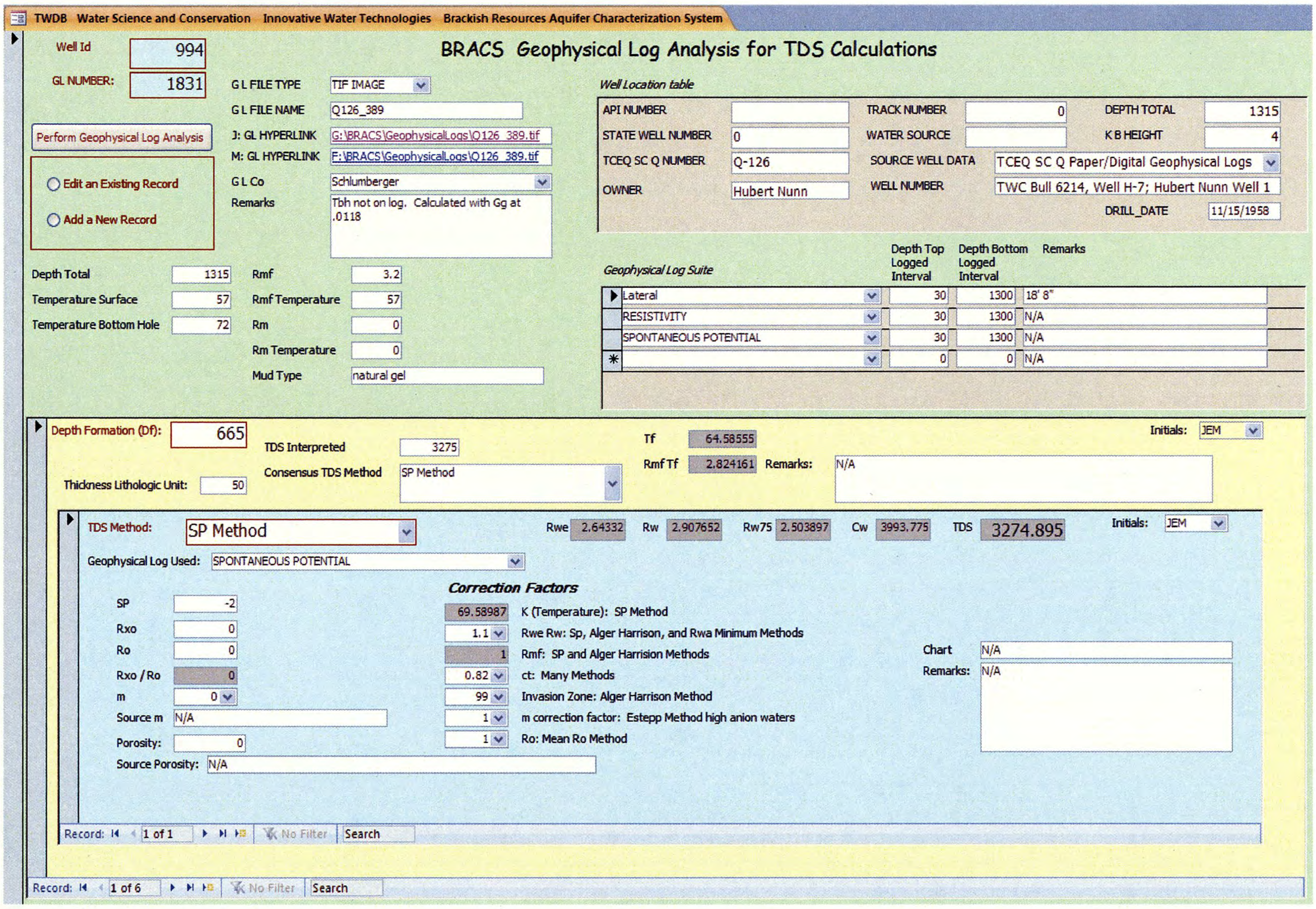
Cross-formational flow between the Pecos Valley Aquifer and the underlying Edwards-Trinity (Plateau), Dockum, and Rustler aquifers has been proposed in many previous investigations (Ashworth, 1990; Jones, 2004; LaFave, 1987; Ogilbee and others, 1962). Water quality changes over time have also been documented in the literature (Armstrong and McMillion, 1961a; Jones, 2004; TWDB Groundwater Database).

Irrigation return flow in western Ward County has led to a large increase in the concentration of total dissolved solids, primarily sodium and chloride, from irrigation practices that use Pecos River water. Over time, declining water levels in the Pecos Valley Aquifer have changed the groundwater gradient so that the Pecos River is losing water along its reach between Red Bluff Reservoir and Girvin (Ashworth, 1990; LaFave, 1987; White, 1971).

Sodium sulfate mining in southeastern Ward County at Ozark Lake is reflected in total dissolved solids concentration of more than 300,000 milligrams per liter in the surrounding Pecos Valley Aquifer (White, 1971).

7. Resistivity analysis of geophysical well logs

In Texas, geophysical well logs have been used for decades to interpret total dissolved solids concentration in order to select the depth of surface casing required in oil and gas wells. Before the start of the project, we had planned to use this technique to interpret total dissolved solids concentration in the aquifer. Unfortunately, there were not enough data for the study area and we could not use the technique. The method will have to be tested in other areas of the state where more data are available.



BRACS Geophysical Log Analysis for TDS Calculations

Well Id: 994
GL NUMBER: 1831
G L FILE TYPE: TIF IMAGE
G L FILE NAME: Q126_389
J: GL HYPERLINK: G:\BRACS\GeophysicalLogs\Q126_389.tif
M: GL HYPERLINK: F:\BRACS\GeophysicalLogs\Q126_389.tif
G L Co: Schlumberger
Remarks: Tbh not on log. Calculated with Gg at .0118

Depth Total: 1315
Temperature Surface: 57
Temperature Bottom Hole: 72
Rmf: 3.2
Rmf Temperature: 57
Rm: 0
Rm Temperature: 0
Mud Type: natural gel

Well Location table

API NUMBER:
STATE WELL NUMBER: 0
TCEQ SC Q NUMBER: Q-126
OWNER: Hubert Nunn
TRACK NUMBER: 0
WATER SOURCE:
SOURCE WELL DATA: TCEQ SC Q Paper/Digital Geophysical Logs
WELL NUMBER: TWC Bull 6214, Well H-7; Hubert Nunn Well 1
DEPTH TOTAL: 1315
K B HEIGHT: 4
DRILL_DATE: 11/15/1958

Geophysical Log Suite	Depth Top Logged Interval	Depth Bottom Logged Interval	Remarks
Lateral	30	1300	18' 8"
RESISTIVITY	30	1300	N/A
SPONTANEOUS POTENTIAL	30	1300	N/A
	0	0	N/A

Depth Formation (Df): 665
Thickness Lithologic Unit: 50
TDS Interpreted: 3275
Consensus TDS Method: SP Method
Tf: 64.58555
Rmf Tf: 2.824161
Remarks: N/A
Initials: JEM

TDS Method: SP Method
Geophysical Log Used: SPONTANEOUS POTENTIAL
Rwe: 2.64332
Rw: 2.907652
Rw75: 2.503897
Cw: 3993.775
TDS: 3274.895
Initials: JEM

SP: -2
Rxo: 0
Ro: 0
Rxo / Ro: 0
m: 0
Source m: N/A
Porosity: 0
Source Porosity: N/A

