Groundwater and Produced Water Quality of the Permian Basin, Southeast New Mexico

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Abstract

The objective of this project is to use existing groundwater and produced water databases to describe the groundwater chemistry of geologic formations, to map the geochemical distributions and trends of solutes, and to discover where, and in which formations, groundwater flushing (in which relatively fresh water moves through a formation, eventually replacing the original saline brine) is taking place. The two main databases used for this purpose include the State Engineer's groundwater quality database, and the USGS database of produced water. Although trends are present, water quality in both databases is highly variable within formations and short sampling distances. Locations for three geologic cross sections across Lea and Eddy counties were chosen after sample distribution was mapped.

In general, shallow groundwater samples found in formations at or near the surface have low chloride concentrations, with the majority of samples having a chloride concentration of less than 1000 mg/L. Their high quality most likely reflects their origin as meteoric water and short residence time within the aquifer. Where the number of samples is sufficient, spatial trends are usually evident, and are usually shown as decreasing chloride concentration with distance away from the Pecos River.

There are distinct chemical trends in the deep basin groundwaters, which are controlled by the flushing of meteoric water through high permeability formations. Stueber (1998, AAPG Bulletin, 82, 1652-1672) and Bein and Dutton (1993, GSA Bulletin, 105, 695-707) used stable isotopes, strontium isotopes, and Cl/Br ratios in order to differentiate connate brines from meteoric waters. Unfortunately I lack these types of

measurements; however, the major ion data can be used to break out similar groups, or genetic classifications.

The work of previous investigators, together with hydrogeological data gathered in the course of this project, have indicated that several patterns of water movement should be expected. These include 1) eastward regional flow, 2) relatively high flow through highly fractured carbonates such as the reef zones in the Capitan and Abo, and regionally extensive carbonates such as the Mississippian through Ordovician, 3) more intermediate flow rates through carbonates with interbedded shales such as the Pennslyvanian and Wolfcamp, and 4) low flow rates through formations with variable lithology including carbonates, evaporites, redbeds, and shales, including the Artesia Group and Upper Leonardian Formations. The Delaware Mountain Group and Ochoan formations, composed of low permeability fine-grained sandstone, and evaporites respectively, are expected to have very low flow rates and briney waters.

Although there is a large amount of variability between samples, these trends are born out in general. A major exception is the presence of brines within the Ordovician despite its carbonate composition; this is because the Ordovician is cut off from the recharge zone by a major fault zone (the Central Basin Platform) and is not vertically connected with the upper formations.

The Permian Basin in southeast New Mexico is complex both geologically and hydrologically. The basin lithology and history, combined with the interaction of groundwater as it moved through the deep basin aquifer through geologic time, has greatly influenced the chemical characteristics of waters within the basin in a reasonably consistent and predictable fashion. The uplift and eastward tilting of the area in the late

Tertiary and Quaternary is likely the cause of much of the chemical distribution of the waters that we see today, although it is impossible to tell the timing of groundwater flushing without more detailed chemical analyses and modelling.

Introduction, Objectives and Scope

The Permian basin in New Mexico and Texas is the most mature petroleum producing area in the world, producing since the 1920's and accounting for nearly 15 percent of the oil produced in the United States (Ruppel et al., 1995). Oil production can lead to contamination of groundwater when saline brines, which are often associated with the presence of oil and gas, are introduced to the fresh groundwater supply. New Mexico oil producers need a way to locate places where it is safe to inject saline waters back into the ground without contaminating fresh water aquifers.

The aim of the NM WAIDS project is to create and maintain a water related geographical information system (GIS) on the internet This system will store water quality data and include qualitative summaries of southeast New Mexico formation water, tools for risk assessment of brine spills onto land surface, and a tool for calculating scale probabilities of formation waters. The website is intended to be used by oil and gas producers, who could use the produced water data and risk assessment tools to obtain data which is not otherwise easily accessible.

The Permian basin in southeastern New Mexico, including Lea, Eddy, and Chaves counties, is a geologically and hydrologically complex area. In general, the area can be divided into three basic hydrologic layers, with a shallow phreatic aquifer on the surface, an evaporite confining layer, and a deep basin aquifer, confined on the bottom by Pre-Cambrian rock. In southeastern New Mexico, numerous studies have been completed in the shallow upper aquifer, focusing upon groundwaters that supply water for agriculture, industry and municipalities. In addition, the evaporite confining layer, especially in and around the Waste Isolation Pilot Plant (WIPP) site near Carlsbad, has been well studied.

The geochemistry of the deep basin groundwaters in southeast New Mexico has received little study. Because of the high salinity of the deep basin groundwater, there are few deep groundwater wells available to sample for groundwater quality in the deep basin; however, produced water records are available. Produced water is groundwater that comes from a producing oil or gas well; for every barrel of oil produced, usually several barrels of water are produced along with it (personal communication, Bruce Lanier, Yates Petroleum Company, 2002). Studies of the Palo Duro Basin, located in the Texas Panhandle, have revealed an unusual amount of meteoric water flushing through the deep basin. This great amount of flushing is attributed to a regional eastern dip, which allows groundwater to flush the deep basin aquifer relatively easily. A study of the geology and geochemistry of the deep basin of southeast New Mexico would help to delineate the geochemical distribution and find possible explanations for the distribution within the area.

The objective of this study is to use existing groundwater and produced water databases to describe the groundwater chemistry of geologic formations, to map the geochemical distributions and trends of solutes, and to increase the current level of understanding of the causes of these distributions by relating them to the depositional history of the area. The ultimate goal of this study is to reconstruct the distribution of natural subsurface water quality, explain the causes of that distribution, and evaluate whether and where meteoric waters are moving in the deep basin in the Permian Basin in New Mexico. Patterns of composition and details of displacement will be looked at on a formational scale. Although the existing chemistry data is limited to major ion concentrations and TDS, the large number of samples will allow an almost three-dimensional look at water chemistry in the deep basin. The mineralogy and relative permeability of formations will also be examined. The databases used for this purpose include: 1) the State Engineer's Groundwater quality database, 2) the USGS database of produced water, and 3) the NM WAIDS database of produced water. A description of the databases is included later in the text. These databases are employed to analyze water chemistry for every formation where water samples are available. Although the existing chemistry data are limited to major ion concentrations and total dissolved solids (TDS), the large number of samples permits an almost three-dimensional look at water chemistry in the deep basin.

In this study, groundwater is defined as water which is not associated with the production of oil or gas, and is most likely from a shallow aquifer. Groundwater samples usually refer to samples which came from the State Engineer's Groundwater quality database. Produced water is defined as water which is produced as oil or gas is pumped from a well (thus the name), and is probably from deeper formations within a basin. Produced water samples refer to samples which came from the USGS database of produced water in New Mexico. English units such as feet (length), millidarcys (permeability), and barrels (volume) are used because they are the standard units in the oil field business; however, SI units will be included in parenthesis when appropriate.

In the shallow aquifer, formations with relatively good water quality (chloride concentration of 3000 mg/L or less) tend to be near the surface and have higher porosity and permeability. Stable isotope studies in the confining layer support findings that good water quality is indicative of recent recharge. Formations that have good water quality in general include the Ogallala, Capitan and San Andres Limestone, and the Artesia Group.

Other shallow formations can have good water quality, but often in small quantities. Although "good," "fair," and "poor" are relative terms, they are used in this study in a field of reference more suited to the oil field rather than that of potable drinking water; "good" quality water will have a chloride concentration of less than 3000 mg/L, fair quality water will have a chloride concentration between 3000 and 30 000 mg/L, and poor quality water will have a chloride concentration of 30 000 and up. The highest chloride concentration found in this study is 245 700 mg/L, which is close to the saturation point of sodium chloride.

This paper will be organized in the following fashion: the environmental setting and the geology of the study area will be discussed, followed by the cross section locations and methods. This will be followed by a discussion of the hydrogeology of the basin, and a literature summary of geochemistry studies done both in southeastern New Mexico and other parts of the Permian Basin, especially the Palo Duro Basin. Next the methods, a description of the databases used, and a discussion of the possible effects of water injection on the geochemistry of the basin will be presented. Following that, the results will be presented, with the groundwater (shallow aquifer) results and the produced water (deep basin aquifer) results discussed separately. Finally, the conclusions and suggestions for future work will be discussed.

Environmental Setting

Geography

The area known informally as the Permian Basin (Figure 1) comprises several adjacent basins separated by fault-bounded uplifts of the Pre-Cambrian basement (Dutton and Simpkins, 1989). These basins include the Palo Duro basin in the Texas Panhandle,

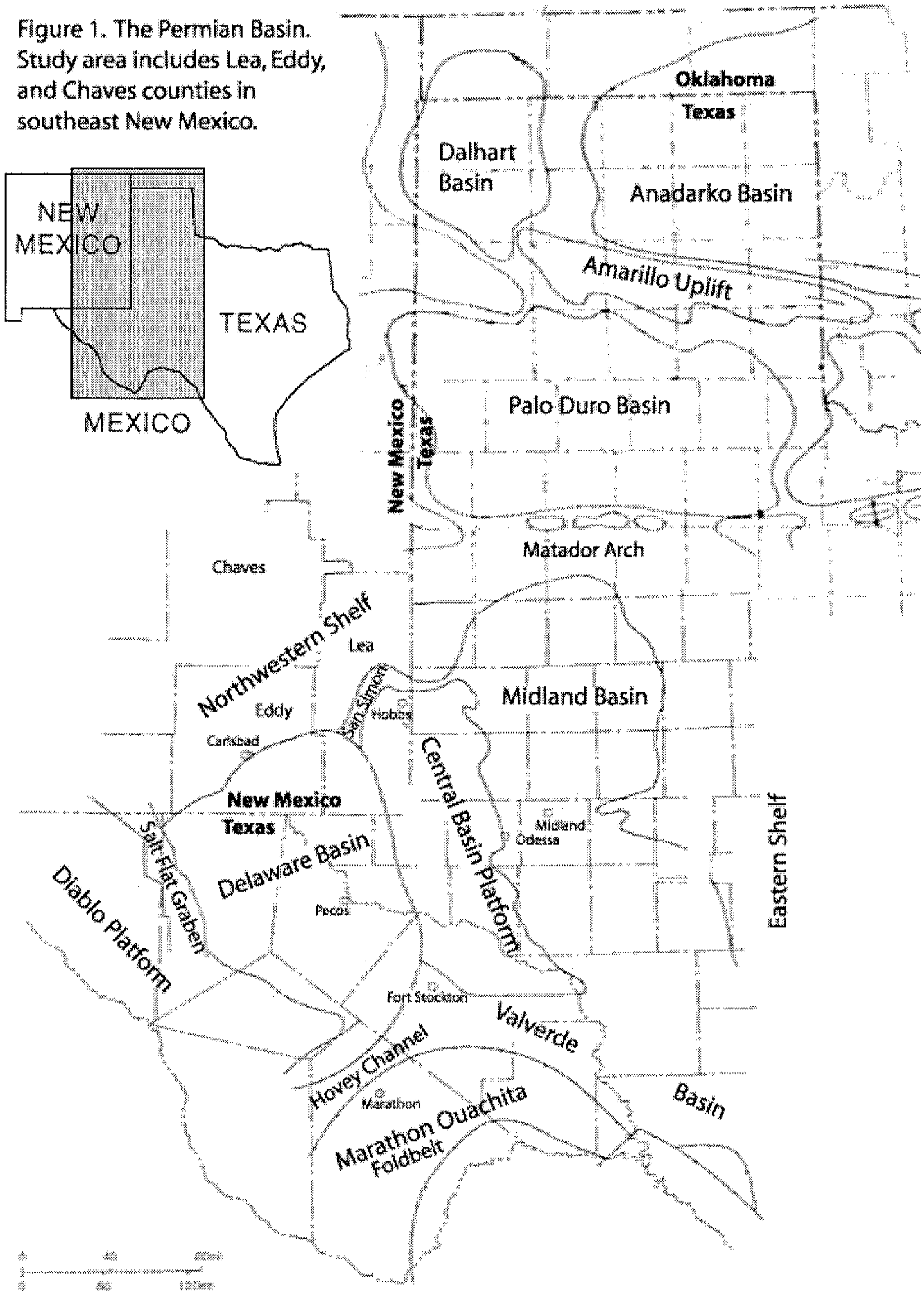


Figure 1. The Permian Basin. Study area includes Lea, Eddy, and Chaves counties in southeast New Mexico.

the Midland Basin in Texas, and the Delaware Basin in southeastern New Mexico and southwest Texas, separated by the Central Basin Platform. The Delaware Basin is bounded on the west side by a series of mountains, named (from north to south), the Guadalupe, the Delaware, the Apache, the Davis and the Glass Mountains. Of these, the only mountain range in New Mexico is the Guadalupe Mountains, located west of the city of Carlsbad. (See figure 2). East of the Delaware basin is the Central Basin Platform, and to the north is the Northwestern Shelf. My study area includes Lea, Eddy, and Chaves counties, which make up the southeast corner of New Mexico. (See Figure 1.) The area includes the northern Delaware basin in Lea and Eddy counties, the Central Basin Platform in Lea county, the Northwest Shelf, and the Roswell basin in Chaves county.

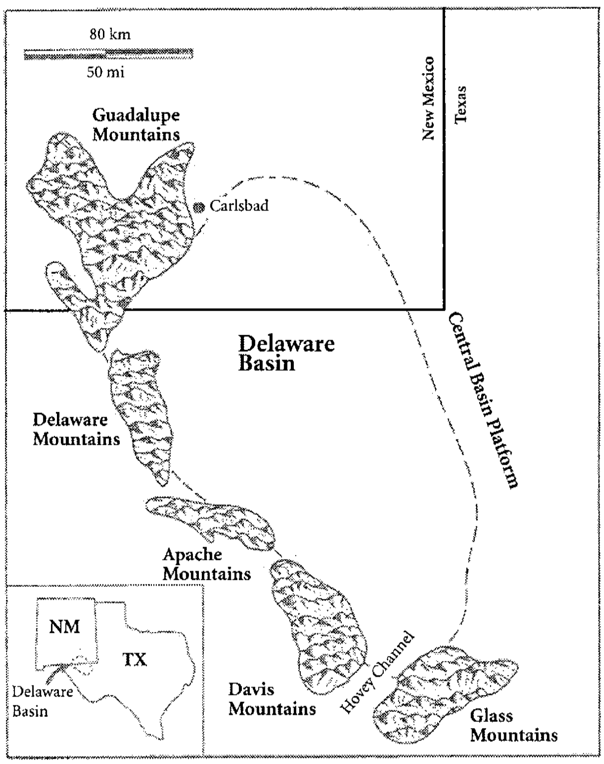


Figure 2. Mountain ranges around the Delaware Basin. Adapted from (Garber et al., 1990)

Climate

Like most of New Mexico and west Texas, the study area, which includes Lea, Eddy, and Chaves counties, has a semiarid to arid climate. It is characterized by high annual temperatures and low humidity and rainfall, receiving less than 38 cm (15 inches) of rain per year on average in the valley, and about 25 inches of rain in the mountains. Precipitation is highly variable both seasonally and areally, with the majority (usually) received during the summer. Temperatures are also highly variable, with the hottest months of June and July having an average high of 35°C (95°F) and average low of 18°C (65°F), and the coldest month in January having an average high of 14°C (57°F) and average low of -4°C (25°F).

Vegetation

Most of the vegetation in southeast New Mexico consists of various grasslands and scrub, with the vast majority of the area covered by plains mesa grassland, plains mesa sand scrub, and desert grassland (Dick-Peddie, 1993). Farmland and urban regions are present in eastern Lea county and along the length of the Pecos River from Roswell in Chaves county to Carlsbad in Eddy county. A swath of Chihuahuan desert scrub also cuts through central Eddy and Chaves counties. On the western sides of Eddy and Chaves counties are more mountainous regions, reflected in change of vegetation to juniper savanna, montane scrub, coniferous and mixed woodland, and small areas of montane coniferous forest (Dick-Peddie, 1993). A vegetation map is shown in Figure 3.

Soils

Two soils of Pleistocene age have been identified in the western part of the Delaware Basin; these are the Mescalero caliche and Berino soil. The Mescalero caliche is an informal stratigraphic marker named for the Mescalero Plain (Bachman, 1984). It was deposited by arid- climate soil-forming processes and consists of nodular to well-cemented calcareous caprock. It has been dated using uranium series disequilibrium;

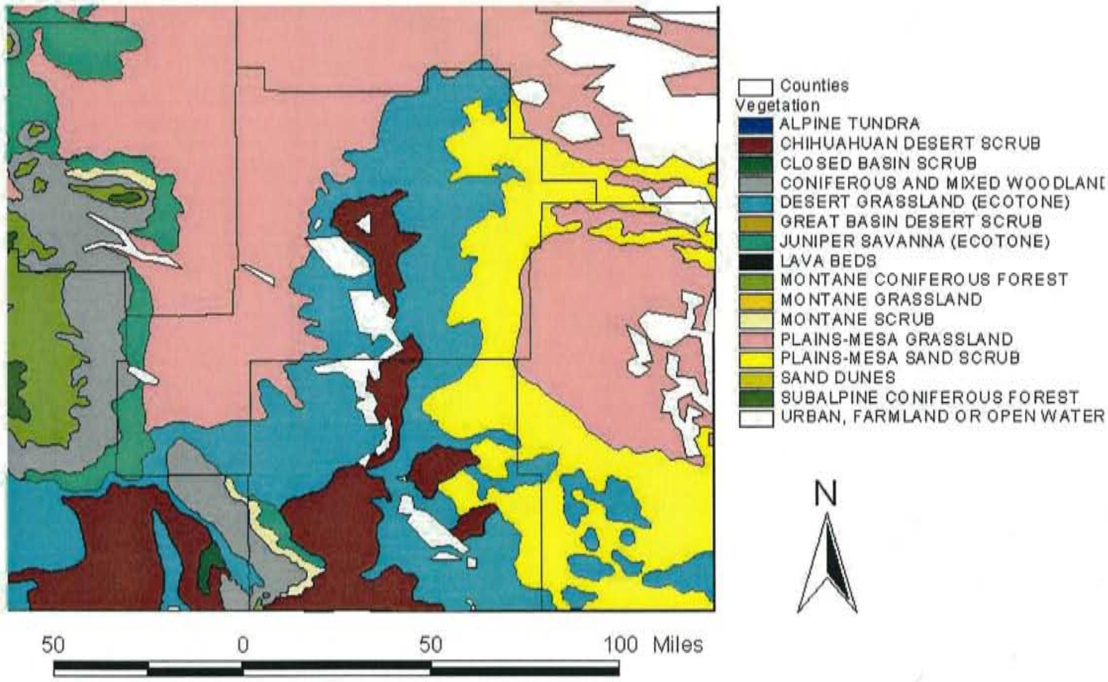


Figure 3. General vegetation map of southeastern New Mexico.

accumulation began about 510 000 years ago and the upper crust formed about 410 000 years ago (Bachman, 1984). The Berino soil is an informal stratigraphic unit consisting of non-calcareous, dark red, sandy, argillic (clay bearing) paleosol. The Berino soil overlies the Mescalero caliche in places, and has been dated using the same technique, indicating formation began about 350 000 years ago (Bachman, 1984).

Demographics

There are several population centers in the area. The largest are, from north to south and west to east, Roswell, Artesia, Carlsbad, Lovington, Hobbs, and Jal. Most municipal and domestic water supplies come from wells in shallow groundwater aquifers such as the San Andres, Capitan, or Ogallala Formations. Additionally, Pecos River water is used for irrigation of cropland. Figure 4 shows some of the political and geological features of the study area, in a format similar to many figures in this study.

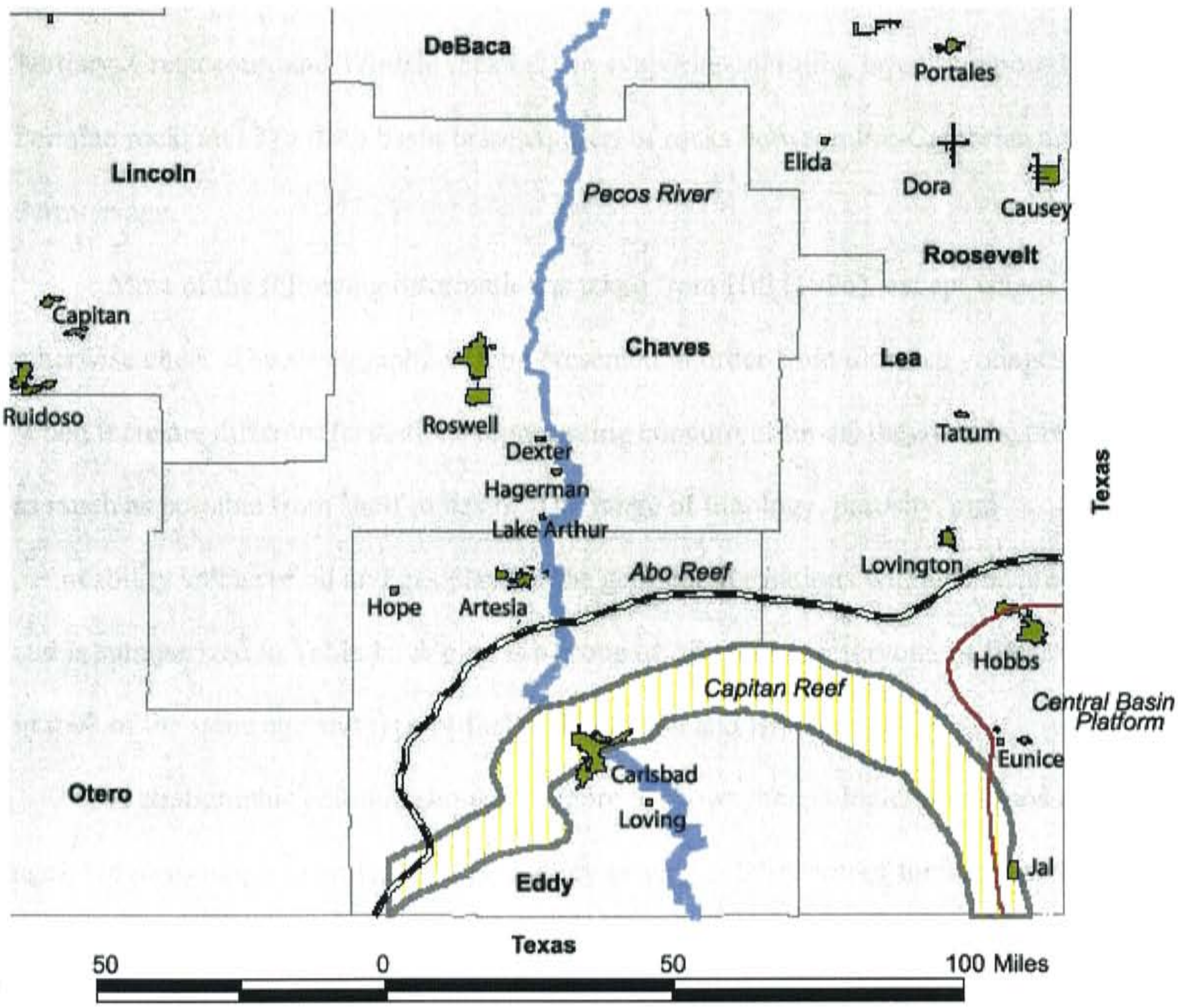


Figure 4. Political and geological features of the study area. The Capitan and Abo "reefs" are fossil reefs composed of limestone.

Geology of Southeastern New Mexico

The geology of southeastern New Mexico is quite varied. There is a large amount of geologic information on Permian rock, since the about one quarter of all the outcrops in the study area are of Permian age, while the remainder is Triassic and younger. In the Delaware Basin, the vast majority of rock outcrops date from the Permian (Hill, 1996). Pre-Permian rock is known mostly through oil exploration and drillholes. The hydrology of the area is complex as well, but in general there are three major hydrological units in southeastern New Mexico. These are: 1) a shallow fresh water aquifer, composed of Tertiary, Cretaceous, and Triassic rocks; 2) an evaporite confining layer, composed of Permian rock; and 3) a deep basin brine aquifer, of rocks between Pre-Cambrian and Permian age.

Most of the following information is taken from Hill (1996), except where otherwise cited. The stratigraphy will be presented in order from oldest to youngest. When there are different formations representing concurrent times, they will be presented as much as possible from shelf to basin. The range of lithology, porosity, and permeability values of oil and gas plays in the geologic formations will also be presented, and is summarized in Table 1. A play is a group of oil and gas reservoirs or fields found in rock of the same age and type of facies (Robertson and Broadhead, 1993).

A stratigraphic column, shown in Figure 5, shows the geologic formations and ages, the three major hydrologic units, and my general subdivision of formations. My subdivisions are based mostly on geologic periods, with the exception of the Guadalupian Series, which was divided into shelf, reef, and basin type facies. This division was done to help simplify the cross sections and sample presentation.

Table 1. Oil and gas plays of southeastern New Mexico. From Robertson and Broadhead (1993).

Play	Formations	Depositional Setting	Lithology	Porosity	Permeability (md)	Traps	Location
Upper Guadalupe Platform	Yates, Queen	Restricted Shelf	Sandstone	0.03 - 0.22	1.8 - 250	Stratigraphic, Anticlines	
Delaware Mountain Basinal Sandstone	Delaware Mountain	Deep Basin	Sandstone	0.23 - 0.25	7.7 - 78.4	Stratigraphic	Del Basin, S Lea and Eddy
San Andres and Grayburg Platform	Grayburg, San Andres	Restricted Shelf	Dolomite and Sandstone	0.06 - 0.286	0.06 - 500	Stratigraphic, Combination	
Glorieta and upper Yeso shelf	Glorieta, Paddock, Yeso	Restricted Shelf	Dolomite	0.02 - 0.12	2.0 - 9.0	Anticlines	
Bone Spring Basinal Sediments	Bone Spring	Deep Basin	Dolomite			Stratigraphic	
Yeso Platform	Blinebry, Tubb, Drinkard	Restricted Shelf	Dolomite and Sandstone	0.15 - 0.20	1.8 - 20	Anticlines	Central Basin Platform
Abo Platform Carbonate	Abo	Shelf Margin Reef, Restricted Shelf	Dolomite	0.015 - 0.183	1.5 - 40	Stratigraphic	NW shelf, CBP
Abo Fluvial Deltaic Sandstone	Abo	Fluvial Deltaic	Sandstone	0.13	0.007	Stratigraphic	Central Chaves
Wolfcamp Carbonate	Wolfcamp	Shelf, Shelf Margin, Basin	Limestone	0.045 - 0.12	0.1 - 124.00	Stratigraphic	Lea and Eddy
Upper Pennsylvanian	Cisco, Canyon	Shallow Open Shelf and Shelf Margin	Limestone and Dolomite	0.04 - 0.13	1.000 - 200.000	Stratigraphic, Combination	Upper Lea, NW Eddy
Strawn	Strawn	Shallow Open Shelf Ramp	Limestone	0.02 - 0.09	0.5 - 100	Stratigraphic, Combination	Lea and Eddy
Atoka	Atoka	Fluvial, Strandplain Shelf and Shelf margin	Sandstone and Limestone	0.01 - 0.16	10 - 22	Stratigraphic, Combination	S Chaves, Lea and Eddy
Morrow	Morrow	Fluvial Deltaic, Strandplain and Submarine fan	Sandstone	0.04 - 0.14	0.13 - 324	Stratigraphic, Combination	S Chaves, Lea and Eddy
Mississippian	Mississippian	Shallow Open Shelf and Shelf Margin	Limestone	0.06 - 0.14	1.6	Stratigraphic	Central Basin Platform
Siluro-Devonian	Thirtyone, Fusselman	Shallow Restricted Shelf	Dolomite	0.019 - 0.14	.1 - 1180	Stratigraphic	Lea
Ordovician	Montoya, Simpson,	Shallow Restricted Shelf	Dolomite and Sandstone	0.04 - 0.16	2.0 - 74	Stratigraphic	Central Basin Platform

Figure 5. Stratigraphic column of southeastern New Mexico

Hydrologic unit	Era	Period	Epoch or Age	Group	Formation	Member	Cross section divisions
Phreatic Aquifer	Cenozoic	Quaternary			Playa Deposits		
					Windblown Sand		
					Alluvium		
		Pleistocene			Travertine		
					Terrace Alluvium		
					Berino Soil		
					Mescalero Caliche		
		Tertiary			Gatuna Formation		
					Ogallala Formation		
	Mesozoic	Cretaceous	Comanche Series		Dockum Formation		
		Jurrassic					
		Triassic	Chinle Group		Santa Rosa sandstone		Triassic
					Dewey Lake Redbeds Formation		
Evaporite Confining Layer	Paleozoic	Permian	Ochoan Series		Rustler Formation	Forty-Niner Member	Ochoan
						Magenta Dolomite	
						Tamarisk Member	
						Culebra Dolomite	
						Virginia Draw Member	
					Salado Formation	Upper Member	
						McNutt Potash Member	
						Lower Member	
					Tessey Limestone		
					Castile Formation	Painthorse Member	
						Anhydrite IV Member	
						Halite III Member	
						Andydrite III Member	
						Halite II Member	
						Anhydrite II Member	
						Halite I Member	
						Anhydrite I Member	
						Basal Limestone Member	
Deep Basin Aquifer			Guadalupian Series	Artesia Group	Tansill Formation	Ocotillo Silt Member	Artesia
					Yates Formation		
					Seven Rivers Formation		
					Queen Formation	Shattuck Member	
						Penrose Sand Member	
					Grayburg Formation		
					San Andres Formation		(San Andres)
					Cherry Canyon tongue Sandstone		
					Cutoff Shale		

Figure 5. Stratigraphic Column (continued.)

	Era	Period	Epoch or Age		Formation	Member	Cross section divisions
Deep Basin Aquifer	Paleozoic	Permian		Reef	Capitan Limestone	Forereef Member	Reef
					Capitan Limestone	Reef Member	
					Goat Seep Dolomite		
				Delaware Mtn. Group	Bell Canyon Formation		Delaware Mtn Group
					Cherry Canyon tongue Formation		
					Brushy Canyon Formation	Manzanita Limestone Member	
						South Wells Limestone Member	
						Getaway Limestone Member	
			Leonardian Series		Glorieta Sandstone		(Upper) Leonardian
					Bone Spring Limestone		
					Hueco Limestone		
						Paddock	
						Blinebry	
					Clear Fork Formation	Tubb Sand	
					Yeso Formation	Drinkard Member	
					Abo Formation		(Abo)
			Wolfcamp Series				Wolfcamp
		Pennsylvanian	Virgil Series		Cisco Formation		Pennsylvanian
			Missourian Series		Canyon Formation		
			Des Moines Series		Strawn Formation		
			Atoka Series		Atoka Formation		
			Morrow Series		Morrow Formation		
		Mississippian			Barnett Shale		Mississippian
		Devonian			Woodford Shale		Devonian
					(Thirtyone) Formation		
		Silurian			(Wristen) Formation		Silurian
					Fusselman Dolomite		
		Ordovician	Montoya Group				Ordovician
			Simpson Group				
			Ellenburger Group				
		Cambrian					

PreCambrian and Cambrian

There are PreCambrian granitic basement rocks, and Cambrian rocks, including the Bliss Sandstone, which is probably late Cambrian to early Ordovician in age, encountered in deep oil and gas wells in southeastern New Mexico. The PreCambrian granites form a boundary of very low permeability for the deep basin. Since there are no water samples from these rocks, they will not be analyzed in this study.

From the Ordovician to Mississippian time, the Tobosa Basin covered the area that is presently known as southeast New Mexico and southeast Texas (see Figure 6a), and accumulated as much as 2000 m of dolomite, limestone, shale, and sandstone, with only brief interruptions in the geologic record. During most of this time, the Tobosa basin was covered by the sea. Most unconformities in the rock record also have karst features, representing drops in sea level.

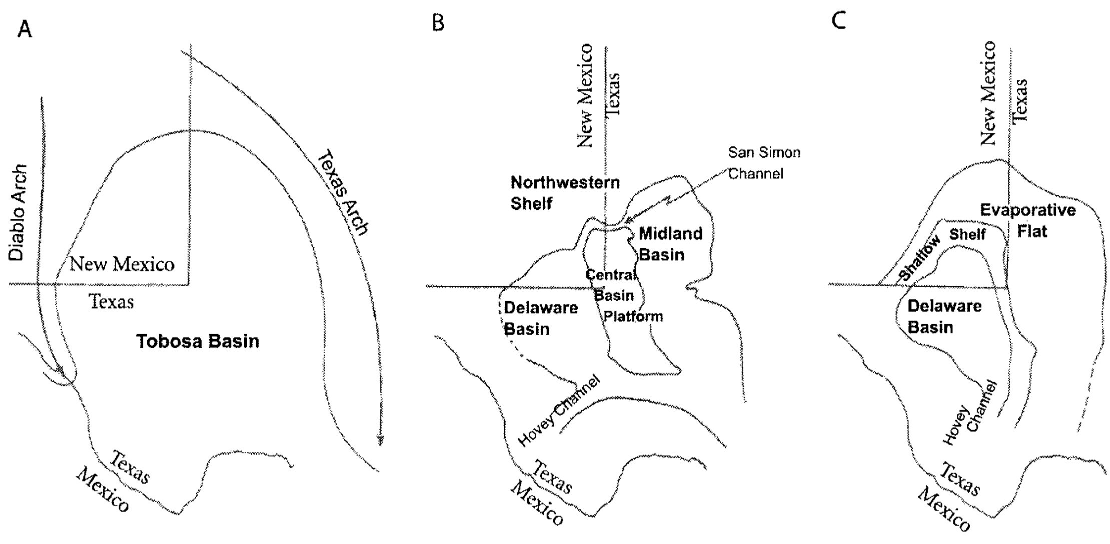


Figure 6. The Delaware basin in the Paleozoic Era. A) The Tobosa Basin in the Ordovician to Pennsylvanian; B) The Permian Basin in the early Permian ; C) the Permian basin in the late Permian (after Hill, 1996)

Ordovician

There are three formations of Ordovician age, the Ellenburger Group, Simpson Group, and Montoya Group. During Ellenburger time, the sea deposited a thick sequence of carbonate rocks. The Ellenburger is a light gray to gray, medium grained, crystalline silicaceous dolomite, about 150 to >330 m thick based on drillholes. It is known as one of the major gas-producing units in the basin. The Simpson Group is of middle Ordovician age, and ranges from 80 to 500 m thick. It has been described as interbedded sandstone, shale, and limestone of various colors ranging from cream to gray to green, with a basal unit of gray crystalline dolomite. The Montoya Group is late Ordovician, and unconformably overlies the Simpson Group. It ranges from about 50 to 150 m thick and is a carbonate limestone-dolomite sequence, with minor amounts of chert and shale. The gas and oil plays within the Ordovician formations are located in the Central Basin Platform in Lea county (Robertson and Broadhead, 1993). Porosity values in the dolomite and sandstone plays range from 0.04 to 0.16, and permeability ranges from 2 to 74 md (a millidarcy is equal to 9.87×10^{-6} m^2)

Silurian and Devonian

The Silurian and Devonian rocks are hydrologically well connected, and are often impossible to separate or distinguish in core or geophysical log. Silurian and Devonian rocks were deposited in a continental sea in both deep waters and the shallow margins of the Tobosa basin. Silurian age rocks in the Delaware basin include the Fusselman dolomite and the Wristen Formation. The Fusselman dolomite unconformably overlies the Montoya Group, and has a wide variation in thickness, ranging from 15 to 300 m in different areas. It consists of white to light gray, coarse to medium crystalline dolomite, contrasting with the darker and finer grained Montoya Group (Hill, 1996). The Wristen Formation is basically a dolomite-dominated shale, thickest (450 m) in the northeastern part of the Delaware basin. There are no water samples from the Wristen Formation in the databases. However, there are a number of samples with formation listed as Silurian or Fusselman.

The formations of Devonian age include the Thirtyone Formation, a siliceous cherty limestone, and the Woodford Shale, a brownish black organic shale with small quantities of calcareous shale and chert, which sits unconformably on top of the Thirtyone Formation. Water samples with these formation names were not found in any of the databases. There are, however, water samples with a formation listed as Devonian and Devonian Lower. In addition, water samples may be from both Silurian and Devonian age rocks, as these two formations are traditionally grouped together in gas and oil plays. Silurian and Devonian plays are mostly located in Lea county (Robertson and Broadhead, 1993); however, water samples reported as coming from Silurian or Devonian formations are found in all three counties (these formations are discussed more thoroughly later in the text; see, e.g., Figure 38). Wells in these plays are completed in dolomite, and to a lesser extent limestone. Porosity in these zones ranges from 0.02 – 0.14, while permeability ranges from <0.1 to 1180 md (9.87×10^{-7} to 0.0116 m^2).

Mississippian

Mississippian age formations include the Mississippian Limestone, composed of limestone with abundant chert and interbedded with shale, and the Barnett Shale, a brown shale containing some fine grained sandstone and siltstone. Similarly to the Silurian and Devonian rocks, Mississippian rocks were deposited in a continental sea. The total thickness of Mississippian strata is up to 250-335 m. There are a small number of produced water samples from Mississippian strata in the database. Mississippian plays, completed in limestone and dolomite, are mainly found in the Central Basin Platform in Lea county. The porosity ranges from 0.06 to 0.14 and the permeability ranges from 1.6 to a maximum of 11903 md (1.6×10^{-5} to 0.1175 m^2) (Robertson and Broadhead, 1993).

Pennsylvanian

During Pennsylvanian time, the Ouachita orogeny caused the formation of a ridge in the middle of Tobosa Basin, known as the Central Basin Platform, which divided the Tobosa basin into the Delaware Basin on the west and Midland Basin on the east (see Figure 6b). This ridge would determine the nature of Pennsylvanian sediments. Depositional environments during Pennsylvanian time ranged between marine to submarine fan to shallow shelf to fluvial deltaic with beaches and bars. The rock record is mostly known through oil and gas exploration, and the distinction between Pennsylvanian formations is fairly hard to correlate from well to well, making them somewhat arbitrary (Hill, 1996.) The names of Pennsylvanian age series and their respective formations in the study area are: Morrow Series, Morrow Formation; Atoka Series, Atoka Formation; Des Moines Series, Strawn Formation; Missourian Series, Canyon formation; and Virgil Series, Cisco Formation.

The Morrow Formation lies unconformably over Mississippian rocks in the Delaware Basin, which was rapidly subsiding in Pennsylvanian time. The record shows four layers of prograding clastics separated by marine shales, representing the fluctuation of deltaic to marine environments. The Morrow consists of a conglomeration of limestones, sandstones, shales and siltstones, over 500 m in thickness. The Atoka, which sits conformably on the Morrow, is a brown, fossiliferous limestone, with the shale content increasing as deposition continued, so that the upper portion contains mostly shale with occasional limestone. The thickness ranges from about 120 m in the north of the Delaware Basin to about 200 m in the south. The reef, which would reach its climax in the Permian, began to build during the Atokan time. The Strawn Formation sits unconformably on the Atoka, and consists of mostly massive brown limestone and gray shale, ranging in thickness from about 90 – 120 m to over 200 m in the Strawn reefs in the northwest part of the basin (Hill, 1996).

During the late Pennsylvanian, the Canyon Formation and Cisco Formation were formed, and these two formations together are often designated "Upper Pennsylvanian". The Canyon is mostly a brown limestone/dolomite with gray shale and some white sandstone and conglomerate near the base. The Cisco also consists of limestone and dolostone with some dark gray and red shale, and some gray sandstone. There are a fairly large number of produced water samples from Pennsylvanian strata, as well as a small number of samples in the groundwater database. There are several plays in Pennsylvanian strata, namely the Morrow, Atoka, Strawn, and Upper Pennsylvanian (Cisco and Canyon Formations). Wells in these plays may be completed in sandstone, limestone, or dolomite. The porosity values range from 0.01 – 0.16 and permeability ranges from 0.5 – 324 md (4.9×10^{-6} to 3.2×10^{-3} m^2) (Robertson and Broadhead, 1993).

Permian, Wolfcamp Series

In Wolfcampian time, the seas spread over the whole of west Texas and southeastern New Mexico. In Leonardian time, they became progressively restricted, allowing redbeds and evaporites to move toward the Delaware Basin, and by the end of

Guadalupian time, the sea was completely restricted to the Delaware Basin (see Figure 6.) During Ochoan time the sea desiccated, allowing evaporites to fill the Delaware Basin and eventually deposit on the surrounding areas, signifying the beginning of a continental rather than marine regime (Hill, 1996).

As stated before, nearly all rock outcrops (approximately 95%) in the Delaware Basin date from the Permian (Hill, 1996). The Wolfcampian series is the oldest, and is composed of mostly limestone with some shale. In the Delaware basin, the Wolfcamp consists of shale and brown sandstone (Nicholson and Clebsch, 1961); it is absent or intermittent in the structurally higher parts of the Central Basin Platform, but is present in the northwestern shelf. Wolfcamp samples are found in large numbers in both the produced water and groundwater databases. Oil and gas plays may be completed in limestone or dolomite and have porosity values between 0.045 and 0.12, and permeability values between 0.1 to 124 md (9.87×10^{-7} to 1.22×10^{-3} m^2) (Robertson and Broadhead, 1993).

Permian, Leonardian Series

The Leonardian series lies above the Wolfcamp, and consists primarily of the Bone Spring limestone in the Delaware Basin, and the Abo, Yeso, and Glorieta formations in the shelf and platform areas (Nicholson and Clebsch, 1961). The Bone Spring limestone is composed of black calcareous shale interbedded with black limestone; there are three large scale sandstone clastic beds which are referred to as the "first", "second", and "third" Bone Spring sands, and were deposited during periods of low sea level (Hill, 1996). The Abo "reef" is a wide band of carbonates north of the Capitan reef (see Figure 4.) Elsewhere, the Abo and Yeso formations have a diverse lithology and underlie the Glorieta, which in this area is a sandstone (Nicholson and Clebsch, 1961). The Leonardian is when the general placement of backreef to reef to basin was established in the Delaware basin, and set the stage for the massive reefs of the Guadalupian (Hill, 1996).

There are a large number of produced water samples in several different plays from Leonardian strata; many of the water samples are labeled by non-formal oil play names rather than geologic formation, although they are correlated. These plays include Drinkard, Tubb, Blinebry, Clear Fork, and Paddock, in order from bottom to top. The Abo Platform Carbonate play, located in the Central Basin Platform and southern Northwest shelf, is a dolomite play. Most produced water samples within this play are along the Artesia Vacuum trend, following the Abo reefs, which were the first carbonate reef formations in the Leonardian series and are correlative with the Bone Spring Formation. Porosity ranges from 0.015 to 0.183, and permeability ranges from 1.5 – 40 md ($1.48 \times 10^{-5} - 3.95 \times 10^{-4}$ m^2). The Yeso Platform play, which includes Blinebry, Tubb, and Drinkard Formations, is on the Central Basin Platform, in dolomite, sandstone, and limestone. Porosity ranges from 0.015 to 0.20, and permeability ranges from 0.5 – 20 md ($4.9 \times 10^{-6} - 1.97 \times 10^{-4}$ m^2). The Glorieta and upper Yeso shelf play, which includes the Glorieta, Paddock, and Yeso formations, is in southern Lea and central Eddy county, in dolomite. Porosity for this play ranges from 0.02 – 0.12, and permeability ranges from 2.0 – 9.0 md ($1.97 \times 10^{-5} - 8.9 \times 10^{-5}$ m^2) (Robertson and Broadhead, 1993). The San Andres Formation, which is composed of a lower cherty limestone member and an upper, non-cherty limestone member, overlies the Glorieta and may be correlated either with the Bone Spring limestone, of Leonardian age, or with the Cherry Canyon

Formation in the Delaware basin, of Guadalupian age. It is included with the Guadalupian Artesia Group in this study because many produced water samples are mixed Grayburg San Andres waters. The San Andres and Grayburg Platform play is in dolomite and sandstone, with small amounts of sand and anhydrite, and is located in northern Eddy and southern Lea counties. Porosity for this play ranges from 0.06 to 0.286, and permeability from 0.06 to 500 md ($5.9 \times 10^{-7} - 4.9 \times 10^{-3}$ m^2) (Robertson and Broadhead, 1993).

Permian, Guadalupian Series

The Guadalupian series, named after the Guadalupe Mountains, is a complex system with abrupt but time-equivalent facies changes. The Capitan Limestone is recognized as a fossil reef, and the surrounding units represent the transition from shelf to backreef to reef to forereef to basin with distance towards the center of the Delaware Basin. There has been much discussion and disagreement between investigators as to which facies and lithologic units correlate with other facies and lithologic units, both within and between outcrop areas and in the subsurface (Hill, 1996).

Shelf/Backreef Facies – The Artesia Group, also known as the Carlsbad Group and the Whitehorse Group, consists of five formations. These are, from oldest to youngest, the Grayburg, Queen (containing the Penrose Sand), Seven Rivers, Yates, and Tansill formations. The Artesia Group formations are notable for their lateral and vertical change of facies. As the Permian sea shrank during middle to upper Guadalupian time, a facies change moved toward the reef front. This facies change, from red beds to evaporites to dolomite to limestone, usually occurs within a distance of 2 km or less within each formation. The location of the carbonate to evaporite contacts for each formations is shown in Figure 7. The Artesia Group is also known for cyclic deposits, found in all five formations, with each cyclothem of sandstone - sandy dolomite - dolomite representing a change in sea level. These cyclothems vary greatly in size, but the most prominent cycles are of medium scale, from 0.3 – 2.5 m (Hill, 1996). There are several plays in the Artesia Group, with oil and gas often coming from several formations within the group. One major play in the Artesia Group is Upper Guadalupe Platform play; found in sandstone, limestone, dolomite, and sand in the Yates and Queen Formations, it is located in southeast Chaves, northeast Eddy and southern Lea counties (Robertson and Broadhead, 1993). Porosity in this play ranges from 0.03 to 0.22 and permeability from 1.8 to 250 md (1.8×10^{-5} to 2.47×10^{-3} m^2). There are large numbers of samples in both produced water and groundwater databases.

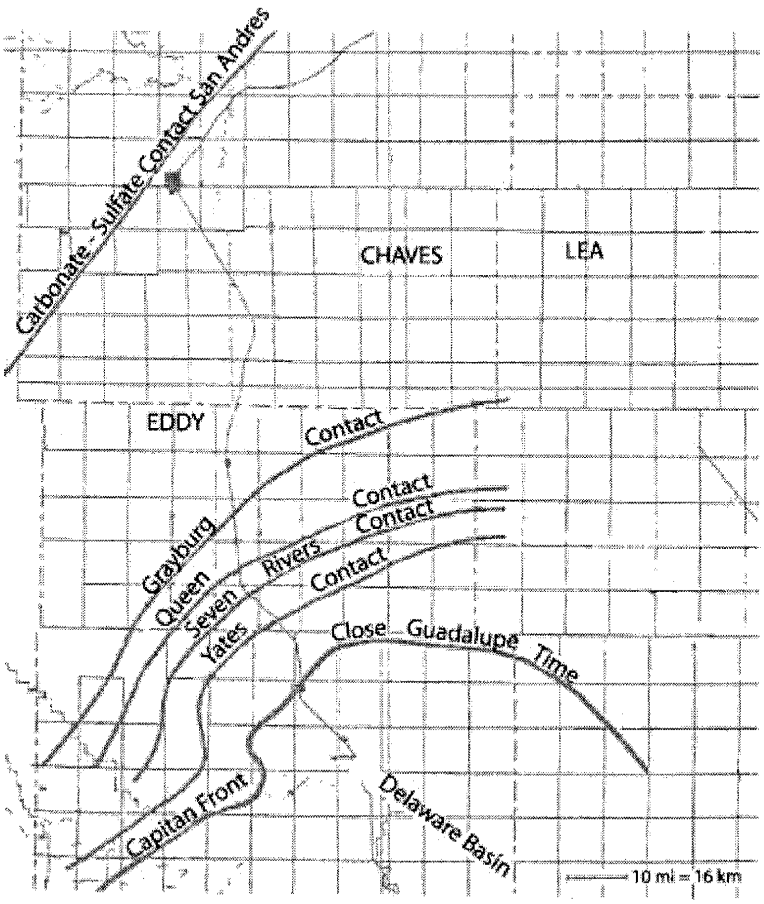


Figure 7. Location of carbonate to evaporite facies contacts for the San Andres, Grayburg, Queen, Seven Rivers, and Yates formations. The Capitan front at the close of Guadalupian time is shown. After Hill, 1996

Reef and Forereef– The Goat Seep dolomite of middle Guadalupian age and the Capitan limestone of late Guadalupian age form the massive reef unit surrounding the Delaware Basin. The Capitan Reef Complex is about 8 km wide and about 650 km long, and it forms one of the best known exposures of rock in the world because of its classic transition from backreef to reef to basinal facies (Hill, 1996). The Goat Seep formed the first well defined reef structure, with sponge and algal reef growth, and is a thickly bedded to massive cream to light gray dolomite. The Capitan limestone, which grew on and over the Goat Seep, is comprised of two (non-formal) members, the reef and forereef member. The reef member is composed of a massive white limestone of low porosity. The forereef member of the Capitan limestone makes up over two-thirds of the Capitan Limestone, and is a fossiliferous dolomitic limestone, forming weathered slopes rather than the massive cliffs of the reef member. The Capitan limestone has a high permeability because of dissolution along fractures and joints, and along with the Goat Seep Dolomite and their correlative backreef units (Artesia Group) form a connected hydrologic unit known as the Capitan aquifer (Hiss et al., 1975). The groundwater database contains many samples from the Capitan; the produced water database has a few samples, but it is not clear if these are from oil or gas wells, or other well types.

Basin – The Delaware Mountain Group is subdivided into three formations which are, from oldest to youngest, Brushy Canyon, Cherry Canyon, and Bell Canyon. They are composed of fine grained sandstone with thin layers of black shale and limestone. The Brushy Canyon Formation is equivalent to the upper San Andres Formation. The Cherry Canyon Formation merges into the Goat Seep Formation, and is equivalent in age to the Queen Formation of the Artesia Group. The Bell Canyon Formation merges into the Capitan reef, and is equivalent to the Seven Rivers, Yates, and Tansill Formations. The Delaware Mountain Group formations are known for their low permeability, and there are few water samples in either the produced water or groundwater databases. Plays in the Delaware Basin (south Lea and Eddy counties) are in sandstones with porosities ranging from 0.03 to 0.22 and permeabilities from 1.8 to 250 md (1.8×10^{-5} to 2.47×10^{-3} m^2) (Robertson and Broadhead, 1993).

Permian, Ochoan Series

During Ochoan time, rocks were deposited as a sequence of evaporites which include anhydrite, gypsum, halite, and associated potash salts (Bachman, 1984). Most of the early deposits were confined to the Delaware basin as defined by the Capitan reef. During Ochoan time, as the basin filled with sediments, some beds spread across the reef and into the surrounding area. The shift from widespread carbonate shelf deposition to evaporite deposition represents the final stages of the Permian sea and the transition from a marine to a continental environment (Hill, 1996). The Ochoan formations include the Castile Formation, the Salado Formation, the Rustler Formation, and the Dewey Lake Redbeds.

The Castile Formation is the basal unit of the Ochoan series, and is basically confined to the Delaware basin. It is known for thin laminae consisting of alternating bands of calcite and anhydrite, which represent seasonal changes. However, massive beds of anhydrite and gypsum are present in the upper part of the formation. There are informal members of the Castile Formation, designated as Basal Limestone, Anhydrite I, Halite I, Anhydrite II, Halite II, Anhydrite III, Halite III, and Anhydrite IV. The contact between the Castile and the Salado is conformable, with both sharp and interfingering contacts, and in some areas (southern part of Eddy county) marked by solution breccias and collapsed beds.

The Salado Formation contains halite, minor beds of anhydrite, and commercial deposits of potash minerals. It has been well studied because of these potash deposits and also because of background studies for the construction of the WIPP site, which is located in the Salado near Carlsbad. In the subsurface, the Salado Formation ranges from about 1200 to 2300 ft (366 – 701 m) in thickness (Bachman, 1984). This variability is due to removal of salt rock by dissolution. Surface exposures are mostly residuum from salt dissolution, consisting of brecciated gypsum embedded in clay (Bachman, 1984).

The Rustler Formation may be divided into five lithologic units. These include, from oldest to youngest, an unnamed sequence of reddish-brown siltstone with interbedded gypsum or anhydrite and halite, the Culebra Dolomite Member, the Tamarisk Member, the Magenta Dolomite Member, and the Forty-niner Member. The two dolomite members, as distinctive stratigraphic markers, are used to estimate the amount of dissolution which has occurred in the other three members, which include halite and some associated potash minerals. Where salts have been dissolved, a "collapse breccia" occupies their stratigraphic position, and anhydrite is usually altered to gypsum (Bachman, 1984).

The Dewey Lake Redbeds consist mainly of alternating thin, even beds of reddish brown to reddish orange siltstone and fine grained sandstone. They rest conformably on the Rustler Formation. The regional distribution and thickness of the Redbeds is directly related to the amount of erosion before the Triassic (Bachman, 1984).

The Ochoan formations formed an evaporite capstone to the deep basin aquifer, trapping the oil and gas reserves underground until the present day, when they are being tapped for human consumption. This evaporite cap is why the Permian basin has one of the largest oil and gas reserves in the world, despite having relatively low amounts of source rock (Schreiber, 1988). The Ochoan formations are also a source of fresh groundwaters, especially in Eddy county and other areas where they crop out on the surface. Thus the groundwater database has a fairly large number of Ochoan samples, while the produced water database has almost none.

Triassic

The boundary between the Permian and Triassic age signifies a period of uplift and change from a marine environment to deltaic, lacustrine, and fluvial environments. Dissolution and erosion occurred during the early to middle Triassic time, and the Chinle Group was deposited in late Triassic time (Hill, 1996). Formations of the Chinle Group include the Santa Rosa and Dockum. Santa Rosa rocks rest unconformably on, and overlap, the Dewey Lake Redbeds. Triassic rocks are found along the eastern rim of Nash Draw and in isolated collapse-sink deposits in the Pecos Valley. They are dark reddish brown, cross-laminated, poorly sorted conglomerate sandstones with interbeds of dark reddish brown sandy shale.

In eastern Lea county, the Santa Rosa Formation is overlain conformably by the Dockum Formation, which is composed of red to purple mudstone, siltstone, and lenticular beds of sandstone. It is about 400 m at its thickest, thinning out till entirely absent in the western part of Lea county.

Jurassic and Cretaceous

Jurassic age rocks were not deposited in southeastern New Mexico because the Jurassic was a period of continued emergence of the Delaware basin, which resulted in extensive erosion and dissolution (Hill, 1996). During the early Cretaceous, a shallow epicontinenal sea transgressed across the region, marking the last marine sedimentation in the study area (Hill, 1996). Although Cretaceous rocks were deposited, they have been almost entirely removed by erosion and do not make up a significant portion of the geological record.

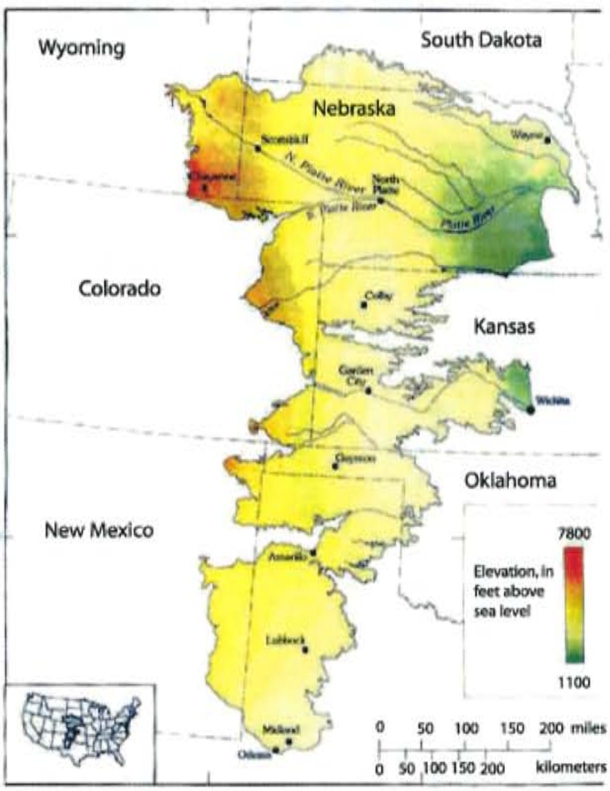


Figure 8. The High Plains aquifer, which includes the Ogallala aquifer, covers eight states and is an important source of fresh water. After Litke (2001).

Miocene-Pliocene

The Ogallala Formation of Pliocene age is a sand and gravel deposit covering a huge eight-state area extending from eastern New Mexico and Texas to South Dakota (see Figure 8). In New Mexico, it covers much of Lea county, and is one of the main sources of fresh water in the area. It is primarily composed of calcareous, unconsolidated sand, with some clay, silt, and gravel, and ranges in thickness from a few centimeters to about 300 feet (91 m).

Quaternary

Several deposits of Quaternary age are present in the study area. There are four early Quaternary formations of Pleistocene age, which was a time of glacial and interglacial periods. These include the Mescalero caliche, the Berino soil, terrace and channel alluvium deposited by the Pecos River, and travertine. Late Quaternary deposits include alluvium, windblown sand and sand dunes, and playa deposits.

Geologic Cross sections

Locations for three geologic cross sections across Lea and Eddy counties were chosen after sample distribution was mapped (see Figure 9). Locations were chosen where there was a high density of produced water samples and where they would best help the interpretation of any chemical trends by formation. The formation top data for the cross sections came from scout cards in the New Mexico Bureau of Geology and Mineral Resources (formerly the New Mexico Bureau of Mines and Mineral Resources). These scout cards, which are well records from oil and gas companies, usually contain location by township and range, elevation of the well in feet above sea level, the depth of formation tops in feet from the surface, the owner/company, and some drill-stem test (DST) information regarding oil production. The location, elevation, and formation tops were used to create the cross

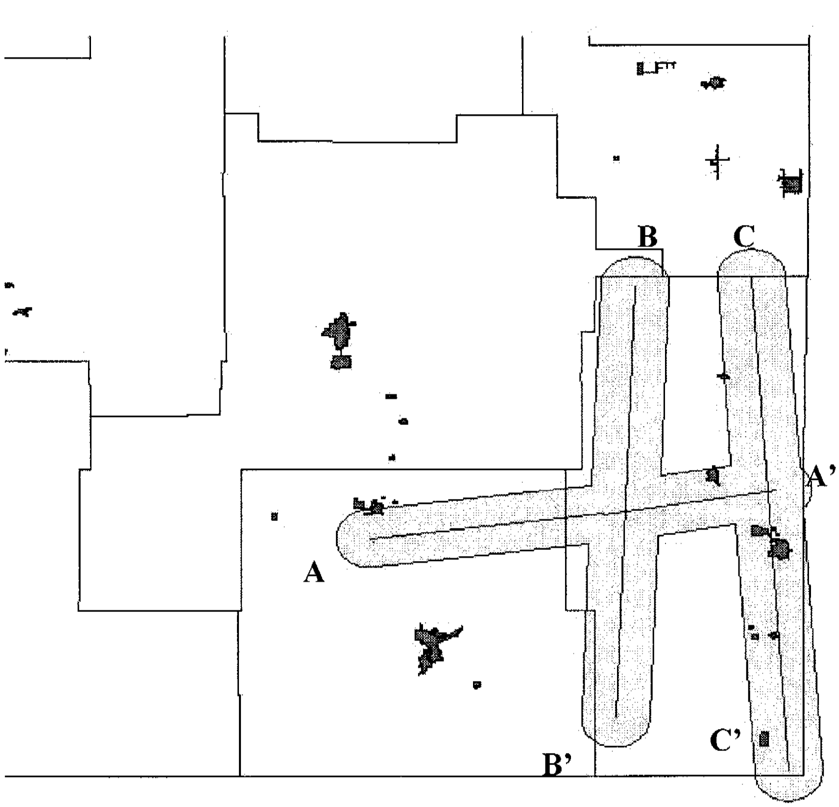


Figure 9. Location of three cross sections and 10 km buffer around each side. Produced water samples that fall within the buffer were projected onto the closest cross sections in a N-S or E-W line, depending on the predominant direction of the cross section.

sections. I attempted to get multiple formation tops from one well in each section that a line of the cross section crossed (i.e., one well per mile.) I then separated all the formation tops by age, e.g., Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Wolfcampian, Leonardian, Guadalupian, and Ochoan, and created three general cross sections. Because most wells did not have every formation top picked, I interpolated where the data were lacking. The original data and general cross section data are included in Appendix A.

I then moved my data into RockWorks to create the cross sections. It was decided not to correct the depth for elevation above sea level since both formation tops and sample data are in terms of feet from the surface. The Capitan Reef was added to the B – B' cross section because it is an important hydrologic unit with a relatively high permeability. However, there is no validation on the location or borders of the reef, and this part of the cross section should be considered with some caution.

After the cross sections were created, all produced water samples located ten kilometers or closer to each cross section were selected using ArcGIS, and then projected onto the closest cross sections in a N-S or E-W line, depending on the predominant direction of the cross section (see Figure 9.) The samples were plotted as depth versus latitude for the N-S cross sections, or depth versus longitude for the E-W cross section. Adobe Illustrator was used to place the water quality data on top of the cross sections.

Basin Hydrogeology

One main objective of this project is to discover where, and in which formations, groundwater flushing (in which relatively fresh water moves through a formation, eventually taking the place of the original saline brine) is taking place. In order to have groundwater movement, there must be areas where recharge and discharge occur, and average permeabilities must be high enough that water movement can occur over geologic time. The use of chemistry data from produced water samples, as well as lithology and permeability data from formations, should allow an initial analysis showing which formations have been or are being flushed. It will also allow comparisons of relative rates of flushing between formations of different lithologies and permeabilities.

Figure 10 shows a lithologic east-west cross section from the Sierra Blanca mountains to the state line through Roswell, adapted from Summers (1981). Carbonates make up a large portion of the rocks, with the San Andres forming a nearly continuous carbonate layer through the entire study area. Carbonates generally exhibit a high permeability, especially those with fracture porosity (Freeze and Cherry, 1979). The Artesia Group and upper Leonardian (Glorieta through Yeso Formations) have a quite variable lithology and thus a low effective permeability. The Abo Formation is composed of redbeds in this area, which would also indicate a relatively low permeability. The Pennslyvanian Formation is composed mostly of carbonates, but there are large lenticular shale layers, which would lower the effective permeability. Although not shown in this cross section, the Mississippian through Ordovician Formations are well fractured carbonates and thus will have a relatively high effective permeability.

