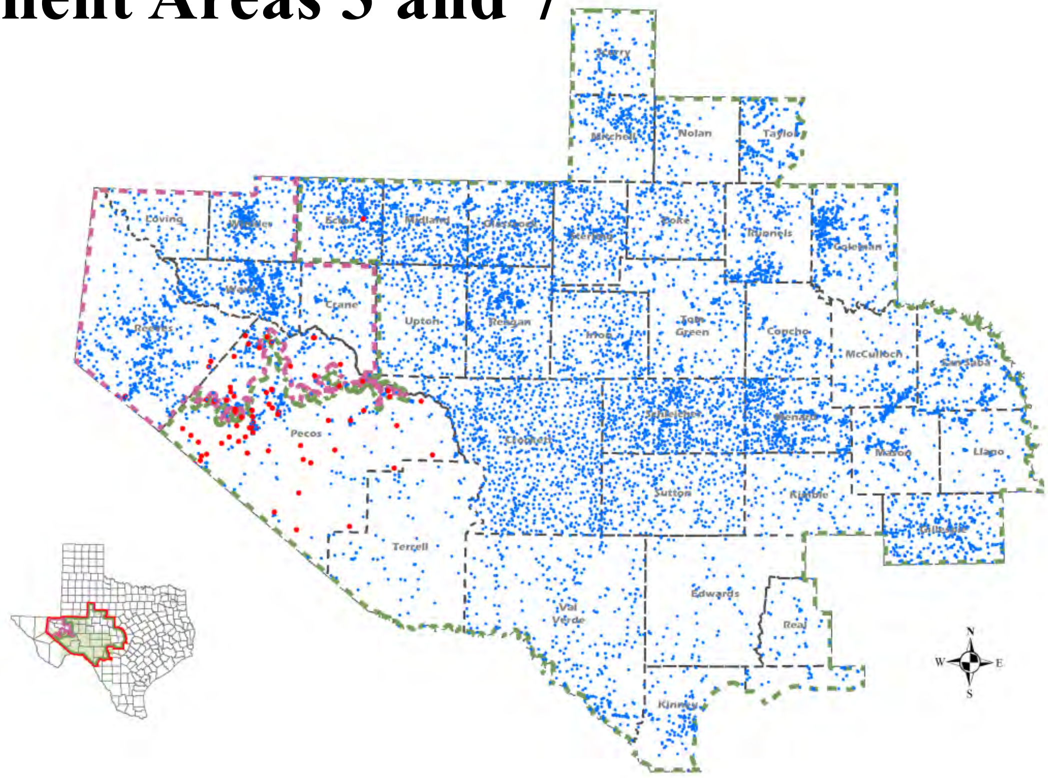
Evaluation of Hydrochemical and Isotopic Data in Groundwater Management Areas 3 and 7



Prepared for:
Texas Water Development Board
May 2013

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1 Executive Summary

The Texas Water Development Board (TWDB) has collected hydrochemical and isotope data in Groundwater Model Areas (GMA) 3 and 7 for over a decade. This study is a comprehensive assessment of the data that has been collected and of new data collected in selected areas. Because the TWDB has several GAMs located throughout GMA 3 and 7, the existing hydrochemical and isotope data was evaluated to assess the conceptual models of these Groundwater Availability Models (GAM) and to support ongoing GAM development and refinement efforts for all aquifers in the study area. Conceptual model development and refinement is important to the TWDB GAM program as the models are living tools that can be updated with recent data and research results.

The geochemical and isotopic data confirm many elements of the conceptual models that have been used to develop GAMs in GMA 3 and 7. The data also provide new insights into the aquifer systems and how they vary from east to west across a large portion of Texas. The findings and conclusions help guide GAM use and application as well as conceptual model changes that might be addressed in GAM updates. The study also provides potential next steps for GAM improvement and for development of sub-regional models.

Data from the Llano Uplift Aquifers have provided insight into those aquifers that encircle the Precambrian core. The hydrogeology of the Ellenburger-San Saba Aquifer, Hickory Aquifer, and the Marble Falls Aquifer vary based on their geologic setting around the Llano Uplift area. The two main aquifers of the Llano Uplift are the Ellenburger-San Saba Aquifer and the Hickory Aquifer. Critical points include:

- On the north side, the Hickory Aquifer is the dominant aquifer. The active flow system is primarily in the outcrop with recharge across the outcrop and discharge to the San Saba River. Deep groundwater in northern McCulloch County is considered old and stagnant.
- On the south side, the Hickory Aquifer and the Ellenburger-San Saba Aquifer are isolated in individual fault blocks. Leakage from the overlying Hensell Formation may be the primary source of recharge. For the Ellenburger-San Saba, groundwater discharge is probably to the Pedernales River.
- On the east side, the Ellenburger-San Saba Aquifer is the primary aquifer. Tectonics has isolated the Ellenburger-San Saba Aquifer into three sections, a northern, middle and a southern section. Recharge appears to be within the outcrop and discharge is to local streams, springs and rivers. Groundwater flow is considered to be local rather than regional.

Evaluation of the hydrochemical and isotope data for the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer confirms that recharge decreases significantly from east to west. The recharge estimates for the Edwards-Trinity (Plateau) GAM are based on percent of average annual precipitation, but do not incorporate a threshold approach as incorporated for other GAMs in west Texas, such as the Igneous and Bolson GAM (Beach and others, 2004). This approach may also be appropriate for the western portions of the Edwards-Trinity (Plateau) GAM. Isotope data from the Edwards-Trinity (Plateau) Aquifer indicate much younger waters probably due to the karstic nature of the aquifer. Groundwater in the Trinity Group (Antlers Formation) and the Pecos Valley Aquifer appear to be generally older water, which indicates that recharge from recent times has been much more limited to the Edwards-Trinity (Plateau) Aquifer. In addition, the hydrochemical and isotope data show a clear distinction between groundwater in the Trinity Group (Antlers Formation) and that in the Edwards Formation to the east. Potentiometric surfaces and the existing Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM indicate consistent flow across the zone, which is not necessarily supported by the data. The Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM should be reevaluated to assess whether it would be beneficial to separate the western portion of Edwards-Trinity (Plateau) Aquifer from the eastern portion.

In the Trans-Pecos Region, three conceptual models were developed that describe and characterize cross-formational flows between several of the important aquifers in the region. The first conceptual model is a large, regional-scale, flow system that is transmitting water from the bolson aquifers in Culberson County through the fractured Permian basin filled strata associated with the Capitan Reef Complex Aquifer GAM into the westernmost extent of the Cretaceous Edwards-Trinity (Plateau) and Pecos Valley Aquifer GAM.

The second conceptual model identifies lateral cross-formational flow moving east from the Rustler Aquifer outcrop area in Culberson County into the western half of the Pecos Valley Aquifer in Reeves County. The results also indicate that the groundwater chemistry in the eastern half of the Pecos Valley Aquifer is probably affected by irrigation return flows or by infiltration of the Pecos River water that was applied for irrigation.

The third conceptual model identifies localized upwelling of deeper waters from the Capitan and Rustler Formations into the Edwards-Trinity (Plateau) Aquifer in the Monument-Belding Trough area south of IH-10 in Pecos County.

2 Introduction

The TWDB has collected hydrochemical and isotope data in GMAs 3 and 7 for over a decade. Prior to this study, a comprehensive assessment of this data has not been undertaken. Because the TWDB has several GAMs located throughout GMA 3 and 7, the existing hydrochemical and isotope data offered a great opportunity to evaluate the conceptual models for the aquifer systems and the GAMs in the study area. In addition to evaluating the existing data, new data was also collected in selected areas and analyzed to help evaluate the existing conceptual models and to support ongoing GAM development efforts for minor aquifers.

The major aquifers in GMAs 3 and 7 include: the Edwards-Trinity (Plateau) Aquifer, the Pecos Valley Aquifer, the Trinity Aquifer and the Ogallala Aquifer as shown in Figure 2-1. Major aquifer GAMs in GMAs 3 and 7 include the Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM (Anaya and Jones, 2009) and the Ogallala Aquifer (southern portion) GAM (Blanford and others, 2003).

The minor aquifers in GMAs 3 and 7 include: the Igneous Aquifer, the Dockum Aquifer, the Capitan Reef Complex Aquifer, the Rustler Aquifer, the Ellenburger-San Saba Aquifer, the Hickory Aquifer, the Lipan Aquifer and the Marble Falls Aquifer as shown in Figure 2-2. At the time the study was completed, GAMs did not exist for the Capitan Reef Complex Aquifer, the Hickory Aquifer, the Ellenburger-San Saba Aquifer or the Marble Falls Aquifer. Minor aquifer GAMs in GMA 3 and 7 include the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) and Igneous Aquifers GAM (Beach and others, 2008), the Dockum Aquifer GAM (Ewing and others, 2008), the Rustler Aquifer GAM (Ewing and others, 2012) and the Lipan Aquifer GAM (Beach and others, 2004). Figure 2-3 shows the model boundaries for the GAMs in GMA 3 and 7. It should be noted that the models for the Ogallala and Lipan aquifers were not considered in this report. This study focused on three different hydrogeologic settings (far west Texas, the Edwards-Trinity Plateau and the aquifers in the Llano region) as being representative of the major aquifers in the GMA 3 & 7 region. It was considered to be more important to place emphasis in these areas than in a small section of the Ogallala Aquifer or the Lipan Aquifer.

An attempt was made to collect data from aquifers in the Trans Pecos region, but gaining access to appropriate wells was not successful. Therefore, data from the recent United States Geological Survey (USGS) study (Pearson and others, 2012) in Pecos County was used to help research the dynamics of several aquifers in that region.

Research completed by Nance (2010) was used as the starting point for the assessment of the Edwards-Trinity (Plateau) Aquifer. Because there has been extensive and recent research done on the Edwards-Trinity (Plateau) Aquifer, new groundwater samples were not collected from that aquifer.

In the Llano Uplift area, a review of available chemical and isotopic data along the hypothesized hydrogeologic setting for the Hickory Aquifer, Ellenburger-San Saba Aquifer and Marble Falls Aquifer indicated a higher density of previously collected data in Mason, McCulloch and Gillespie counties. To supplement this data, additional samples were collected in Gillespie and Burnet counties to provide more insight into various sections of the Llano Uplift Aquifers.

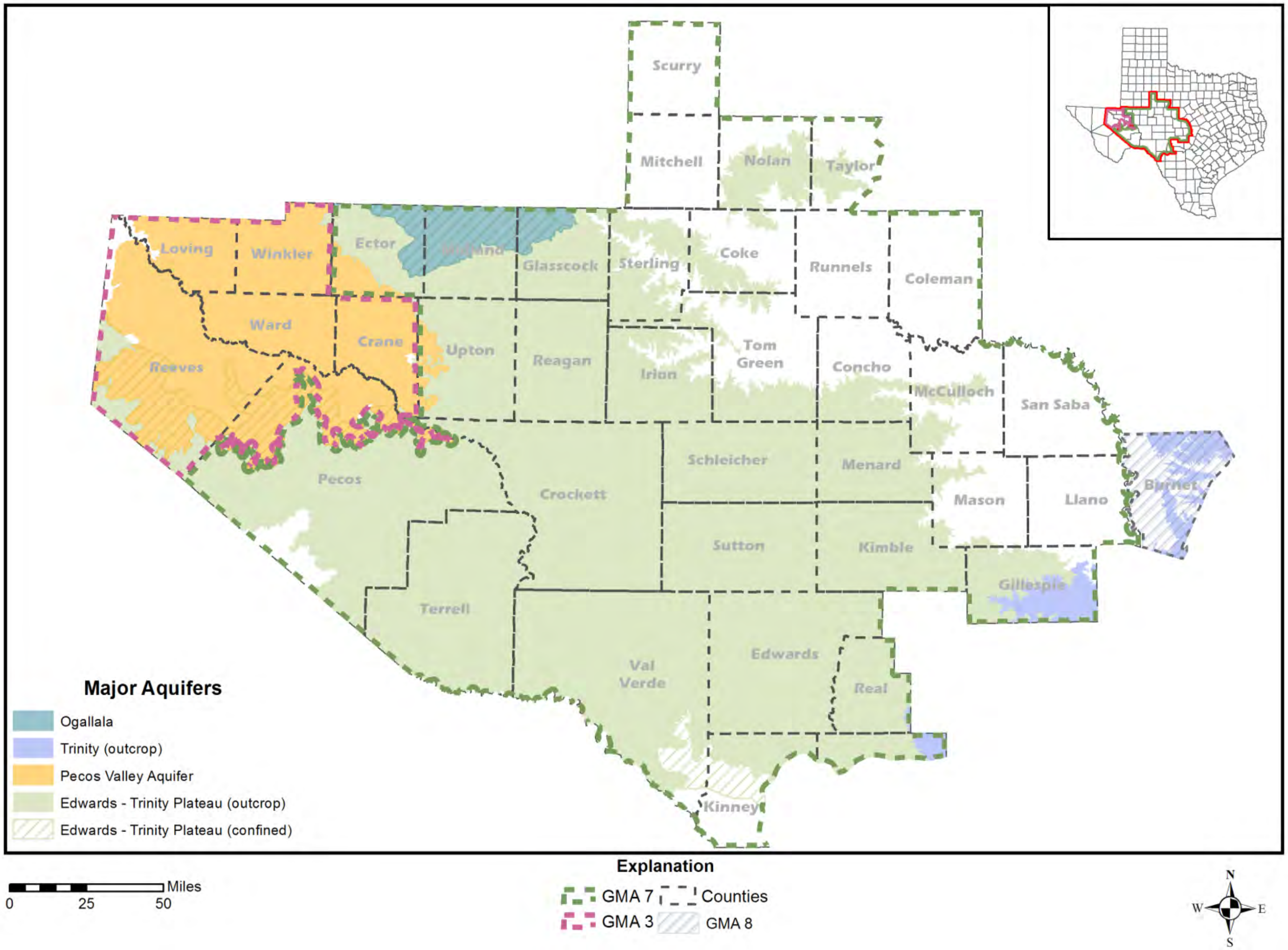


Figure 2-1. **Location of major aquifers in GMAs 3 & 7.**

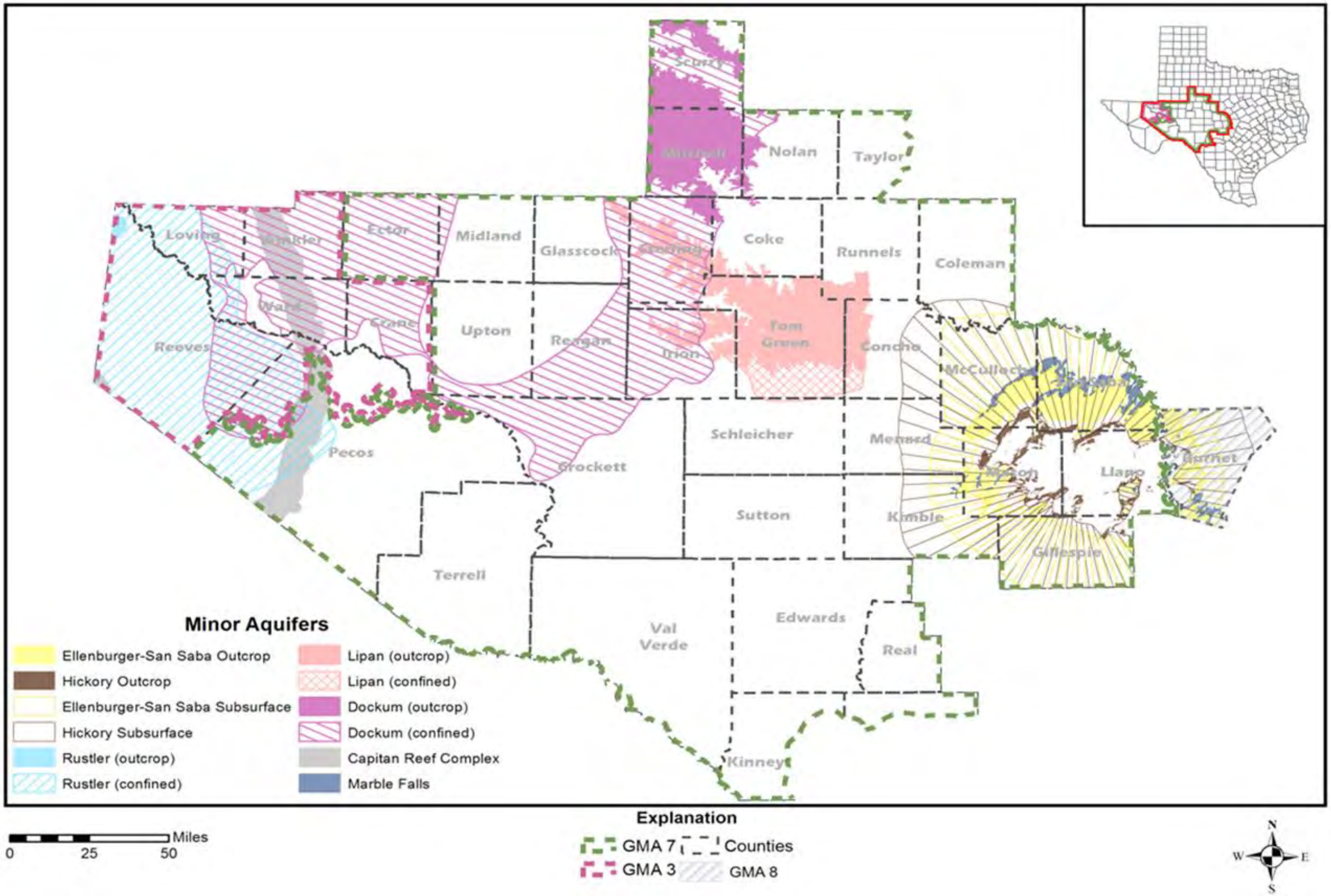


Figure 2-2. Location of minor aquifers in GMAs 3 & 7.

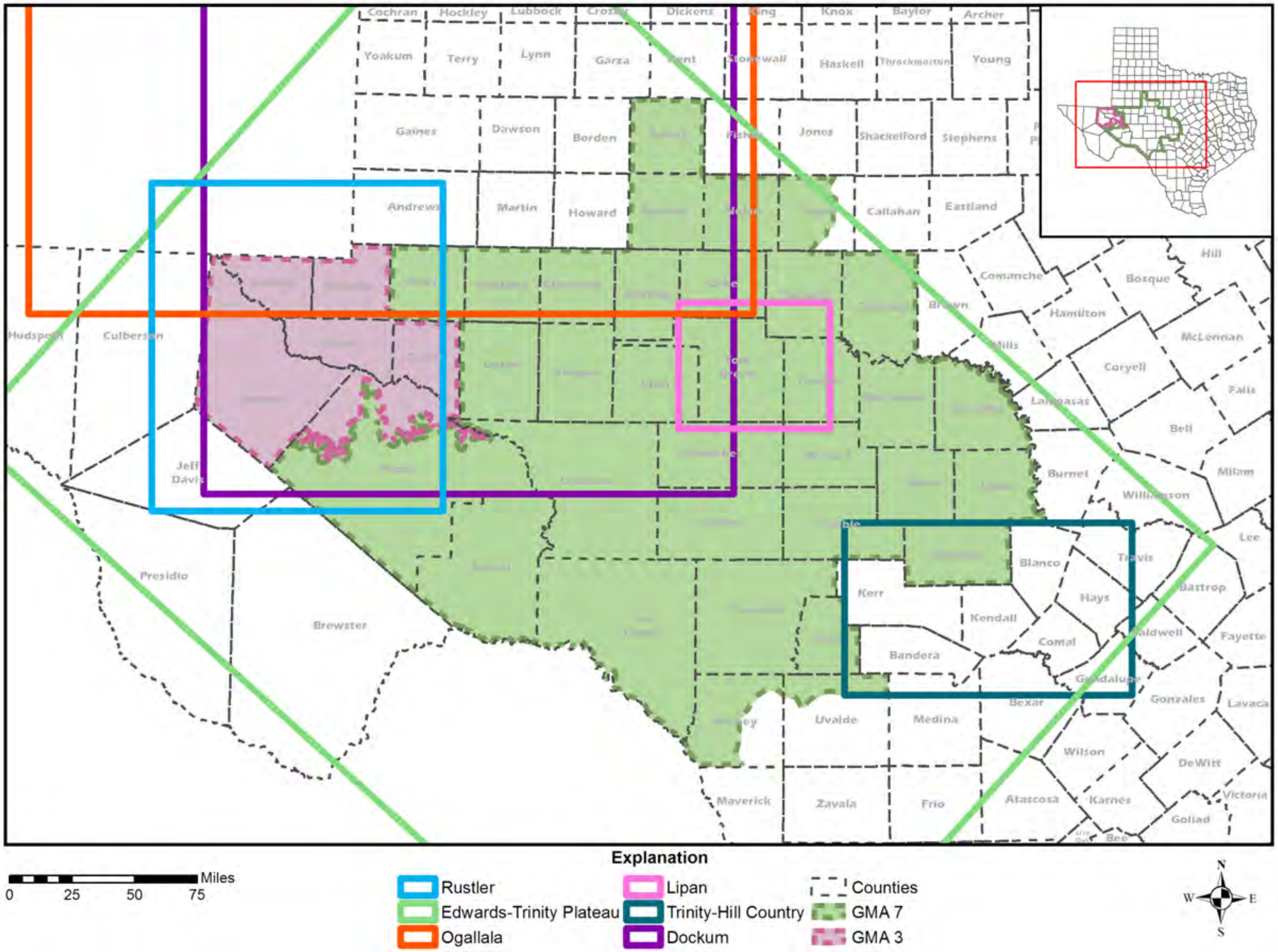


Figure 2-3. **Location of existing TWDB GAMs in GMAs 3 and 7.**

3 Approach for Evaluating Aquifers in the Study Area

The goals of the project were to collect new data and to use existing data to assess the conceptual models for the GAMs in GMA 3 and 7. The GAMs in GMA 3 and 7 include the Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM, the Ogallala Aquifer (southern portion) GAM, the Dockum Aquifer GAM, the Lipan Aquifer GAM, the Rustler Aquifer GAM and the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat) and Igneous Aquifer GAM. The major aquifers included in those GAMs are the Edwards-Trinity (Plateau) Aquifer, the Pecos Valley Aquifer, the Trinity Aquifer and the Ogallala Aquifer. The minor aquifers included in those GAMs are the Dockum Aquifer, the Lipan Aquifer, Igneous Aquifer and Rustler Aquifer. At the time the study was completed, GAMs did not exist for the Capitan Reef Complex Aquifer, the Hickory Aquifer, the Ellenburger-San Saba Aquifer, or the Marble Falls Aquifer, all of which are minor aquifers.

After review of the major and minor aquifers (Figure 2-1 and Figure 2-2) and the hydrochemistry and isotope data, three unique geographic and hydrogeologic areas were selected for a more detailed study. These areas include:

1. The Llano Uplift Aquifers, which included the Hickory Aquifer, the Ellenburger-San Saba Aquifer and the Edwards-Trinity (Plateau) Aquifer.
2. Aquifers of the Edwards-Trinity (Plateau) that comprise the Edwards-Trinity Plateau Aquifer and underlying aquifers in the western region of the Plateau.
3. Aquifers of the Trans-Pecos region, with a focus on the Edwards-Trinity (Plateau) Aquifer and other aquifer systems that interact with the Edwards-Trinity (Plateau) Aquifer. The “interacting” aquifers include the western groundwater system that flows on the north side of the Davis Mountains (mountain front recharge), the Pecos Valley Aquifer, the Dockum Aquifer, the Capitan Reef Complex Aquifer and the Rustler Aquifer.

This provides a wide geographic coverage of the aquifers in GMA 3 and 7 as shown in Figure 3-1. Each geographic and hydrogeological area has a specific set of questions that need to be asked in developing or updating the current conceptual groundwater flow model for each area.

3.1 Llano Uplift Aquifers

The TWDB is currently developing a GAM for the Llano Uplift Aquifers and a conceptual model is needed. The Paleozoic Hickory Aquifer and the Ellenburger-San Saba Aquifer ring the Llano Uplift area. They crop out at the Llano Uplift area and then dip away from the core into the subsurface. The Hickory Aquifer and the Ellenburger-San Saba Aquifer are faulted at different locations around the Llano Uplift area creating a complex network of fault blocks which can create some isolation of aquifers within discrete fault blocks.

At some locations the Edwards-Trinity (Plateau) Aquifer overlie the Paleozoic aquifers of the Llano Uplift area. The Hickory Aquifer and the Ellenburger-San Saba Aquifer may subcrop immediately beneath the Edwards-Trinity (Plateau) Aquifer where there may be hydrologic communication between the Edwards-Trinity (Plateau) Aquifer and Paleozoic aquifers.