Correction Factors

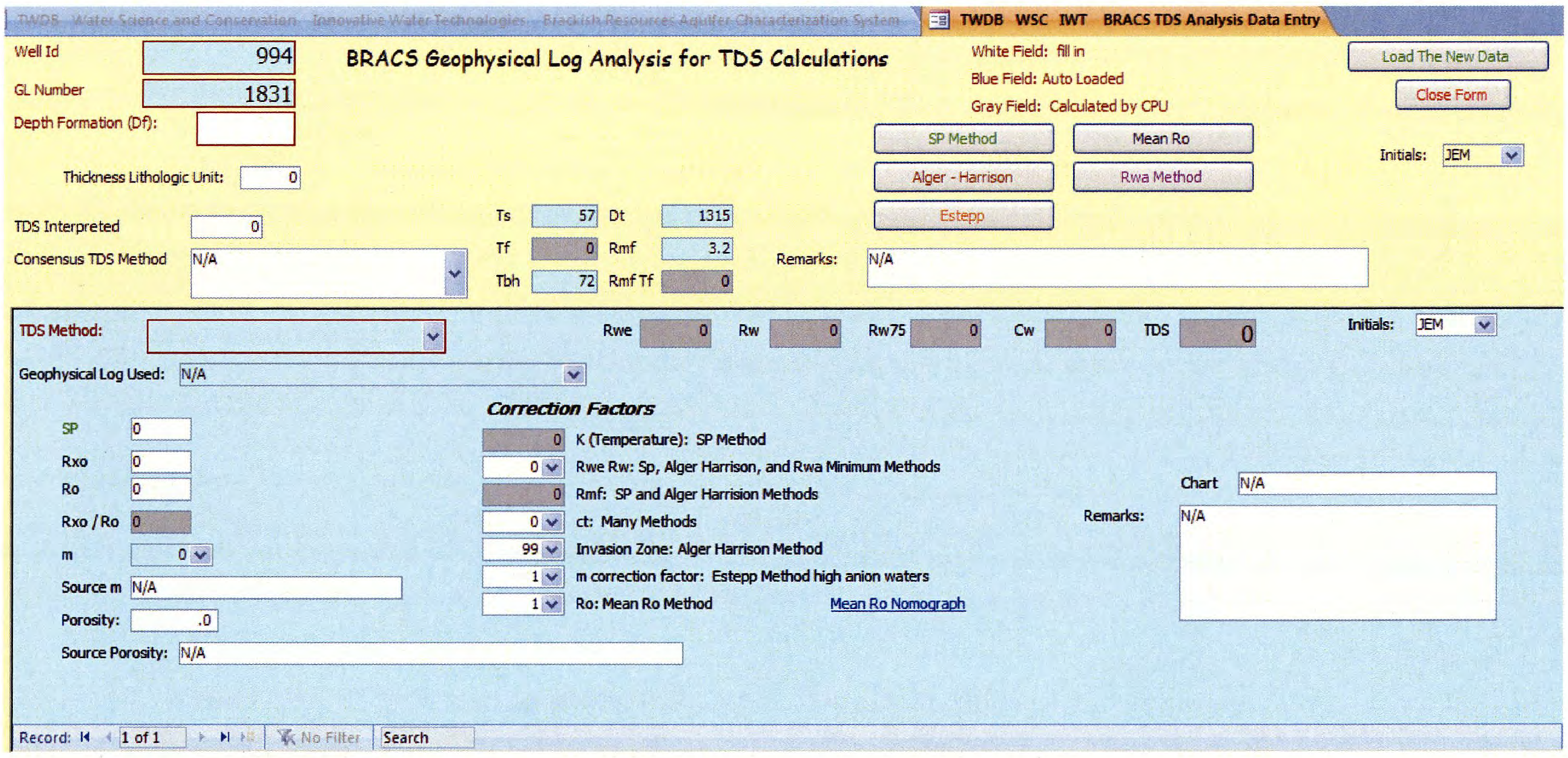
69.58987 K (Temperature): SP Method
1.1 Rwe Rw: Sp, Alger Harrison, and Rwa Minimum Methods
1 Rmf: SP and Alger Harrision Methods
0.82 ct: Many Methods
99 Invasion Zone: Alger Harrison Method
1 m correction factor: Estepp Method high anion waters
1 Ro: Mean Ro Method

Chart: N/A
Remarks: N/A

Figure 7-1. **BRACS Database primary form for total dissolved solids analysis using geophysical well logs. Completed analysis for BRACS Well 994 at depth 665 feet is shown in this screenshot.**

The interpretation of geophysical well logs began in and is a standard technique of the oil and gas industry, but the application of these tools to water analysis poses significant challenges. Resistivity recorded on geophysical well logs is a combination of the resistivity of the rock formation and the water contained in the pores combined with borehole effects and the resistivity of the mud and mud filtrate. In other traditional oil field interpretations, the dominant ions are sodium and chloride. In fresher waters, different cations and anions may dominate the groundwater and the traditional oil field interpretation techniques must be modified (Alger, 1966). The correction factors that must be applied to tool interpretation vary with the techniques used, the aquifer being studied, and the tools used to record resistivity. Estepp (1998, 2010) provides an excellent review and treatment of six different techniques that can be applied. Collier (1993a, 1993b) and Keys (1990) provide discussions on tools and limitations in assessment.

In the early stages of the project we made a decision to automate the calculations for five of the techniques described by Estepp (1998). Automation reduces the amount of time spent, which can be considerable, and the errors that can result from doing manual calculations. We decided that logs should be evaluated at multiple depth intervals using one or more methods per interval. Each method was reviewed; formulas with consistent terms written; and tables designed to contain raw, intermediate, and finished computation results (Figures 7-1 and 7-2). Visual Basic for Applications code was prepared and tested against the case studies presented by Estepp (2010). The Visual Basic for Applications code was written in BRACS Database modules and embedded in data entry forms linked to the primary tables. This work will be presented in a future TWDB report once testing for the different methods is completed. The work described in the next section should be considered a prototype of the spontaneous potential method.



BRACS Geophysical Log Analysis for TDS Calculations

White Field: fill in
Blue Field: Auto Loaded
Gray Field: Calculated by CPU

Well Id: 994
GL Number: 1831
Depth Formation (Df):
Thickness Lithologic Unit: 0
TDS Interpreted: 0
Consensus TDS Method: N/A
Ts: 57
Tf: 0
Tbh: 72
Dt: 1315
Rmf: 3.2
Rmf Tf: 0
Remarks: N/A
Initials: JEM

TDS Method:
Rwe: 0
Rw: 0
Rw75: 0
Cw: 0
TDS: 0
Initials: JEM
Geophysical Log Used: N/A
SP: 0
Rxo: 0
Ro: 0
Rxo / Ro: 0
m: 0
Source m: N/A
Porosity: .0
Source Porosity: N/A

0 K (Temperature): SP Method
0 Rwe Rw: Sp, Alger Harrison, and Rwa Minimum Methods
0 Rmf: SP and Alger Harrision Methods
0 ct: Many Methods
99 Invasion Zone: Alger Harrison Method
1 m correction factor: Estepp Method high anion waters
1 Ro: Mean Ro Method

Chart: N/A
Remarks: N/A

Figure 7-2. **BRACS Database secondary data entry form for total dissolved solids analysis using geophysical well logs. Beginning of data entry for BRACS Well 994 is shown in this screenshot.**

Table 7-1. **Working ranges of total dissolved solids for five interpretation methods (after Estepp, 2010).**

Total dissolved solids method	**Total dissolved solids range (milligrams per liter)**			
	100–1,000	**1,000–3,000**	**3,000–10,000**	**10,000–100,000**
Spontaneous potential	Fresh water correction required		Working range	
Alger-Harrison	Fresh water correction required		Working range	
Rwa Minimum	Fresh water correction required		Working range	
Estepp	Working range		Possible use	Not applicable
Mean Ro	Working range			

Note: Rwa = apparent formation water resistivity; Ro = deep resistivity

Table 7-2. **Parameters and correction factors required for geophysical well log interpretation of total dissolved solids.**