The lithology shown in the cross section adapted from Summers is similar to that of cross section A-A', which nearly parallels it to the south, going from Artesia almost to the New Mexico-Texas state line. Figure 11 shows cross section A-A' in elevation above sea level, in formations, facies, and relative permeability. The major difference between

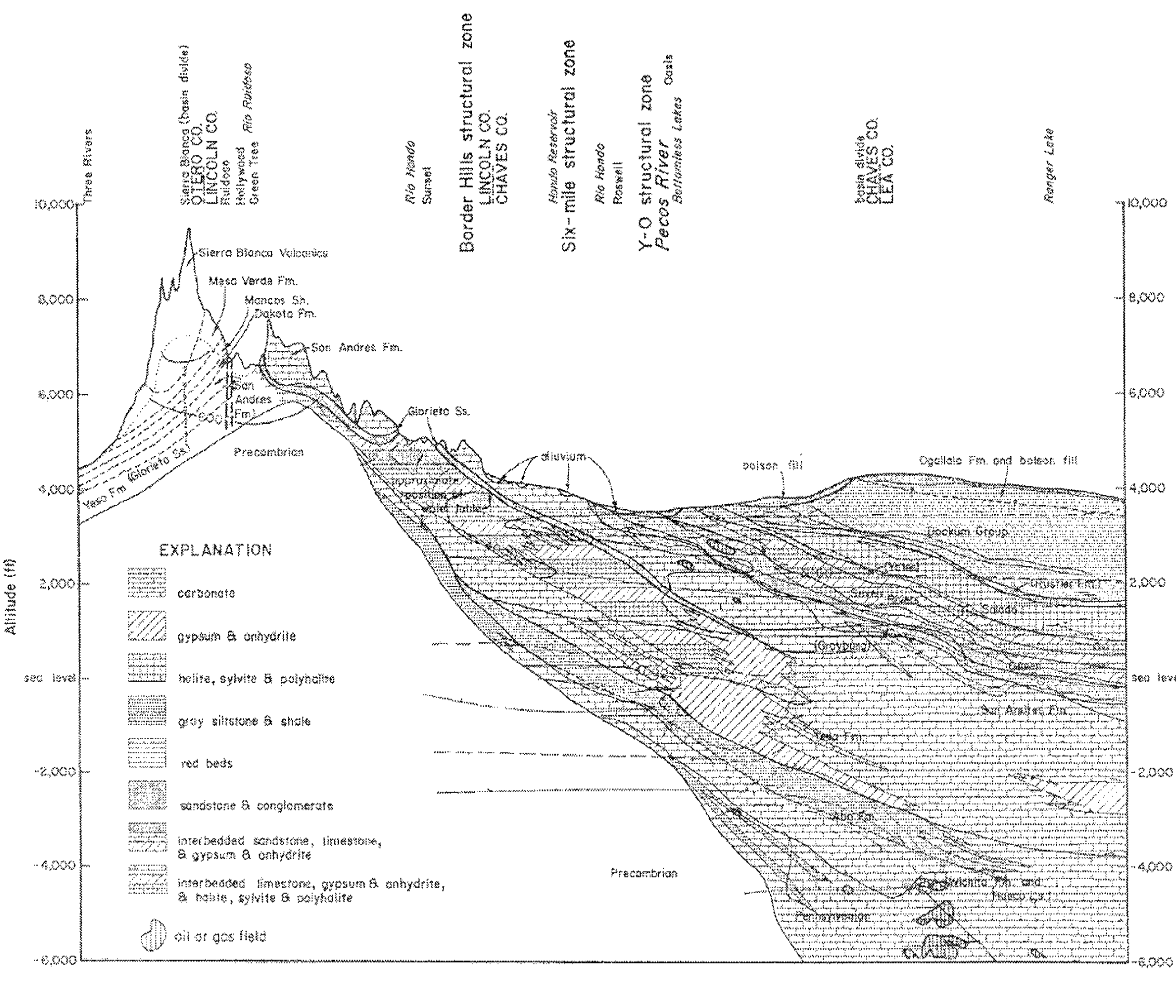


Figure 10. Lithologic EW cross section from the Sierra Blanca Mountains to the eastern New Mexico-Texas state line, through Roswell. Adapted from Summers (1981).

cross section A – A' and Summers' cross section is the Abo Formation; the Abo carbonate reef is crossed in cross section A – A', though the Abo is mostly composed of redbeds elsewhere. As shown, highly fractured carbonates have a relatively high

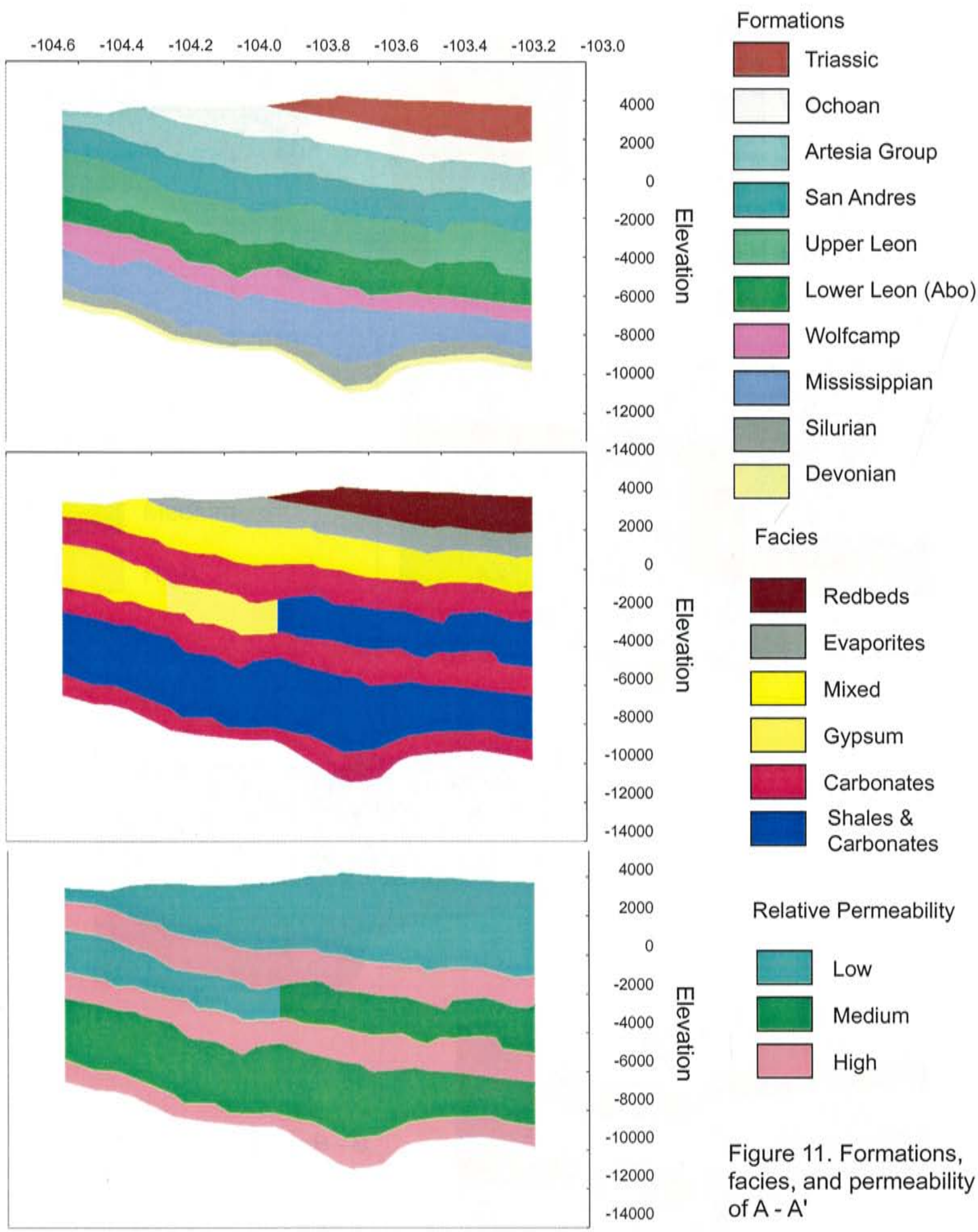


Figure 11. Formations, facies, and permeability of A - A'

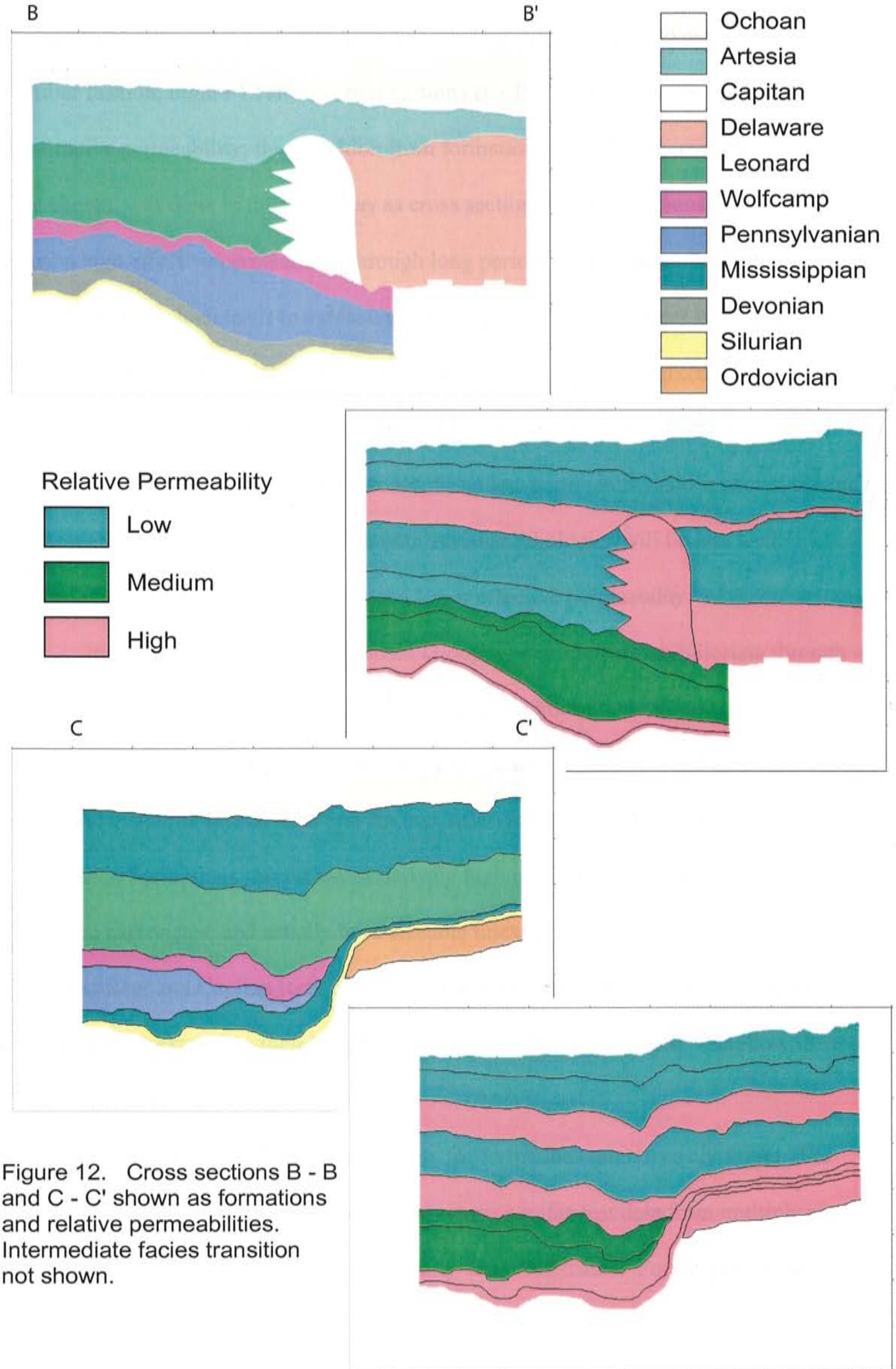


Figure 12. Cross sections B - B and C - C' shown as formations and relative permeabilities. Intermediate facies transition not shown.

permeability, followed by carbonates mixed with shale, redbeds and evaporites. In a similar fashion, Figure 12 shows cross sections B – B' and C – C' in both formations and qualitative permeability; the transition from formation to facies to permeability, although not shown, was done in the same way as cross section A – A'. Carbonates, shown in red, have a high effective permeability through long periods of time because of their thickness and brittleness which leads to extensive fracture porosity. Carbonates interbedded with shale, which will have a lower porosity, are shown in purple; and mixed evaporites or redbeds, which will have the lowest permeability are shown in blue. The Delaware Mountain Group, composed of sandstones, has a low permeability and is shown in blue in cross section B – B'. The formations with variable lithologies will be less well hydrologically connected and will have a lower effective permeability.

In general the Delaware Mountain Group, Upper Leonardian (Glorieta through Yeso), Artesia Group, Wolfcamp, and Pennslyvanian Formations should have relatively low effective permeabilities, since they are commonly lenticular formations with lots of shale and evaporite layers. The San Andres, Mississippian, Silurian, Devonian, and Ordovician Formations should have relatively high permeabilities because they are highly fractured carbonates, and usually have sizeable thicknesses and are areally extensive. The Abo Reef and Capitan Reef will also act as high permeability units; although they are not areally extensive, their long length and carbonate composition will allow them to act as flow channels through the area.

Average permeability measurements for formations are not easily found. For formations in the upper fresh water aquifer, where aquifer-test data from multiple sources is available, permeability values may be fairly well established. For deeper formations, however, the only source of permeability data is from oil and gas fields. This will tend to bias the data towards higher average values for several reasons: 1) permeability is usually only measured in areas where oil and gas can be easily obtained (i.e., high permeability fields) 2) measurement methods vary, and permeabilities measured in the lab rather than in situ or in drill-stem tests will be biased towards the low side because of scale issues; 3) permeability will vary over such a large area; those formations that have large elevation changes from the Delaware Basin to the Central Basin Platform (Ordovician through Pennsylvanian), for example, often only have permeability measurements in the Central Basin Platform. 4) areas with permeability too low to economically extract oil and gas have few wells and few permeability measurements. 5) the presence of oil and gas in a rock unit tends to preserve higher porosities and permeabilities than the presence of water, since water is so much more reactive and may cause a decrease of porosity and permeability through precipitation of minerals.

Permeability data for southeast New Mexico were obtained from the proceedings of the Symposium of Oil and Gas Fields in Southeastern New Mexico (Stipp, 1956) and several supplements (1960; 1966; 1977; 1988; 1995; 1999) There were several variations of permeability measurements. The older forms had places for both horizontal and vertical permeability, as well as high and low values. The more recent forms had areas for a high, low, and average permeability. In order to average the data, all recent values were taken as horizontal permeabilities and the older vertical values were thrown out. The measurements with only a high and low value (no average) were combined as a logarithmic average. Then box and whisker plots of all measurements were made for each formation (see Figure 13.) A box and whisker plot is a way of presenting a large

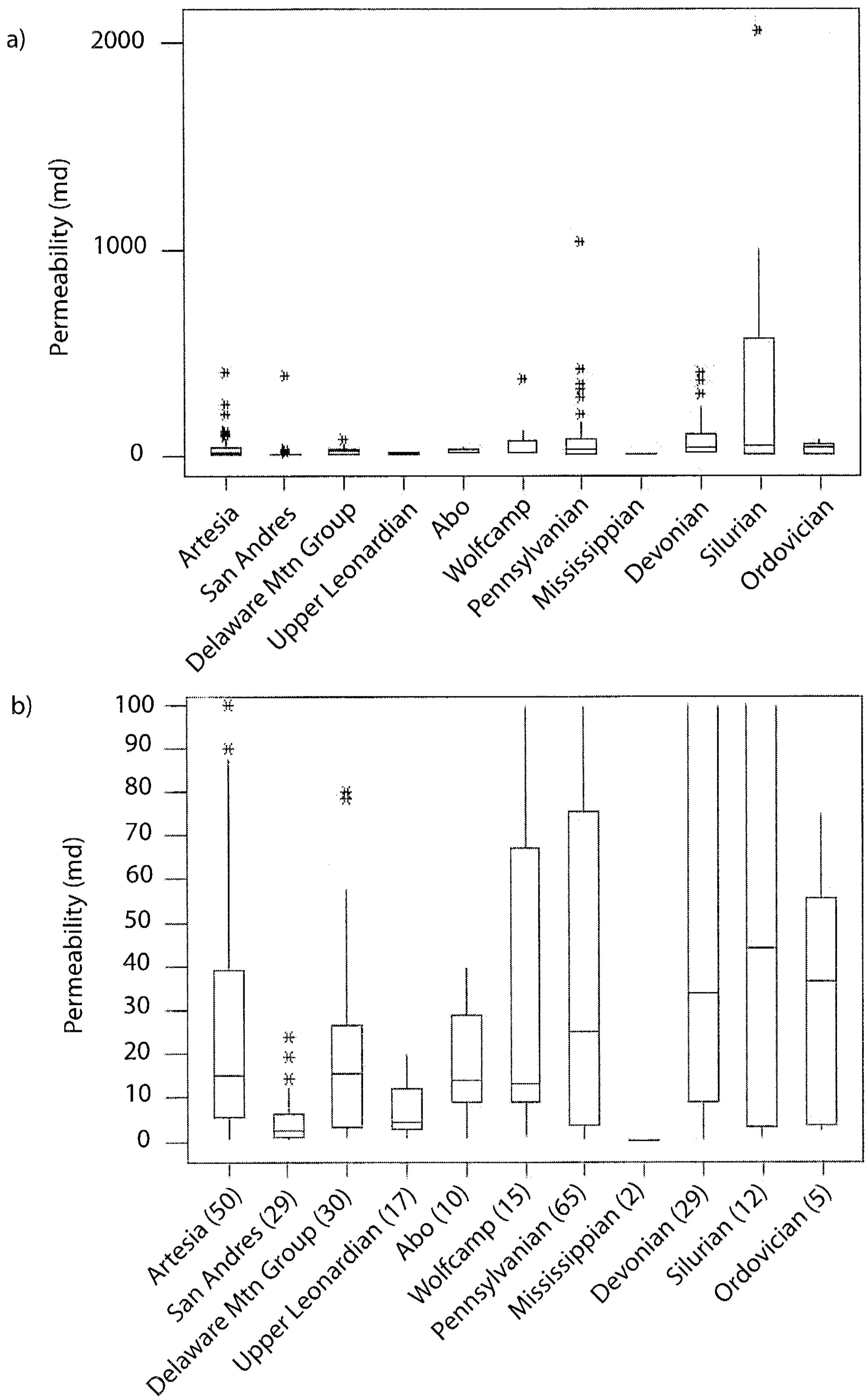


Figure 13. a) Box plot of permeability (md) by formation. b) same plot with y axis upscaled. Number of samples is in parentheses.

amount of simple statistical data in a dataset, with the box encompassing the 25th to 75th percentiles with the median value in the middle, and the top and bottom lines (whiskers) showing the high and low values of the dataset. Outliers are shown as stars above the box. Table 2 shows the general hydrogeologic characteristics of the Permian and older formations within the study area. Permeability data is in Appendix B.

The boxplot of permeability measurements probably in general reflects the relative trends in permeability; however, because the number of samples is small and the origins of the samples are unknown, they may not always be representative values. It is believed that because of the measurement methods, these data reflect matrix permeability more than effective permeability, which would include fractures and karst features. In particular, the San Andres and Abo formations in the box and whisker plot in Figure 13 appear to exhibit anomalously low permeability. This is likely because the permeability measurements for these two formations are likely from core samples, which are taken so as to avoid any size of fractures within the formation, and thus underestimate the effective permeability through the formation (Dickey, 1986). The Delaware Mountain Group and Artesia Group show anomalously high average matrix permeabilities, which may possibly reflect high permeability channels within the formations. Figures 11 and 12 show generalized effective permeability zones in cross section.

Table 2. Hydrogeologic characteristics of Permian and older formations within the study area.

Formation	Lithology/Facies	Depositional Setting	Relative Permeability	Measured Permeability (md)			
				Median	Low	High	n
Ochoan	Evaporites	desiccating sea	Low				
Artesia Group	Mixed evaporites, carbonates	shallow shelf	Low	15	0.2	404.5	50
San Andres	Carbonate	restricted shelf	High	2.4	0.1	387.3	29
Capitan	Carbonate	reef	High				
Delaware Mtn Group	Sandstone	deep basin	Low	15.5	0.5	80	30
Upper Leonardian	Mixed evaporites, carbonates	restricted shelf	Low	4.5	0.52	20	17
Abo (Lower Leon)	Redbeds/carbonate	shelf/reef	Low/High	14	0.5	40	10
Wolfcamp	Carbonate and shale	shallow sea	Medium	13	1	373	15
Pennsylvanian	Carbonate and shale	shallow sea	Medium	25	0.1	1035	65
Mississippian	Carbonate	sea	High		0	19903	2
Silurian	Carbonate	sea	High	33.9	0.1	400	29
Devonian	Carbonate	sea	High	44	1	2065	12
Ordovician	Carbonate	sea	High	36.6	2	75	5

Literature Summary of Previous Geochemical Studies

There is a large number of references about water geochemistry in the Permian basin. These references can be loosely grouped into three categories, which are the following: 1) older references describing the general hydrology of the upper aquifers and groundwater use in southeast New Mexico; 2) detailed hydrologic and geochemical studies of the Waste Isolation Pilot Plant (WIPP) site, near Carlsbad, New Mexico, and 3) geochemical studies of the Palo Duro basin, part of the Permian basin located in the Texas panhandle. A description of these references follows.

References about groundwater and surface water in Lea, Eddy, and Chaves counties are quite numerous. However, these references are often quite old, and most of the references within the study area cover only the upper fresh water aquifer, not the deep brines. In addition, there is very little interpretation about the origin or history of water chemistry in the basin. References include studies by Motts (1968) and Bjorklund and Motts (1959), Hiss (1975), Hendrickson and Jones (1952), and Nicholson and Clebsh (1961). Also in this category are Summers (1972; 1981), who studied the geology and hydrology (but not water chemistry) of the Pecos River basin in its entirety, from the head waters near Las Vegas, New Mexico to its final discharge to the Rio Grande, on the Texas-Mexico border.

Nicholson and Clebsh (1961) studied groundwater in southern Lea county, which forms the southeast corner of New Mexico. They found that the principal fresh water aquifers were in Quaternary alluvium, the Ogallala Formation, and Dockum Group rocks, with the Ogallala as most important aquifer. Quaternary alluvium, often derived from the Ogallala Formation, forms another aquifer, and forms an aquifer continuous with the

Ogallala in the eastern part of the area. Small quantities of water are obtained from the sandstones and shales of the Dockum Group, and the Rustler anhydrite Formation forms the lower limit of potable groundwater. Most of the water pumped is being removed from storage, since there is a very low recharge rate. The chemical quality of water from these aquifers is fairly good, with TDS typically less than 1100 ppm.

Hendrickson and Jones (1952) began the study of groundwater in Eddy County, located on the south border of New Mexico west of Lea county. Water was taken from surface formations from depths up to 900 feet (274 m), including the Artesia Group, Capitan limestone, Bell Canyon Formation, Castile and Rustler Formations, and alluvium. In general, groundwater flows towards the Pecos River, almost parallel to the river in the southern part of the county, and more diagonally in the northern part. Water quality is generally good, with most samples having a TDS less than 3000 ppm, and mostly calcium sulfate composition. Waters with a TDS of greater than 4000 (10 samples out of 88) usually have a relatively higher percentage of chloride.

Motts (1968) and Bjorklund and Motts (1959) studied geology and groundwater occurrence in Eddy county. Motts (1968) studied the occurrence and movement of groundwater in Guadalupian Series rocks, and found that lithofacies change and the associated change in permeability is the main factor controlling groundwater occurrence and movement. He found four highly permeable aquifers, the first being the limestone aquifer along the shelf margin and reef zone, the second and third west of and subparallel to the reef zone, along the transition from carbonate to evaporite faces in the Seven Rivers and Queen Formations, and the fourth in the San Andres Formation. The first three aquifers act as collectors for groundwater, as they are enclosed by rocks of lower conductivity, and are drained by springs. Rocks overlying the San Andres limestone generally drain into the reef aquifer (Capitan), while the San Andres drains toward the Roswell basin (Bjorklund and Motts, 1959). The water table in the alluvium generally slopes towards the Pecos River, and depths to water range from less than one to more than 260 feet (0.3 – 79 m) below the surface (Bjorklund and Motts, 1959). The chemical quality of water in the Capitan and alluvium was described in Bjorklund and Motts; the Capitan is divided into a fresh water zone, a zone of mixed fresh and moderately saline, and a zone of moderately saline water. Water in the alluvium increases in salinity with distance towards the Pecos river. This increase in concentration is attributed to irrigation, in particular irrigation before 1919, when drains were constructed to stop waterlogging (Bjorklund and Motts, 1959).

Hiss (1975) furthered the groundwater study in Eddy county and lower Lea county as well as western Texas, and examined water salinity (especially chloride concentration) in greater detail. He prepared a map of chloride concentrations in waters from aquifers in the Guadalupian Series in southeastern New Mexico, using samples taken between 1926 and 1971. He found that water quality in these rocks is controlled primarily by the hydraulic conductivity of the aquifer and the proximity to the surface outcrop in the western and southern part of the basin. As fresh water enters the aquifer in outcrops in the Guadalupe Mountains, along with other exposures along the western edge of the basin, it replaces saline water in proportion to the hydraulic conductivity of the aquifer. Water with high chloride concentrations can be found on the Northwest Shelf northwest of Hobbs, on the Central Basin platform, and in the Delaware Basin. Water with relatively low chloride concentrations (<10 000 mg/L) is associated with the Capitan aquifer, the San Andres Limestone, and the Artesia Group along the margins of the Delaware basin and at the north end of the Central Basin Platform. Water with low salinity is found interfingering with water of high salinity throughout the area.

Hiss suggested three aquifer systems in the area; the first is the Capitan aquifer, and includes shelf-margin carbonate rocks and other rocks of similar hydraulic conductivity in the shelf (Artesia Group rocks.) The second aquifer is the shelf aquifer, consisting of strata from the San Andres Limestone and Artesia Group in the Northwestern shelf and the Central Basin Platform shelfward from the Capitan aquifer. The third aquifer is the basin aquifer, and consists of the Delaware Mountain Group (Hiss, 1977).

The second group of references in the study area include a large number of geochemical studies around the WIPP site, located in the Salado Formation, near Carlsbad, New Mexico. The WIPP site is a geologic repository for transuranic radioactive waste generated by the Department of Defense (Siegel and Anderholm, 1994). The focus of these studies was the possible hydrologic transport of radioactive waste through units of high hydraulic conductivity within the Ochoan series evaporite formations. The repository member of the WIPP site is in the Salado Formation, and there are three members of the overlying Rustler Formation that produce water, which are, in order of descending stratigraphic sequence, the Magenta Dolomite Member, the Culebra Dolomite Member, and the basal Rustler zone near the Salado contact. These studies go into great detail about the Rustler and Salado Formations of the Ochoan series, including major and minor solutes and stable isotope data of the waters. Stable isotopes can be used as environmental tracers because different types of water have different fractions of heavier isotopes, and the amount of fractionation can help to interpret the original source of the water (Chapman, 1986). Unfortunately the study area of these reports is much smaller than my study area, encompassing only about 1600 km^2, an area including and surrounding the actual WIPP site (see Figure 14.) Some of these studies are by Lambert, Chapman, and Ramey.

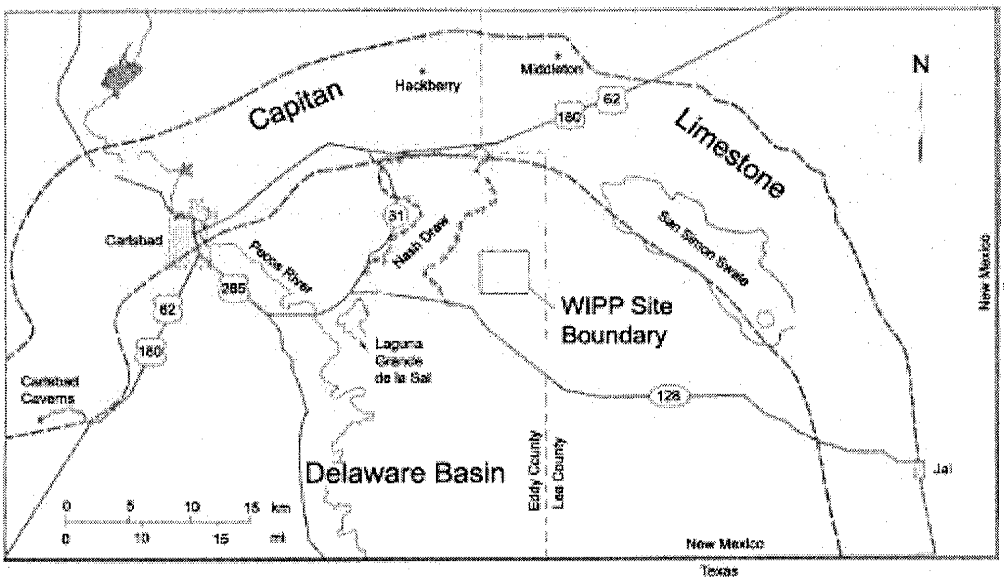


Figure 14. Location of the WIPP site. Adapted from Siegel and Anderholm (1994).

The Culebra Dolomite Member seems to produce the most water in the Rustler Formation, and lies approximately 450 m above the repository member of the WIPP site in the Salado Formation. It has been the focus of numerous studies, including many by Lambert (1977, 1983, 1987, 1992), who has extensively studied the water chemistry of the Rustler Formation. He took water samples from the alluvium, Triassic, Capitan, Rustler, surface waters, and Salado and Castile brines, and compared the stable isotope ratios ($\delta^{18}O$ / $\delta^{16}O$ and δD/ δH). The Salado and Castile brines were isotopically enriched in comparison to modern meteoric waters, and are interpreted to have been recharged in an environment different than that of the present day. A small number of Rustler samples have enriched isotopic compositions, which may be due to mixing with deeper groundwater (similar to that of Salado and Castile brines) or exchange between the groundwater and hydrous minerals.

He found two groups of meteoric isotopic signatures in the region; one of demonstrably modern waters, including Capitan, alluvium, Ogallala, and near surface waters. The other group was composed of confined Rustler and Capitan groundwaters; these were isotopically heavier than the modern samples. Lambert (1992) suggested that it is unlikely that the confined Rustler and Capitan aquifers are receiving modern recharge under the present climatic conditions, and hypothesized that they are discharging their water during the process of reaching equilibrium with modern hydrologic conditions.

Chapman (1986) also examined the stable isotope ratios, and contrary to Lambert, found that there was no distinction between most Rustler water and verifiably young groundwater from surface waters, alluvium, Triassic, and Capitan waters. Physical measurements of the Rustler flow system made by Chapman show that water in the Culebra Dolomite flows southeast from the center of the WIPP site and then westward. Ramey (1985) studied the chemistry of these fluids and observed that the chemistry along this flow path would require a transformation from a saline Na-Cl brine to a dilute Ca-SO_4 solution. Currently, there is no good explanation for this discrepancy.

Making up the third group of references are several good studies of water geochemistry in the Permian Basin in Texas, especially the Palo Duro basin, located in the Texas panhandle north of the Midland Basin. Although these studies were not done in southeastern New Mexico, the systematic interpretation of the geochemistry of the waters of the Palo Duro will be used as interpretive aids to my analysis. These studies include, from oldest to youngest, Bassett and Bentley (1982), Fisher and Kreitler (1987), Knauth (1988), Dutton (1987), Bein and Dutton (1993), and Stueber et al. (1998).

The geochemistry of the study area is highly influenced by meteoric groundwater flushing, and the area is unusual because of the large spatial extent in which flushing occurs. The objective of this study is to employ existing databases to delineate areas which are influenced by meteoric flushing and those which have brines. The work of Stueber et al. (1998) is heavily relied on as a key link to the genetic history of waters within the basin, and is of critical importance in understanding the interpretation of the geochemistry.

Bassett and Bentley (1982) used drill-stem test data from petroleum wildcat wells to find pressure (head) and transmissivity of the saline deep basin aquifer, and found the hydrodynamics of the Palo Duro basin showed a general decline of head from west to east, following the topographic dip from the Rocky Mountains. Geochemistry of the basin was investigated using chemical analyses from petroleum companies; these were predominantly samples from wildcat drilling. Similar to my data, most of the data collected in this study were of limited use for hydrogeochemical analysis. Samples often only had major ions, with Na+K usually found by charge balance; occasionally pH, temperature, and some minor components were included. They used the model AQ/SALT to find the reaction state of the brine with respect to many common minerals in the host rock, focusing on halite, anhydrite, dolomite, and calcite. Although the pH of the samples was altered because of degassing of carbon dioxide and iron oxidation, a reconstruction of in situ partial pressure of CO_2 indicates that brines in the carbonate host rocks are in equilibrium with calcite. Wolfcamp brines appear to be saturated with anhydrite, while brines in the granite wash are not because of sulfate reduction.

Fisher and Kreitler (1987) further analyzed the saline deep basin aquifer of the Palo Duro basin by using four wells drilled for the U.S. Department of Energy Salt Repository Program and two wells drilled by independent oil and gas companies. Samples from these wells were analyzed for major, minor, and trace ions, as well as isotopic compositions. Formation waters are Na-Cl brines that contain between 124-290 g/L TDS. Fisher and Kreitler (1987) fitted their data to hydrodynamic models that suggested that the basin has been completely flushed by meteoric water, and thus brine chemistry has evolved strictly through water-rock interactions. Concentrations of major and minor ions appear to be controlled by volumetrically important basin minerals, including calcite, dolomite, anhydrite, celesite, low albite, microcline, and Na-smectite. Chemical equilibrium and high Na activities tend to drive ion exchange reactions, which elevate the concentrations of divalent cations and lower the concentrations of dissolved SO_4 and carbonate.

Chemical and isotopic compositions of the samples suggested two groups of waters: western Palo Duro basin samples, and eastern and central Palo Duro basin samples (Fisher and Kreitler, 1987). These two groups formed from evolution along their respective flow paths. The western Palo Duro basin samples came from predominantly siliciclastic sedimentary rocks, and had high Cl/Br ratios, highly radiogenic Sr ratios, and depleted oxygen ratios with respect to calcite; they acquired salinity by dissolving halite along a lateral flow path from the recharge zone, and high radiogenic Sr from detrital silicate minerals. Their relatively short flow path (and short residence time) means the samples have not reached oxygen isotopic equilibrium with the calcite. On the other hand, the eastern and central Palo Duro basin samples, which come from predominantly carbonate rocks, had low Cl/Br ratios, Sr ratios slightly higher than Permian marine Sr, and O ratios in equilibrium with calcite. These brines originated as either recharge that achieved chemical and isotopic equilibrium with the host rock during long residence times or as Permian seawater concentrated by evaporation.

Knauth (1988) obtained samples from the same wells as Fisher and Kreitler (1987) did, but he analyzed his geochemical data independently of hydrodynamic models, with no constraints as to whether the water was originally meteoric. He separated his samples into four groups based on chemical and isotopic characteristics: 1) interbed brines within the major Permian evaporite aquitard, which are the most chemically-concentrated and ^{18}O-rich fluids, and are interpreted as evaporatively concentrated sea water which has been hydrologically isolated since the Permian; 2) brines below the evaporite sequence on the eastern side of the basin that have Cl/Br, divalent cation, and isotopic signatures indicating a mixture of evaporatively concentrated sea water and meteoric waters of $\delta D = -20^{o}/_{oo}$; 3) brines below the evaporite sequence on the western side of the basin with chemical and isotopic signatures suggesting a mixture of two pulses of meteoric water, one with $\delta D = -20^{o}/_{oo}$ and the other with $\delta D = -55^{o}/_{oo}$; and 4) waters above the evaporites (Dockum and Ogallala Formations) that have the isotopic composition of meteoric waters. Below the evaporite aquifer on the eastern side, waters are interpreted to be a mixture of dense Permian evaporite brines in various amounts with a basin-wide pulse of Triassic meteoric water. On the western side of the deep aquifer, Triassic meteoric waters became saline via dissolution of halite and are currently mixing with a Tertiary pulse of meteoric water initiated by the Laramide uplift to the west. The two different groups of water in the deep basin suggests flow on the western side and static conditions on the eastern side, and also an unrecognized, approximately N-S discontinuity or restriction to flow in the aquifers.

Dutton (1987) focused on the evaporite confining system of the Palo Duro Basin, specifically looking at stable isotope ratios of brines in the San Andres carbonate rock and of Permian fluid inclusions in halite beds. Hydrochemical facies coincide with changes in salinity (Figure 15.) Although regional hydrogeologic data and models suggested that groundwater flows downwards through these beds, the isotopic similarity of the two groups of waters implies that the brine in the carbonate rock is connate and originated as Permian evaporatively concentrated sea water. In addition, the water-rock reactions needed to account for the chemical and isotopic composition of the water samples seem simpler and better substantiated for the connate brines than circulating meteoric groundwater. The disparity between the hydrogeologic and chemical interpretations can be reconciled if (1) there has not been enough time for flow of meteoric groundwater to flush the connate brine from the carbonates since the hydraulic head gradient developed, (2) present cross-formational flow is unevenly distributed between fractured and unfractured areas, and (3) the brine sampled at the test wells is compositionally different from the brine in unsampled fracture zones.

Bein and Dutton (1993) studied the distribution of high TDS, Na-Cl and Ca-Cl water types for three units, Wolfcamp, Pennsylvanian, and Pre-Pennsylvanian. They found that Na-Cl brine was derived from meteoric water which has dissolved halite and anhydrite, while Ca-Cl brines were interpreted to be modified connate Permian brine. In general, the positions of these brines correspond with the flow velocities and permeabilities, with displacement of Ca-Cl brine occurring as the Na-Cl brines move east

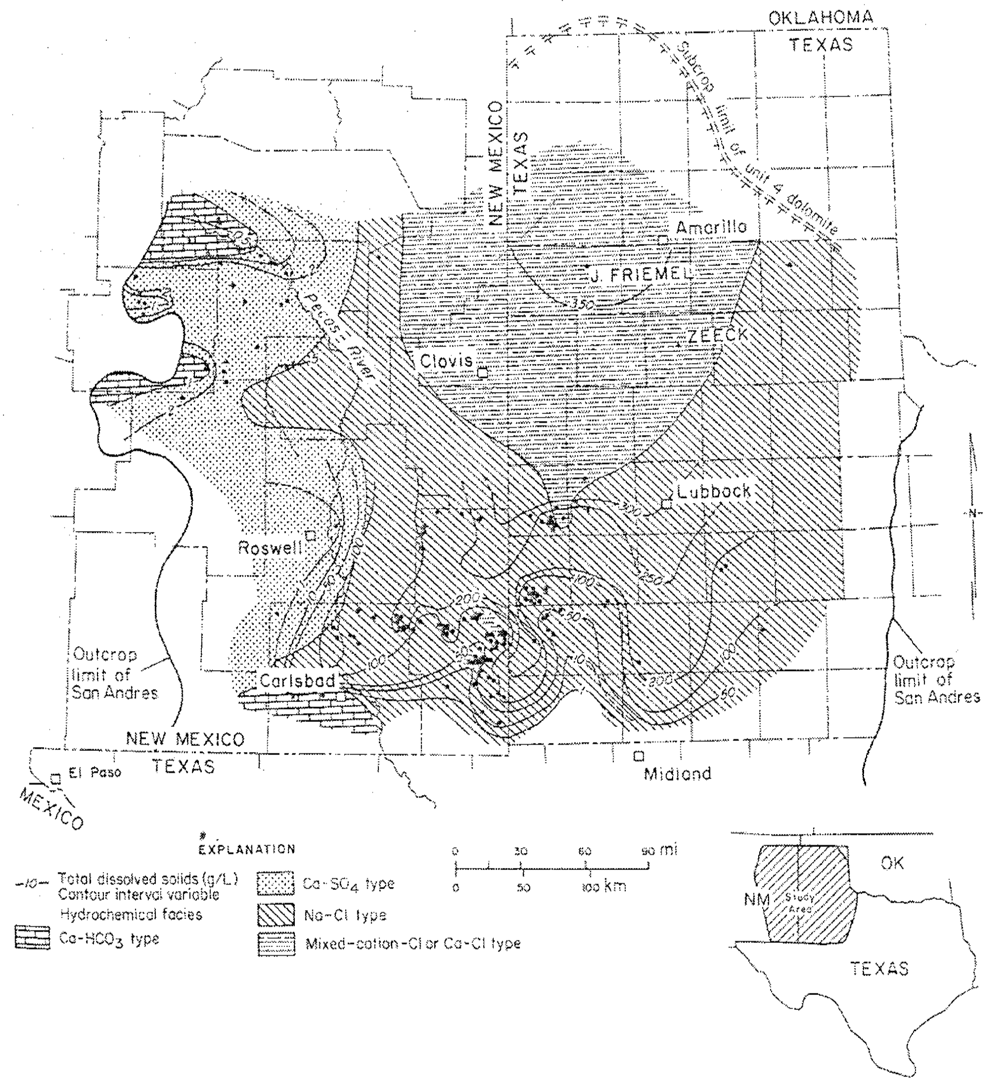


Figure 15. Hydrochemical facies and contours of TDS in the San Andres Formation (Dutton, 1987)

from western recharge areas. Dutton showed the distribution of TDS and Na-Cl and Ca-Cl brines in most of Lea county, but the small number of samples in New Mexico warrants further study. In addition, details of displacement and patterns of composition are not shown on a formational scale, where they would likely be more complex.

Stueber et al. (1998) focused on waters in carbonates in the San Andres-Grayburg, Wolfcamp, Pennsylvanian, and Devonian formations in the Central Basin platform in west Texas. They examined chemical and isotopic signatures from these waters and found basically two groups of waters. The first group, loosely labeled saline meteoric water, included water from the San Andres Formation and Devonian limestones, and had salinities of 26-59 g/L and $\delta D - \delta^{18}O$ values in the same range as modern precipitation and groundwater in the Ogallala aquifer. This water probably acquired its salinity from halite dissolution, shown by Na, Cl, and Br concentrations. The second group of water samples, called modified evaporitic marine brines, were from the Pennsylvanian and Wolfcamp limestones and were more saline, with salinities of 70-215 g/L. They are apparently a result of mixing of two fluids. These fluids are highly evaporated seawater and saline meteoric water similar to the first group waters. These modified evaporitic marine brines were the dominant fluids in Paleozoic carbonates until the late Tertiary, when the tectonic uplift began 5-10 Ma, apparently causing meteoric water to flow into deeper strata. This study confirms the findings of the studies cited above that meteoric waters can migrate large distances and displace saline waters in deep basins.

In summary, the study area is a geologically and hydrologically complex area. Formations with good water quality (chloride concentration of 3000 mg/L or less) tend to be near the surface and have higher porosity and permeability. Formations that have good water quality in general include the Ogallala, Capitan and San Andres Limestone, and the Artesia Group. Other surface formations can have good water quality, but more often in small quantities. Meteoric waters are displacing connate water in areas and formations of relatively high permeability, and where the gradient exists to move water.

In southeastern New Mexico, both the shallow upper aquifer and the evaporite confining layer (especially in and around the WIPP site) have been well studied. Stable isotope studies support findings that good water quality is indicative of recent recharge. The presence of connate brines and meteoric water, as well as flow direction of meteoric water, are well established in the literature for the upper aquifer and evaporite confining layer of the Permian Basin, but there is very little information about the deep basin aquifer. More detailed groundwater studies in the Permian basin have focused on the Palo Duro basin in the Texas panhandle. Studies by Dutton (1993) showed the distribution of TDS and Na-Cl and Ca-Cl brines in Texas and in Lea county, for three units, Wolfcamp, Pennsylvanian, and Pre-Pennsylvanian, but the small number of samples in New Mexico did not clearly reveal the patterns of water-quality distribution. Another study by Dutton (1987) focused on the San Andres Formation in the Permian basin. Water types mapped throughout my study area suggest that east of the Pecos River, the water is Na-Cl type. Southern Eddy county San Andres water is Ca-HCO_3 type, and water west of the Pecos River is Ca-SO_4 type, based on Piper diagrams of the water (Figure 15.)

Methods

In order to achieve the objectives stated above, both produced water and groundwater water quality data from various sources were gathered, and databases were created. To find and map water quality trends by formation, several methods were used, including calculating simple statistics, and mapping samples by different components in ArcView GIS. For produced water samples, piper diagrams were plotted, and cross sections were selected based on the distribution of produced water samples. Cross sections were created using formation-top data found on scout cards, and the water samples were projected on the cross section figures. Produced water samples were separated into groups, analogous to Stueber et al. (1998), and these groups were also mapped in cross-sectional view and plan view using ArcView 3.1. The relative permeabilities of cross sections were found by consolidating lithology into facies and using these facies as predictors, with categories of low, medium, and high relative permeability. Additionally, permeability measurements from oil field data were compiled and, for each formation, the range and average permeability was found. This data was used in order to compare the relative permeability of various formations with the maps of water quality trends. The results were compared with the available knowledge of water quality and geology of the area.

Database Description

The databases used to evaluate whether and where meteoric waters are moving in the deep basin in the Permian Basin in New Mexico include: 1) the State Engineer's Groundwater quality database, 2) the USGS database of produced water, and 3) the NM WAIDS database of produced water. Although the third database was not used in this study, a description of the NM WAIDS database is included because it is one of the main goals of the project that funded this study. It contains the USGS database of produced water as well as data from numerous other sources, and is available on the world wide web.

Groundwater Quality Database

The groundwater quality database was provided by the State Engineer Water Resources Division District 2 in Roswell, New Mexico. It was compiled over many years as numerous paper files and was turned into an electronic file of over 30,000 samples, which was generously donated to the NM WAIDS project.

Data categories include location in township and range, including New Mexico quarter quarter coordinates, depth, formation, date collected, collector, use, land surface elevation, chloride concentration, conductivity, TDS, temperature, card date, ownership, and other categories.

Sample dates range from August 1925 to August 1998. The groundwater data also covers quite a large area, with most samples occurring in the southeast quarter of New Mexico, including Lea, Eddy, Chaves, Otero, Lincoln, Guadalupe, Roosevelt, DeBaca, Curry, and Quay counties. However, the only chemical analysis for the vast majority of the samples is temperature (°F), conductivity (μS/cm), and chloride (mg/L).

In addition, much information is missing. For example, there are approximately 1700 samples with no indication of what geologic formation the sample came from, and 12 300 samples with a depth of 0, and about 450 with no depth data at all.

USGS Produced Water Database

The USGS Produced Water Database was publicly released on the internet in May 2002. It contains produced water data for 34 states, of which 3850 samples were taken in New Mexico. This database is a revision of a database originally compiled at the DOE Fossil Energy Research Center that was located in Bartlesville, Oklahoma. The USGS modified the original database by removing redundancies, verifying internal consistency and adding information to the fields that describe the location, geologic setting, sample type, and major ion chemical composition. (Breit, 2002).

Data categories include locators such as state, county, latitude and longitude, township, range, and section, and oil and gas field name. The geologic setting of the sample is described by the geologic basin (province), the name of the geologic unit from which the fluid was produced and the age of that geologic unit. General description of samples include well name, sample date, sample method, upper and lower depth (feet), pH, and TDS. The major dissolved species typically include sodium, potassium, calcium, magnesium, chloride, bicarbonate, and sulfate.

Of the 3850 samples from New Mexico, 3518 were from the Permian Basin. Sample dates range from January 1928 to July 1979. The area covered includes Lea, Eddy, Chaves, and Roosevelt counties. However, 705 samples had no depth information and about 170 samples had no geologic formation data. Those samples were not used for water quality analysis.

Some caution must be employed when using these data. Many different companies contributed to the database, which means that there is little control on accuracy of the data. Sampling methods between companies may vary considerably, and there is no indication of the method of analysis (some measurements may be taken at the field, others in the laboratory) or how long the sample sat before analysis was made. In addition, the data spans a long period of time, and even samples from the same company may have drastic differences in sampling and analysis methods.

In the database, there are thirteen listed sampling methods, including an "unknown" category, all with varying degrees of accurately representing the actual composition of water produced by the well. Because this study is a first look at the water geochemistry distributions and trends, all the data available was used to allow as large a sample population as possible for each formation.

NM WAIDS Produced Water Database

The NM WAIDS Produced Water Quality Database, created by the Petroleum Technology Transfer Council under the Petroleum Recovery Research Center, is being compiled from a large variety of source data. Several oil and gas producers in the area were solicited for data, and many have been very generous in sharing this information. Some of the data has been provided in digital format, either as Microsoft Excel spreadsheets, Microsoft Access databases, or simple text files. Much, however, came from producers as paper forms supplied to them by the various companies employed to run the water analyses. Each data source must be analyzed to determine what kind of data is available and in what format (numeric, text, semi-quantitative), so the correct fields and data definitions can be built into the database structure. Examination of the digital and paper forms revealed that data could be divided into four main categories: general information, general sample properties, anions, and cations. A number of tables and views were used in the database construction: primary tables are the general sample information (items such as sample name, location, formation, physical parameters), anion information (CO_3, SO_4, etc.), and cation information (Ca, Na, Mg, etc). After the initial database was constructed, digital data sets were imported into the database. As new data sets, either paper or digital, are acquired, some modifications to the NM WAIDS database may be required, but it is believed that the current structure will accommodate new data types.

There are currently over 6600 records in the NM WAIDS database. Not all of these samples have quality data; some may be lacking either a location or any significant chemical data. There are samples with a specific lat/long location, and have some kind of geographical distribution and may simply need a calculation of lat/long coordinates. Over 5570 samples have no depth data, and much of the formation data needs cleaning (correcting abbreviations, wrong spelling, and other problems.)

Two significant problems were faced in construction of the NM WAIDS database. The first of these was the extreme variability of the data provided. At least 30 different form types have been encountered so far, and the types of data available on each of these can vary tremendously. Simple variations, such as designating the amount of a component as either a number, or as a text descriptor (e.g. nil, trace, present, significant) are difficult to distill into database. Additionally, data is presented in a variety of units such as parts per million, equivalents per million, milligrams/liter or milliequivalent per liter. The problem of data variability was surmounted by the creation of a flexible database structure that will allow for change if necessary. Units conversion routines have been created and eventually will be incorporated into the system so that users can easily switch from one measurement system to another. Also, an attempt was made to preserve as much of the water quality information as possible through the use of database fields designed to hold miscellaneous notes. In this way, information that did not easily fit into any of the specified data fields can be recorded.

The second major problem in the NM WAIDS database construction was that of data entry. Much of the information was supplied as thousands of pages of paper forms. Some were typed, some handwritten. Student employees were trained in the use of the data entry system, and online instructions are also available in the system. However, data entry is still time-consuming and error prone. Use of an Optical Character Recognition (OCR) program, combined with an automated database entry system has been investigated and used. At least some of the labor and error can be avoided if samples can be scanned, the images converted to text, the text manually verified, and then automatically entered into the NM WAIDS database. The use of OCR for handwritten forms is a complex task, and is beyond scope of this project.

The NM WAIDS database is not used to further the objectives of this study for several reasons, the first being the high variability of the data with respect to the amount of chemical and data, units, and errors created as the data was entered (e.g. data in the wrong categories, wrong or abbreviated formation names, dates, etc.) It was decided that the time required to turn the data into a useable format was too high for the amount of return. The second reason is that the database was continually being updated and checked for consistency. However, the database is described because it is one of the main goals of the NM WAIDS project, and will soon be available on the internet.

Converting databases for use on ArcView GIS

The easiest way to put data points on ArcView GIS is to put coordinates in the latitude-longitude coordinate system. Although the produced water database already had coordinates in this format, the coordinates of the groundwater database were in township and range format, in the New Mexico coordinate system of quarter quarter divisions. This format divides up each section (one square mile) into smaller and smaller quarters

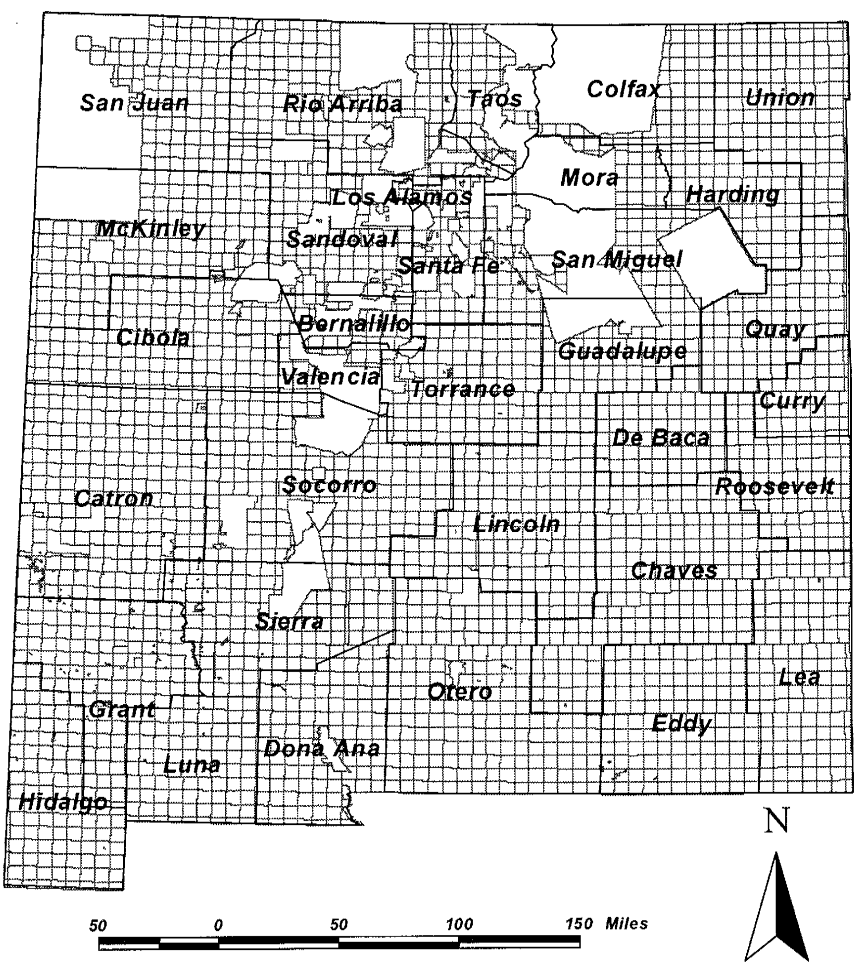


Figure 16. Townships and Ranges in New Mexico

for greater accuracy. Each quarter division has a number; 1 is NW, 2 is NE, 3 is SW, and 4 is SE. Thus, a location given as 1N, 21E, 30.11243 would actually mean the SW quarter of the SE quarter of the NE quarter of the NW quarter of the NW quarter of section 30, in the first township north of the baseline, and 21st range east of the principal meridian.

The township and range system was established in 1785 as a way of subdividing land in the western United States. On a map, township lines are horizontal (similar to latitude) and range lines are vertical (longitude). If every section is exactly square, the same size, and the lines are exactly north/south and east/west, an extremely accurate latitude/longitude can be calculated. However, this is seldom the case. Township lines are normally adjusted every fourth or fifth township to account for the curvature of the earth. If this were the only irregularity, a very accurate latitude/longitude of each section could still be predicted by choosing rectangular areas delimited by these adjustments. However, it seems that sometimes townships are often offset a considerable amount, sections are elongated or shrunk, and 1/2 townships and 1/2 ranges are added (see Figure 16).

A computer program to convert between township and range to latitude and longitude is available on the internet, at http://www.geocities.com/jeremiahobrien/trs2ll.html. This program was developed by Marty Wefald in Montana as part of a system for locating wildfires. His program calculates the coordinates of the center of a section, and is accurate to within 1/4 to 1/10 of a mile. However, he does not convert the quarter quarter part of the location, so the worst accuracy for the groundwater quality coordinates would be approximately 3/4 mile. This program was used to find latitude and longitude coordinates for the State Engineer's Groundwater Database.

Water injection

There are two types of water injection wells. The first kind is a water injection well which is used to keep pressure up within a formation and usually injects water of similar composition to the water produced from that formation. The second type is known as a salt water disposal well, which is a deep well used to dispose of large

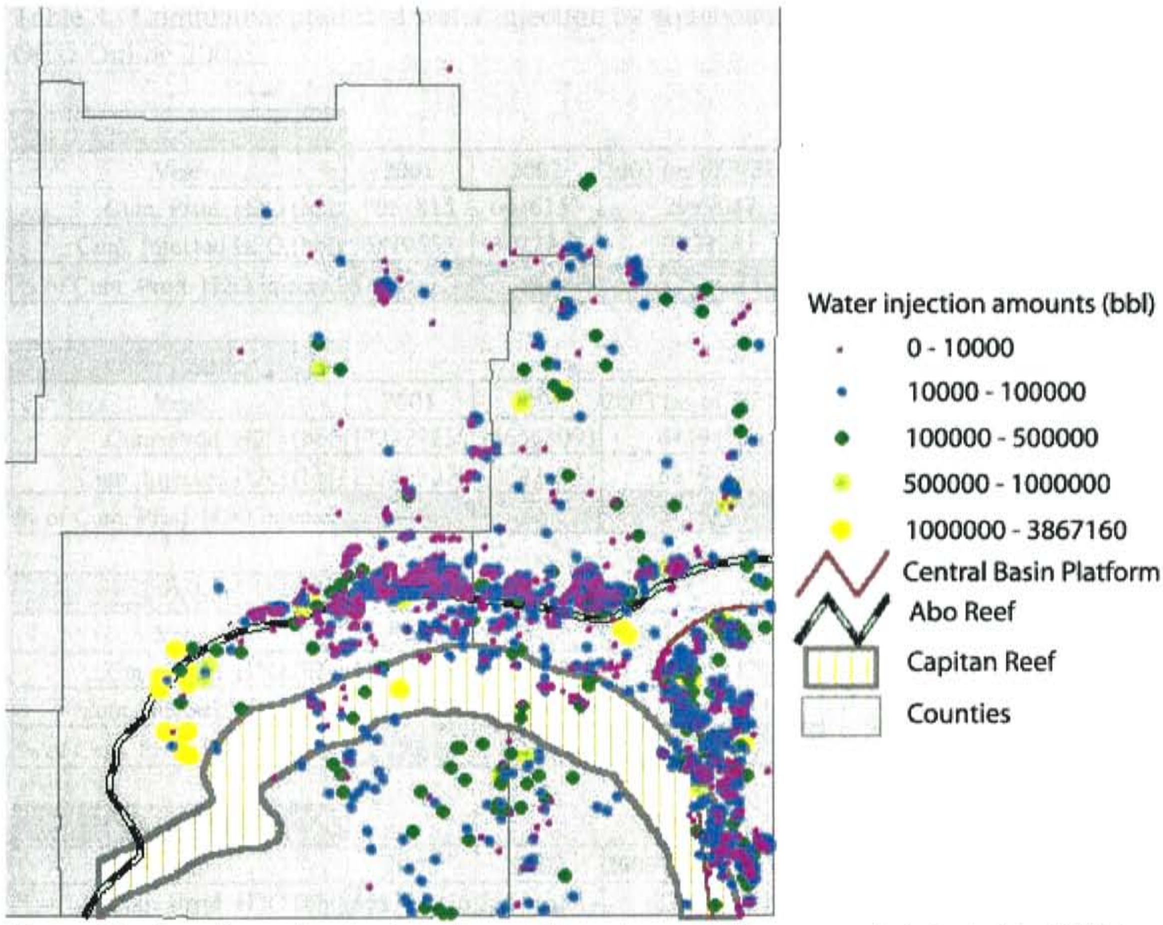


Figure 17. Location of water injection wells and cumulative amounts injected in 2002 in barrels (1 bbl = 42 gal = 158.97 L)

amounts of highly saline brines, which may be of any composition. Water injection occurs over the entire study area (see Figure 17), in nearly all formations, with the exception of those formations with low porosities and permeabilities ("tight" formations).

Water injection is a way of maintaining the pressure within a formation, mostly pumping produced water from the same formation in order to prevent scaling within the formation from mixing incompatible waters. Nearly the same amount of water is injected that is produced (see Table 3); however, the composition of the injected water is usually somewhat different than the original produced water. There are several reasons for this

Table 3. Cumulative produced water injection by county and total for 2001 to 2003. OCD Online 2003.

Chaves County			
Year	2001	2002	2003 (as of 7/21/03)
Cum. Prod. H2O (bbl)	7051815	6446153	2999047
Cum. Injected H2O (bbl)	6819553	6772747	2822281
% of Cum. Prod. H2O injected	97	105	94

Eddy County			
Year	2001	2002	2003 (as of 7/21/03)
Cum. Prod. H2O (bbl)	172329258	166563993	64194936
Cum. Injected H2O (bbl)	152829075	146926205	63197886
% of Cum. Prod. H2O injected	89	88	98

Lea County			
Year	2001	2002	2003 (as of 7/21/03)
Cum. Prod. H2O (bbl)	429351183	412605679	154455426
Cum. Injected H2O (bbl)	403614286	428160672	156906731
% of Cum. Prod. H2O injected	94	104	102

TOTAL			
Year	2001	2002	2003 (as of 7/21/03)
Cum. Prod. H2O (bbl)	608732256	585615825	221649409
Cum. Injected H2O (bbl)	563262914	581859624	222926898
% of Cum. Prod. H2O injected	93	99	101

difference in composition. The first is that there is often mixing of produced waters in a holding tank within an oil field; as producing and reinjection continues over time, the composition of water within a formation will tend to homogenize over distance. The second reason is that oil makes up a certain percentage of the produced water, and for injection into the ground, the lost volume of liquid is often made up by fresh water (often from the Ogallala Formation.) Again, this is to prevent possible scaling from mixing two incompatible brines; water from the Ogallala is fresh enough that the produced brine will only be diluted.

The effect of water injection of produced water quality must be considered in light of the goal of this study, which is to reconstruct the distribution of natural subsurface water quality. Inasmuch as water injection to maintain formation pressure usually employs water from the same formation, variations of composition over time are usually not large. Although caution must be exercised in considering the effect of injection on any individual data point, the broad spatial trends of the data should be representative of natural water quality.

Geochemical Interpretation

In the following sections of this paper, the terms "groundwater" and "groundwater samples" are used to refer to the New Mexico State Engineer's Groundwater Database, and "produced water" and "produced water samples" are used to refer to the USGS Produced Water Database. These two databases are discussed separately because samples in the Groundwater database are from near surface shallow aquifers and the only geochemical data available is chloride concentration, while samples from the Produced Water Database are from the deep basin and generally have all major ions. The NM WAIDS Database was not used because of the high variability of the data, and also because it was continually being updated and checked for consistency.

Geochemistry of Groundwater, Southeastern New Mexico

In the State Engineer's groundwater database, there are 25083 water samples in Lea, Eddy, and Chaves counties. These samples have a wide range of sample dates and include many water wells designated for various uses, including stock, irrigation, domestic, mining of ore, oil, gas, and many others. Samples in the study area with no formation data were deleted. Figures 18 – 20 show the samples separated by formation with chloride concentration in mg/L. A noticeably higher concentration occurs near the Pecos River, indicating possible upward movement of deep groundwater towards a topographic and potentiometric low. Samples are described by formation, from oldest to youngest. Table 4 contains a summary of the groundwater data.

Surface water

There are 159 lake samples (from 15 locations) and 3 river samples (from 2 locations) in the database. All are in Chaves county east of Roswell except for two lake samples near the center of the Lea/Eddy border. Of the lake samples, there is one anomalous sample with a chloride concentration of 110 750 mg/L; the rest have concentrations between 0 and 11 000 mg/L. The mean chloride concentration is 3038 mg/L, the median is 2160, and the standard deviation is 8781. Sample dates range from 1927 to 1984, with most between 1938 and 1958. The river samples include 2 labeled "RIO" with chloride concentrations of 1240 and 1250, and one from the Pecos, with chloride concentration of 268 mg/L.

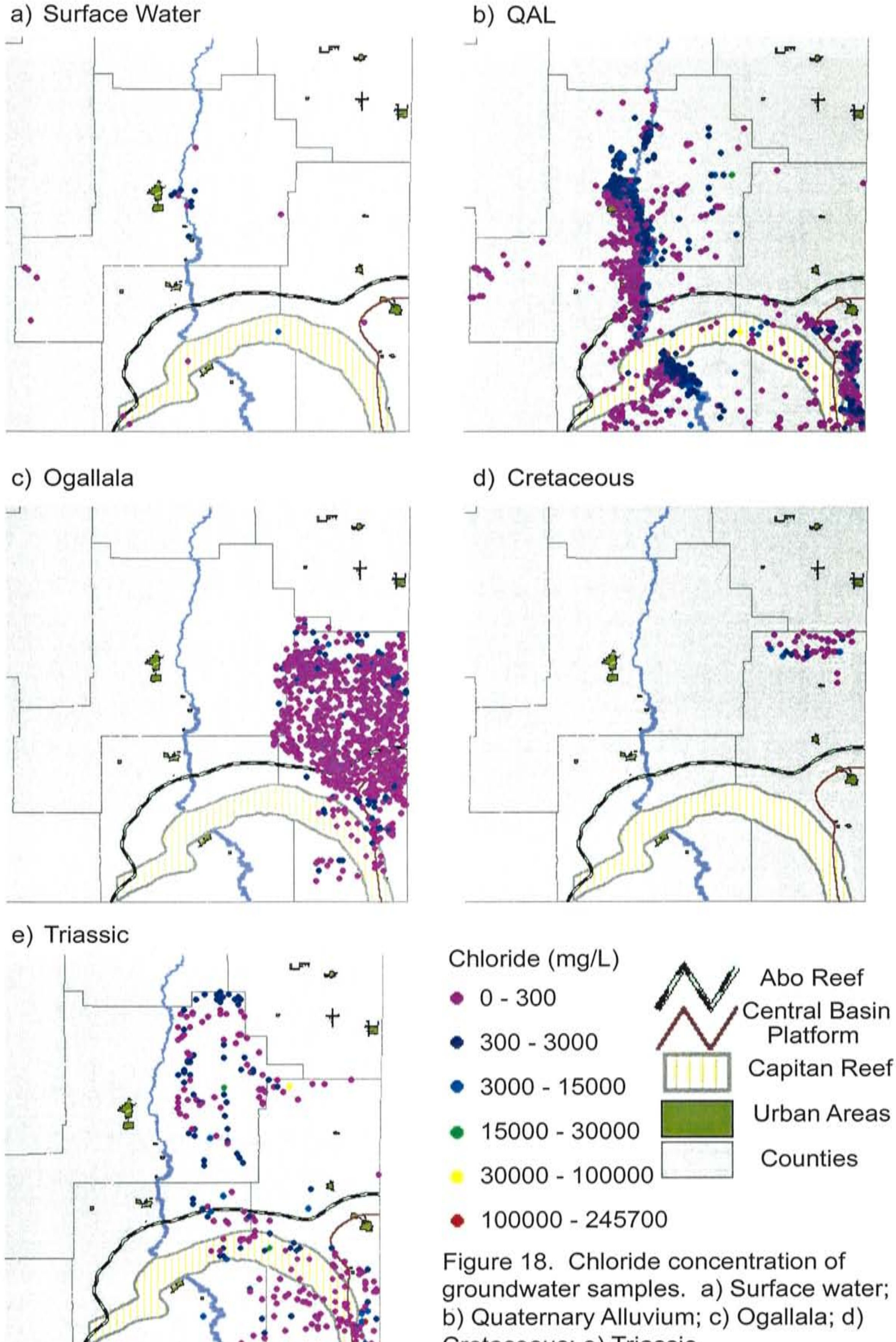


Figure 18. Chloride concentration of groundwater samples. a) Surface water; b) Quaternary Alluvium; c) Ogallala; d) Cretaceous; e) Triassic.