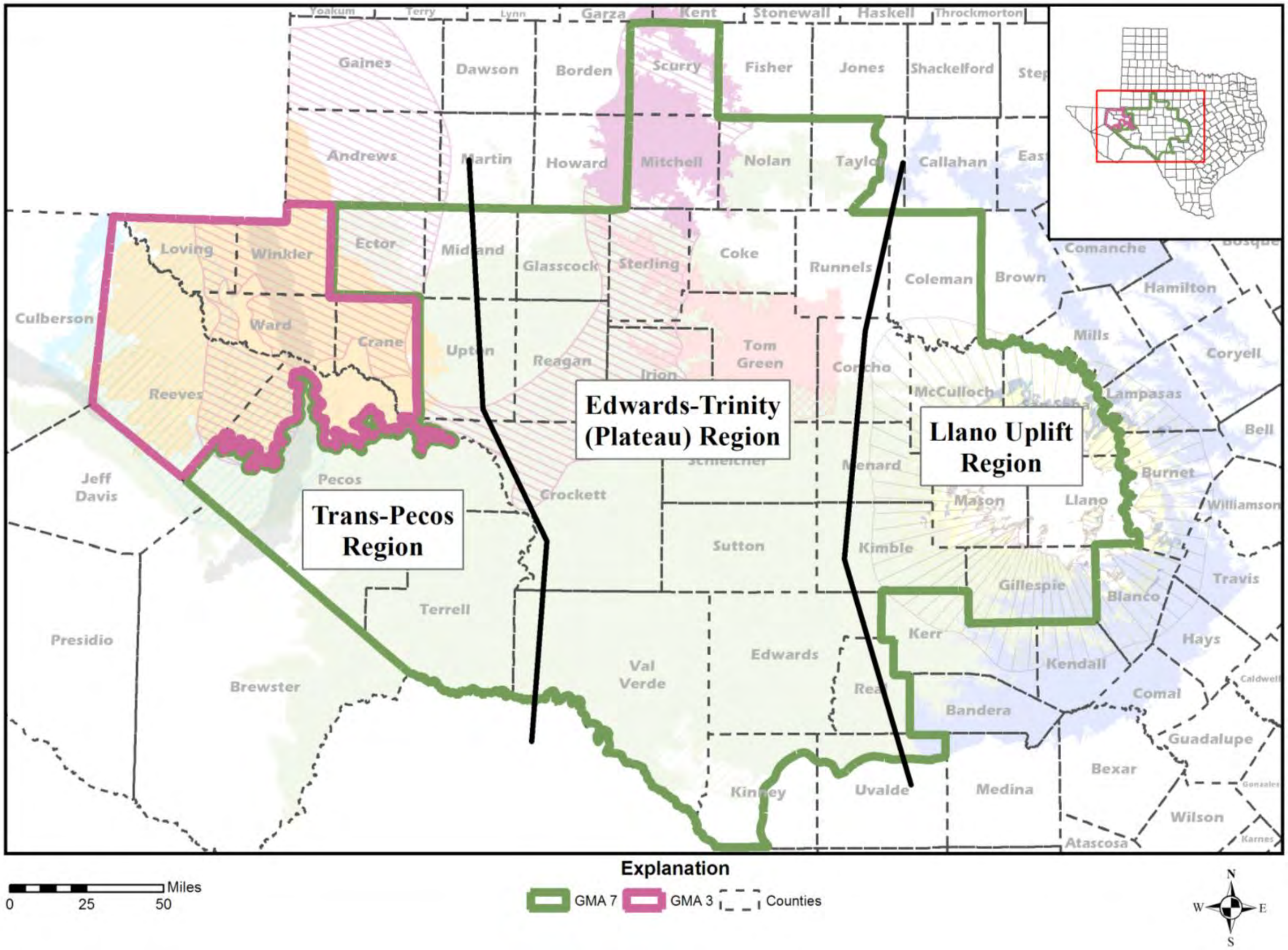


Figure 3-1. GMAs 3 and 7 study area divisions.

In some Texas aquifers, there are consistent chemical changes or trends as groundwater flows down the hydraulic gradient and therefore can be used as a proxy for groundwater flow directions. The Carrizo-Wilcox Aquifer in northeast Texas is an example where the chemical composition of major anions and cations change with down gradient flow. Water chemistry in the Carrizo-Wilcox Aquifer outcrop typically is a calcium-sulfate-bicarbonate-chloride water, whereas, down gradient water in confined sections has the general composition of a calcium-bicarbonate water (Fogg and Kreitler, 1982).

Review of the major anion and cation hydrochemical data for the Hickory Aquifer and the Ellenburger-San Saba Aquifer indicated a non-evolving chemical composition. There is not an evolution of a sodium-bicarbonate water in the Llano Uplift Aquifers as observed in the Carrizo-Wilcox Aquifer. The important chemical parameters that appear to have regional trends are tritium and nitrate in shallow groundwater and the presence of low concentrations of carbon-14 and depleted isotopes of deuterium in the relatively deep groundwater. The aquifers also contain elevated activities of radium and strontium ratios possibly indicative of groundwater derived from basement rocks.

Faulted grabens close to the Llano Uplift area appear to contain young water, whereas the downdip portions appear to contain relatively older water. A more active flow system occurs in the outcrop areas and the downdip parts of the aquifer. Farther from the outcrop, groundwater may be relatively stagnant.

Head data indicates that leakage from the Cretaceous into the Paleozoic rocks might be occurring. The chemistry was evaluated to determine if there are chemical signatures that indicate leakage from the Cretaceous down into the Paleozoic aquifers. As much as the data allowed, water level maps were evaluated to determine regional directions of groundwater flow and potential upward or downward leakage between aquifers.

The following questions are being addressed by evaluating the hydrogeology of the aquifer surrounding the Llano Uplift area:

- Does groundwater from the outcrop that surrounds the igneous core flow down the structural dip of the aquifers away from the Llano Uplift area?
- Is groundwater isolated within discrete fault blocks?
- Is groundwater flow “short circuited” in shallow grabens close to the Llano Uplift area back to surface streams such that significant amounts of groundwater are not flowing into the deeper confined parts of the aquifers?

Because the regional groundwater flow in the aquifers surrounding the Llano Uplift area has not been studied as extensively as other aquifers in the state, a more thorough basic hydrogeologic investigation was completed for this region. We focused in the McCulloch, Gillespie and Burnet counties area. This provided a more detailed evaluation over a wide geographic area that is on the north, the south and the east sides of the Llano Uplift area.

3.2 Aquifers of the Edwards-Trinity (Plateau)

The TWDB has developed a GAM model that extends from the New Mexico border to the hill country near San Antonio, Texas and Austin, Texas (Anaya and Jones, 2009). The conceptual model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM define two basic hydrostratigraphic units. The lower unit represents the partially confined Trinity Group and is contiguously extended to the southeast to include the Trinity (Hill Country) Aquifer. The upper unit represents the mostly unconfined Edwards Group and also the Pecos Valley Aquifer of the Trans-Pecos region.

The GAM contains two layers, the overlying karstic limestone, Edwards Group, and an underlying sandstone, Trinity Group. The Edwards Group is generally more permeable than the Trinity Group. The Edwards Group is generally unconfined and the Trinity Group is mostly semi-confined to confined. The Trinity Group does not outcrop anywhere within the model area. Groundwater production from the aquifer varies across the aquifer with most production in the western section from the Antlers Formation, which is part of the Trinity Group of the Edwards-Trinity (Plateau) Aquifer. Wells in the eastern part of the Edwards-Trinity (Plateau) Aquifer are primarily from the Edwards Group. There are dual production wells from both the Edwards Group and the Trinity Group in the overlap area between the eastern and western sections.

The Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM conceptual model contains two layers to represent the Edwards and the Trinity Groups across the plateau. However, there are very few documented Trinity wells in the eastern area. Similarly, there is no current Edwards Group production in the western area. Early production in the western area may have been from the Edwards Group, but according to recent water level measurements in the TWDB database, water levels have declined below the base of the Edwards Group in Reagan and Glasscock counties. This water level decline may be related to irrigation pumpage in the area.

The model calculates approximately 150,000 acre-feet/year of annual flow of groundwater between the Edwards and the Trinity Groups. The hydrochemistry and isotope data might be helpful in developing a better understanding of if and where this leakage is occurring.

Recharge estimates for the model range from 3 to 5 percent of precipitation. The annual average precipitation decreases from about 32 inches/year in the east to about 14 inches/year in the western section of the model area. This reduced precipitation on the west should result in far less recharge in the western area than in the eastern areas. The hydrochemistry and isotope data might provide some insight into whether this assumption is valid.

Nance (2010) evaluated the hydrochemistry of the Edwards-Trinity (Plateau) Aquifer. That study included an evaluation of TWDB data as well as collecting several new water samples for hydrochemical and isotope analysis.

With these data he reached several conclusions:

- The Antlers Formation groundwater production occurs primarily in the western area of the Edwards-Trinity (Plateau) Aquifer. Edwards Group groundwater production occurs primarily in the eastern section.
- Based on the potentiometric surface for the overall aquifer, groundwater flow is from northwest to southeast. The potentiometric map he uses combines both the Antlers Formation and Edwards Group wells.
- Chemistry of the Antlers Formation water is different than for Edwards Group water. The Antlers Formation water are “old” (low tritium and low carbon-14 activities) while Edwards Group waters routinely contain tritium and more modern carbon-14. The total dissolved solids, sulfate and chloride concentrations for the Antlers Formation water

typically are higher than for Edwards Group. Edwards Group water is often a $CaCO_3$ water. Oxygen-18 and deuterium for Edwards Group water is heavier than for the Antlers Formation water, which may indicate that the Edwards Group is experiencing more recent recharge. The lighter isotopic composition in the Antlers Formation may be explained in that the Antlers Formation was recharged at an earlier and cooler time (Pleistocene).

- Anions in some of the Antlers Formation waters are dominated by sulfate. Nance (2010) attributes this sulfate to upward leakage from the saline Permian evaporite section.
- Edwards Group water in Crockett County show a chemical transition between the Antlers Formation and Edwards Group wells. Edwards Group wells show high sulfate concentrations. Nance suggests that this is the result of upward flow by the Antlers Formation water into the Edwards Group.
- Strontium ratio data suggest that the Ogallala Aquifer waters in the northwest area of the model may be leaking down into underlying Antlers Formation.
- High sulfate Edwards Group water in Crockett County has "light" oxygen-18 values, which suggests mixing with the Antlers Formation water.
- Nance (2010) argues that the presence of tritium in water prevents accurate estimation of the age based on the carbon-14 percent modern. The presence of tritium means that new 100 percent modern carbon carbon-14 is being added to the water, which may preclude accurate age-dating using a traditional $\delta^{13}C$ correction factor because the geochemistry of carbon-14 age correction becomes very complex. Nance (2010) also observed that magnesium and calcium ratios increase with decreasing carbon-14 percent modern. He attributes this to slower dissolution of the dolomite in the Edwards Group. He uses the magnesium and calcium ratio as an indicator of the relative age of the water in Edwards Group. Review of his data indicates that as magnesium and calcium ratios increase, magnesium is increasing, but calcium and bicarbonate are decreasing. The decrease in calcium and bicarbonate suggests the precipitation of calcite. If calcite is precipitating, then the precipitation of calcite may be depleting the aqueous bicarbonate of carbon-14 as well. He therefore concludes that it may be best to recognize that dating with carbon-14 percent modern is only a relative estimate and trying to correct the raw carbon-14 percent modern value may not be realistic. If Nance is correct, his conclusion has great bearing on the evaluation of many of the other aquifers being evaluated in this study.
- Nance (2010) mapped the magnesium and calcium ratio in Schleicher and Sutton counties and found that higher magnesium and calcium ratios were from topographic divide areas. The lower magnesium and calcium ratios were in the ephemeral drainage ways. This suggested to Nance (2010) that recharge to the aquifer is primarily through the ephemeral stream beds during heavy rainfalls and not through the general soils in the topographic highlands. The conceptual model of recharge in the Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM should be assessed in light of Nance's conclusion. Specifically, whether or not an average annual recharge value based on a percent annual precipitation is appropriate for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM at the geographic and time scales the model was developed.

3.3 Aquifers of the Trans-Pecos Region

The TWDB developed the Edwards-Trinity (Plateau) and Pecos Valley Aquifers groundwater model. The Pecos Valley region of the GAM is an important part of this model. The study area is often referred to as the Trans-Pecos region. This area contains several aquifers, which have a focus area in Pecos County. There is potential interaction between the Edwards-Trinity (Plateau) Aquifer (the western flow path from the Balmorhea Springs area), the Capitan Reef Complex Aquifer, the Pecos Valley Aquifer and the Rustler Aquifer in this area. The springs in Pecos County have been a major point of discharge for this aquifer system. Groundwater discharge, either as groundwater well production or spring discharge in Pecos County, may come from all these aquifer sources.

The Edwards-Trinity (Plateau) and Pecos Valley Aquifers GAM indicates an interaction between these different aquifers. The TWDB has identified the Cretaceous aquifer in Pecos County collectively as the Edwards-Trinity (Plateau) Aquifer containing the Edwards Group, Antlers Formation, and the Trinity Group. The water chemistry in the Edwards-Trinity (Plateau) Aquifer varies from fresh (less than 1,000 mg/l) to brackish (greater than 1,000 mg/l). The higher total dissolved solids waters occur primarily in the Leon-Belding-Fort Stockton area.

The increased salinity (Leon-Belding-Fort Stockton area) in the Edwards-Trinity (Plateau) Aquifer looks similar to the areas of increased salinity that Nance (2010) identified in Reagan, Irion and Crockett counties. He attributed this increased salinity to upwelling from deeper, more saline Paleozoic formations. Similar processes may be occurring in the Edwards-Trinity (Plateau) Aquifer in Pecos County.

Nance (2010) and others have also identified a mixing of a) young groundwater (with tritium) and high carbon-14 percent modern carbon activities and b) old (low tritium) and low carbon-14 percent modern carbon activities in the main Edwards-Trinity (Plateau) Aquifer. A similar mixing of “old” and “new” waters may be occurring in the Edwards-Trinity (Plateau) Aquifer’s groundwater in Pecos County.

3.4 Limitations of the Data and Study

The data analyzed in this report are mostly from wells for which accurate screen information does not exist or from wells that have open-hole completion across more than one formation or aquifer zone. Therefore, vertical mixing of water from different formations likely occurs in most of the samples. When using data from the TWDB databases, we eliminated wells that were screened across multiple aquifers as identified by the aquifer code in the database. The exceptions were wells that were screened in both the Ellenburger and San Saba aquifers. Obviously, there are still many wells that were included in the analysis that are screened across multiple formations, even if the aquifer code in the TWDB database indicates only a single aquifer, such as the Edwards or Trinity. This limits the conclusions that can be drawn regarding vertical distinction of groundwater based on the hydrochemical and isotope data. It may also limit the value of three dimensional or vertical cross-section visualizations from much of the Edwards-Trinity (Plateau) Aquifer and other aquifers where wells are completed across multiple formations.

4 Hydrochemical Approach Toward Understanding Aquifer Dynamics

4.1 Approach

Ground water flow systems for individual aquifers or aquifer systems are often developed with the aid of numerical groundwater computer models. A typical model is constructed with several different data sets. These data sets often include 1) the geometry of individual formations and aquitards, 2) the hydraulic characteristics (e.g., hydraulic conductivity, thickness, storativity), 3) the water levels in the model (that are either known or assigned), 4) rates of recharge based on annual precipitation minus evapotranspiration and 5) rates of discharge from known springs, rivers, and pumping wells. With these parameters incorporated into a numerical groundwater flow model directions of flow, rates of flow and changes in potentiometric surface elevations can be estimated.

An alternate approach is to use naturally-occurring chemical data along with geologic data (e.g., formational aquifer distribution), hydrologic data (e.g., potentiometric surfaces) to address similar flow conditions as are studied with numerical groundwater flow models.

The basic geochemical tools that are used are:

1. Major and minor element chemistry. This often includes sodium, calcium, magnesium, potassium, bicarbonate, chloride, sulfate, nitrate, ammonium, and total dissolved solids, plus radium, strontium, bromine, iodine, temperature and pH. These data are often displayed visually on 1) Piper diagrams, 2) graphs comparing two chemical constituents or one constituent compared to a physical property such as depth or geographic location or 3) maps.
2. Stable isotopes. Stable isotopes are often used in hydrologic studies. These include oxygen-18 and deuterium of water, $\delta^{13}C$ of dissolved carbonates and gases, $\delta^{15}N$ and oxygen-18 of nitrate and strontium. Data often is viewed and interpreted graphically or on a map.
3. Radioactive isotopes such as tritium, carbon-14, chlorine-36, radium have known half-lives and can be used to estimate water ages and other hydrochemical processes.
4. Composition of dissolved gases in groundwater such as dissolved oxygen, nitrogen, carbon dioxide and methane (and heavier hydrocarbons) can be measured to determine whether a groundwater still contains the atmospheric gases present at the time of recharge or whether gas composition has been altered by geochemical reactions within the aquifer. For example, the presence of hydrocarbon-related gases may indicate the migration of deeper waters from deeper saline formations.
5. Geochemical computer models are used to explain complex changes in water chemistry as groundwater flows through an aquifer. For example geochemical modeling is used to correct an apparent carbon-14 age. Apparent groundwater ages have been inferred from carbon-14 data of bicarbonate. The amount of bicarbonate dissolved in groundwater may change as groundwater flows through an aquifer. If the bicarbonate concentration increases as it flows through an aquifer, it may be dissolving carbonate minerals (such as calcite) within the aquifer. This additional dissolved bicarbonate from the geology is assumed to contain no carbon-14. Without subtracting out the “dead” carbon component,

an age of water may be overestimated. Chemical modeling of hydrochemistry of water as it flows down the hydraulic gradient of an aquifer can help determine a more precise age.

6. References that provide an overview of these approaches are Clark and Fritz (1997), Fritz and Fontes (1986), Hem (1985) and Richter and Kreitler (1993).

4.2 Pertinent Issues

Assessment of hydrochemical and isotope data from groundwater samples has proven to be a valuable tool for developing and refining conceptual models in groundwater systems. In GMAs 3 and 7, hydrochemical and isotope data has been used to evaluate a variety of issues discussed below.

4.2.1 Defining Recharge Areas

Outcrop areas where recharge is considered to be actively occurring often have higher concentrations of nitrate and chloride. Higher concentrations may indicate an anthropogenic impact and therefore recent recharge. Higher nitrate and chloride may be coming from cultivation or animal wastes. Nitrate from "cultivation" can include downward percolation from "dry land" farming and irrigation. Lower nitrate concentrations in shallow groundwaters may occur in the naturally oxidizing conditions in these aquifers. Higher concentrations probably result from agriculture or animal wastes. Similarly elevated activities of radioactive isotopes such as carbon-14, tritium and chlorine-36 may indicate recent recharge. In GMA 3 and 7 with its sub-humid to semi-arid climate it is important to know whether aquifers are currently being recharged.

4.2.2 Age of Groundwater

Being able to estimate the age of a groundwater is important in understanding the hydrodynamics of an aquifer. An aquifer may currently be recharging, but the majority of the groundwater may not be flowing into the deeper sections of the aquifer, but actually flowing to streams, springs and rivers proximal to the outcrop. Deeper groundwater in the down dip confined part of an aquifer may be stagnant. Measuring the age of a groundwater may help identify areas within aquifers where there is active groundwater circulation and areas that may be relatively stagnant. This can be accomplished with radioactive isotopes such as tritium, carbon-14 and chlorine-36.

4.2.3 Mixing Between Aquifers or Aquifer and Surface Water

Vertical leakage and horizontal flow within and between aquifers is an important issue in understanding the hydrodynamics of a single aquifer or the hydrologic interaction between aquifers. Three examples from the aquifers in GMA 3 and 7 demonstrate the importance of the geochemistry in demonstrating aquifer interaction:

1. The higher total dissolved solids and the higher sulfate waters in the Antlers Formation in the northwest region of the Edwards-Trinity (Plateau) Aquifer may indicate the upward leakage of groundwater from the underlying Triassic and Permian Formations.
2. The Antlers Formation waters in the northwest parts of the Edwards-Trinity (Plateau) Aquifer are higher total dissolved solid waters than the Edwards Group waters in the central and eastern parts of the Edwards-Trinity (Plateau) Aquifer that are hydrologically

down dip from the Antlers Formation. The Edwards Group waters are calcium-bicarbonate water and not sodium-sulfate waters as occur in the Antlers Formation. From this data it appears that there is not regional groundwater flow down the potentiometric surface from the Antlers Formation to the Edwards Group.

3. In the Llano Uplift area, the Hickory Aquifer can have higher activities of radium-226 and radium-228. This occurs on the north side of the Llano Uplift area. The overlying Ellenburger aquifer, in contrast has low activities of radium-226 and radium-228. Based on this geochemical relationship, groundwater in the Hickory Aquifer downdip does not appear to be leaking upward into the Ellenburger-San Saba Aquifer by cross-formational flow.

Groundwater geochemistry can be a powerful tool in understanding the hydrodynamics of an aquifer and the hydrologic interaction between aquifers. Its use, however, is done on an aquifer by aquifer basis. Because of the variability of lithology, mineralogy, interaction with other aquifers with differing geochemistry i.e., the use of geochemistry has to be customized to each aquifer investigation. A geochemical approach that works in one aquifer may not be appropriate for another. The isotopes of water and the ages of water (based on isotopes) may provide a more regional understanding because there is less potential rock-water interaction on an aquifer by aquifer basis. Because of their importance, additional discussion of some of the isotopes is provided.

4.3 Radioactive Isotopes

The radioactive isotopes evaluated include: 1) carbon-14 of the bicarbonate in the groundwater, 2) chlorine-36 of the dissolved chloride and 3) tritium in the water. There are some data in the TWDB groundwater database for these three isotopes. The carbon-14 percent modern, chlorine-36 and the tritium provide information on the age of the water in that all three radioactive isotopes decay at a known rate from a background atmospheric value. The approximate age can be estimated by knowing its half-life and estimating its original atmospheric value. The half-life refers to the time it takes for one half the activity of a radioisotope to decay to another isotope on its decay series. Carbon-14 has a half-life of 5,730 years; tritium has a half-life of 12.3 years and chlorine-36 has a half-life of 301,000 years. In addition, thermonuclear atmospheric testing in the 1950s resulted in elevated valves for all three isotopes. Because of the short half-life of tritium, the 1950s tritium spike is no longer evident, but because of the long half-lives of carbon-14 and chlorine-36, elevated carbon-14 and chlorine-36 activities associated with nuclear testing may still be present. The presence of high carbon-14 and chlorine-36 activities in groundwater may indicate the presence of atmospheric nuclear testing and therefore recent recharge.

4.3.1 Carbon-14

Carbon-14 values of groundwater bicarbonate may be reported three different ways:

1. Carbon-14 percent modern, which is the percentage of carbon-14 in a sample relative to the naturally occurring amount of carbon-14 that is estimated to be in the atmosphere,
2. Carbon-14 apparent age years before present, which represents an apparent age based solely on the half-life decay of carbon-14,
3. Carbon-14 corrected age, which is based on both a half-life decay correction and a correction for the geochemical alteration of the dissolved bicarbonate in the groundwater

as it flows through the aquifer. Carbon-14 data in this report is presented primarily as carbon-14 percent modern.

Figure 4-1 shows carbon-14 data as carbon-14 percent modern. Figure 4-2 shows carbon-14 data as an apparent age. This "age" is often the value received from the laboratory making the carbon-14 measurement. The dates should only be considered as qualitative because we don't know all the variables that have caused the measured values. A maximum age of a water, using carbon-14, can be estimated by applying only a half-life decay correction. More accurate and younger carbon-14 ages of groundwaters are often estimated with the addition of a correction factor that is based on the bicarbonate geochemistry of groundwater as it flows from recharge to downdip parts of an aquifer. The true age of a water using the carbon-14 approach needs to reflect both the radioactive decay and the addition of dead carbon resulting from geochemical reactions in the aquifer. In the discussion of the ages of waters in the Hickory Aquifer in McCulloch County on the north side of the Llano Uplift area this approach was taken to provide for this additional correction. Without knowing the geochemical reactions associated with bicarbonate dissolution (and precipitation), it is only prudent to provide a qualitative estimate of age and not a precise quantitative one.

4.3.2 Tritium

The presence of tritium in groundwater indicates recent recharge. Tritium is measured in tritium units (TU). For this study the presence of greater than 0.5 TU is considered evidence for "recent" recharge.

The age dating terms young and old are used in a relative sense. Figure 4-1 and Figure 4-2 show the correlation of tritium and carbon-14 percent modern and tritium and carbon-14 apparent. On both graphs two limbs can be observed. The break between the two trends is considered to have a tritium value of about 0.5 TU. Tritium measurements can be made such that old, pre 1950s bomb waters can have "0" values, depending on the method of analysis. Many of the analyses in the TWDB data have "0" values, but there are also several water samples with low carbon-14 and some that have measureable but low tritium activities. A threshold of 0.5 TU was therefore assigned to define recently recharged waters. Clark and Fritz (1997) have used similar ranges such that modern waters (up to 10 years old) have tritium activities in the range of 5 to 10 TU while submodern aged water (recharged prior to 1952) have tritium activities of less than 0.8 TU.