Parameter			**Total dissolved solids methods**				
Name	**Symbol**	**Units**	**Spontaneous potential**	**Alger-Harrison**	**Rwa Minimum**	**Estepp**	**Mean Ro**
Depth of well	Dt	feet	Yes	Yes	Yes	Yes	Yes
Depth of formation	Df	feet	Yes	Yes	Yes	Yes	Yes
Temperature at surface	Ts	degree Fahrenheit	Yes	Yes	NA	NA	NA
Temperature at bottom of hole	Tbh	degree Fahrenheit	Yes	Yes	NA	NA	NA
Resistivity of mud filtrate	Rmf	ohm-meter	Yes	Yes	NA	NA	NA
Rmf temperature	none	degree Fahrenheit	Yes	Yes	NA	NA	NA
Spontaneous potential	Spontaneous potential	+ / - millivolts	Yes	NA	NA	NA	NA
Deep resistivity	Ro	ohm-meter	NA	Yes	Yes	Yes	Yes
Shallow resistivity	Rxo	ohm-meter	NA	Yes	NA	Yes	NA
Porosity	none	percent	NA	NA	Yes	NA	Yes
Correction factors							
Total dissolved solids Specific conductivity	ct	none	Yes	Yes	Yes	NA	NA
High anions: Rwe to Rw	Rwe Rw	none	Yes	Yes	Yes	NA	NA
Resistivity: invasion zone	none	none	NA	Yes	NA	NA	NA
Cementation factor	m	none	NA	NA	Yes	Yes	NA
High anions: m correction	m cor	none	NA	NA	NA	Yes	NA
High anions: mean Ro	none	none	NA	NA	NA	NA	Yes
Mean Ro nomograph	none	none	NA	NA	NA	NA	Yes

Note: NA = not applicable

Each method of interpreting concentration of total dissolved solids is applicable only within a specific range of total dissolved solids concentration and requires correction factors (Table 7-1). Table 7-2, which summarizes the parameters for each method, can be used to select a method based on the types of geophysical well log tools and header information available.

7.1 Interpretive techniques

Only a handful of geophysical well logs in the study area contained spontaneous potential or resistivity tools within the depth range of the drinking water aquifers. Unfortunately, many logs were unsuitable for analysis of Pecos Valley Aquifer water because of the depth range, log quality, adequate input parameters, or tool type. Two example geophysical well logs analyzed for total dissolved solids are discussed next. The spontaneous potential tool provided the best results, and a brief discussion of this tool is also presented.

The spontaneous potential log is a record of the direct current reading between a fixed electrode at the ground surface and a movable electrode (spontaneous potential tool) in the well bore. The tool must be run in an open borehole with a conductive mud. Spontaneous potential is measured in millivolts. The electrochemical factors that create the spontaneous potential response are based on the differences in salinity between the mud filtrate in the borehole (Rmf) and the formation water resistivity (Rw) within permeable beds (Asquith, 1982). A negative deflection of the spontaneous potential response occurs when Rmf > Rw, and a positive deflection occurs when Rmf < Rw. When Rmf = Rw there is no deflection from the shale baseline. The spontaneous potential response of shale is relatively constant and is referred to as the shale baseline. The permeable bed boundaries are detected at the point of inflection of spontaneous potential response. The magnitude of deflection of the spontaneous potential response is due to the difference in resistivity between Rmf and Rw, not permeability.

Spontaneous potential is most affected by cation species, and oilfield analysis equations assume that the formation water is dominated by sodium and chloride. Divalent cations in dilute formation water have a larger impact on spontaneous potential response than sodium (Alger, 1966). The spontaneous potential response of high calcium or magnesium waters indicates that the water is more saline than an analysis using resistivity tools. Alger (1966) described a method for correcting this effect; however, a complete water quality analysis is needed to apply the correction. He indicated that once a well is calibrated, the analysis can be extrapolated from one well to another assuming that water quality remains relatively constant.

The spontaneous potential response is affected by bed thickness; thin beds do not allow a full spontaneous potential response and must be corrected (Asquith, 1982; Estepp, 1998; Schlumberger, 1972). If a sand unit is less than 10 feet thick, the response curve tends to have a pointed shape, and requires a thickness correction. Spontaneous potential response is also affected by bed resistivity, borehole invasion of drilling fluid, hydrocarbons, and shale content. Shale content reduces the spontaneous potential response. Spontaneous potential tools run in freshwater water wells commonly use native mud when, prior to logging, the borehole fluid is essentially formation water. In this situation, the resistivity of formation water and borehole fluid is almost equal and the spontaneous potential tool cannot be used to estimate total dissolved solids concentration (Keys, 1990).

7.1.1 BRACS Well 1376

BRACS Well 1376 lateral log was analyzed at 530 feet below ground surface using the 2/3 rule correction technique and the Alger-Harrison Method (Estepp, 1998). It produced an interpreted total dissolved solids concentration of 1,992 milligrams per liter. The spontaneous potential method when used at the same depth produced an interpreted total dissolved solids concentration of 3,150 milligrams per liter. When applied at a depth of 815 feet, the spontaneous potential method produced an interpreted total dissolved solids concentration of 2,603 milligrams per liter. The decrease in total dissolved solids with depth could be natural: higher salinity water occurring over lower salinity water. Alternatively, it could be due to an increase in clay content in a sand layer located at this depth, which creates a lower spontaneous potential response with a concomitant higher concentration of estimated total dissolved solids.

Seven water wells located within about a mile of BRACS Well 1376 contained total dissolved solids at an average concentration of 2,860 milligrams per liter (Table 7-3 and Figure 7-3). The percent sodium divided by the sum of cations ranged from 42 to 93 percent in wells nearby (Table 7-3). Well screens varied above and slightly below the interpreted depths of 530 and 815 feet sands in BRACS Well 1376. Total dissolved solids concentration also varied with depth, with some wells showing zones of higher salinity located above zones of lower salinity and vice versa. The contributions of water to, and the mixing relationships within, the well bore among the sampled wells is not known. The data suggest that water chemistry in the region may be highly variable.

Table 7-3. **Water quality samples surrounding BRACS Well 1376. Refer to Figure 7-3 for well locations. Asterisk in total dissolved solids field indicates an average of multiple samples.**

State well number	Well ID	Total dissolved solids (milligrams per liter)	% Sodium in summed cations	Well screen (feet below ground surface)	Well depth (feet below ground surface)
4635906	925	2,261	93	480-910	910
N/A	3116	2,540	49	200-885	885
N/A	3132	2,880	49	N/A	400
4635902	N/A	3,352*	74	200-585	585
4635905	N/A	2,868*	74	N/A	850
4635907	N/A	2,706*	63	N/A	839
4636707	N/A	3,415*	42	295-815	871

Note: N/A = not available; ID = identification number

The concentration of total dissolved solids estimated by the spontaneous potential method is well within the upper and lower range recorded in samples collected from wells installed within the same depth zone in this part of Reeves County. The spontaneous potential was not corrected for cations in this analysis. The concentration of total dissolved solids estimated using the Alger-Harrison method using the lateral tool was lower than the range in total dissolved solids. This may be due to tool idiosyncrasy (described next) or because of the presence of high concentrations of sulfate anions that have a large effect on the resistivity tool response.

Resistivity tools using the lateral log were determined to be inadequate for our study because the tool response needs corrections for asymmetrical curves and anomalous signals created by adjacent bed thickness and resistivity differences (Schlumberger, 1972).

7.1.2 BRACS Well 994

BRACS Well 994 was analyzed at six different depths (Table 7-4). The well-screen in this well was installed at depths of between 457 and 1,005 feet, but the well itself was logged to a total depth of 1,315 feet below ground surface. The spontaneous potential response and interpreted total dissolved solids concentration increased progressively with depth. Existing lab analysis of water samples collected from the well shows total dissolved solids concentration of 3,660 milligrams per liter. The average interpreted total dissolved solids concentration for the three depth zones (665–1,055 feet) was 3,567 milligrams per liter, matching the concentration determined in the lab very closely.