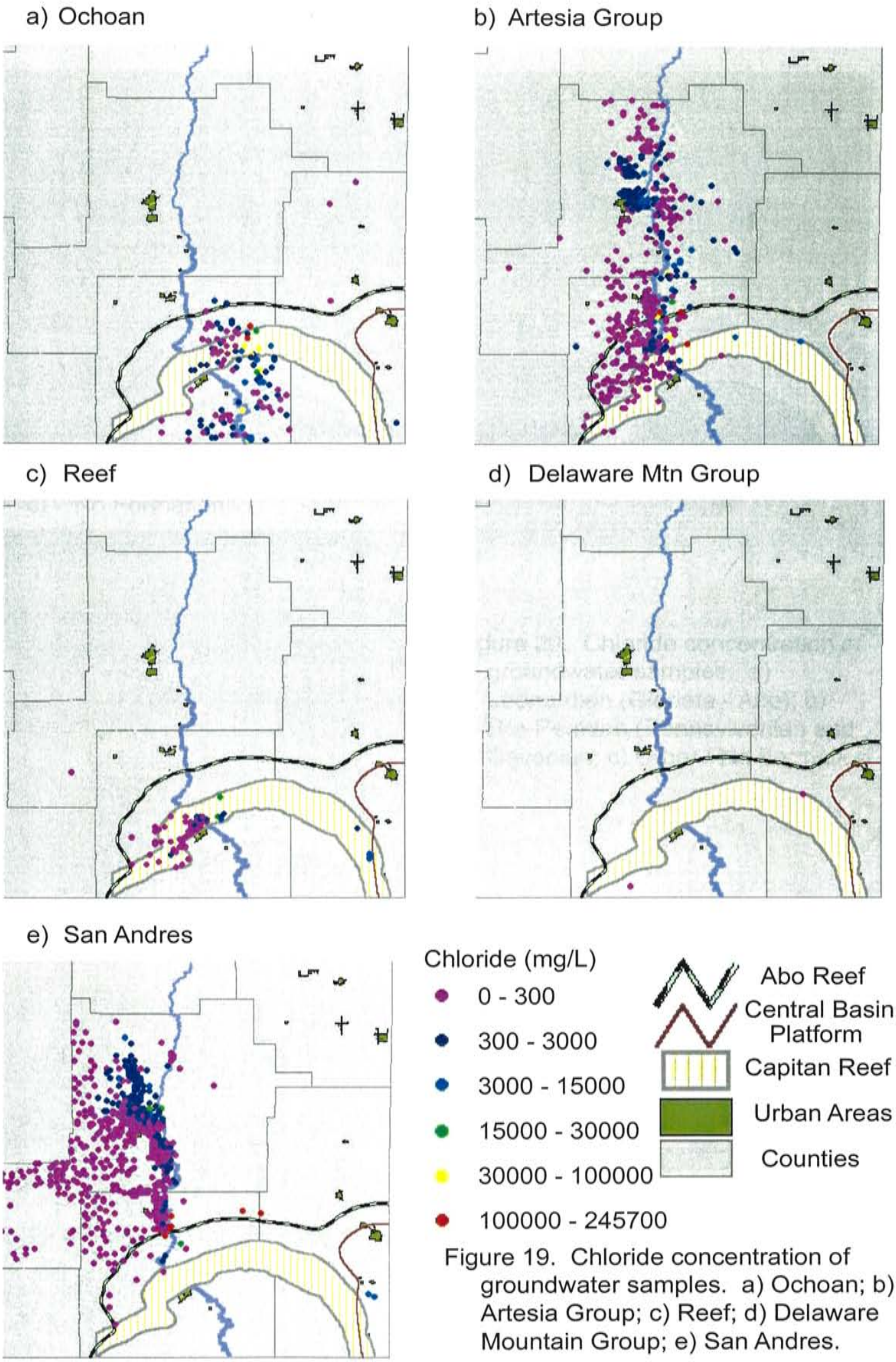
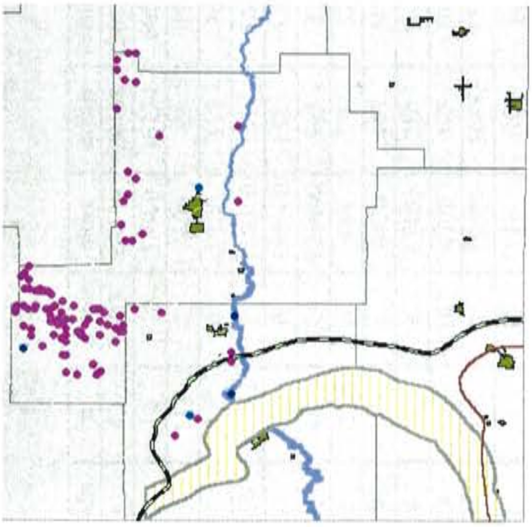
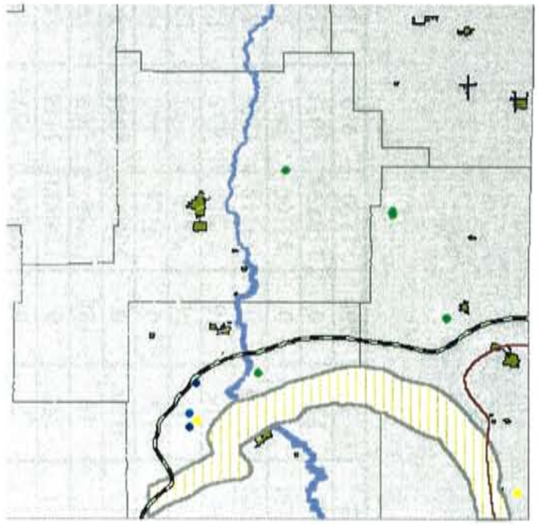


Figure 19. Chloride concentration of groundwater samples. a) Ochoan; b) Artesia Group; c) Reef; d) Delaware Mountain Group; e) San Andres.

a) Leonardian



b) Pennsylvanian and Devonian



c) No Formation

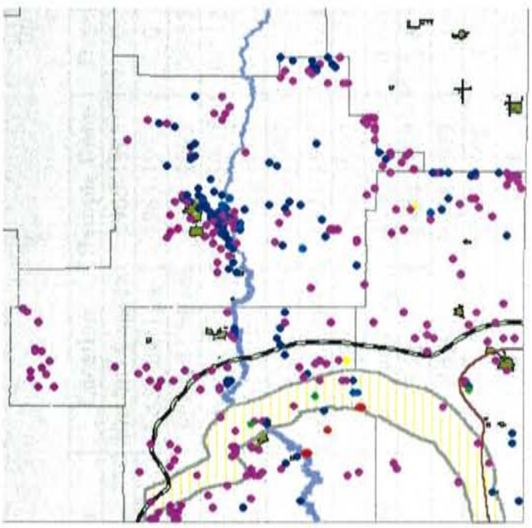


Figure 20. Chloride concentration of groundwater samples. a) Leonardian (Glorieta - Abo); b) Pre-Permian (Pennsylvanian and Devonian; c) Other / No Formation

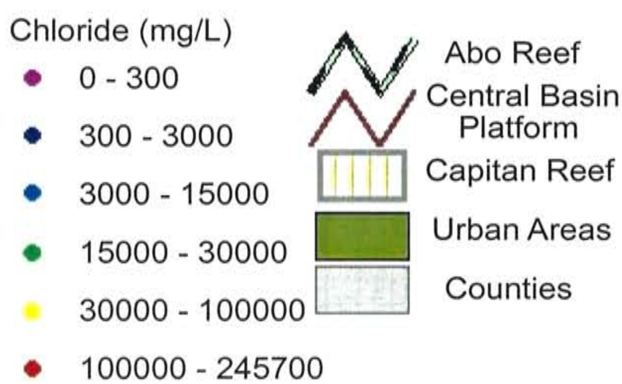


Table 4. Summary of Groundwater samples

Age	Formation	Location	Sample Dates	Depth	Wells	n	Cl min	max	mean	median	st dev.
Devonian	Devonian	Lea and Chaves	1965-1985	0	5	13	7000	68130	28468	26277	13164
Pennsylvanian	Pennsylvanian	Eddy and Lea	1965-1985	0	6	16	770	57500	16224	6000	20717
Leonardian	Yeso	Eddy and Chaves	1950-1995	0-1550	73	153	2	3600	62	19	332
Leonardian	Glorieta	Eddy and Chaves	1926, 1950-1995	0-1120	25	37	0	9700	117	20	766
Guadalupe	San Andres	All three	1925-1998	0-10510	1096	12563	0	159300	1017	580	5283
Guadalupe, Artesia	Artesia	Eddy and Chaves	1926-1997	0-924	376	1693	0	158000	1585	620	4988
Guadalupe, Artesia	Grayburg	Eddy and Chaves	1921-1997	0-1232	113	443	0	125000	945	22	9346
Guadalupe, Artesia	Queen	Eddy	1940-1997	0-300	14	21	6	440	79	52	100
Guadalupe, Artesia	Seven Rivers	Eddy and Lea	1940-1997	0-610	33	180	0	7420	449	417	729
Guadalupe, Artesia	Yates	Eddy	1944-1997	0-418	38	145	4	13400	284	260	1108
Guadalupe, Artesia	Tansill	Eddy	1938-1997	0-464	20	70	10	4770	375	201	643
Guadalupe, Reef	Capitan	Eddy and Lea	1946-1998	4500	103	236	2	18000	1074	127	2315
Guadalupe, Reef	Goat Seep	Chaves	1988	863	1	1	16	16	16	16	N/A
Guadalupe, Delaware Mtn Group	Bell Canyon	Eddy and Lea	1963	0, 595	2	6	0	17600	5814	38	8976
Ochoan	Castile	Eddy	1948-1998	0-350	19	54	2	39960	1399	201	5603
Ochoan	Salado	Eddy and Lea	1938-1977	0	4	7	0	57600	17371	0	25992
Ochoan	Rustler	Eddy and Lea	1927-1997	0-1604	111	280	0	124000	5116	443	15370
Ochoan	Dewey Lake Redbeds	Eddy	1970-1997	0-365	3	10	124	750	267	190	193
Triassic	Santa Rosa	All three	1938-1997	0-1472	155	320	0	106300	1088	86	7072
Triassic	Chinle	All three	1927-1997	0-660	160	350	0	19120	442	165	1194
Triassic	Triassic	Chaves	1985-1994	0-194	20	25	14	3310	273	122	644
Cretaceous	Cretaceous	Lea	1953-1995	0-250	48	115	16	22980	635	126	4325
Pliocene	Ogallala	All three	1930-1995	0-350	1379	3318	0	29118	1229	81	4325
Quaternary	Alluvium	All three	1900-1998	0-1200	1654	4341	0	88100	903	300	2954
Surface Water	Lake	All three	1927-1984	0	15	159	0	110750	3038	2160	8781
Surface Water	River	Chaves	1956-1982	0	2	3	268	1250	919	1240	564

Quaternary Alluvium

There are 4341 water samples taken from Quaternary Alluvium in Lea, Eddy, and Chaves counties. Of these, only 111 have chloride concentrations greater than 5000 mg/L, with a highest concentration of 88 100 mg/L. The mean concentration is 903 and median is 300 mg/L, with a standard deviation of 2954. Samples were taken between 1900 and 1998 from depths between 0 and 1200 feet (0 – 366 m).

Ogallala

The Ogallala aquifer extends through much of Lea county in New Mexico. There are 3138 samples from the Ogallala, most in Lea county, and a few on the eastern edge of Chaves county and northeast corner of Eddy county. Sample dates from 1930 to 1995 and are from depths up to 350 feet (107 m). Most of the samples have good quality water with chloride concentrations of 3000 mg/L or less. However, there are areas, especially T11S R32E 24 (northern Lea county) with high salinities, and chloride concentrations between 10 000 and 30 000 mg/L. The mean concentration is 1229 mg/L and median is 81 mg/L, with a standard deviation of 4325.

Cretaceous

There are 115 Cretaceous samples in northern Lea county, with sample dates from 1953 to 1995. Most of these samples have low chloride and conductivity (< 1000 mg/L), with six samples with chloride concentration between 1000 and 5000 mg/L, and 2 samples with >10000 mg/L. The mean chloride concentration is 635 mg/L, median 126 mg/L, and standard deviation of 2407.

Triassic

There are 695 samples from Triassic age formations, all located east of the Pecos River except one; of these, 350 are Chinle, sampled 1927 to 1997, 320 are Santa Rosa, sampled 1938 to 1997, and 25 in Chaves county are simply labeled "Triassic," sampled 1985 to 1994. All but 31 of the samples have a chloride concentration less than 2000 mg/L; the highest concentration is 106 300 mg/L. The mean chloride concentration is 733 mg/L, the median is 121 mg/L, and the standard deviation is 4881. The samples were taken between depths of 0 and 1500 feet (0 – 457 m).

Ochoan

The Ochoan age formations include the Dewey Lake Redbeds, the Rustler, Salado, and Castile Formations. These are composed of evaporites, including anhydrite, halite, and potash. There are 10 Dewey Lake Redbeds from three wells, 280 Rustler from 111 wells, seven Salado samples from four wells, and 54 Castile samples from 19 wells. All of the samples are in Eddy county except seven in Lea county. The Castile and Dewey Lake Redbeds samples have relatively low salinities, with an mean of 1223, median of 201 mg/L chloride and standard deviation of 5157; all but two Castile samples have a chloride concentration less than 3000 mg/L. The Rustler and Salado samples have samples with much higher salinities, with concentrations over 120 000 mg/L chloride. The mean chloride concentration for Rustler and Salado samples is 5415 mg/L, the median is 440 mg/L and standard deviation is 15 755.

Artesia Group

The Artesia Group includes samples from the Tansill, Yates, Seven Rivers, Queen, Grayburg, and San Andres Formations, in addition to samples called "Artesia

Group". There are 15 115 total samples in this group; of these, there are 1693 samples labeled Artesia Group, 70 Tansill, 145 Yates, 180 Seven Rivers 21 Queen, 443 Grayburg, and 12563 San Andres. Nearly all the samples except those labeled Artesia Group and San Andres are in Eddy county, with two Grayburg samples in Chaves and two Seven Rivers Samples in Lea. The Artesia Group and San Andres are in Eddy and Chaves counties, in addition to three San Andres samples in Lea. Sample dates range from 1926 to 1997. All samples are from depths of 1500 feet (457 m) or less, with the exception of three San Andres samples, two in Lea county with depths of 4999 (1524 m) and 5774 feet (1760 m), and one in Chaves with a depth of 10510 feet (3023 m). For the Artesia Group samples, the mean chloride concentration is 1061 mg/L, the median is 554 mg/L, and the standard deviation is 5349.

Reef

There are 236 samples from the Capitan Formation in Eddy and Lea counties, and one from the Goat Seep Formation in Chaves county, collected between 1946 and 1998. The great majority of these samples have chloride concentrations of less than 2000 mg/L. In T24S R36E, there are seven deep wells (4500 feet, 1372 m)) with high chloride concentrations of 2000 – 4500 mg/L chloride, and an observation well sampled in October of 1962 in T21S R28E 30 with concentrations between 8000 and 9500 mg/L; other than that, there are three samples with concentrations between 9000 and 18000 mg/L. The mean Capitan chloride concentration is 1074 mg/L, median 127mg/L, and standard deviation is 2315. The Goat Seep sample has a very low concentration of 16 mg/L chloride.

Basin

In the Delaware Mountain Group, there are six samples from the Bell Canyon Formation in the database. These samples are from two wells, an oil well in Lea county and an irrigation well in Eddy county. The samples from the oil well were taken in December 1963, and have a depth value of zero. They have high chloride (> 16 000 mg/L) and conductivity values. The samples from the irrigation well were taken at a depth of 595 feet (181 m), and have low chloride (<70 mg/L) and conductivity values. Although the statistics are listed in Table 2, the number of wells and samples in the basin are not statistically significant, which should be taken into consideration if this data is used in another study.

Leonardian

The Glorieta and Yeso Formations are Leonardian age, and there are 37 Glorieta samples and 153 Yeso samples found in Chaves and Eddy counties. These samples were taken between 1950 and 1995, except for one Glorieta sample, which was taken in 1926 and has an anomalously high chloride concentration of 9700. Most of the rest of the samples have concentrations less than 200 mg/L; the exceptions are one Glorieta sample with a concentration of 1552 and two Yeso samples, one with 646 and the other with 3600 mg/L chloride. The mean chloride concentration for Leonardian samples is 117 mg/L, the median is 20 mg/L, and the standard deviation is 766.

Pre-Permian

There are 13 Devonian samples from five wells (four oil wells and one SWD well) in Lea and Chaves counties, with sample dates from 1965 to 1985. The mean chloride concentration is 28468 mg/L, the median is 26277 mg/L, and the standard deviation is 13164; all of these except one have chloride concentrations > 25 000 mg/L. There are 16 Pennsylvanian samples from six wells (four oil and one PPP in Eddy county, and one OTH in Lea county near Lovington), with sample dates from 1961 to 1968. These have a fairly wide range of chloride concentration, from 770 to 57500 mg/L. The mean chloride concentration is 16224 mg/L, the median is 6000 mg/L and the standard deviation is 20717. All of the Pre-Permian samples have a listed depth and land surface elevation of 0, meaning no data.

Other/ No Formation Data

There are 45 samples whose formation category was apparently mislabeled with water type or collector; these include two Mining of Ore, one Pecos Valley, 2 USGS Personnel, one 01, one ART, one POA, one SRO, 34 SUS, and two SWW. They all have chloride concentrations of 7000 mg/L or less. There are many more samples (477) with no formation data at all; these samples range all across the area and have concentrations varying between 0 and 203 700 mg/L chloride, and depths between 0 and 1201 feet (0 – 366 m).

Groundwater conclusions

Groundwater samples are present in 24 formations, as well as a small number of samples from surface waters. In general, groundwater samples are found in formations at or near the surface, and have low chloride concentrations, with the majority of samples having a chloride concentration of less than 1000 mg/L. Their high chemical quality most likely reflects their origin as meteoric water and short residence time within the aquifer. Where number of samples is sufficient, spatial trends are usually evident, and are usually shown as increasing chloride concentration with proximity toward the Pecos

River. There are several possible reasons for the increase of chloride with distance towards the Pecos, which include increased salinity from return flow irrigation waters, deep basin groundwater moving up towards the topographic and hydraulic potential low, the dissolution of evaporites near the surface, and the addition of saline water from deeper zones within the San Andres limestone as the Pecos enters these zones. Although upward movement of deep basin groundwater likely plays a large role in the increasing salinity of groundwater towards the river, in the area between Roswell and Carlsbad most of the salinity increase is probably from the dissolution of local evaporites and addition of saline water from deeper formations, especially the San Andres (Welder, 1983).

In the upper phreatic aquifer, meteoric waters are displacing connate brines in areas and formations of relatively high permeability, and where the gradient exists to move water. Samples with high chloride concentration (greater than 15 000 mg/L) are present in 15 of the 24 the formations in the State Engineer's groundwater database, and are often found near the Pecos river. Those samples with high concentrations that are not near the river, especially those in the Ochoan and Triassic formations, are likely in areas of low permeability and have at least somewhat equilibrated with their surrounding minerals.

Geochemistry of Produced Waters, Southeast New Mexico

The USGS produced water quality database has data including the major cations and anions. Summary statistics of produced water quality by formation are listed in Table 5, including percentages of samples with a chloride concentration less than 30 000 mg/L for each formation. Since the produced water database has all the major ions, an easy way to look at chemical data by formation is to plot samples onto Piper diagrams. The Piper diagram plots the major ions as percentages of milli-equivalents, and both the total cations and the total anions are set equal to 100%. A typical Piper diagram and the San Andres and Grayburg Piper diagram are shown in Figures 21 and 22. The cation data is in the left triangle, the anion data is in the right triangle, and a center diamond shows the composite of the two triangles. This plot reveals useful properties and relationships for large sample groups. Its main purpose is to show clustering of data points to indicate samples that have similar compositions. Looking at these diagrams, it seems that all of the samples except for some of the San Andres and Grayburg samples show signs of halite dissolution, with linear increases in percent sodium and chloride. The piper diagram of San Andres and Grayburg samples has much more variability, and some of the samples do not reflect halite dissolution; this is because these samples have high chemical quality (low TDS) and most likely reflects their origin as meteoric water and a short residence time within the aquifer.

There are several techniques and measurements used to fingerprint the origins of deep-basin brines. Stueber and Dutton used stable isotopes, strontium isotopes, and Cl/Br ratios in order to differentiate connate brines from meteoric waters. Although my data does not include stable isotope, strontium isotope, or bromide data, the major ion

Table 5. Summary of Produced water samples

Age	Formation	Location	Sample Dates	Depth	Wells	n	Cl min	max	mean	median	st dev.
Ordovician	Ellenburger	Lea, Eddy	1950-1978	7720-12866	33	49	950	147000	79287	75000	37235
Ordovician	Montoya	Lea, Chaves	1959-1966	6604-6946	6	12	32180	161091	61616	38825	48018
Ordovician	Simpson	Lea	1958	7360-9360	7	10	89700	120900	97412	91960	11216
Silurian	Fusselman	Lea, Eddy	1956-1966	6730-14180	19	31	11176	129000	37695	34030	26578
Silurian	Silurian	Lea, Eddy	1957-1968	3770-14081	12	19	100	137900	40166	17430	46009
Devonian	Devonian Lower	Lea, Eddy	1951-1966	7108-15764	194	280	48	100300	33017	31950	16943
Devonian	Devonian	All three	1949-1978	2120-16578	57	140	2580	136964	37022	33000	19131
Mississippian	Mississippian	Lea, Eddy	1949-1954	10734-15545	6	10	21200	126796	86465	92958	34975
Pennsylvanian	Atoka	Lea, Eddy	1956-1979	9130-13325	15	18	140	71800	30430	35670	17023
Pennsylvanian	Morrow	Lea, Eddy	1959-1978	8833-13288	33	46	566	166000	52970	33705	45270
Pennsylvanian	Cisco	All three	1951-1969	7396-11501	19	32	426	110124	24089	16705	29183
Pennsylvanian	Canyon	Eddy	1959-1964	7375-8535	3	5	1821	4862	3059	2004	1563
Pennsylvanian	Strawn	Lea, Eddy	1957-1967	9884-13010	22	38	323	132400	68665	75230	29581
Pennsylvanian	Pennsylvanian	All three	1949-1967	3235-13230	109	186	1450	245000	49927	45600	30425
Wolfcamp	Wolfcamp	All three	1950-1975	93-14927	133	269	932	186000	54440	48910	32389
Leonardian	Abo	All three	1955-1978	3100-10977	116	176	8	223400	44566	29140	41161
Leonardian	Bone Spring	Lea, Eddy	1958-1978	3736-10631	13	18	2631	156699	68650	87090	55553
Leonardian	Clear Fork	Lea, Eddy	1945-1959	3850-7300	11	14	1240	236900	84365	71550.5	66722
Leonardian	Tubb	Lea	1958-1978	5800-7644	28	33	2520	191000	96843	98000	48459
Leonardian	Yeso	Lea, Eddy	1957-1964	2000-8736	19	12	12	148083	80260	97200	56426
Leonardian	Glorieta	All three	1950-1959	2570-10400	53	68	7691	155000	71913	67310	45906
Leonardian	Leonardian	Lea	N/A	6245-9746	3	3	81430	89440	85570	85840	4011.8
Guadalupian	San Andres	All three	1949-1979	510-5980	220	329	1500	245700	65556	30160	66547
Guadalupian	Grayburg	Lea, Eddy	1930-1977	2000-5525	162	207	324	200400	40105	10730	50521
Guadalupian	Queen	All three	1952-1978	1250-5137	121	145	1263	233337	84951	56435	76692
Guadalupian	Seven Rivers	Lea, Eddy	1949-1978	300-4137	86	112	130	212000	38340	14520	48513
Guadalupian	Tansill	Lea	1959-1960	3260-3895	5	7	3513	112336	37782	12600	46340
Guadalupian	Yates	Lea, Eddy	1940-1968	532-4244	108	150	1933	203212	17231	10890	17046
Guadalupian	Capitan	Lea, Eddy	1956-1972	414-4545	18	47	1622	229934	20856	16690	32181
Guadalupian	Delaware	Lea, Eddy	1959-1978	1900-9714	60	84	2460	231400	111866	126500	55455
Ochoan	Ochoan	Lea	N/A	1260-1290	2	2	1593	232700	117147	117147	163417
Triassic		Lea	1929-1955	62-3969	5	5	198	3383	1553	1015	1464
Miocene	Ogallala	Lea	N/A	222-4770	2	2	382	400	391	391	12.7

Table 5 (continued.) Summary of Produced water samples

Age	Formation	% < 30000 mg/L Cl	Cl/SO4 min	max	mean	median	st dev.	Ca/Mg min	max	mean	median	st dev.
Ordovician	Ellenburger	10.2	0.3	590	114.8	68.6	106.9	1.6	31.7	5.9	5.2	4.4
Ordovician	Montoya	0.0	8.8	212	49.5	15.2	75.2	2.8	8.2	4.2	4	1.5
Ordovician	Simpson	10.0	72	186.5	130.6	127.1	43.7	1.5	10.1	6.3	6.2	2.5
Silurian	Fusselman	35.5	7.2	64.3	21.6	14.7	15.7	1.2	23	4.8	3.3	4.7
Silurian	Silurian	63.2	0.2	142.8	34.7	16.9	41.1	1.9	8.1	4.5	4.1	1.9
Devonian	Devonian Lower	45.4	0.02	361.1	27.4	18.6	35	0.04	54.7	6	4.8	6.2
Devonian	Devonian	34.3	2.4	185	26.4	19.6	24.7	0.6	62.5	6.1	5.4	6.8
Mississippian	Mississippian	10.0	8.48	151.7	93.1	95.1	53.9	5	55.6	11.8	7.4	15.4
Pennsylvanian	Atoka	35.3	0.3	136	71.3	77.2	49.3	0.9	20.5	7.5	6.8	4.6
Pennsylvanian	Morrow	43.5	0.1	557	107.8	60.6	142.3	0.7	24	5.6	5.4	3.7
Pennsylvanian	Cisco	65.6	0.2	662.3	60.5	5.4	166.5	0.8	28	5.6	3.2	6.1
Pennsylvanian	Canyon	100.0	0.9	3.3	1.7	0.9	1.2	1.9	4	2.9	2.7	0.8
Pennsylvanian	Strawn	12.8	0.1	881.4	223.5	159.2	229.4	0.5	20.7	6	5.5	3.9
Pennsylvanian	Pennsylvanian	30.1	0.5	554	56.4	34.7	78.3	0.4	55.7	6.2	4.9	6.5
Wolfcamp	Wolfcamp	24.2	0.6	4170	75.9	23.8	271.2	0.1	55	5.6	4.2	5.4
Leonardian	Abo	51.1	0.004	237.3	28.9	12.4	44	0.2	26.2	4	3.3	3
Leonardian	Bone Spring	38.9	1	201.1	44.1	21.7	58.2	0.9	38.8	6.8	4.7	9.5
Leonardian	Clear Fork	42.9	0.5	532	78.8	16.7	165.3	2.3	6.6	3.2	4	1.6
Leonardian	Tubb	12.1	0.8	295	57.1	36	60.6	0.5	8.4	3	2.9	1.6
Leonardian	Yeso	26.3	0.01	1610	128	31.4	362.3	2	14.5	4.5	3.4	2.9
Leonardian	Glorieta	27.9	1.9	766.9	45.6	21.5	104.3	0.3	13.8	3.7	2.9	2.4
Leonardian	Leonardian	0.0	54.2	63.2	58.2	57.1	4.6	2.7	5	3.9	4	1.1
Guadalupian	San Andres	61.6	1.3	11278	217.8	23.6	986	0.06	83.3	3.4	2.6	5.4
Guadalupian	Grayburg	68.4	0.1	9897	224	17.3	1099	0.1	201	3.9	1.9	17.2
Guadalupian	Queen	43.3	0.3	1462	115.8	26	214	0.05	7.6	1.5	1.2	1.2
Guadalupian	Seven Rivers	64.5	0.06	1311	39.7	12.4	146.5	0.03	8.1	1.9	1.8	1.4
Guadalupian	Tansill	71.4	1.8	4.7	7.6	4.7	6.3	1.1	2280	331	5.2	859
Guadalupian	Yates	63.8	0.8	5900	11.4	10.4	8.9	0.04	18.4	1	1	0.6
Guadalupian	Capitan	93.6	1	51.6	7.8	4.9	10.9	1	4.7	2.5	2.4	0.8
Guadalupian	Delaware	15.6	0.4	2223	257.1	147	346	0.3	394	10.6	5.2	42.8
Ochoan	Ochoan	50.0	0.3	26.9	13.6	13.6	18.8	0.2	6.8	3.5	3.5	4.6
Triassic		100.0	0.2	3.3	1.3	0.8	1.4	0.8	4.5	2.3	2.3	1.5
Miocene	Ogallala	100.0	1.3	2.3	1.8	1.8	0.7	4.9	7.1	6	6	1.6

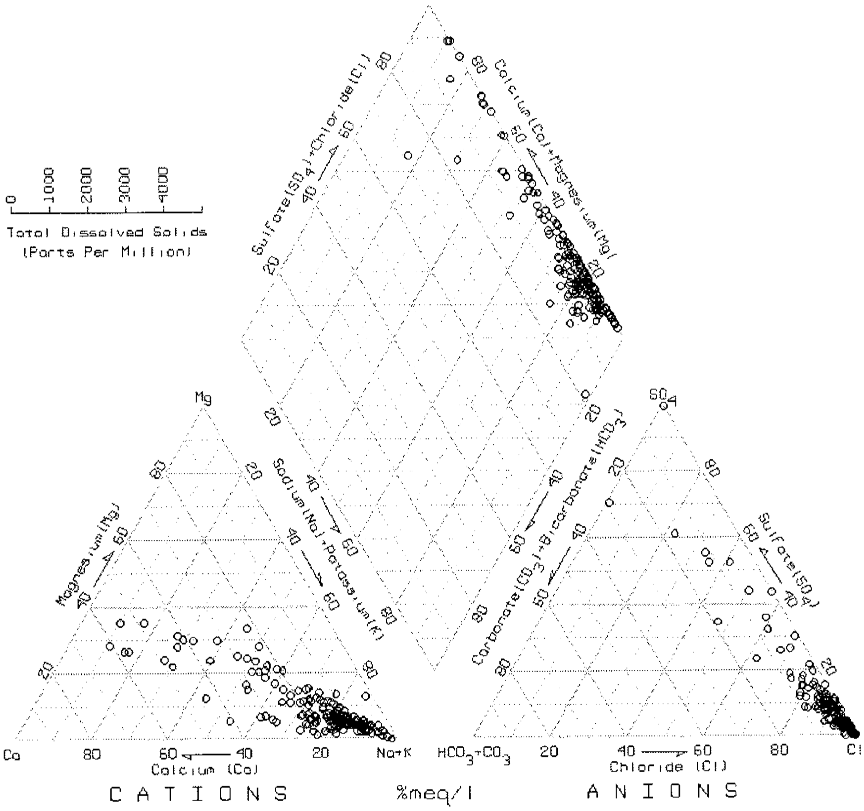


Figure 21. Typical piper diagram of produced water samples, (Leonard) Abo shown.

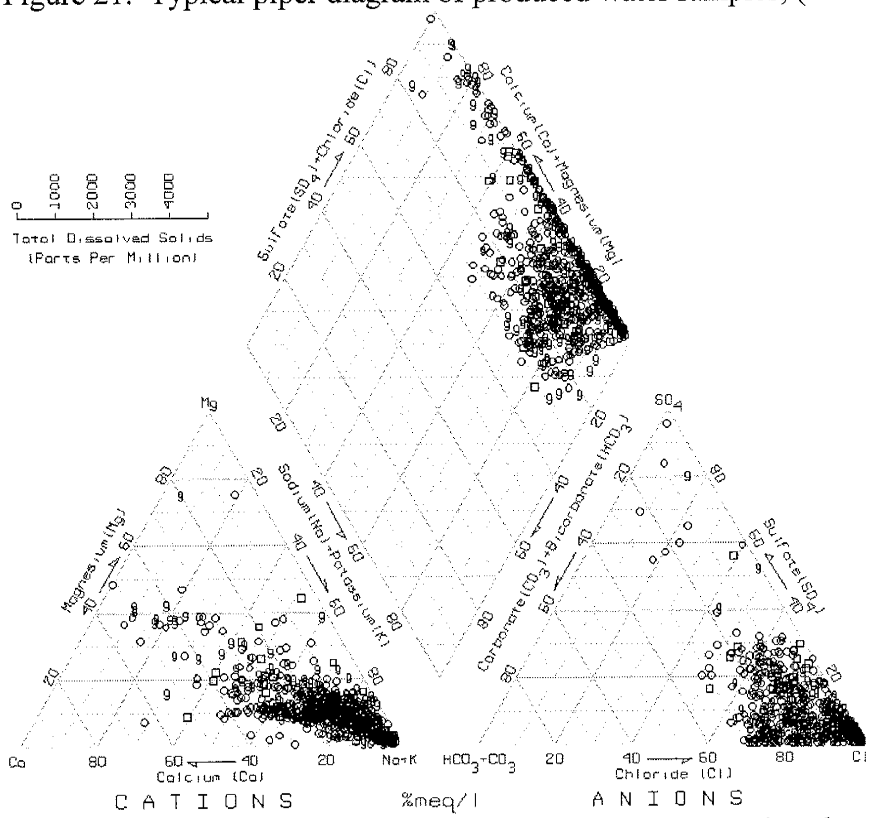


Figure 22. Piper diagram of San Andres and Grayburg produced water samples.

data can be used to break out similar groups, or genetic classifications. The work of Stueber et al. (1998) is used as my primary focus because almost all of the geochemistry of the water samples was included in the paper (see Table 2, Stueber, et al., 1998), allowing me to see how their two groups compared using only major ions and TDS.

These samples were all taken from formations composed of carbonate, in the form of calcite or dolomite. The different groups can also be delineated using TDS and ratios of some major ions, including Cl^-/SO_4^{2-}, Ca^{2+}/Mg^{2+} and Cl^-/Na^++K^+ ratios. These ratios are useful because they divide waters into groups in a similar fashion as that of stable isotopes and other measurements which are unavailable in this dataset. Figures 23 – 25 show the water quality data from Stueber graphed as TDS versus various ion ratios. The significance of the groups delineated by Ca/Mg ratios is equivocal, because all the samples were from carbonate formations. The Cl^-/Na^++K^+ ratio in conjunction with the TDS was also examined; however, although there is some separation between groups, it is mostly a function of the TDS; there is not enough difference between the Cl^-/Na^++K^+ ratios to separate the two groups. Stueber did not include HCO_3^- in his description, so that ion is ignored; however this seems reasonable considering the highly dynamic nature of both the pH and HCO_3^- concentration when a produced water sample is taken. Looking at the graphs of TDS versus different ion ratios we also see some samples are a mixture of the two groups of water.

Using the data from Stueber et al. (1998) as an example, I grouped my samples by formation into four groups. The first genetic classification corresponds with the first group described by Stueber et al. (1998), i.e. saline meteoric water originating through halite dissolution. This group has a TDS of less than 75 g/L, a Cl/SO_4 ratio of less than

50, and a Ca/Mg ratio between 2 and 4. The second genetic classification also corresponds with the second group of Stueber et al. (1998), the modified evaporitic marine brines, and has a TDS of 125 g/L or above, a Cl/SO_4 ratio greater than 50, and a Ca/Mg ratio between 4 and 7. The third genetic classification is a mixture of the first two groups. It has a TDS between 75 and 125 g/L, a Cl/SO_4 ratio less than 50, and a Ca/Mg ratio between 4 and 6 (see Figures 23-25). The fourth genetic classification includes all the samples that do not fall under the other three. The genetic classifications are presented at two levels of confidence. For the highest level, only samples that met all three criteria (TDS, Cl/SO_4, and Ca/Mg) were included. These are indicated by filled symbols on all figures with genetic classifications. For the lower confidence level, samples meeting the TDS and Cl/SO_4 ratio criteria, but not the Ca/Mg ratio, were included. These are indicated by open symbols on those same figures. Table 6 shows the percentages of samples meeting these two confidence levels.

Therefore, there are seven groups in total, represented thusly: Groups one and four, meteoric saline water, are represented by solid and open blue diamonds, respectively; groups two and five, modified brines, are solid and open red squares; groups three and six, a mix of brine and meteoric waters, are shown in solid and open yellow triangles; and group seven, none of the above, is represented by gray stars. This means that samples with solid color symbols, grouped using TDS and both the Cl/SO_4 and Ca/Mg ratios, are better constrained than those with open symbols, which are grouped using TDS and the Cl/SO_4 ratio only. See Appendix C for graphs of TDS versus various ion ratios. Once the data was grouped I examined spatial patterns using ArcView GIS and projected the data on to the geologic cross sections.

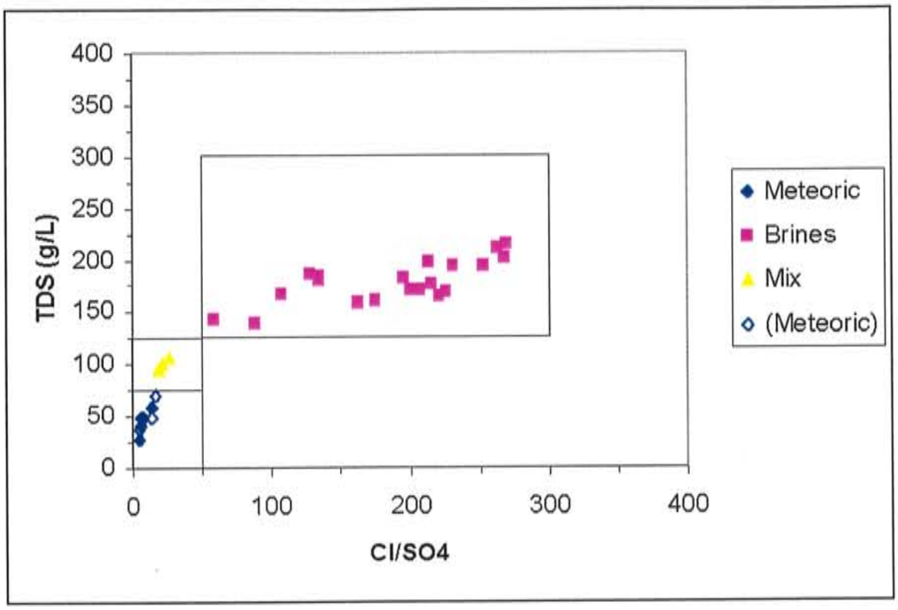


Figure 23. Graph of TDS vs Cl/SO_4 ratio for water samples from Stueber et al. (1998) divided into three genetic classifications. Boxes show the possible range for each group.

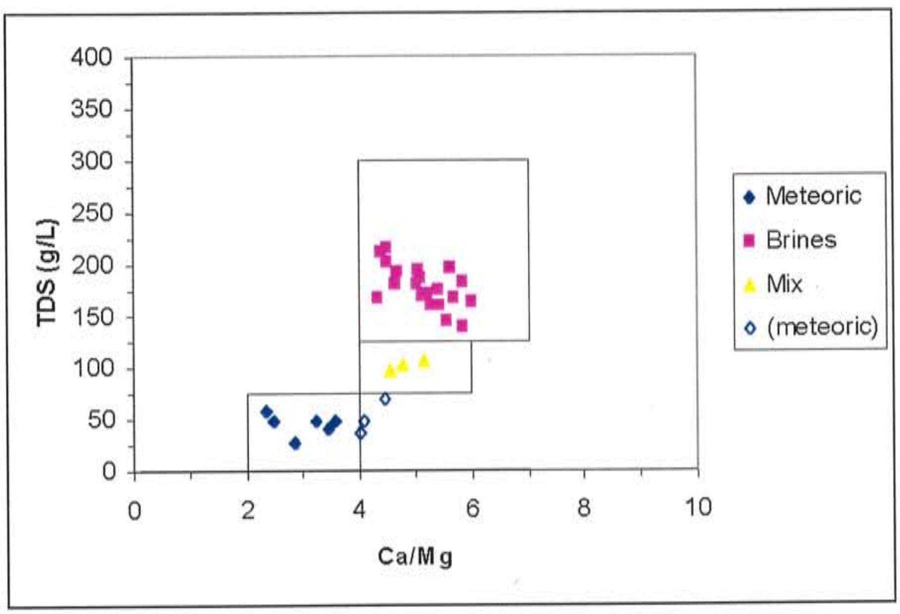


Figure 24. Graph of TDS vs Ca/Mg ratio for water samples from Stueber et al. (1998) divided into three genetic classifications. Note some of the meteoric waters are outside the ranges given.

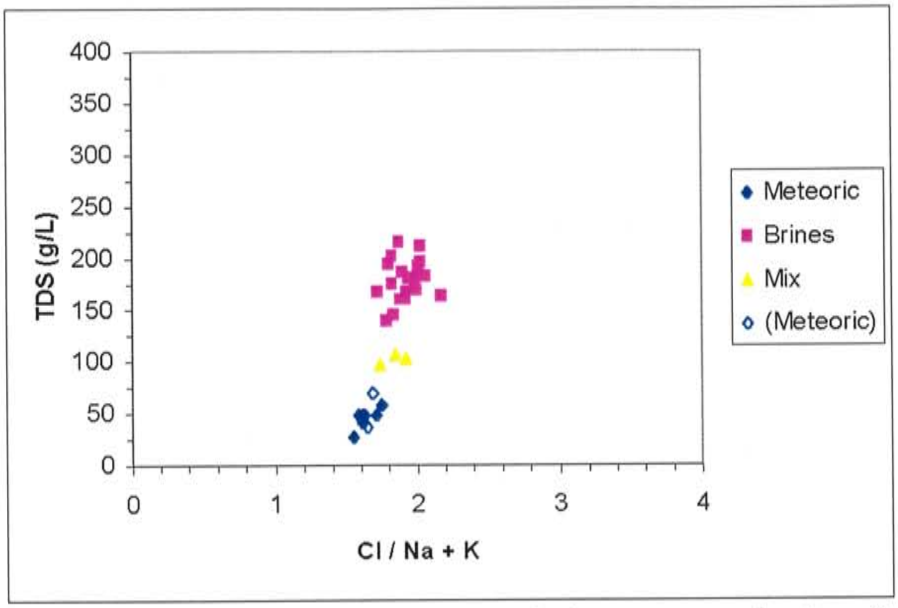


Figure 25. Graph of TDS vs Cl/Na+K ratio for water samples from Stueber et al. (1998) divided into three genetic classifications. No boxes are present because there is not enough statistical difference between the Na + K ratios of the different groups.

Three sets of data were projected on each geologic cross section, so there are three figures per cross section. The first cross section figure (Figures 26, 29, and 32) shows the reported formation of the produced water sample, which illustrates how well the water sample formations match the geologic cross section. On the whole, the samples' assigned formation matches well with the cross section formations. However, the Mississippian through Ordovician samples are often seemingly randomly scattered across the bottoms of the cross sections, which are not necessarily accurate, as explained previously in the text. Additionally, there is little validation upon the placement of the Capitan Reef in cross section B – B', and the few Capitan Reef samples do not seem to match it.

The second cross section figure (Figures 27, 30, and 33) shows produced water samples by genetic classification. The third figure (Figures 28, 31, and 34) shows the chloride concentration of the produced water samples. Chloride concentration can also be used as a proxy for the distribution of TDS within the cross section. Cross sections showing produced water samples by formation, groups, and chloride concentration are shown in Figures 26 – 34 and map view figures of groups and chloride concentration are shown in Figures 35 – 38. In addition to groups and chloride, plan view maps of sulfate, calcium, magnesium, sodium plus potassium, and TDS concentrations are shown in Figures 39 – 48. These maps help show directional trends and are most helpful in finding groundwater flushing within a formation.

Figures 49 – 51 show water samples' genetic classifications projected on cross sections showing the relative permeability rather than geologic formation. These figures show that the relative permeabilities, which were assigned on the basis of facies within each formation, reasonably match with the water samples' genetic classifications, and give credence to the hypothesis that the permeability of a formation is a direct influence on the salinity and ion ratios of water samples within a formation, and that groundwater flushing is occurring in the deep basin aquifer. These figures also help show that there is relatively high flow through highly fractured carbonates such as the reef zones and regionally extensive carbonates, more intermediate flow rates through carbonates with interbedded shales, and low flow rates through formations with variable lithology including carbonates, evaporites, redbeds, and shales.

Table 6. Percentage of Produced water samples in each group.

Artesia Group (including San Andres)

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	256	22.2	652	56.6
Brine	7	0.6	98	8.5
Mix	5	0.4	61	5.3
Other	884	76.7	341	29.6
Total	1152	100.0	1152	100.0

Delaware Mountain Group

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	2	2.2	13	14.4
Brine	16	17.8	27	30.0
Mix	0	0.0	6	6.7
Other	72	80.0	44	48.9
Total	90	100.0	90	100.0

Glorieta

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	13	19.1	22	32.4
Brine	5	7.4	7	10.3
Mix	1	1.5	13	19.1
Other	49	72.1	26	38.2
Total	68	100.0	68	100.0

Leonard

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	10	11.5	22	25.3
Brine	10	11.5	22	25.3
Mix	0	0.0	7	8.0
Other	67	77.0	36	41.4
Total	87	100.0	87	100.0

Abo

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	62	35.0	115	65.0
Brine	4	2.3	19	10.7
Mix	1	0.6	20	11.3
Other	110	62.1	23	13.0
Total	177	100.0	177	100.0

Table 6 (continued.) Percentage of Produced water samples in each group.

Wolfcamp

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	46	17.1	117	43.5
Brine	13	4.8	40	14.9
Mix	15	5.6	47	17.5
Other	195	72.5	65	24.2
Total	269	100.0	269	100.0

Pennsylvanian

Group	Cl/SO4 + Ca/Mg			
Meteoric	59	18.2	135	41.7
Brine	17	5.2	31	9.6
Mix	14	4.3	37	11.4
Other	234	72.2	121	37.3
Total	324	100.0	324	100.0

Mississippian

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	0	0.0	2	20.0
Brine	4	40.0	7	70.0
Mix	0	0.0	1	10.0
Other	6	60.0	0	0.0
Total	10	100.0	10	100.0

Devonian

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	64	15.2	307	73.1
Brine	1	0.2	4	1.0
Mix	17	4.0	50	11.9
Other	338	80.5	59	14.0
Total	420	100.0	420	100.0

Silurian

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	15	30.0	31	62.0
Brine	0	0.0	3	6.0
Mix	1	2.0	3	6.0
Other	34	68.0	13	26.0
Total	50	100.0	50	100.0

Ordovician

Group	Cl/SO4 + Ca/Mg	% of total	Cl/SO4 Only	% of total
Meteoric	4	5.6	15	21.1
Brine	21	29.6	31	43.7
Mix	4	5.6	13	18.3
Other	42	59.2	12	16.9
Total	71	100.0	71	100.0

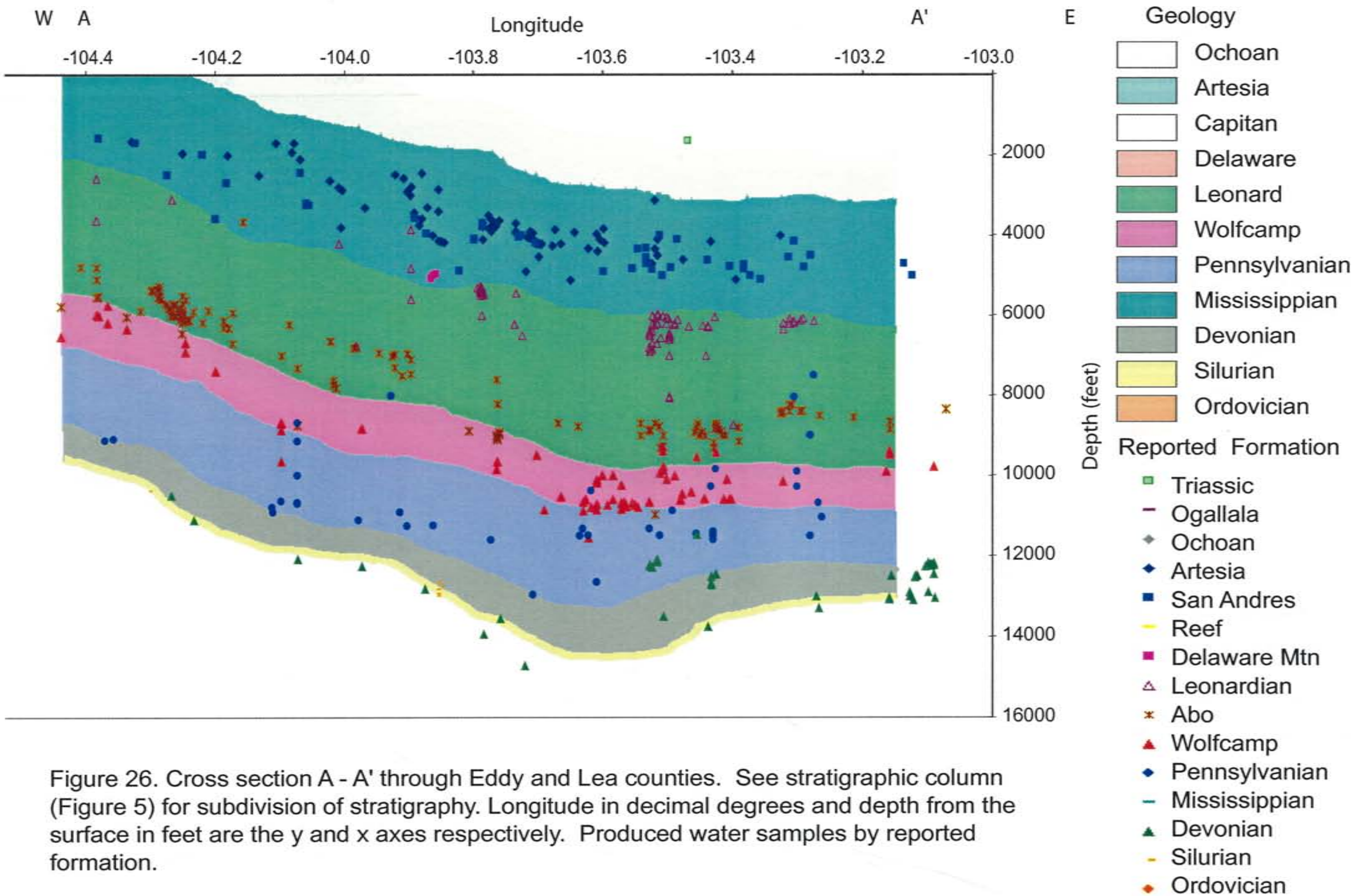


Figure 26. Cross section A - A' through Eddy and Lea counties. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Longitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Produced water samples by reported formation.

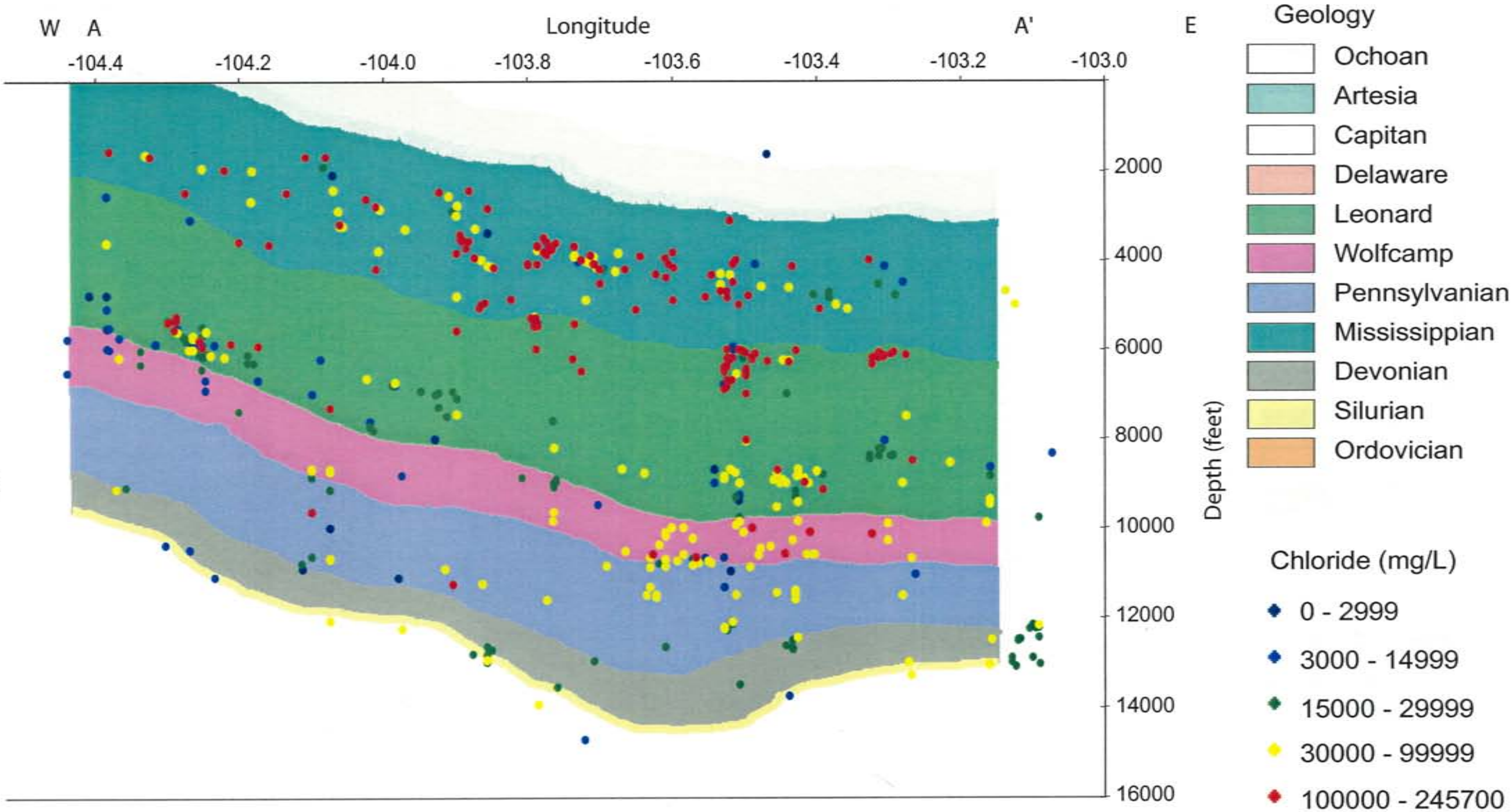


Figure 27. Cross section A - A' through Eddy and Lea counties. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Longitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Chloride concentration in mg/L of produced water samples.

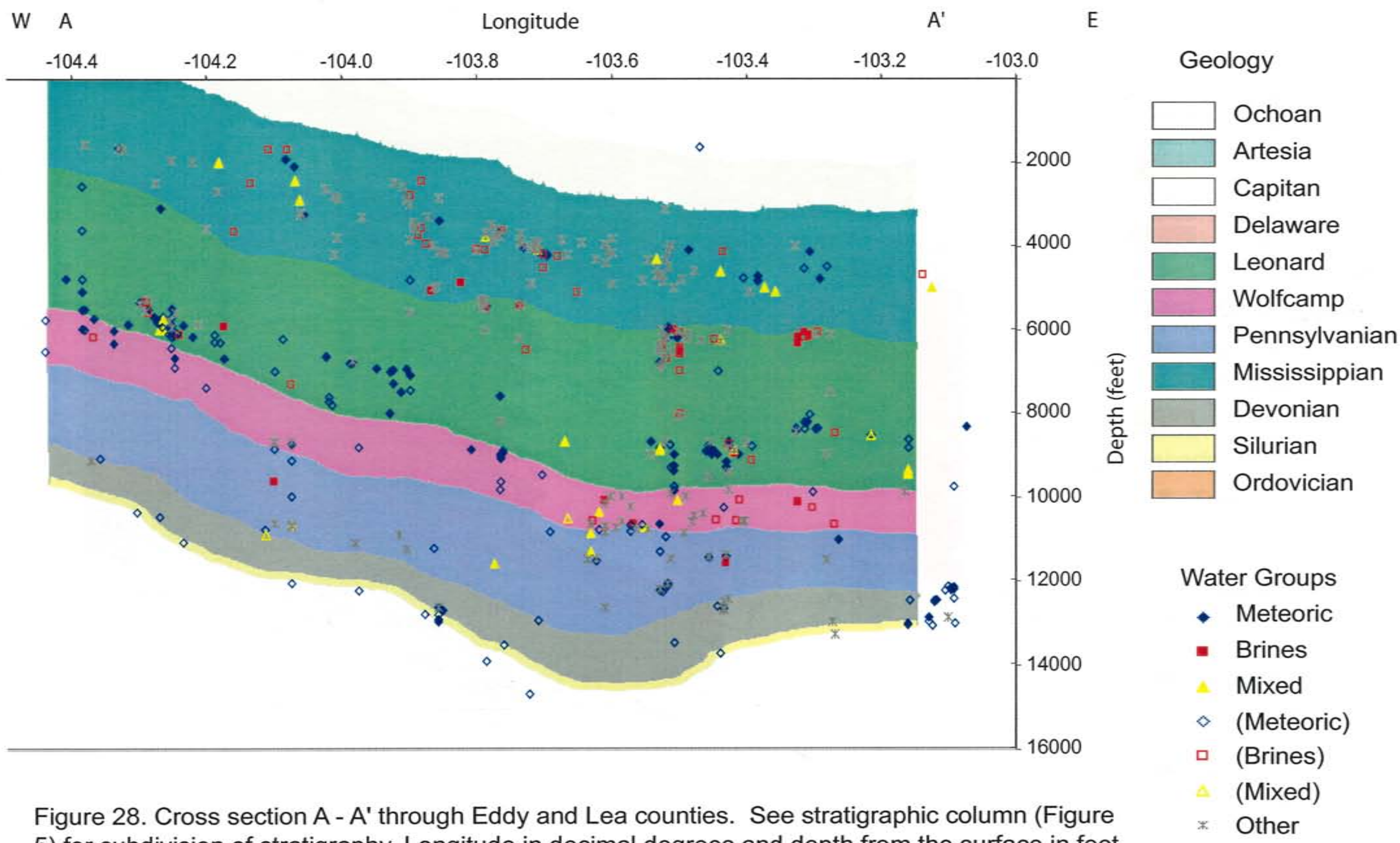


Figure 28. Cross section A - A' through Eddy and Lea counties. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Longitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Solid points show chemistry of produced water samples based on Cl/SO4 and Ca/Mg ratios, while open points are based on Cl/SO4 ratios only.

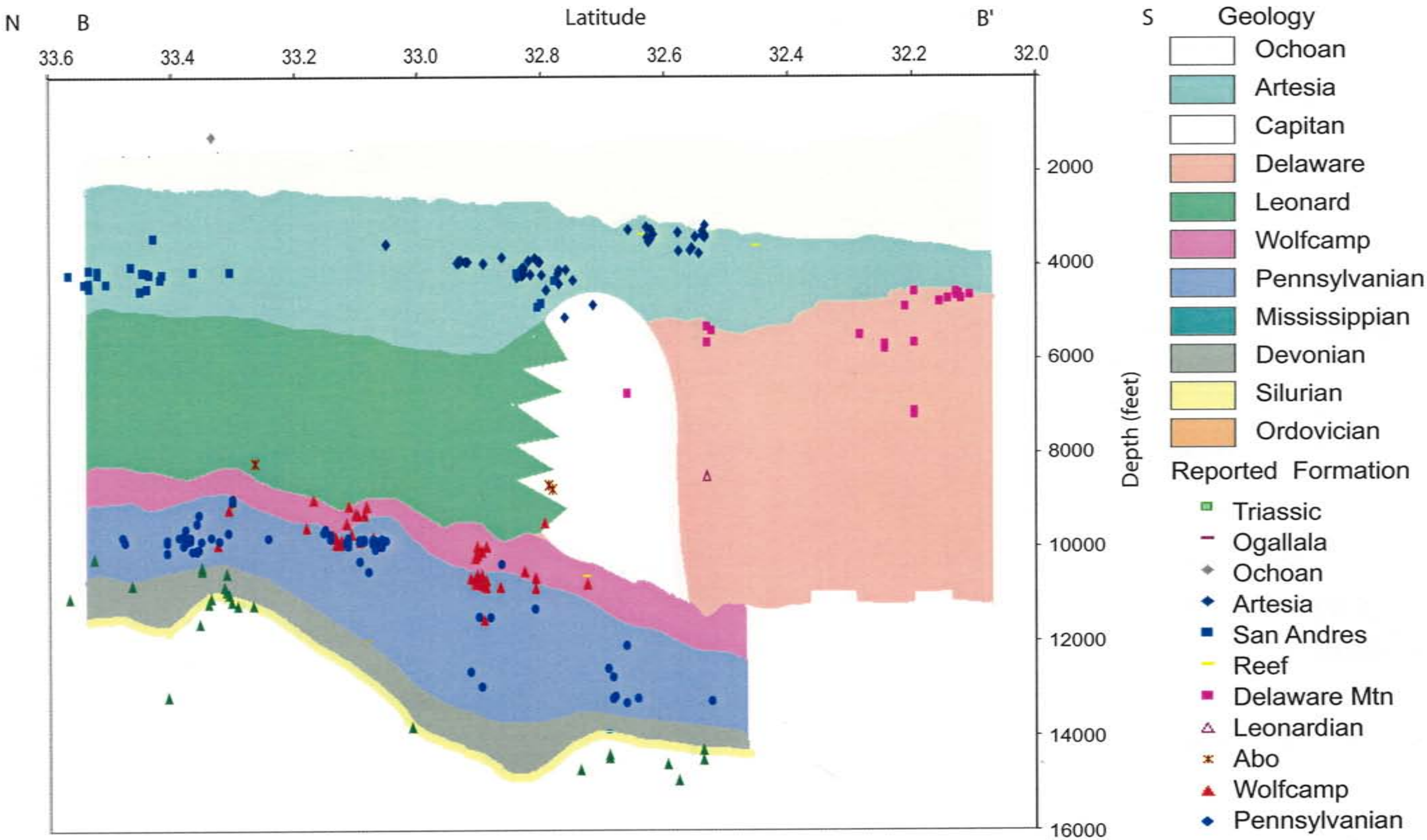


Figure 29. Cross section B - B' through western Lea county. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Produced water samples by reported formation.

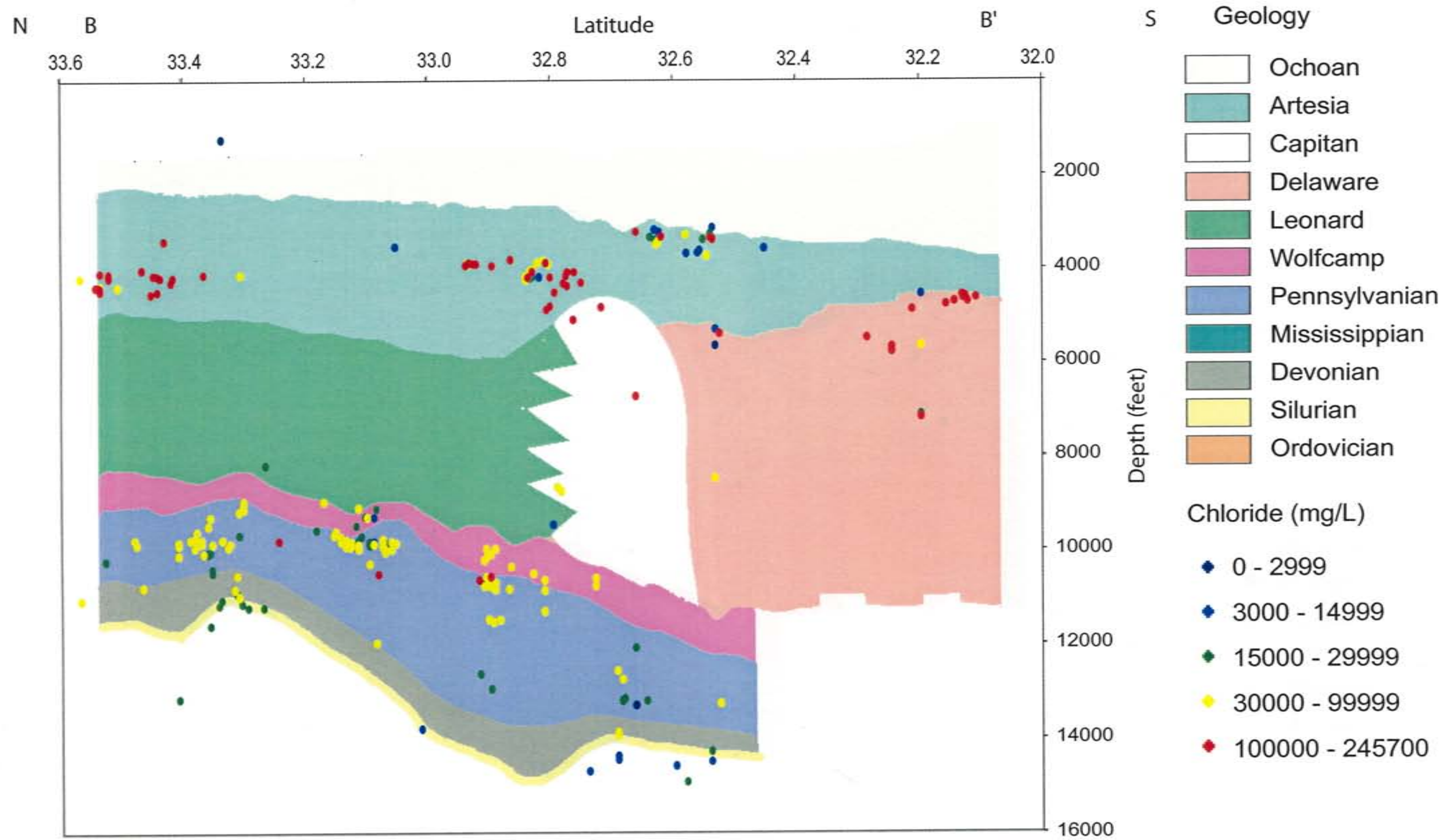


Figure 30. Cross section B - B' through western Lea county. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Chloride concentration in mg/L of produced water samples.

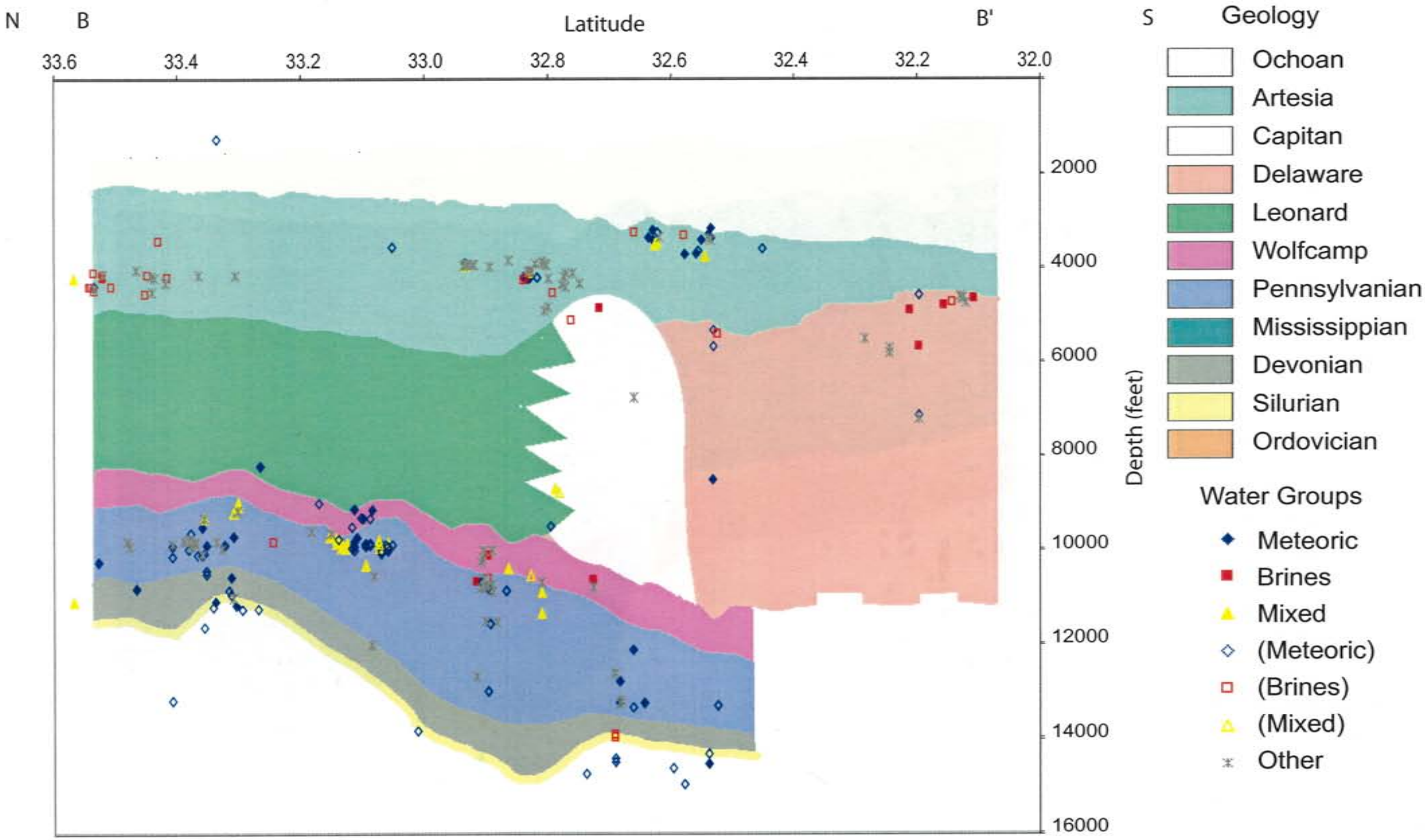


Figure 31. Cross section B - B' through western Lea county. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Solid points show chemistry of produced water samples based on Cl/SO4 and Ca/Mg ratios, while open points are based on Cl/SO4 ratios only.