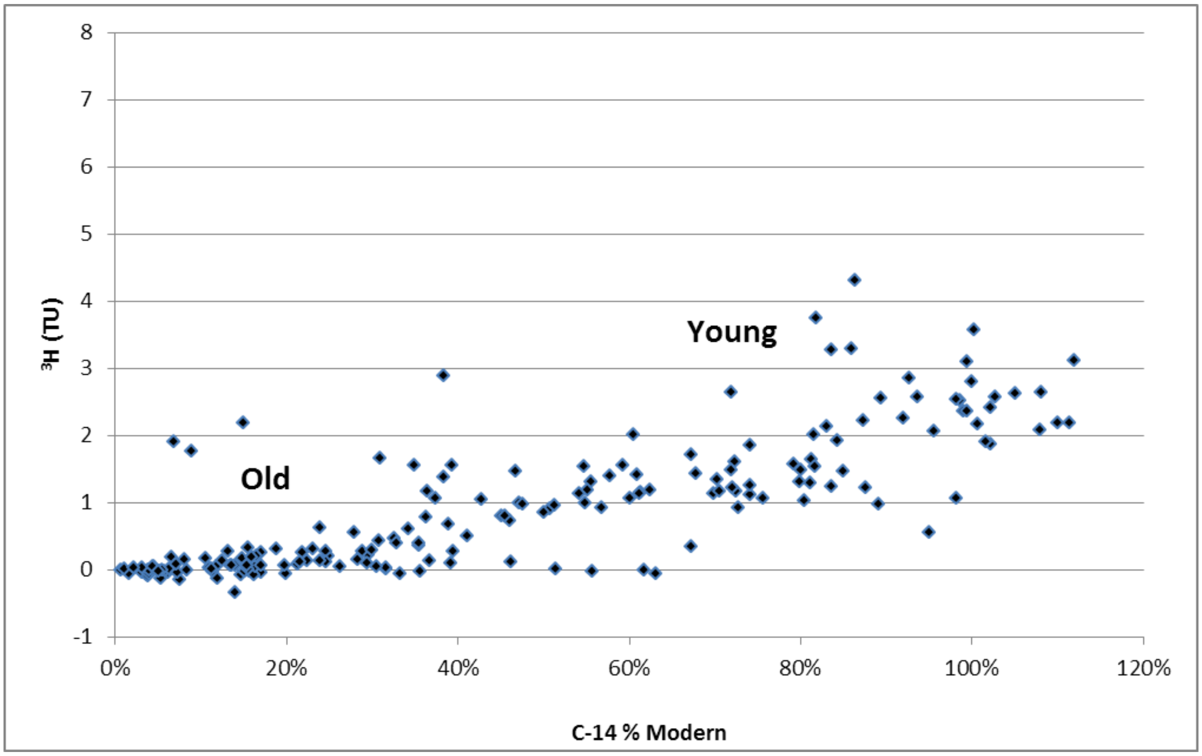


Figure 4-1. Tritium (^{3}H) vs carbon-14 percent modern (C-14%) from aquifers in GMA 3 and 7.

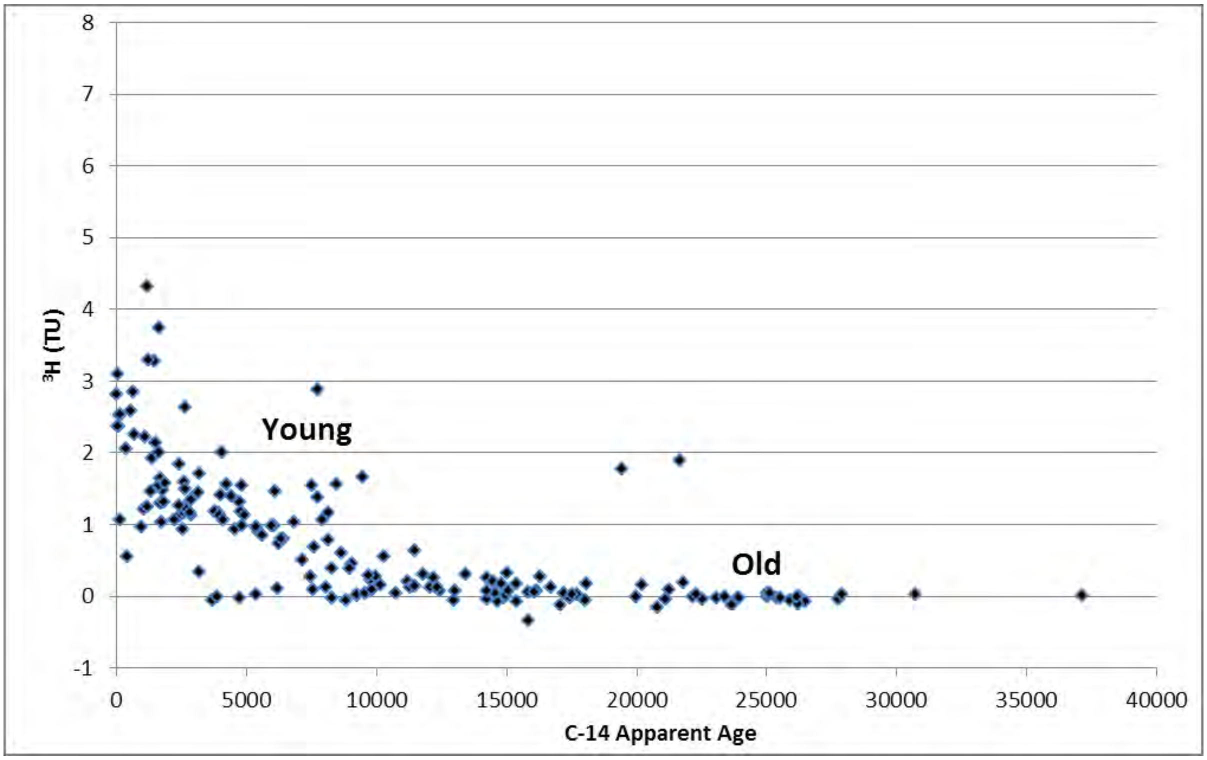


Figure 4-2. Tritium (^{3}H) vs carbon-14 apparent age (C-14) from aquifers in GMA 3 and 7.

4.3.3 Chlorine-36

Chlorine-36 is created naturally by cosmogenic processes in the upper atmosphere as well within the subsurface *(in situ* production). The half-life of chlorine-36 is 301,000 years. The chlorine-36 values are reported as ratios to total chloride in water which is predominantly chlorine-35 and chlorine-37. The natural atmospheric production for chlorine-36 is such that recently recharged groundwater should have a concentration in the range of 100 to 200 δ^{36}Cl x 10^{15}. The more elevated ratios (greater than 400) indicate some contribution of chlorine-36 from atmospheric nuclear testing and that the groundwater might be recently recharged. Values less than 100 are potentially indicative of old groundwater beyond the ages measured by carbon-14 (e.g., greater than 40,000 years before present). The benefit of the chlorine-36 signature for this data set is in detecting: 1) recent recharge which would have large value derived from nuclear testing (greater than 400), 2) values that indicated pre-bomb testing and water of only a few thousand years (100 to 300) and 3) very old water sources beyond the age dating range of carbone-14 (chlorine-36 less than 50) (Bentley and other, 1986).

4.3.4 Radium-226 and Radium-228

Radium-226 and Radium-228 provide an additional hydrologic tool. Radium activities often are high in igneous lithologies and formations derived from basement rocks. Formations such as the Hickory Aquifer in the Llano Uplift area are often high in radium because their lithology is derived from the granite lithology. Presence of high radium in a limestone (e.g., the Ellenburger Aquifer) may indicate leakage from deeper units (e.g., the Hickory Aquifer or deeper saline formations). The differing half-lives of radium-226 and radium-228 also provide important hydrologic information. The half-life of radium-228 is 5.75 years where as the half-life of radium-226 is 1,601 years. Because of the very short half-life for radium-228, elevated values, which often are higher than radium-226, probably are generated by radioactive decay within the "aquifer" rather than having leaked in from another formation. High radium-228 may indicate an *in situ* generation of radium rather than leakage from another formation.

4.4 Stable Isotopes

4.4.1 Deuterium and Oxygen-18

The two stable (non-radioactive) isotopes of groundwater, deuterium and oxygen-18, are also available in the TWDB database. Groundwater recharged by normal hydrogeologic processes in continental aquifer settings (e.g., Texas aquifers) should have an isotopic composition similar to the rainwater from which it was originally derived. These waters are often referred to as meteoric waters. The original source of rainfall for Texas is either the Gulf of Mexico or possibly the Pacific Ocean in west Texas. As atmospheric moisture moves inland from the "ocean" and precipitates, the rain becomes isotopically lighter (less of the heavy isotopes of hydrogen and oxygen). Their isotopic composition (deuterium and oxygen-18) will often follow the global meteoric water line (GMWL) (Craig, 1961). The isotope depletion typically follows an equilibrium line defined by the equation $\delta D = 8 \times \delta^{18}O + 10‰$ SMOW. Pape and others, (2010) found this relationship to be true for Texas, i.e., rainfall should become isotopically lighter as it moves from east to west across Texas, but they also found a wide range in variability for rains associated within individual storms and for storms from a single site over a yearly basis. They confirmed this variability by measuring the isotopic composition of rain in Austin, Texas. Pape and others, (2010) also analyzed and reported on drip water from limestone caves from central Texas to eastern New Mexico. This included samples from Inner Space Caverns (central Texas), Natural Bridge Caverns (central Texas), Caverns of Sonora (Edwards-Trinity (Plateau) Aquifer) and Carlsbad Caverns (eastern New Mexico) (Chapman and others, 1992). The drip waters from central Texas to west Texas and New Mexico showed appreciable isotopic depletion for samples farther to the west, and samples from a single location had a relatively narrow range (Figure 4-3). The oxygen-18 and deuterium for cave drip water in central Texas (Inner Space Caverns and Natural Bridge Caverns) caves ranged from -4 to -5‰ and -15 to -30‰, respectively. Caverns of Sonora ranged from -4.5 to -5.5‰ to -25 to -35‰, respectively. The oxygen and hydrogen isotopic composition of drip waters in Carlsbad Caverns exhibited a wider range from -5 to -9‰ and -30 to -50‰, respectively, than the other caves, possibly because the source of original rainfall had shifted from a predominantly Gulf of Mexico source to more of a Pacific Ocean source, depending on the storm (Figure 4-3). Regardless, Pape and others, (2010) observed a consistent isotopic depletion of rainwater from east to west which follows the GMWL. They concluded that this line defines the expected isotopic composition of current rainwater, and used this relationship to better understand the history of cave speleothem and paleo climates. These data can also be used to estimate the isotopic composition of water currently recharging in Texas aquifers along this transect. It should be noted that other physical processes affecting precipitation can also fractionate the isotopes of water. These include temperature, altitude, timing of a rainfall event and evaporation (Clark and Fritz, 1997). For example, rain water recharged in the Pleistocene period may have occurred under a cooler climate and may be isotopically lighter.

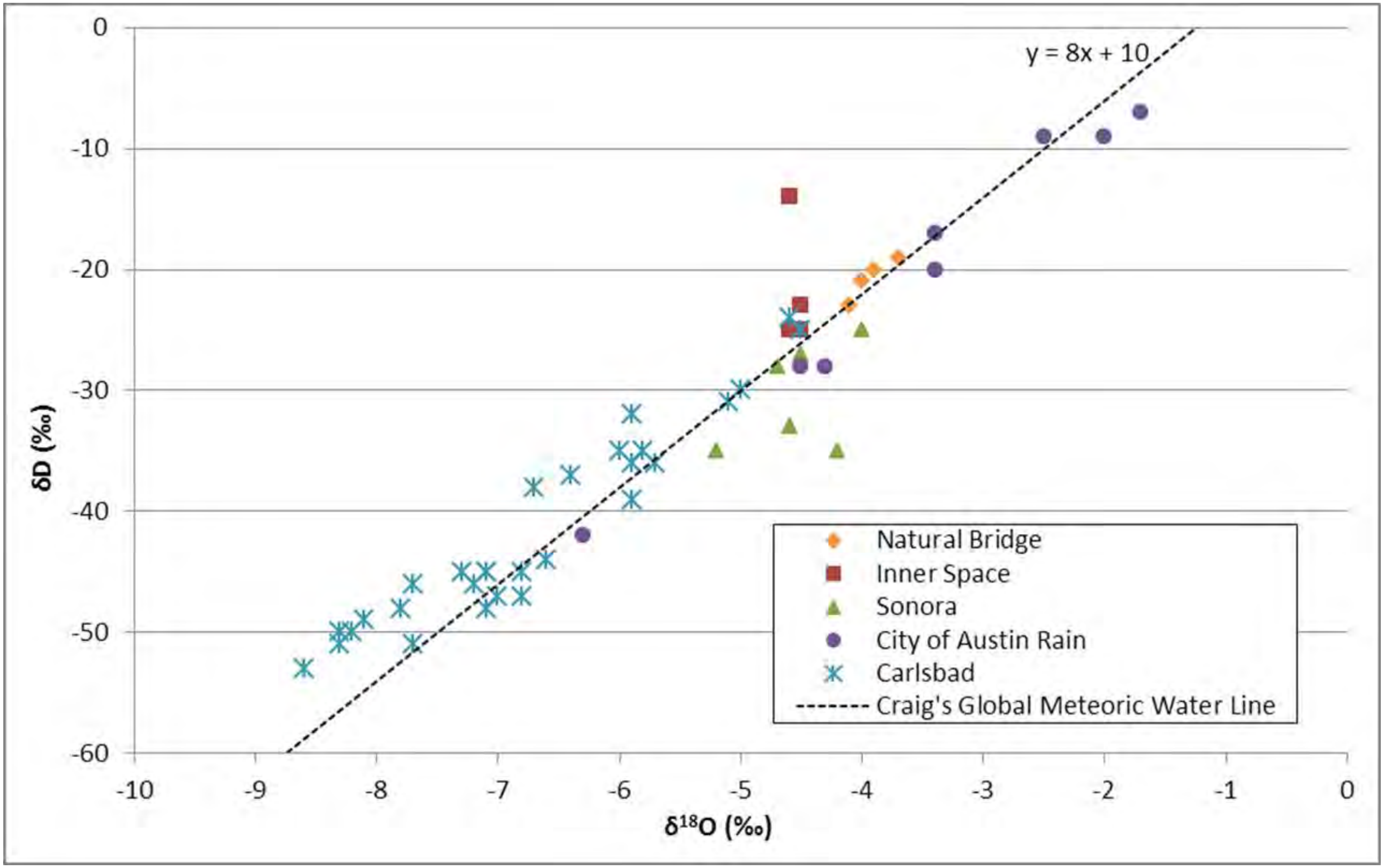


Figure 4-3. **Deuterium (δD) and oxygen-18 (δ^{18}O) composition of cave drip water from central Texas to eastern New Mexico.**

4.4.2 Strontium isotopic compositions

Strontium isotopic compositions also has utility in hydrologic studies. The general questions often asked are:

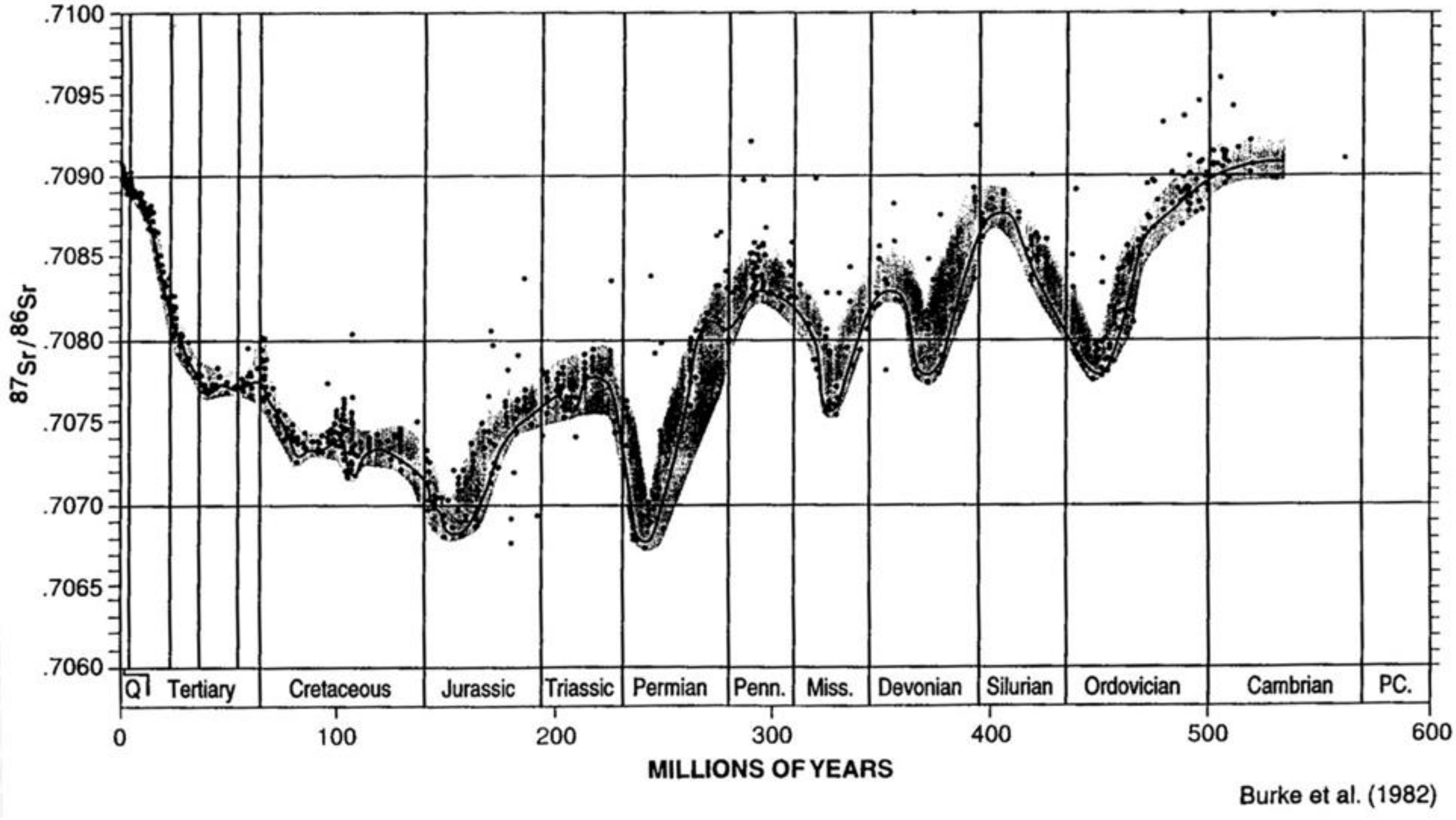
1. Are there unique strontium isotope signatures associated with each formation within each county and/or sub-regions?
2. Does the strontium isotopic data provide any evidence of leakage from one formation to another, or mixing of groundwater between formations within a sub-region?

Strontium isotopic compositions data from the Trans-Pecos region and from the Llano Uplift area have been evaluated to determine if the data are of value in determining these two previous questions. In the Trans-Pecos region, it helped define Conceptual Model 1. In the Llano Uplift area the strontium isotopic compositions data is less conclusive primarily because of the difficulty of breaking out unique signatures for each aquifer and source. Assumptions regarding the strontium isotopic compositions isotopic system and the strontium isotopic composition of potential sources of strontium in the study area are as follows:

1. Strontium is very similar in size to calcium, and readily substitutes into mineral crystal lattices for calcium-bearing minerals such as calcite, dolomite, anhydrite, and calcium-plagioclase feldspars; therefore, the source of strontium is primarily calcium-bearing minerals.
2. The isotopic composition of dissolved strontium experiences negligible fractionation during mineral-solution reactions; therefore, the isotopic composition of dissolved strontium in a water that is in equilibrium with a strontium -bearing mineral will be the same as the isotopic composition of the mineral (Banner and Kaufman, 1994 and Banner, 2004).
3. Burke and others, (1982) reconstructed the historic strontium isotopic composition of the oceans throughout the Phanerozoic (Figure 4-4). Based on this curve, marine carbonates deposited during the late Cambrian and early Ordovician, such as those that make up the Ellenburger-San Saba Aquifer, should have strontium isotopic compositions ranging from about 0.7085 to 0.7091. This can also vary depending on the amount of siliciclastic sediment within the carbonate rocks.
4. Strontium isotopic composition is a radiogenic daughter product of the decay of rubidium-87. The relative abundance of strontium isotopic composition in strontium-bearing minerals is greater in older rocks; therefore, older igneous rocks and siliciclastics composed of sediments derived from older rocks will tend to have strontium isotopic compositions that are enriched in Strontium isotopic composition compared to typical marine carbonates. Groundwaters in siliciclastics, such as the Cambrian Hickory, will therefore tend to have higher strontium isotopic compositions than those in marine carbonates. This is not a hard and fast rule, as the actual strontium isotopic compositions values in groundwater in siliciclastic aquifers could be affected by the following:
    a. Degree of equilibrium with the silicate minerals: silicates tend to be much less soluble than carbonates, so groundwaters in regional multi-formation aquifer systems that contain both carbonates and siliciclastics may be dominated by the strontium input from the carbonate formations.

b. Presence of any carbonate material in the actual sediments that could dominate the strontium isotopic signature.
c. Composition of inter-granular mineral cements in the siliciclastics: if the sediment grains are cemented by carbonate minerals that are originally derived from dissolution of marine carbonates, then the strontium isotopic composition could reflect the original strontium source.

It should be noted that it is difficult to use strontium isotopes as groundwater tracers without some knowledge of the strontium isotopic composition of the aquifer matrix minerals. In all applications of strontium isotopes in this report, we have made an attempt to establish, based on all available data and any appropriate assumptions, a representative strontium isotopic composition or range of compositions for the matrix minerals in the aquifers in the study area.



Burke et al. (1982)

Figure 4-4. Graph of the strontium ($^{87}Sr/^{86}Sr$) isotopic composition of seawater throughout the Phanerozoic.

5 Assimilation of Existing Data and Collection of New Data

5.1 Data Sources

Water well information used in this study was from four primary data sources. The first and most extensive was the TWDB groundwater database. The second data set was the recently collected chemical and isotopic data from the USGS in Pecos County (Pearson and others, 2012). The third data set is from Nance (2010). The fourth source was the sampling of water wells in Gillespie and Burnet counties and Llano Uplift area. Sampling the Paleozoic aquifers in these two counties offered us a better understanding of the hydrogeology of the eastern and southern sections of the aquifers that surround the Llano Uplift area. Both the Hill Country Groundwater Conservation District and the Central Texas Groundwater Conservation District provided direction and assistance in collecting waters from this two-county area. Data such as lab analysis sheets and field notes are included as an electronic appendix.

5.1.1 Quality Control for TWDB data

TWDB groundwater data for major and minor aquifers in GMA 3 and 7 were reviewed for correctness. The types of well data reviewed included latitude and longitude, water levels, water chemistry and isotopes. The number of wells and analyses reviewed is shown below.

<u>Well Data</u>

17,903 well locations total, of which:

2,826 had no well depths (springs excluded);

14 had aquifer code discrepancies or aquifer code was not applicable

<u>Latitude and Long Accuracy</u>

12,880 wells had coordinates accurate to 1 second or better;

1,796 wells had coordinates accurate from 1 to 5 seconds;

2,067 wells had coordinates accurate from 5 to 10 seconds;

202 wells had coordinates accurate from 10 seconds to 1 minute;

958 had coordinates accurate from 1 to ± 2 ½ minutes or undocumented

<u>Water Levels</u>

77,666 publishable readings total, of which:

311 measurements in 116 individual wells were below bottom well

Water Chemistry

7,743 analyses total, of which:

1,706 largely followed established field sampling protocols;

3,954 have not followed sampling protocols entirely (older analyses);

2,083 had undocumented field sampling protocols;

25 not balances within 5% (based on file *msdwq_mr_meq_chargebal_facies_37*)

Isotopes

3,174 analyses total (2,090 for $\delta^{18}O$, ^{14}C, ^{3}H, etc.), of which:

4 had typos - each of the typos was corrected

Data were corrected when possible; otherwise they were not used in the analysis. The final data sets meet the following criteria:

1. All wells have total depth estimate or documented completion intervals and springs have been deleted. Springs were excluded because of the source of the water discharging from a spring may differ from the surface formation where discharge is occurring;
2. All sites have location accuracies of ± 1 minute or better;
3. No wells having aquifer codes such as “UNKNOWN” or “NON-APPLICABLE”;
4. Only publishable water level measurements are used;
5. All water level readings that plot below the bottom of the borehole have been excluded.
6. All water quality analyses with charge balance outside ± 5 percent have been excluded.

Final data sets by aquifer of best available data were then used for any analysis of TWDB data in this report.

5.1.2 Previously Collected Data by Aquifer and by Region

Figure 5-1 shows the location of wells in GMA 3 and 7 where some type of chemical or isotopic data have been previously collected and were used in this evaluation. With the exception of USGS data in Pecos County, all of the data were previously collected by TWDB or other sources including Nance (2010), USGS and other state agencies.