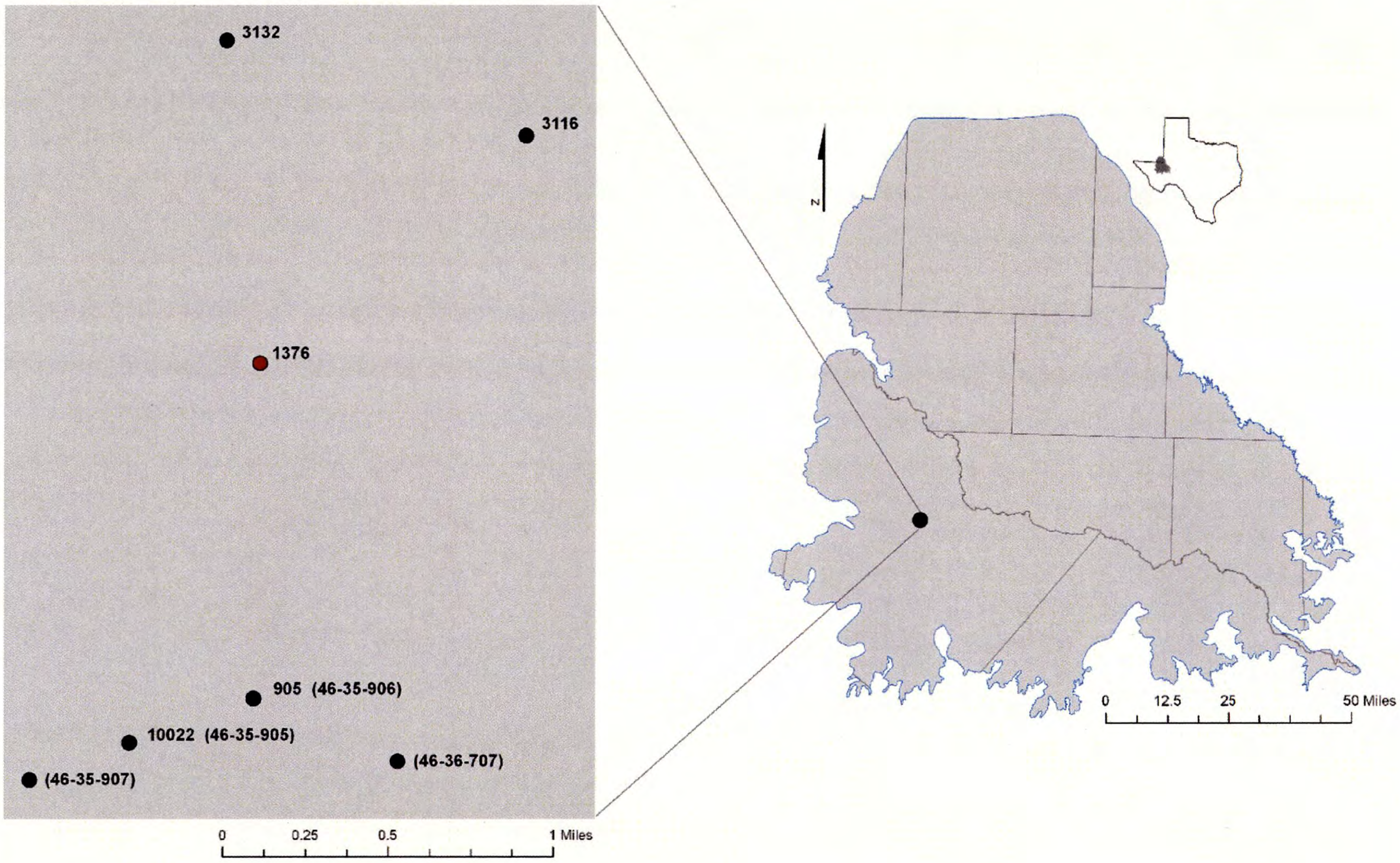


Figure 7-3. **Locations of wells used for interpreted total dissolved solids from geophysical well log 1376 and wells with water quality data. Numbers refer to the BRACS well identification number and state well number (in parentheses). See Table 7-3 for total dissolved solids information.**

The interpreted total dissolved solids concentration did not include a cation correction, even though the percent sodium concentration divided by the sum of cations for well 994 was 40 percent and ranged from 39 to 48 percent for nearby wells (Table 7-5). Water quality measured in six nearby wells (Table 7-5 and Figure 7-4) averaged 3,759 milligrams per liter. An examination of Table 7-4 shows an increase in total dissolved solids concentration to 7,400 milligrams per liter in the lowest sand encountered during drilling. This suggests that there is stratification of saline water in the Pecos Valley Aquifer in the Pecos Trough. Because most water wells, including all the nearby wells, do not fully penetrate the aquifer in this region (Figure 6-10), a thorough examination of this phenomenon is not possible without additional well control or spontaneous potential logs.

Table 7-4. **The spontaneous potential log from BRACS Well 994 located in Reeves County was assessed at six depth intervals for interpreted total dissolved solids. The well was also screened and sampled for total dissolved solids. This table shows the vertical relationships of the assessment.**

Depth (feet below ground)	Interpreted total dissolved solids (milligrams per liter)	Average total dissolved solids (milligrams per liter)	Well screen (feet below ground)	Lab total dissolved solids (milligrams per liter)
457	N/A	N/A	457-1,005	3,660
665	3,275	3,567		
820	3,441			
1,005	N/A			
1,055	3,985		N/A	N/A
1,145	4,253	N/A	N/A	N/A
1,245	6,499	N/A	N/A	N/A
1,295	7,400	N/A	N/A	N/A

Note: N/A = not available

Table 7-5. **Water quality samples surrounding BRACS Well 994. Refer to Figure 7-4 for well locations.**

State well number	Well ID	Total dissolved solids (milligrams per liter)	% Sodium in summed cations	Well screen (feet below ground)	Well depth (feet below ground)
4635503	992	3,941*	45	344-1,053	1,053
N/A	994	3,660	40	457-1,005	1,005
N/A	3101	3,630	39	N/A	800
4635501	N/A	3,966	48	300-865	865
4635801	N/A	3,638*	40	125-780	780
4635803	N/A	3,718	45	N/A	550