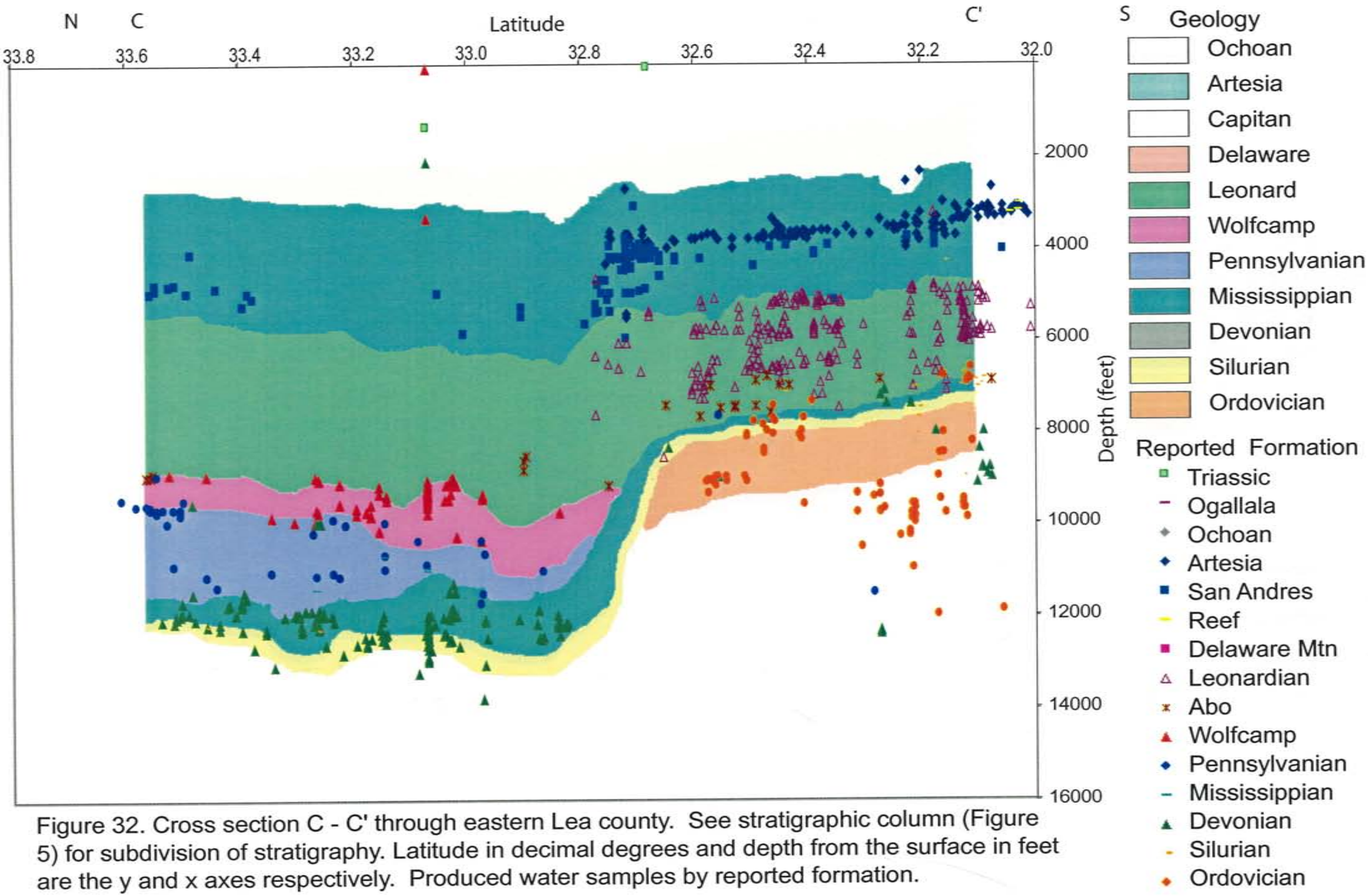


Figure 32. Cross section C - C' through eastern Lea county. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Produced water samples by reported formation.

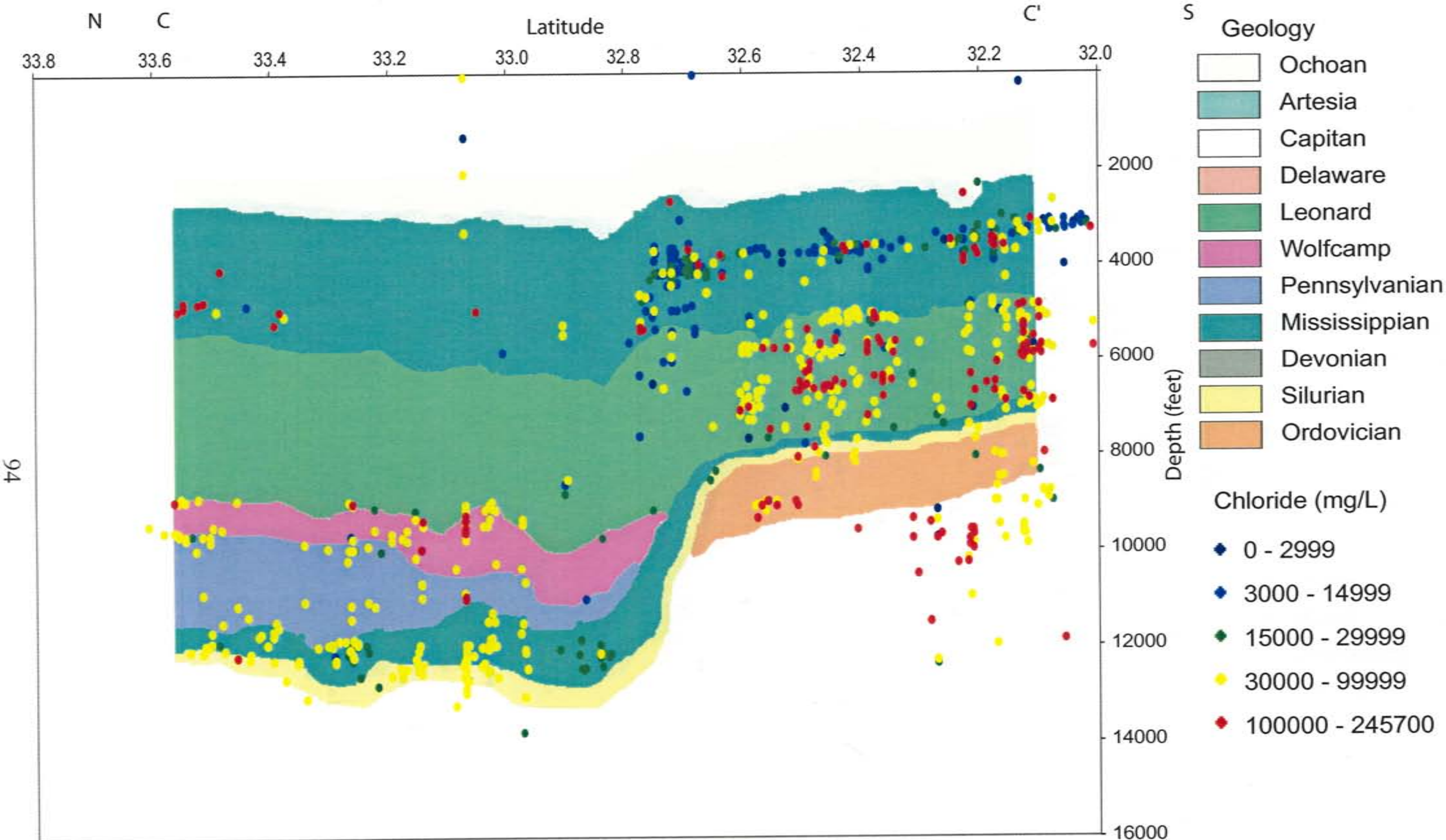


Figure 33. Cross section C - C' through eastern Lea county. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Chloride concentration in mg/L of produced water samples.

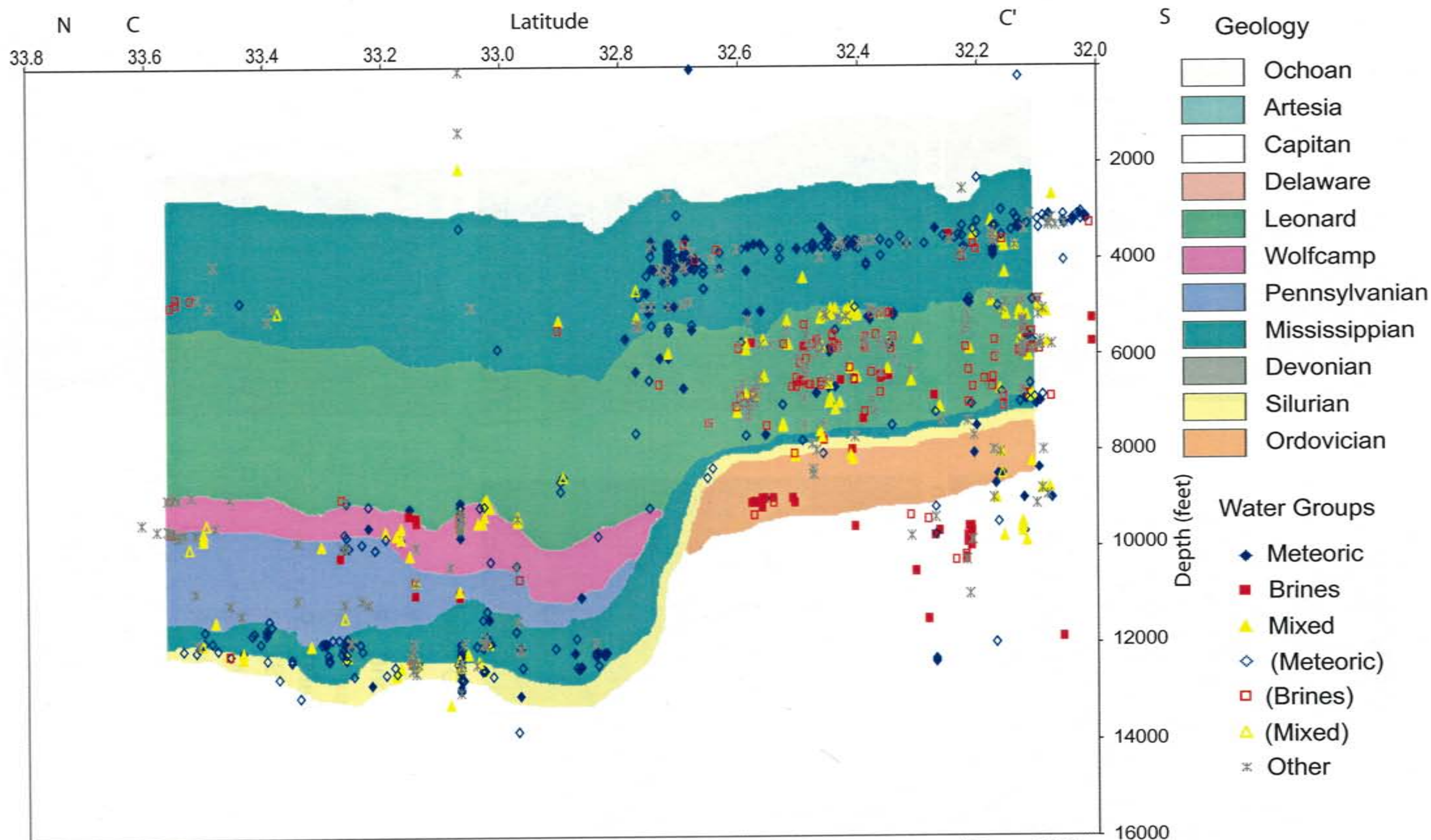


Figure 34. Cross section C - C' through eastern Lea county. See stratigraphic column (Figure 5) for subdivision of stratigraphy. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Solid points show chemistry of produced water samples based on Cl/SO4 and Ca/Mg ratios, while open points are based on Cl/SO4 ratios only.

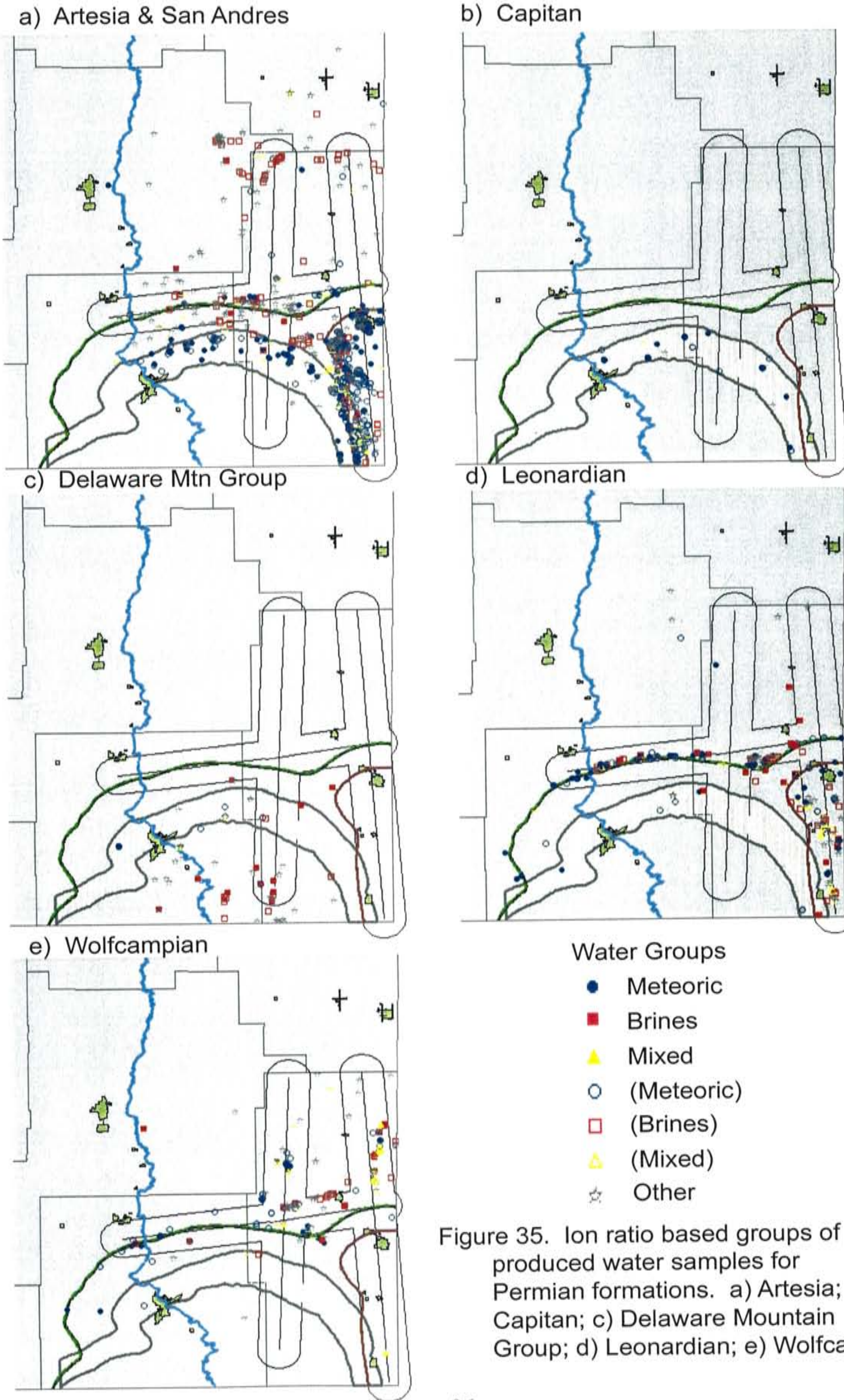


Figure 35. Ion ratio based groups of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcamp.

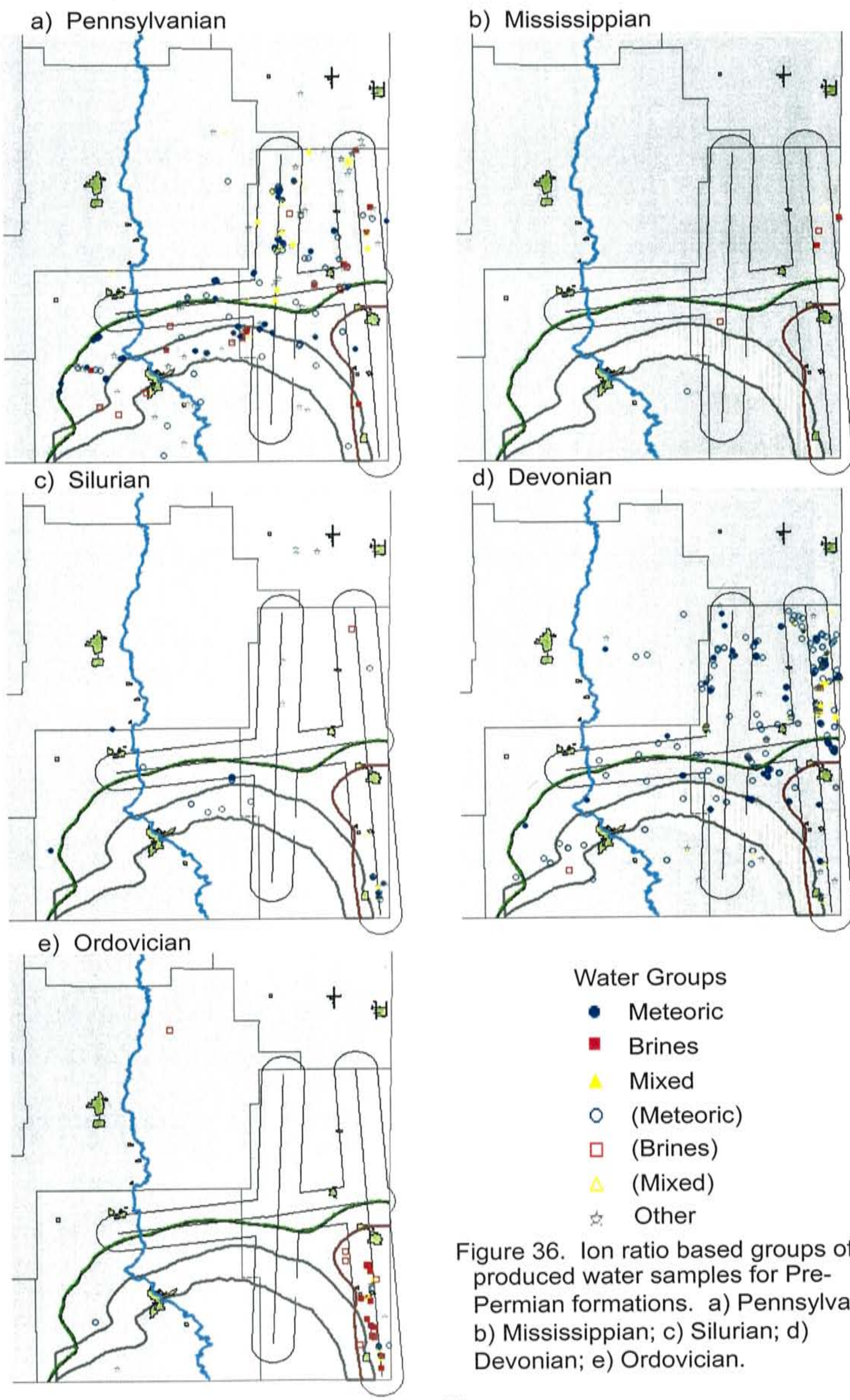


Figure 36. Ion ratio based groups of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.

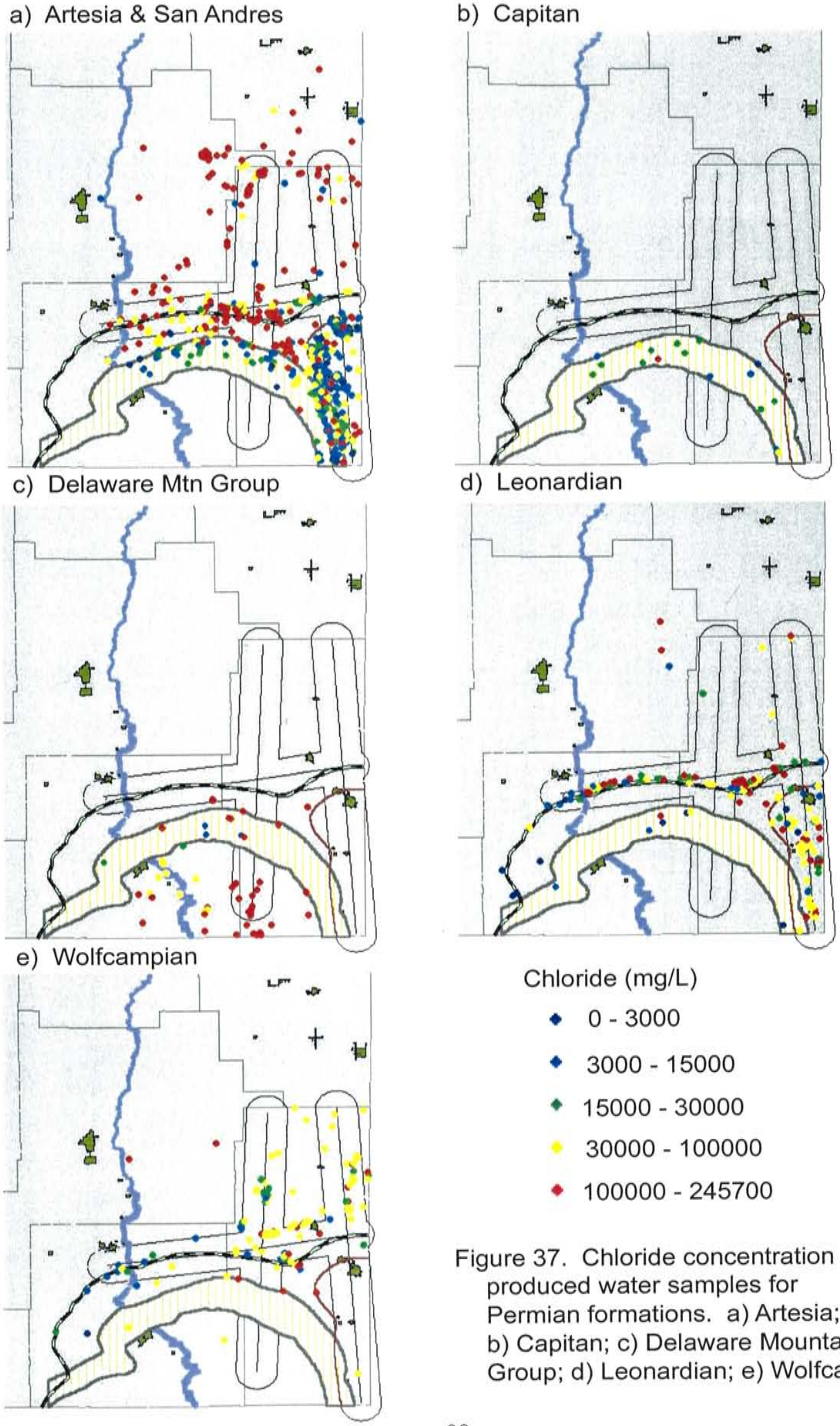
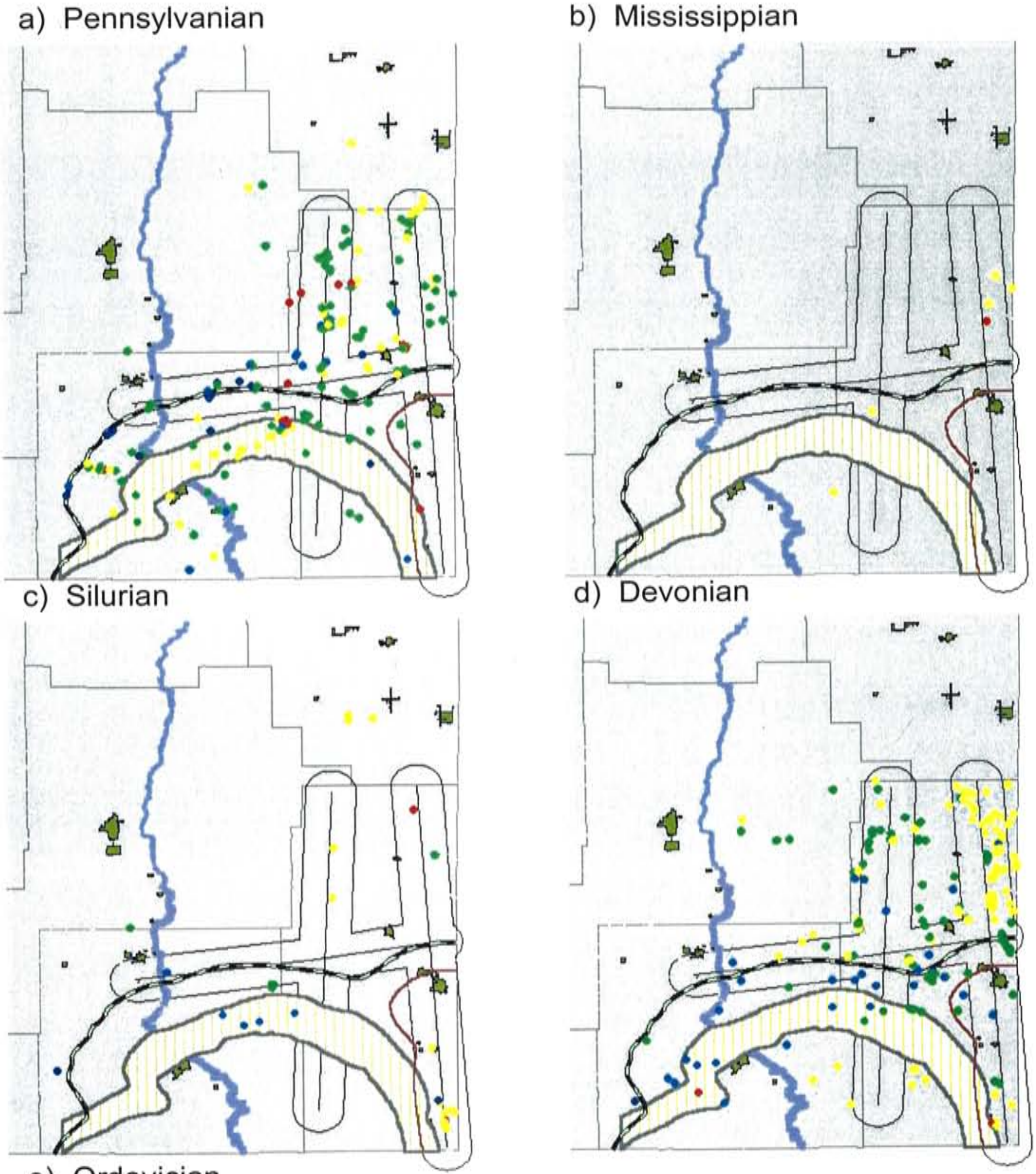
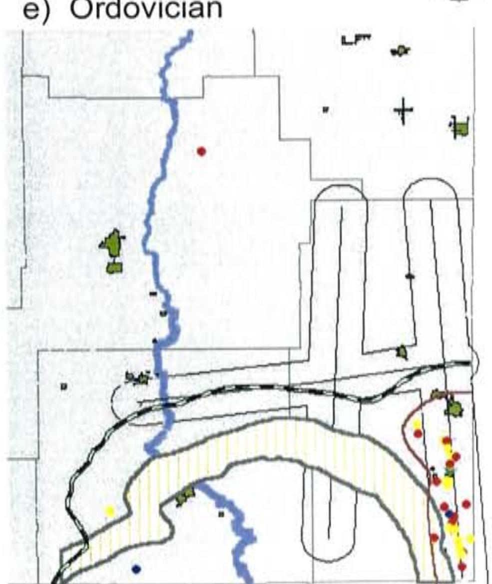


Figure 37. Chloride concentration of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcamp.





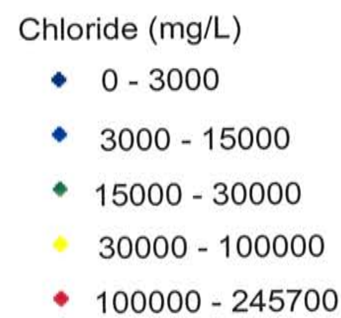


Figure 38. Chloride concentration of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.

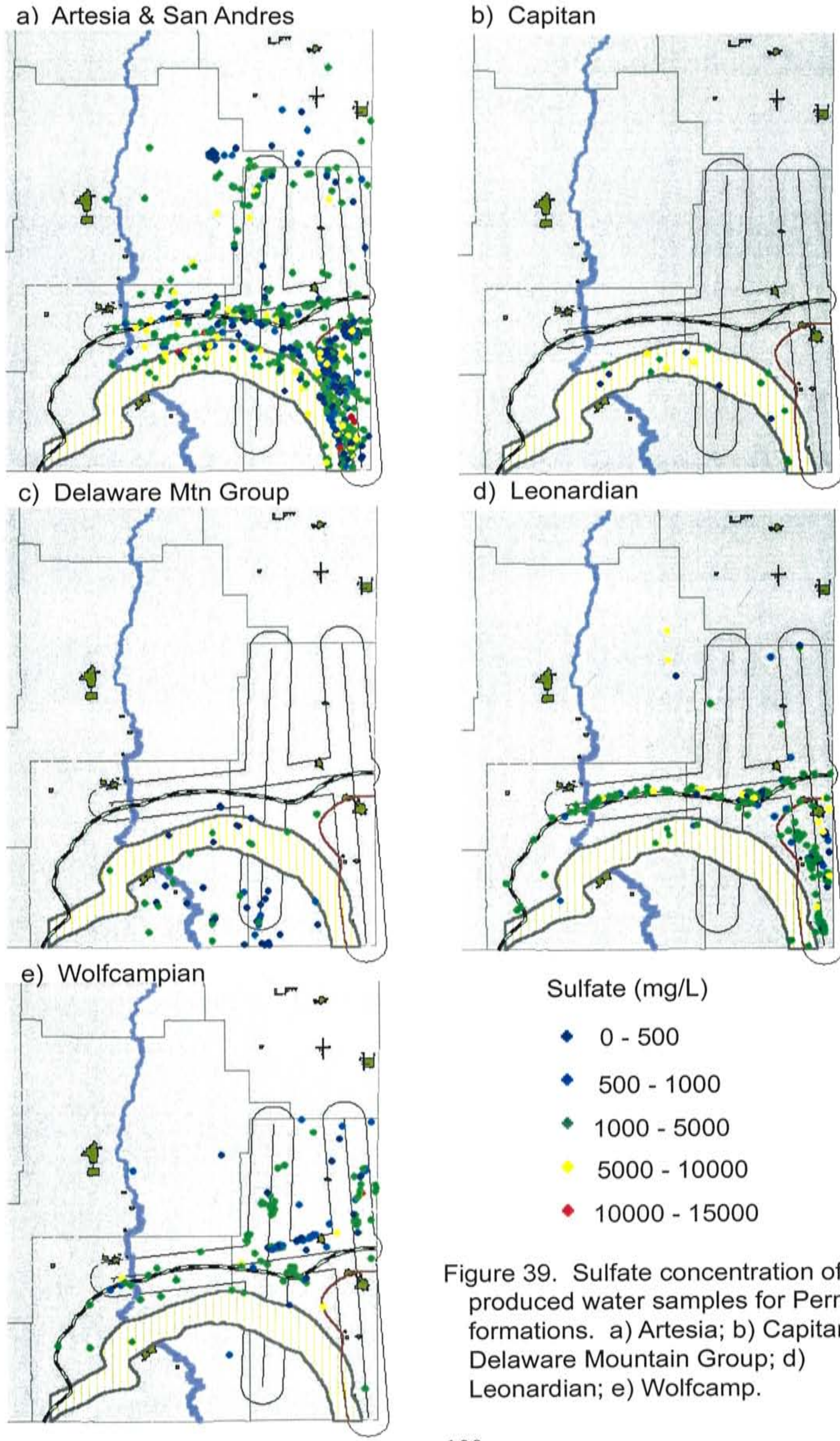
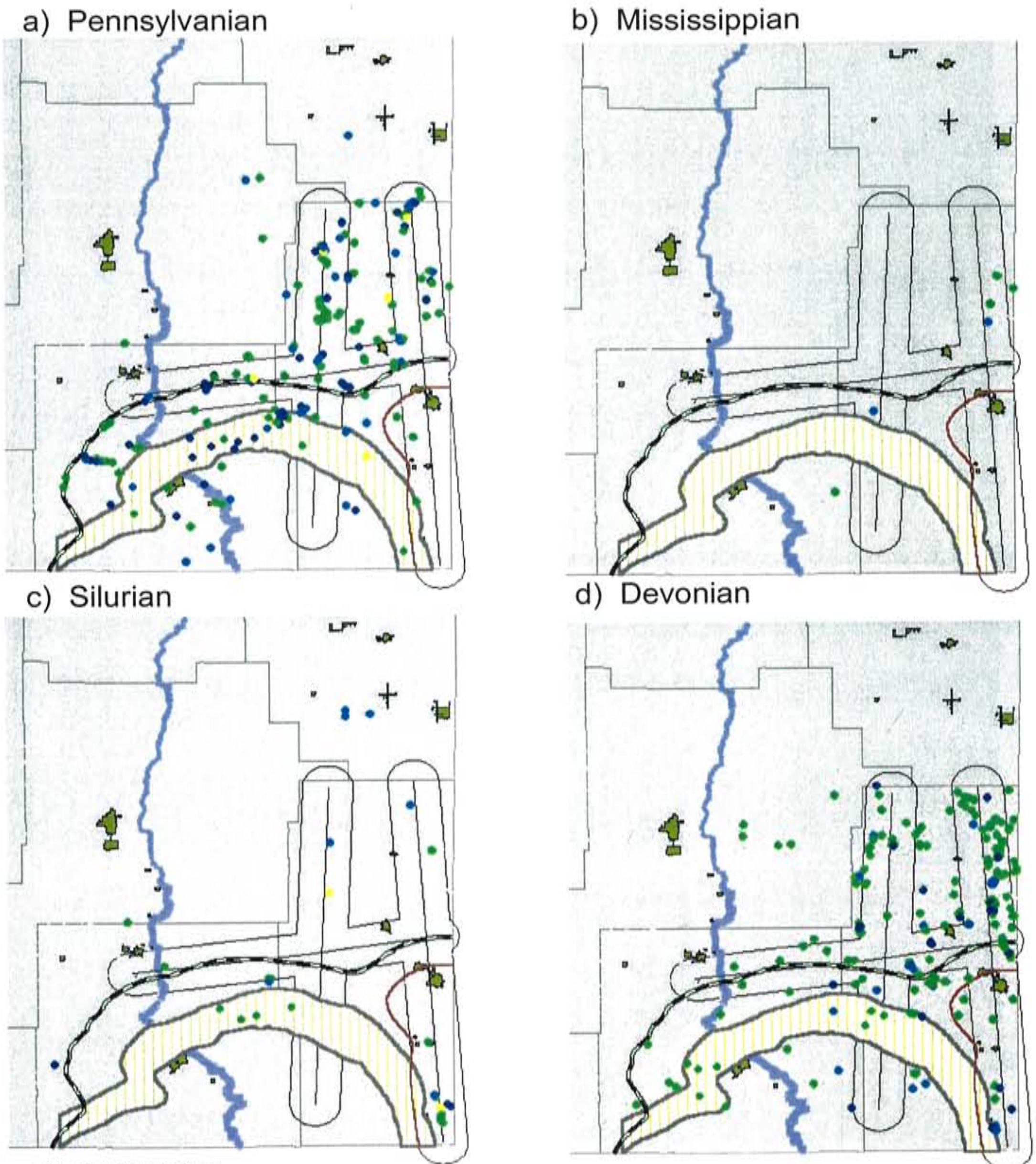


Figure 39. Sulfate concentration of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcamp.



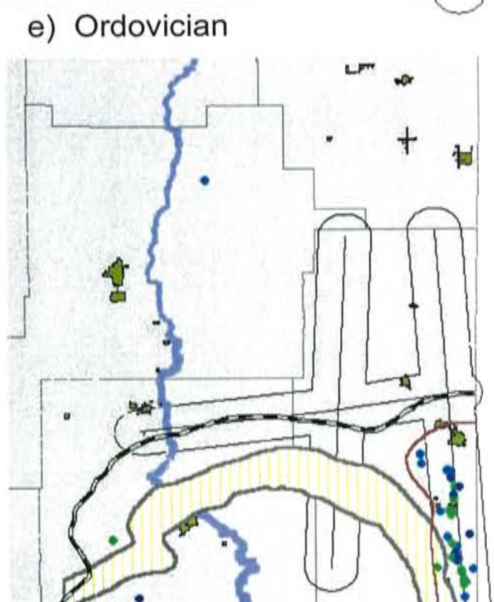


Figure 40. Sulfate concentration of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.

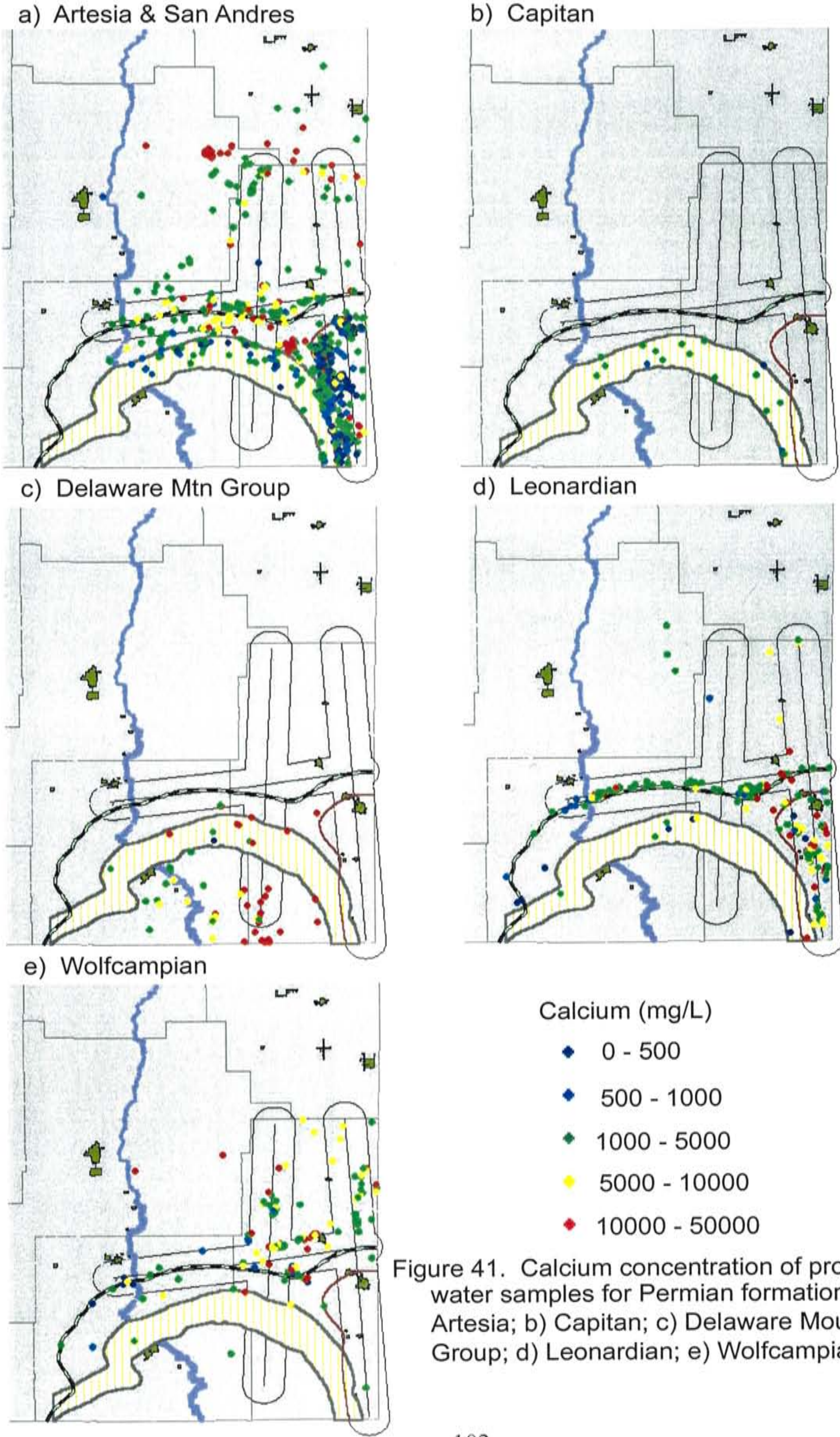
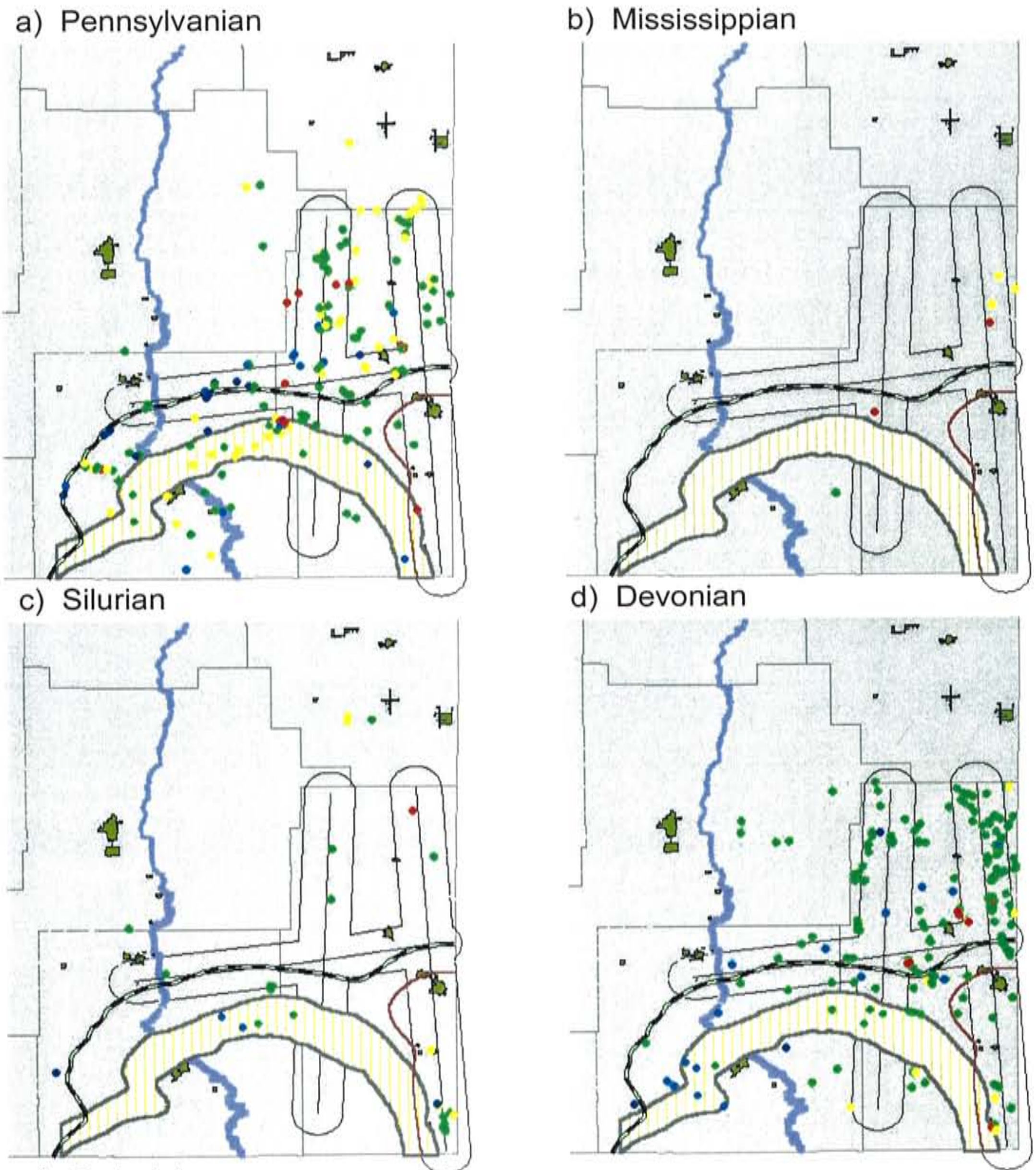
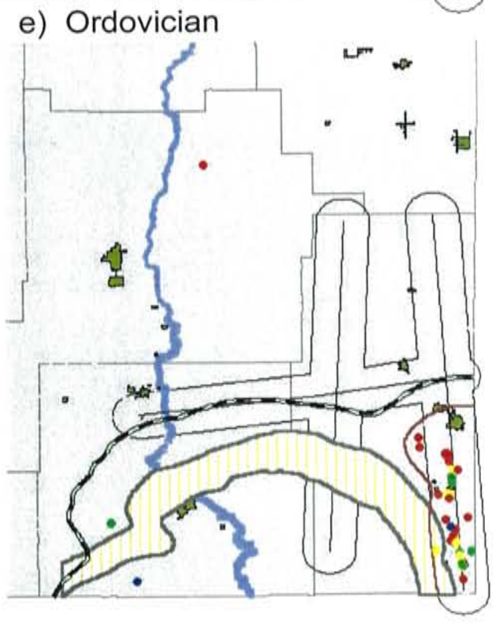


Figure 41. Calcium concentration of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcampian.





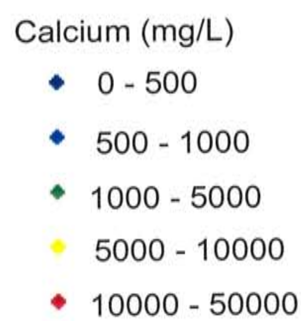


Figure 42. Calcium concentration of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.

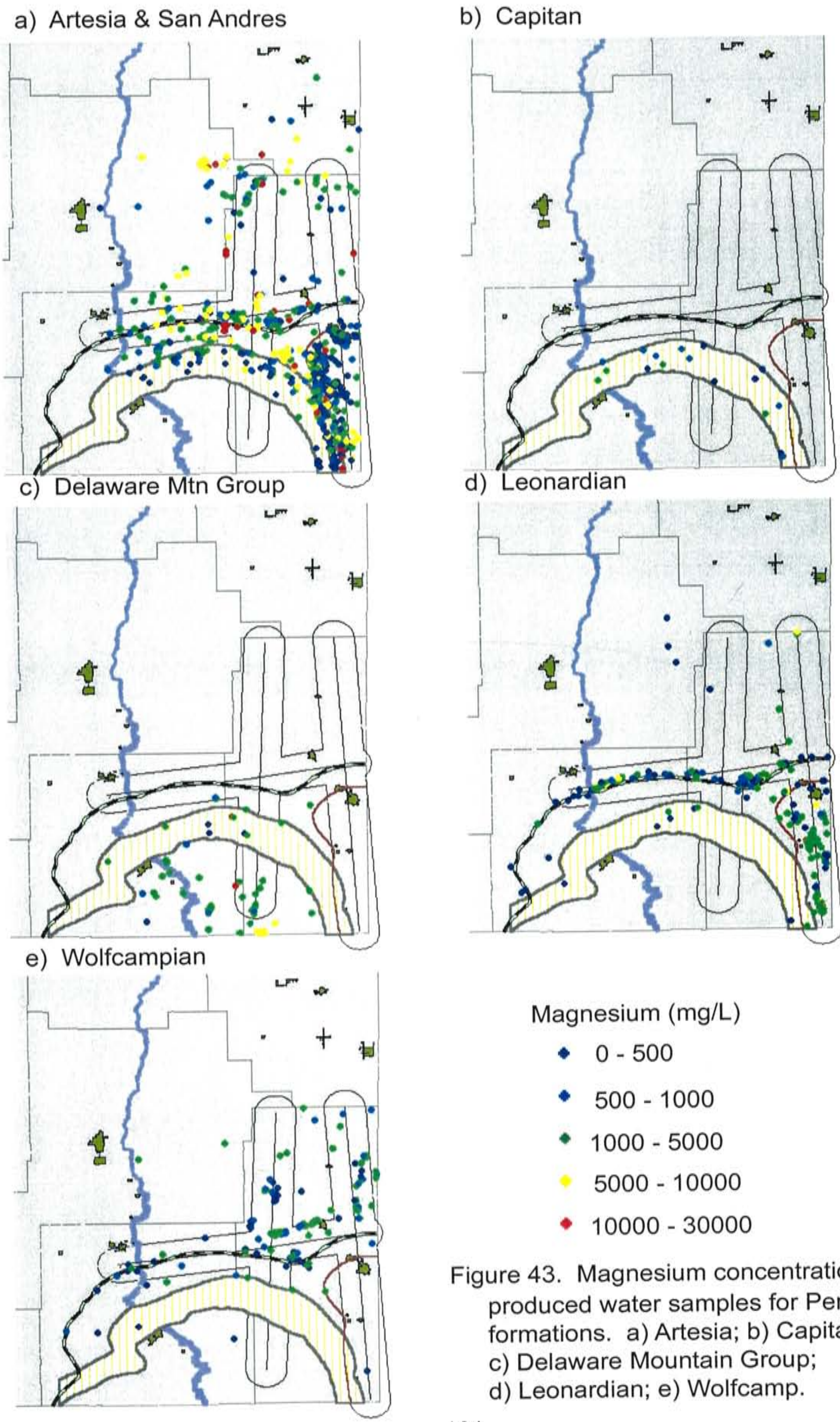


Figure 43. Magnesium concentration of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcamp.

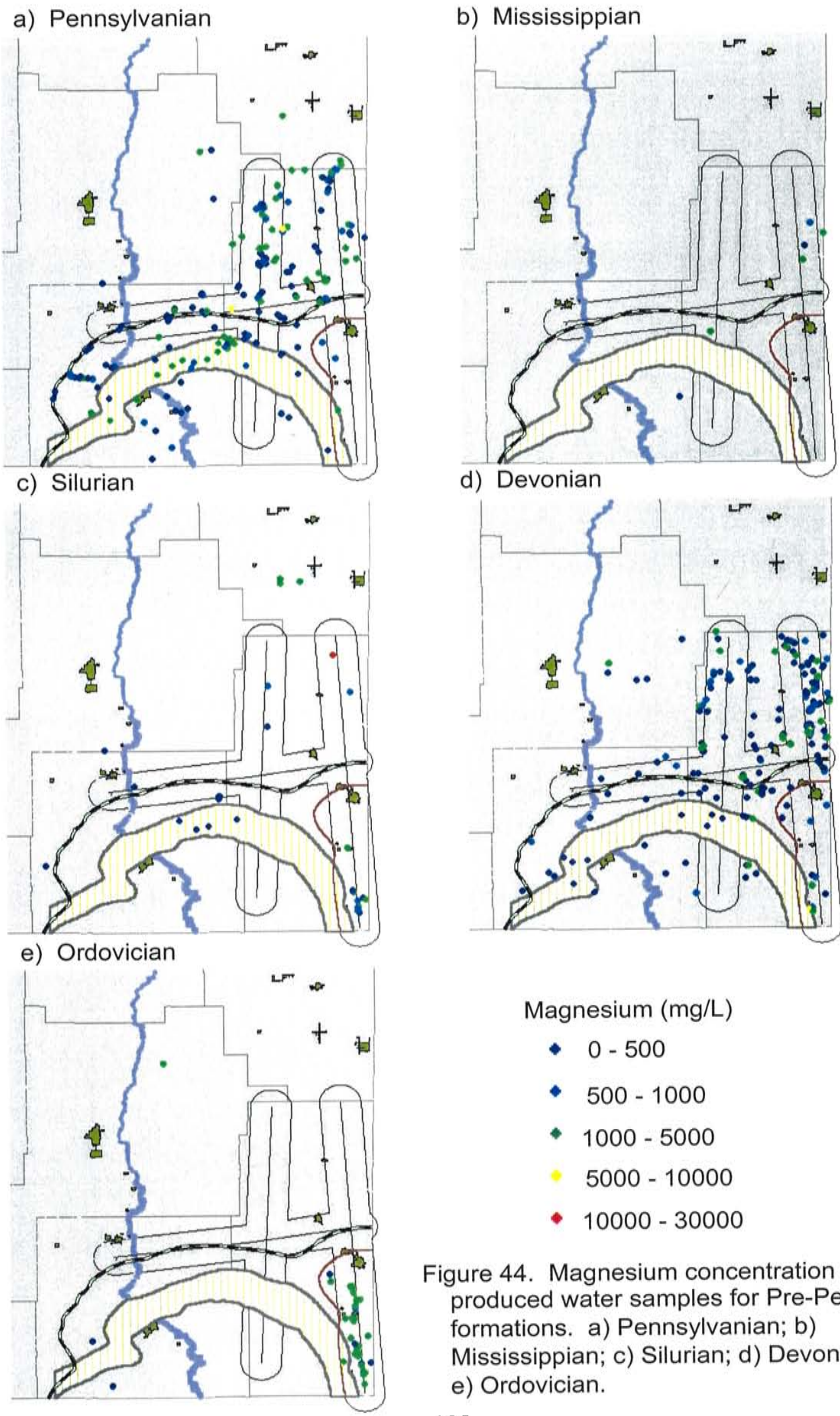


Figure 44. Magnesium concentration of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.

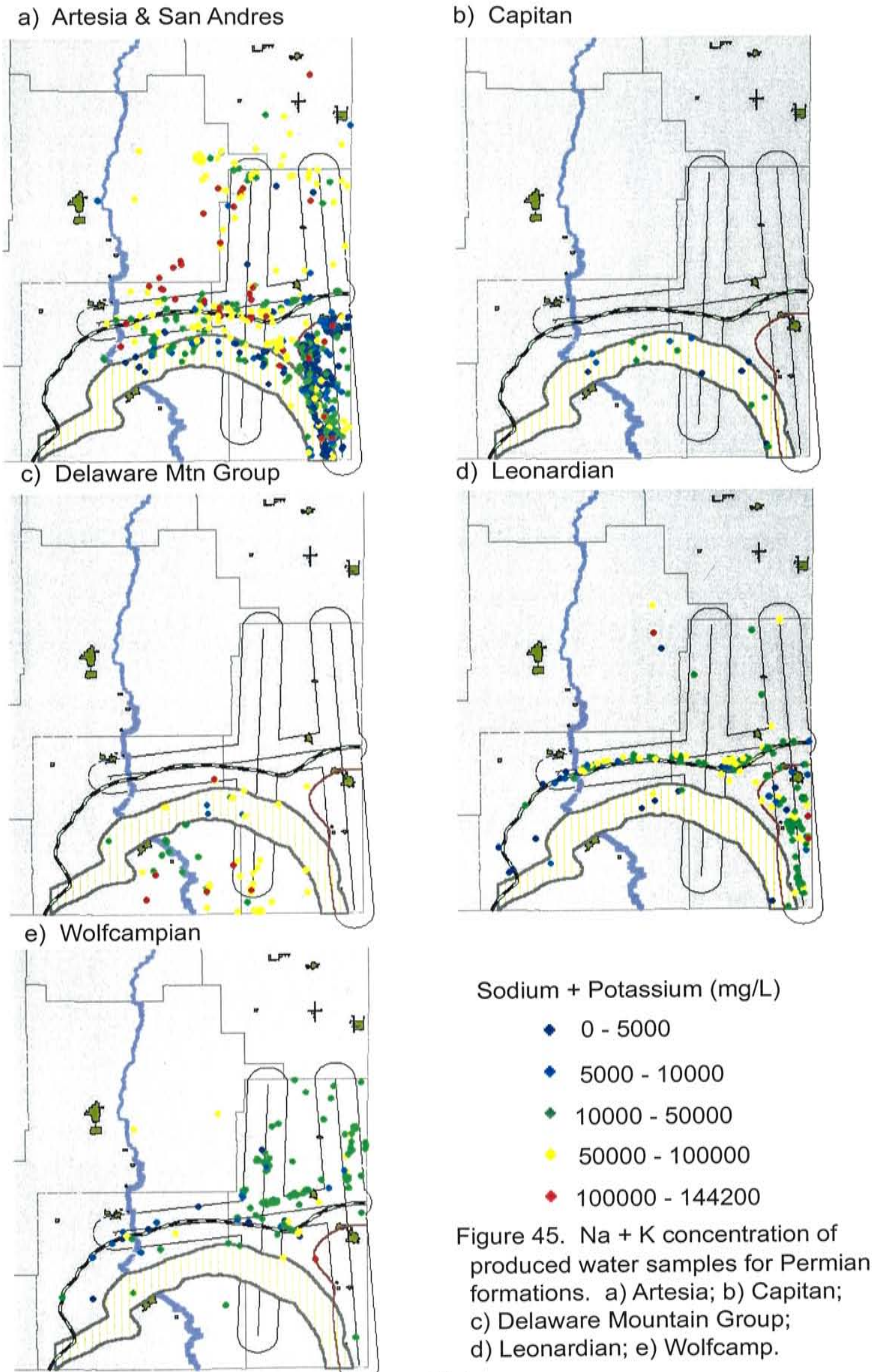
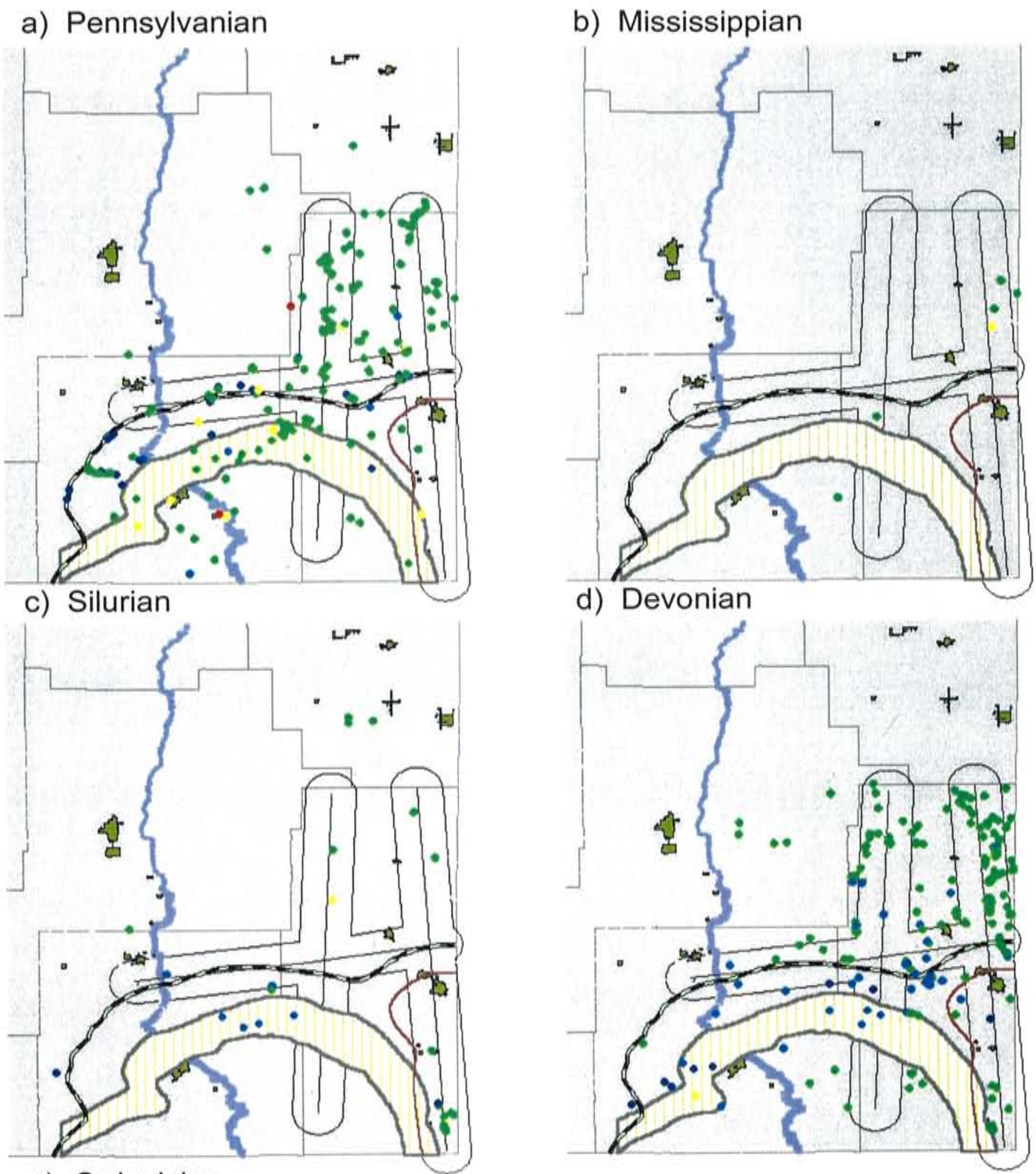
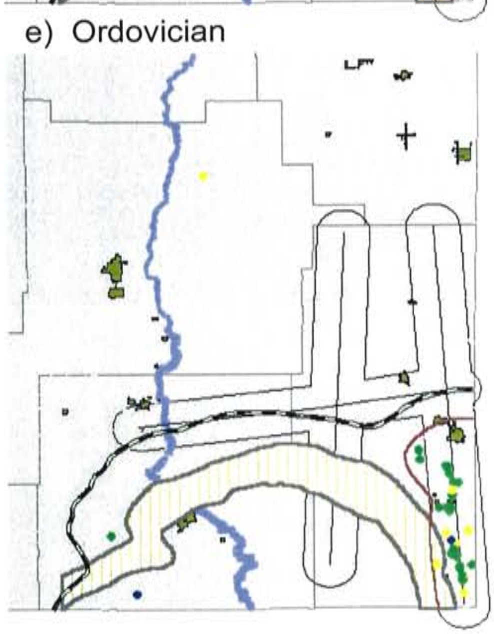


Figure 45. Na + K concentration of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcamp.





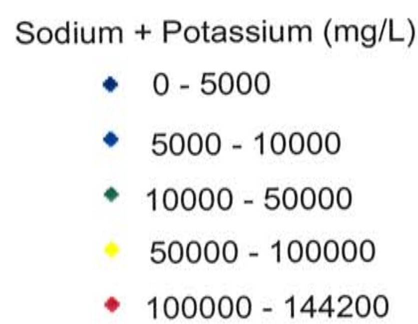
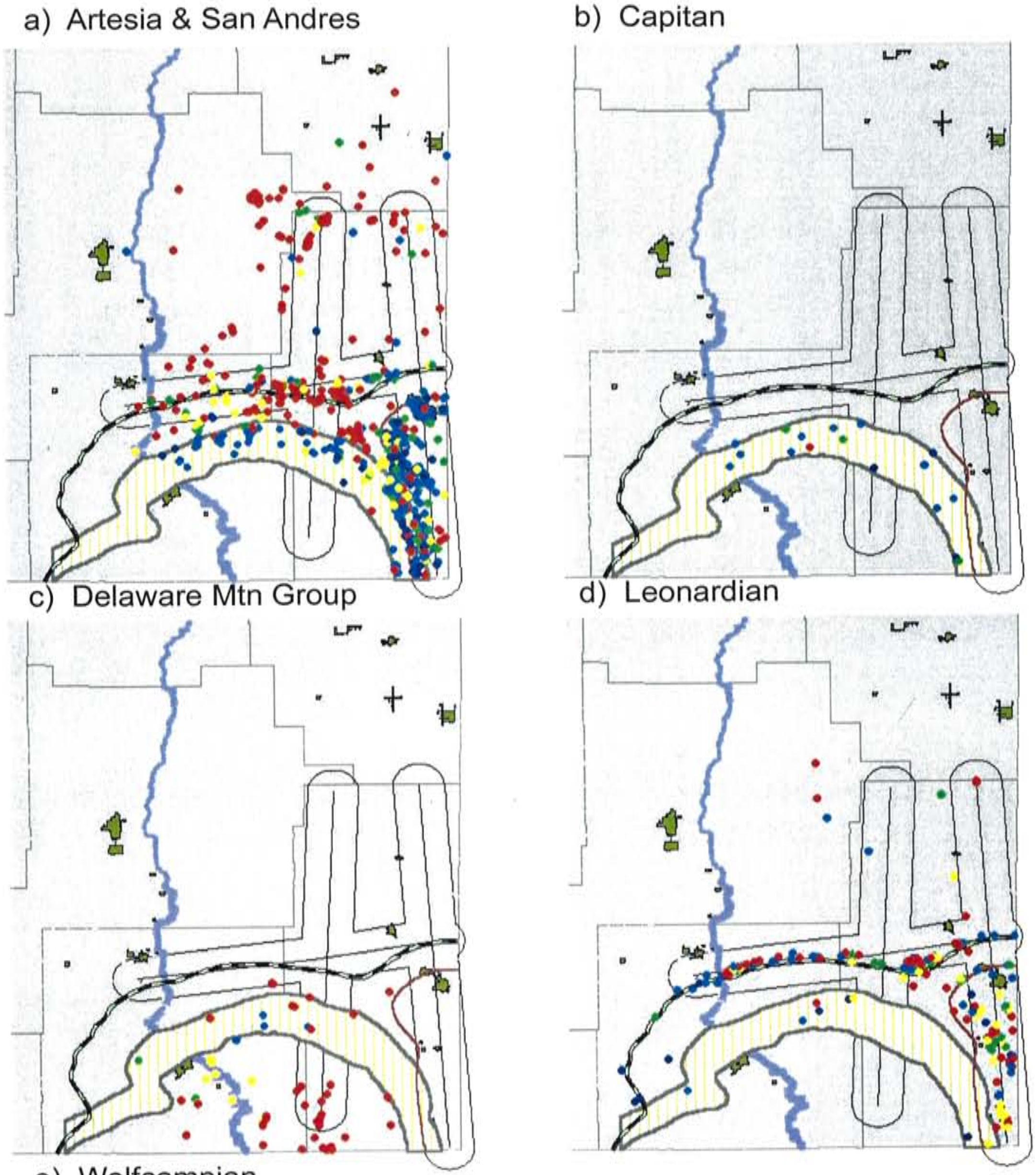
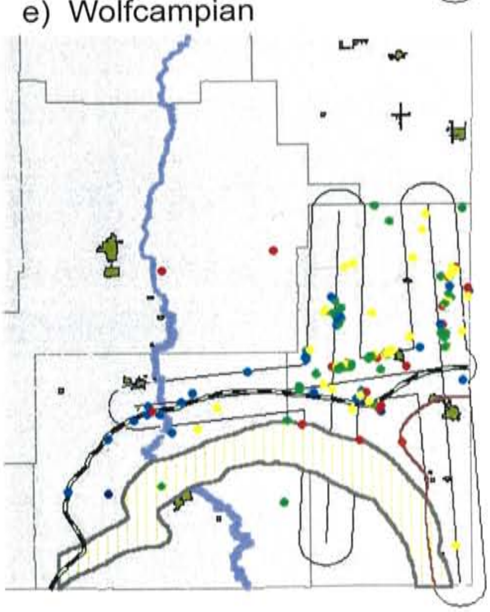


Figure 46. Na + K concentration of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.