5.2 Newly Collected Data in the Llano Uplift Area

Figure 5-2 shows the location of wells in GMA 7 where groundwater samples were collected in 2012 from wells and chemical or isotopic analysis were performed and were used in this evaluation. These new data were all collected in Gillespie and Burnet counties around the Llano Uplift area of GMA 7 because that is where the least data had been collected previously. All new data collected during this study can be found in the Appendix.

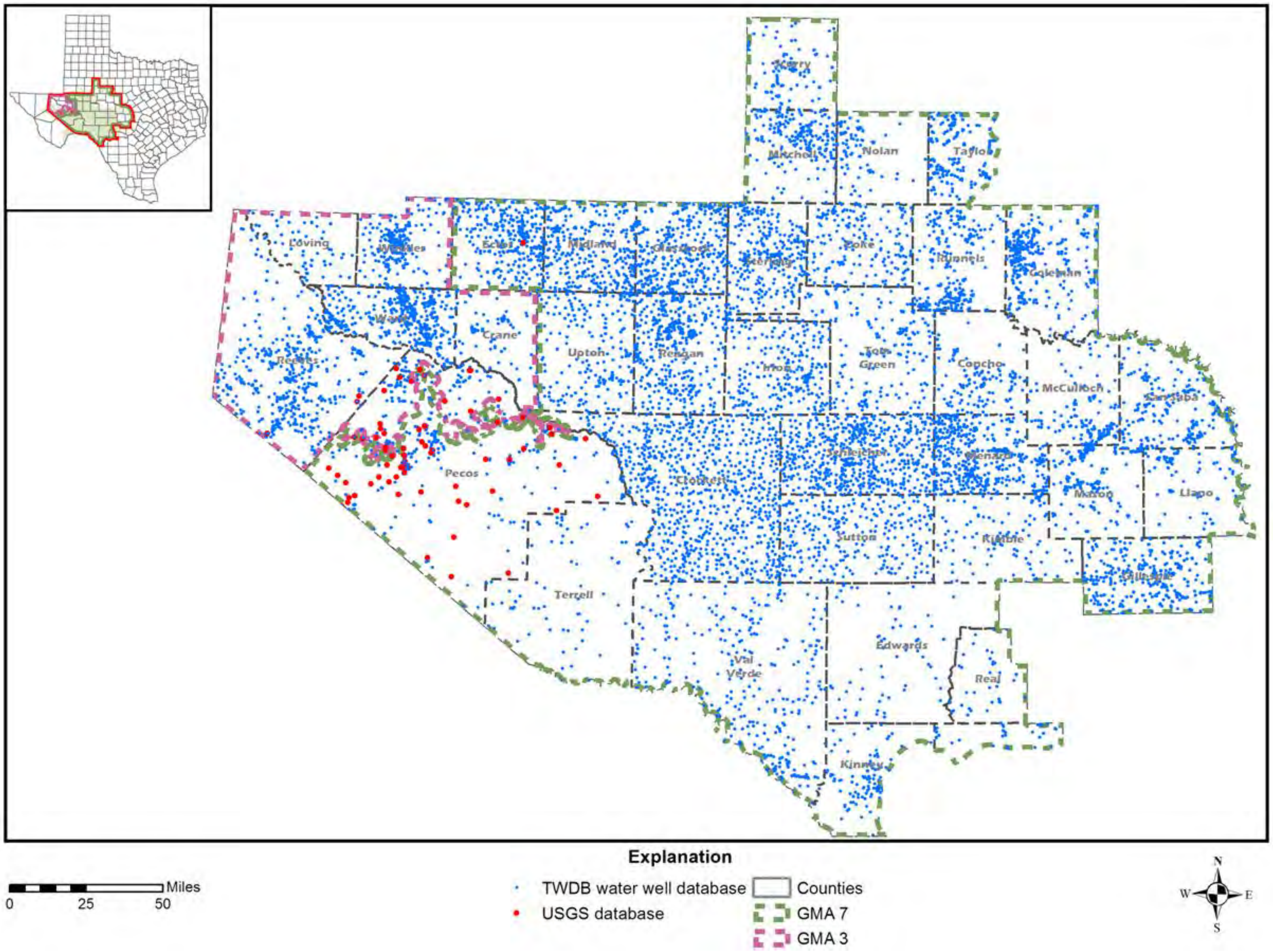


Figure 5-1. Previously collected chemical or isotopic data for wells in GMA 3 and 7.

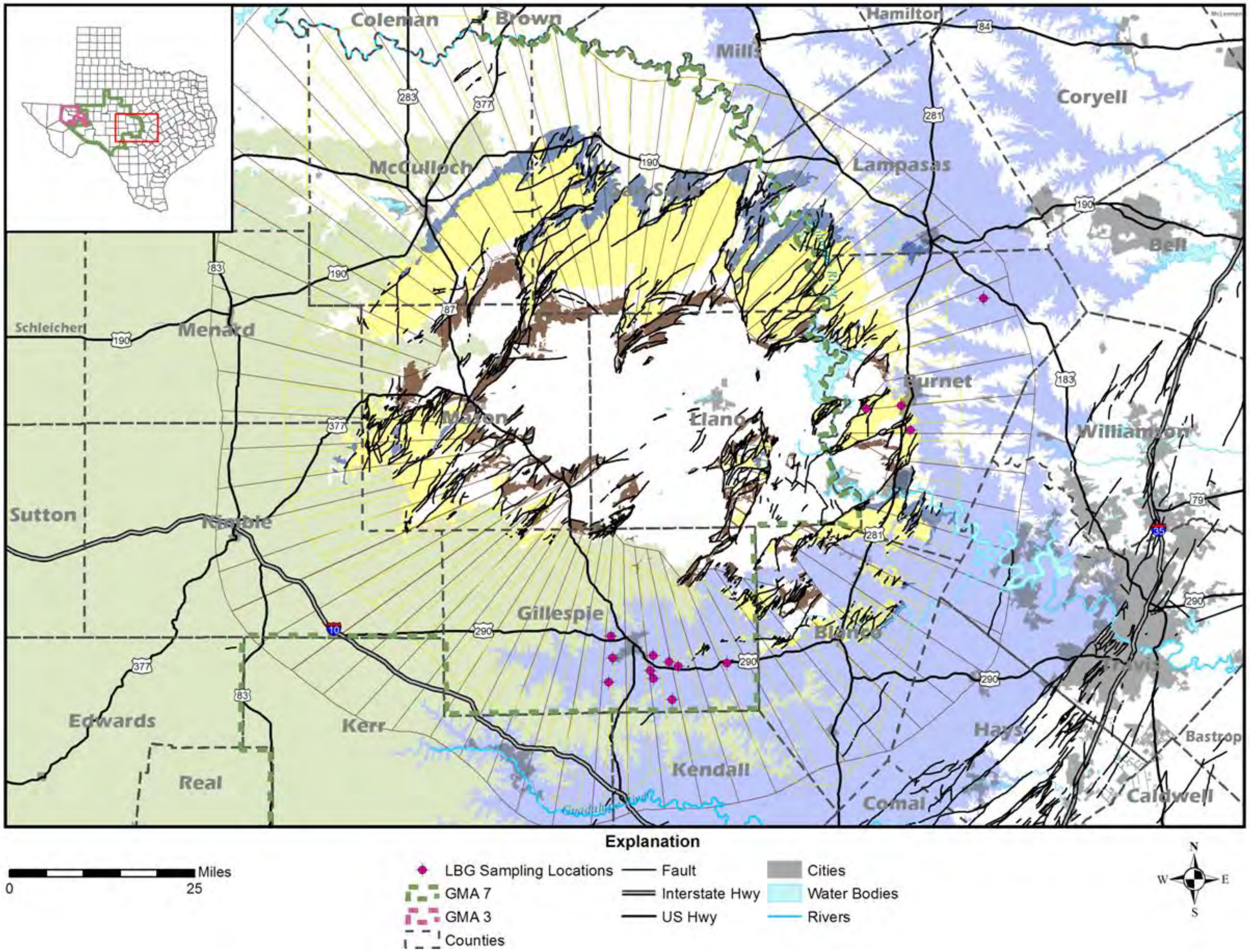


Figure 5-2. Location of groundwater samples taken in GMA 7.

6 Regional Aquifer Isotope Analysis

Regional evaluation of the isotopic composition of the aquifers across the GMA 3 and 7 regions provides such a test where a wide range of aquifer types and hydrologic conditions can be evaluated. The Hickory Aquifer on the east side of GMA 7 is a fractured and lithified Cambrian sandstone located in a climatic region with about 30 inches of average annual precipitation. In contrast the Pecos Valley Aquifer on the west side of 3 and 7 is an unconsolidated alluvial aquifer in an arid climate (about 12 inches of average annual precipitation). Because of this wide range of aquifer types and climatic conditions, the conceptual models may vary significantly between aquifers. A primary test of this variability can be accomplished by evaluating the stable isotopes and radiogenic isotopes of the groundwaters in the aquifers. A preliminary cataloging of aquifer conditions based on their isotopic compositions permits a major grouping of aquifer types for further study.

Along with the collection of the major anions and cations for the aquifers in GMA 3 and 7, the TWDB has also collected isotopic data for many of the aquifers over the last twenty years. These data are available in the TWDB groundwater database. For this study the isotopic composition of the groundwater in the major and minor aquifers in the GMA 3 and 7 regions have been compiled from the TWDB groundwater database to determine whether aquifer waters can be considered as 1) recently recharged (young waters) or 2) old waters. Young versus old is based on interpretation of the stable isotopes of deuterium, oxygen-18 and the radioisotopes of tritium, carbon-14 percent modern and chlorine-36. For this section no specific quantitative age is assigned to old waters other than having been recharged at least "thousands" of years ago. Similarly no specific age is assigned to young waters other than they are relatively younger than older waters. The reason for this semi-quantitative description will be explained in the following sections.

6.1 Estimated Age of Groundwater from Aquifers

First, all isotopic data will be evaluated without regard for aquifer or location. Then an aquifer specific assessment will be discussed.

6.1.1 Assessment of Aquifers

A plot of carbon-14 percent modern versus tritium for the major and minor aquifers in GMA 3 and 7 shows two different isotopic groups (Figure 4-1):

1. Carbon-14 percent modern and tritium values within a range of 0-60% and 0.0 to .5 TU respectively. These waters are considered to be old and not recently recharged. Using only a carbon-14 half-life correction, these waters would have a calculated age of about 7,500 years to possibly greater than 30,000 years (Figure 4-2). This calculation of "uncorrected" age does not include the addition of dead carbon from expected carbonate dissolution reactions and therefore represents only a maximum age estimate. A significant portion of the aquifers in GMA 3 and 7 appear to contain groundwaters that are old.
2. Carbon-14 percent modern and the tritium values within a range of 60-100% and 0.5 to 4 TU respectively (Figure 4-1). These waters are considered to be young. The descriptions old and young are not intended to indicate that there are no waters that are between these relative ages or that there are no waters that are a mix of both ages.

A plot of deuterium versus oxygen-18 for the major and minor aquifers in GMA 3 and 7 show a progressive depletion of their isotopic composition from the eastern aquifers (the Edwards-Trinity (Plateau) Aquifer, the Hickory Aquifer and the Ellenburger-San Saba Aquifer) to the western aquifers (the Edwards-Trinity (Plateau) Aquifer, the Antlers Formation, the Pecos Valley Aquifer and the Rustler Aquifer) (Figure 6-1). A comparison of these isotopic ranges of the groundwater to the cave drip water isotopic composition (Figure 4-3) indicates that the groundwater for several of the aquifers is isotopically lighter than the recharge (cave drip) water for a similar region. This is particularly true for groundwater in the Antlers Formation, the Edwards-Trinity (Plateau) Aquifer, the Pecos Valley Aquifer and the Rustler Aquifer. The overlap of the Pecos Valley Aquifer wells with the Edwards Group wells confirms: 1) the complexity of the aquifer systems and 2) that many of the findings of the hydrochemical and isotope studies should be considered semi-quantitative in nature.

These western aquifers have isotopic compositions similar to or lighter than for drip waters found in Carlsbad Caverns (about 100 miles farther to the west). The implication is that some of these waters appear to have been recharged in an earlier climatic period. It is interesting to note that several earlier studies on the aquifers in west Texas also suggest that these aquifers contain groundwater that is isotopically lighter than anticipated if recharge was actively occurring. This includes Dutton and Simpkins (1986) study of the Dockum Aquifer, Nance (2010) study of the Antlers Formation along the northwestern edge of the Edwards-Trinity (Plateau) Aquifer, Darling (1997) study in the Eagle Flat and Red Light Basins of the West Texas Bolsons Aquifer, Uliana and others (2007) for aquifers in the Trans-Pecos region, and Chowdhury and others (2008) for aquifers in the Trans-Pecos region. These papers all conclude that some of the groundwater in these west Texas aquifers was recharged in an earlier period of time.

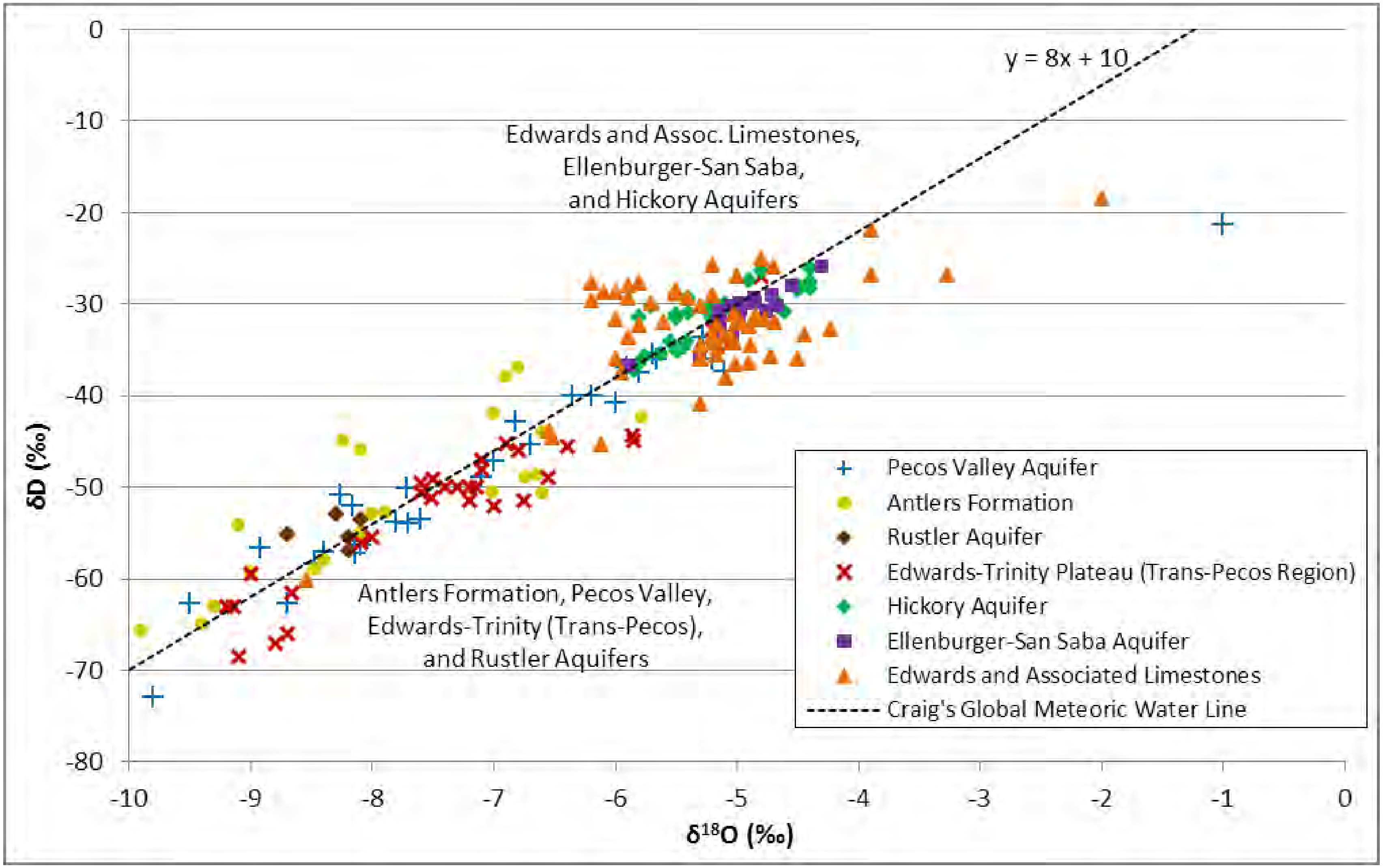


Figure 6-1. **Deuterium (δD) and oxygen-18 (δ^{18}O) of groundwater from aquifers in GMA 3 and 7.**

6.2 Assessment of Individual Aquifers

Evaluation of the carbon-14 percent modern versus tritium for each of these aquifers also shows the relationship of old versus young water. The following section compares the carbon-14 percent modern to the tritium for each of the major and minor aquifers in GMA 3 and 7.

6.2.1 Ellenburger-San Saba Aquifer

Comparison of the carbon-14 percent modern to tritium for the Ellenburger-San Saba Aquifer in the Llano Uplift area shows two different groupings (Figure 6-2).

1. Waters that have very low carbon-14 percent modern and tritium values. These are considered as old waters and are all located in downdip portions of the aquifer. These older waters are also isotopically lighter than the outcrop waters with respect to tritium and oxygen-18 (Figure 6-3).
2. Carbon-14 percent modern values from 0.7 to 1.0 and tritium values from 0.75 to 3.0 TU. These waters are considered as young. They are located either in the outcrop or slightly downdip from the Ellenburger-San Saba Aquifer outcrop (Figure 6-4).

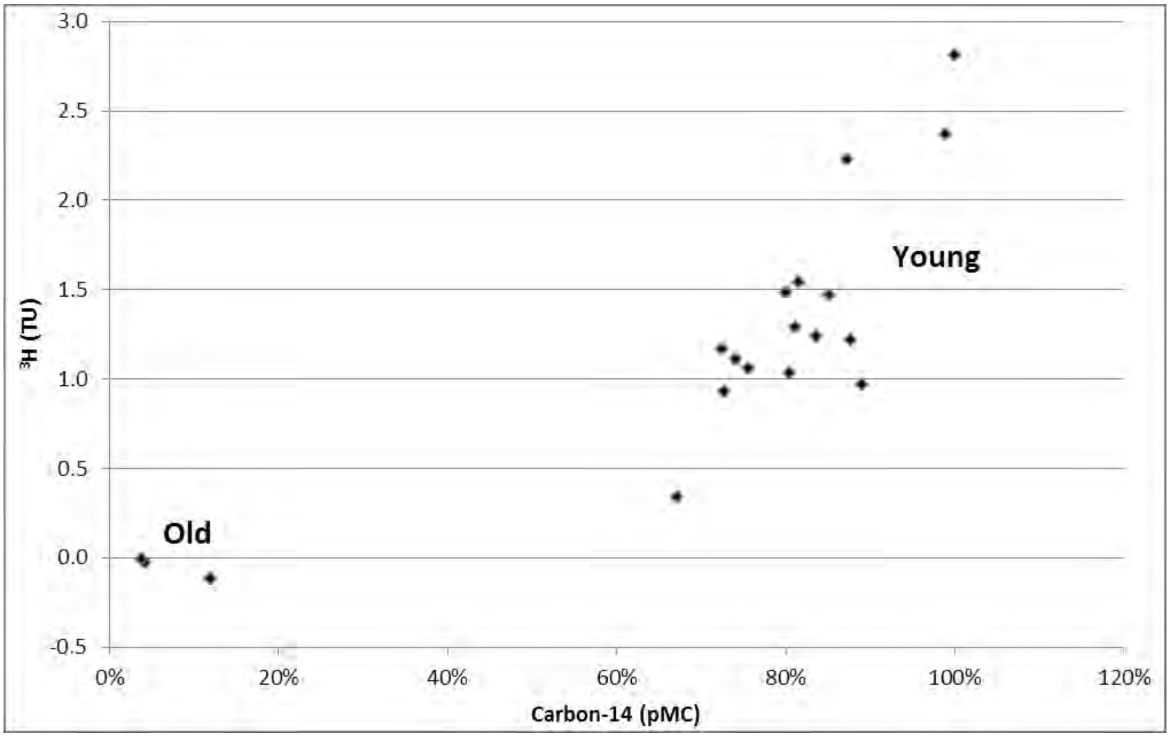


Figure 6-2. Tritium (^3H) vs carbon-14 percent modern (C-14%) for the Ellenburger-San Saba Aquifer in the Llano Uplift area.

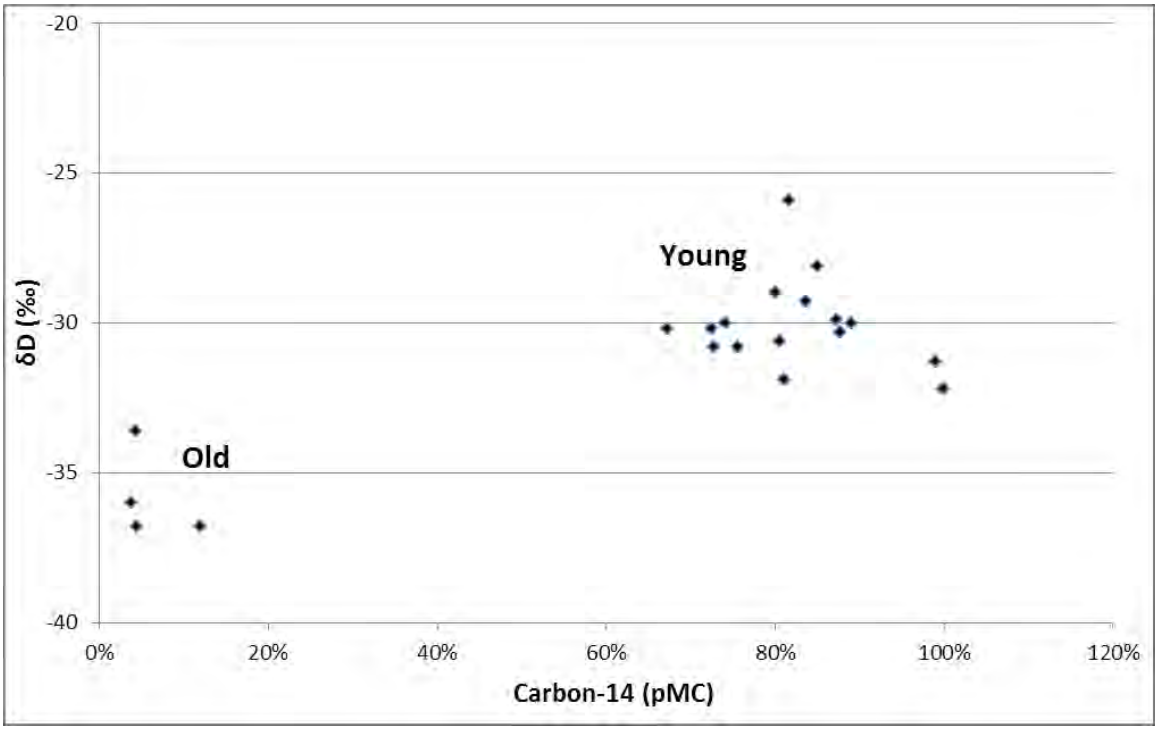


Figure 6-3. Deuterium (δD) permil vs carbon-14 percent modern (C-14%) for the Ellenburger-San Saba Aquifer in the Llano Uplift area.