Notes: *=average total dissolved solids from multiple samples

N/A = not available

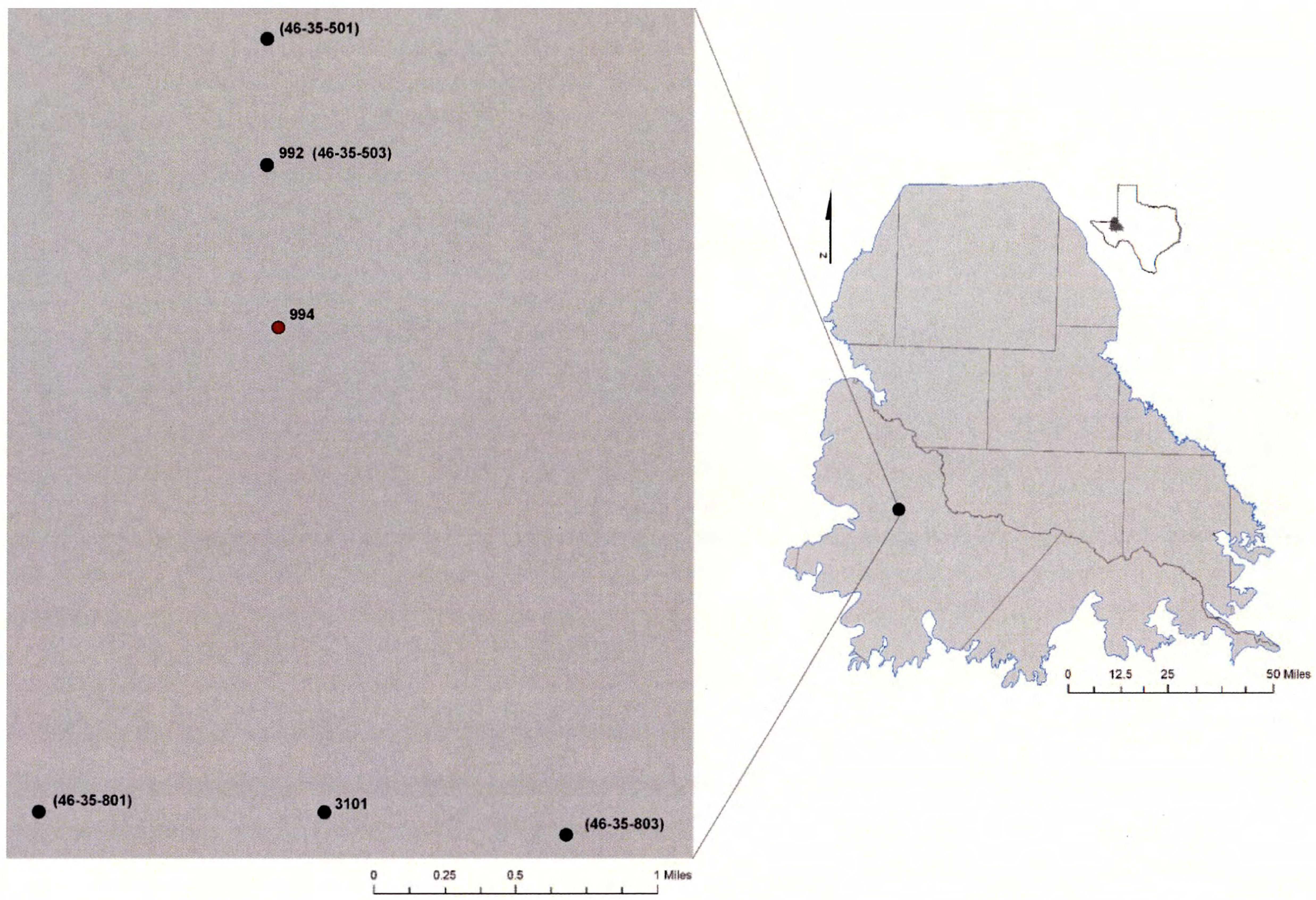


Figure 7-4. **Locations of wells used for interpreted total dissolved solids from geophysical well log 994 and wells with water quality data. Numbers refer to BRACS well identification number and state well number (in parentheses). See Table 7-5 for total dissolved solids information.**

7.2 Results

The lack of appropriate geophysical well logs at shallow depths within the study area precluded a thorough assessment of the geophysical well log techniques to interpret the total dissolved solids concentration in groundwater. Additional work needs to be done in other areas of Texas to better test the technique and understand its limitations. The principal requirement for using this technique is the availability of data and control on the correction factors necessary to interpret the logs.

The interpretation of total dissolved solids using the spontaneous potential tool in the Pecos Valley Aquifer study area appears promising, despite the limited number of logs available. Additional work will need to be done to incorporate a cation-correction process for this method. Interested users should continue to look for shallow geophysical well logs that may be available in other collections.

8. Database description

The TWDB Groundwater Database, which has been in use for more than 25 years, is in the process of being redesigned to meet future requirements. The redesign project is expected to be completed within a few years. During the early stages of the Brackish Resources Aquifer Characterization System program, we determined that the existing TWDB Groundwater Database was not capable of managing all of the new information and storing the procedures that are needed to analyze the data to meet the project objectives. To meet these objectives and deadlines, and the long-term goal of merging the BRACS Database tables with the future Groundwater Database, staff selected Microsoft® Access® 2007 as the BRACS Database software. Microsoft Access has proved to be excellent software for managing project information and testing new table and analysis designs.

All well information and supporting databases for the Pecos Valley Aquifer project are managed in Microsoft® Access® 2007. When spatial analysis is required, copies of information are exported into ArcGIS®. Information developed in ArcGIS® is then exported back into Microsoft® Access® and the tables are updated accordingly. Although this approach may be cumbersome, it takes advantage of the strengths of the software. The project also relied on other software for specific tasks, including Microsoft® Excel®, Schlumberger Blueview (for geophysical well log analysis), and ViewLog from EarthFX (for developing geologic cross-sections).

For the project, we assembled information from external agencies and updated these databases frequently. All of these databases are maintained in Microsoft® Access® and GIS files developed for spatial analysis and well selection. Many of the databases were built from scratch or were redesigned to meet project objectives. Data from external agencies or projects were available in many different data designs, so establishing a common design structure proved beneficial in leveraging information compiled by other groups. For example, well location attributes available in the Railroad Commission of Texas oil and gas well database were easily copied to the BRACS Database table. This saved us a tremendous amount of time and helped reduce errors during data entry.

The BRACS and supporting databases are fully relational. Data fields common to multiple datasets have been standardized in data type and name with lookup tables shared between all databases. Database object names use a self-documenting style that follows the Hungarian naming convention (Novalis, 1999). The volume of project information required us to develop comprehensive data entry and analysis procedures (coded as tools) that were embedded on forms used to display information. Visual Basic for Applications is the programming language used in Microsoft® Access®, and all code was written at the Microsoft® ActiveX® Data Objects level with full code annotation. The code for geophysical well log resistivity analysis was specifically written with class objects to support a rapid analysis of information with the benefit of only having data appended when the user approved the results.

The BRACS Database is documented in a data dictionary, which is available from the TWDB Web site (http://www.twdb.state.tx.us/innovativewater/bracs/). The following two sections will briefly describe the BRACS Database table relationships and the supporting databases developed to date.

8.1 Table relationships

The BRACS Database contains 16 primary tables of information (Table 8-1), 35 lookup tables, 9 tables designed for GIS export, and many supporting tables for analysis purposes. A brief description of each of the primary tables is provided in this section. Lookup tables provide control on data entry codes or values for specific data fields (for example, a county lookup table with all 254 county names in Texas). The tables for GIS export are copies of information obtained from one or more tables and in some cases are reformatted to meet GIS analysis needs. These tables can be custom tailored to meet project needs and will not be discussed further.

A fully relational database design has information organized into tables based on a common theme. Information must be segregated into separate tables for each one-to-many data relationship. For example, one well may have many well screens with unique top and bottom depth values; each well screen constitutes one record. Tables are linked by key fields. For each one-to-many relationship at least one additional key field is required. The field well_id is the primary key field for every table in the BRACS Database.

8.1.1 Well locations

The table tblWell_Location contains one record for each well record in the BRACS Database and is assigned a unique well_id as the key field. The well_id field links all the tables together. This table contains information such as well owner, well depth(s), location attributes (such as latitude, longitude, and elevation), source of well information, county name, and date drilled.

8.1.2 Foreign keys

The table tblBracs_ForeignKey has zero to many unique well identification names or numbers assigned to it (for example, state well number and American Petroleum Institute number). These identifiers, also known as foreign keys, permit database linkage to the supporting databases developed from external agencies and other TWDB project databases with geophysical well logs and stratigraphic pick information.

8.1.3 Digital well reports

The table tblBracsWaterWellReports contains zero to many records for digital copies of water well reports and miscellaneous records including oil and gas well scout tickets. The purpose of this table is to track the digital file names, file types, and hyperlinks to the documents.

8.1.4 Geophysical well logs

Information on the digital geophysical well logs is recorded in the table tblGeophysicalLog_Header. This includes the type of digital file, digital file name, data hyperlink to the log image, and well log parameters such as depth, temperature of the bottom hole, and resistivity of the mud filtrate. The well log parameters were only recorded if the well log was to be used for resistivity analysis for total dissolved solids.

Each geophysical well log may have one or more tools used to record subsurface parameters. This information is recorded in the table tblGeophysicalLog_Suite. Each tool name and its start and bottom depth values in feet below ground surface were recorded in this table.