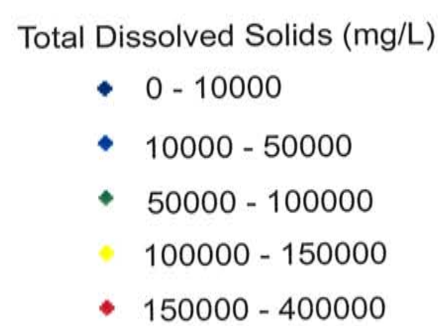
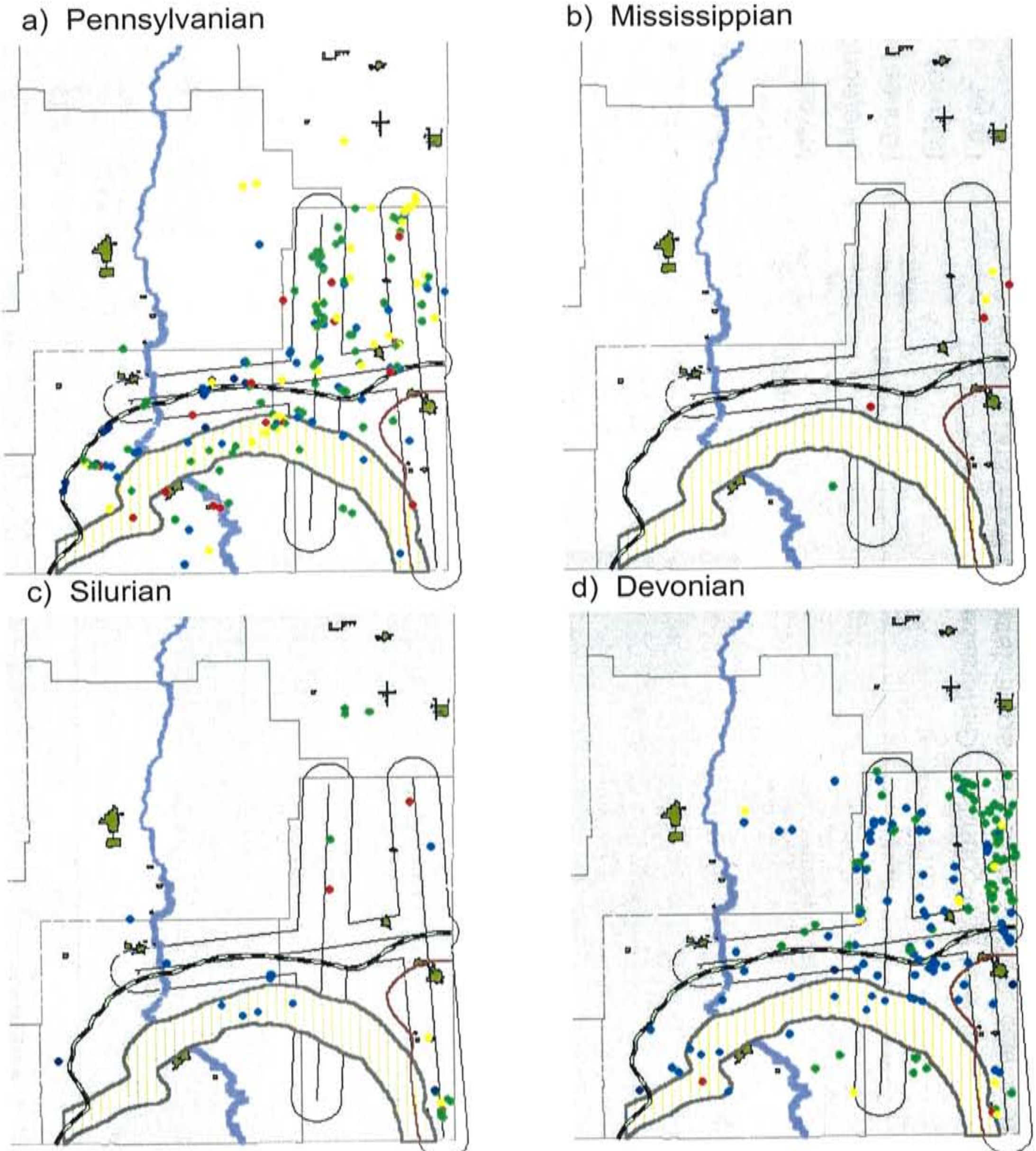
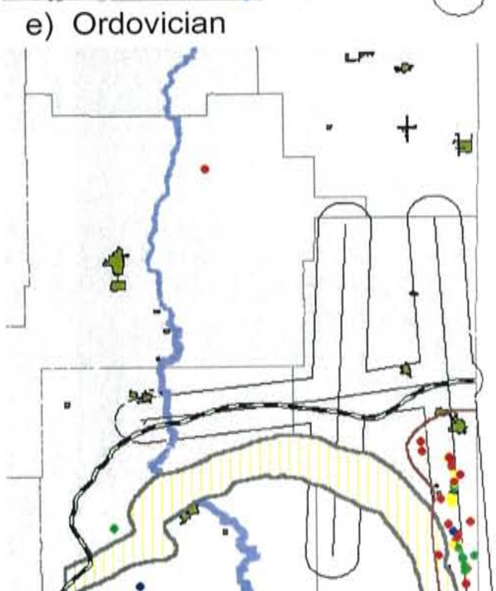


Figure 47. TDS concentration of produced water samples for Permian formations. a) Artesia; b) Capitan; c) Delaware Mountain Group; d) Leonardian; e) Wolfcamp.





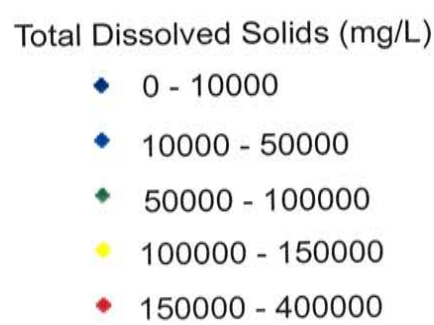


Figure 48. TDS concentration of produced water samples for Pre-Permian formations. a) Pennsylvanian; b) Mississippian; c) Silurian; d) Devonian; e) Ordovician.

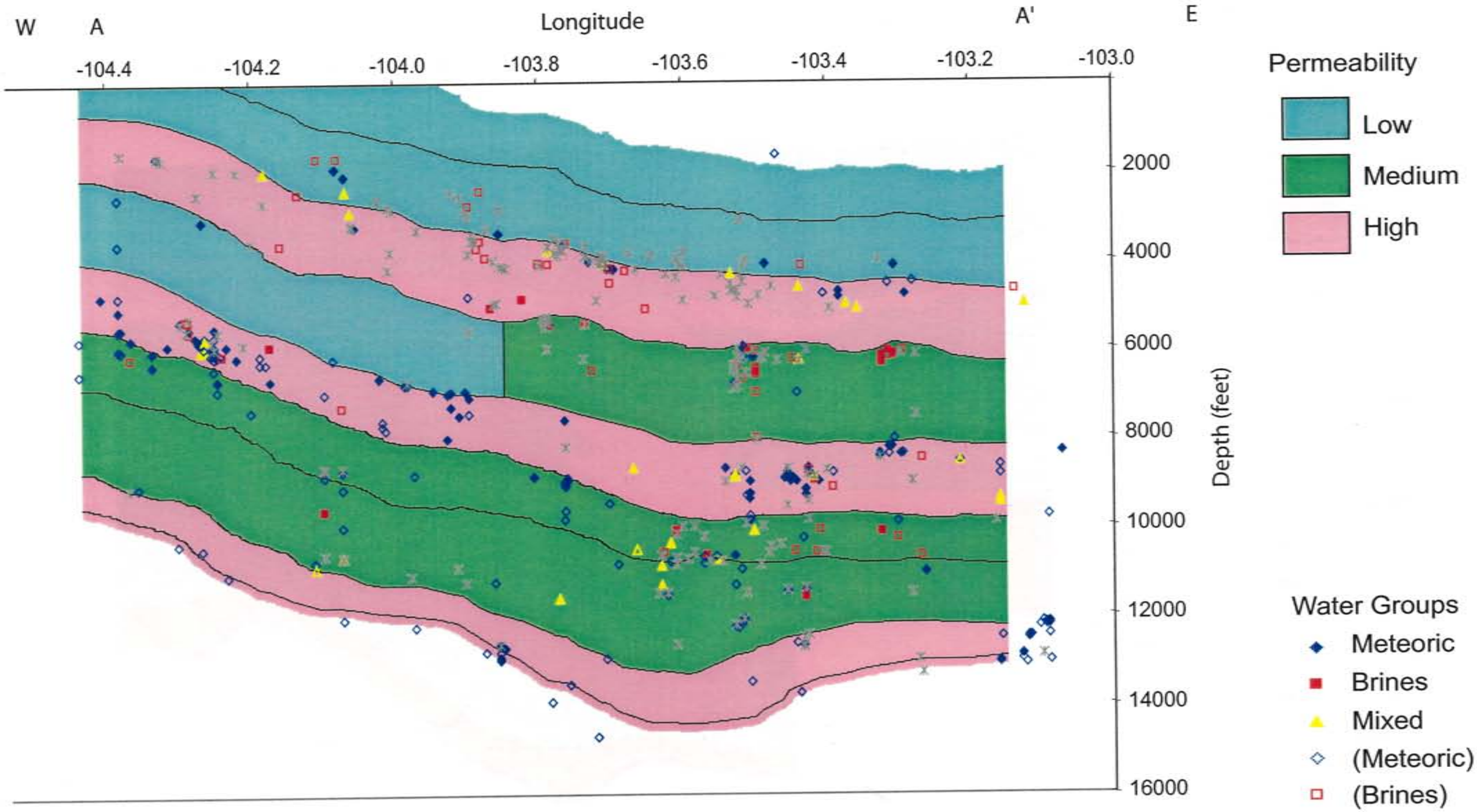


Figure 49. Cross section A - A' through Eddy and Lea counties. Generalized permeability based on facies. Longitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Solid points show chemistry of produced water samples based on Cl/SO4 and Ca/Mg ratios, while open points are based on Cl/SO4 ratios only.

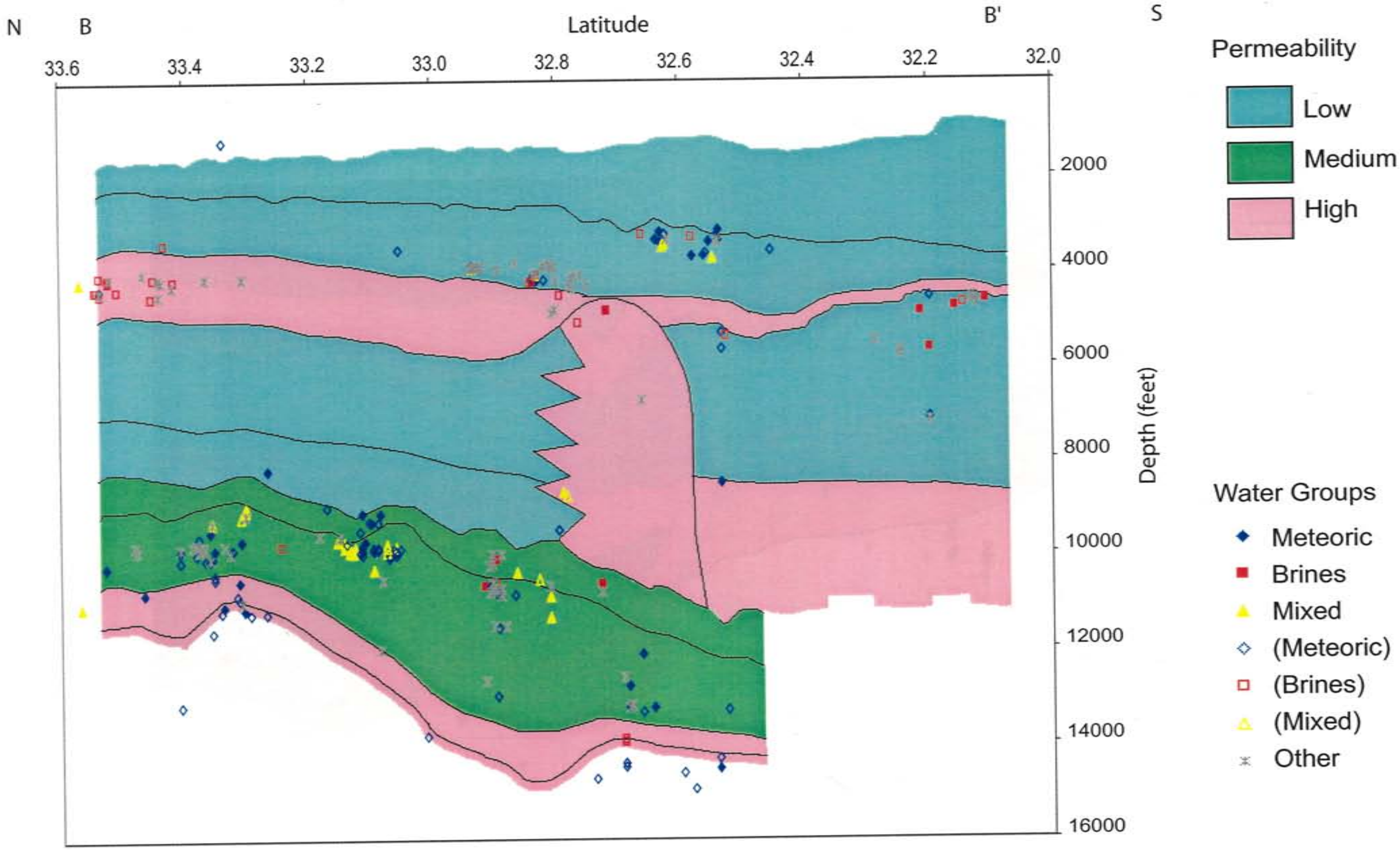


Figure 50. Cross section B - B' through western Lea county. Generalized permeability based on facies. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Solid points show chemistry of produced water samples based on Cl/SO4 and Ca/Mg ratios, while open points are based on Cl/SO4 ratios only.

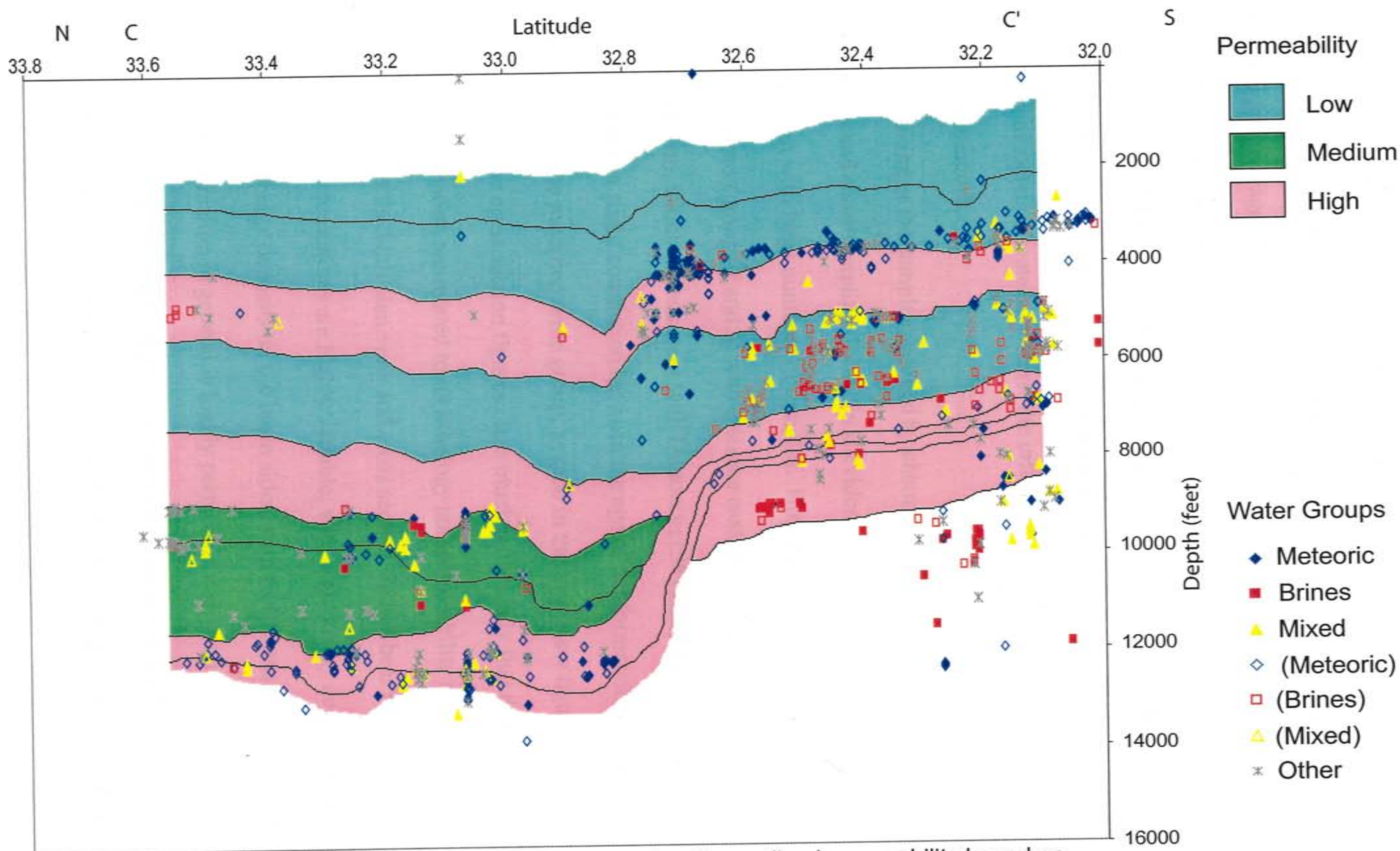


Figure 51. Cross section C - C' through eastern Lea county. Generalized permeability based on facies. Latitude in decimal degrees and depth from the surface in feet are the y and x axes respectively. Solid points show chemistry of produced water samples based on Cl/SO4 and Ca/Mg ratios, while open points are based on Cl/SO4 ratios only.

Produced water conclusions: General trends

Produced water samples are present in nearly all geologic formations, and have a much higher average chloride concentration than the groundwater samples. The piper diagrams for all formations except those in the Artesia Group are similar and show halite dissolution. The larger range of Artesia Group samples in the piper diagrams is likely due to the effect of samples with low chloride (higher water quality). Such samples are likely recent meteoric water and show the influence of a shorter time for equilibration with local minerals.

Looking at the samples grouped by chemical ratio, the high variability within formations and short sampling distances is evident. Thus spatial trends are not as evident, even with large numbers of samples. However, it appears that there are more modified brines (groups 2 and 5) with distance east, especially once over the Central Basin Platform, which is consistent with Dutton's (1987) findings of eastward regional flow. There is a slight correlation between the age of the formation and the number of samples from the modified brine group, as seen in the map view figures, but it is not very noticeable in the cross section figures. It is much more likely that the percentage of brines in a formation are related to its lithology and permeability rather than to its age, and in large part the both plan view and cross section figures bear this out.

Permian formations are highly variable, with high energy deposits on the shelf sides and low energy deposits on the basin sides, with reef formations in the middle. The San Andres Formation in general is highly permeable and waters are more saline with distance east. The Artesia Group formations can be locally well connected, but will have poor vertical permeability because of evaporite deposits. Regionally these formations will have highly variable permeabilities because of the changing mineralogy. The Artesia Group and San Andres samples show a trend of high TDS, briney samples in the north and eastern Central Basin Platform, and lower TDS, meteoric waters in the south, near the Capitan reef. This presence of meteoric waters in the reef and brines north of the reef illustrates the difference in permeability between the reef and other rocks in these formations.

The majority of the Delaware Mountain Group samples are brines; however, there are a few meteoric waters in the western part of the Delaware Basin. This reflects the low permeability of the fine grained sandstone. The meteoric waters may also indicate the presence of channel deposits, which have larger grainsize sandstones and a higher permeability.

Leonardian samples (including Glorieta through Abo Formations) generally follow the Abo Reef along the Artesia Vacuum trend and also occur in the Central Basin Platform. Most samples within the Abo are meteoric waters with low chloride concentrations, though there are notable exceptions. The Abo reef carbonate acts as a permeable aquifer, allowing flushing to occur along the main flow paths. Pockets of brines may represent elevationally high areas of low flow where oil and gas are more likely to accumulate. Samples within the Glorieta through Yeso Formations are much more briney, reflecting the relatively low permeability and connectivity of these formations.

Although there are not large numbers of Wolfcampian samples, they seem to agree with the eastward regional flow regime. Wolfcamp samples occur north of the Abo reef and show a basic trend of increasing salinity with distance east (fresh water moving east and displacing brines.) The carbonate and shale composition, which would suggest an intermediate permeability, is supported by the sample distribution. However, the use of major ions gives no interpretation of the timing of groundwater flushing or the effective permeability of the formation.

Pennsylvanian samples, though numerous, are quite variable and do not show much of a distinct trend. This is because Pennsylvanian formations are highly heterogeneous both vertically and laterally, and there are many different oil and gas fields within Pennsylvanian formations, all with different characteristics. For example, in Eddy county, the depositional environment for the lower Morrow sandstones is interpreted to be a prograding fluvial-deltaic sequence of channels and point bars with a northwest source (James, 1985). The middle Morrow sandstones were deposited as a transgressive series of marine beaches and bars along the northeast-trending ancient shoreline. Stratigraphic traps for oil and gas in Morrow sandstones are created by variations in cementation and depositional patterns (James, 1985). Productive Atokan sandstones were deposited as a series of prograding barrier bars along the northeast-trending shoreline. Strawn limestones produce from a series of small, low-relief algal banks that developed along a northeast trend (James, 1985). Most of the time, producing sandstone channels are interbedded with and separated by shales of low porosity and permeability. Grouping all the Pennsylvanian produced water samples together thus leads to a random looking pattern, and interpretation is difficult if not impossible. Separating Pennsylvanian fields by depositional environment or other similar physical characteristics is beyond the scope of this project.

Mississippian samples appear to be briney with relatively high TDS. Unfortunately, because there are so few Mississippian samples in the database, little interpretation can be done.

The Silurian and Devonian formations are often impossible to separate or distinguish in core or geophysical log, and are likely well connected hydrologically. They are well fractured and have relatively high permeability in comparison to other formations. The Devonian especially stands out for being mostly meteoric water (nearly totally flushed), and has increasing salinity in a northeastern trend. The eastern edge of northern Lea county has more samples in the mixed group, and moving further along the trend into Texas will likely show more modified brines until reaching the Midland Basin, where there is a recharge zone. The Silurian and Devonian Formations have two possible times where meteoric water could infiltrate and flush out brines. The first was during the period of the ancestral Rocky mountains, where areas to the west and north of the study area were uplifted. The second time period is today, where the modern Basin and Range uplift has caused a Silurian outcrop west of the Pecos. This is why these two formations have mostly meteoric waters although their age and depth would suggest otherwise.

The Ordovician samples are almost all located in the Central Basin Platform of southeastern Lea county, and are mostly saline brines. The Ordovician does not have a recharge zone (no outcrop) west of the Pecos as the Devonian and Silurian do, and thus there is no gradient available to cause flushing of saline brines. In addition, the Ordovician is discontinuous at the edge of Central Basin Platform and may pinch out underneath the Delaware Basin. Although the Ordovician has an effective permeability value similar to the Devonian and Silurian, it is separated by an unconformity and is probably not vertically connected with these formations. Thus, although the Ordovician is a well fractured carbonate with high effective permeability, similar to the Silurian and Devonian Formations, there is little chance of groundwater flushing.

Summary and Conclusions

The main objective of this project is to discover where, and in which formations, groundwater flushing (in which relatively fresh water moves through a formation, eventually taking the place of the original saline brine) is taking place. In order to have groundwater movement, there must be areas where recharge and discharge occur, and average permeabilities must be high enough that water movement can occur over geologic time. Both groundwater and produced water maps and cross sections of groundwater chemistry help to describe geochemical distributions and trends. The permeability, lithology, and depositional history of each geologic formation relates to the water chemistry.

The two main databases used for this purpose include the State Engineer's groundwater quality database, and the USGS database of produced water. These databases were used to analyze water chemistry for every formation where water samples are available. Although the existing chemical data of produced water samples is limited to major ion concentrations and TDS, the large number of samples allow an almost three-dimensional look at water chemistry in the deep basin, especially with the use of cross sectional views. Spatial trends in some formations are often hard to find because of lack of samples. For example, in Ochoan and younger formations, large numbers of produced water samples are not present because of the lack of oil or gas; additionally, there are no groundwater samples in formations older than Guadalupian age because of poor water quality and increasing cost of well drilling with depth. Although trends are present, water quality in both databases is highly variable within formations and short sampling distances.

In general, groundwater samples are found in formations at or near the surface, and have low chloride concentrations, with the majority of samples having a chloride concentration of less than 1000 mg/L. Their high chemical quality most likely reflects their origin as meteoric water and short residence time within the aquifer. Where number of samples is sufficient, spatial trends are usually evident, and are usually shown as increasing chloride concentration with distance towards the Pecos River. Although there is undoubtedly deep basin groundwater moving up towards the topographical and potential low, in the area between Roswell and Carlsbad most of the salinity increase is probably from the dissolution of local evaporites and addition of saline water from deeper formations, especially the San Andres. Those samples with high concentrations that are not near the river, especially those in the Ochoan and Triassic formations, are likely in areas of low permeability and have at least somewhat equilibrated with their surrounding minerals.

In the deep basin aquifer, there are three major groups of geologic formations, the first of which is Permian age deposits. These have variable lithology but have similar thickness over the study area. Pennsylvanian formations form the second group. They have variable thickness, especially moving from the Delaware Basin to the Central Basin Platform. They have relatively low permeability and are considered tight formations. The third group includes the Mississippian, Devonian, Silurian, and Ordovician formations. These formations are compositionally similar, with dolomite and limestone making up most of the volume. They also have variable thickness.

There are distinct chemical trends in the deep basin groundwaters, which are controlled by the flushing of meteoric water through high permeability formations.

Produced water samples serve as a proxy for groundwater samples, although there is some bias and uncertainty introduced, both because these are water samples from the oil and gas fields, and because of the uncertain sampling methods and analyses. Piper diagrams show that produced water samples from nearly all formations show signs of halite dissolution. Brine origins were determined using ion ratios, dividing samples into genetic classifications of connate brines, saline meteoric waters, and a mixture of the two.

There are several trends that were tested by the produced water sample distribution. These include eastward regional flow, relatively high flow through highly fractured carbonates such as the reef zones in the Capitan and Abo, and regionally extensive carbonates such as the Mississippian through Ordovician, more intermediate flow rates through carbonates with interbedded shales such as the Pennslyvanian and Wolfcamp, and low flow rates through formations with variable lithology including carbonates, evaporites, redbeds, and shales, including the Artesia Group and Upper Leonardian (Glorieta through Yeso) Formations. The Delaware Mountain Group and Ochoan formations, composed of low permeability fine-grained sandstone, and evaporites respectively, were expected to have very low flow rates and briney waters. Although there is a high amount of variability between samples, these trends are born out in general. A major exception is the presence of brines within the Ordovician despite its carbonate composition; this is because the Ordovician is cut off from the recharge zone by a major fault zone (the Central Basin Platform) and is not vertically connected with the upper formations.

The Permian Basin in southeast New Mexico is complex both geologically and hydrologically. The basin lithology and history, combined with the interaction of groundwater as it moved through the deep basin aquifer through geologic time, has greatly influenced the chemical characteristics of waters within the basin in a reasonably consistent and predictable fashion. The uplift and eastward tilting of the area in the late Tertiary and Quaternary is likely the cause of much of the chemical distribution of the waters that we see today, although it is impossible to tell the timing of groundwater flushing without more detailed chemical analyses and modeling. The interaction between groundwater and lithology in southeastern New Mexico should also affect areas to the south and east, including most of Texas, because groundwater will flow down the regional southeastern dip towards the hydraulic potential low of the ocean.

Suggestions for Future Work

Although there was a large amount of data used in this study, there is a limit to the amount of interpretation and understanding of geochemistry and groundwater history that can be done only using only major cations and anions. Several things can be done to further the knowledge of deep groundwater geochemistry, including the use of ratios of stable isotopes such as $\delta^{18}O / \delta^{16}O$ and $\delta D / \delta H$, strontium isotopes, and conservative tracers like chloride and bromide. The use of these constituents can be used to better quantify how groundwater in different formations and areas differ, and better interpret the complex history of groundwater through time. Bein and Dutton (1993), Knauth (1988) and Stueber et al. (1998) used all of these ratios to determine the sources and amount of mixing of waters in different areas, and also to constrain the ages and timing of mixing of the various water types. Effective permeabilities should also be better constrained by obtaining more detailed lithology information and permeability measurements.

Modeling using a standard numerical model can also be used to increase knowledge of the Permian basin in southeastern New Mexico by helping to confirm the effect of permeability and facies upon the chemical distribution, constraining the amount of time needed for flushing, and delineating areas needing more sampling. Movement of groundwater and brine flushing should be modeled in 3D because of the complex reef structure, and variable density flow should be taken into account. Although lithology is important, I would ignore mineral reactions as the fresh water moves through the basin with the possible exception of halite dissolution, because that would make the model much more complex. A conceptual model should include each formation, and its respective location, thickness and average permeability. I would have the Pecos River as the western edge of the model, and probably the edge of Midland basin as the eastern limit. The modeler should also consider lowering the average permeability for each formation by a factor of ten in order to help correct for upward bias in oil and gas permeability measurements. Boundary conditions would include fixed temperatures at the bottom and top of the model, and initial conditions would include a constant salinity under the salt cap (Ochoan formations.) Some models worth considering include SEAWAT and MOCDENSE because they can handle variable density flow.

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Appendix A. Cross section data

Cross sections were drawn using ArcView, and each section that a line crossed was recorded as a possible well location, resulting in cross sections with approximately one well per mile (see Table A1.) Then for each section, scout cards were searched for the best formation top record, and the location, elevation, and formation tops were recorded where available (see Tables A2-A4). Then the formation top information was divided up into my geologic divisions. These divisions are based on period except for Permian formations, which were divided up by age and for Guadalupian age, shelf, reef and basin (see stratigraphic column, Figure 5, pages 13 – 14). Once divided, the formation tops were decided by finding the highest depth available. The tops were most often Rustler or Anhydrite for Ochoan, Yates for Artesia, Glorieta for Leonard, Penn or Pennsylvanian for Pennsylvanian, Barnett for Mississippian, Woodford for Devonian, Fusselman for Silurian, and Montoya for Ordovician. The lower formations (Mississippian and down) had very sparse data so usually any top within the division became the formation top.

Cross sections were made using the resulting cross section data (Tables A5-A7.) Latitude and longitude of the center of each section where formation tops were available were calculated using Marty Wefald's program. Certain sections had questionable formation tops; additional data was added where available, shown as the shaded columns in Tables A5 – A7. The Capitan Reef was added to the B – B' cross section because it is an important hydrologic unit with a relatively high permeability. However, there is no validation on the location or borders of the reef, and this part of the cross section should be considered with some caution. The final cross sections can be seen in Figures 26 – 34 of the main text.

Table A1. Possible section locations for formation top data for cross section A - A'

township		range		section
18	s	25	e	13
18	s	26	e	18
				17
				16
				15
				11
				12
18	s	27	e	7
				8
				9
				10
				11
				12
18	s	28	e	6
				5
				4
				3
				2
				1
18	s	29	e	6
				5
17	s	29	e	33
				34
				35
				36
17	s	30	e	31
				32
				33
				34
				26
				25
17	s	31	e	30
				29
				28
				27
				26
				25
17	s	32	e	19
				20
				21
				22
				23
				24
17	s	33	e	19
				20
				16
				15
				14
				13
17	s	34	e	18
				17
				9
				10
				11
				12

township		range		section
17	s	35	e	7
				8
				4
				3
				2
				1
17	s	36	e	6
				5
16	s	36	e	33
				34
				35
				36
16	s	37	e	31
				32
				33
				27
				26
				25
16	s	38	e	30
				29
				28

Table A1 (continued.) Possible section locations for formation top data for cross section B - B'
B - B'

township		range		section
9	s	33	e	18
				19
				30
				31
10	s	33	e	6
				7
				18
				19
				30
				31
11	s	33	e	3
				10
				15
				22
				27
				34
12	s	33	e	3
				10
				15
				21
				28
				33
13	s	33	e	4
				9
				16
				21
				28
				33
14	s	33	e	4
				9
				16
				21
				28
				33
15	s	33	e	4
				9
				16
				21
				28
				33
16	s	33	e	1
				11
				14
				23
				26
				35
17	s	33	e	2
				11
				14
				23
				26
				35
18	s	33	e	2
				11
				14
				23
				26
				35
19	s	33	e	2
				11
				14
				23
				26
				35
20	s	33	e	2
				11
				14
				22
				27
				34
21	s	32	e	2
				11
				14
				23
				26
				35
22	s	32	e	11
				14
				23
				26
				35
23	s	32	e	2
				10
				15
				22
				27
				34
24	s	32	e	3
				10
				15
				22
				27

Table A1 (continued.) Possible section locations for formation top data for cross section C - C'

township		range		section
9	s	36	e	2
				11
				14
				23
				26
				35
10	s	36	e	2
				11
				14
				23
				25
				36
11	s	37	e	5
				8
				16
				21
				28
				33
12	s	37	e	4
				9
				16
				21
				28
				33
13	s	37	e	4
				9
				16
				21
				28
				33
14	s	37	e	4
				10
				15
				22
				27
				34
15	s	37	e	3
				10
				15
				22
				27
				34
16	s	38	e	6
				7
				18
				19
				30
				31
17	s	38	e	5
				8
				17
				20
				29
				32

township		range		section
18	s	38	e	5
				8
				17
				20
				29
				32
19	s	38	e	5
				8
				17
				20
				28
				33
20	s	38	e	4
				9
				16
				21
				28
				33
21	s	37	e	3
				10
				15
				22
				27
				34
22	s	37	e	3
				10
				15
				22
				26
				35
23	s	37	e	2
				11
				14
				23
				26
				35
24	s	37	e	2
				11
				14
				23
				26
				35
25	s	37	e	2
				11
				14
				24
				25
				36
26	s	37	e	1
				12
				13
				24
				25

Table A2. Cross section A - A' scoutcard data.

	18s25e13	18s26e18	18s26e17	18s26e16	18s26e15	18s26e14	18s26e11
Lat	32.7473	32.7473	32.7473	32.7473	32.7473	32.7473	32.7618
Long	-104.4388	-104.422	-104.4045	-104.387	-104.3702	-104.353	-104.353
API	30015-20471		30015-27028				30015-20739
Elev	3445	3412	3420		3352	3342	3319
Santa Rosa							
Rustler							
Anhydrite							
Salt							
B/Salt							
Tansill							
Yates							
Seven Rivers							
Queen							
Penrose sand							
Grayburg							
San Andres	805		908	785		945	980
Slaughter C					1625		
Glorieta	2157		2218	2260	2298		2280
Paddock							
ClearFork							
Blinebry							
Tubb		3712	3728				3825
Drinkard							
Yeso				2375	2422		
Abo (shelf)	4285	4303		4360	4470	4495	4475
Abo (reef)							
Bone Spring							
Wolfcamp	5628	5595	5578	5690		5890	5865
Pennsylvanian						6952	7760
Cisco		6970		7190		6988	
Canyon	7507	7500	7568	8120			
Strawn	8027	8049	7972	8585			
Atoka	8451	8462	8472	8810	8610	8327	8614
Morrow	8546	8700	8710				8726
Barnett	8796					9272	
Chester	8896		8960	9075			9130
Mississippian				9235		9160	
Woodford						9916	
Devonian							
Fusselman							
Silurian							
Montoya						10369	
Simpson							
McKee							
Ellenburger							
Granite							

Table A2 (continued). Cross section A - A' scoutcard data.

	18s26e12	18s27e7	18s27e8	18s37e9	18s27e10	18s27e11
Lat	32.7618	32.7618	32.7618	32.7618	32.7618	32.7618
Long	-104.3359	-104.3188	-104.3016	-103.2559	-104.2673	-104.2502
API	30015-20931	30015-21528	30015-21114	30015-20523		30015-20510
Elev	3291	3300	3388	3498	3531	3587
Santa Rosa						
Rustler						
Anhydrite						
Salt						
B/Salt						
Tansill						
Yates						
Seven Rivers						
Queen		351	565	828	910	970
Penrose sand						
Grayburg		759	1385			
San Andres	998	1022		1530	1730	1887
Slaughter C						
Glorieta	2330	2177	3097			
Paddock			3233			
ClearFork						
Blinebry						
Tubb	3867					
Drinkard			4525			
Yeso				3032	3260	3457
Abo (shelf)	4526	5650	5100	5173	5100	5087
Abo (reef)					5960	6036
Bone Spring						
Wolfcamp	5917	5970	6143			6405
Pennsylvanian	7787	7130				
Cisco			7202			7745
Canyon		7773	8410			8365
Strawn		8287	8916			8680
Atoka	8658	8760				9277
Morrow	8772		9093			
Barnett			9354			
Chester						9960
Mississippian		9218				
Woodford						
Devonian						
Fusselman						
Silurian						
Montoya						
Simpson						
McKee						
Ellenburger						
Granite						

Table A2 (continued). Cross section A - A' scoutcard data.

	18s27e12	18s28e6	18s28e5	18s28e4	18s28e3	18s28e2
Lat	32.7618	32.7763	32.7763	32.7763	32.7763	32.7763
Long	-104.233	-104.2159	-104.1988	-104.1816	-104.1645	-104.1473
API	30015-20894	3001521395	7972		30015-30002	30015-24655
Elev	3607	3644	3649		3648	3646
Santa Rosa						
Rustler						
Anhydrite						
Salt					400	
B/Salt					520	583
Tansill						
Yates			414	464	794	760
Seven Rivers					975	1050
Queen		1068	1293	1337	1624	1703
Penrose sand						
Grayburg				1816	2070	
San Andres	2005	1995	2110	2159	2510	2600
Slaughter C						
Glorieta		3463	3665			4292
Paddock						
ClearFork						
Blinebry						
Tubb						
Drinkard						
Yeso				3697		
Abo (shelf)	5506	5520				5775
Abo (reef)			6143	6295		
Bone Spring						
Wolfcamp	6745					7120
Pennsylvanian						
Cisco	7645					8573
Canyon	8390					8753
Strawn	8894					9493
Atoka						10090
Morrow						10526
Barnett						
Chester						
Mississippian						10798
Woodford						
Devonian						
Fusselman						
Silurian						
Montoya						
Simpson						
McKee						
Ellenburger						
Granite						

Table A2 (continued). Cross section A - A' scoutcard data.

	18s28e1	18s29e6	18s29e5	17s29e33	17s29e34	17s29e35
Lat	32.7763	32.7763	32.7763	32.7908	32.7908	32.7908
Long	-104.1302	-104.114	-104.0968	-104.0797	-104.0625	-104.045
API	30015-25002	30015-20492	30015-21947	30015-21556	30015-23034	
Elev	3665	3643	3567	3534	3531	3545
Santa Rosa						
Rustler						
Anhydrite						315
Salt	370			350	328	420
B/Salt	818			750	814	772
Tansill						
Yates	955	950			1002	
Seven Rivers	1310					
Queen	1935			2003	1977	2033
Penrose sand						
Grayburg	2370			2435	2422	2420
San Andres	2720	2730	2730	2835	2854	2899
Slaughter C						
Glorieta	4321	4333	4368	4399	4420	4412
Paddock						
ClearFork						
Blinebry						
Tubb						
Drinkard						
Yeso						
Abo (shelf)	5770	5782	6154	6200	6222	6230
Abo (reef)						
Bone Spring						
Wolfcamp			7860			
Pennsylvanian						
Cisco			8900			
Canyon			9508			
Strawn			9740			
Atoka		10234	10198			
Morrow		10380	10640			
Barnett			10980			
Chester			11130			
Mississippian		11260				
Woodford		11781				
Devonian		11825				
Fusselman						
Silurian						
Montoya						
Simpson						
McKee						
Ellenburger						
Granite						

Table A2 (continued). Cross section A - A' scoutcard data.

	17s29e36	17s30e31	17s30e32	17s30e33	17s30e34	17s30e35
Lat	32.7908	32.7908	32.7908	32.7908	32.7908	32.7908
Long	-104.0282	-104.011	-103.9939	-103.9767	-103.9595	-103.9424
API	30015-29985	30015-23213	30015-28960	30015-22664	30015-23998	30015-26969
Elev	3558	3582	3555	3616	3550	3548
Santa Rosa						
Rustler						
Anhydrite						
Salt		555		590		
B/Salt		1032		1170		
Tansill		1075		1215		
Yates		1180		1335		1532
Seven Rivers		1665		1850		
Queen	2180	2112	2363	2465		2532
Penrose sand						
Grayburg	2580	2595	2751	2860		
San Andres	2840	3050	3235	3328		3368
Slaughter C						
Glorieta	4623	4632	4759	4766	4855	4978
Paddock						
ClearFork						
Blinebry						
Tubb						
Drinkard						
Yeso						
Abo (shelf)	6270	6322	6398		6977	6678
Abo (reef)						
Bone Spring						6456
Wolfcamp	7938		8300		8667	8200
Pennsylvanian						
Cisco					9649	
Canyon						
Strawn	10276		10380		10402	10208
Atoka			10583		10660	10517
Morrow	11006		11284		10872	11103
Barnett	11157					
Chester			11628			11428
Mississippian						11551
Woodford						12086
Devonian						12147
Fusselman						12310
Silurian						
Montoya						
Simpson						
McKee						
Ellenburger						
Granite						

Table A2 (continued). Cross section A - A' scoutcard data.

	17s30e36	17s30e26	17s30e25	17s31e30	17s31e29	17s31e28
Lat	32.7908	32.8053	32.8053	32.8053	32.8053	32.8053
Long	-103.925	-103.942	-103.9252	-103.908	-103.8909	-103.8737
API	8037		30015-29476	30015-29530	30015-28142	30015-28140
Elev	3654		3568	3646	3753	3788
Santa Rosa						
Rustler			317	297		665
Anhydrite						
Salt				520		
B/Salt						
Tansill			1288	1471		
Yates	1638		1443	1633		1850
Seven Rivers			1788	2000		2172
Queen	2675		2480	2669	2815	2858
Penrose sand						
Grayburg	3075		2895	3076		3230
San Andres	3520			3520	3600	3725
Slaughter C						
Glorieta	5045	5190	5375	5355		
Paddock						
ClearFork						
Blinebry						
Tubb						
Drinkard						
Yeso						
Abo (shelf)		6782		6910	6940	7000
Abo (reef)	7722					
Bone Spring			6180			7957
Wolfcamp	8359		7946		8038	8088
Pennsylvanian						
Cisco	9446				9680	
Canyon					9898	
Strawn	10492		10370		10770	10842
Atoka	10746		10543		11014	10998
Morrow	11130		10832		11231	11357
Barnett	11798					
Chester			11340		11766	11903
Mississippian						
Woodford						
Devonian						
Fusselman						
Silurian						
Montoya						
Simpson						
McKee						
Ellenburger						
Granite						

Table A2 (continued). Cross section A - A' scoutcard data.

	17s31e27	17s31e26	17s31e25	17s32e19	17s33e19	17s32e20	17s32e20
Lat	32.8053	32.8053	32.8053	32.8198	32.8198	32.8198	32.8198
Long	-103.8566	-103.839	-103.8222	-103.805	-103.805	-103.7879	-103.788
API	30025-26233		30015-26067-0002		14362	30025-33584	14378
Elev	4145	3840	3869	3941		4007	4017
Santa Rosa							
Rustler	700		720	613			
Anhydrite		540					
Salt	600	733		729			850
B/Salt		1680				2490	1922
Tansill	1672						
Yates	1874	1855		1952	1963		2080
Seven Rivers	2150	2226					2450
Queen	2865	2854	3030	2922	2940		3055
Penrose sand		3026					
Grayburg	3235	3248		3299	3303		3426
San Andres	3700	3682	3760	3646	3670		3807
Slaughter C							
Glorieta	5400		5432				5310
Paddock	5670		5648			5620	
ClearFork							
Blinebry							
Tubb							
Drinkard							
Yeso							
Abo (shelf)		7021		7487	7370	7509	7544
Abo (reef)							
Bone Spring			6180				
Wolfcamp					8994	8890	9079
Pennsylvanian							
Cisco							10453
Canyon							
Strawn							11647
Atoka							11952
Morrow							
Barnett							
Chester							
Mississippian					12574	12550	12742
Woodford					13670	13600	13824
Devonian					13770	13701	13939
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A2 (continued). Cross section A - A' scoutcard data.

	17s32e21	17s32e22	17s32e22	17s32e23	17s32e24	17s33e19	17s33e20
Lat	32.8198	32.8198	32.8198	32.8198	32.8198	32.8198	32.8198
Long	-103.771	-103.754	-103.7536	-103.736	-103.7193	-103.7021	-103.685
API			3002530363	14411	30025-33423	30-025-3308	30025-24446
Elev	4027	4023		4086	4082	4105	4201
Santa Rosa							
Rustler	810				1180	1162	
Anhydrite							1340
Salt	932	933		1158	1314	1297	1450
B/Salt		1995		2230	2347	2274	2580
Tansill	1983						
Yates	1983	2145		2392	2450	2500	2700
Seven Rivers	2494	2498		2750	2737	2866	
Queen	3100	3102		3367	3385	3479	3100
Penrose sand							
Grayburg	3483	3485		3775	3770	3852	4000
San Andres	3864	3869		4165	4160	4227	4350
Slaughter C							
Glorieta	5350	5375	5355	5431	5682	5833	5989
Paddock	6433						
ClearFork							
Blinebry							
Tubb		6830	6833				
Drinkard							
Yeso							
Abo (shelf)	7550	7560	7583			7700	
Abo (reef)							
Bone Spring							
Wolfcamp	9048	9061	9040				
Pennsylvanian		9983					
Cisco	10373						
Canyon	10945	10935					
Strawn	11396	11355					
Atoka	11688	11674					
Morrow	12010	12025					
Barnett							
Chester							
Mississippian	12510						
Woodford	13504						
Devonian	13619						
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A2 (continued). Cross section A - A' scoutcard data.

	17s33e16	17s33e15	17s33e14	17s33e13	17s34e18	17s34e18
Lat	32.8343	32.8343	32.8343	32.8343	32.8343	32.8343
Long	-103.668	-103.6506	-103.6335	-103.6163	-103.5991	-103.5991
API	14557	30025-24543	30025-24206	30025-25437	30025-25256	30025-30223
Elev	4189	4174	4156	4130	4108	
Santa Rosa				1398		
Rustler		1477	1483	1502		1549
Anhydrite						
Salt				1689	1673	1660
B/Salt						
Tansill						
Yates	2748	2778	2782	2795	2833	2850
Seven Rivers				3125		
Queen	3720	3755	3772	3802	3832	3830
Penrose sand			4205			
Grayburg	4148	4227	4548	4310	4349	4449
San Andres	4496	4507		4600	4639	4603
Slaughter C						
Glorieta	6008		6020		6086	6047
Paddock			6104			6130
ClearFork	6210					
Blinebry			6760			
Tubb	7460		7435			7520
Drinkard						
Yeso			7576			
Abo (shelf)	8100		8120		8150	8143
Abo (reef)						
Bone Spring						
Wolfcamp	9720		9720		10080	9850
Pennsylvanian			10320			
Cisco					10846	11060
Canyon					11400	11400
Strawn					12190	
Atoka					12578	
Morrow						
Barnett						
Chester						
Mississippian	13680				13438	
Woodford	14800					
Devonian						
Fusselman						
Silurian						
Montoya						
Simpson						
McKee						
Ellenburger						
Granite						

Table A2 (continued). Cross section A - A' scoutcard data.

	17s34e17	17s34e9	17s34e10	17s34e10	17s34e11	17s34e11	17s34e12
Lat	32.8343	32.8488	32.8488	32.8488	32.8488	32.8488	32.8488
Long	-103.582	-103.565	-103.548	-103.5477	-103.531	-103.531	-103.5133
API	30025-25272	14943	14947	30025-23829	14961	14968	30025-23638
Elev	4086	4083	4051	4061	4039	4040	4037
Santa Rosa							
Rustler							
Anhydrite			1653	1652	1652	1648	
Salt							
B/Salt							
Tansill							
Yates		2891	2896	2933	2900	2887	2920
Seven Rivers		3240					3226
Queen		3914		3895	3888	3873	3874
Penrose sand							
Grayburg		4403					
San Andres		4702	4683	4687	4663	4646	4643
Slaughter C							
Glorieta	6096		6094	6088	6070	6065	6110
Paddock							
ClearFork							
Blinebry							
Tubb			7428	7428	7360	7360	7340
Drinkard							
Yeso							
Abo (shelf)			8126	8116	8062	8070	8050
Abo (reef)							
Bone Spring							
Wolfcamp	10080	9967	9912		9902	9568	9912
Pennsylvanian						10230	
Cisco	10720						
Canyon							
Strawn	12134						
Atoka	12512						
Morrow	12884						
Barnett							
Chester							
Mississippian	13352						
Woodford							
Devonian							
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A2 (continued). Cross section A - A' scoutcard data.

	17s35e7	17s35e7	17s35e8	17s35e9 (r	17s35e6	17s35e5	17s35e3
Lat	32.8488	32.8488	32.8488	32.8488	32.8633	32.8633	32.8633
Long	-103.4962	-103.4962	-103.479	-103.462	-103.4962	-103.479	-103.445
API	30025-25328	30025-26955	30025-24281	15222	30025-29703	30025-31458-0000	
Elev	4014		3984	3983			3960
Santa Rosa							
Rustler					1974		2000
Anhydrite			1870	1895			
Salt							2110
B/Salt							
Tansill							
Yates	3095	3010	3150	3150	3132		3253
Seven Rivers				3355		3383	
Queen		3976	4095	4065	4058	3804	4197
Penrose sand							
Grayburg				4400		4499	
San Andres	4778	4718	4824	4645		4694	4960
Slaughter C							
Glorieta	6253	6188	6270		6179		6496
Paddock							
ClearFork							
Blinebry							
Tubb	7530		7636		7573		7815
Drinkard							
Yeso							
Abo (shelf)	8247	8620	8356		8231		8542
Abo (reef)							
Bone Spring							
Wolfcamp	9824	8738	9800		9348		9890
Pennsylvanian		10317					
Cisco							
Canyon		10650					
Strawn			11592		11179		11867
Atoka					11282		11927
Morrow			12165		11492		12469
Barnett							
Chester					11611		
Mississippian					11761		12864
Woodford							
Devonian					12677		
Fusselman							
Silurian							
Montoya					14602		
Simpson					14923		
McKee					15112		
Ellenburger							
Granite					15244		

Table A2 (continued). Cross section A - A' scoutcard data.

	17s35e3	17s35e2	17s35e1	17s35e1	17s36e6	17s36e5	16s36e33
Lat	32.8633	32.8633	32.8633	32.8633	32.8633	32.8633	32.8778
Long	-103.4447	-103.428	-103.4104	-103.4104	-103.3932	-103.3761	-103.359
API	30025-02813	15205	30025-29546	30025-30276	30025-33934	30025-2881	
Elev	3969	3952			3954	3948	
Santa Rosa							
Rustler			1999	2000		1880	
Anhydrite							
Salt						1965	
B/Salt						2965	
Tansill							
Yates			3206	3215		3085	
Seven Rivers							
Queen				4120			
Penrose sand							
Grayburg							
San Andres			4828	4828	4640	4725	
Slaughter C							
Glorieta	6490	6456		6200	6760	6213	
Paddock					6870		
ClearFork							
Blinebry							
Tubb		7666	7568	7620	7488	7479	
Drinkard	7845				7745		
Yeso			6804				
Abo (shelf)	8590		8198	8250	8218	8201	
Abo (reef)							
Bone Spring							
Wolfcamp	9805	10324	9818	9415	9692	10031	
Pennsylvanian	11160	10792	10782		11060		
Cisco							
Canyon				10805			
Strawn		11956	11156		11420		
Atoka		12122	11248		11655		
Morrow		12574					
Barnett							
Chester							
Mississippian			11634				
Woodford			12426				
Devonian							
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A2 (continued). Cross section A - A' scoutcard data.

	16s36e34	16s36e35	16s36e36	16s37e31	16s37e32	16s37e33	16s37e27
Lat	32.8778	32.8778	32.8778	32.8778	32.8778	32.8778	32.8923
Long	-103.342	-103.325	-103.3074	-103.29	-103.2731	-103.2559	-103.2388
API		14065	30025-31066	14159	30025-05387	30025-27927	30025-24876
Elev		3854		3823	3799	3778	3776
Santa Rosa							
Rustler			2010			2084	
Anhydrite		2040		2000	2031		2100
Salt		2152	2152	2148		2146	
B/Salt		2960		2946		2989	
Tansill							
Yates		3087	3105	3070	3088	3102	
Seven Rivers			3350			3372	
Queen			3768			3991	
Penrose sand							
Grayburg			4440			4438	
San Andres		4655	4649	4625	4698	4745	4858
Slaughter C							
Glorieta		6015	6000	5995	6100	6130	6244
Paddock			6103	6770		6220	
ClearFork							
Blinebry							
Tubb				7520		7627	7918
Drinkard						7780	
Yeso							
Abo (shelf)						8055	8570
Abo (reef)							
Bone Spring							
Wolfcamp						10097	
Pennsylvanian					10597	10818	
Cisco							
Canyon						10946	
Strawn					11038	11208	11325
Atoka							11760
Morrow							
Barnett							
Chester							
Mississippian					11604		12372
Woodford					12370		
Devonian					12500		
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A2 (continued). Cross section A - A' scoutcard data.

	16s37e26	16s37e25	16s38e30	16s38e29	16s38e28
Lat	32.8923	32.8923	32.8923	32.8923	32.8923
Long	-103.2216	-103.2044	-103.187	-103.17	-103.153
API	30025-27691	30025-23908	14224	14223	30025-24039
Elev	3771	3757	3769	3752	3716
Santa Rosa					
Rustler					
Anhydrite		2105		2083	2040
Salt	3050				
B/Salt					
Tansill					
Yates	3180	3290	3250	3210	3150
Seven Rivers			3565		
Queen			4170	4155	
Penrose sand					
Grayburg					
San Andres		5050	5070	5057	4930
Slaughter C					
Glorieta	6285	6445	6500	6463	6310
Paddock	6410				
ClearFork					
Blinebry					
Tubb	7815	8010	8070	8034	7840
Drinkard	7932	8188			8198
Yeso					
Abo (shelf)	8600	8565		8730	
Abo (reef)					
Bone Spring					
Wolfcamp					
Pennsylvanian					
Cisco					
Canyon					
Strawn	11438				
Atoka			11515		
Morrow					
Barnett					
Chester					
Mississippian					
Woodford			13025		
Devonian			13075		
Fusselman					
Silurian					
Montoya					
Simpson					
McKee					
Ellenburger					
Granite					

Table A3. Cross section B - B' Scoutcard data

	9s33e18	9s33e19	9s33e30	10s33e6	10s33e19	10s33e30	10s33e31
Lat	33.5336	33.5192	33.5048	33.476	33.4328	33.4185	33.4041
Long	-103.6076	-103.6076	-103.6076	-103.6076	-103.6076	-103.6076	-103.6076
API							
Elev	4407	4394	4631		4212	4270	4247
Santa Rosa							
B/ S.Rosa							
Rustler							
Anhydrite	1847	1736	1808		1732	1740	1756
X (salt)						1806	1837
B/Salt							
Tansill							
Yates	2437		2356	2333	2413	2472	2443
Seven Rivers		2390					
Queen				3160	3105		
Penrose							
Grayburg							
San Andres	3650	3709	3684	3602	3680	3742	3750
Capitan							
Delaware							
Cherry Canyon							
Brushy Canyon							
Glorieta	5072	5030	5030		5073		5137
Yeso							
Clear Fork							
Tubb		6497			6520	6528	6593
Abo (shelf)	7387	7370	7320		7351	7383	7320
Abo (reef)							
Bone Spring							
BoneSpring 1							
BoneSpring 2							
BoneSpring 3							
Wolfcamp	8516	8335	8446		8487	8678	8550
Penn			9088			9292	
Bough "C"		9108			9216		
Cisco							
Canyon							
Strawn						10254	10222
Atoka							
Morrow							
(Miss) Barnett							
Mississippian							11245
Woodford							11905
Devonian							11990
Silurian (Fusselman)							
Montoya							
Simpson							
PreCambrian							

Table A3 (continued). Cross section B - B' Scoutcard data

	11s33e3	11s33e10	11s33e15	11s33e22	11s33e27	11s33e34	12s33e3
Lat	33.3946	33.3801	33.3656	33.3511	33.3366	33.322	33.3075
Long	-103.6014	-103.6014	-103.6014	-103.6014	-103.6014	-103.6014	-103.6014
API							
Elev	4275		4273	4258	4264	4272	4258
Santa Rosa							
B/ S.Rosa							
Rustler							
Anhydrite	1835	1740	1673	1610	1740	1663	1643
X (salt)						1743	
B/Salt			2405			2357	
Tansill							
Yates	2490	2487	2477	2465	2470	2455	2444
Seven Rivers			2615				
Queen	3212	3204	3174			3163	
Penrose							
Grayburg							
San Andres	3762	3748	3750	3698	3740	3750	3730
Capitan							
Delaware							
Cherry Canyon							
Brushy Canyon							
Glorieta		5153	5140	5120	5140		
Yeso							
Clear Fork						5830	
Tubb	6588	6553	6547	6507	6510	6496	
Abo (shelf)	7435	7371	7360	7301	7280	7276	7260
Abo (reef)							
Bone Spring							
BoneSpring 1							
BoneSpring 2							
BoneSpring 3							
Wolfcamp	8818		8620	9412	8479	8415	8395
Penn	9215	9089		9006		8638	8963
Bough "C"	9400	9364			9017		
Cisco		9089	9068				
Canyon		9700	9500				
Strawn	10092	10053	9830	9867	9778		
Atoka							
Morrow							
(Miss) Barnett							
Mississippian					10459		
Woodford					11012		
Devonian					11040		
Silurian (Fusselman)							
Montoya							
Simpson							
PreCambrian							

Table A3 (continued). Cross section B - B' Scoutcard data

	12s33e15	13s33e21	13s33e28	13s33e33	14s33e4	14s33e9	14s33e16
Lat	33.2785	33.1769	33.1624	33.1479	33.1334	33.1189	33.1044
Long	-103.6014	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187
API							
Elev	4260	4263	4248	4256	4238	4240	4231
Santa Rosa							
B/ S.Rosa							
Rustler				1695			
Anhydrite	1662	1660	1702		1676	1645	1642
X (salt)		1770	1805				1690
B/Salt			2455				2560
Tansill							
Yates	2475	2550	2548	2596	2605	2647	2635
Seven Rivers			2698				
Queen		3330		3370	3372	3405	
Penrose							
Grayburg							
San Andres	3772	3958	3956	4025	4034	4135	4147
Capitan							
Delaware							
Cherry Canyon							
Brushy Canyon							
Glorieta	5170	5415	5420			5555	5555
Yeso							
Clear Fork			6084				
Tubb	6565	6845	6860	6925	6943	6993	6980
Abo (shelf)	7295	7615	7643	7660	7675	7645	7765
Abo (reef)							
Bone Spring							
BoneSpring 1							
BoneSpring 2							
BoneSpring 3							
Wolfcamp	8500	9025	9047		9268		9725
Penn			9512	9845		9810	
Bough "C"		9612			9883		
Cisco	9425						
Canyon							
Strawn							
Atoka							
Morrow							
(Miss) Barnett							
Mississippian							
Woodford							
Devonian							
Silurian (Fusselman)							
Montoya							
Simpson							
PreCambrian							

Table A3 (continued). Cross section B - B' Scoutcard data

	14s33e21	14s33e28	14s33e33	15s33e4	15s33e9	15s33e16	15s33e22
Lat	33.0899	33.0754	33.0608	33.0463	33.0318	33.0173	33.0028
Long	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6014
API							
Elev	4232	4219	4214	4211	4188	4202	4179
Santa Rosa							
B/ S.Rosa							
Rustler							
Anhydrite		1541	1514	1503	1525	1460	1492
X (salt)		1637	1610	1602		1603	1650
B/Salt		2466	2451	2543		2445	2470
Tansill							
Yates	2656	2626	2608	2622	2678	2627	2645
Seven Rivers							2890
Queen		3404	3395		3486		3455
Penrose							
Grayburg	3434						3800
San Andres	4099	4115	4105	4145	4158	4190	4190
Capitan							
Delaware							
Cherry Canyon							
Brushy Canyon							
Glorieta		5632	5650		5780		5840
Yeso							
Clear Fork		6360	6370	6363	6330		
Tubb	7005	7005	7003	6993	7055		7087
Abo (shelf)	7790	7747	7745	7733	7725	7830	7845
Abo (reef)							
Bone Spring							
BoneSpring 1							
BoneSpring 2							
BoneSpring 3							
Wolfcamp		9078	9080	9077	9185	9240	9320
Penn		9361	9363	9355			10150
Bough "C"							
Cisco	9970						
Canyon							
Strawn							
Atoka							
Morrow							
(Miss) Barnett							
Mississippian						13150	
Woodford						13745	
Devonian						13830	
Silurian (Fusselman)							
Montoya							
Simpson							
PreCambrian							

Table A3 (continued). Cross section B - B' Scoutcard data

	15s33e28	16s33e1	16s33e11	16s33e14	16s33e22	16s33e26	13s33e35
Lat	32.9883	32.9543	32.9358	32.9213	32.9068	32.8923	33.1479
Long	-103.6187	-103.6163	-103.6335	-103.6335	-103.6506	-103.6335	-103.5842
API			3002328648				3002528630
Elev	4214	4182	4188	4177	4191	4184	4169
Santa Rosa							
B/ S.Rosa							
Rustler							1510
Anhydrite		1517		1510	1481		
X (salt)				1630			
B/Salt	2518			2700			
Tansill							
Yates	2693	2743	2780	2795	2741	2794	2815
Seven Rivers			3037				
Queen	3512	3851	3635	3655		3693	3705
Penrose							
Grayburg		4363		4095			
San Andres				4480	4428	4462	4485
Capitan							
Delaware							
Cherry Canyon							
Brushy Canyon							
Glorieta	5850	5890	5950		5929	5950	5930
Yeso							
Clear Fork		6523				6570	
Tubb	7170	7139	7156		7189	7190	
Abo (shelf)	7870	7802	7915		7942	7972	
Abo (reef)							
Bone Spring							
BoneSpring 1							
BoneSpring 2							
BoneSpring 3							
Wolfcamp		9782	9560			9710	10110
Penn			10510				
Bough "C"	10383						
Cisco		10545				11178	11558
Canyon		10907				11483	
Strawn		11833	12043				
Atoka			12300				
Morrow			12840				
(Miss) Barnett							
Mississippian		13403					
Woodford		14132					
Devonian		14267					
Silurian (Fusselman)							
Montoya							
Simpson							
PreCambrian							

Table A3 (continued). Cross section B - B' Scoutcard data

	17s33e2	17s33e11	17s33e14	17s33e23	17s33e26	17s33e35
Lat	32.8633	32.8488	32.8343	32.8198	32.8053	32.7908
Long	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335
API	3002524386	3002525288	3002525230		3002527764	3002532733
Elev	4180	4138	4123	4158	4282	4133
Santa Rosa			1168			
B/ S.Rosa			1350			
Rustler		1473	1468		1412	1450
Anhydrite	1510			1483		
X (salt)			1700		1612	1600
B/Salt						2650
Tansill						
Yates	2815	2760	2762	2803	2764	2800
Seven Rivers		3200	3111		3237	3196
Queen		3732	3758	3803	3751	3793
Penrose			3962		3938	
Grayburg		4235	4267	4222	4120	4340
San Andres	4505	4521	4555	4605	4444	4470
Capitan						
Delaware						
Cherry Canyon						
Brushy Canyon						
Glorieta				6055	5881	
Yeso						
Clear Fork						
Tubb						
Abo (shelf)	7992			8190		
Abo (reef)						
Bone Spring						
BoneSpring 1						
BoneSpring 2						
BoneSpring 3						
Wolfcamp				9805		
Penn						
Bough "C"						
Cisco	11165					
Canyon	11652					
Strawn						
Atoka						
Morrow						
(Miss) Barnett						
Mississippian				13805		
Woodford				14960		
Devonian				15110		
Silurian (Fusselman)						
Montoya				16147		
Simpson				16452		
PreCambrian				16827		