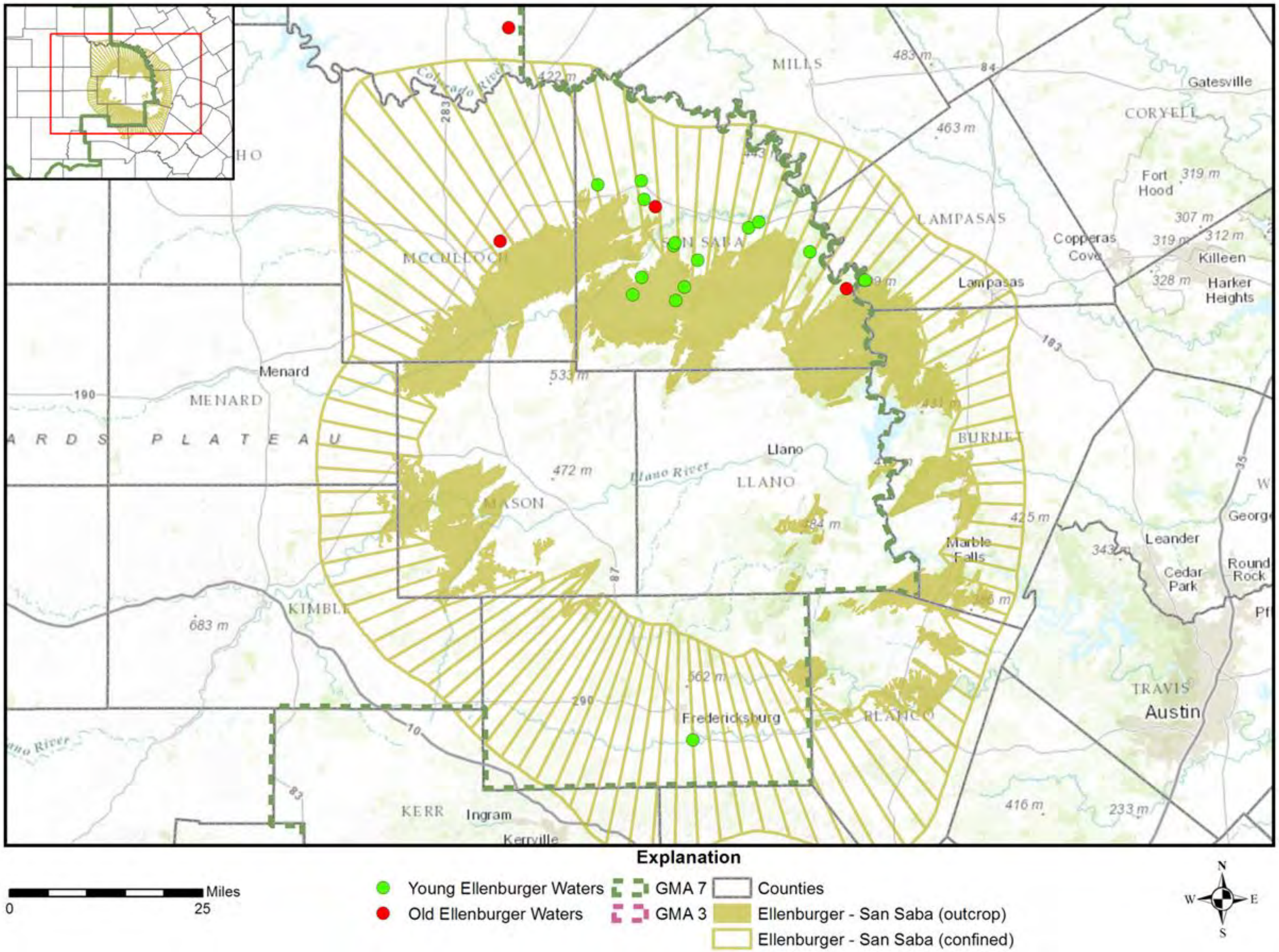


Figure 6-4. Old and young sample locations for the Ellenburger-San Saba Aquifer in the Llano Uplift area.

6.2.2 Hickory Aquifer

Comparison of the carbon-14 percent modern to tritium for the Hickory Aquifer in the Llano Uplift area shows two different groupings (Figure 6-5).

1. Young waters with carbon-14 percent modern values from 0.4 to 1.1 and tritium values from 0.5 to 3.25 TU (Figure 6-5). These waters are considered young and are located either in the outcrop or slightly downdip.
2. Old waters with carbon-14 percent modern values that range from less than 0.1 to 0.55 and tritium values from less than 0.5 TU (Figure 6-5). The TWDB has previously analyzed chlorine-36 values for the Hickory Aquifer. The old carbon-14 waters also have the lowest chlorine-36 values, which is an additional confirmation of their older age (Figure 6-6). Assessment of these old waters also indicates lighter deuterium and oxygen-18 values than the young waters (Figure 6-7). These samples are generally located in the downdip sections of the Hickory Aquifer (Figure 6-8).

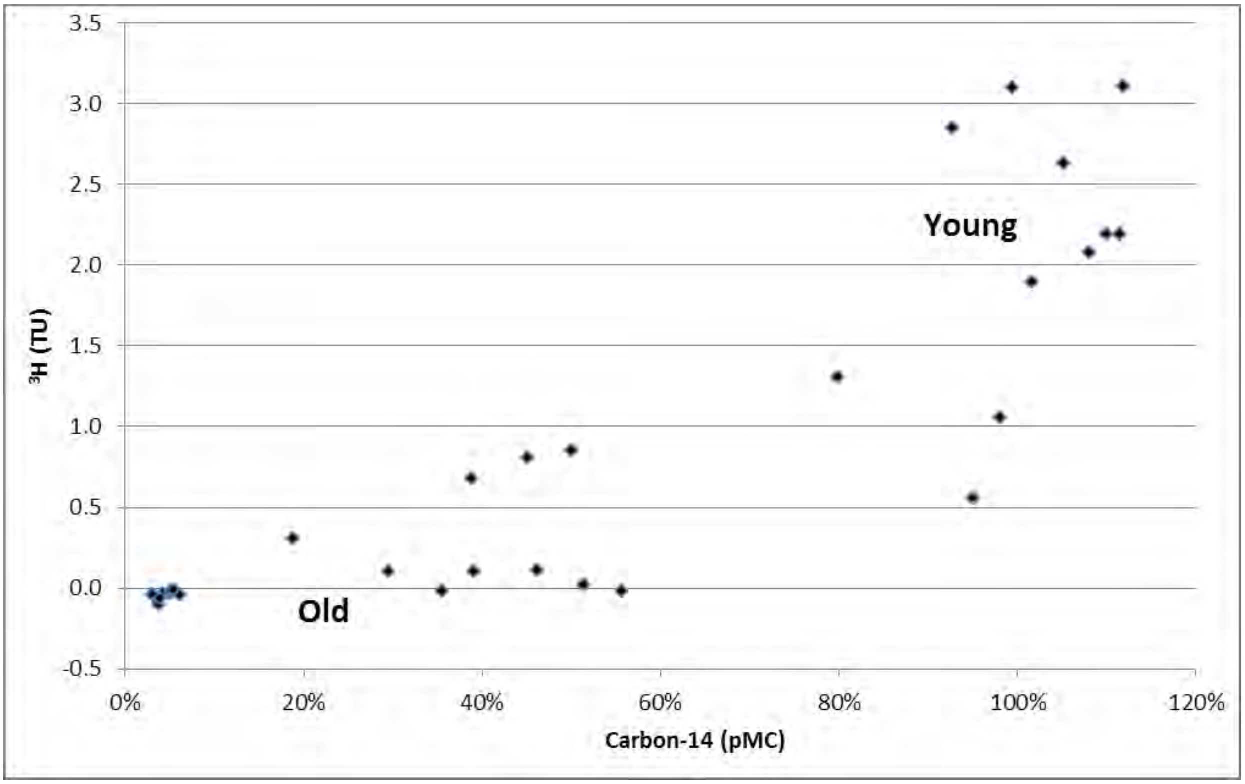


Figure 6-5. Tritium (^{3}H) vs carbon-14 percent modern (C-14%) for the Hickory Aquifer in the Llano Uplift area.

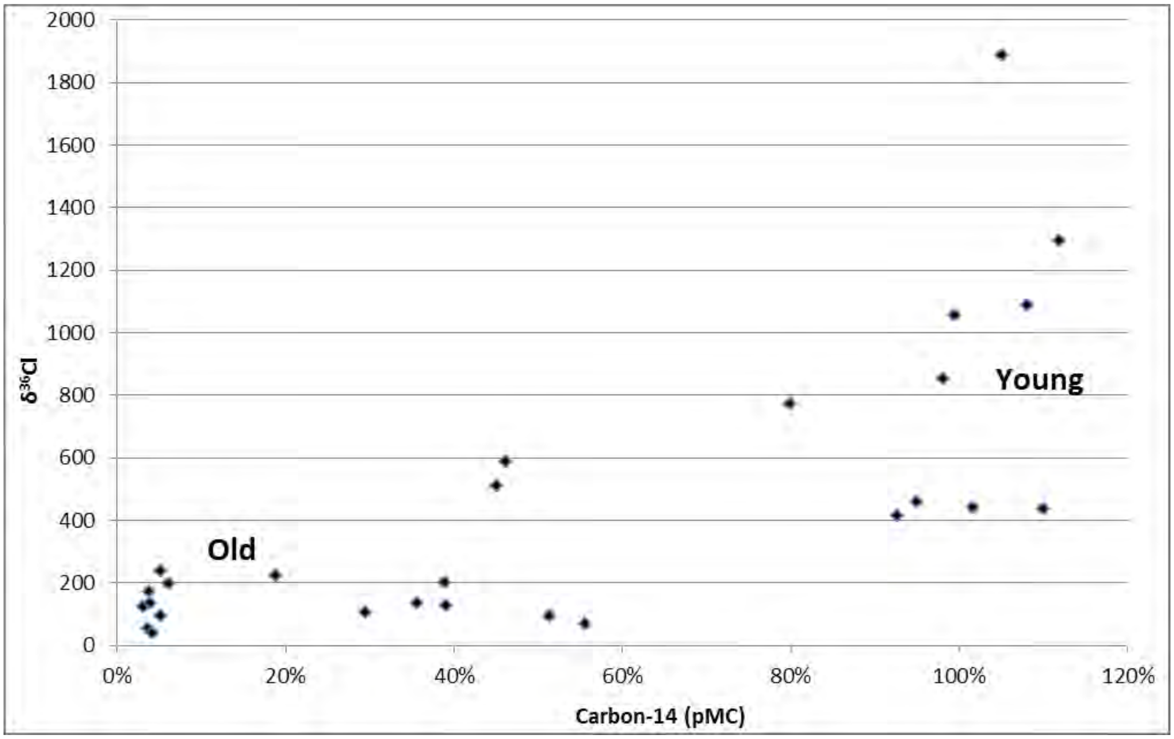


Figure 6-6. Chlorine-36 (δ^{36}Cl) vs carbon-14 percent modern (C-14%) for the Hickory Aquifer in the Llano Uplift area.

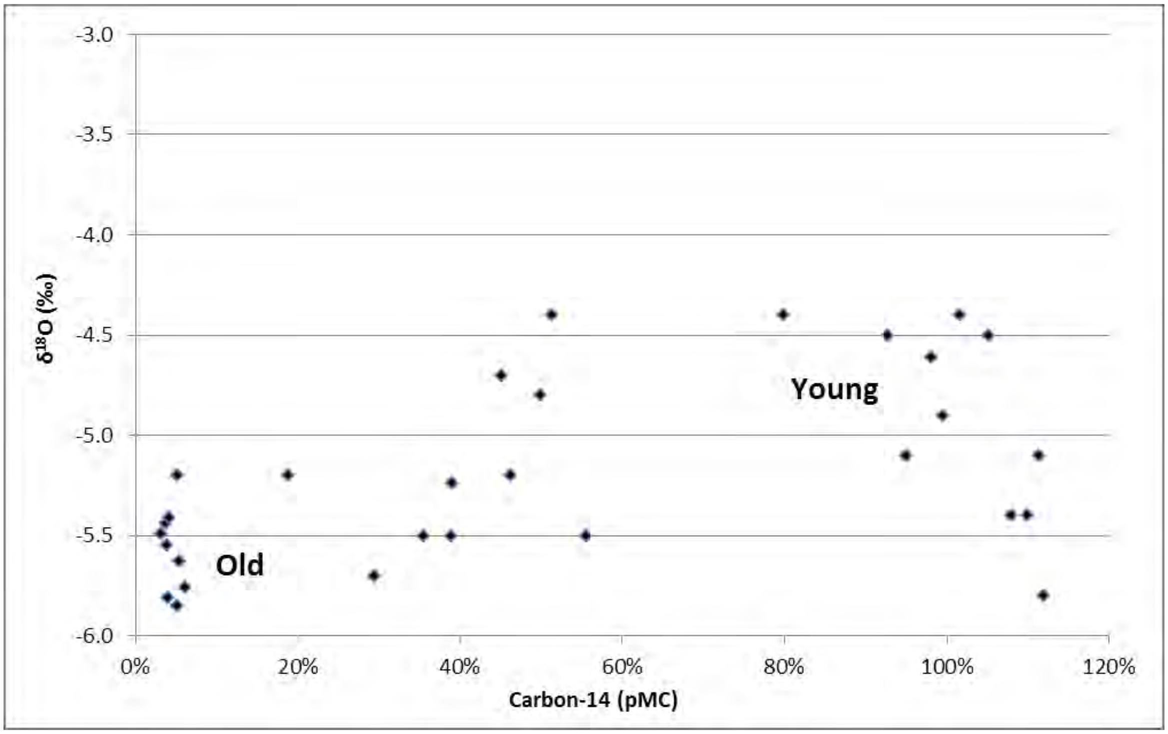


Figure 6-7. Oxygen-18 (δ^{18}O) permil vs carbon-14 percent modern (C-14%) for the Hickory Aquifer in the Llano Uplift area.

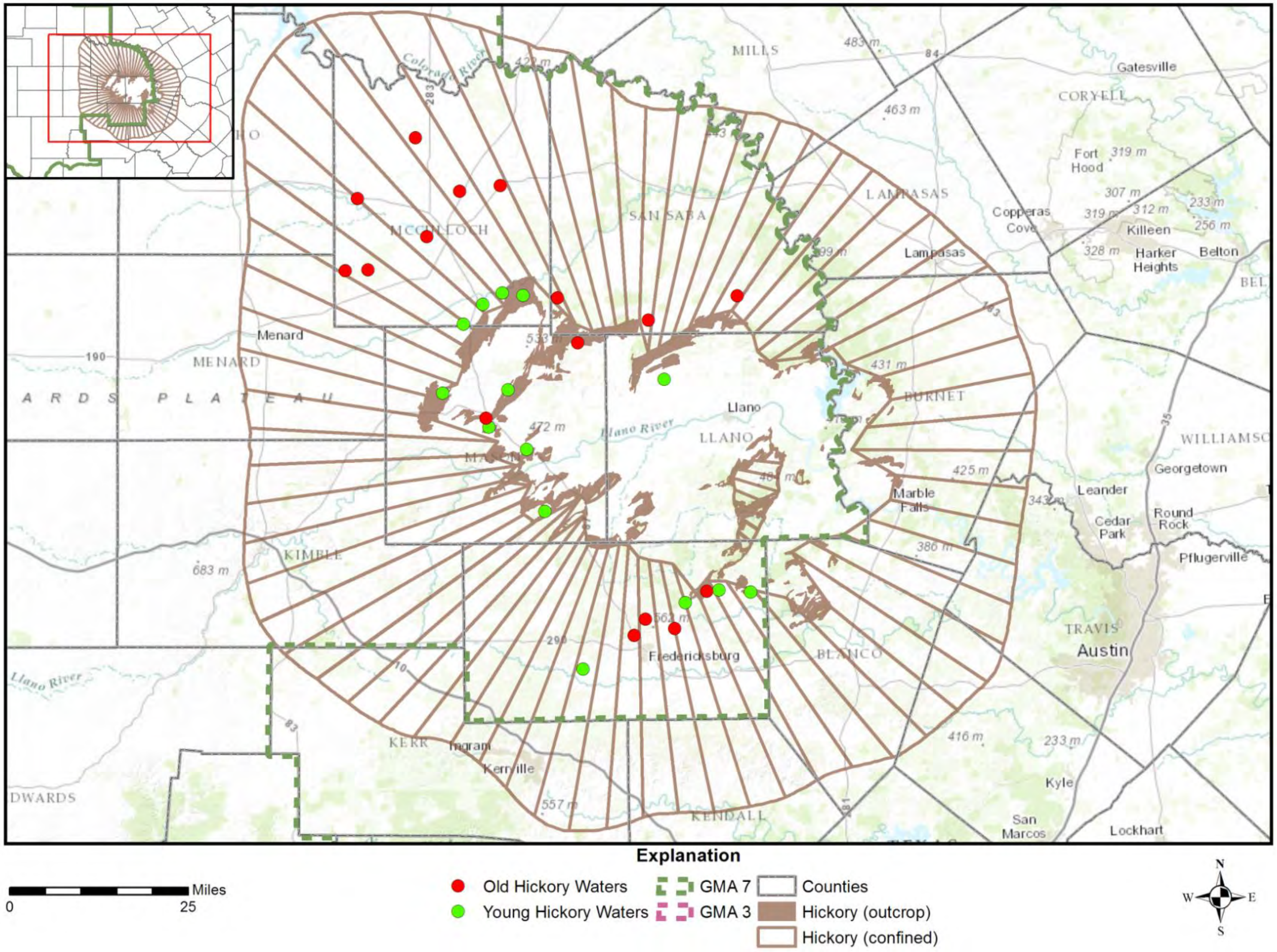


Figure 6-8. Old and young sample locations for the Hickory Aquifer in the Llano Uplift area (based on age of water designation from Figure 6-5).

6.2.3 Edwards-Trinity (Plateau) Aquifer

Comparisons of the carbon-14 percent modern to tritium for the Edwards Group on the Edwards-Trinity (Plateau) Aquifer show two different groupings (Figure 6-9).

1. Carbon-14 percent modern from 0.4 to 1.1 and tritium from 0.5 to 3.5 TU. These waters are considered as young and being actively recharged. They represent a vast majority of the Edwards Group waters from the Edwards-Trinity (Plateau) Aquifer (Figure 6-10).
2. Waters with carbon-14 percent modern less than 0.4 and tritium values less than 0.5 TU. These waters are considered as old.

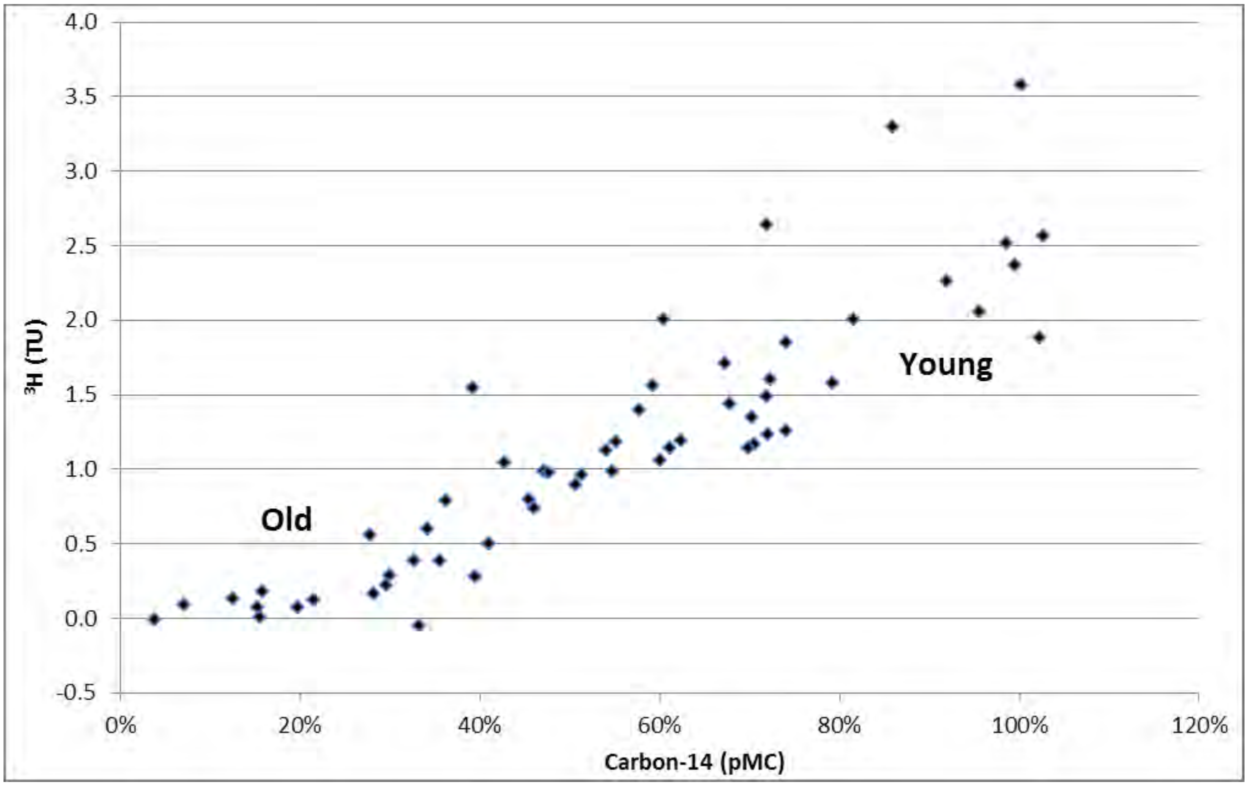


Figure 6-9. **Tritium (^{3}H) vs carbon-14 percent modern (C-14%) for the Edwards Group (and associated limestones) in the Edwards-Trinity (Plateau) Aquifer.**

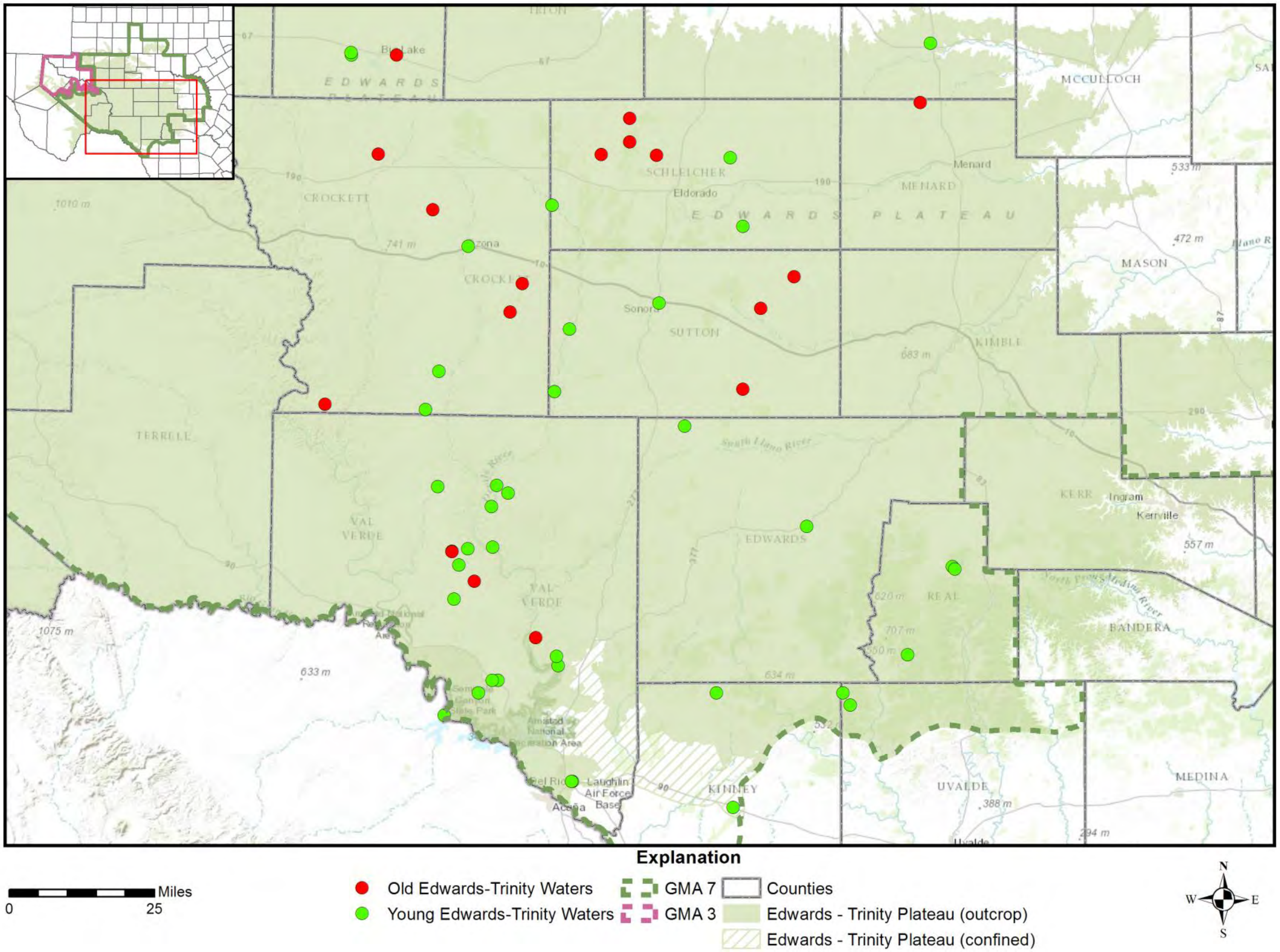


Figure 6-10. Old and young sample locations for the Edwards Group in the Edwards-Trinity (Plateau) Aquifer (based on age of water designation from Figure 6-9).

6.2.4 Antlers Formation

Comparison of the carbon-14 percent modern to tritium for the Antlers Formation waters in the northwestern region of the Edwards-Trinity (Plateau) Aquifer shows two different groupings (Figure 6-11).

1. Waters with carbon-14 percent modern greater than 0.4 and tritium values greater than 0.5 TU. These waters are considered as young waters. There are only a few of these young waters. These waters are isotopically light and have a wider range of deuterium and oxygen-18 values (Figure 6-12Figure 6-13).
2. Waters with carbon-14 percent modern less than 0.4 and tritium values less than 0.5 TU. These are considered as old waters and represent a majority of the collected samples. Figure 6-10 shows this is the prevalent water type across the Antlers Formation (Figure 6-13).

As a note: in this figure there is “old” water designation for the Edwards-Trinity (Plateau) Aquifer outside of the TWDB designated aquifer bounds in the Glass Mountains of Pecos County. To be clear, TWDB aquifer designations were used for this study, therefore this location fell into the Edwards-Trinity (Plateau) Aquifer dataset. It is unclear if this inconsistency is due to incorrect aquifer designation for the well or if the reach of the Edwards-Trinity (Plateau) Aquifer boundary does not extend far enough west in this area.