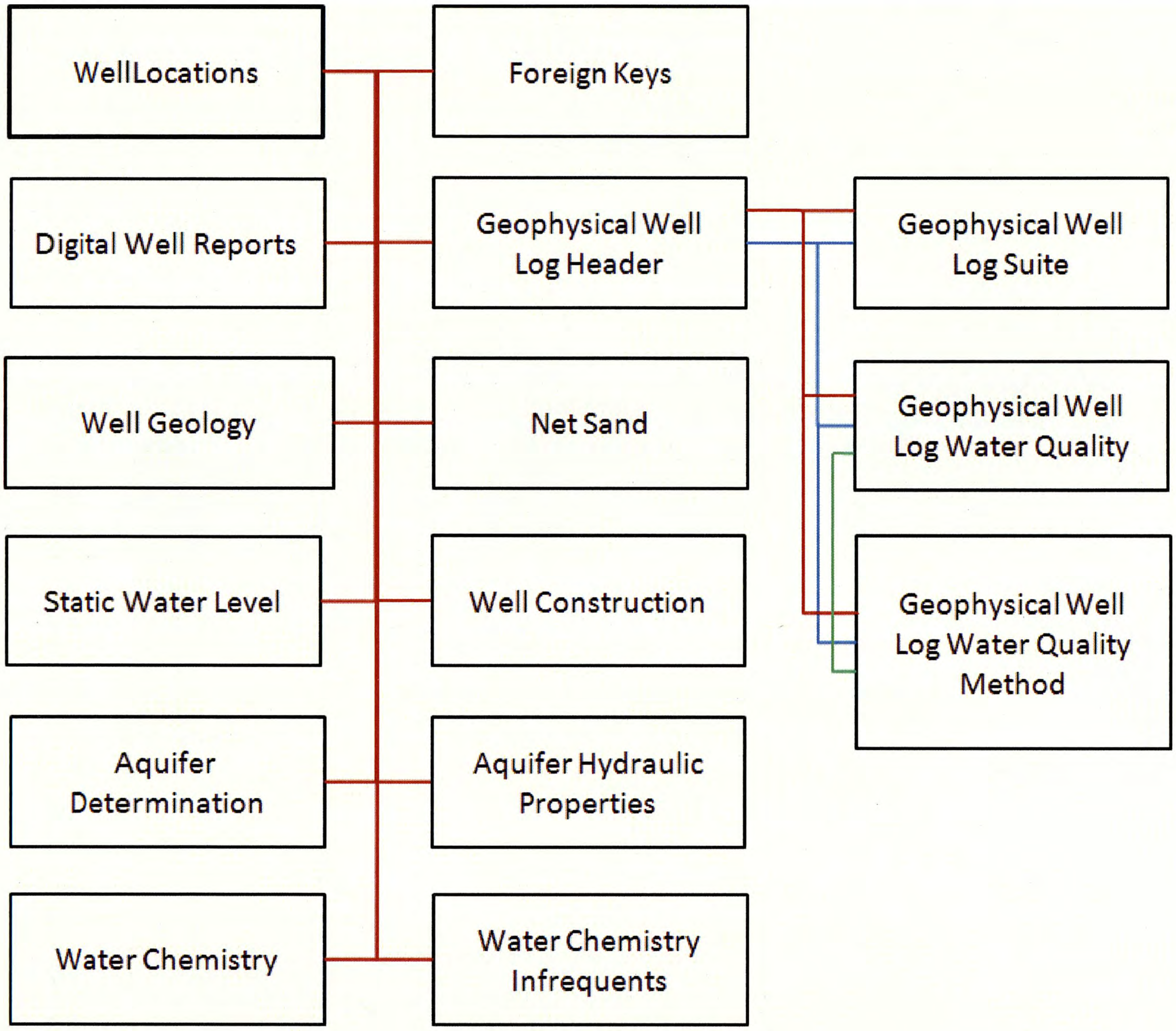


Figure 8-1. BRACS Database table relationships. Each rectangle represents a primary data table. The lines connecting the tables represent key fields: red represents the primary key well_id; blue represents the second key; green represents the third key. New well records must be appended to the well locations table to set the unique well_id.

The results from resistivity analysis for total dissolved solids are recorded in two tables. Evaluating more than one depth interval per well necessitated designing the table, tblGeophysicalLog_WQ, to hold the depth of formation, temperature, and resistivity of the mud filtrate values for that interval. Evaluating more than one resistivity technique per depth interval dictated designing one table, tblGeophysicalLog_WQ_Method, to hold the analysis results including interpreted total dissolved solids, log correction values, method used, geophysical well log used, and a multitude of intermediate values.

8.1.5 Well geology

The descriptions of rock types reported on drillers' well logs, simplified lithologic descriptions, stratigraphic picks, and hydrogeologic names are all contained in the table tblWell_Geology. Each record contains a top and bottom depth, thickness of the unit, top and bottom elevations, source of data, and a value for type of geologic pick (for example, lithologic, stratigraphic, or hydrogeologic). The latter field permits the storage of all this information in one table and the ability to view the information in one form.

The analysis of net sand, maximum sand thickness, and sand percent for each well record is contained in the table tblWell_Geology_NetSand. The table is custom-designed for this project because the analysis is for the Pecos Valley Alluvium and Dockum Group.

8.1.6 Well construction

Well casing and screen information is contained in the table tblBracs_Casing. This table design is similar to the well-casing table in the TWDB Groundwater Database and contains top and bottom depths for casing and screen.

8.1.7 Water quality

Two tables contain the results of water quality analyses recorded for wells that are not in the TWDB Groundwater Database: tblBracsWaterQuality and tblBracsInfrequentConstituents. The table designs are similar to those in the TWDB Groundwater Database. The analogous table designs will be helpful when the BRACS and TWDB Groundwater databases are merged in the future.

All water quality records for wells in the study area were appended to the table tblBRACS_PV_MasterWaterQuality. These include records obtained from the TWDB Groundwater Database and records obtained from research for wells in the BRACS Database.

8.1.8 Static water level

Static water level information is contained in the table tblBRACS_SWL. The table is similar to its equivalent in the TWDB Groundwater Database. Information on dates, water levels, and source of measurement are recorded in the table.

8.1.9 Aquifer hydraulic properties

Information from existing aquifer tests conducted in the Pecos Valley and Dockum aquifers is contained in the table tblBRACS_AquiferTestInformation. The table contains fields for hydraulic conductivity, transmissivity, specific yield, storage coefficient, drawdown, pumping rate, specific capacity, the types of units for each measurement, date of analysis, source of information, and remarks. If an analysis included the top and bottom depths of the screen, well depth, and static water level, it was captured in this table in case the values differed from that presented in the casing table (test may have been performed before total depth of the well was reached). The length of aquifer tests, values for drawdown versus recovery, pumping and static water levels, and two analysis remarks fields complete the table design. Because many results are from Myers (1969), a page reference to that report for each test is recorded and references to other published reports and table numbers are also included.

8.1.10 Aquifer determination

The results of the aquifer determination for well records described in Section 6.2 are presented in table tblAquiferDetermination. This table includes fields for the project region, new aquifer decision, TWDB Groundwater Database aquifer code assigned to the well (if any), well and screen depths, whether the well has multiple screens, aquifer decision codes, well owner, and latitude/longitude coordinates. Fields for formation top and bottom depths of the Pecos Valley Alluvium, Cretaceous Undivided, Dockum Group-Dewey Lake Formation, Rustler Formation, and Capitan Reef Complex are listed.

8.2 Supporting datasets

Many GIS datasets were created during the course of this project. The GIS techniques used to build the files are explained in the following sections. Each GIS file contains metadata.

8.2.1 GIS dataset development

The raster grid files are limited to 12 characters, necessitating the development of a file naming scheme for all GIS files. This scheme was also applied to table field names and Visual Basic Coding within the Microsoft® Access® database for consistency among datasets. A list of the file naming conventions and GIS files organized by formation is presented in Appendix 13.1.

8.2.2 Processes to create datasets

ArcGIS® and the Spatial Analyst extension software by Environmental Systems Research Institute, Inc. were critical components of the GIS creation and analysis of spatial data for the project. Files created and managed in GIS consist of point, polyline, and polygon shapefiles and grid files.

All well records were managed in Microsoft® Access® databases. Well records were queried from the databases and imported into ArcGIS® for spatial analysis. When new attributes were added to a well using ArcGIS®, the information was imported into Microsoft® Access® and the well records updated.

Every well record in each database used for this project contained latitude and longitude coordinates in the format of decimal degrees with a North American Datum of 1983. All of these well records were imported into ArcGIS® and georeferenced in a geographic coordinate system, North America, North American Datum 1983 projection. A point shapefile was then saved in a working directory. Every well record then had an elevation assigned from the U.S. Geological Survey seamless 30-meter digital elevation model using the ArcGIS® tool (toolbox, extraction, and extract value to point). The dbase file from each shapefile was then imported into Microsoft® Access® and the elevation data updated to each well record, along with date, method, vertical datum, and agency attributes. Each well record also recorded the kelly bushing height when available. GIS point files subsequently created for each formation were corrected for kelly bushing height and elevation.