Table A3 (continued). Cross section B - B' Scoutcard data

	18s33e2	18s33e23	18s33e26	18s33e35	19s33e2	19s33e11	19s33e14
Lat	32.7763	32.7328	32.7183	32.7038	32.6893	32.6748	32.6603
Long	-103.634	-103.6335	-103.6335	-103.634	-103.634	-103.6335	-103.6335
API			3002524475			30025-30118	30025-32092
Elev	4131	3987	3794	3827	3767	3730	3665
Santa Rosa							
B/ S.Rosa							
Rustler						1522	
Anhydrite	1640	1585		1540			
X (salt)		1790					1632
B/Salt	2937	2985	2869				
Tansill							3074
Yates	3015	3090	3038	3320			3300
Seven Rivers		3590	3238				3580
Queen	4115	4260	4233			4342	4250
Penrose			4498	4570			
Grayburg	4810						
San Andres	5132	5132	5080			5033	5000
Capitan							
Delaware							5930
Cherry Canyon	5208	5340					
Brushy Canyon							
Glorieta	6725						
Yeso							
Clear Fork							
Tubb							
Abo (shelf)	8530						
Abo (reef)	8710						
Bone Spring					7610	7781	7888
BoneSpring 1					8917		
BoneSpring 2					9462	9554	
BoneSpring 3					10275	10460	
Wolfcamp					10608	10764	
Penn							
Bough "C"							
Cisco							
Canyon							
Strawn					11896	12034	
Atoka						12336	
Morrow					12530		
(Miss) Barnett							
Mississippian					13464		
Woodford					14036		
Devonian					14156		
Silurian (Fusselman)					14639		
Montoya							
Simpson							
PreCambrian							

Table A3 (continued). Cross section B - B' Scoutcard data

	19s33e23	19s33e26	19s33e35	20s33e2	20s33e11	20s33e14
Lat	32.6458	32.6313	32.6168	32.6023	32.5878	32.5733
Long	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335
API	30025-30510	30025-26440	30025-34749	30025-34841		
Elev		3596	3586	3606	3578	3601
Santa Rosa						
B/ S.Rosa						
Rustler		1329		1376		1320
Anhydrite					1318	
X (salt)		1506		3058		1510
B/Salt		2932				
Tansill						2980
Yates	3365	3053		3254	3225	3205
Seven Rivers	3460				3472	
Queen	4330					
Penrose						
Grayburg						
San Andres						
Capitan		3472				
Delaware	5380	5324		5282		
Cherry Canyon						
Brushy Canyon				6598		
Glorieta						
Yeso						
Clear Fork						
Tubb						
Abo (shelf)						
Abo (reef)						
Bone Spring	8020	7974	8070	8240		
BoneSpring 1	9230		9155			
BoneSpring 2			9681			
BoneSpring 3	10556		10514			
Wolfcamp	10969	10808	10970			
Penn						
Bough "C"						
Cisco		11748				
Canyon		11950				
Strawn	12089	12054	12043			
Atoka	12424	12308	12278			
Morrow	12661	12782	12815			
(Miss) Barnett						
Mississippian						
Woodford						
Devonian						
Silurian (Fusselman)						
Montoya						
Simpson						
PreCambrian						

Table A3 (continued). Cross section B - B' Scoutcard data

	20s33e22	20s33e28	20s33e34	21s32e2	21s32e11	21s32e14
Lat	32.5588	32.5443	32.5298	32.5114	32.4943	32.4797
Long	-103.6506	-103.6678	-103.6506	-103.6463	-103.6463	-103.6463
API		30025-34404	30025-34302	30025-24690		30025-33999
Elev	3595	3623	3646	3771	3813	3885
Santa Rosa						
B/ S.Rosa						
Rustler		1482		1568		
Anhydrite	1293				1552	
X (salt)	1520					1515
B/Salt	2995	3185				3394
Tansill						
Yates	3400	3390			3350	3515
Seven Rivers						
Queen						
Penrose						
Grayburg						
San Andres						
Capitan						3670
Delaware		5228	5832	5543	5555	5536
Cherry Canyon						
Brushy Canyon			8259			
Glorieta						
Yeso						
Clear Fork						
Tubb						
Abo (shelf)						
Abo (reef)						
Bone Spring		8458	8566	8718	8770	8814
BoneSpring 1		9510	9460			9864
BoneSpring 2		10054	10121			10634
BoneSpring 3		10985	11018	11270		11481
Wolfcamp		11430	11716	11630	11314	11842
Penn						
Bough "C"						
Cisco		12430				
Canyon						
Strawn		12662	12729	12878	12885	13096
Atoka		12830	12976	13088		13290
Morrow		13357	13260	13334		13507
(Miss) Barnett		13820		14491	14530	14736
Mississippian					14740	
Woodford					14340	
Devonian					15550	
Silurian (Fusselman)						
Montoya						
Simpson						
PreCambrian						

Table A4. Cross section C - C' Scoutcard data

	9S36E2	9s36e11	9s36e15	9s36e23	9s36e26	9s36e35	10S36e2
Lat	33.5624	33.548	33.5336	33.5192	33.5048	33.4904	33.476
Long	-103.2269	-103.2269	-103.2442	-103.2269	-103.2269	-103.2269	-103.2269
API							
Elev	4062	4070	4060	4036	4026	4028	
Rustler							
Anhydrite	2232		2210	2226	2250		
X (salt)	2323		2312	2308	2350		
B/Salt	2694		2730	2800	2760		
Tansill							
Yates	2804		2850	2848	2862	2850	
Seven Rive	3300						
Queen			3566		3603		
Penrose sand							
Grayburg							
San Andre	4087	4114	4104	4120	4137		
Glorieta	5518	5548	5555	5566	5576	4855	
Yeso							
Paddock							
Clear Fork				6210			
Blinebry							
Tubb	6927	6956	6952	6936	6956	5565	
Drinkard							
Abo (shelf)	7700	7748	7740	7718	7730	6947	7745
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp	8947	9018		8918		8980	8986
Permian-Penn			8970	9289	8966		
Bough "C"	9673	9705	9695	9659	9677		
Cisco							
Canyon							
Strawn							
Atoka							
Morrow							
Mississippian				11658	11760	11718	
Woodford				12070	12180	12193	
Devonian				12179	12290	12266	
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A4 (continued). Cross section C - C' Scoutcard data

	10s36e10	10s36e14	10s36e24	10s36e35	11s37e3	11s37e8	11s37e17
Lat	33.4616	33.4472	33.4328	33.4041	33.3946	33.3801	33.3656
Long	-103.2442	-103.2269	-103.2095	-103.2269	-103.1876	-103.2221	-103.2221
API			3002526160	3002524809		3002631374	
Elev	4026	4010	3972	3987	3958		3960
Rustler	2197		2205				
Anhydrite		2234		2187	2210		
X (salt)		2342	2320		2289		
B/Salt		2772	2929		2883		
Tansill						2218	
Yates	2867	2924	2929	2881	2970	2976	2990
Seven Rivers			3750				
Queen		3654	3842	3623	3694		
Penrose sand							
Grayburg			3935				
San Andre	4152	4182	4212	4174	4262	4302	4320
Glorieta	5595	5639		5683			
Yeso							
Paddock							
Clear Fork							
Blinebry							
Tubb	6987	7000		7028	7030	7103	7105
Drinkard							
Abo (shelf)	7745	7736		7754	7730	7837	7845
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp	9005			9140	8910	9118	9178
Permian-Penn		8995			9280	10675	
Bough "C"		9650		9754			
Cisco							
Canyon							
Strawn				10595			
Atoka						11340	
Morrow							
Mississippi	11740	11622			11604	11950	
Woodford	12222	12275				12600	
Devonian		12330				12677	12695
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A4 (continued). Cross section C - C' Scoutcard data

	11s37e23	11s37e29	12s37e2	12s37e4	12s37e21	12s37e29	12s37e34
Lat	33.3511	33.3366	33.3075	33.3075	33.264	33.2495	33.235
Long	-103.1704	-103.2221	-103.1704	-103.2049	-103.2049	-103.2221	-103.1876
API					30025-24728		
Elev	3931	3968		3946	3925	3930	3905
Rustler							2240
Anhydrite	2249	2330		2225			
X (salt)							
B/Salt							
Tansill							
Yates	3013	3020		3055			3080
Seven Rivers				3190			
Queen		3830		3830			3842
Penrose sand							
Grayburg							
San Andre	4353	4383		4449	4460	4480	4470
Glorieta		5845		5926		5964	5922
Yeso	5837						
Paddock							
Clear Fork							
Blinebry							
Tubb		7159		7244	7250	7318	
Drinkard							7205
Abo (shelf)	7829	7878	7916	7964		8037	7895
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp	9210	9262	9265	9334	9252		
Permian-Penn							
Bough "C"							
Cisco		10026	10132				
Canyon			10563				
Strawn			10844				
Atoka		11500		11520	11282	11645	11133
Morrow			11611				
Mississippi	11754	12213	12057	12155	11990	12544	11480
Woodford	12360	12913	12836	13130	12706	13220	12184
Devonian	12438			13232	12808	13324	12260
Fusselman							
Silurian		13010					
Montoya							
Simpson							
McKee							
Ellenburger							
Granite						Chester HU	HU

Table A4 (continued). Cross section C - C' Scoutcard data

	13s37e2	13s37e3	13s37e10	13s37e22	13s37e32	14s37e5	14s37e11
Lat	33.2205	33.2205	33.206	33.1769	33.1479	33.1334	33.1189
Long	-103.1704	-103.1876	-103.1876	-103.1876	-103.2221	-103.2221	-103.1704
API	30025-24825	30025-24200		30025-25987			
Elev	3873		3888		3899	3881	3831
Rustler	2220	2244		2227			
Anhydrite			2194			2192	
X (salt)							
B/Salt							
Tansill							
Yates	3112	3153	3070	3183		3218	3254
Seven Rivers		3901					
Queen					4012		4074
Penrose sand							
Grayburg		4295					
San Andre	4510	4560	4513	4645	4675	4700	4813
Glorieta	5810	6045	5986	6172	6242	6240	6275
Yeso							
Paddock							
Clear Fork	6650						
Blinebry							
Tubb		7360	7300	7527	7604	7560	
Drinkard							7523
Abo (shelf)	7960	8053	7998	8210	8337	8295	8195
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp		9547	9342	9492	9900		9921
Permian-P	9595	9833				10550	
Bough "C"					10732		
Cisco							
Canyon					11090	11220	
Strawn				11115	11812	11475	
Atoka	11182	11583					12225
Morrow							
Mississippi	11510		11830				
Woodford	12190		12474				
Devonian	12298	12906	12603				
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite	Fullerton			3 Brothers Saunders		Hueco	

Table A4 (continued). Cross section C - C' Scoutcard data

	14s37e27	14s37e34	15s37e3	15s37e10	15s37e15	15s37e14	15s37e22
Lat	33.0754	33.0608	33.0463	33.0318	33.0173	33.0173	33.0028
Long	-103.1876	-103.1876	-103.1876	-103.1876	-103.1876	-103.1704	-103.1876
API	30025-26585						30025-30463
Elev	3820	3825	3814	3812	3812	3799	
Rustler	2156						2146
Anhydrite		2260	2160	2167	2130	2110	
X (salt)	2270						
B/Salt	2974						
Tansill							
Yates	3130		3050	3153	3110	3110	3276
Seven Rivers							
Queen							
Penrose sand							
Grayburg							
San Andres	4265	4693	4605	4686	4610	4665	4925
Glorieta	6156	6238	6105	6347	6400	6260	6378
Yeso							
Paddock							
Clear Fork						6789	
Blinebry							
Tubb	7346		7290	7463		7335	7684
Drinkard					7300		
Abo (shelf)	8052	8100	7970	8176	8205	8018	
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp	9358	9340	9110	9353		9120	9700
Permian-P	10635						
Bough "C"							
Cisco							
Canyon							
Strawn	11010						11715
Atoka							
Morrow							
Mississippi	11268	11143	11065	11714		11840	
Woodford		12465					
Devonian		12596	11940	12618		12480	
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite							

Table A4 (continued). Cross section C - C' Scoutcard data

	15s37e27	15s37e35	16s38e6	16s38e19	16s38e30	16s38e31	17s38e5
Lat	32.9883	32.9738	32.9543	32.9068	32.8923	32.8778	32.8633
Long	-103.1876	-103.1704	-103.1871	-103.1873	-103.1873	-103.1873	-103.1701
API				30025-33933		30025-23718	30025-24192
Elev	3780	3766	3784	3754	3769	3749	3742
Rustler	2138		2160				2115
Anhydrite		2180				2121	
X (salt)							
B/Salt						3208	
Tansill							
Yates	3242	3203	3315		3250	3332	3295
Seven Rivers					3565		
Queen	4084		4215		4170	4244	
Penrose sand							
Grayburg		4637					
San Andre	4490	4947		5084	5070	5123	5167
Glorieta		6467		6430	6500	6558	6502
Yeso			6725				
Paddock				7194			
Clear Fork		6997					
Blinebry							7015
Tubb	7722	7648	7955	8076	8070	8260	8250
Drinkard				8204			
Abo (shelf)	8415	8366	8670	8650		8797	9470
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp	9703	9565	9970	10220			
Permian-P	10904	10602	11240	11222			
Bough "C"							
Cisco							10286
Canyon							10760
Strawn				11788		11230	
Atoka	11948			12264	11515		
Morrow							11386
Mississippi	13100	11428		12790		11530	12192
Woodford	13880	12734			13025		12884
Devonian	14074	12844		14034	13075	12681	12950
Fusselman							
Silurian				14132			
Montoya							
Simpson							
McKee							
Ellenburger							
Granite	Chester Barnett	Bend Barnett	Chester				

Table A4 (continued). Cross section C - C' Scoutcard data

	17s38e8	17s38e17	17s38e20	17s38e32	18s38e5	18s38e7	18s38e17
Lat	32.8488	32.8343	32.8198	32.7908	32.7763	32.7618	32.7473
Long	-103.1701	-103.1701	-103.1701	-103.1701	-103.1701	-103.1873	-103.1701
API			30025-30150				
Elev	3727	3721		3698	3677	3693	3676
Rustler		2229	2248		1843	1695	1710
Anhydrite			2144				1650
X (salt)			2353				1740
B/Salt							2750
Tansill							
Yates	3473	3555	3410	3167	2940	2900	2815
Seven Rivers		3780	3783	3458	3183	3165	
Queen		4544	4455	4090	3750	3707	3620
Penrose sand							3889
Grayburg						4110	4048
San Andre	5308		5507	5330	4930	4470	
Glorieta	6860		6845		5752		5575
Yeso							
Paddock						5846	
Clear Fork							
Blinebry							
Tubb	8445				7497	6990	
Drinkard						7033	
Abo (shelf)				8188	7450		
Abo (reef)				8925			
Bone Spring							
Bone Spring 1		8360	8440				
Bone Spring 2		8616	8840				
Bone Spring 3		9112	9300				
Wolfcamp		9584					
Permian-Penn							
Bough "C"							
Cisco			10538				
Canyon							
Strawn		11182	11201				
Atoka			11304				
Morrow							
Mississippian							
Woodford	12812						
Devonian	12945						
Fusselman							
Silurian							
Montoya							
Simpson							
McKee							
Ellenburger							
Granite	Bend						
	Barnett						

Table A4 (continued). Cross section C - C' Scoutcard data

	18s38e2	18s38e29	18s38e3	19s38e5	19s38e8	19s38e1	19s38e1	19s38e29
Lat	32.7328	32.7183	32.7038	32.6893	32.6748	32.6603	32.6458	32.6313
Long	-103.17	-103.1701	-103.17	-103.1701	-103.17	-103.17	-103.19	-103.1701
API		30025-34644		30025-34946				30025-29846
Elev	3654	3646	3636	3609	3616	3605	3594	
Rustler		1553			1612			1670
Anhydrite		1462	1492					
X (salt)								1688
B/Salt						2740		2736
Tansill								
Yates	2636	2723	2670	2825	2988	2885	2900	2882
Seven Rive	2856			3061		2995	3139	3410
Queen	3366	3380	3402	3559	3600	3675	3217	3674
Penrose sand					3761	3818	3855	
Grayburg	3975	3722		3756	3966	4304	3995	4202
San Andre	4250	3989	4045	4015		4400	4265	4338
Glorieta		5343					5610	
Yeso								
Paddock								5950
Clear Fork								
Blinebry	5990		5746					6056
Tubb			6562					6600
Drinkard								6869
Abo (shelf)							7307	
Abo (reef)								
Bone Spring								
Bone Spring 1								
Bone Spring 2								
Bone Spring 3								
Wolfcamp								
Permian-Penn								
Bough "C"								
Cisco								
Canyon								
Strawn								
Atoka								
Morrow								
Mississippian								
Woodford								
Devonian								
Fusselman								
Silurian								
Montoya								
Simpson								
McKee								
Ellenburger								
Granite								

Table A4 (continued). Cross section C - C' Scoutcard data

	19s38e33	20s38e4	20s38e9	20s38e17	20s38e21	20s38e28
Lat	32.6168	32.6023	32.5878	32.5733	32.5588	32.5443
Long	-103.153	-103.153	-103.153	-103.1701	-103.153	-103.153
API	30025-27290	30025-27875	30025-27545	30025-07783-0001		30025-32521
Elev	3594	3583	3564	3573	3580	3535
Rustler	1611	1565	1555			
Anhydrite						
X (salt)	1648	1635	1635			
B/Salt	2670					
Tansill						
Yates	2814	2780	2780			2683
Seven Rivers						2944
Queen	3625	3482	3482			3513
Penrose sand						3664
Grayburg			4130			3838
San Andres		4186		4115	4349	4067
Glorieta	5515	5486	5486		5725	
Yeso						
Paddock						
Clear Fork				5880		
Blinebry		5986	6020			5823
Tubb		6508	6460	6350	6790	6315
Drinkard		6855	6914			6604
Abo (shelf)					7330	6912
Abo (reef)						
Bone Spring						
Bone Spring 1						
Bone Spring 2						
Bone Spring 3						
Wolfcamp						
Permian-Penn						
Bough "C"						
Cisco						
Canyon						
Strawn						
Atoka						
Morrow						
Mississippian						
Woodford					9040	
Devonian				7940	9210	
Fusselman						
Silurian				8215		
Montoya				8490		
Simpson						
McKee				9104		
Ellenburger						
Granite						

Table A4 (continued). Cross section C - C' Scoutcard data

	20s38e33	21s37e3	21s37e10	21s37e15	21s37e22	21s37e27
Lat	32.5298	32.5114	32.4943	32.4797	32.4652	32.4506
Long	-103.153	-103.1502	-103.1499	-103.1499	-103.1499	-103.1499
API	30025-27105	30025-06517	30025-34798	30025-06608	30025-34891	
Elev	3514	3439	3457	3431	3401	3425
Rustler	1410		1273		1220	
Anhydrite						1180
X (salt)	1500					
B/Salt						2360
Tansill	2570					
Yates	2610		2555		2518	2660
Seven Rive	2990					
Queen	3550					3334
Penrose sa	3695					
Grayburg	3880					
San Andre	4112		3754		3671	
Glorieta	5405	5118	5166	5112	5067	5060
Yeso						
Paddock			5251		5114	
Clear Fork		5654				
Blinebry	5777		5551		5452	
Tubb		6156	6128	6065	6030	
Drinkard		6502	6478	6394	6392	
Abo (shelf)		6788	6835		6682	6645
Abo (reef)						
Bone Spring						
Bone Spring 1						
Bone Spring 2						
Bone Spring 3						
Wolfcamp						
Permian-Penn						
Bough "C"						
Cisco						
Canyon						
Strawn						
Atoka						
Morrow						
Mississippian						
Woodford						
Devonian						
Fusselman						
Silurian						
Montoya		7395				
Simpson		7475		7310		7456
McKee		7775		7613		
Ellenburger		8128		8007		7615
Granite						

Table A4 (continued). Cross section C - C' Scoutcard data

	21s37e34	22s37e3	22s37e10	22s37e15	22s37e22	22s37e26
Lat	32.436	32.4215	32.4069	32.3923	32.3778	32.3632
Long	-103.1499	-103.1499	-103.1499	-103.1499	-103.1499	-103.1328
API	30025-34321	30025-10004	30025-33528	30025-28204	30025-34497-0001	
Elev	3441	3425	3382	3889	3346	3324
Rustler	1170		1090	1121		
Anhydrite						1115
X (salt)				1256		1205
B/Salt				2400		
Tansill						
Yates	2532	2570	2656	2587		2550
Seven Rivers			2730	2785		2810
Queen	3335	3334	3402	3340		3660
Penrose sand						
Grayburg	3610		3578	3646		
San Andre	3865	3895	3809	3900	3975	
Glorieta	5070	5060			5062	
Yeso						
Paddock			4968		5200	
Clear Fork		5500				
Blinebry	5530	5503	5369		5418	
Tubb	6006	5985	5801		6004	5935
Drinkard	6350	6290	6206		6383	
Abo (shelf)	6640	6570	6480		6820	
Abo (reef)						
Bone Spring						
Bone Spring 1						
Bone Spring 2						
Bone Spring 3						
Wolfcamp			7250			
Permian-Penn						
Bough "C"						
Cisco						
Canyon						
Strawn		7290				
Atoka						
Morrow						
Mississippian						
Woodford						
Devonian						
Fusselman						
Silurian						
Montoya					7218	
Simpson						
McKee						7366
Ellenburger		7350				7696
Granite						7740

Table A4 (continued). Cross section C - C' Scoutcard data

	22s37e35	23s37e2	23s37e11	23s37e22	23s37e23	23s37e26
Lat	32.3486	32.3341	32.3195	32.2904	32.2904	32.2758
Long	-103.1328	-103.1328	-103.1328	-103.1499	-103.1328	-103.1328
API	30025-24135	30025-28425	30025-23170	30025-33136	30025-34357	30025-32511
Elev	3319	3296	3262	3294	3261	3273
Rustler		1208		1022		
Anhydrite	1160					1100
X (salt)		1285				1250
B/Salt	2490	2506	2370			2330
Tansill						
Yates	2645		2522		2760	2530
Seven Rivers	2847				3011	
Queen	3420	3655			3372	
Penrose sand				3364		
Grayburg						3842
San Andres			3968	3774		4052
Glorieta	5167	5167		5338	5324	4930
Yeso						
Paddock				4935		5389
Clear Fork						
Blinebry		5553	5462	5280		5959
Tubb		6410	5985	5940		6350
Drinkard		6356	6128			6475
Abo (shelf)	6634	6634			6719	
Abo (reef)						
Bone Spring						
Bone Spring 1						
Bone Spring 2						
Bone Spring 3						
Wolfcamp						
Permian-Penn						
Bough "C"						
Cisco						
Canyon						
Strawn						
Atoka						
Morrow						
Mississippian					7630	7578
Woodford					7745	
Devonian					8117	8142
Fusselman					9505	
Silurian						
Montoya						9090
Simpson					10114	10188
McKee						10575
Ellenburger					10950	11020
Granite						

Table A4 (continued). Cross section C - C' Scoutcard data

	23s37e35	24s37e2	24s37e11	24s37e14	24s37e23	24s37e26
Lat	32.2612	32.2467	32.2321	32.2175	32.203	32.1884
Long	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328
API		42025-25941	30025-34768	30025-25607		30025-26074
Elev	3260	3368	3369	3341	3352	3324
Rustler		1210		1245		1215
Anhydrite				1245		950
X (salt)	1420		1370	1350	1340	1045
B/Salt	2829		2850	2755	2683	2210
Tansill		2965			2848	
Yates	2980	3095	2965	2920	3070	2370
Seven River	3195	3305	3185			
Queen	3565	3685				3106
Penrose sar	3482					
Grayburg			3820			
San Andres	3820				4600	
Glorieta				6180		4666
Yeso						
Paddock						
Clear Fork					6280	
Blinebry						
Tubb	5894					
Drinkard						
Abo (shelf)						
Abo (reef)						
Bone Spring						
Bone Spring 1						
Bone Spring 2						
Bone Spring 3						
Wolfcamp						
Permian-Penn						
Bough "C"						
Cisco						
Canyon						
Strawn						
Atoka						
Morrow						
Mississippian						
Woodford						
Devonian	7170					
Fusselman						
Silurian						
Montoya	8610					
Simpson	8962					
McKee	9360					
Ellenburger	10070					
Granite						

Table A4 (continued). Cross section C - C' Scoutcard data

	24s37e35	25s37e2	25s37e11	25s37e14	25s37e24	25s37e25	24s37e36
Lat	32.1738	32.1593	32.1447	32.1301	32.1156	32.101	32.1738
Long	-103.1328	-103.1328	-103.1328	-103.1328	-103.116	-103.116	-103.1157
API	30025-11362-0004		30025-27354	30025-32304			30025-32638
Elev	3156	3173	3143	3141	3079	3071	3046
Rustler			940				
Anhydrite				794	754		
X (salt)				896	904		
B/Salt				2127	2093		
Tansill		2198					
Yates		2400		2283	2277		
Seven Rivers		2772		2490			
Queen		3050					
Penrose sar	3199				3070	3107	
Grayburg			3334		3224	3269	
San Andres	3607						
Glorieta			4705			4790	
Yeso							
Paddock					4658		
Clear Fork					5101	5089	
Blinebry		5002		5090			5069
Tubb	5741	5737		5805	5624		5810
Drinkard	5950			5960			5937
Abo (shelf)							
Abo (reef)							
Bone Spring							
Bone Spring 1							
Bone Spring 2							
Bone Spring 3							
Wolfcamp							
Permian-Penn							
Bough "C"							
Cisco							
Canyon							
Strawn							
Atoka							
Morrow							
Mississippian							
Woodford							
Devonian							
Fusselman	6976	6894					
Silurian							
Montoya		7175					
Simpson		7622					
McKee	7783	7986					
Ellenburger	8372	8444					
Granite							

Table A5. Cross section A - A' data

	18s25e13	18s26e18	18s26e17	18s26e16	18s26e15	18s26e14	18s26e11	18s26e12	18s27e7	18s27e8
Lat	32.7473	32.7473	32.7473	32.7473	32.7473	32.7473	32.7618	32.7618	32.7618	32.7618
Long	-104.4388	-104.4216	-104.4045	-104.3873	-104.3702	-104.353	-104.353	-104.3359	-104.3188	-104.3016
API	30015-20471		30015-27028				30015-20739	30015-20931	30015-21528	30015-21114
Elev	3445	3412	3420		3352	3342	3319	3291	3300	3388
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan										
Artesia										
Leonard	2157	2190	2218	2260	2298	2290	2280	2330	2177	3097
Wolfcamp	5628	5595	5578	5690	5790	5890	5865	5917	5970	6143
Pennsylvar	6980	6970	7100	7190	7050	6952	7760	7787	7130	7202
Mississippi	8796	8820	8960	9075	9170	9272	9250	9260	9218	9354
Devonian						9916				
Silurian										
Ordovician						10369				

	18s27e11	18s27e12	18s28e6	18s28e5	18s28e4	18s28e3	18s28e2	18s28e1	18s29e6	18s29e5
Lat	32.7618	32.7618	32.7763	32.7763	32.7763	32.7763	32.7763	32.7763	32.7763	32.7763
Long	-104.2502	-104.233	-104.2159	-104.1988	-104.1816	-104.1645	-104.1473	-104.1302	-104.114	-104.0968
API	30015-20510	30015-20894	3001521395	7972		30015-30002	30015-24655	30015-25002	30015-20492	30015-21947
Elev	3587	3607	3644	3649		3648	3646	3665	3643	3567
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan										
Artesia				414	464	794	760	955	950	960
Leonard	3200	3300	3463	3665	3800	4000	4292	4321	4333	4368
Wolfcamp	6405	6745	6800	6860	6950	7090	7120	7300	7500	7860
Pennsylvar	7745	7645	7800	7900	8000	8200	8573	8680	8750	8900
Mississippi	9960	10000	10200	10350	10500	10600	10798	11100	11260	10980
Devonian									11781	
Silurian										
Ordovician										

Table A5 (continued). Cross section A - A' data

			18s27e9	18s27e10	17s29e35	17s29e36	17s30e31	17s30e32	17s30e33	17s30e34
Lat	17s29e33	17s29e34	32.7618	32.7618	32.7908	32.7908	32.7908	32.7908	32.7908	32.7908
Long	32.7908	32.7908	-103.2559	-104.2673	-104.0453	-104.0282	-104.011	-103.9939	-103.9767	-103.9595
API	-104.0797	-104.0625	30015-20523			30015-29985	30015-23213	30015-28960	30015-22664	30015-23998
Elev	30015-21556	30015-23034	3498	3531	3545	3558	3582	3555	3616	3550
	3534	3531								
Surface			0	0	0	0	0	0	0	0
Ochoan	0	0								
Artesia					1050	1100	1180	1230	1335	1430
Leonard	980	1002	2900	3100	4412	4623	4632	4759	4766	4855
Wolfcamp	4399	4420	6200	6300	7915	7938	8160	8300	8500	8667
Pennsylvar	7885	7900	7450	7600		9300				9649
Mississippian			9600	9700		11157	11300	11628	11500	11450
Devonian										
Silurian										
Ordovician										

	17s30e35	17s30e36	17s30e26	17s30e25	17s31e30	17s31e29	17s31e28	17s31e27	17s31e26	17s31e25
Lat	32.7908	32.7908	32.8053	32.8053	32.8053	32.8053	32.8053	32.8053	32.8053	32.8053
Long	-103.9424	-103.9252	-103.9424	-103.9252	-103.908	-103.8909	-103.8737	-103.8566	-103.8394	-103.8222
API	30015-26969	8037		30015-29476	30015-29530	30015-28142	30015-28140	30025-26233		30015-26067
Elev	3548	3654	3600	3568	3646	3753	3788	4145	3840	3869
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan				317	297	400	665	700	710	720
Artesia	1532	1638	1600	1443	1633	1700	1850	1874	1855	1900
Leonard	4978	5045	5190	5375	5355	5380	5390	5400	5415	5432
Wolfcamp	8200	8359	8100	7946	8000	8038	8088			
Pennsylvanian		9446				9680				
Mississippi	11428	11798	11500	11340	11600	11766	11903			
Devonian	12086									
Silurian	12310									
Ordovician										

Table A5 (continued). Cross section A - A' data

	17s32e19	17s32e20	17s32e21	17s32e22	17s32e23	17s32e24	17s33e19	17s33e20	17s33e16	17s33e15
Lat	32.8198	32.8198	32.8198	32.8198	32.8198	32.8198	32.8198	32.8198	32.8343	32.8343
Long	-103.8051	-103.7879	-103.7708	-103.7536	-103.7364	-103.7193	-103.7021	-103.685	-103.6678	-103.6506
API		30025-33584			14411	30025-33423	30-025-3308	30025-24446	14557	30025-24543
Elev	3941	4007	4027	4023	4086	4082	4105	4201	4189	4174
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan	613	750	810	900	1000	1180	1162	1340	1400	1477
Artesia	1952	1970	1983	2145	2392	2450	2500	2700	2748	2778
Leonard	5410	5390	5350	5375	5431	5682	5833	5989	6008	6010
Wolfcamp	8994	8890	9048	9061					9720	
Pennsylvanian			10373	9983						
Mississippi	12574	12550	12510						13680	
Devonian	13770	13600	13504						14800	
Silurian										
Ordovician										

	17s33e14	17s33e13	17s34e18	17s34e17	17s34e9	17s34e10	17s34e11	17s34e12	17s35e7	17s35e8
Lat	32.8343	32.8343	32.8343	32.8343	32.8488	32.8488	32.8488	32.8488	32.8488	32.8488
Long	-103.6335	-103.6163	-103.5991	-103.582	-103.5648	-103.5477	-103.5305	-103.5133	-103.4962	-103.479
API	30025-24206	30025-25437	30025-25256	30025-252	14943	14947	14961	30025-23638	30025-25328	30025-24281
Elev	4156	4130	4108	4086	4083	4051	4039	4037	4014	3984
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan	1483	1502	1550	1560	1600	1653	1652	1700	1780	1870
Artesia	2782	2795	2833	2850	2891	2896	2900	2920	3095	3150
Leonard	6020	6050	6086	6096	6095	6094	6070	6110	6253	6270
Wolfcamp	9720		10080	10080	9967	9912	9902	9912	9824	9800
Pennsylvar	10320		10846	10720						
Mississippian			13438	13352						
Devonian										
Silurian										
Ordovician										

Table A5 (continued). Cross section A - A' data

	17s35e9 (no	17s35e6	17s35e5	17s35e3	17s35e2	17s35e1	17s36e6	17s36e5	16s36e33	16s36e34	16s36e35
Lat	32.8488	32.8633	32.8633	32.8633	32.8633	32.8633	32.8633	32.8633	32.8778	32.8778	32.8778
Long	-103.4619	-103.4962	-103.479	-103.4447	-103.4275	-103.4104	-103.3932	-103.3761	-103.359	-103.3417	-103.3246
API	15222	30025-29703	30025-31458-0000		15205	30025-29546	30025-33934	30025-2881			14065
Elev	3983			3960	3952		3954	3948			3854
Surface	0	0	0	0	0	0	0	0	0	0	0
Ochoan	1895	1974	1980	2000	1990	1999	1950	1880	1900	1980	2040
Artesia	3150	3132	3200	3253	3225	3206	3160	3085	3080	3090	3087
Leonard	6400	6179	6350	6496	6456	6500	6760	6213	6150	6090	6015
Wolfcamp	9760	9348	9700	9890	10324	9818	9692	10031			
Pennsylvanian					10792	10782	11060				
Mississippian		11611		12864		11634					
Devonian		12677				12426					
Silurian											
Ordovician		14602									

	16s36e36	16s37e31	16s37e32	16s37e33	16s37e27	16s37e26	16s37e25	16s38e30	16s38e29	16s38e28
Lat	32.8778	32.8778	32.8778	32.8778	32.8923	32.8923	32.8923	32.8923	32.8923	32.8923
Long	-103.3074	-103.2902	-103.2731	-103.2559	-103.2388	-103.2216	-103.2044	-103.1873	-103.17	-103.153
API	30025-31066	14159	30025-05387	30025-27927	30025-24876	30025-27691	30025-23908	14224	14223	30025-24039
Elev		3823	3799	3778	3776	3771	3757	3769	3752	3716
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan	2010	2000	2031	2084	2100	2090	2105	2100	2083	2040
Artesia	3105	3070	3088	3102	3150	3180	3290	3250	3210	3150
Leonard	6000	5995	6100	6130	6244	6285	6445	6500	6463	6310
Wolfcamp				10097						
Pennsylvanian			10597	10818						
Mississippian			11604		12372					
Devonian			12370					13025		
Silurian										
Ordovician										

Table A6. Cross section B - B' data

	9s33e18	9s33e19	9s33e30	10s33e6	10s33e19	10s33e30	10s33e31	11s33e3	11s33e10	11s33e15	11s33e22	11s33e27
Lat	33.5336	33.5192	33.5048	33.476	33.4328	33.4185	33.4041	33.3946	33.3801	33.3656	33.3511	33.3366
Long	-103.6076	-103.6076	-103.6076	-103.6076	-103.6076	-103.6076	-103.6076	-103.6014	-103.6014	-103.6014	-103.6014	-103.6014
API												
Elev	4407	4394	4631		4212	4270	4247	4275		4273	4258	4264
Surface	0	0	0	0	0	0	0	0	0	0	0	0
Ochoan	1847	1736	1808	1750	1732	1740	1756	1835	1740	1673	1610	1740
Artesia	2437	2380	2356	2333	2413	2472	2443	2490	2487	2477	2465	2470
Reef												
Basin												
Leonard	5072	5030	5030	5050	5073	5100	5137	5145	5153	5140	5120	5140
Wolfcamp	8516	8335	8446	8450	8487	8678	8550	8818	8700	8620	9412	8479
Pennsylvanian			9088			9292		9215	9089		9006	
Mississippian												
Devonian							11905					11012
Silurian												
Ordovician												
Granite												

Table A6 (continued). Cross section B - B' data

	11s33e34	12s33e3	12s33e15	13s33e21	13s33e21	13s33e28	13s33e28	13s33e33	13s33e33	14s33e4	14s33e4	14s33e9
Lat	33.322	33.3075	33.2785	33.1769	33.1769	33.1624	33.1624	33.1479	33.1479	33.1334	33.1334	33.1189
Long	-103.6014	-103.6014	-103.6014	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187
API											3002528082	
Elev	4272	4258	4260	4263	4270	4248	4255	4256	4251	4238	4241	4240
Surface	0	0	0	0		0		0		0		0
Ochoan	1663	1643	1662	1660	1648	1702	1687	1690		1676	1690	1645
Artesia	2455	2444	2475	2550	2560	2548	2551	2596		2605	2600	2647
Reef												
Basin												
Leonard	5150	5160	5170	5415	5410	5420	5362	5470	5468	5500		5555
Wolfcamp	8415	8395	8500	9025	9020	9047	9038	9200	9070	9268	9250	9300
Pennsylvar	8638	8963			9612	9512	9500	9845	9546		9854	9810
Mississippian												
Devonian												
Silurian												
Ordovician												
Granite												

Table A6 (continued). Cross section B - B' data

	14s33e9	14s33e16	14s33e16	14s33e21	14s33e21	14s33e28	14s33e28	14s33e33	14s33e33	15s33e4	15s33e4	15s33e9
Lat	33.1189	33.1044	33.1044	33.0899	33.0899	33.0754	33.0754	33.0608	33.0608	33.0463	33.0463	33.0318
Long	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187	-103.6187
API	12816		30025-28214		30025-27942		30025-27942		13903		30025-26611	
Elev	4243	4231	4223	4232		4219	4219	4214	4212	4211	4195	4188
Surface		0		0		0		0		0		0
Ochoan		1642	1657	1600	1702	1541	1702	1514	1506	1503	1529	1525
Artesia		2635		2656	2650	2626		2608	2613	2622	2680	2678
Reef												
Basin												
Leonard	5550	5555	5553	5600		5632		5650	5650	5700	5724	5780
Wolfcamp		9725	8855	9100	9112	9078	9112	9080	9363	9077	9106	9185
Pennsylvar	9856		9320			9361		9363		9355	9392	
Mississippian												
Devonian												
Silurian												
Ordovician												
Granite												

Table A6 (continued). Cross section B - B' data

	15s33e16	15s33e22	15s33e28	16s33e1	16s33e11	16s33e14	16s33e22	16s33e26	13s33e35	17s33e2	17s33e11
Lat	33.0173	33.0028	32.9883	32.9543	32.9358	32.9213	32.9068	32.8923	33.1479	32.8633	32.8488
Long	-103.6187	-103.6014	-103.6187	-103.6163	-103.6335	-103.6335	-103.6506	-103.6335	-103.5842	-103.6335	-103.6335
API					3002328648				3002528630	3002524386	3002525288
Elev	4202	4179	4214	4182	4188	4177	4191	4184	4169	4180	4138
Surface	0	0	0	0	0	0	0	0	0	0	0
Ochoan	1460	1492	1500	1517	1500	1510	1481	1490	1493	1510	1500
Artesia	2627	2645	2693	2743	2780	2795	2741	2794	2815	2815	2760
Reef											
Basin											
Leonard	5800	5840	5850	5890	5950	5940	5929	5950	5930	5950	5970
Wolfcamp	9240	9320	9500	9782	9560	9600	9650	9710	10110	10090	10000
Pennsylvanian		10150			10510						
Mississippian											
Devonian	13745			14132							
Silurian											
Ordovician											
Granite											

Table A6 (continued). Cross section B - B' data

	17s33e14	17s33e14	17s33e23	17s33e26	17s33e26	17s33e35	18s33e2	18s33e23	18s33e26	18s33e35	19s33e2
Lat	32.8343	32.8343	32.8198	32.8053	32.8053	32.7908	32.7763	32.7328	32.7183	32.7038	32.6893
Long	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335
API	3002525230	30025-24206		3002527764	14610	3002532733			3002524475		
Elev	4123	4156	4158	4282	4148	4133	4131	3987	3794	3827	3767
Surface	0		0	0		0	0	0	0	0	0
Ochoan	1490	1482	1483	1500	1484	1550	1640	1585	1560	1540	1520
Artesia	2762	2782	2803	2764	2828	2800	3015	3090	3038	3320	3315
Reef											
Basin							5208	5340	5400	5450	5600
Leonard	5985	6020	6055	5881	6084	6225	6725				
Wolfcamp	9900	9720	9805		9860						10608
Pennsylvanian		10320			11330						
Mississippian											
Devonian			14960								14036
Silurian											14639
Ordovician			16147								
Granite											

Table A6 (continued). Cross section B - B' data

	19s33e11	19s33e14	19s33e23	19s33e26	19s33e35	20s33e2	20s33e11	20s33e14	20s33e22	20s33e28
Lat	32.6748	32.6603	32.6458	32.6313	32.6168	32.6023	32.5878	32.5733	32.5588	32.5443
Long	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6335	-103.6506	-103.6678
API	30025-30118	30025-32092	30025-30510	30025-26440	30025-34749	30025-34841				30025-34404
Elev	3730	3665		3596	3586	3606	3578	3601	3595	3623
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan	1480	1440	1400	1390	1360	1340	1318	1300	1293	
Artesia	3310	3300	3365	3053	3200	3254	3225	3205	3400	3390
Reef				3472						
Basin	5400	5930	5380	5324	5300	5282	5270	5300	5325	5228
Leonard										
Wolfcamp	10764	10820	10969	10808	10970	11000	11070	11200	11250	11430
Pennsylvanian										
Mississippian										13820
Devonian										
Silurian										
Ordovician										
Granite										

Table A6 (continued). Cross section B - B' data

	20s33e34	21s32e2	21s32e11	21s32e14	24s32e22	24s32e27	24s32e28	24s32e34	25s32e3	25s32e22	25s32e27
Lat	32.5298	32.5114	32.4943	32.4797	32.203	32.1884	32.1884	32.1738	32.1593	32.1156	32.101
Long	-103.6506	-103.6463	-103.6463	-103.6463	-103.6634	-103.6634	-103.6805	-103.6634	-103.6634	-103.6634	-103.6634
API	30025-34302	30025-24690		30025-33999		30025-28654					
Elev	3646	3771	3813	3885				3512	3487	3411	3390
Surface	0	0	0	0							
Ochoan			1552		1088			883	800	750	755
Artesia	3400	3450	3350	3515				4520	4518	4380	4384
Reef				3670	4596						
Basin	5832	5543	5555	5536	4867	4832	4717	4775	4746	4628	4606
Leonard											
Wolfcamp	11716	11630	11314	11842							
Pennsylvanian											
Mississippian		14491	14530	14736							
Devonian			14340								
Silurian											
Ordovician											
Granite											

Table A7. Cross section C - C' data

	9S36E2	9s36e11	9s36e15	9s36e23	9s36e26	9s36e35	10S36e2	10s36e10	10s36e14	10s36e24	10s36e35	11s37e3
Lat	33.5624	33.548	33.5336	33.5192	33.5048	33.4904	33.476	33.4616	33.4472	33.4328	33.4041	33.3946
Long	-103.2269	-103.2269	-103.2442	-103.2269	-103.2269	-103.2269	-103.2269	-103.2442	-103.2269	-103.2095	-103.2269	-103.1876
API										3002526160	3002524809	
Elev	4062	4070	4060	4036	4026	4028		4026	4010	3972	3987	3958
Surface	0	0	0	0	0	0	0	0	0	0	0	0
Ochoan	2232	2221	2210	2226	2250	2230	2210	2197	2234	2205	2187	2210
Artesia	2804	2830	2850	2848	2862	2850	2856	2867	2924	2929	2881	2970
Leonard	5518	5548	5555	5566	5576	5555	5500	5595	5639	5670	5683	5700
Wolfcamp	8947	9018	8940	8918	8940	8980	8986	9005	9030	9100	9140	8910
Pennsylvar	9673	9705	9695	9659	9677	9700	9710	9712	9750	9775	9900	9280
Mississippian				11658	11760	11718	11730	11740	11622	11620	11610	11604
Devonian				12070	12180	12193	12200	12222	12275			
Silurian												
Ordovician												
Granite												

	11s37e8	11s37e17	11s37e23	11s37e29	12s37e2	12s37e4	12s37e21	12s37e29	12s37e34	13s37e2	13s37e3	13s37e10
Lat	33.3801	33.3656	33.3511	33.3366	33.3075	33.3075	33.264	33.2495	33.235	33.2205	33.2205	33.206
Long	-103.2221	-103.2221	-103.1704	-103.2221	-103.1704	-103.2049	-103.2049	-103.2221	-103.1876	-103.1704	-103.1876	-103.1876
API	3E+09						30025-24728			30025-24825	30025-24200	
Elev		3960	3931	3968		3946	3925	3930	3905	3873		3888
Surface	0	0	0	0	0	0	0	0	0	0	0	0
Ochoan	2220	2221	2249	2330	2275	2225	2230	2245	2240	2220	2244	2194
Artesia	2976	2990	3013	3020	3030	3055	3070	3070	3080	3112	3153	3070
Leonard	5750	5775	5800	5845	5895	5926	5940	5964	5922	5810	6045	5986
Wolfcamp	9118	9178	9210	9262	9265	9334	9252	9350	9380	9460	9547	9342
Pennsylvar	10675									9595	9833	9900
Mississippi	11950	11900	11754	12213	12057	12155	11990	12544	11480	11510		11830
Devonian	12600		12360	12913	12836	13130	12706	13220	12184	12190		12474
Silurian												
Ordovician												
Granite												

Table A7 (continued). Cross section C - C' data

	13s37e22	13s37e32	14s37e5	14s37e11	14s37e27	14s37e34	15s37e3	15s37e10	15s37e15	15s37e14	15s37e22
Lat	33.1769	33.1479	33.1334	33.1189	33.0754	33.0608	33.0463	33.0318	33.0173	33.0173	33.0028
Long	-103.1876	-103.2221	-103.2221	-103.1704	-103.1876	-103.1876	-103.1876	-103.1876	-103.1876	-103.1704	-103.1876
API	30025-25987				30025-26585						30025-30463
Elev		3899	3881	3831	3820	3825	3814	3812	3812	3799	
Surface	0	0	0	0	0	0	0	0	0	0	0
Ochoan	2227	2210	2192	2175	2156	2260	2160	2167	2130	2110	2146
Artesia	3183	3200	3218	3254	3130	3100	3050	3153	3110	3110	3276
Leonard	6172	6242	6240	6275	6156	6238	6105	6347	6400	6260	6378
Wolfcamp	9492	9900	9910	9921	9358	9340	9110	9353	9200	9120	9700
Pennsylvania	10000	10300	10550	10600	10635						
Mississippian					11268	11143	11065	11714		11840	
Devonian						12465					
Silurian											
Ordovician											
Granite											

	15s37e27	15s37e35	16s38e6	16s38e19	16s38e30	16s38e31	17s38e5	17s38e8	17s38e17	17s38e20	17s38e32
Lat	32.9883	32.9738	32.9543	32.9068	32.8923	32.8778	32.8633	32.8488	32.8343	32.8198	32.7908
Long	-103.1876	-103.1704	-103.1871	-103.1873	-103.1873	-103.1873	-103.1701	-103.1701	-103.1701	-103.1701	-103.1701
API				30025-33933		30025-237	30025-24192			30025-30150	
Elev	3780	3766	3784	3754	3769	3749	3742	3727	3721		3698
Surface	0	0	0	0	0	0	0	0	0	0	0
Ochoan	2138	2180	2160	2140	2130	2121	2115	2160	2229	2144	1950
Artesia	3242	3203	3315	3295	3250	3332	3295	3473	3555	3410	3167
Leonard	6430	6467	6440	6430	6500	6558	6502	6860	6850	6845	
Wolfcamp	9703	9565	9970	10220					9584		
Pennsylvania	10904	10602	11240	11222							
Mississippian	13100	11428		12790		11530	12192				
Devonian	13880	12734			13025		12884	12812			
Silurian											
Ordovician											
Granite											

Table A7 (continued). Cross section C - C' data

	18s38e5	18s38e7	18s38e17	18s38e20	18s38e29	18s38e32	19s38e5	19s38e8	19s38e17	19s38e19	19s38e29
Lat	32.7763	32.7618	32.7473	32.7328	32.7183	32.7038	32.6893	32.6748	32.6603	32.6458	32.6313
Long	-103.1701	-103.1873	-103.1701	-103.1701	-103.1701	-103.1701	-103.1701	-103.1701	-103.1701	-103.1873	-103.1701
API					30025-34644		30025-34946				30023-29846
Elev	3677	3693	3676	3654	3646	3636	3609	3616	3605	3594	

Surface	0	0	0	0	0	0	0	0	0	0	0
Ochoan	1843	1695	1650	1575	1462	1492	1560	1612	1620	1650	1670
Artesia	2940	2900	2815	2636	2723	2670	2825	2988	2885	2900	2882
Leonard	5752	5620	5575	5400	5343	5400	5480	5500	5540	5610	5580
Wolfcamp											
Pennsylvanian											
Mississippian											
Devonian											
Silurian											
Ordovician											
Granite											

	19s38e33	20s38e4	20s38e9	20s38e17	20s38e21	20s38e28	20s38e33	21s37e3	21s37e10	21s37e15	21s37e22
Lat	32.6168	32.6023	32.5878	32.5733	32.5588	32.5443	32.5298	32.5114	32.4943	32.4797	32.4652
Long	-103.153	-103.153	-103.153	-103.1701	-103.153	-103.153	-103.153	-103.1502	-103.1499	-103.1499	-103.1499
API	30025-272	30025-278	30025-275	30025-07783-0001		30025-325	30025-27105	30025-065	30025-347	30025-066	30025-34891
Elev	3594	3583	3564	3573	3580	3535	3514	3439	3457	3431	3401

Surface	0	0	0	0	0	0	0	0	0	0	0
Ochoan	1611	1565	1555	1530	1470	1430	1410	1350	1273	1250	1220
Artesia	2814	2780	2780	2730	2700	2683	2610	2575	2555	2530	2518
Leonard	5515	5486	5486	5500	5725	5600	5405	5118	5166	5112	5067
Wolfcamp											
Pennsylvanian											
Mississippian											
Devonian					9040						
Silurian											
Ordovician				8490				7395			
Granite											

Table A7 (continued). Cross section C - C' data

	21s37e27	21s37e34	22s37e3	22s37e10	22s37e15	22s37e22	22s37e26	22s37e35	23s37e2	23s37e11
Lat	32.4506	32.436	32.4215	32.4069	32.3923	32.3778	32.3632	32.3486	32.3341	32.3195
Long	-103.1499	-103.1499	-103.1499	-103.1499	-103.1499	-103.1499	-103.1328	-103.1328	-103.1328	-103.1328
API		30025-34321	30025-10004	30025-335	30025-28204	30025-34497-0001		30025-24135	30025-28425	30025-23170
Elev	3425	3441	3425	3382	3889	3346	3324	3319	3296	3262
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan	1180	1170	1100	1090	1121	1120	1115	1160	1208	1100
Artesia	2660	2532	2570	2656	2587	2570	2550	2645	2570	2522
Leonard	5060	5070	5060	5070	5076	5062	5090	5167	5167	5200
Wolfcamp				7250						
Pennsylvanian										
Mississippian										
Devonian										
Silurian										
Ordovician						7218				
Granite							7740			

	23s37e22	23s37e23	23s37e26	23s37e35	24s37e2	24s37e11	24s37e14	24s37e23	24s37e26	24s37e35
Lat	32.2904	32.2904	32.2758	32.2612	32.2467	32.2321	32.2175	32.203	32.1884	32.1738
Long	-103.1499	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328	-103.1328
API	30025-33136	30025-34357	30025-32511		42025-25941	30025-34768	30025-25607		30025-26074	30025-11362
Elev	3294	3261	3273	3260	3368	3369	3341	3352	3324	3156
Surface	0	0	0	0	0	0	0	0	0	0
Ochoan	1022	1070	1100	1150	1210	1230	1245	1100	950	948
Artesia	2595	2760	2530	2980	3095	2965	2920	3070	2370	2380
Leonard	5338	5324	4930				6180		4666	4670
Wolfcamp										
Pennsylvanian										
Mississippian		7630	7578							
Devonian		7745								
Silurian										
Ordovician			9090	8610						
Granite										

Table A7 (continued). Cross section C - C' data

	25s37e2	25s37e11	25s37e14	25s37e24	25s37e25	24s37e36
Lat	32.1593	32.1447	32.1301	32.1156	32.101	32.1738
Long	-103.1328	-103.1328	-103.1328	-103.1157	-103.1157	-103.1157
API		30025-27354	30025-32304			30025-32638
Elev	3173	3143	3141	3079	3071	3046

Surface	0	0	0	0	0	0
Ochoan	945	940	794	754		
Artesia	2400	2350	2283	2277		
Leonard	4680	4705	4740	4763	4790	
Wolfcamp						
Pennsylvanian						
Mississippian						
Devonian						
Silurian						
Ordovician	7175					
Granite						

Appendix B: Permeability data

The original permeability data is in Table B1. Columns in this table include field, whether the well was oil or gas, formation or play, township, range, date of reference, and permeability data, including general high, low, and average, horizontal high and low, and vertical high and low. Table B2 contains the modified data, with the last column used to make the boxplots found in Figure 13 (page 38). Columns again include field, whether the well was oil or gas, formation or play, township, range, and date of reference in order to correlate the data with Table B1. Permeability columns include (general) high, low, and average; for those with no average value, the next columns have a log average and linear average, and the last column has the measured average permeability if available, or log average permeability if not. Figure B1 shows a comparison between the log average and linear average for those data where a high, low, and average measurement was available.

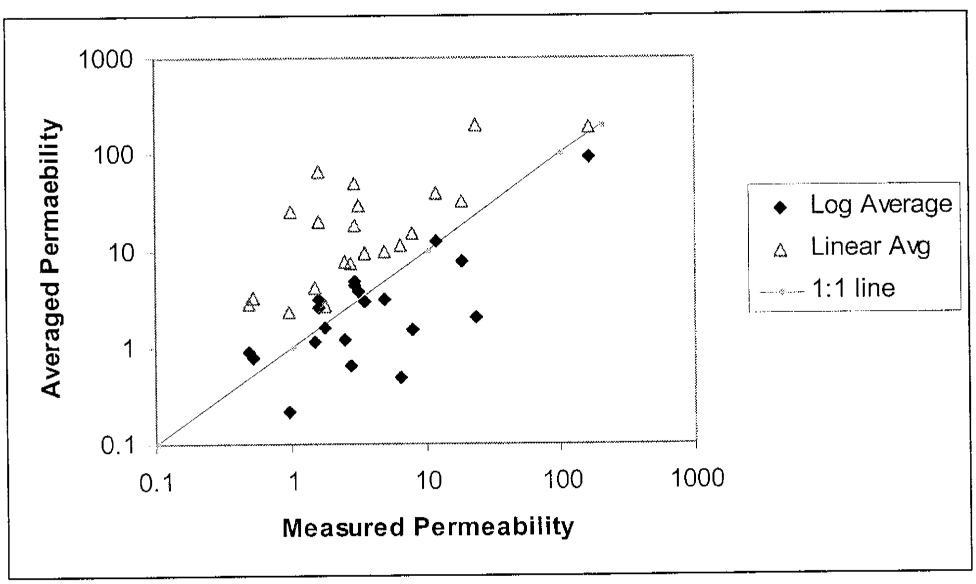


Figure B1. Plot of measured average permeability versus log averaged and linearly averaged permeability. Those points which lie on the 1:1 line are good estimates of the actual average permeability values.

Table B1. Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Baish		Yates	17s	32e	1956				60			
North Hackberry Yates		Yates	19s	31e	1960				1.1			
Lea Yates		Yates	20s	34e	1960				13			
Russell		Yates	20s	28e	1956				30.5		6.8	
San Simon		Yates	21+22s	35e	1960				5.3			
Tonto South		Yates	19s	33e	1967			16				
Jalmat		Yates-Seven Rivers	21-26s	35-37e	1956				1.8			
Scarborough		Yates-Seven Rivers	26s	36+37e	1967			4.6				
Rhodes	Gas	Yates-Seven Rivers	26s	37e	1988	0.1	8					
Teas West		Yates-Seven Rivers	20s	33e	1967	6	60					
West Teas Yates		Yates-Seven Rivers	20s	33e	1960				6	60		
Bowers		Seven Rivers	18+19s	37+38e	1956				36.5			
Tonto West		Seven Rivers	19s	32+33e	1967			17				
Brown Queen		Queen	10s	26e	1960				30			
Bunker Hill Penrose (Associated)		Queen	16s	31e	1988			0.21				
Chaves Queen, southeast	Oil	Queen	12+13s	31e	1988			25				
Coyote Queen		Queen	11s	27e	1960				13			
Culwin Queen		Queen	18+19s	30+31e	1960				3.8			
Double L Queen Associated		Queen	14+15s	29+30e	1976			121				
E.K.		Queen	18s	33e	1956				31			
High Lonesone		Queen	16s	29e	1956				13.75			
High Lonesone		Queen	16s	29e	1960				13.75			
Hume		Queen	16s	34e	1960				5.6			
High Lonesome	Oil	Queen	16s	29e	1988			14				
Maljamar	Gas	Queen	17s	32e	1960			15.8				
Pearl		Queen	19s	35e	1956				2	62		
Mesa		Queen	16s	32e	1967			100				
Pearsall		Queen	17+18s	32e	1956				21			
Pearl		Queen	19s	35e	1960				2	62		
Querecho Plains		Queen	18s	32e	1976			10				
Round Tank		Queen	15s	28+29e	1976			200				
Sanmal	Oil	Queen	17s	33e	1988			87.6				
Vacuum Queen	Gas	Queen	17s	34e	1960				5.6			
Caprock		Queen	12,13,14,15S	31+32e	1956				250		150	

Table B1 (continued.) Original Permeability Data

Field	Oil or Gas	Formation	Location Township	Range	Date (Source)	Permeability High	Permeability Low	Average	Horiz High	Horiz Low	Vert High	Vert Low
Benson Queen-Grayburg North		Queen-Grayburg	18s	30e	1967	0.5	19	5				
Skaggs		Queen-Grayburg	20s	37+38e	1956				7			
Cave Grayburg		Grayburg	16+17s	29e	1960				1.5	149		
Dayton		Grayburg	18s	26e	1956				4			
Dog Canyon Grayburg		Grayburg	16s	27e	1960				18			
Dayton		Grayburg	18s	26e	1956				4			
Roberts		Grayburg	17s	32+33e	1956				9.3			
Roberts		Grayburg	17s	32+33e	1960				9.3			
Artesia Queen Grayburg San Andres		Grayburg-San Andres	17+18s	27+28e	1956				90			
Cave Grayburg San Andres	Oil	Grayburg-San Andres	16+17s	28+29e	1988	1.5	150					
Hobbs		Grayburg-San Andres	18+19s	37+38e	1956				50			
Loco Hills		Grayburg-San Andres	17+18s	29+30e	1956				49.9			
Maljamar		Grayburg-San Andres	17+18s	31+32+33e	1956				47			
Red Lake		Grayburg-San Andres	17+18s	27+28e	1956				2		2	
Square Lake		Grayburg-San Andres	16+17s	30+31e	1956				110			
Vacuum		Grayburg-San Andres	17+18s	33+34+35e	1956				404.5		374.5	
Acme San Andres		San Andres	7+8s	27e	1960				12.3		9.5	
Arkansas Junction		San Andres	18s	36e	1976			0.2				
Acme San Andres, Southeast		San Andres	8s	27e	1995	0.01	392	24				
Bitter Lake		San Andres	10s	25e	1960				2.5			
Bitter Lakes, South and West		San Andres	10s	25e	1967			2.5				
Button Mesa San Andres		San Andres	8s	32e	1960				2.4			
Bluitt San Andres Assiciated		San Andres	8s	37+38e	1976			5				
Crossroads Slaughter San Andres		San Andres	9s	36e	1960				2.5		1.6	
Crossroads San Andres West		San Andres	9s	35e	1960				0.1	58	0.1	5.2
Cato San Andres		San Andres	8s	30e	1967	0.1	1.5					
Chaveroo		San Andres	7+8s	34+33e	1967			0.7				
Cato		San Andres	7+8+9s	30e	1976	5	40					
Eagle Creek		San Andres	17s	25e	1976			0.4				
E.K.		San Andres	18s	33e	1956				6.4			
Flying M		San Andres	9s	33e	1967			7.5				
Grayburg Keely		San Andres	17s	29e	1956				0.1	5.8	0.1	8.7
Foster		San Andres	19s	39e	1960						6.5	
Hobbs east		San Andres	18s	39e	1956				500	300		

Table B1 (continued.) Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Lakewood		San Andres	19s	26e	1960						0.1	
Linda		San Andres	6+7s	26e	1967			2				
Milnesand		San Andres	8s	34e (roosev	1960				0.4			
Mescalero		San Andres	10s	32e	1967	0.1	150					
Milnesand		San Andres	8s	34+35e (roo	1967			0.1				
Pecos San Andres		San Andres	7s	26e	1967			2				
Sawyer		San Andres	9s	37+38e	1956				1.7			
Sawyer		San Andres	9s	37+38e	1960				5.9			
Sawyer		San Andres	9s	37+38e	1967			5.9				
West Sawyer		San Andres	9+10s	37e	1976			0.89				
Siete		San Andres	8s	31e	1976			1.5				
Spencer		San Andres	17s	36e	1976	15	25					
Tom-Tom		San Andres	7+8s	31e	1976	1	2					
Sulfate Delaware Southwest		Bell Canyon	25s	26e	1988			20				
Welch Delaware		Bell Canyon	26s	27e	1960				28			
Nash Draw Brushy Canyon		Brushy Canyon	23s	29+30e	1995	0.5	18	3.5				
Parkway Delaware		Brushy Canyon	19+20s	29+30e	1995	0.16	8.1	1.5				
Red Tank West		Brushy Canyon	22s	32e	1995	0.01	23	6.5				
Willow Lake Delaware		Brushy Canyon	24+25s	28+29e	1995	0.15	5.5	0.5				
Bradley Delaware		Delaware	26s	34e	1960				78.4			
Brushy Draw		Delaware	26s	29e	1960						30	
Cabin Lake Delaware		Delaware	22s	30e	1995	2	75	12				
Corbin Delaware west		Delaware	18s	33e	1995	0.93	63.96	19				
Cruz Delaware		Delaware	23s	32+33e	1967			34				
Corral Canyon		Delaware	25s	30e	1976			25				
DiamondTail		Delaware	23s	32e	1995	0.23	97.1	3				
El Mar Delaware		Delaware	26s	32+33e	1960				25			
Double X Delaware		Delaware	24s	32e	1967			10				
Geronimo		Delaware	19s	32+33e	1995	0.08	30	8				
Golden Land Delaware, south		Delaware	21s	29e	1995			26				
Hat Mesa Delaware		Delaware	20+21s	32+33e	1995	0.5	36	3				
Herradura Bend Delaware east		Delaware	22+23s	28e	1995	0.25	40	1.6				
Indian Draw Delaware	Oil	Delaware	22s	28e	1988			19.4				
Livingston Ridge Delaware		Delaware	22s	31e	1995	0.03	14.4	2.8				

Table B1 (continued.) Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Los Medanos Delaware		Delaware	23s	31e	1995	0.01	4.6	0.97				
Lost Tank Delaware		Delaware	21+22s	31e	1995	0.26	57	3.23				
Malaga		Delaware	24s	28+29e	1956				55			
Mason North		Delaware	26s	31+32e	1956				24			
Paduca		Delaware	25s	32e	1967			24.65				
Salado Draw		Delaware	26s	33e	1967			12				
Sand Dunes		Delaware	23+34s	31e	1995	0.1	15	2.5				
Shugart Delaware East		Delaware	18s	31e	1995	14	197					
Triple X Delaware		Delaware	24s	32+33e	1976	25	135					
Triste Draw		Delaware	23+24s	32e	1967			80				
Justis Paddock	Gas	Glorieta	25s	37e	1960				9		8	
Justis Paddock		Glorieta	25s	37e	1960				4		3	
Airstrip Bone Spring	Oil	Bone Spring	18s	34e	1988	1	7					
Old Millman Ranch Bone Spring		Bone Spring	20s	28e	1995	0.1	6.34	0.52				
Young Bone Spring, North	Oil	Bone Spring	18s	32e	1988	8	18					
Young Bone Spring, North	Oil	Bone Spring	18s	32e	1988			0.62				
Maljamar		Paddock	17s	32e	1956				13.3			
Justis Blinebry		Blinebry	25s	37+38e	1960				3		0.6	
Hobbs Blinebry		Blinebry	18s	38e	1976	5	28					
Terry		Blinebry	20+21s	37+38e	1956				0.5	20		
Blinebry	Oil	Yeso	21+22S	37+38e	1956				4.5			
Drinkard		Yeso	21+22+23s	37+38e	1956				5.6			
Fowler Upper Yeso Pool		Yeso	24s	37e	1976			5				
Paddock		Yeso upper	21+22s	37+38e	1956				0	4		
Goodwin Drinkard		Drinkard	18s	37e	1976			20				
Hobbs Drinkard		Drinkard	18+19s	38e	1976	1.1	15					
West Knowles Drinkard		Drinkard	16s	37e	1976			15				
Cedar Lake Abo		Abo	17s	31e	1967			9.5				
Corbin Abo		Abo	17s	33e	1967			25				
Empire Abo		Abo	17+18s	27+28e	1960				0.1	1970		
Double A Abo		Abo	17s	36e	1967			39.7				
Goodwin Abo		Abo	18s	37e	1976			40				
Jackson Abo		Abo	17s	30e	1967			8.1				
Loco Hills Abo		Abo	17s	30e	1967			9.1				