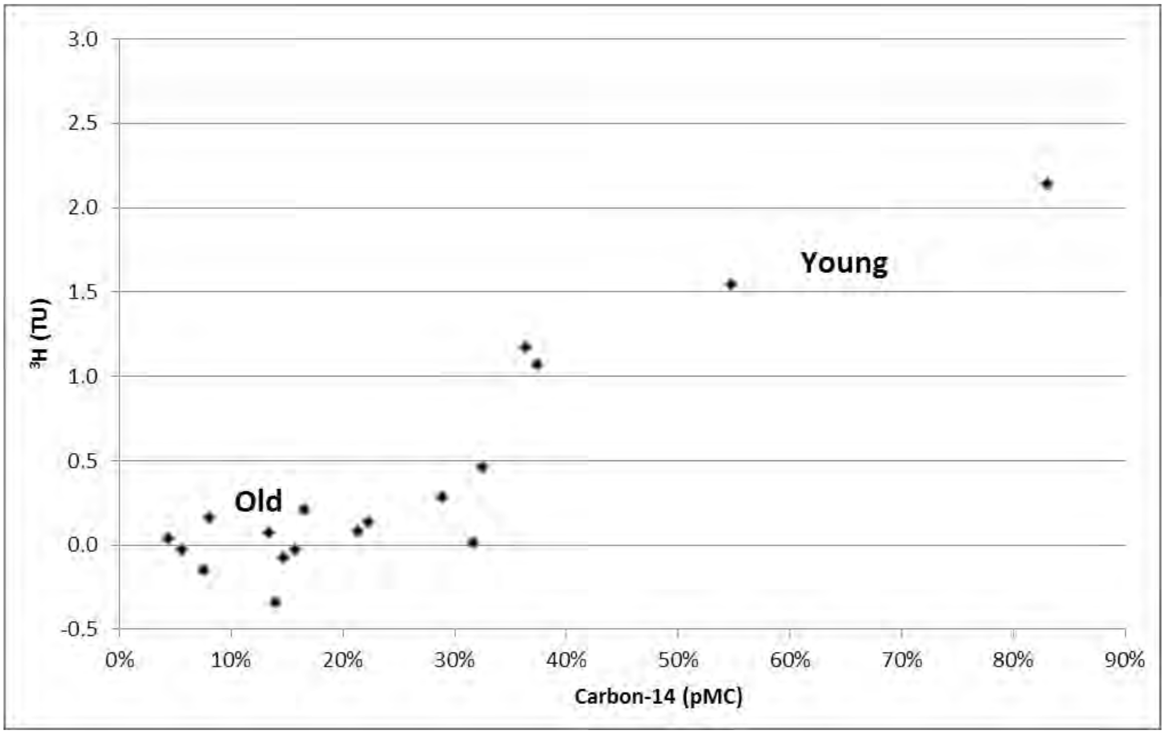


Figure 6-11. **Tritium (^{3}H) vs carbon-14 percent modern (C-14%) for the Antlers Formation in Edwards-Trinity (Plateau) Aquifer.**

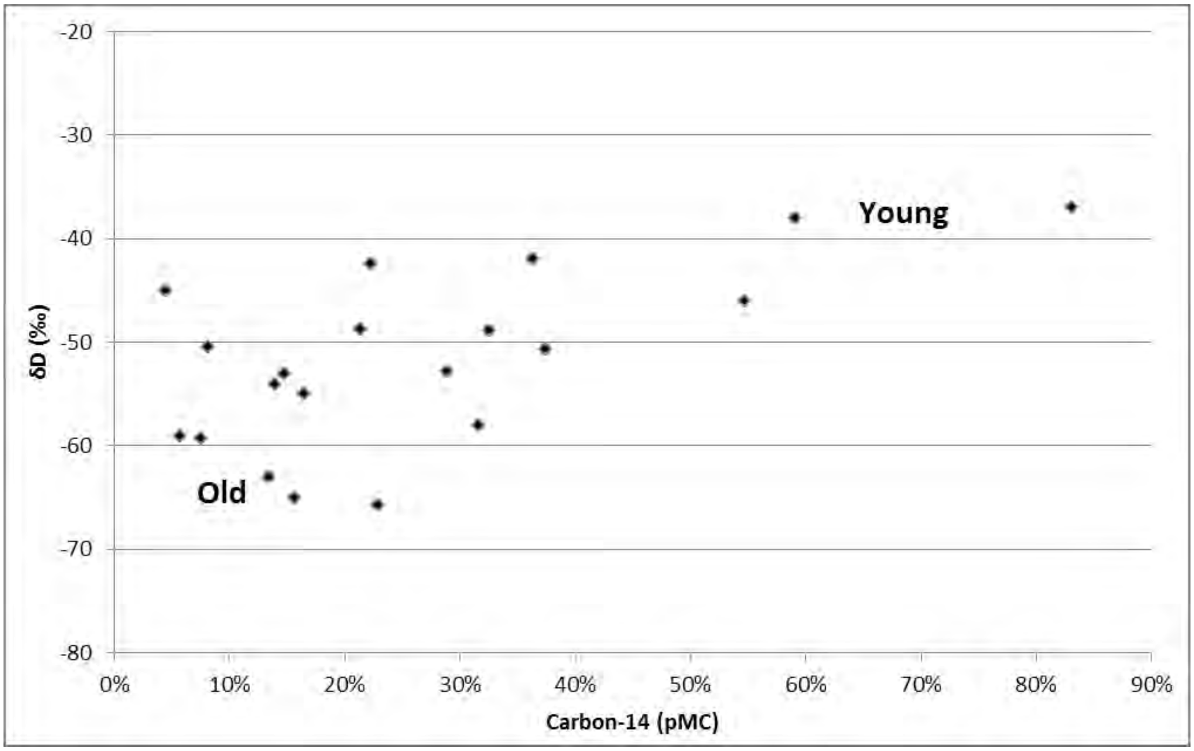


Figure 6-12. **Deuterium (δD) vs carbon-14 percent modern (C-14%) for the Antlers Formation in Edwards-Trinity (Plateau) Aquifer.**

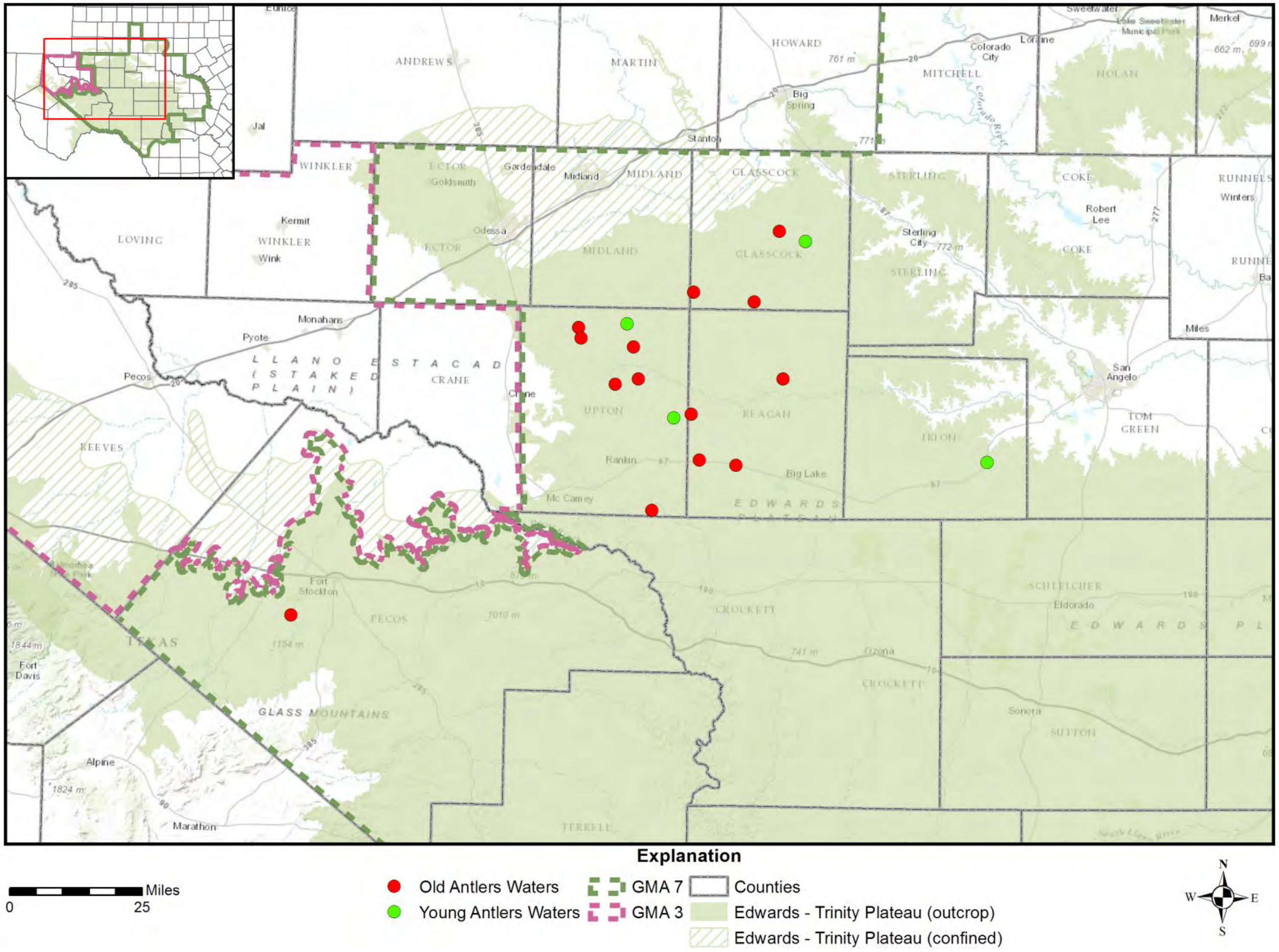


Figure 6-13. **Old and young sample locations for the Antlers Formation in the Edwards-Trinity (Plateau) Aquifer (based on age of water designation from Figure 6-11).**

6.2.5 *Edwards -Trinity (Plateau) Aquifer (Trans-Pecos Region)*

Comparison of the carbon-14 percent modern to tritium for the Edwards-Trinity (Plateau) Aquifer in the Trans-Pecos region (Pecos, Reeves and Terrell counties) generally shows two different groupings (Figure 6-14).

1. Waters with carbon-14 percent modern from about 0.4 to about 1.1 and tritium values greater than 0.5 TU. These waters are considered as young waters.
2. Waters with carbon-14 percent modern values less than 0.4 and tritium values greater than 0.5 TU. These waters are considered to be old.
3. These waters are isotopically light and have a wide range of deuterium and oxygen-18 values as indicated by the red dot symbols in Figure 6-15.
4. There are a few samples in this data set that have high tritium values, but low carbon-14 percent modern values. They are considered as young water because of the presence of tritium (Figure 6-14).

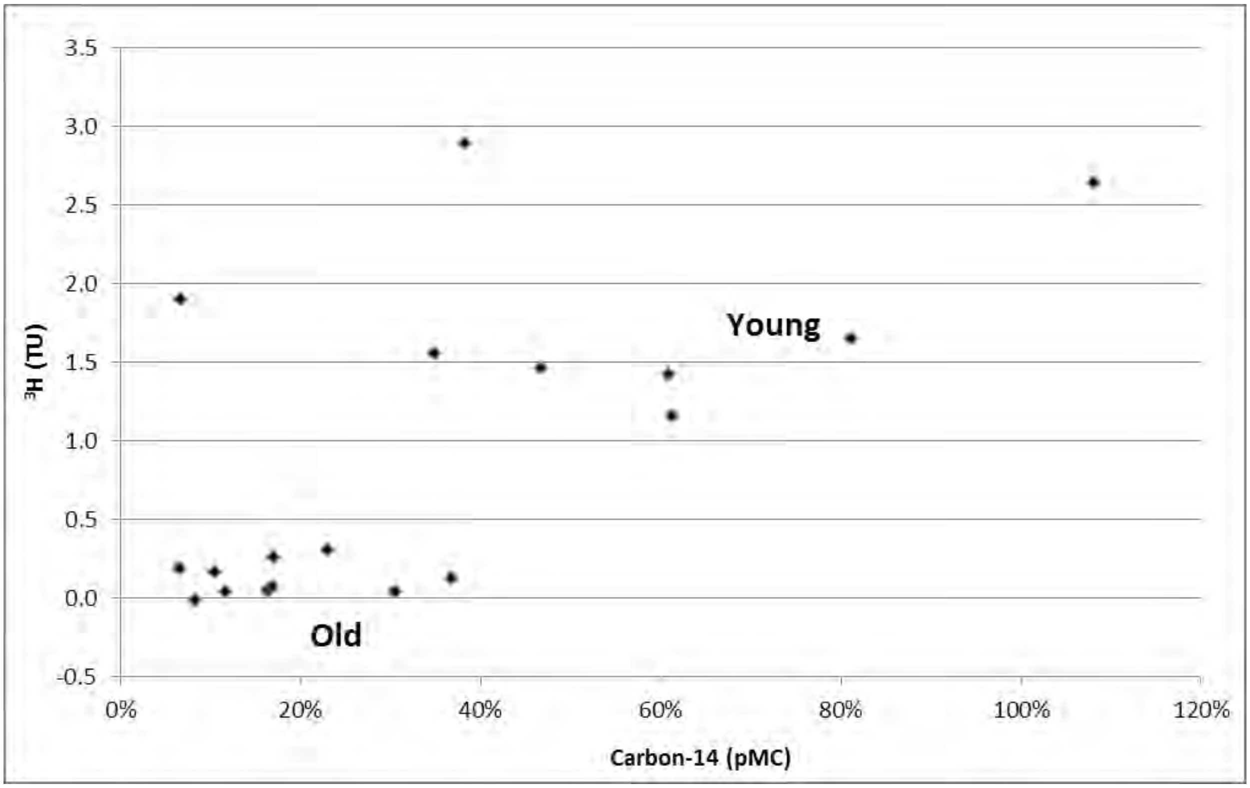


Figure 6-14. **Tritium (^{3}H) vs carbon-14 percent modern (C-14%) for the Edwards-Trinity (Plateau) Aquifer in the Trans-Pecos region.**

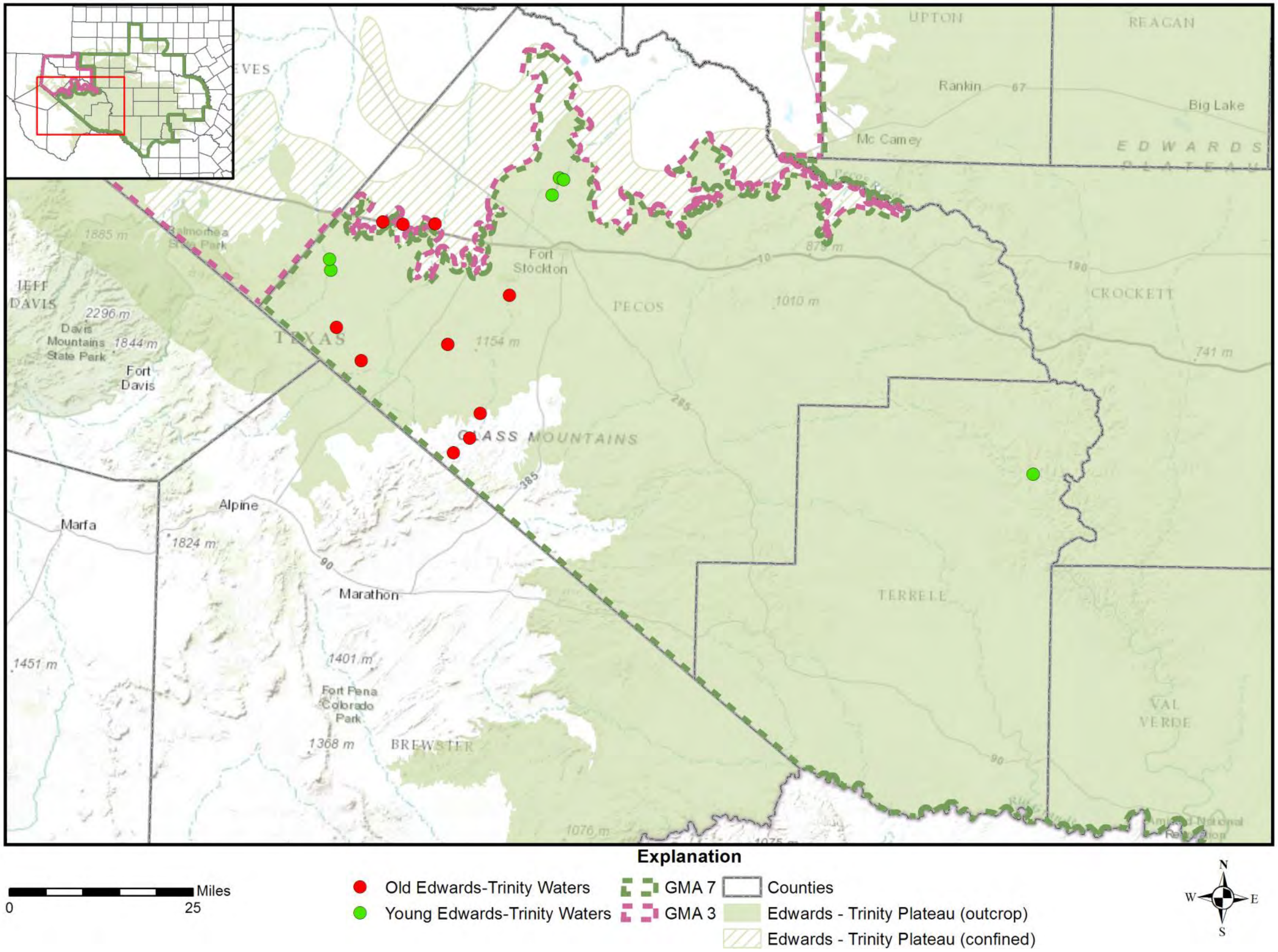


Figure 6-15. Old and young sample locations for the Edwards-Trinity (Plateau) Aquifer in the Trans-Pecos region (based on age of water designation from Figure 6-14).

6.2.6 Pecos Valley Aquifer

Comparison of carbon-14 percent modern to tritium for the Pecos Valley Aquifer in the Trans-Pecos region shows two different groupings (Figure 6-16).

1. Four samples with carbon-14 percent modern from 0.5 to 1.0 and tritium values greater than 1.0 TU. The four wells are 71, 94, 150, and 150 feet deep. These wells are relatively shallow wells compared to the total thickness of the Pecos Valley Aquifer, and may be subject to more recent recharge events than wells screened in deeper portions of the aquifer.
2. Eleven samples have carbon-14 percent modern less than 0.7 and tritium values less than 0.5 TU. These are considered as old waters and represent a majority of the groundwaters in the Pecos Valley Aquifer (Figure 6-17).
3. These waters are isotopically light and have a wide range of deuterium and oxygen-18 (Figure 6-17).

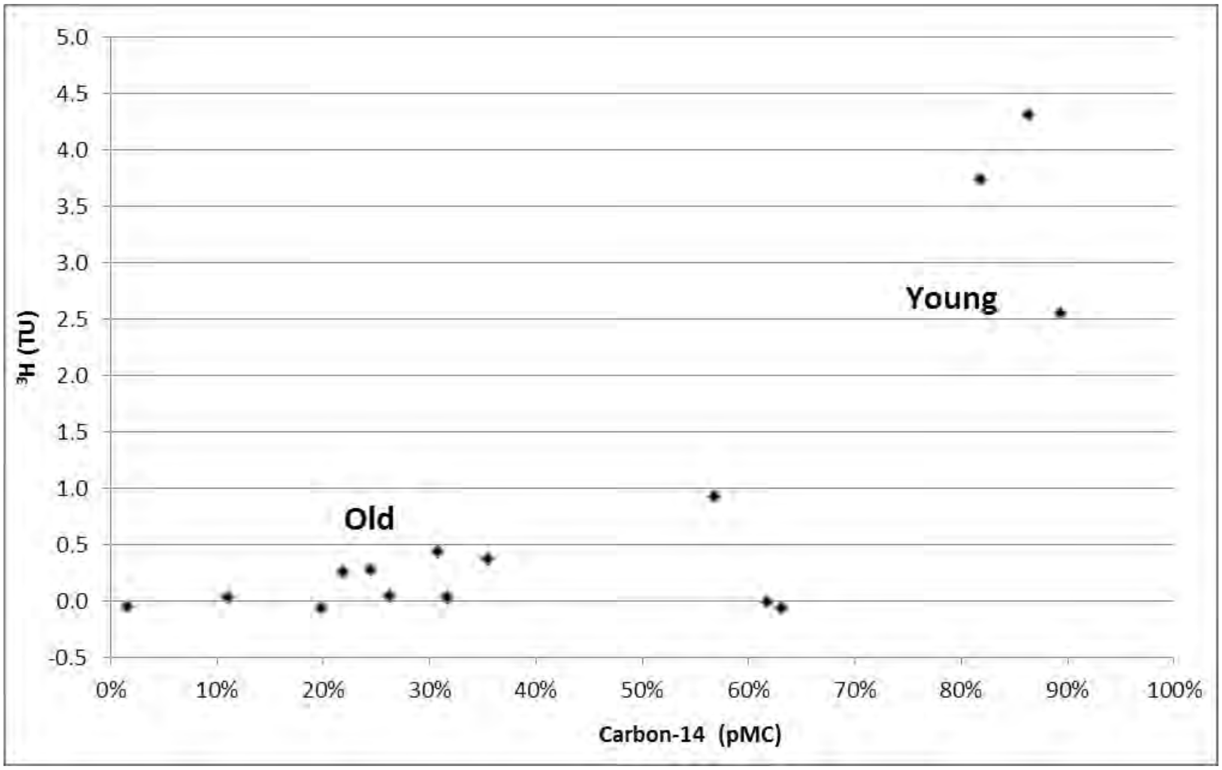


Figure 6-16. **Tritium (^{3}H) vs carbon-14 percent modern (C-14%) for the Pecos Valley Aquifer in the Trans-Pecos region.**

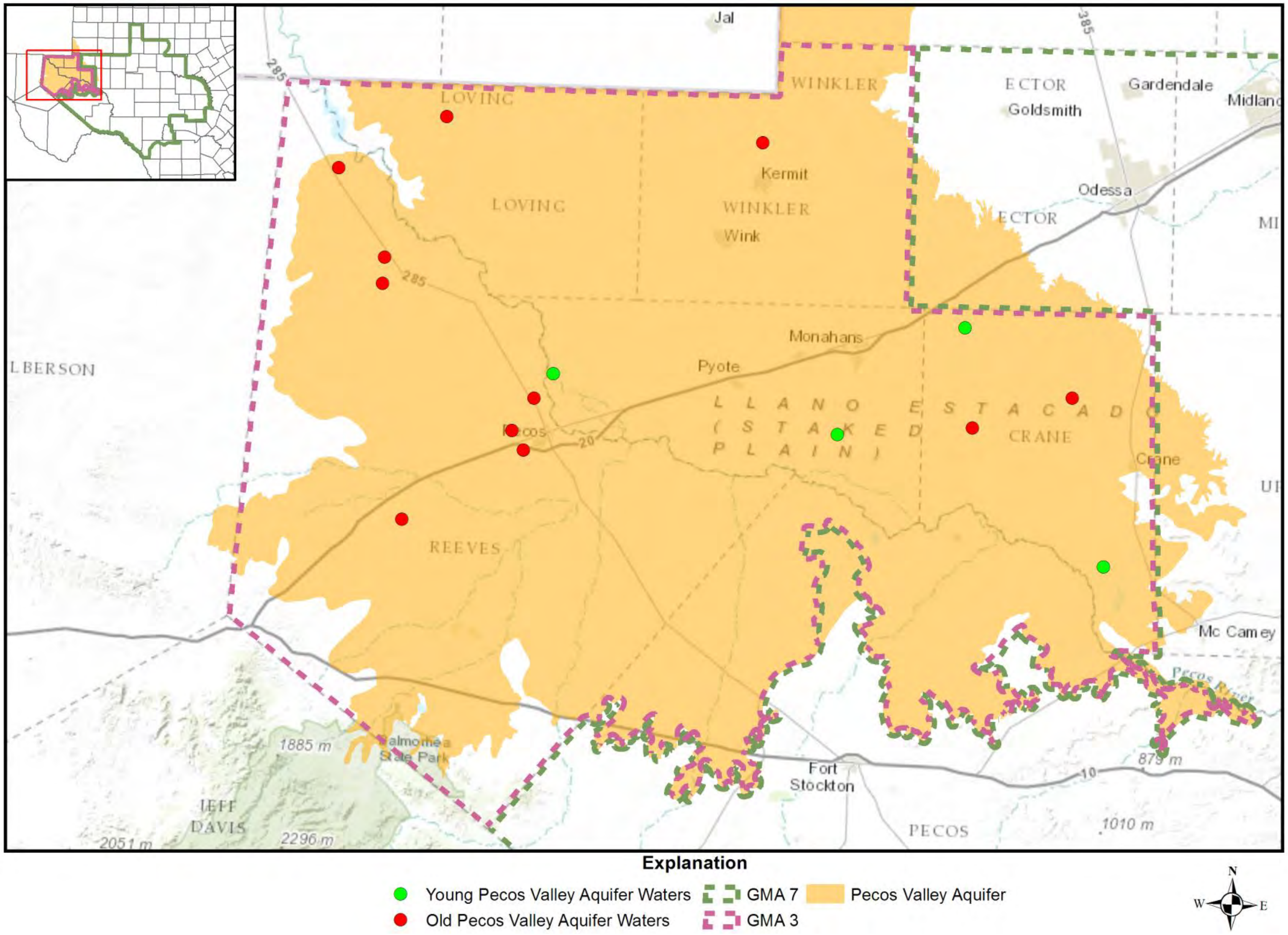


Figure 6-17. **Old and young sample locations for the Pecos Valley Aquifer in the Trans-Pecos region (based on age of water designation from Figure 6-16).**

6.2.7 *Rustler Aquifer*

Comparison of the carbon-14 percent modern to tritium for the Rustler Aquifer in the Trans-Pecos region shows only one group (Figures 6-15 and 6-16). Although it is a small data set, all waters sampled from the Rustler Aquifer have very low tritium values and low carbon-14 percent modern values. These waters are considered as old waters.