In many cases, new wells were plotted in ArcGIS® and the latitude, longitude, and elevation were determined and appended to the database tables manually. The Original Texas Land Survey obtained from the Railroad Commission of Texas was the principal base map used to plot well locations; county highway maps and topographic maps were used on occasion.

All formation surfaces (top, bottom, and thickness) began with a finished point file that was interpolated with ArcGIS® Spatial Analyst. Formation surfaces were prepared using the Environmental Systems Research Institute integer grid format that stores raster information. Every grid created used a reference grid with a 250-foot cell size for coordinate system, grid extent, and snap raster.

As an example, the Pecos Valley Alluvium bottom depth surface was interpolated with the topo to raster tool, where sinks were not enforced. The next step was to create a contour map using the Spatial Analyst, Surface, and Contour tool. The contour map was manually edited to fit the data points and conform to the geology of the area. Data points were reviewed, and in many cases new data were collected and interpreted to fill in problematic areas. When the final contour map was completed, the polylines of the contour map were converted to points using the ArcGIS® tool (data management, features, and feature vertices to points). Latitude and longitude coordinates were assigned to each point. All contour points and well points were appended to one file and then georeferenced. This new point file was then interpolated with the natural neighbor tool. Although the natural neighbor tool did a reasonable job with point interpolation, it did not create a surface that extended beyond point control. In some cases, points had to be added along the edge of the study area to force the tool to extend a surface to cover the entire study area.

Areas representing outcrops of the Dockum Group and Cretaceous formations were extracted from the Geologic Atlas of Texas geodatabase and converted into shapefiles and grid files. The outcrop areas were converted to no-data cells in the Pecos Valley bottom depth surface. Data cells extending beyond the extent of the Pecos Valley Alluvium were also converted to no-data cells. Finally, a grid of each well data point was created and this cell value was used to replace the cell value in the master surface grid so that the stratigraphic value at each well was accurately reflected on the surface map. This step was critical to ensuring that the solution collapse sinks were accurately represented.

The depth surfaces for the Pecos Valley Alluvium, Cretaceous Undivided, and Rustler Formation top were all processed with the previously described techniques. Intervening formation surfaces were created by processing the adjacent surface: for example, the bottom surface of the Dewey Lake Formation is the top surface of the Rustler Formation.

A project elevation surface matching the snap raster was created from the U.S. Geological Survey seamless 30-meter digital elevation model. The elevation surfaces of geological formations were created by subtracting the depth to the surface from the project elevation (DEM) surface. These surfaces were then contoured using the ArcGIS® contour tool.

8.2.3 Map projection parameters

Map projection parameters are contained in the metadata associated with each GIS file.

Each point shapefile in GIS was georeferenced using latitude and longitude in a decimal degree format using the ArcGIS® geographic coordinate system projection, North America, North American Datum 1983.

Polyline and polygon shapefiles and grid files are in a Lambert Conformal Conic projection, North American Datum 1983, known as the Texas State Mapping System that covers the entire state of Texas. Grid files used the Texas State Mapping System with a linear unit of a foot because this file format was required as an input to the ViewLog software for cross-section creation and analysis.

Supporting GIS files may be in a variety of projections with a North American Datum 1983 horizontal datum.

The project snap raster was created to synchronize every grid file in terms of extent, coordinate system projection, and especially grid cell size and registration. Grid files must be "snapped" to a standard grid so that the corners of each grid are registered exactly, ensuring that subsequent grid calculations will be accurate.

9. Future improvements

The technique of applying geophysical well log analysis to estimate the concentration of total dissolved solids could not be fully examined in the study because of the scarcity of geophysical well logs containing the requisite information. This will have to be investigated in future studies where the data are available. The spontaneous potential analysis will require a correction process for cations added to the Visual Basic Code and database table design that must be developed and tested. After these techniques are thoroughly tested and proved, a user manual can be written to document the methodology and data entry processes.

During the course of this project, we became aware of consultant reports prepared for some of the well field exploration and development in the region. Unfortunately, we were not able to procure these reports. This will always be a challenge even in future projects, especially if the reports are several decades old and in some cases are still considered proprietary. A greater effort must be made to identify and procure this valuable information.

The TWDB will need to identify methods of providing the digital geophysical well logs to the public via the World Wide Web. The TWDB will also need to scan the paper geophysical well logs in its collection and convert them into electronic files.

Collecting enough hydraulic parameter information (for example, transmissivity and hydraulic conductivity) to produce detailed GIS maps is and will always be a challenge. The productivity of proposed wells is crucial to evaluating a brackish resource for desalination. Although well data from regional projects will never be as good as site-specific well testing in a proposed field, we will continue to collect this valuable information and append it into the BRACS Database even after a study has been completed. We need to evaluate techniques to interpret geophysical well logs to determine whether we can gain additional knowledge about these parameters.

The BRACS Database will continue to evolve as new projects are undertaken, new methods of data analysis used, and additional datasets generated. In the future, the BRACS Database will be integrated with the TWDB Groundwater Database to produce one comprehensive database.

As the Brackish Resources Aquifer Characterization System program moves into new study areas across the state, the program will need to be flexible to handle the challenges of data availability, geology, and changing priorities for the brackish groundwater resources of the state. Forging partnerships with organizations, agencies, and other interested entities will be crucial to the success of the program.

10. Conclusions

We estimate that the Pecos Valley Aquifer contains about 15 million acre-feet of fresh water, 85 million acre-feet of brackish groundwater (1,000 to 10,000 milligrams per liter of total dissolved solids), and 1 million acre-feet of very saline water (>10,000 milligrams per liter of total dissolved solids). The brackish water is present almost everywhere in the aquifer but appears to be more prevalent in the central and western parts. These are also areas where the saturated thickness of the aquifer is the greatest.

The 2010 approved Region F water plan projects water shortages of about 28,887 acre-feet in 2010, increasing to 35,342 acre-feet in 2060. Desalination of brackish groundwater present in the Pecos Valley Aquifer may be one option to meet at least some of these projected shortages.

Using the detailed datasets compiled for and generated during the study, water planners can begin to more closely focus on areas of specific interest and evaluate potential well field locations. The information presented in the report and that available in the datasets cannot, however, replace or be a substitute for a detailed site investigation that involves test well drilling, aquifer testing, and water quality analysis.

The pilot study has helped lay the foundation for future Brackish Resources Aquifer Characterization System projects by developing a database management system in which a variety of data can be stored and processed.

11. Acknowledgments

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13. Appendices

13.1 GIS datasets

Table of GIS file naming conventions

Each code will be separated from the next code with an underscore character. For example, the code pv_b_d_snmi refers to the Pecos Valley Alluvium bottom depth surface created by the natural neighbor surface technique, masked, integer value.