Table B1 (continued.) Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Midway		Abo	17s	37e	1967			22				
Vacuum Abo Reef		Abo	17+18s	34+35e	1967			13.9				
Warren		Abo	20s	38+39e	1956				0.5		0.3	
Anderson Ranch		Wolfcamp	16s	32e	1956				79		167	
Anderson Ranch Wolfcamp North		Wolfcamp	15+16s	32e	1967			124				
Caudill		Wolfcamp	15s	36e	1956						1	
Denton		Wolfcamp	14+15s	37e	1956				13		6.6	
Denton		Wolfcamp	14+15s	37e	1956				13		16	
Henshaw Wolfcamp		Wolfcamp	16s	30e	1967			9				
Lane		Wolfcamp	10s	33e	1956				373		100	
Kemnitz		Wolfcamp	16s	33+34e	1960				8.8			
Morton Lower Wolfcamp		Wolfcamp	15s	34+35e	1967			67				
Saunders East		Wolfcamp	14s	34e	1967			46				
Red Hills		Wolfcamp	25+26s	33e	1976			1.04				
Shoe Bar Wolfcamp North		Wolfcamp	16s	35+36e	1976	0.1	20					
Tatum Wolfcamp		Wolfcamp	13s	36e	1960				12		11	
Townsend		Wolfcamp	15+16s	34+35e	1956				38			
Eidson		Penn or Wolfcamp	16s	35e	1956				20			
Wantz Granite Wash	Oil	Granite Wash	22s	37+38e	1988	0.05	129	1.6				
North Morton Permo-Penn		PermoPenn	14s	35e	1976			420				
Saunders		PermoPenn	14+15s	33e	1956				1		0.5	
Dean		PermoPennsylvanian (	15+16s	36+37e	1960				0.5	3.8		
Cerca		Upper Penn	13+14s	34e	1976			80				
Indian Basin		Upper Penn	21+22s	23+24e	1967	0.1	1780					
Haystack Cisco	Gas	Cisco	6s	27e	1976			13				
Anderson Ranch	Oil	Cisco, Canyon	15+16s	32e	1988			70				
Baum Upper Penn		Bough c	13+14s	32+33e	1976			<1				
Inbe Pennsylvanian		Bough c	10+11s	33+34e	1967			104				
Prairie Cisco, south		Bough c	8s	36e (roosev	1967			1035				
Vada Pennsylvanian		Bough c	8+9+10s	33+34+36e	1976	100	200					
Tobac		Bough c	8s	32+33e	1967			100				
Lost Lake Strawn		Strawn	8+9s	29e	1988	8	12					
Big Eddy Strawn		Strawn	20s	31e	1967			100				
Casey Strawn		Strawn	16s	37e	1976			30				

Table B1 (continued.) Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Jal west		Strawn	25s	36e	1967			27				
Humble City		Strawn	17s	37e	1976			25				
Humble City south	Oil	Strawn	17s	37e	1988			66				
Kemnitz		Strawn	16s	34e	1988			1				
Lost Lake Strawn		Strawn	8+9s	29e	1988	8	12					
Loving Penn Northeast	Oil	Strawn	16s	36+37e	1988			75				
Lusk Strawn		Strawn	18+19s	31+32e	1967			21.6				
Shoe Bar Strawn North		Strawn	16s	35e	1976	10	50					
Shipp	Oil	Strawn	16+17s	37e	1988			55				
Antelope Ridge		Atoka	24s	34e	1967			25				
Atoka Pennsylvanian		Atoka	18s	26e	1967			35				
Kemnitz	Gas	Atoka & Morrow	16s	33+34e	1988	1	20					
Crow Flats Morrow	Oil	Morrow	16 + 17s	37e	1999			53				
Dagger Draw	Oil	Morrow	20S	25E	1967			35				
Antelope Ridge		Morrow	24s	34e	1967			25				
Cedar Lake, East morrow		Morrow	17s	31e	1999	25	355	165				
Empire South Morrow		Morrow	17 + 18s	28 + 29e	1999			342				
Humphreys Mill Morrow	Gas	Morrow	25s	35e	1988			38				
Illinois camp Morrow, North		Morrow			1995	0.5	5	1.8				
Kemnitz Morrow, south		Morrow	16s	33+34e	1988	1	20					
Little Box Canyon (lower) Morrow		Morrow	20+20.5+21s	21+22e	1999	3	1154					
Logan Draw		Morrow	16+17s	37e	1999			53				
Rock Tank Morrow		Morrow	23s	24+25e	1976			324				
Burton Flat Morrow Field		Morrow	20+21e	28+27e	1976			2.03				
Cemetary Morrow Gas	Gas	Morrow	20s	25e	1976	10	60					
Corbin South Morrow		Morrow	18s	32+33e	1976			2.7				
Humphrey's Mill	Gas	Morrow	25s	35e	1988			0.064				
Illinois Camp Morrow North		Morrow	17+18s	27+28e	1995	0.5	5	1.8				
Rock Tank Morrow Field		Morrow	23s	24+25e	1976			324				
Wilson Deep		Morrow	21s	34e	1976			4				
Indian Basin Upper Pennsylvanian		Pennsylvanian	21 + 22s	23 + 24 e	1967	0.1	1780					
Shugart Pennsylvanian		Pennsylvanian	18s	31e	1960				3.1			
White City Penn Gas	Gas	Pennsylvanian	24+25s	26e	1999	<1	50	1				
Vada Pennsylvanian		Pennsylvanian	8+9+10s	33+34+36e	1976	100	200					

Table B1 (continued.) Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Wilson Pennsylvanian		Pennsylvanian	21s	34e	1976	4						
Allison		Pennsylvanian	9s	36e	1956				281		95	
Allison Pennsylvanian		Pennsylvanian	8+9s	36+37e	1960				200		125	
Allison Pennsylvanian		Pennsylvanian	8+9s	36+37e	1967			200				
Bough (permo Pennsylvanian)		Pennsylvanian	9s	35+36e	1956				76		8.7	
Dean		Pennsylvanian	15+16s	36+37e	1956				0.5	3.8		
Dean		Pennsylvanian	15+16s	36+37e	1956				0.5	3.8		
Eidson		Pennsylvanian	16s	34+35e	1956				20			
King Pennsylvanian		Pennsylvanian	13s	37e	1960				38			
Lazy "J"		Pennsylvanian			1976			8.1				
Lake Penn		Pennsylvanian	9+10s	33e	1960				3.1		2.6	
Lazy "J"		Pennsylvanian	13s	33e	1956				8.1			
Milnesand		Pennsylvanian	8s	34+35e (roo	1960				1.4		0.45	
Peterson	Oil	Pennsylvanian	4s	33e (roosev	1988	0.5	50					
Ranger Lake		Pennsylvanian	12s	34e	1960				28			
Shugart		Pennsylvanian	18s	31e	1960				3.1			
Shoebar Chester	Gas	Mississippian	16s	36e	1988			0.25				
Bronco Mississippian		Mississippian	13s	38e	1960		19903					
Anderson Ranch		Devonian	16s	32e	1956				61			
Arkansas Junction Devonian		Devonian	18s	36e	1960				0.06			
Bough Devonian		Devonian	9s	35e	1967			400				
Caudill		Devonian	15s	36e	1956				10			
Chisum		Devonian	11s	27+27.5+28	1956				150		150	
Crosby		Devonian	25s	37e	1956				36			
Crossroads devonian south		Devonian	10s	36e	1956				21		10	
Dean		Devonian	15+16s	36+37e	1956				10	115		
Denton		Devonian	14+15s	37e	1956				9.6		7.2	
Crossroads Devonian		Devonian	9s	36e	1960				0.1	12	0.1	5.6
East CrossRoads Devonian		Devonian	9s	37e	1960				0.1	80	0.1	25
South Crossroads Devonian		Devonian	10s	36e	1960				21		10	
Dean		Devonian	15+16s	36+37e	1956				10	115		
Denton		Devonian	14+15s	37e	1956				9.6		7.2	
Echol		Devonian	10+11s	37e	1956				34.3			
South Denton		Devonian	15+16s	37+38e	1960				238		154	

Table B1 (continued.) Original Permeability Data

Field	Oil or	Formation	Location		Date	Permeability			Horiz	Horiz	Vert	Vert
	Gas		Township	Range	(Source)	High	Low	Average	High	Low	High	Low
Dickinson		Devonian	10s	34e	1960				110	1180		
Southwest Gladiola Devonian		Devonian	12s	37e	1960				300			
Knowles		Devonian	16+17s	38e	1956				299		299	
Knowles		Devonian	17s	38+39e	1956				26		7.4	
Lightcap		Devonian	8s	30e	1956				37.6		9.5	
Mescalero		Devonian	10s	32e	1956				2	36	18	
Medicine Rock (fractured porosity/permea		Devonian	15s	38e	1967	20	300					
Midway	Oil	Devonian	17s	37e	1988			0.18				
Squyres		Devonian	7s	32e (roosev	1956				0	400		
Shoe Bar Devonian North		Devonian	16s	25e	1960				4.5			
South Prairie Devonian		Devonian	8s	36e (roosev	1976			92.5				
Vacuum Devonian		Devonian	17s	34e	1967			<0.1				
South Vacuum Devonian		Devonian	18s	35e	1960				116		86	
Bagley		SiluroDevonian	11+12s	33e	1956				3		1.3	
Southwest Gladiola Devonian		Siluro-Devonian	12s	37e	1976			700				
Haystack Siluro-Devonian		Siluro-Devonian	6s	27e	1976			28				
Gladiola		Siluro-Devonian	11+12s	37+38e	1960				0.1	5.8	0.1	286
Lea unit Devonian		Siluro-Devonian	20s	34+35e	1967			50				
King Camp Devonian North		Siluro-Devonian	14s	29e	1995		1000					
Lone wolf devonian southwest		Siluro-Devonian	13s	29e	1995			38				
Long Arroyo		Siluro-Devonian	13s	28e	1995			2065				
Shugart		Siluro-Devonian	18s	31e	1960				115.32			
Vacuum North Devonian		Siluro-Devonian	18s	35e	1967			0.5				
White Ranch		Siluro-Devonian	11s	29e	1956				150			
Justis Fusselman		Fusselman	25s	37+38e	1960				3		0.2	
Justis Montoya		Ordovician	25s	37e	1960				5		0.3	
Justis McKee		Ordovician	25s	37+38e	1960				75			
Justis Ellenburger		Ordovician	25s	37+38e	1960				2		0.5	
Warren (McKee)		Ordovician	20s	38e	1956				36.6			
Warren North (McKee)		Ordovician	20s	38e	1956				36.6			

Table B2. Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Baish		Yates	17s	32e	1956			60			60
North Hackberry Yates		Yates	19s	31e	1960			1.1			1.1
Lea Yates		Yates	20s	34e	1960			13			13
Russell		Yates	20s	28e	1956			30.5			30.5
San Simon		Yates	21+22s	35e	1960			5.3			5.3
Tonto South		Yates	19s	33e	1967			16			16
Jalmat		Yates-Seven Rivers	21-26s	35-37e	1956			1.8			1.8
Scarborough		Yates-Seven Rivers	26s	36+37e	1967			4.6			4.6
Rhodes	Gas	Yates-Seven Rivers	26s	37e	1988	0.1	8		0.894427	4.05	0.894427
Teas West		Yates-Seven Rivers	20s	33e	1967	6	60		18.97367	33	18.97367
West Teas Yates		Yates-Seven Rivers	20s	33e	1960	6	60		18.97367	33	18.97367
Bowers		Seven Rivers	18+19s	37+38e	1956			36.5			36.5
Tonto West		Seven Rivers	19s	32+33e	1967			17			17
Brown Queen		Queen	10s	26e	1960			30			30
Bunker Hill Penrose (Associated)		Queen	16s	31e	1988			0.21			0.21
Chaves Queen, southea	Oil	Queen	12+13s	31e	1988			25			25
Coyote Queen		Queen	11s	27e	1960			13			13
Culwin Queen		Queen	18+19s	30+31e	1960			3.8			3.8
Double L Queen Associated		Queen	14+15s	29+30e	1976			121			121
E.K.		Queen	18s	33e	1956			31			31
High Lonesone		Queen	16s	29e	1956			13.75			13.75
High Lonesone		Queen	16s	29e	1960			13.75			13.75
Hume		Queen	16s	34e	1960			5.6			5.6
High Lonesome	Oil	Queen	16s	29e	1988			14			14
Maljamar	Gas	Queen	17s	32e	1960			15.8			15.8
Pearl		Queen	19s	35e	1956	2	62		11.13553	32	11.13553
Mesa		Queen	16s	32e	1967			100			100
Pearsall		Queen	17+18s	32e	1956			21			21
Pearl		Queen	19s	35e	1960	2	62		11.13553	32	11.13553
Querecho Plains		Queen	18s	32e	1976			10			10
Round Tank		Queen	15s	28+29e	1976			200			200
Sanmal	Oil	Queen	17s	33e	1988			87.6			87.6
Vacuum Queen	Gas	Queen	17s	34e	1960			5.6			5.6
Caprock		Queen	12,13,14,1	31+32e	1956			250			250
Benson Queen-Grayburg North		Queen-Grayburg	18s	30e	1967	0.5	19	5	3.082207	9.75	5
Skaggs		Queen-Grayburg	20s	37+38e	1956			7			7
Cave Grayburg		Grayburg	16+17s	29e	1960	1.5	149		14.94992	75.25	14.94992

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Dayton		Grayburg	18s	26e	1956			4			4
Dog Canyon Grayburg		Grayburg	16s	27e	1960			18			18
Dayton		Grayburg	18s	26e	1956			4			4
Roberts		Grayburg	17s	32+33e	1956			9.3			9.3
Roberts		Grayburg	17s	32+33e	1960			9.3			9.3
Artesia Queen Grayburg San Andre		Grayburg-San Andres	17+18s	27+28e	1956			90			90
Cave Grayburg San And	Oil	Grayburg-San Andres	16+17s	28+29e	1988	1.5	150		15	75.75	15
Hobbs		Grayburg-San Andres	18+19s	37+38e	1956			50			50
Loco Hills		Grayburg-San Andres	17+18s	29+30e	1956			49.9			49.9
Maljamar		Grayburg-San Andres	17+18s	31+32+33e	1956			47			47
Red Lake		Grayburg-San Andres	17+18s	27+28e	1956			2			2
Square Lake		Grayburg-San Andres	16+17s	30+31e	1956			110			110
Vacuum		Grayburg-San Andres	17+18s	33+34+35e	1956			404.5			404.5
Acme San Andres		San Andres	7+8s	27e	1960			12.3			12.3
Arkansas Junction		San Andres	18s	36e	1976			0.2			0.2
Acme San Andres, Southeast		San Andres	8s	27e	1995	0.01	392	24	1.979899	196.005	24
Bitter Lake		San Andres	10s	25e	1960			2.5			2.5
Bitter Lakes, South and West		San Andres	10s	25e	1967			2.5			2.5
Button Mesa San Andres		San Andres	8s	32e	1960			2.4			2.4
Bluitt San Andres Assiciated		San Andres	8s	37+38e	1976			5			5
Crossroads Slaughter San Andres		San Andres	9s	36e	1960			2.5			2.5
Crossroads San Andres West		San Andres	9s	35e	1960	0.1	58		2.408319	29.05	2.408319
Cato San Andres		San Andres	8s	30e	1967	0.1	1.5		0.387298	0.8	0.387298
Chaveroo		San Andres	7+8s	34+33e	1967			0.7			0.7
Cato		San Andres	7+8+9s	30e	1976	5	40		14.14214	22.5	14.14214
Eagle Creek		San Andres	17s	25e	1976			0.4			0.4
E.K.		San Andres	18s	33e	1956			6.4			6.4
Flying M		San Andres	9s	33e	1967			7.5			7.5
Grayburg Keely		San Andres	17s	29e	1956	0.1	5.8		0.761577	2.95	0.761577
Foster		San Andres	19s	39e	1960						
Hobbs east		San Andres	18s	39e	1956	300	500		387.2983	400	387.2983
Lakewood		San Andres	19s	26e	1960						
Linda		San Andres	6+7s	26e	1967			2			2
Milnesand		San Andres	8s	34e (roosev	1960			0.4			0.4
Mescalero		San Andres	10s	32e	1967	0.1	150		3.872983	75.05	3.872983
Milnesand		San Andres	8s	34+35e (ro	1967			0.1			0.1
Pecos San Andres		San Andres	7s	26e	1967			2			2

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Sawyer		San Andres	9s	37+38e	1956			1.7			1.7
Sawyer		San Andres	9s	37+38e	1960			5.9			5.9
Sawyer		San Andres	9s	37+38e	1967			5.9			5.9
West Sawyer		San Andres	9+10s	37e	1976			0.89			0.89
Siete		San Andres	8s	31e	1976			1.5			1.5
Spencer		San Andres	17s	36e	1976	15	25		19.36492	20	19.36492
Tom-Tom		San Andres	7+8s	31e	1976	1	2		1.414214	1.5	1.414214
Sulfate Delaware Southwest		Bell Canyon	25s	26e	1988			20			20
Welch Delaware		Bell Canyon	26s	27e	1960			28			28
Nash Draw Brushy Canyon		Brushy Canyon	23s	29+30e	1995	0.5	18	3.5	3	9.25	3.5
Parkway Delaware		Brushy Canyon	19+20s	29+30e	1995	0.16	8.1	1.5	1.13842	4.13	1.5
Red Tank West		Brushy Canyon	22s	32e	1995	0.01	23	6.5	0.479583	11.505	6.5
Willow Lake Delaware		Brushy Canyon	24+25s	28+29e	1995	0.15	5.5	0.5	0.908295	2.825	0.5
Bradley Delaware		Delaware	26s	34e	1960			78.4			78.4
Brushy Draw		Delaware	26s	29e	1960						
Cabin Lake Delaware		Delaware	22s	30e	1995	2	75	12	12.24745	38.5	12
Corbin Delaware west		Delaware	18s	33e	1995	0.93	63.96	19	7.712509	32.445	19
Cruz Delaware		Delaware	23s	32+33e	1967			34			34
Corral Canyon		Delaware	25s	30e	1976			25			25
DiamondTail		Delaware	23s	32e	1995	0.23	97.1	3	4.72578	48.665	3
El Mar Delaware		Delaware	26s	32+33e	1960			25			25
Double X Delaware		Delaware	24s	32e	1967			10			10
Geronimo		Delaware	19s	32+33e	1995	0.08	30	8	1.549193	15.04	8
Golden Land Delaware, south		Delaware	21s	29e	1995			26			26
Hat Mesa Delaware		Delaware	20+21s	32+33e	1995	0.5	36	3	4.242641	18.25	3
Herradura Bend Delaware east		Delaware	22+23s	28e	1995	0.25	40	1.6	3.162278	20.125	1.6
Indian Draw Delaware	Oil	Delaware	22s	28e	1988			19.4			19.4
Livingston Ridge Delaware		Delaware	22s	31e	1995	0.03	14.4	2.8	0.657267	7.215	2.8
Los Medanos Delaware		Delaware	23s	31e	1995	0.01	4.6	0.97	0.214476	2.305	0.97
Lost Tank Delaware		Delaware	21+22s	31e	1995	0.26	57	3.23	3.849675	28.63	3.23
Malaga		Delaware	24s	28+29e	1956			55			55
Mason North		Delaware	26s	31+32e	1956			24			24
Paduca		Delaware	25s	32e	1967			24.65			24.65
Salado Draw		Delaware	26s	33e	1967			12			12
Sand Dunes		Delaware	23+34s	31e	1995	0.1	15	2.5	1.224745	7.55	2.5
Shugart Delaware East		Delaware	18s	31e	1995	14	197		52.51666	105.5	52.51666
Triple X Delaware		Delaware	24s	32+33e	1976	25	135		58.09475	80	58.09475

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Triste Draw		Delaware	23+24s	32e	1967			80			80
Justis Paddock	Gas	Glorieta	25s	37e	1960			9			9
Justis Paddock		Glorieta	25s	37e	1960			4			4
Airstrip Bone Spring	Oil	Bone Spring	18s	34e	1988	1	7		2.645751	4	2.645751
Old Millman Ranch Bone Spring		Bone Spring	20s	28e	1995	0.1	6.34	0.52	0.796241	3.22	0.52
Young Bone Spring, No	Oil	Bone Spring	18s	32e	1988	8	18		12	13	12
Young Bone Spring, No	Oil	Bone Spring	18s	32e	1988			0.62			0.62
Maljamar		Paddock	17s	32e	1956			13.3			13.3
Justis Blinebry		Blinebry	25s	37+38e	1960			3			3
Hobbs Blinebry		Blinebry	18s	38e	1976	5	28		11.83216	16.5	11.83216
Terry		Blinebry	20+21s	37+38e	1956	0.5	20		3.162278	10.25	3.162278
Blinebry	Oil	Yeso	21+22S	37+38e	1956			4.5			4.5
Drinkard		Yeso	21+22+23s	37+38e	1956			5.6			5.6
Fowler Upper Yeso Pool		Yeso	24s	37e	1976			5			5
Paddock		Yeso upper	21+22s	37+38e	1956	0	4		#NUM!	2	1
Goodwin Drinkard		Drinkard	18s	37e	1976			20			20
Hobbs Drinkard		Drinkard	18+19s	38e	1976	1.1	15		4.062019	8.05	4.062019
West Knowles Drinkard		Drinkard	16s	37e	1976			15			15
Cedar Lake Abo		Abo	17s	31e	1967			9.5			9.5
Corbin Abo		Abo	17s	33e	1967			25			25
Empire Abo		Abo	17+18s	27+28e	1960	0.1	1970		14.03567	985.05	14.03567
Double A Abo		Abo	17s	36e	1967			39.7			39.7
Goodwin Abo		Abo	18s	37e	1976			40			40
Jackson Abo		Abo	17s	30e	1967			8.1			8.1
Loco Hills Abo		Abo	17s	30e	1967			9.1			9.1
Midway		Abo	17s	37e	1967			22			22
Vacuum Abo Reef		Abo	17+18s	34+35e	1967			13.9			13.9
Warren		Abo	20s	38+39e	1956			0.5			0.5
Anderson Ranch		Wolfcamp	16s	32e	1956			79			79
Anderson Ranch Wolfcamp North		Wolfcamp	15+16s	32e	1967			124			124
Caudill		Wolfcamp	15s	36e	1956						
Denton		Wolfcamp	14+15s	37e	1956			13			13
Denton		Wolfcamp	14+15s	37e	1956			13			13
Henshaw Wolfcamp		Wolfcamp	16s	30e	1967			9			9
Lane		Wolfcamp	10s	33e	1956			373			373
Kemnitz		Wolfcamp	16s	33+34e	1960			8.8			8.8
Morton Lower Wolfcamp		Wolfcamp	15s	34+35e	1967			67			67

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Saunders East		Wolfcamp	14s	34e	1967			46			46
Red Hills		Wolfcamp	25+26s	33e	1976			1.04			1.04
Shoe Bar Wolfcamp North		Wolfcamp	16s	35+36e	1976	0.1	20		1.414214	10.05	1.414214
Tatum Wolfcamp		Wolfcamp	13s	36e	1960			12			12
Townsend		Wolfcamp	15+16s	34+35e	1956			38			38
Eidson		Penn or Wolfcamp	16s	35e	1956			20			20
Wantz Granite Wash	Oil	Granite Wash	22s	37+38e	1988	0.05	129	1.6	2.539685	64.525	1.6
North Morton Permo-Penn		PermoPenn	14s	35e	1976			420			420
Saunders		PermoPenn	14+15s	33e	1956			1			1
Dean		PermoPennsylvanian (str	15+16s	36+37e	1960	0.5	3.8		1.378405	2.15	1.378405
Cerca		Upper Penn	13+14s	34e	1976			80			80
Indian Basin		Upper Penn	21+22s	23+24e	1967	0.1	1780		13.34166	890.05	13.34166
Haystack Cisco	Gas	Cisco	6s	27e	1976			13			13
Anderson Ranch	Oil	Cisco, Canyon	15+16s	32e	1988			70			70
Baum Upper Penn		Bough c	13+14s	32+33e	1976			<1			1
Inbe Pennsylvanian		Bough c	10+11s	33+34e	1967			104			104
Prairie Cisco, south		Bough c	8s	36e (roose	1967			1035			1035
Vada Pennsylvanian		Bough c	8+9+10s	33+34+36e	1976	100	200		141.4214	150	141.4214
Tobac		Bough c	8s	32+33e	1967			100			100
Lost Lake Strawn		Strawn	8+9s	29e	1988	8	12		9.797959	10	9.797959
Big Eddy Strawn		Strawn	20s	31e	1967			100			100
Casey Strawn		Strawn	16s	37e	1976			30			30
Jal west		Strawn	25s	36e	1967			27			27
Humble City		Strawn	17s	37e	1976			25			25
Humble City south	Oil	Strawn	17s	37e	1988			66			66
Kemnitz		Strawn	16s	34e	1988			1			1
Lost Lake Strawn		Strawn	8+9s	29e	1988	8	12		9.797959	10	9.797959
Loving Penn Northeast	Oil	Strawn	16s	36+37e	1988			75			75
Lusk Strawn		Strawn	18+19s	31+32e	1967			21.6			21.6
Shoe Bar Strawn North		Strawn	16s	35e	1976	10	50		22.36068	30	22.36068
Shipp	Oil	Strawn	16+17s	37e	1988			55			55
Antelope Ridge		Atoka	24s	34e	1967			25			25
Atoka Pennsylvanian		Atoka	18s	26e	1967			35			35
Kemnitz	Gas	Atoka & Morrow	16s	33+34e	1988	1	20		4.472136	10.5	4.472136
Crow Flats Morrow	Oil	Morrow	16 + 17s	37e	1999			53			53
Dagger Draw	Oil	Morrow	20S	25E	1967			35			35
Antelope Ridge		Morrow	24s	34e	1967			25			25

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Cedar Lake, East morrow		Morrow	17s	31e	1999	25	355	165	94.20722	190	165
Empire South Morrow		Morrow	17 + 18s	28 + 29e	1999			342			342
Humphreys Mill Morrow	Gas	Morrow	25s	35e	1988			38			38
Illinois camp Morrow, North		Morrow			1995	0.5	5	1.8	1.581139	2.75	1.8
Kemnitz Morrow, south		Morrow	16s	33+34e	1988	1	20		4.472136	10.5	4.472136
Little Box Canyon (lower) Morrow		Morrow	20+20.5+2	21+22e	1999	3	1154		58.83876	578.5	58.83876
Logan Draw		Morrow	16+17s	37e	1999			53			53
Rock Tank Morrow		Morrow	23s	24+25e	1976			324			324
Burton Flat Morrow Field		Morrow	20+21e	28+27e	1976			2.03			2.03
Cemetary Morrow Gas	Gas	Morrow	20s	25e	1976	10	60		24.4949	35	24.4949
Corbin South Morrow		Morrow	18s	32+33e	1976			2.7			2.7
Humphrey's Mill	Gas	Morrow	25s	35e	1988			0.064			0.064
Illinois Camp Morrow North		Morrow	17+18s	27+28e	1995	0.5	5	1.8	1.581139	2.75	1.8
Rock Tank Morrow Field		Morrow	23s	24+25e	1976			324			324
Wilson Deep		Morrow	21s	34e	1976			4			4
Indian Basin Upper Pennsylvanian		Pennsylvanian	21 + 22s	23 + 24 e	1967	0.1	1780		13.34166	890.05	13.34166
Shugart Pennsylvanian		Pennsylvanian	18s	31e	1960			3.1			3.1
White City Penn Gas	Gas	Pennsylvanian	24+25s	26e	1999	1	50	1	7.071068	25.5	1
Vada Pennsylvanian		Pennsylvanian	8+9+10s	33+34+36e	1976	100	200		141.4214	150	141.4214
Wilson Pennsylvanian		Pennsylvanian	21s	34e	1976			4			4
Allison		Pennsylvanian	9s	36e	1956			281			281
Allison Pennsylvanian		Pennsylvanian	8+9s	36+37e	1960			200			200
Allison Pennsylvanian		Pennsylvanian	8+9s	36+37e	1967			200			200
Bough (permo Pennsylvanian)		Pennsylvanian	9s	35+36e	1956			76			76
Dean		Pennsylvanian	15+16s	36+37e	1956	0.5	3.8		1.378405	2.15	1.378405
Dean		Pennsylvanian	15+16s	36+37e	1956	0.5	3.8		1.378405	2.15	1.378405
Eidson		Pennsylvanian	16s	34+35e	1956			20			20
King Pennsylvanian		Pennsylvanian	13s	37e	1960			38			38
Lazy "J"		Pennsylvanian			1976			8.1			8.1
Lake Penn		Pennsylvanian	9+10s	33e	1960			3.1			3.1
Lazy "J"		Pennsylvanian	13s	33e	1956			8.1			8.1
Milnesand		Pennsylvanian	8s	34+35e (ro	1960			1.4			1.4
Peterson	Oil	Pennsylvanian	4s	33e (roosev	1988	0.5	50		5	25.25	5
Ranger Lake		Pennsylvanian	12s	34e	1960			28			28
Shugart		Pennsylvanian	18s	31e	1960			3.1			3.1
Shoebar Chester	Gas	Mississippian	16s	36e	1988			0.25			0.25
Bronco Mississippian		Mississippian	13s	38e	1960			19903			19903

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Anderson Ranch		Devonian	16s	32e	1956			61			61
Arkansas Junction Devonian		Devonian	18s	36e	1960			0.06			0.06
Bough Devonian		Devonian	9s	35e	1967			400			400
Caudill		Devonian	15s	36e	1956			10			10
Chisum		Devonian	11s	27+27.5+2	1956			150			150
Crosby		Devonian	25s	37e	1956			36			36
Crossroads devonian south		Devonian	10s	36e	1956			21			21
Dean		Devonian	15+16s	36+37e	1956	10	115		33.91165	62.5	33.91165
Denton		Devonian	14+15s	37e	1956			9.6			9.6
Crossroads Devonian		Devonian	9s	36e	1960	0.1	12		1.095445	6.05	1.095445
East CrossRoads Devonian		Devonian	9s	37e	1960	0.1	80		2.828427	40.05	2.828427
South Crossroads Devonian		Devonian	10s	36e	1960			21			21
Dean		Devonian	15+16s	36+37e	1956	10	115		33.91165	62.5	33.91165
Denton		Devonian	14+15s	37e	1956			9.6			9.6
Echol		Devonian	10+11s	37e	1956			34.3			34.3
South Denton		Devonian	15+16s	37+38e	1960			238			238
Dickinson		Devonian	10s	34e	1960	110	1180		360.2777	645	360.2777
Southwest Gladiola Devonian		Devonian	12s	37e	1960			300			300
Knowles		Devonian	16+17s	38e	1956			299			299
Knowles		Devonian	17s	38+39e	1956			26			26
Lightcap		Devonian	8s	30e	1956			37.6			37.6
Mescalero		Devonian	10s	32e	1956	2	36		8.485281	19	8.485281
Medicine Rock (fractured porosity/pe		Devonian	15s	38e	1967	20	300		77.45967	160	77.45967
Midway	Oil	Devonian	17s	37e	1988			0.18			0.18
Squyres		Devonian	7s	32e (roosev	1956	0	400		#NUM!	200	20
Shoe Bar Devonian North		Devonian	16s	25e	1960			4.5			4.5
South Prairie Devonian		Devonian	8s	36e (roosev	1976			92.5			92.5
Vacuum Devonian		Devonian	17s	34e	1967			0.1			0.1
South Vacuum Devonian		Devonian	18s	35e	1960			116			116
Bagley		SiluroDevonian	11+12s	33e	1956			3			3
Southwest Gladiola Devonian		Siluro-Devonian	12s	37e	1976			700			700
Haystack Siluro-Devonian		Siluro-Devonian	6s	27e	1976			28			28
Gladiola		Siluro-Devonian	11+12s	37+38e	1960	0.1	5.8		0.761577	2.95	0.761577
Lea unit Devonian		Siluro-Devonian	20s	34+35e	1967			50			50
King Camp Devonian North		Siluro-Devonian	14s	29e	1995			1000			1000
Lone wolf devonian southwest		Siluro-Devonian	13s	29e	1995			38			38
Long Arroyo		Siluro-Devonian	13s	28e	1995			2065			2065

Table B2 (continued.) Modified permeability data

Field	Oil or Gas	Formation	Location		Date	Permeability Values High	Low	Average	Log ave	linear ave	Box Plot K Value
Shugart		Siluro-Devonian	18s	31e	1960			115.32			115.32
Vacuum North Devonian		Siluro-Devonian	18s	35e	1967			0.5			0.5
White Ranch		Siluro-Devonian	11s	29e	1956			150			150
Justis Fusselman		Fusselman	25s	37+38e	1960			3			3
Justis Montoya		Ordovician	25s	37e	1960			5			5
Justis McKee		Ordovician	25s	37+38e	1960			75			75
Justis Ellenburger		Ordovician	25s	37+38e	1960			2			2
Warren (McKee)		Ordovician	20s	38e	1956			36.6			36.6
Warren North (McKee)		Ordovician	20s	38e	1956			36.6			36.6

Appendix C: Graphs of TDS vs Ion Ratios and Piper diagrams by formation

The following graphs show TDS versus Cl/SO_4, Ca/Mg, and Cl/Na+K for each formation (Figures C1 – C30). There are seven genetic classifications in all. The genetic classifications are presented at two levels of confidence. For the highest level, only samples that met all three criteria (TDS, Cl/SO_4, and Ca/Mg) were included. These are indicated by filled symbols on all figures with genetic classifications. For the lower confidence level, samples meeting the TDS and Cl/SO_4 ratio criteria, but not the Ca/Mg ratio, were included. These are indicated by open symbols on those same figures.

Groups one and four correspond with the first group described by Stueber et al (1998), i.e., saline meteoric water. These groups have a TDS of less than 75 g/L, a Cl/SO4 ratio of less than 50, and for group one, a Ca/Mg ratio between 2 and 4. The second and fifth group also correspond with the second group of Stueber et. al., the modified evaporitic marine brines. They have a TDS of 125 g/L or above, a Cl/SO4 ratio greater than 50, and for group 2, a Ca/Mg ratio between 4 and 7. The third and sixth group is a mixture of the first two groups. It has a TDS between 75 and 125 g/L, a Cl/SO4 ratio less than 50, and a Ca/Mg ratio between 4 and 6. The seventh group includes all the samples that do not fall under the others.

Groups one and four, meteoric saline water, are represented by solid and open diamonds, respectively; groups two and five, modified brines, are solid and open squares; groups three and six, a mix of brine and meteoric waters, are shown in solid and open triangles; and group seven, none of the above, is represented by stars. The x axis (ion ratio) may be cut short so that comparisons between formations may be easily made; therefore, not all samples may be shown.

Following the graphs of ion ratios versus TDS are Figures 40 – 57, Piper diagrams shown by formation. As stated in the main text, all the Piper diagrams show halite dissolution trends. The Grayburg San Andres samples show much more variablity because there are more meteoric water samples of low TDS and otherwise high quality, reflecting short reaction times with their surrounding minerals.

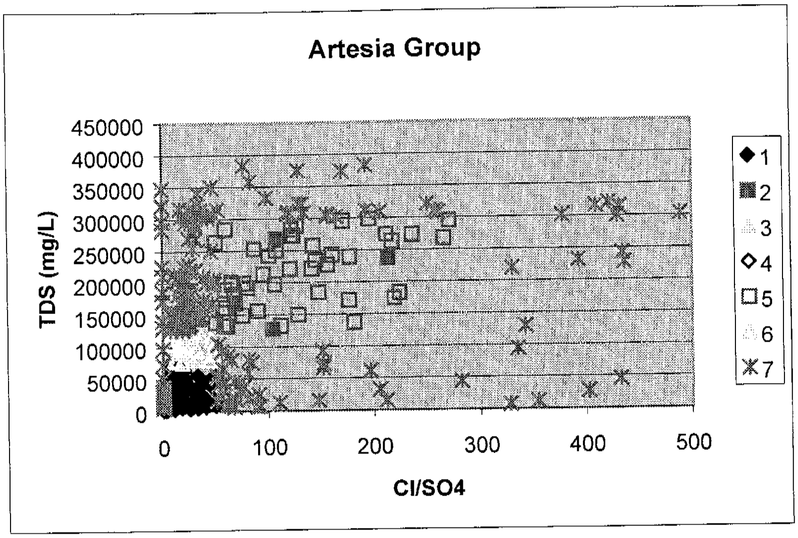


Figure C1. Artesia Group.

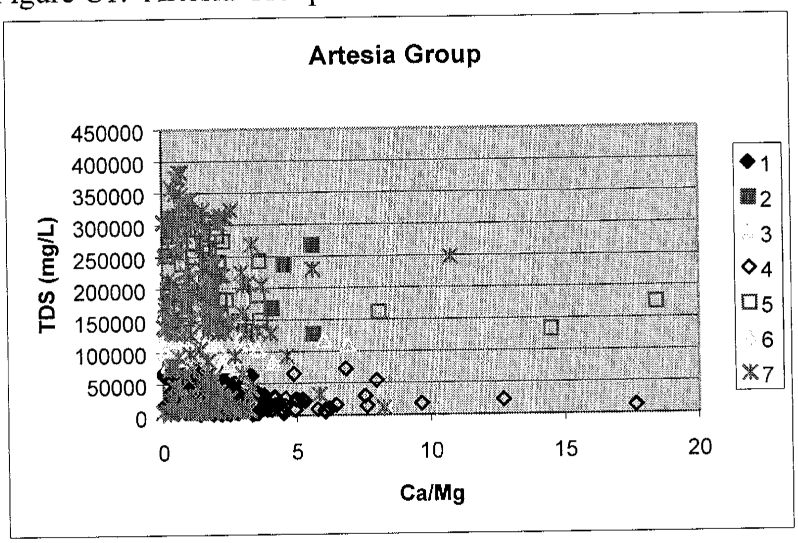


Figure C2. Artesia Group.

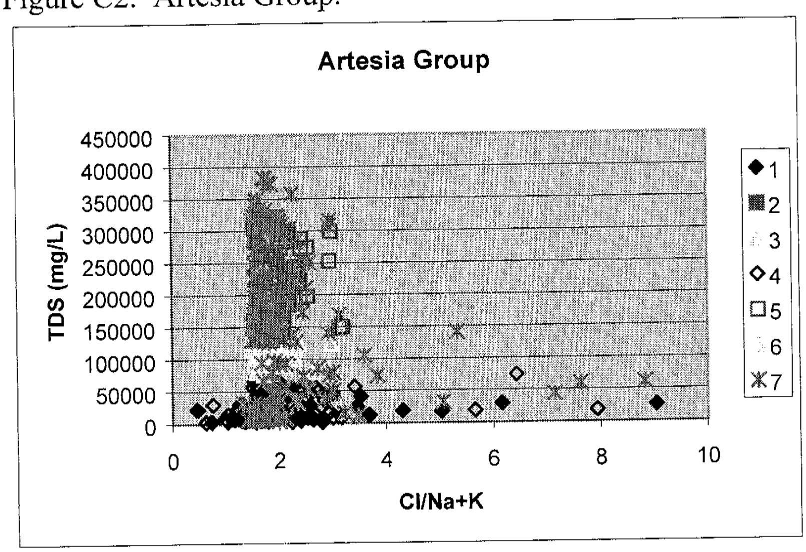


Figure C3. Artesia Group.

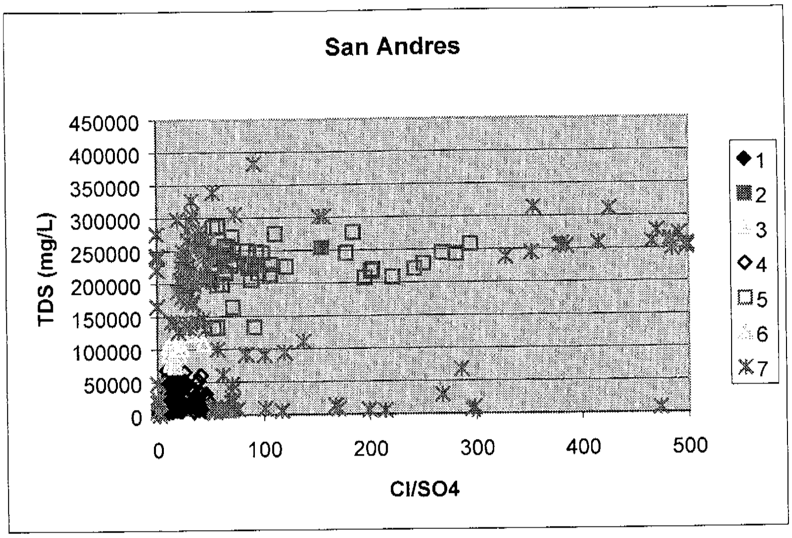


Figure C4. San Andres.

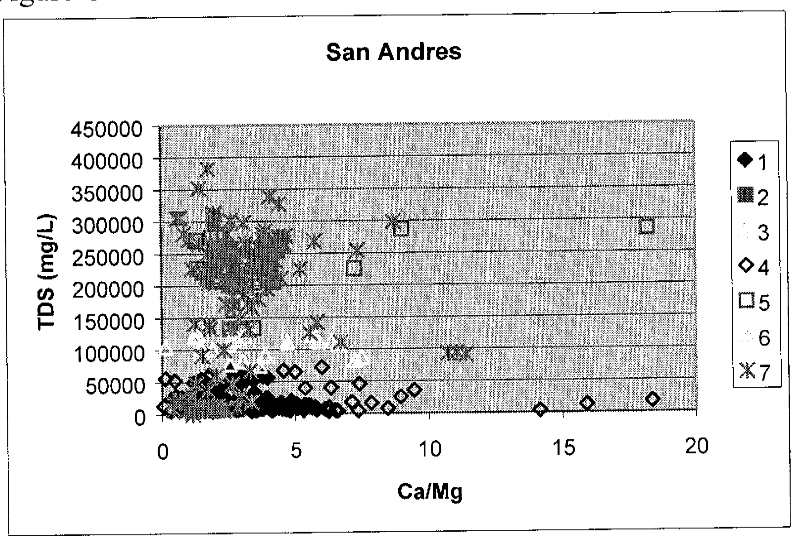


Figure C5. San Andres.

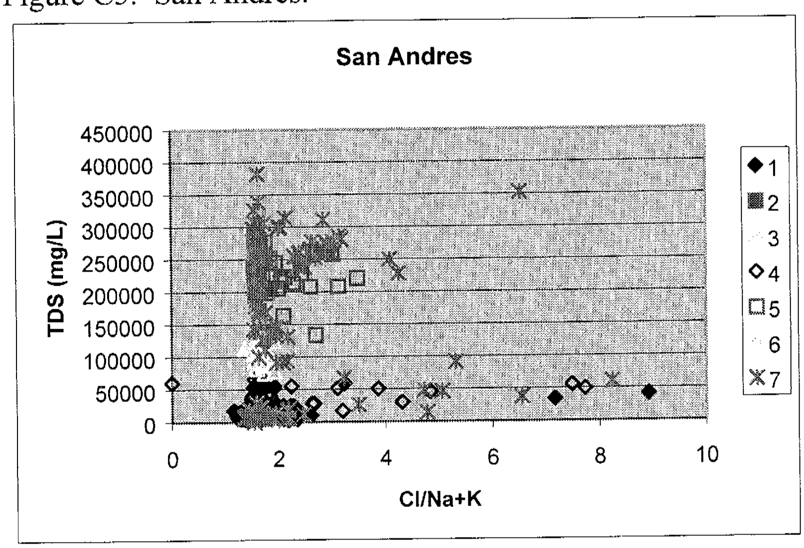


Figure C6. San Andres.

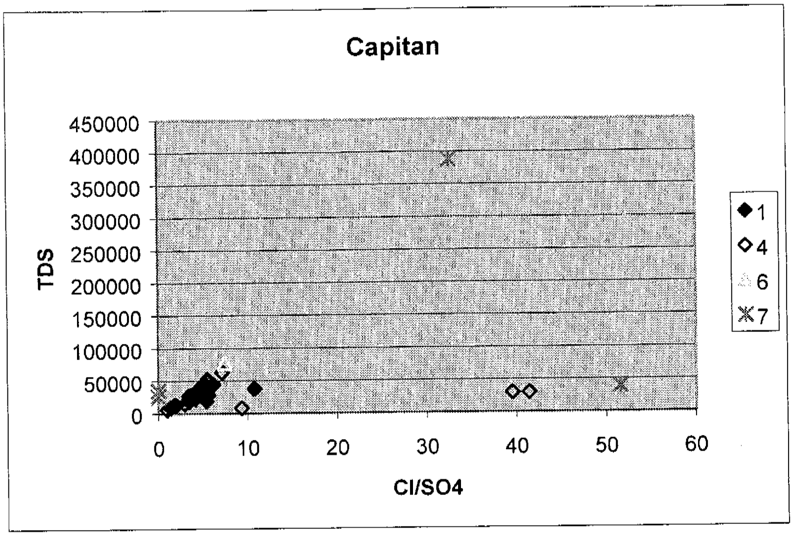


Figure C7. Capitan.

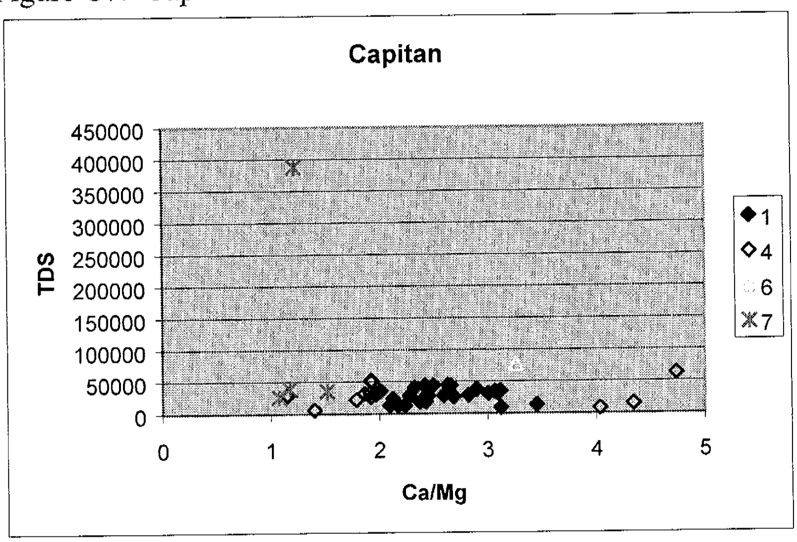


Figure C8. Capitan.

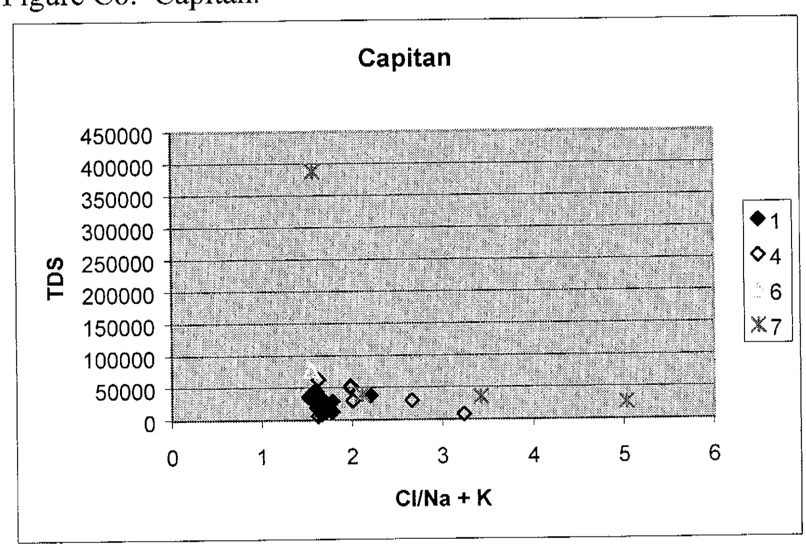


Figure C9. Capitan.

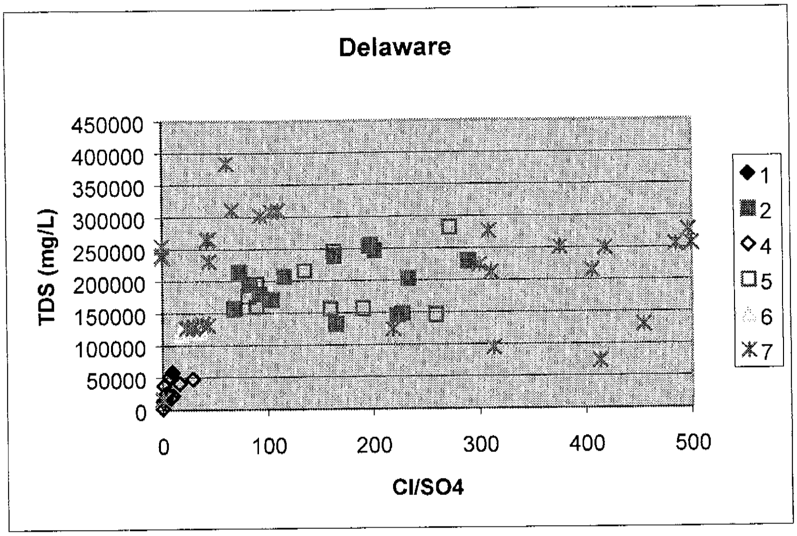


Figure C10. Delaware Mountain Group.

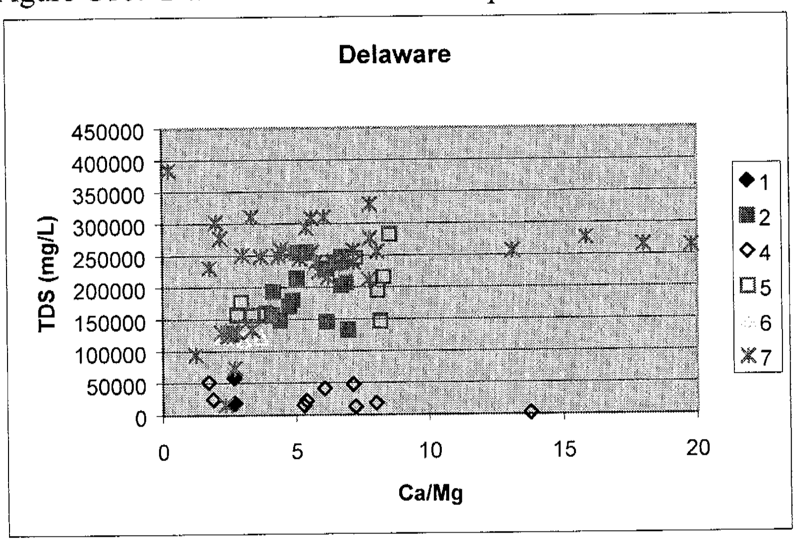


Figure C11. Delaware Mountain Group.

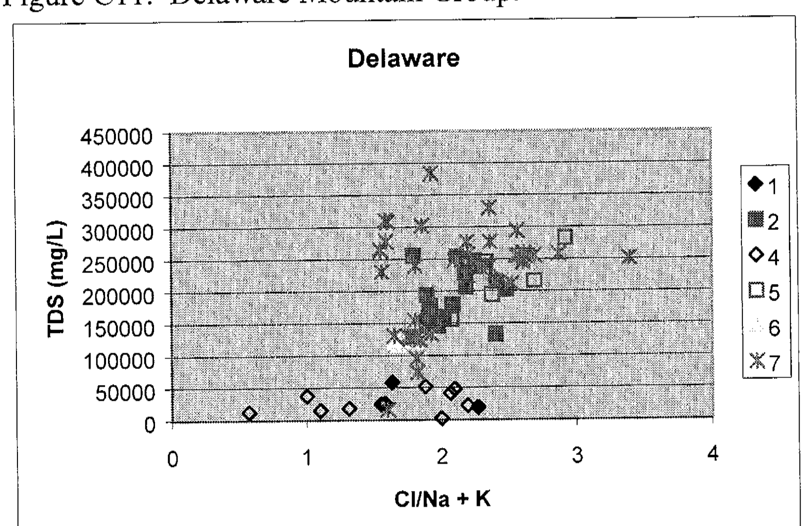


Figure C12. Delaware Mountain Group.

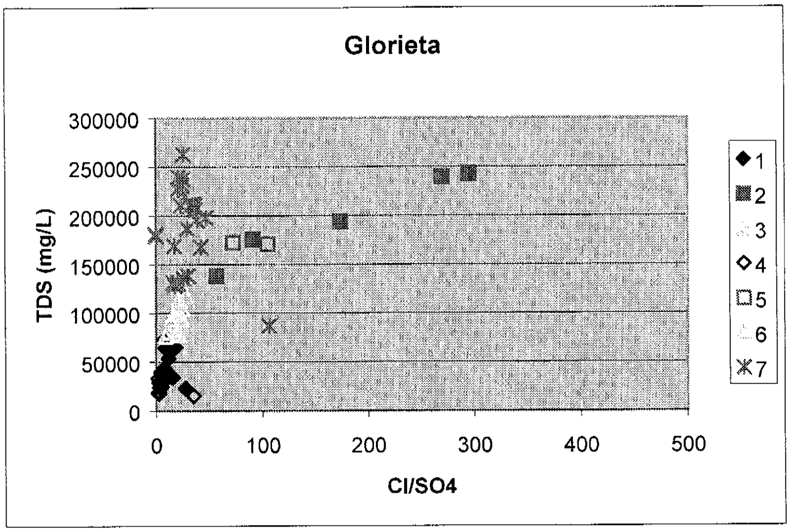


Figure C13. (Leonardian) Glorieta.

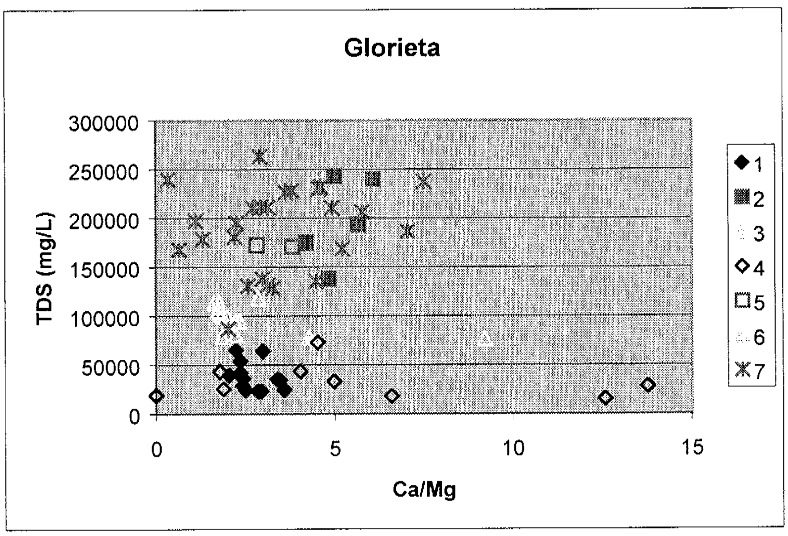


Figure C14. (Leonardian) Glorieta.

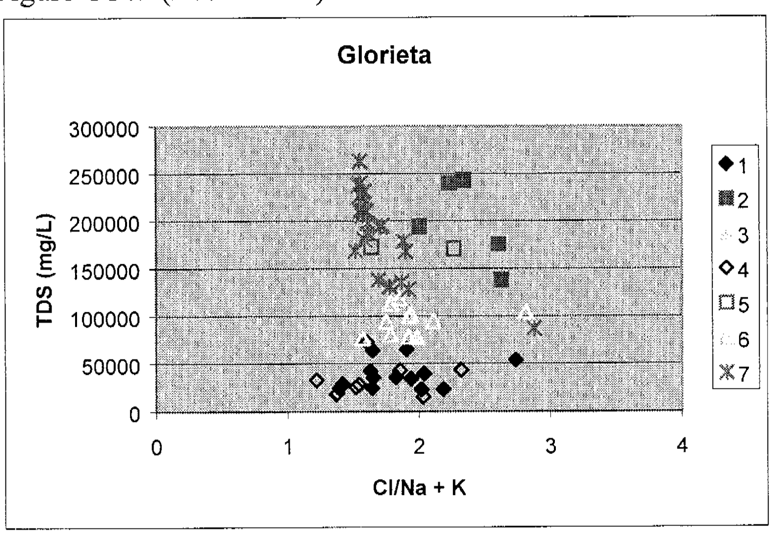


Figure C15. (Leonardian) Glorieta.

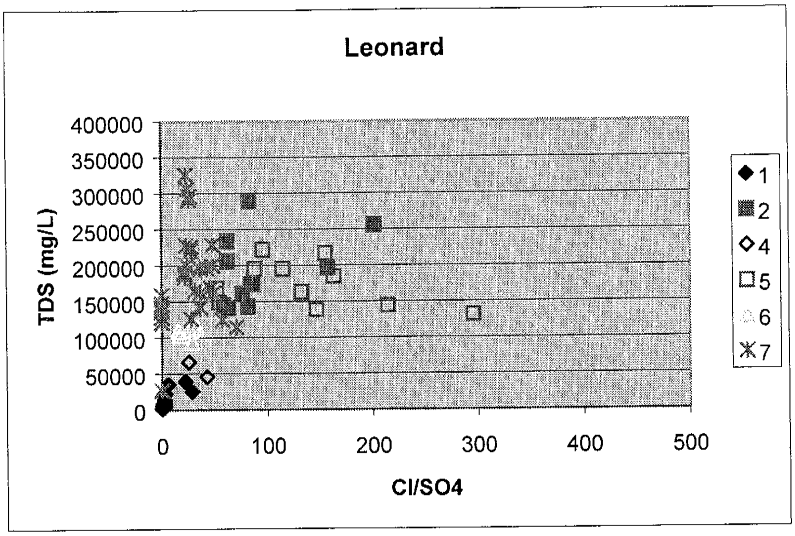


Figure C16. Leonard.

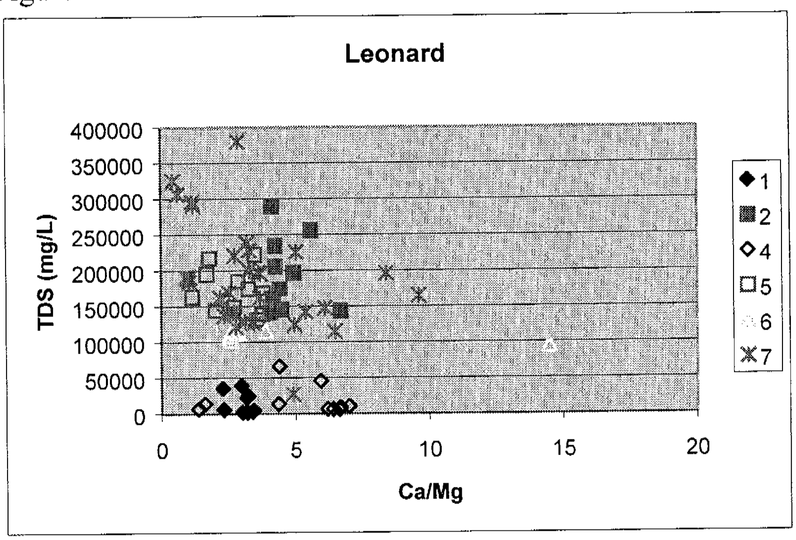


Figure C17. Leonard.

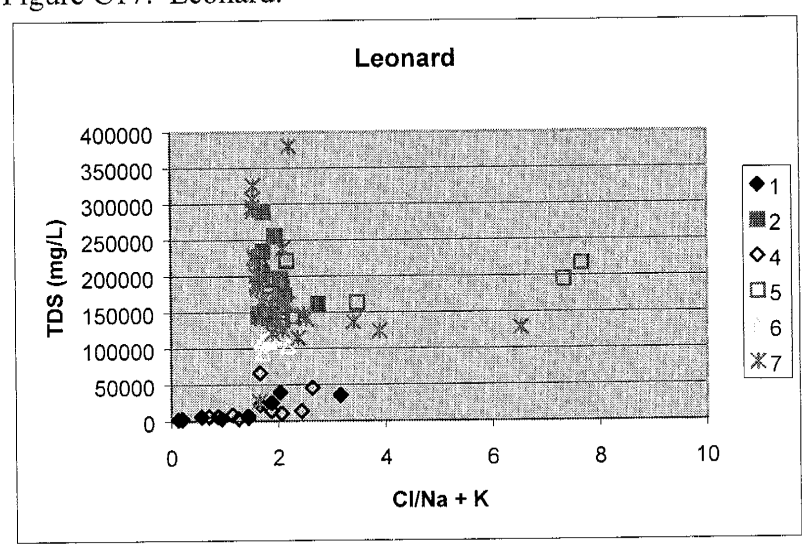


Figure C18. Leonard.

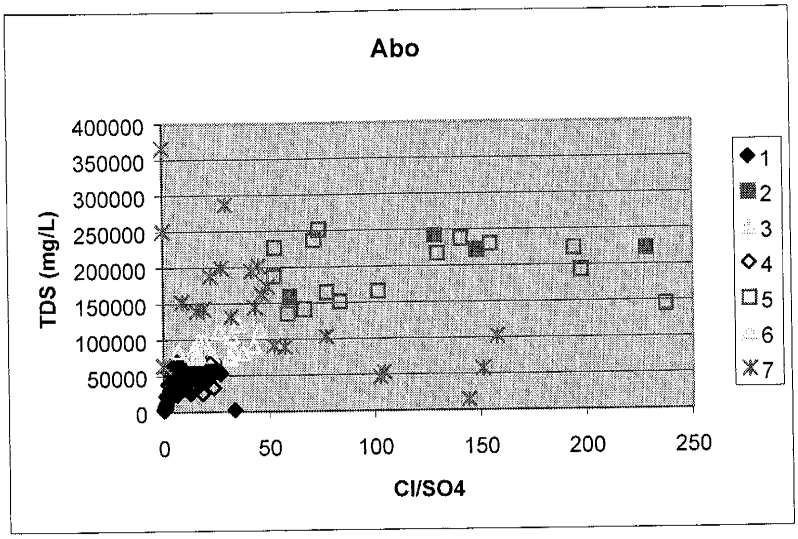


Figure C19. (Leonardian) Abo.

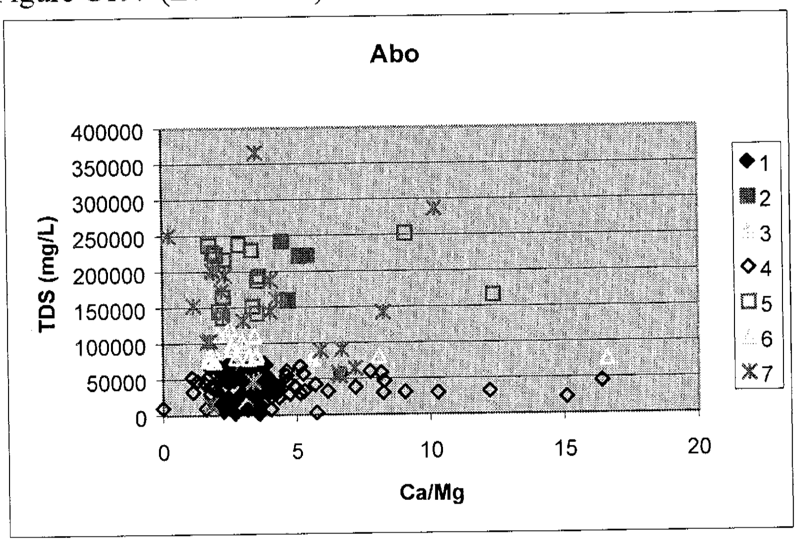


Figure C20. (Leonardian) Abo.

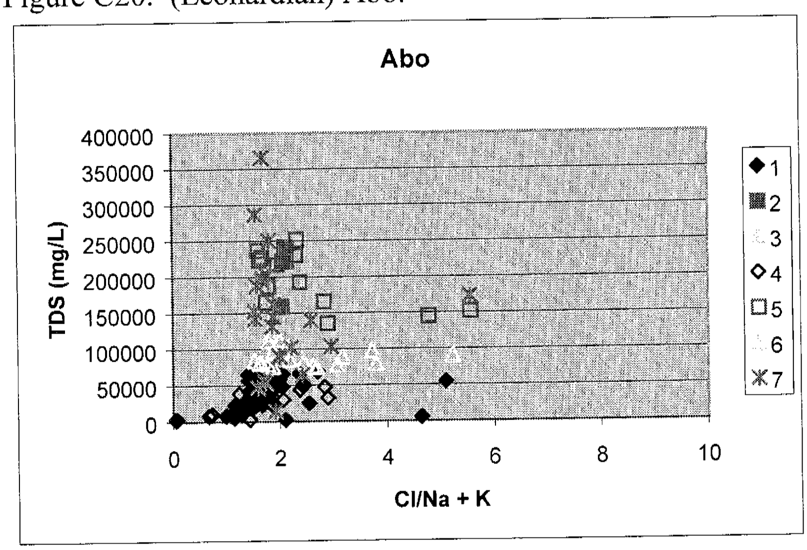


Figure C21. (Leonardian) Abo.

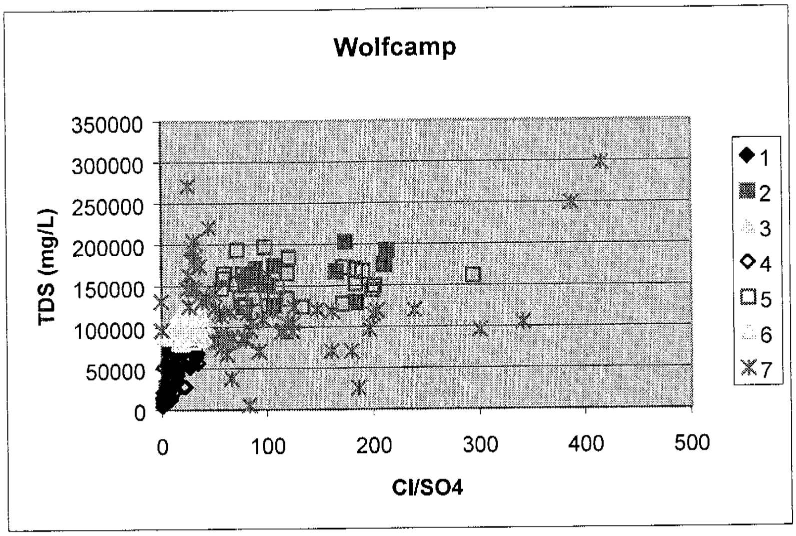


Figure C22. Wolfcamp.