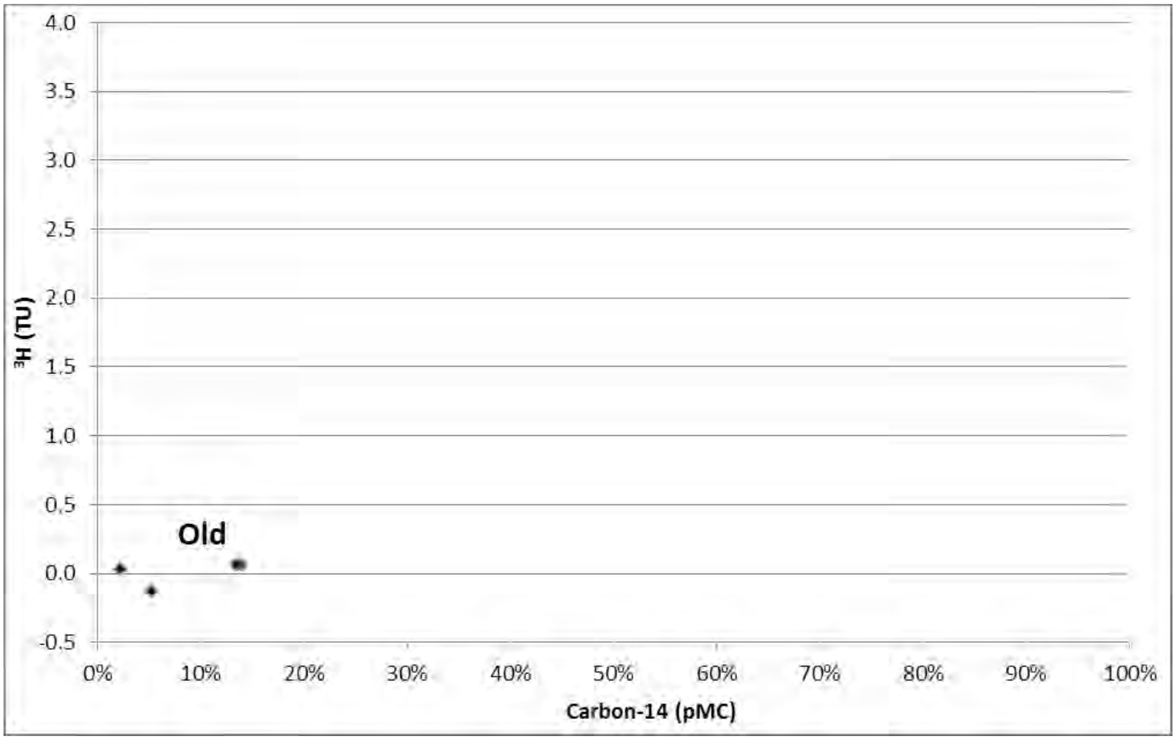


Figure 6-18. **Tritium (^{3}H) vs carbon-14 percent modern (C-14%) for the Rustler Aquifer in the Trans-Pecos region.**

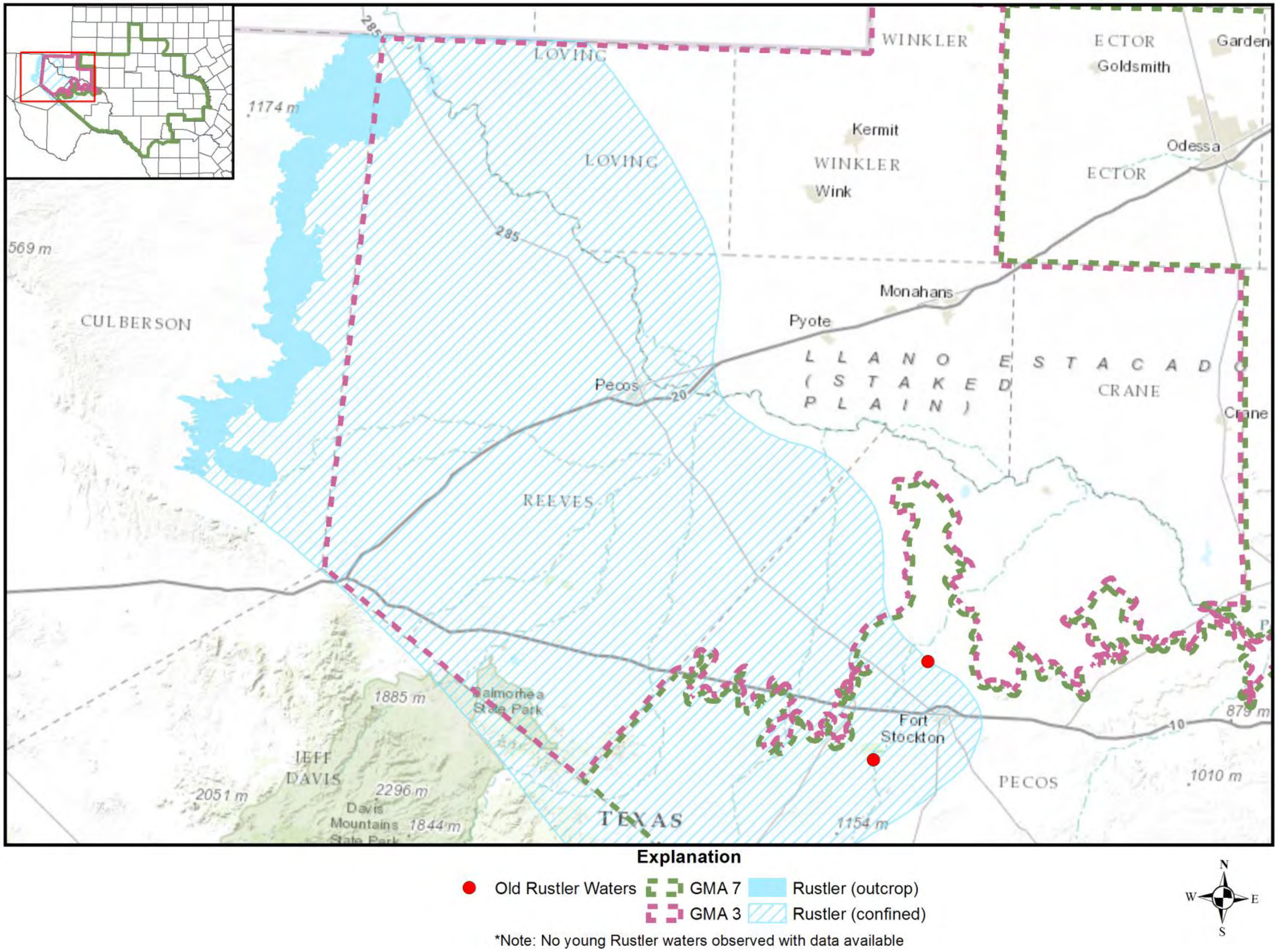


Figure 6-19. Old and young sample locations for the Rustler Aquifer in the Trans-Pecos region. (based on age of water designation from Figure 6-18).

6.3 Hydrochemical Profiles

Conceptual hydrogeologic cross-sections were developed to better visualize hydrochemical and isotope data within the aquifer systems in GMA 3 and 7. To develop the conceptual cross-sections and to represent the aquifer tops and bases, GAM layer top and bottom elevation data were used in conjunction with Surfer, ArcGIS, and ET Surface software to develop triangulated, irregular network (TIN) surfaces, which have geographical x, y, and z components. These raster and TIN layers were imported into a map document where, using a profile selection tool, cross-sections lines were digitized. GIS point features with water quality and depth information were used to apply a depth reference to the data points within the profile.

Five cross-sections were developed within GMAs 3 and 7 to provide some insight into the different aquifer systems in this region. Data from the TWDB groundwater database and laboratory results from wells sampled during this study were included in the cross-sections. Transect A-A' runs from eastern Reeves County to western Gillespie County as shown in Figure 6-20 through Figure 6-22. Data for nitrate, carbon-14 percent modern and oxygen-18 were plotted on the transect at the depth of the wells located within 1,000 feet of the transect. This transect shows most of the aquifers within GMA 3 and 7.

Figure 6-23 through Figure 6-25 show plots of nitrate, carbon-14, and total dissolved solids along transect B-B', which runs from Winkler County to Pecos County through the Pecos Valley Aquifer, the Capitan Reef Complex Aquifer, the Dockum Aquifer, the Rustler Aquifer, and the Edwards-Trinity (Plateau) Aquifer in the Trans-Pecos region.

In the central region of GMA 7, transect C-C' traverses the Edwards-Trinity (Plateau) Aquifer from northern Glasscock County to southern Val Verde County. Figure 6-26 through Figure 6-28 shows plots of nitrate, carbon-14 percent modern and $\delta 18O$ within the Dockum Aquifer, Edwards-Trinity (Plateau) Aquifer and the Trinity Group along the C-C' transect.

The last two transects are located in the Llano Uplift area. D-D' runs from the center of the Llano Uplift area in the northeast sub-region (McCulloch County) and highlights data in the Hickory Aquifer and the Ellenburger-San Saba Aquifer. Figure 6-29 through Figure 6-31s contains data for nitrate, carbon-14 percent modern, and tritium, respectively. Cross-section E-E', shown in Figure 6-32 also runs downdip from the center of the Llano Uplift area in the eastern sub-region (Burnet County). Only Nitrate was plotted within a mile of this transect due to the lack of isotope data.

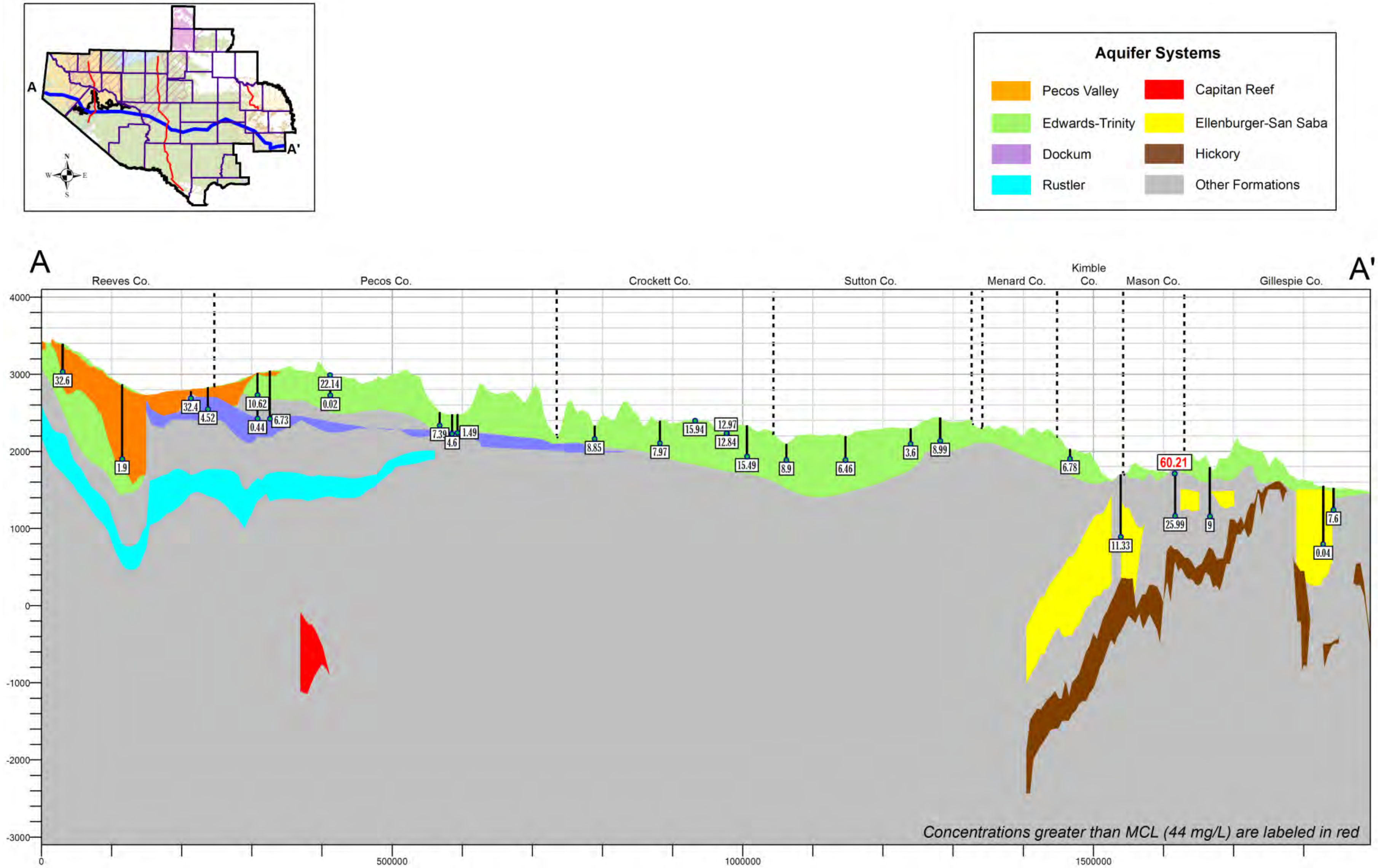


Figure 6-20. **West to east profile (A-A') showing nitrate concentration at depth for various aquifers in GMAs 3 and 7.**

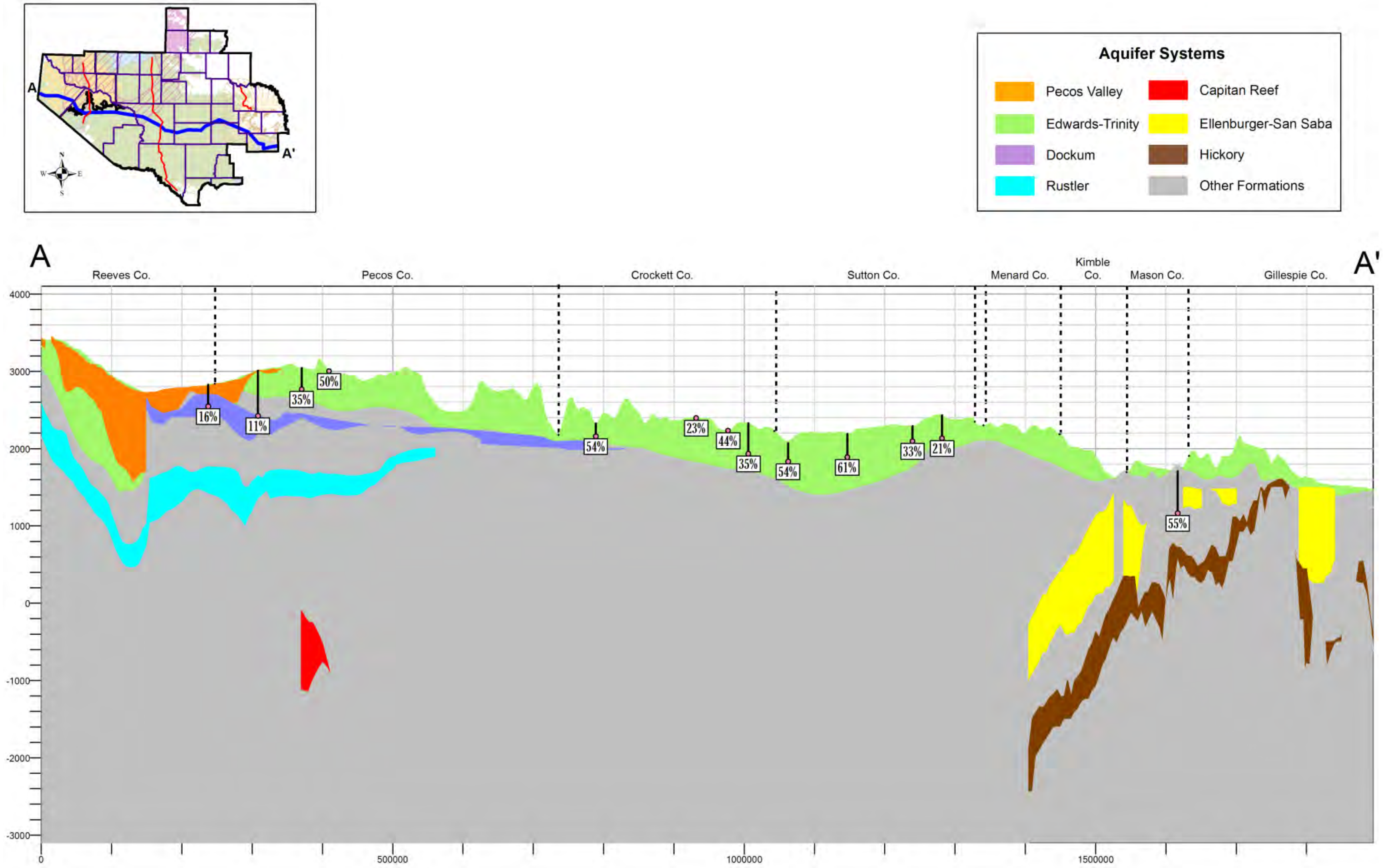


Figure 6-21. West to east profile (A-A') showing carbon-14 percent modern at depth for various aquifers in GMAs 3 and 7.

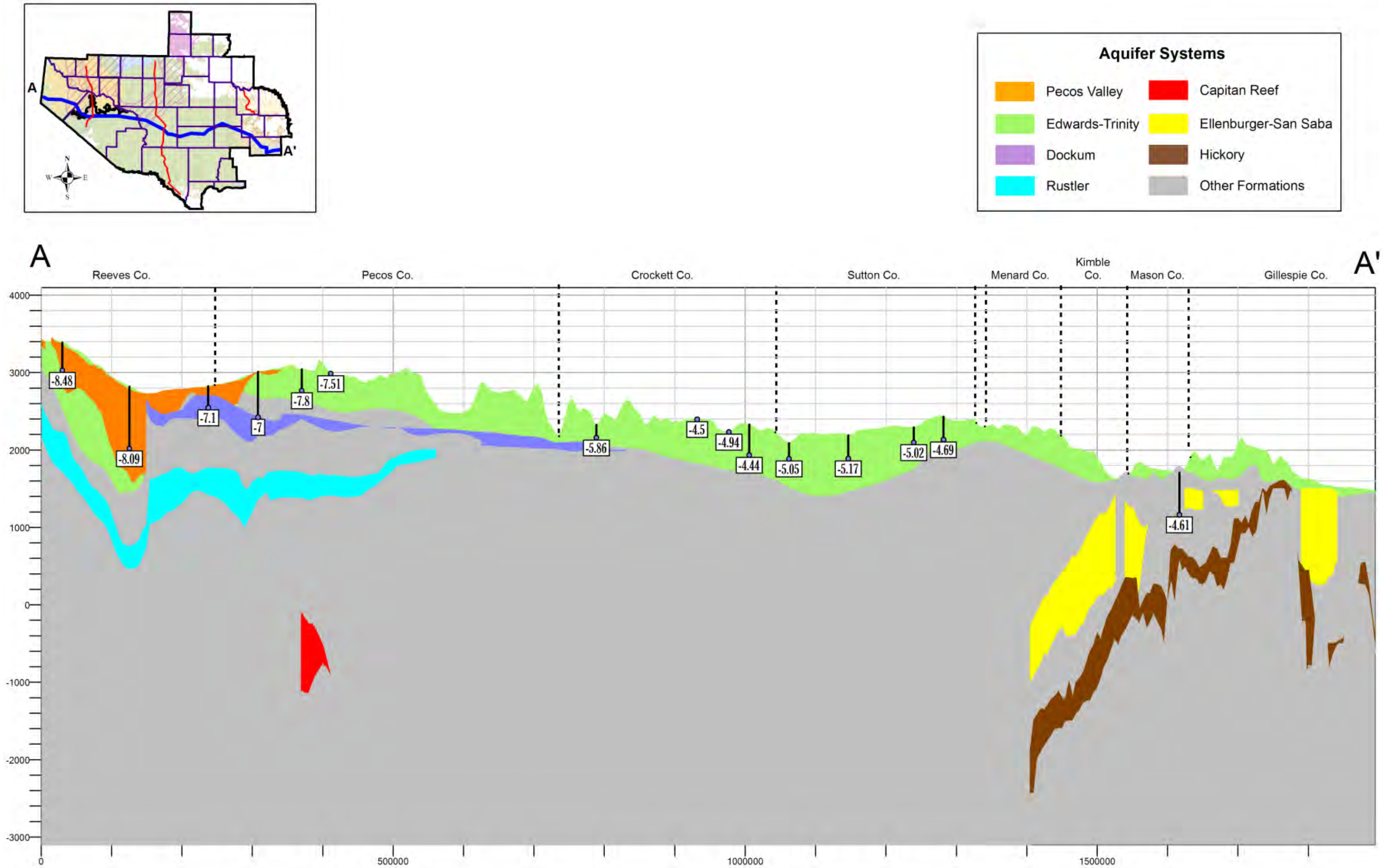
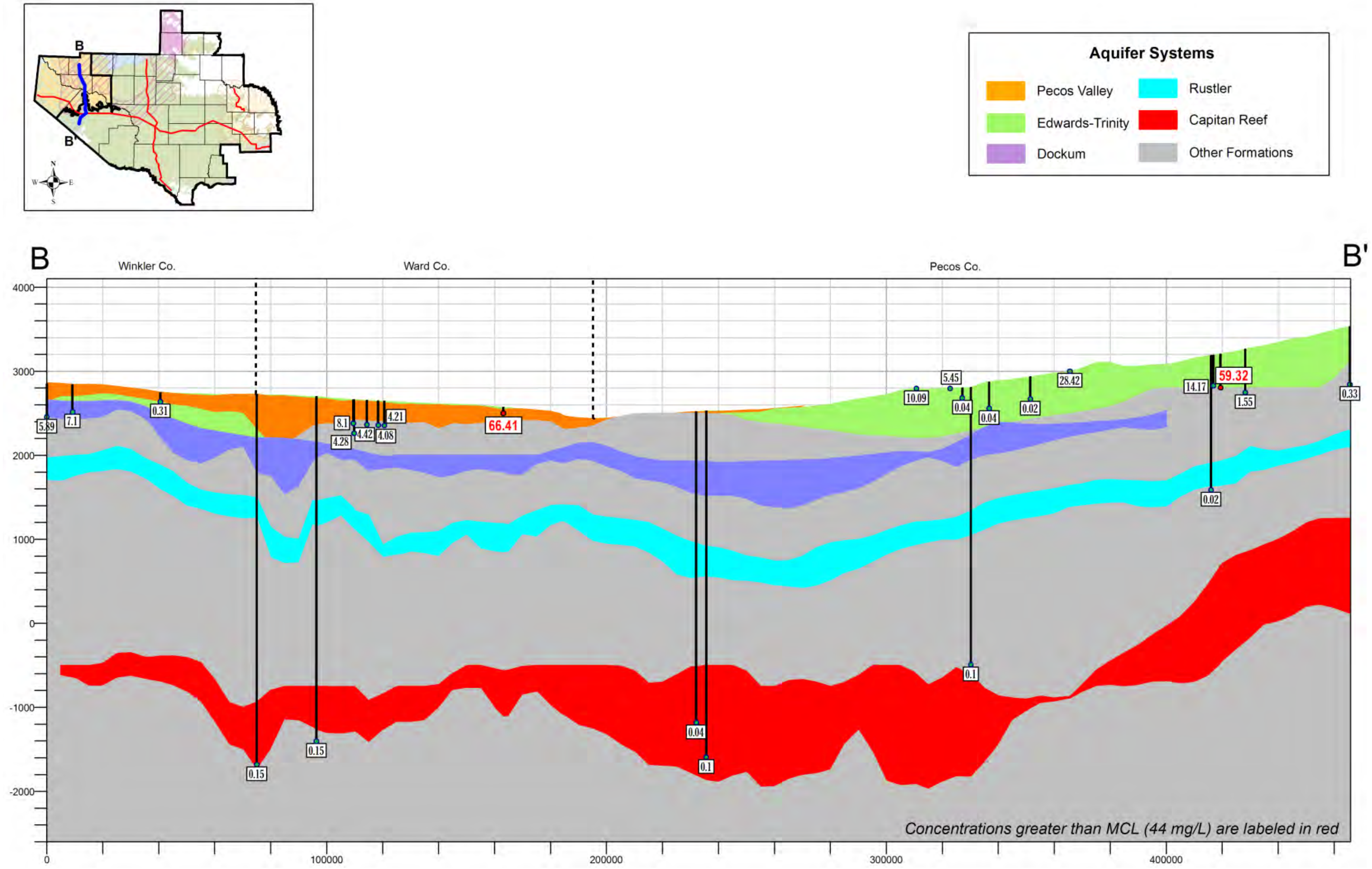


Figure 6-22. West to east profile (A-A') showing $\delta^{18}O$ at depth for various aquifers in GMAs 3 and 7.