Code position	**Code type**	**Code**	**Code description**
1	Stratigraphic	bc	Bell Canyon Formation
1	Stratigraphic	cr	Capitan Reef Complex
1	Stratigraphic	dd	Dockum Group-Dewey Lake .Formation Interval
1	Stratigraphic	dl	Dewey Lake Formation
1	Stratigraphic	do	Dockum Group
1	Stratigraphic	ku	Cretaceous Undivided (Edwards-Trinity (Plateau))
1	Stratigraphic	o	Ogallala Aquifer
1	Stratigraphic	pkd	Pecos-Cretaceous-Dockum-Dewey Lake Grouped Interval
1	Stratigraphic	pv	Pecos Valley Alluvium
1	Stratigraphic	rsc	Rustler-Salado-Castile Interval
1	Stratigraphic	ru	Rustler Formation
2	Outcrop	otc	Dataset represents the extent of formation outcrop
2	Surface Position	b	Bottom surface
2	Surface Position	t	Top surface
3	Value	d	Depth (feet below ground surface)
3	Value	e	Elevation (feet above mean sea level)
3	Value	sat	Saturated
3	Value	tds	Total dissolved solids
3	Value	thk	Thickness (feet)
3	Value	vbw	Volume brackish water
3	Value	wq	Water quality analysis of well
4	Data Type	c,con,cwb	Contour
4	Data Type	conpts	Point file containing contour vertex points and well point stratigraphic picks. Used to generate a grid surface.
4	Data Type	pg	Polygon
4	Data Type	pl	Polyline
4	Data Type	pt	Point (generally stratigraphic pick values)
4	Data Type	s,sur	Surface
4	Data Type	st	Stratigraphic pick, point
4	Value	swl	Static water level
5	Surface Method	id	Inverse distance weighted
5	Surface Method	k	Kriging
5	Surface Method	n	Natural neighbor
5	Surface Method	s	Spline
5	Surface Method	swb	Spline with barrier (fault; escarpment)
5	Surface Method	tr	Topo to raster
6	Contour Interval	100	100 foot contour interval
6	Contour Interval	250	250 foot contour interval
6	Contour Method	wb	Contouring perform with barrier (fault; escarpment)
7	Mask	m	Mask (set at the project boundaries)
8	Surface Data Value	fp	Floating point
8	Surface Data Value	i	Integer value
9	Elevation	elev	Elevation data extracted to snap grid
10	Snap Raster	snap	Snap raster file used to snap all project cells into conformable alignment
11	Snap Raster Cell Size	250	Square cell size in feet (cell size in meters will be followed by m)
11	Snap Raster Cell Size	500	Square cell size in feet (cell size in meters will be followed by m)

Table field definitions:

Point file: all point files are shapefiles.

Surface file: all surface files are raster integer grid files.

Contour file: all contour files are polyline shapefiles.

Outcrop correction (Yes/No): Were outcrops of other formations used to correct the formation surfaces.

Well Point Correction (Yes/No): Were well point stratigraphic values used to replace surface cell values after the formation surface was prepared. This step allows well points database and GIS files to match exactly.

Elevation Correction (Yes/No): Were formation surfaces compared with project elevation surfaces for "porpoising," where an interpolated surface projects above a known elevation of a cell site.

Pecos Valley Alluvium

Formation surface	Point file	Surface file	Contour file	Outcrop correction	Well point correction	Elevation correction
Bottom depth	pv_b_d_pt o_b_d_pt	pv_b_d_snmi	pv_b_d_cwb	Yes	Yes	No
Top elevation	none	pv_t_e_si	none	Yes	none	Yes
Bottom elevation	pv_b_e_pt o_b_e_pt	pv_b_e_snmi	pv_b_e_cwb	Yes	Yes	Yes
Thickness	pv_b_d_pt o_b_d_pt	pv_b_d_snmi	pv_b_d_cwb	Yes	Yes	Yes
Saturated thickness	none	pv_sat_thk	none	Yes	none	none
Static water level	pv_swl_pt_00-09	pv_swl_00-09	none	Yes	none	none
Brackish volumes	none	pv_vbw_1 pv_vbw_2 pv_vbw_3 pv_vbw_4	none	Yes	none	none

Notes:

Ogallala points extracted for Texas and New Mexico in areas within and adjoining the study area to develop the Pecos datasets.

Pecos Valley Alluvium top elevation surface based on U.S. Geological Survey 30-meter elevation grid re-sampled to project 250-ft cell size.

File pv_con_barrier.shp was used to construct contours in Reeves County along the Cretaceous escarpment.

Brackish Volumes: pv_vbw_1 contains the volume of the 0–999 milligrams per liter range of total dissolved solids.

pv_vbw_2 contains the volume of the 1,000–2,999 milligrams per liter range of total dissolved solids.

pv_vbw_3 contains the volume of the 3,000–9,999 milligrams per liter range of total dissolved solids.

pv_vbw_4 contains the volume of the > 10,000 milligrams per liter range of total dissolved solids.

Cretaceous Undivided

Formation surface	Point file	Surface file	Contour file	Outcrop correction	Well point correction	Elevation correction
Top depth	ku_t_d_pt	ku_t_d_snmi		Yes	Yes	No
Bottom depth	ku_b_d_pt	ku_b_d_snmi	ku_b_d_con	Yes	Yes	No
Top elevation	ku_t_e_pt	ku_t_e_snmi		Yes	Yes	Yes
Bottom elevation	ku_b_e_pt	ku_b_e_snmi	ku_b_e_con	Yes	Yes	Yes

Notes:

The mapped surfaces in the outcrop areas in northwest Ward and northeast Reeves counties used 25-foot bottom depth as a default value and zero contour thickness surrounding the outcrops.

Cretaceous Undivided top depth/elevation is based on the Pecos Valley Alluvium base in regions 3 and 4 (Figure 6-1).

Dockum Group

Formation surface	Point file	Surface file	Contour file	Outcrop correction	Well point correction	Elevation correction
Top depth	do_t_d_pt	do_t_d_snmi		Yes	Yes	No
Top elevation		do_t_e_snmi		Yes	Yes	Yes

Notes:

For most of the study area, the Dockum Group and Dewey Lake Formation are mapped as one group. There is an area in Reeves County where the Dockum Group is missing, and the Dewey Lake Formation does have a top surface mapped. The Dockum Group bottom surfaces (depth, elevation) not prepared.

Individual formations within the Dockum Group were not mapped; however, the sandy part of the Dockum Group (commonly referred to as the Santa Rosa where it occurs) can be identified based on lithology determined from water wells and geophysical well log, gamma ray interpretations.

Dewey Lake Formation

Formation surface	Point file	Surface file	Contour file	Outcrop correction	Well point correction	Elevation correction
Top depth	dl_t_d_pt	dl_t_d_snmi		No	Yes	No
Bottom depth	dl_b_d_pt	dl_b_d_snmi	dl_b_d_con	No	Yes	No
Top elevation	dl_t_e_pt	dl_t_e_snmi		No	Yes	No
Bottom elevation	dl_b_e_pt	dl_b_e_snmi	dl_b_e_con	No	Yes	No

Notes:

For most of the study area, the Dockum Group and Dewey Lake Formation are mapped as one group. There is an area in Reeves County where the Dockum Group is missing, and the Dewey Lake Formation does have a top surface mapped (equals base of Pecos Valley Alluvium or base of Cretaceous Undivided where present).

The Dewey Lake bottom depth/elevation is based on the Rustler top. Dewey Lake Formation bottom depth/elevation contours based on Rustler Formation top contours.

Rustler Formation

Formation surface	Point file	Surface file	Contour file	Outcrop correction	Well point correction	Elevation correction
Top depth	ru_t_d_pt	ru_t_d_snmi	ru_t_d_con	No	Yes	No
Bottom depth						
Top elevation	ru_t_e_pt	ru_t_e_snmi	ru_t_e_con	No	Yes	No

Notes:

The Rustler Formation bottom information can be found in the report and datasets of Jones and others, 2011.

Support Files

File type	Surface file	Description
Elevation statewide	Texas30m.img	Texas 30-meter digital elevation model statewide.
Elevation masked	Elev_snap250	Re-sampled 30-meter DEM in a 250-foot cell snapped to project files.
Snap grid	Snap_250ft	Snap grid for project, 250-foot cell, with project extent and coordinate system. Every raster grid snapped to this file. Cell values are random numbers to visualize cell boundaries when checking project grids.
Project boundary	Bracs_PVA_ProjectBoundary_Simple	Project boundary, polygon, used as mask file.
Aquifer regions	Bracs_AquiferRegions_pv_project BAR_S (raster grid file)	Study area mapped as regions with different stratigraphic profile of the principal aquifers. Polygon file and raster grid file prepared.
BRACS well point files	BRACS_ST BRACS_AD BRACS_WQ BRACS_WL BRACS_AT	Each well record containing the stratigraphic picks. Each well record containing the aquifer selected for each well and the well id and state well number. Well records with water quality data. Well records with static water level data. Well records with aquifer test data.
Cross sections	Cross_Section_Points Cross_Section_Lines	Published cross section point locations. Published cross section line locations.

Texas Water
Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231