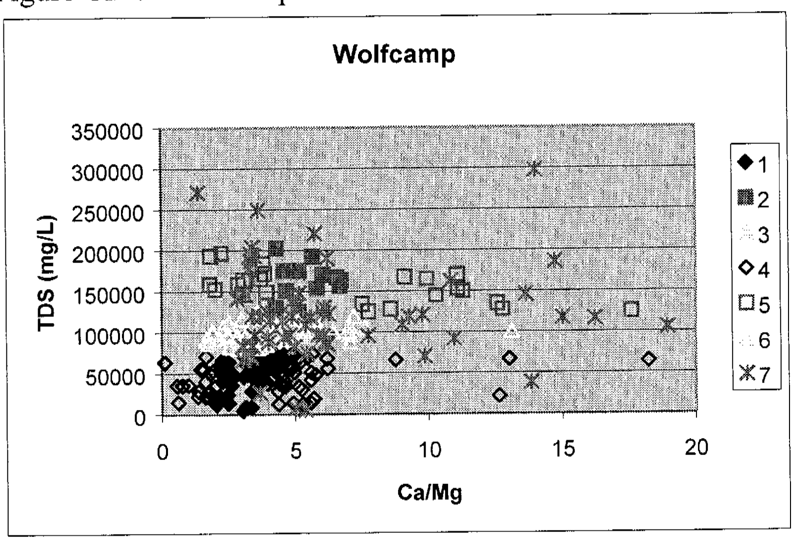


Figure C23. Wolfcamp.

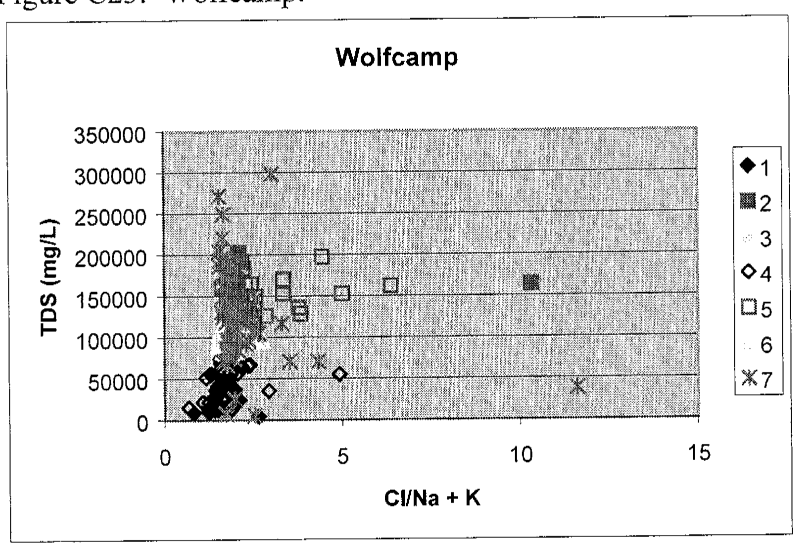


Figure C24. Wolfcamp.

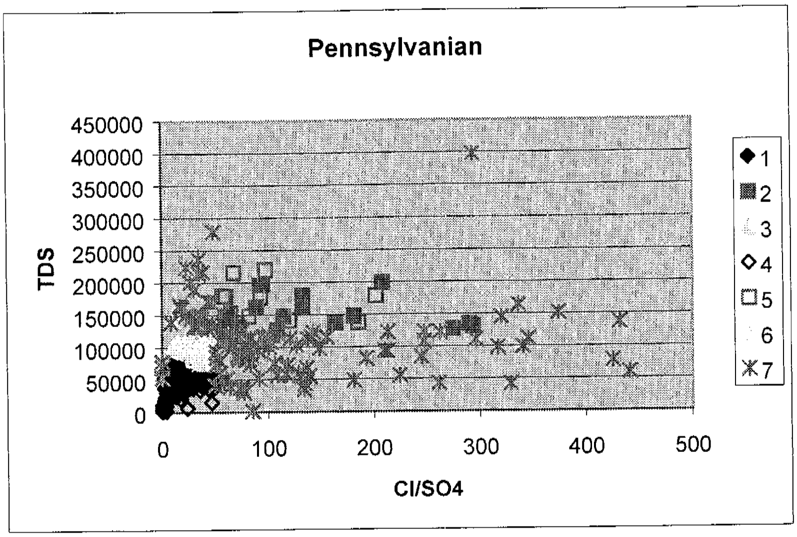


Figure C25. Pennsylvanian.

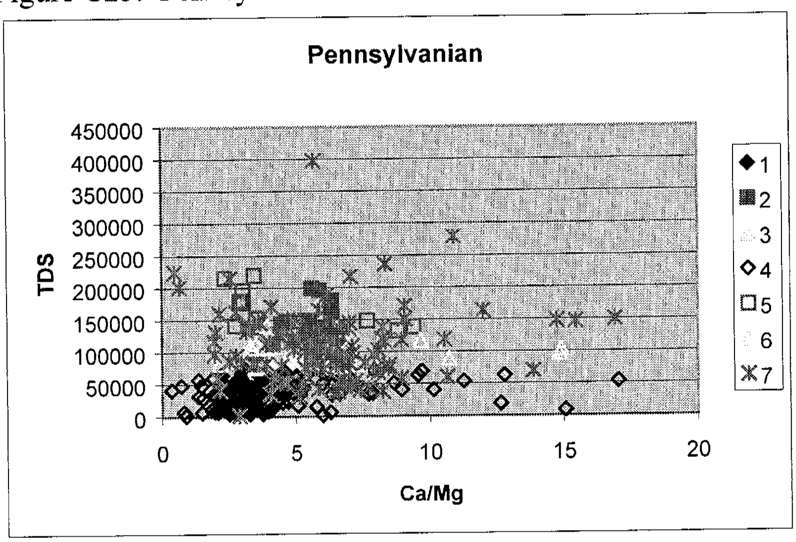


Figure C26. Pennsylvanian.

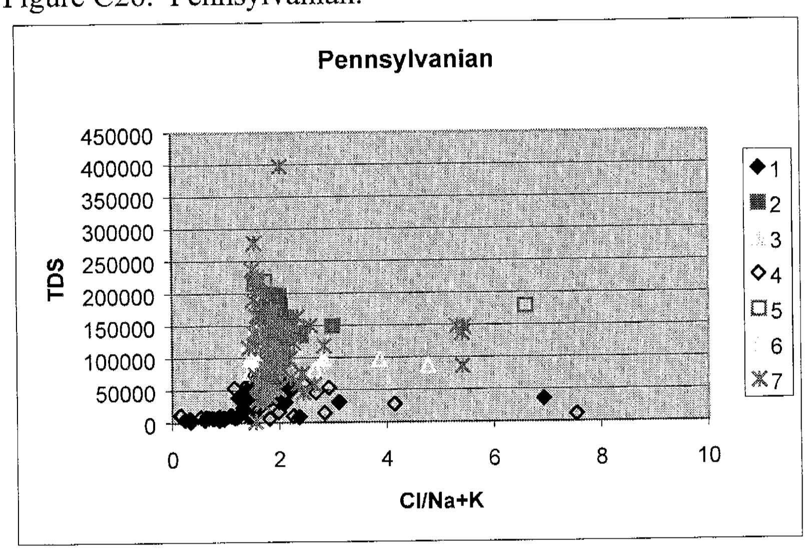


Figure C27. Artesia Group.

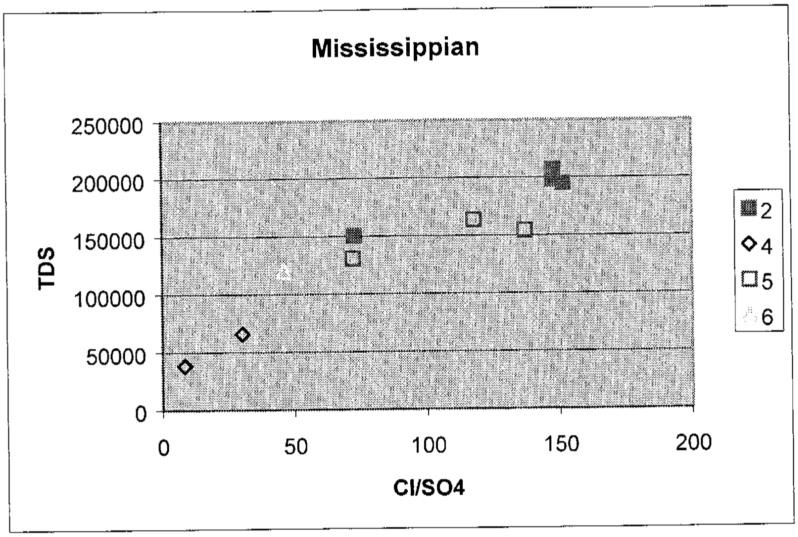


Figure C28. Mississippian.

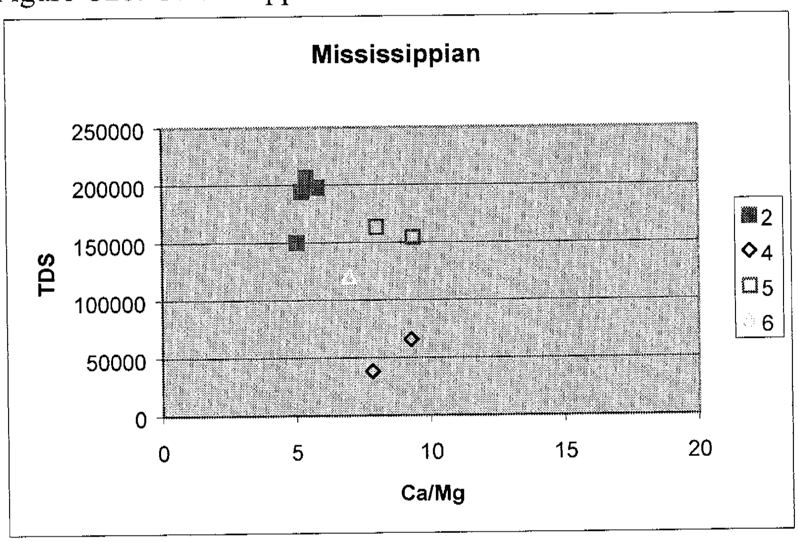


Figure C29. Mississippian.

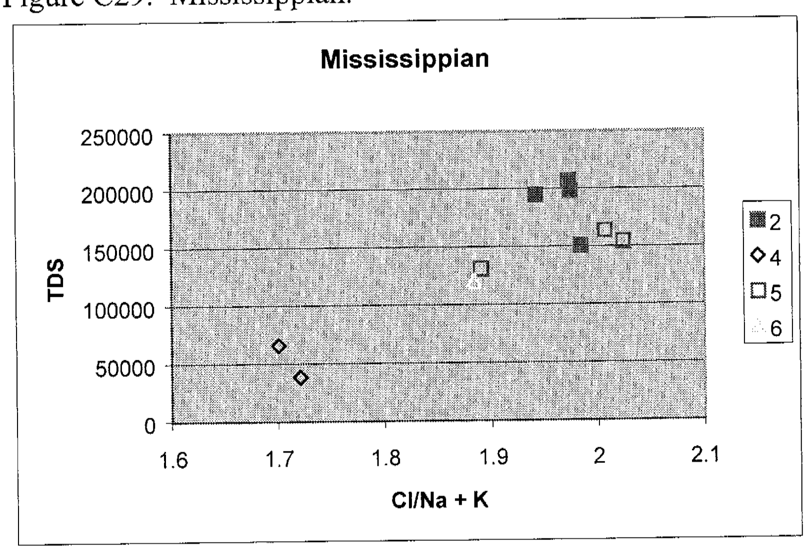


Figure C30. Mississippian.

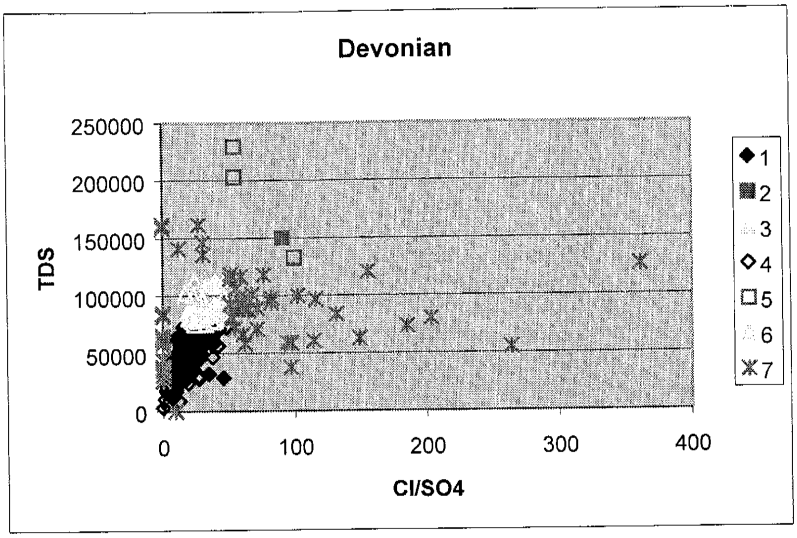


Figure C31. Devonian.

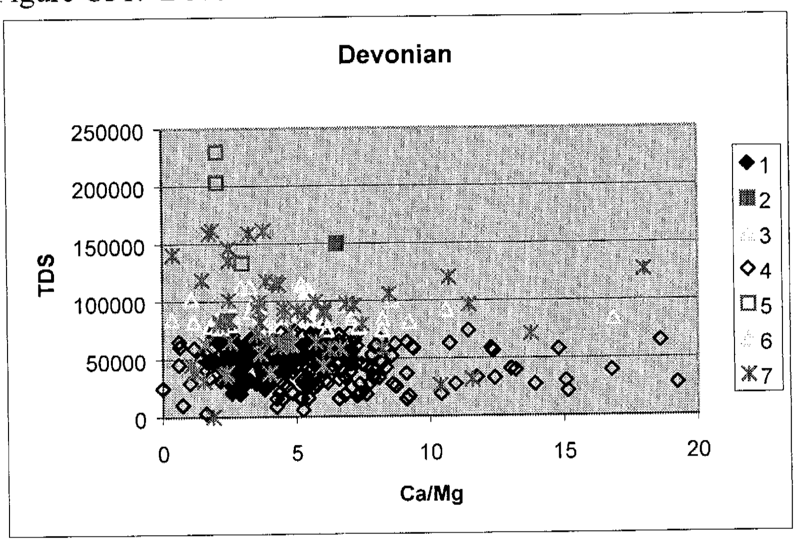


Figure C32. Devonian.

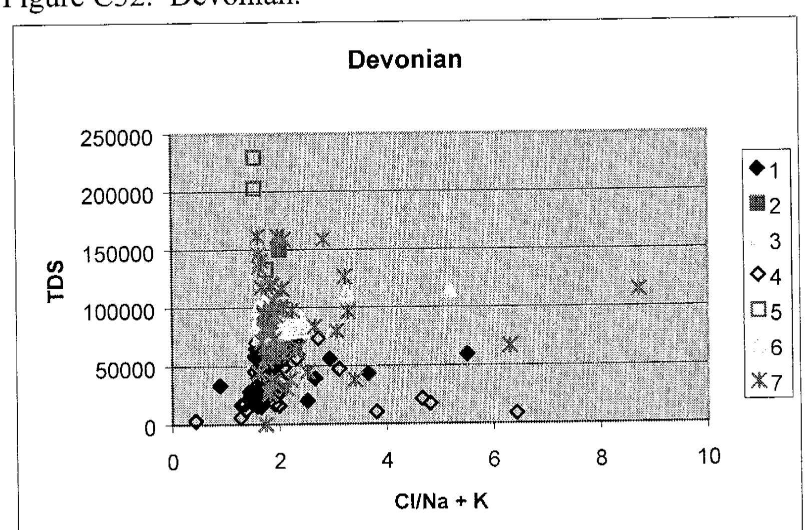


Figure C33. Devonian.

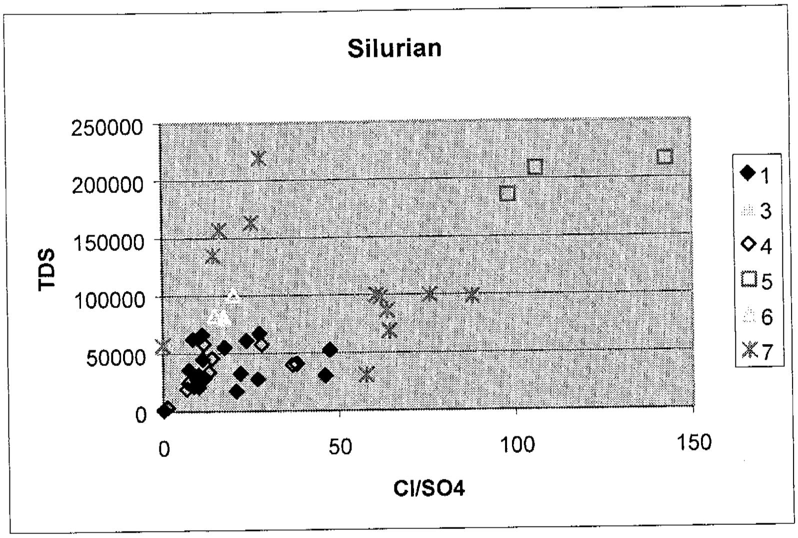


Figure C34. Silurian.

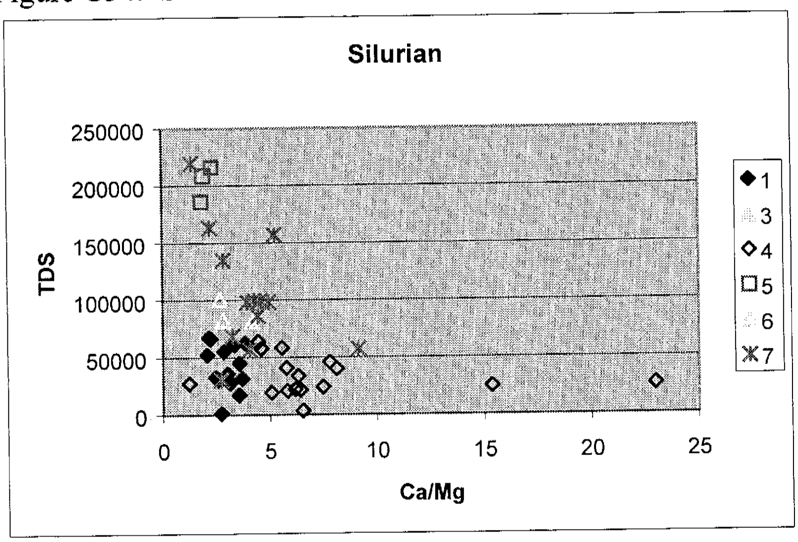


Figure C35. Silurian.

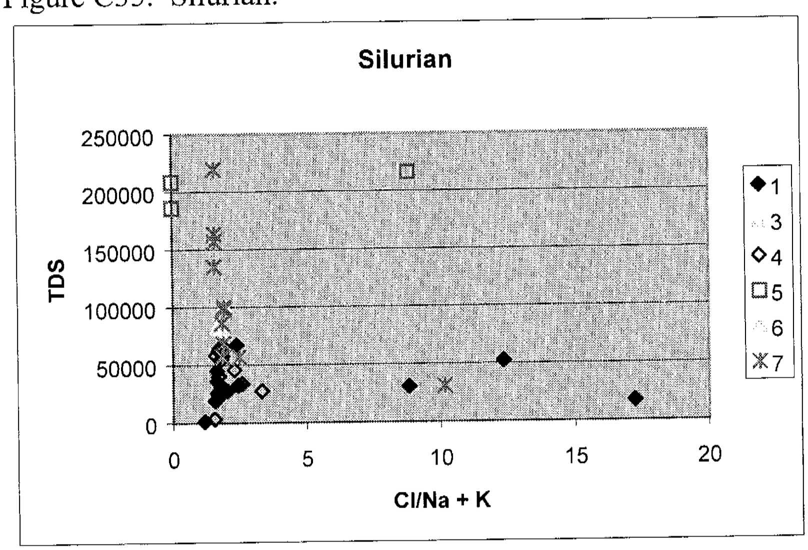


Figure C36. Silurian.

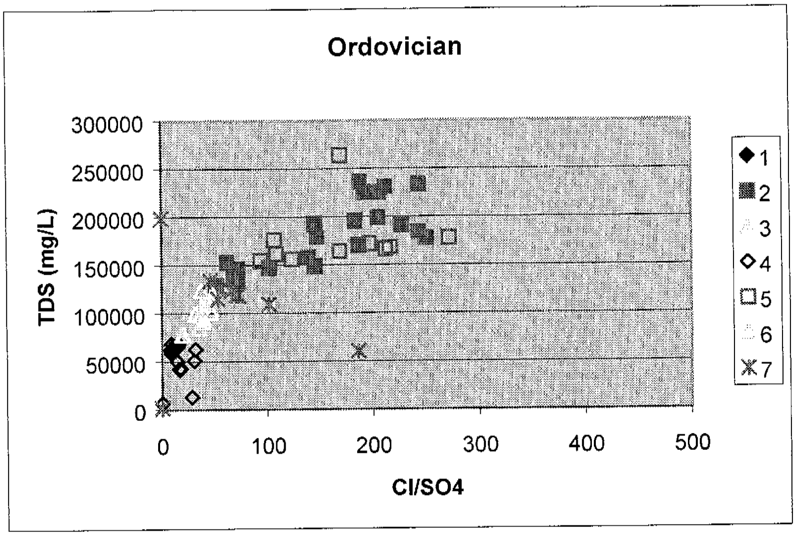
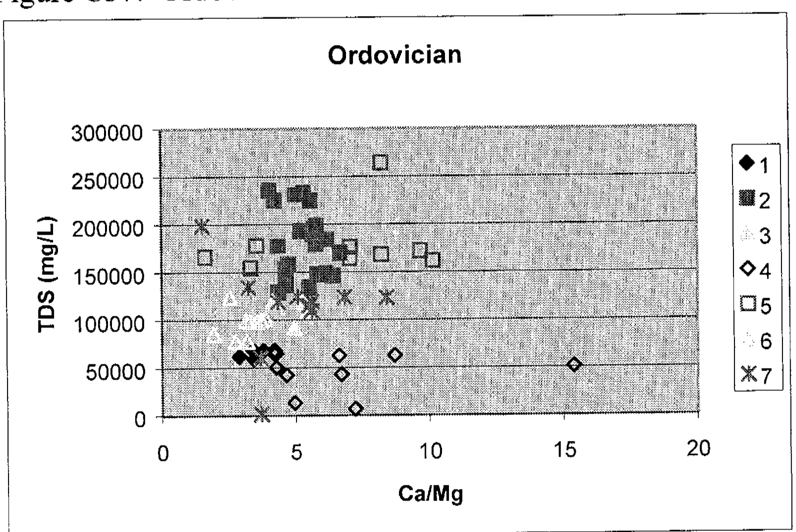


Figure C37. Ordovician.



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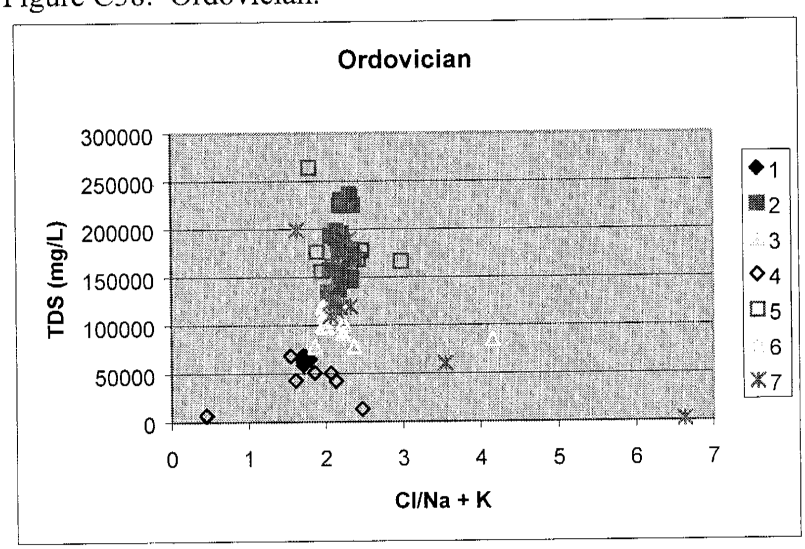

Figure C39. Ordovician.

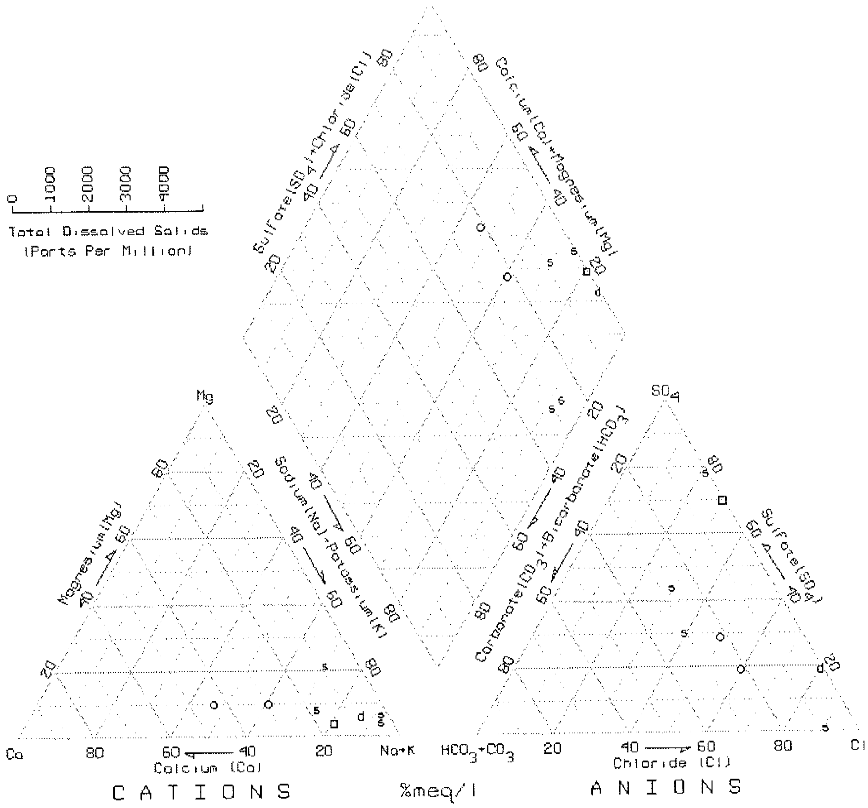

Figure C40. Piper diagram of Dewey Lake, Santa Rosa, Ogallala produced water samples.

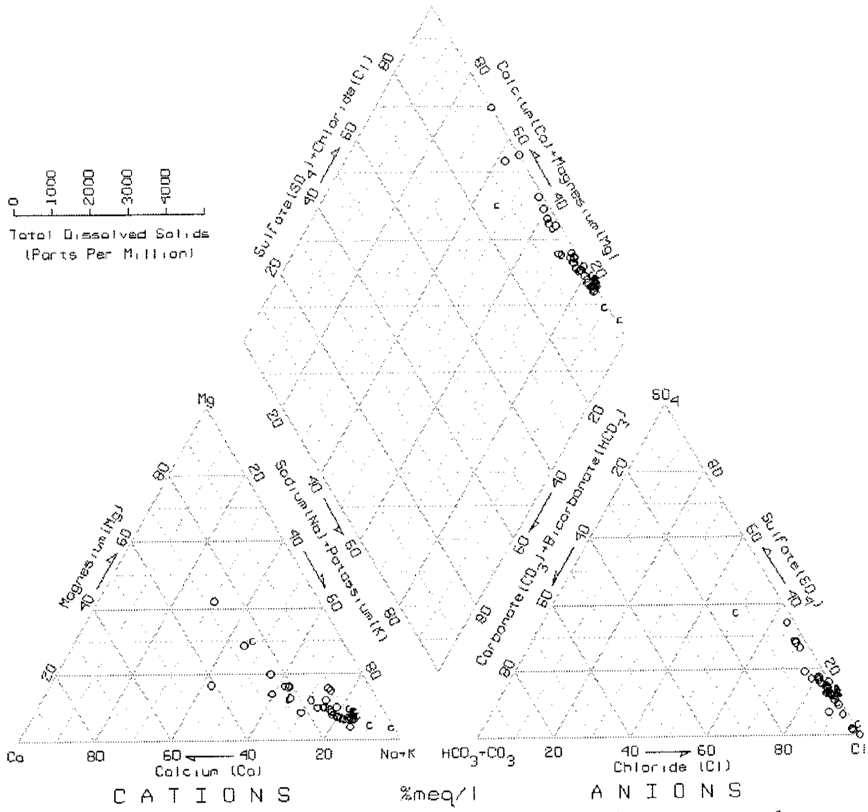

Figure C41. Piper diagram of Capitan produced water samples.

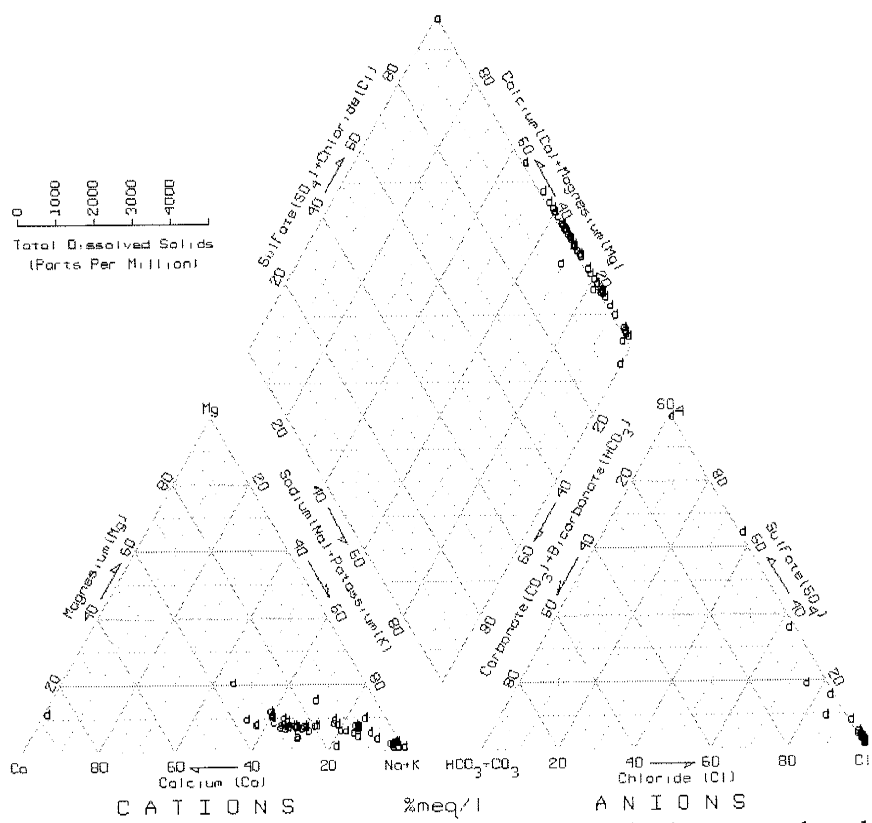

Figure C42. Piper diagram of Delaware Mountain Group produced water samples.

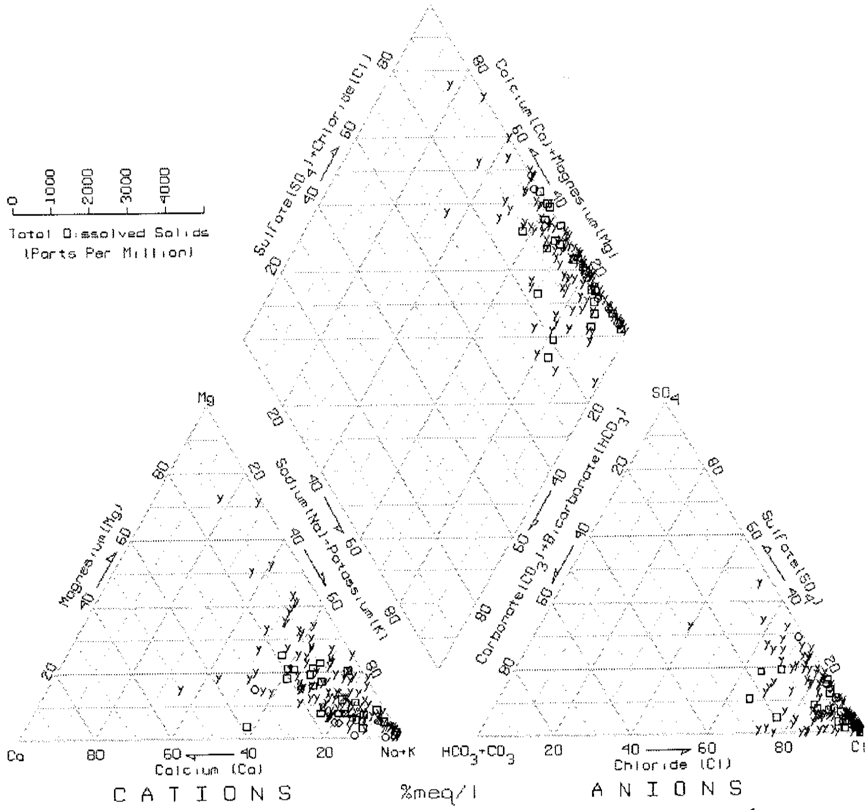

Figure C43. Piper diagram of Yates produced water samples.

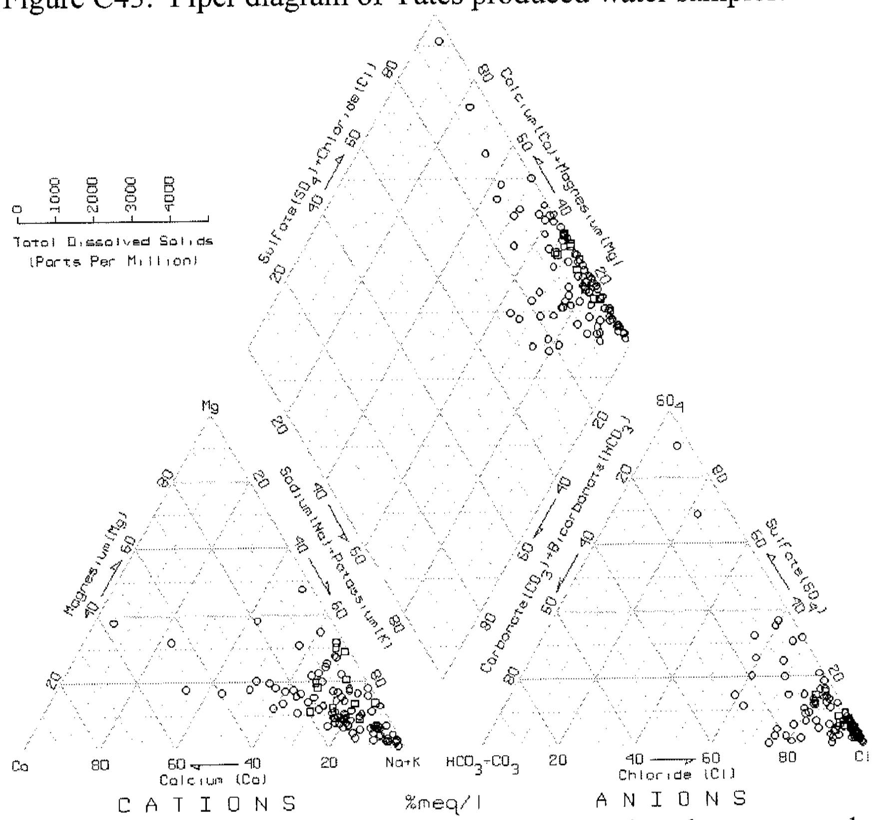

Figure C44. Piper diagram of Seven Rivers produced water samples.

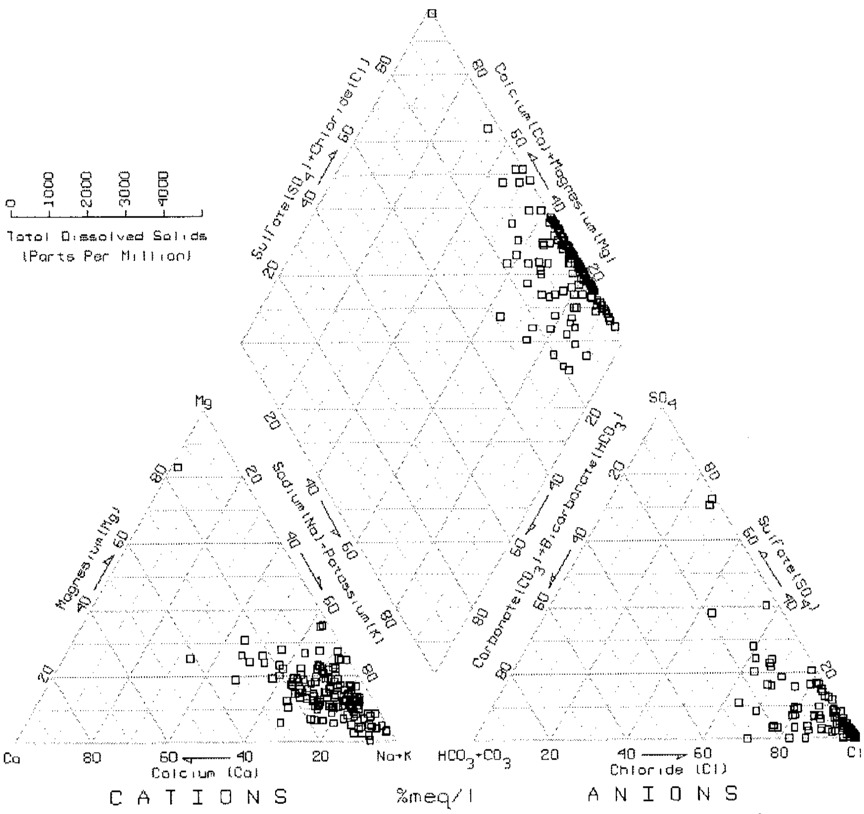

Figure C45. Piper diagram of Queen produced water samples.

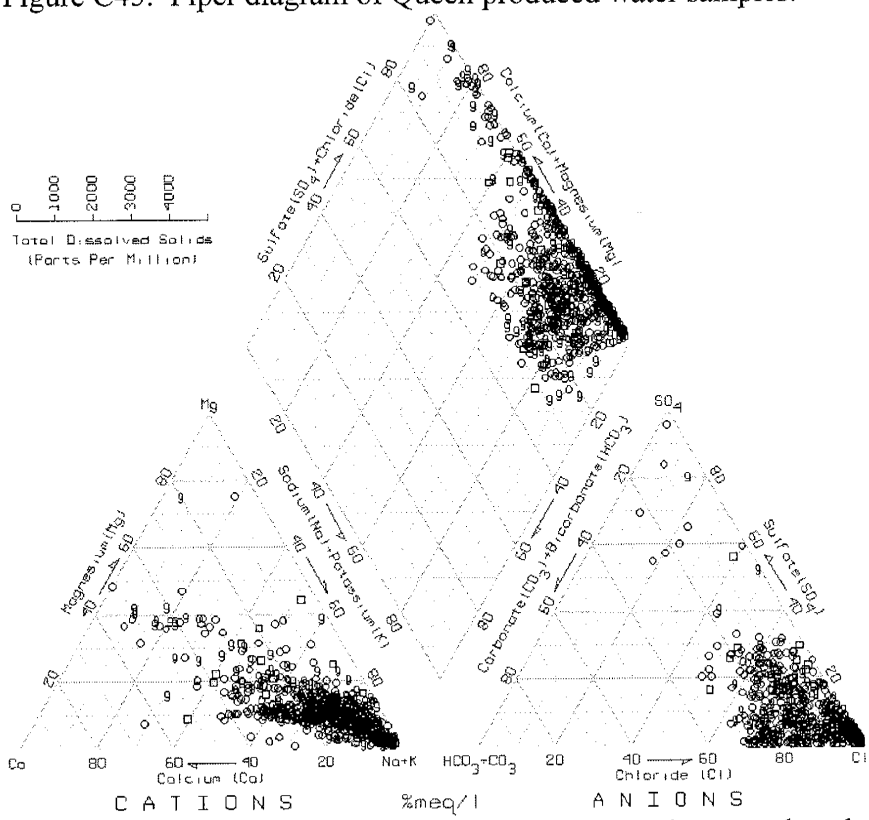

Figure C46. Piper diagram of San Andres and Grayburg produced water samples.

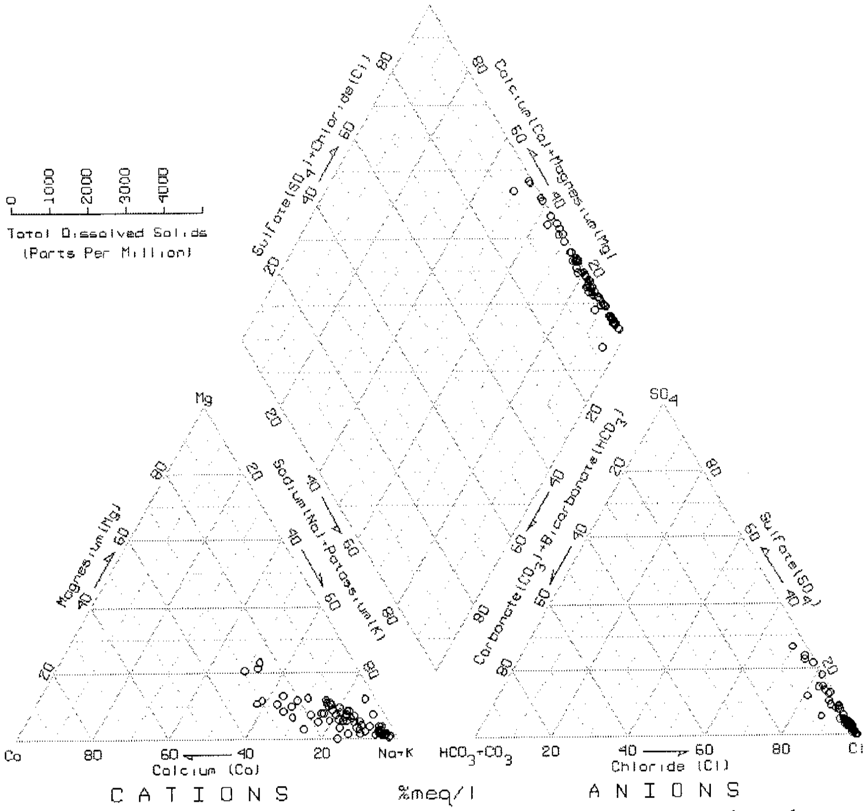

Figure C47. Piper diagram of Leonardian (Glorieta) produced water samples.

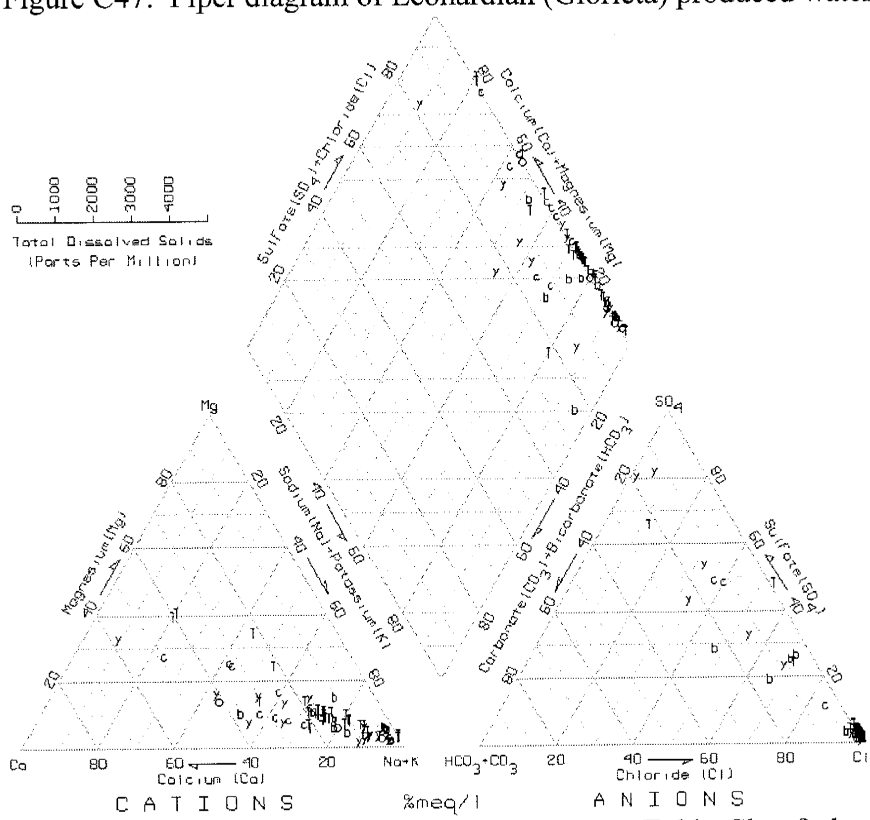

Figure C48. Piper diagram of Leonardian (Yeso, Tubb, Clearfork, and Bone Spring) produced water samples.

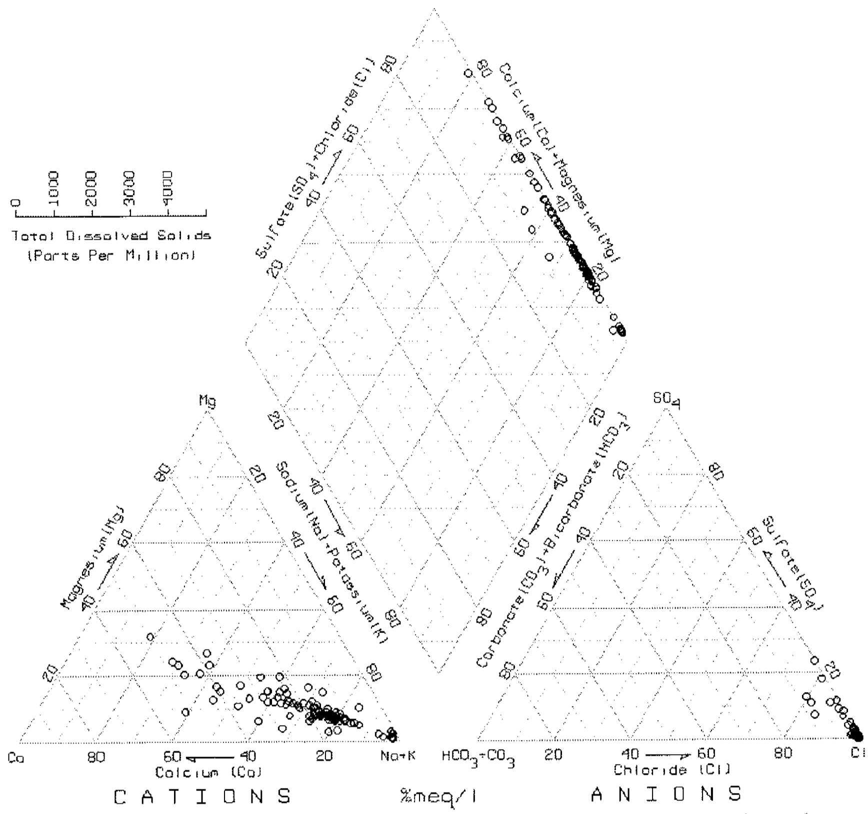

Figure C49. Piper diagram of Leonardian (Drinkard) produced water samples.

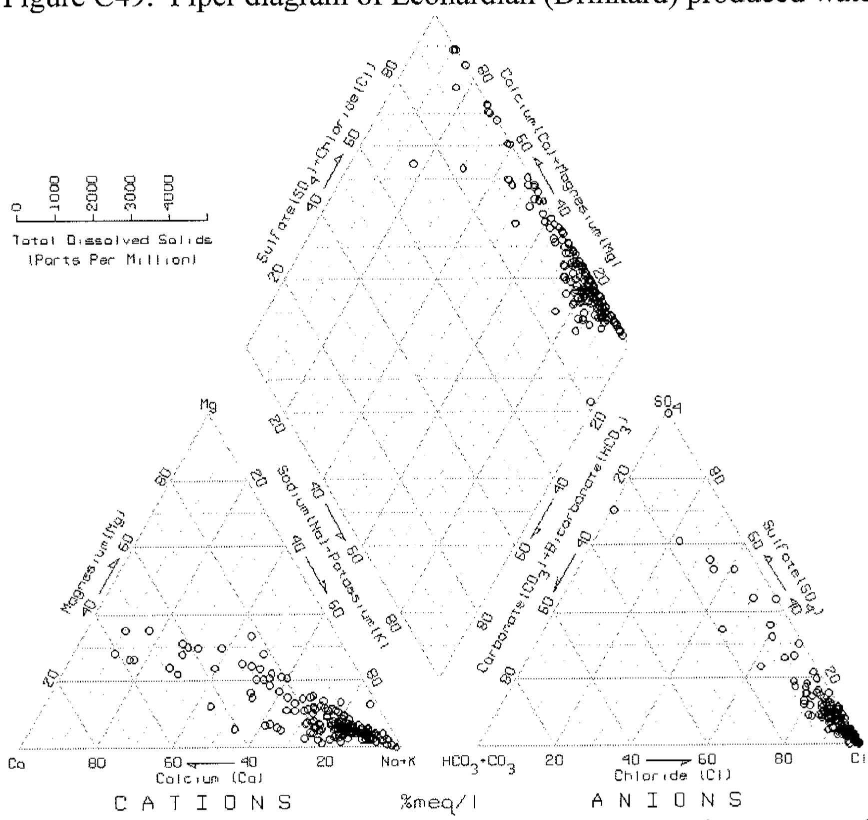

Figure C50. Piper diagram of (Leonard) Abo produced water samples.

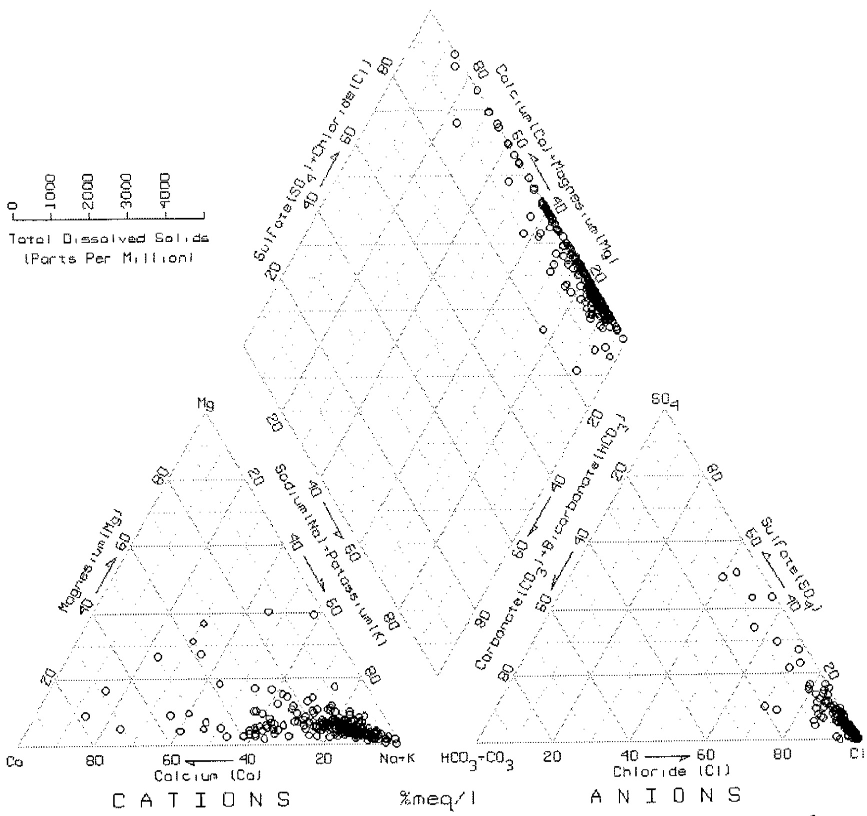

Figure C51. Piper diagram of Wolfcamp produced water samples.

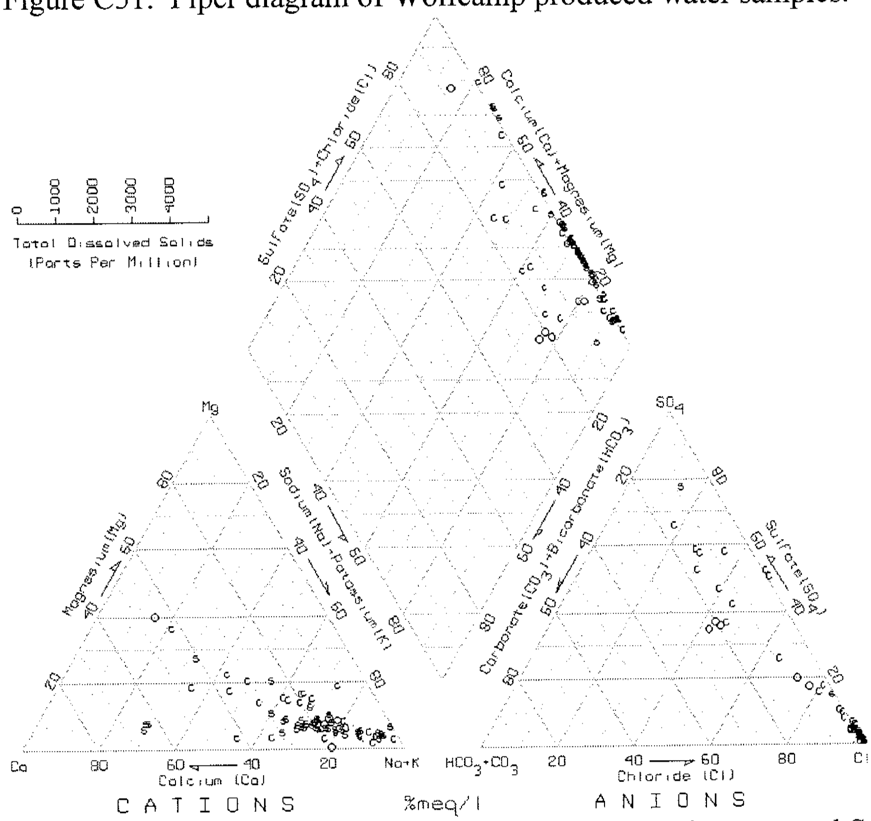

Figure C52. Piper diagram of Pennsylvanian Cisco, Canyon, and Strawn produced water samples.

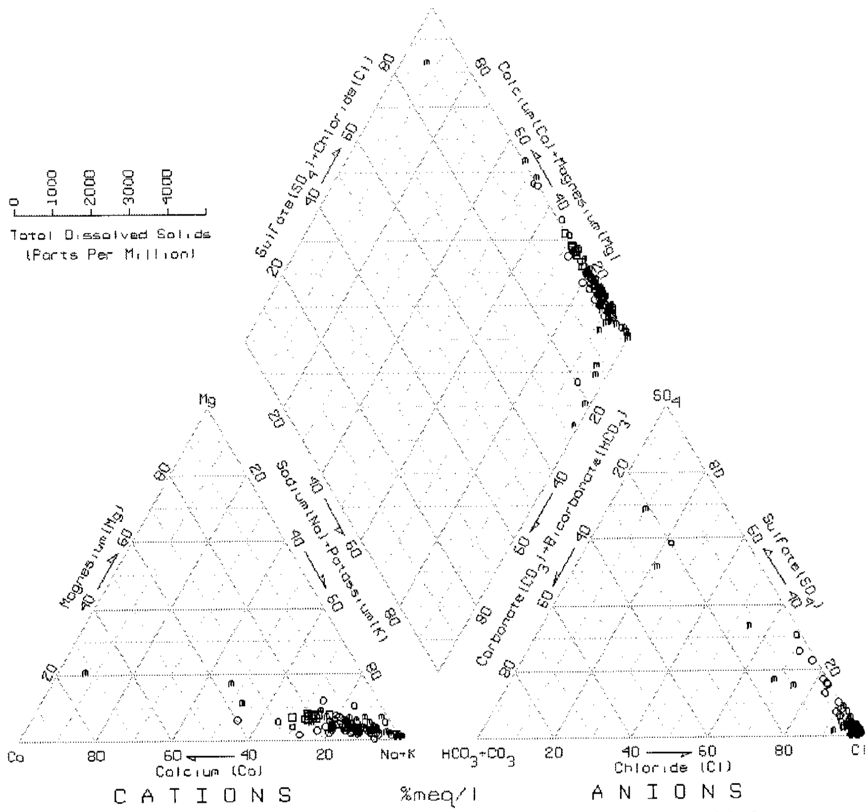

Figure C53. Piper diagram of Pennsylvanian Atoka and Morrow produced water samples.

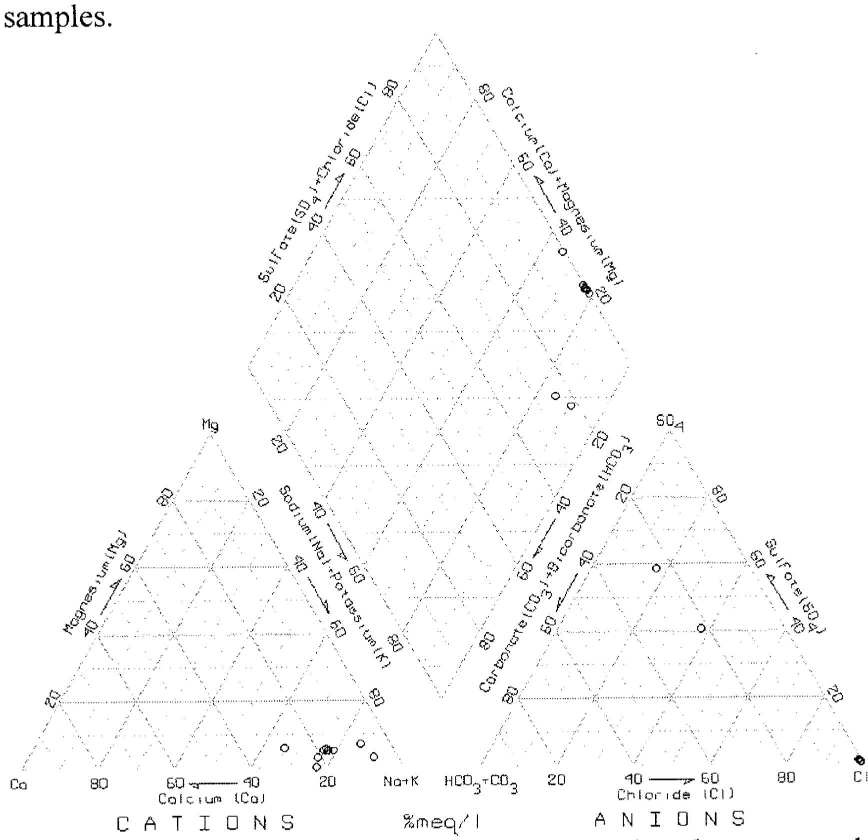

Figure C54. Piper diagram of Mississippian produced water samples.

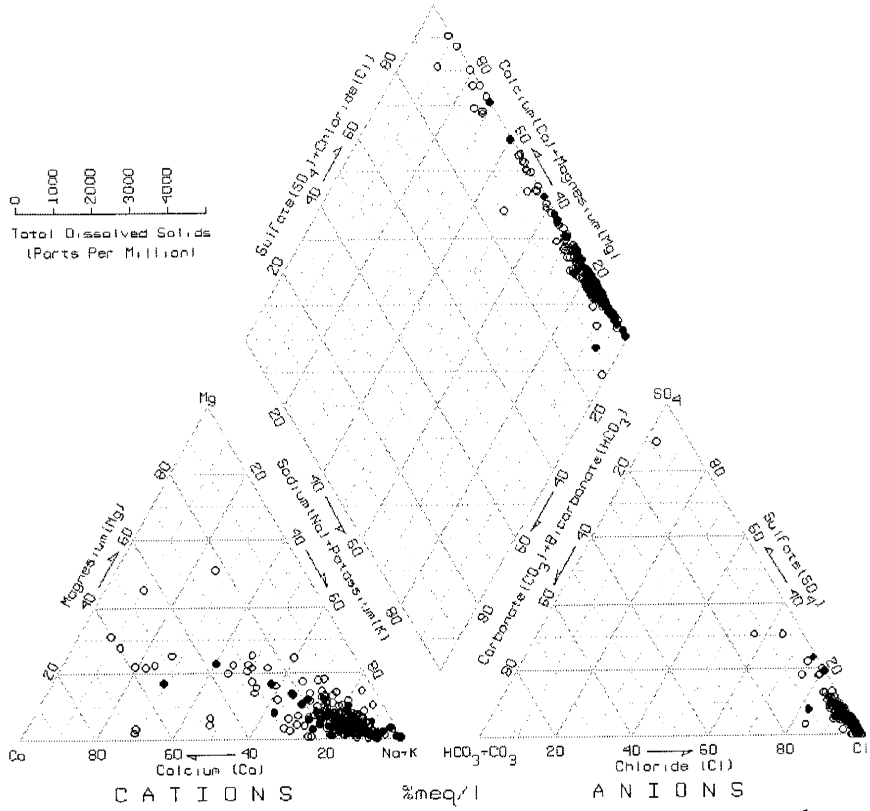

Figure C55. Piper diagram of Devonian produced water samples.

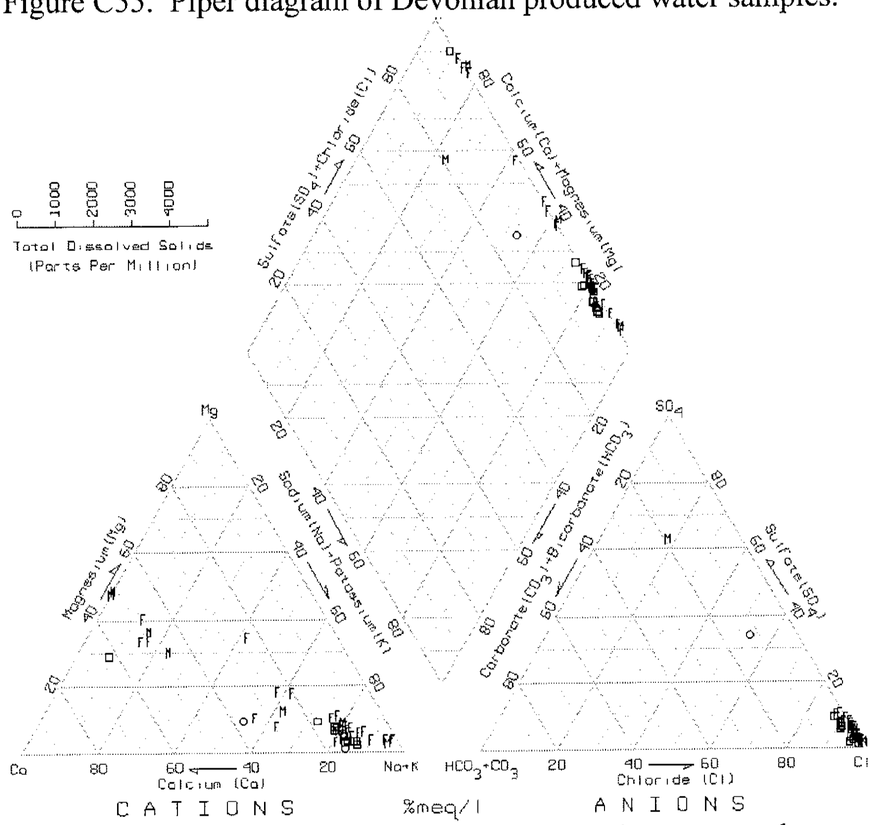

Figure C56. Piper diagram of Silurian produced water samples.

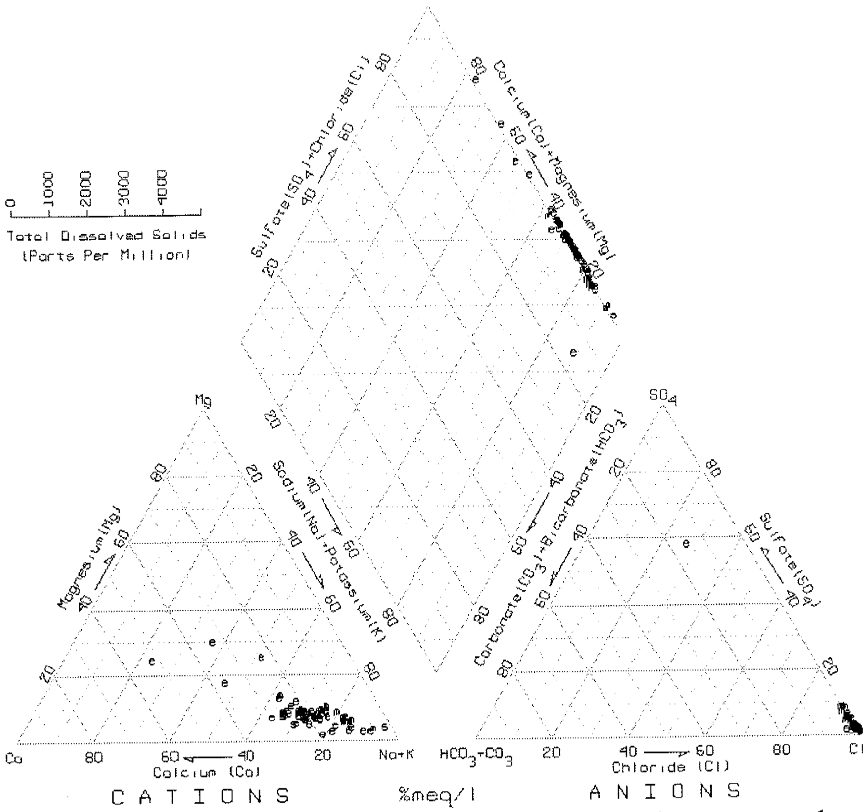

Figure C57. Piper diagram of Ordovician produced water samples.

This Thesis is accepted on behalf of the faculty
of the Institute by the following committee:

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Academic Adviser

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Research Advisor

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Committee Member

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Committee Member

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Committee Member

16 January 2004
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Date

I release this document to New Mexico Institute of Mining and Technology

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Students Signature Date