Concentrations greater than MCL (44 mg/L) are labeled in red

Figure 6-23. **North to south profile (B-B') showing nitrate concentration at depth for various aquifers in GMAs 3 and 7.**

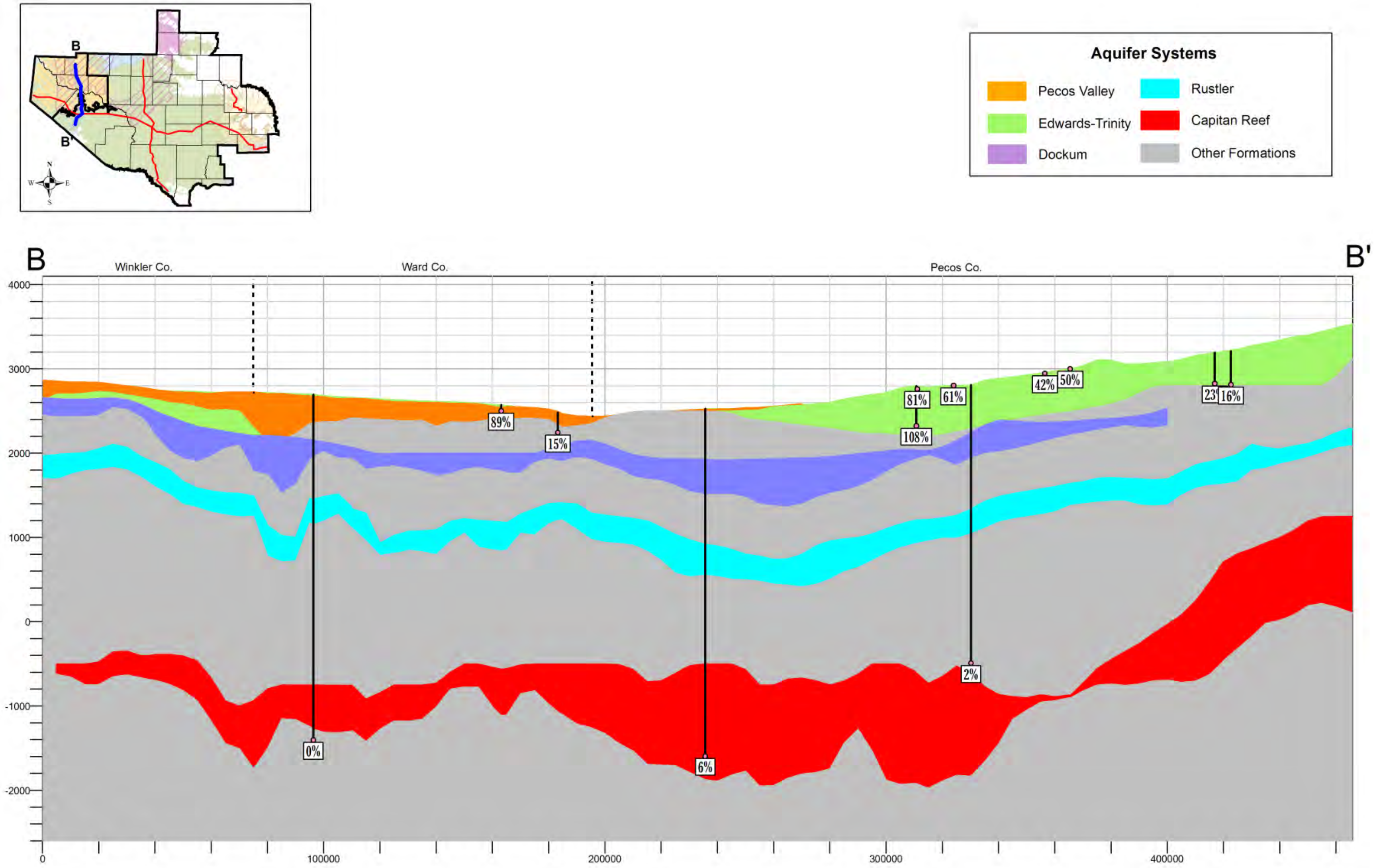


Figure 6-24. North to south profile (B-B') showing carbon-14 percent modern at depth for various aquifers in GMAs 3 and 7.

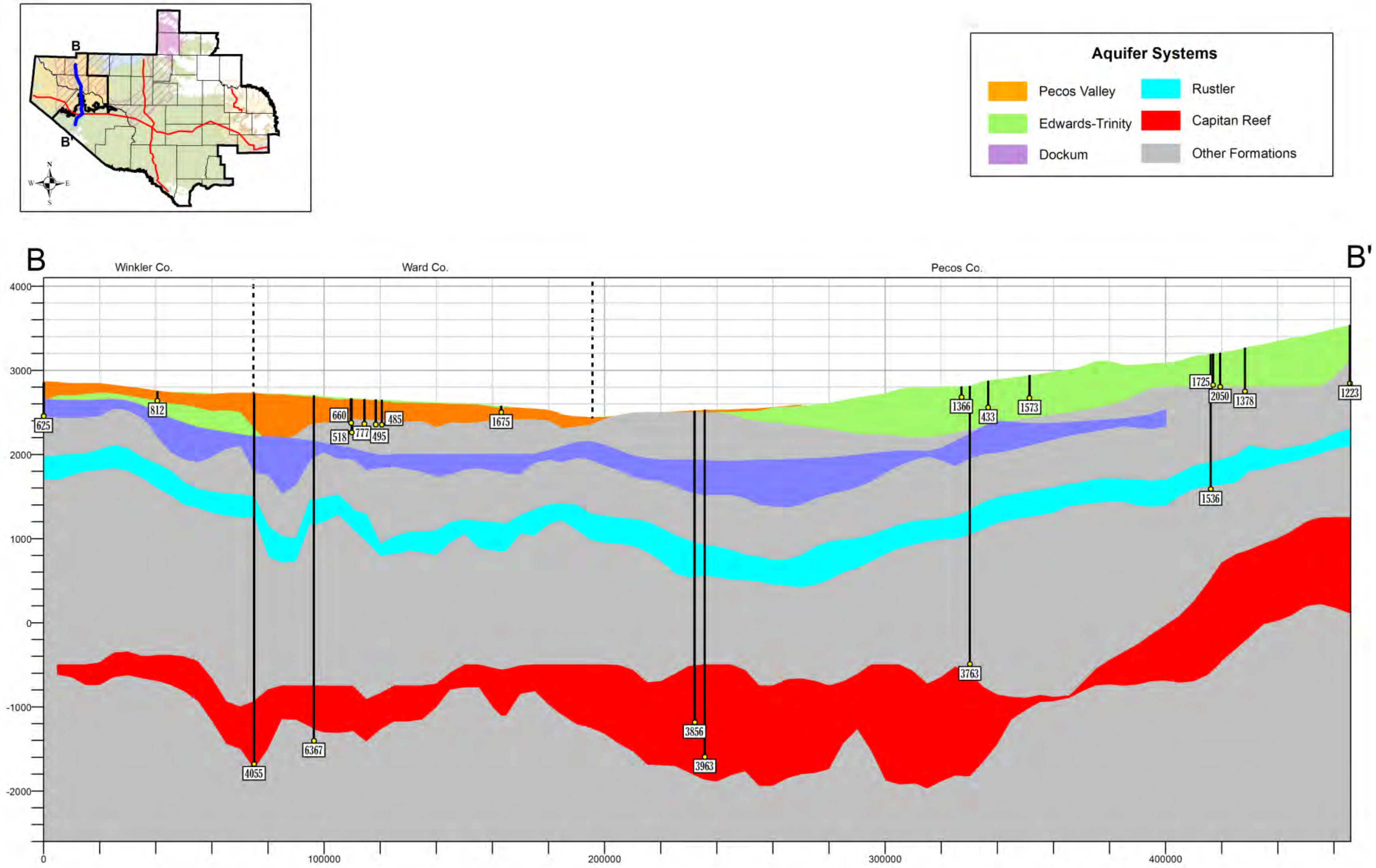


Figure 6-25. North to south profile (B-B') showing total dissolved solids concentration at depth for various aquifers in GMAs 3 and 7.

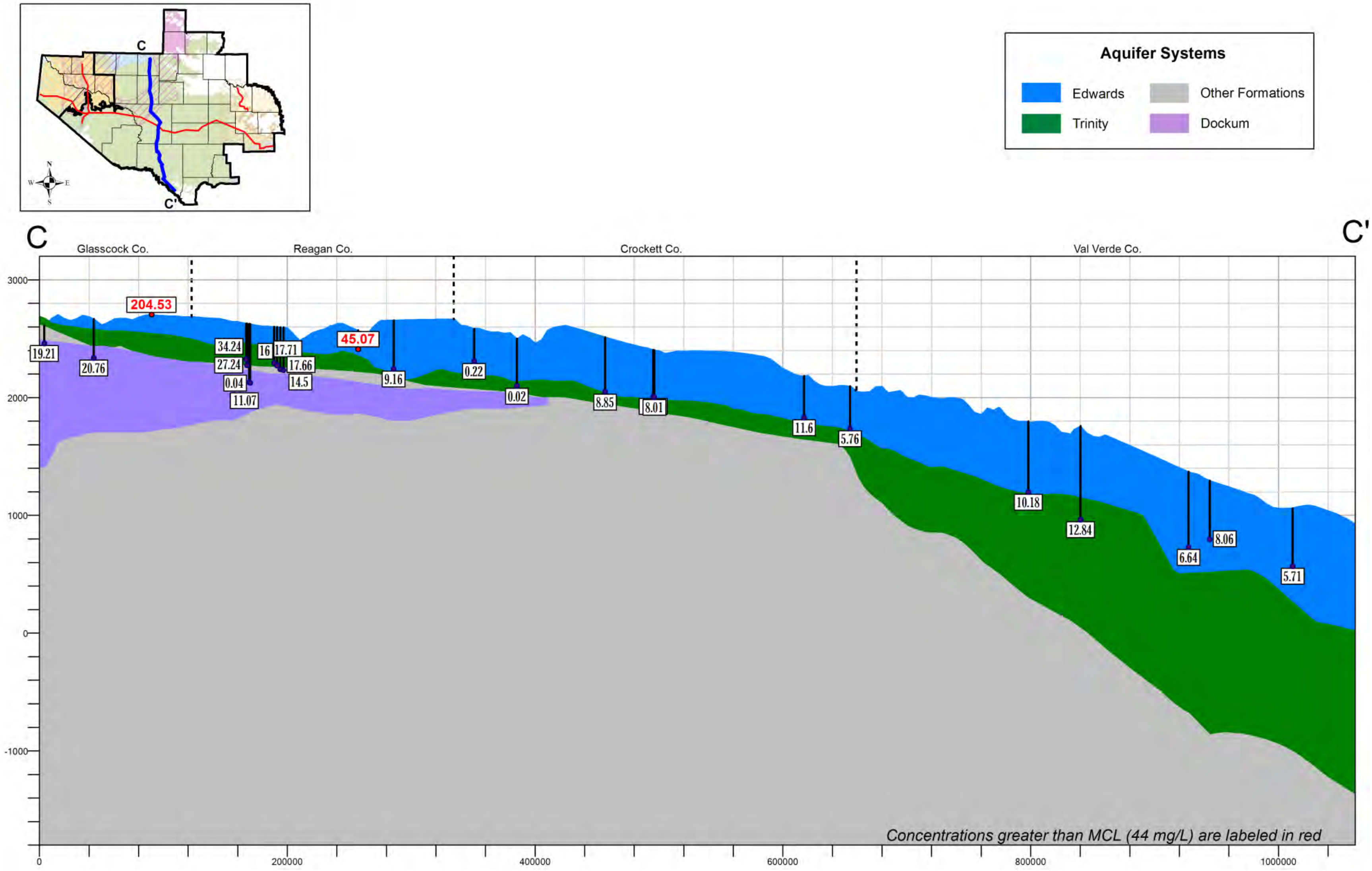


Figure 6-26. North to south profile (C-C') showing nitrate concentration at depth for the Edwards-Trinity (Plateau) Aquifer and the Dockum Aquifer in GMA 7.

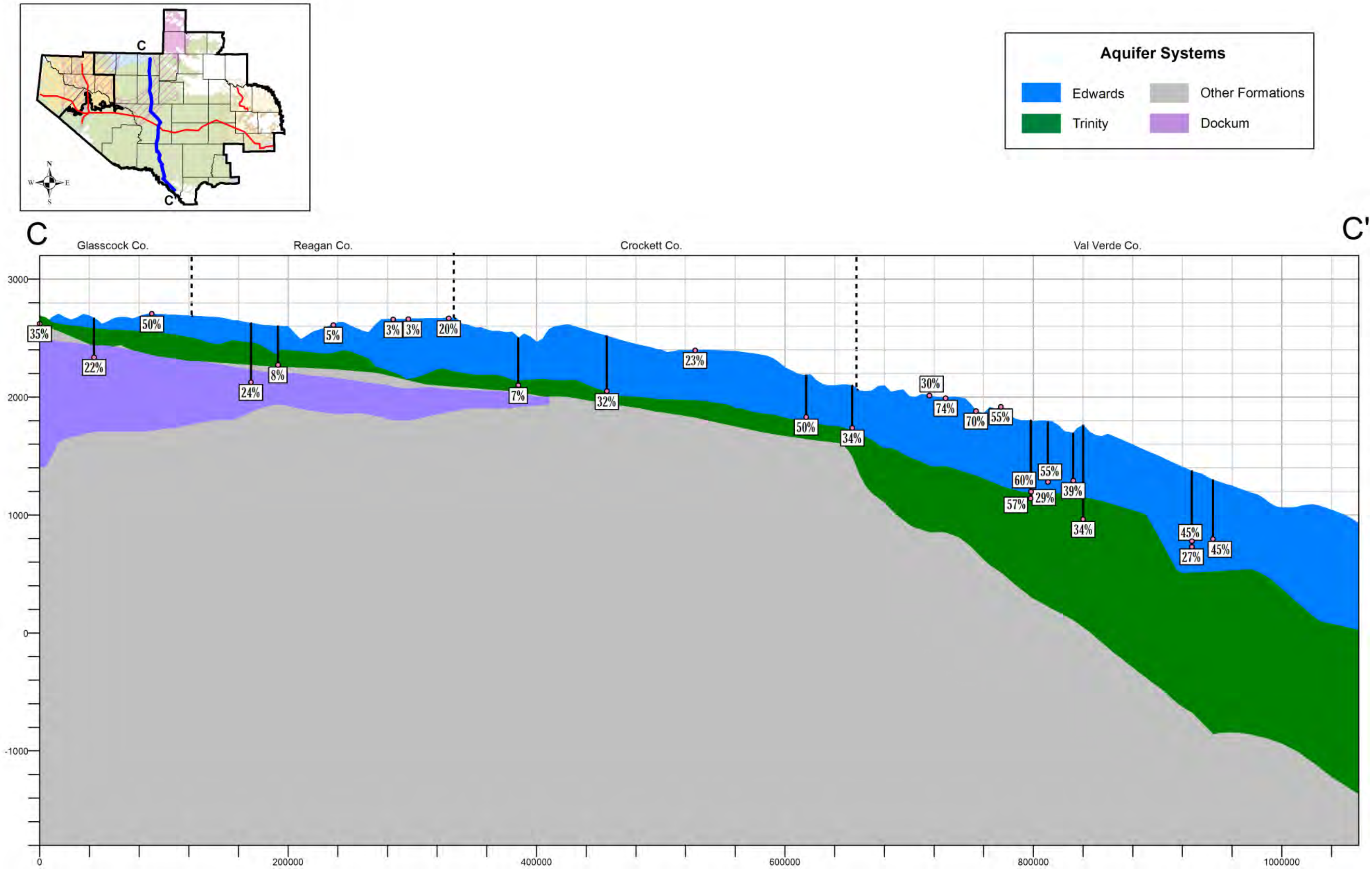


Figure 6-27. North to south profile (C-C') showing carbon-14 percent modern at depth for the Edwards-Trinity (Plateau) and the Dockum Aquifer in GMA 7.

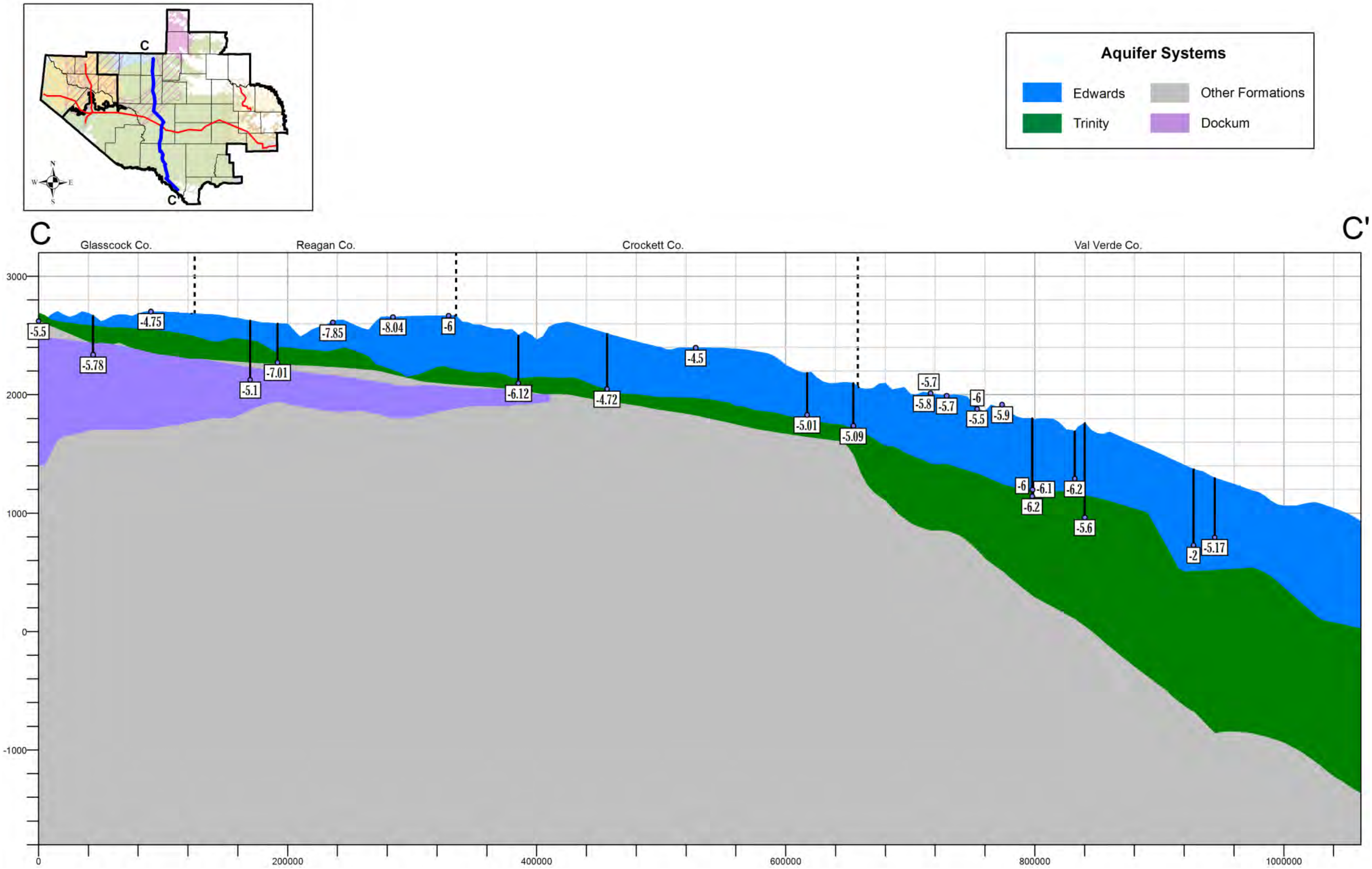


Figure 6-28. North to south profile (C-C') showing $\delta^{18}O$ at depth for the Edwards-Trinity (Plateau) Aquifer and the Dockum Aquifer in GMA 7.

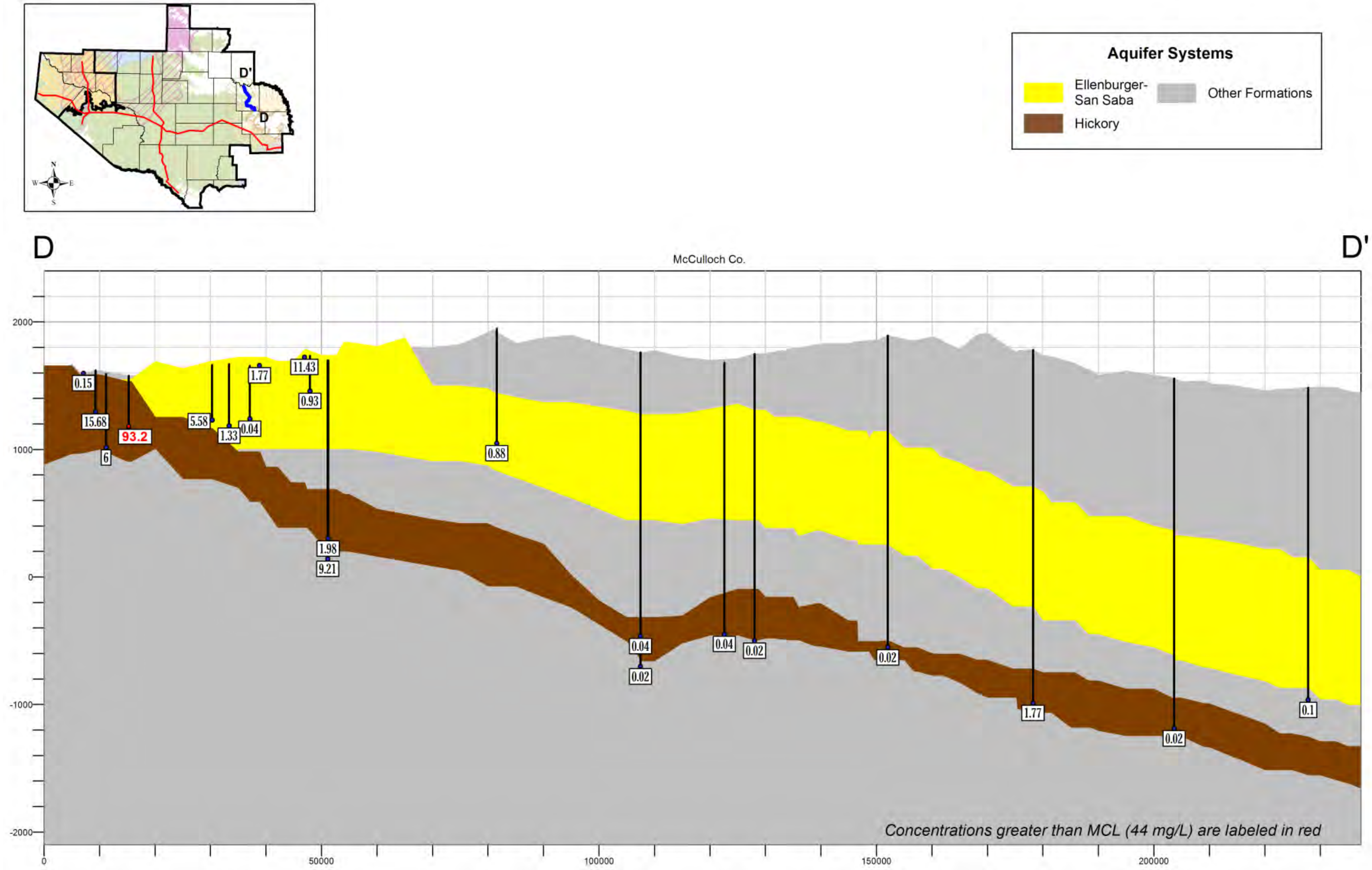


Figure 6-29. Southeast to northwest profile (D-D') showing nitrate concentration at depth for Llano Uplift aquifers in GMA 7.

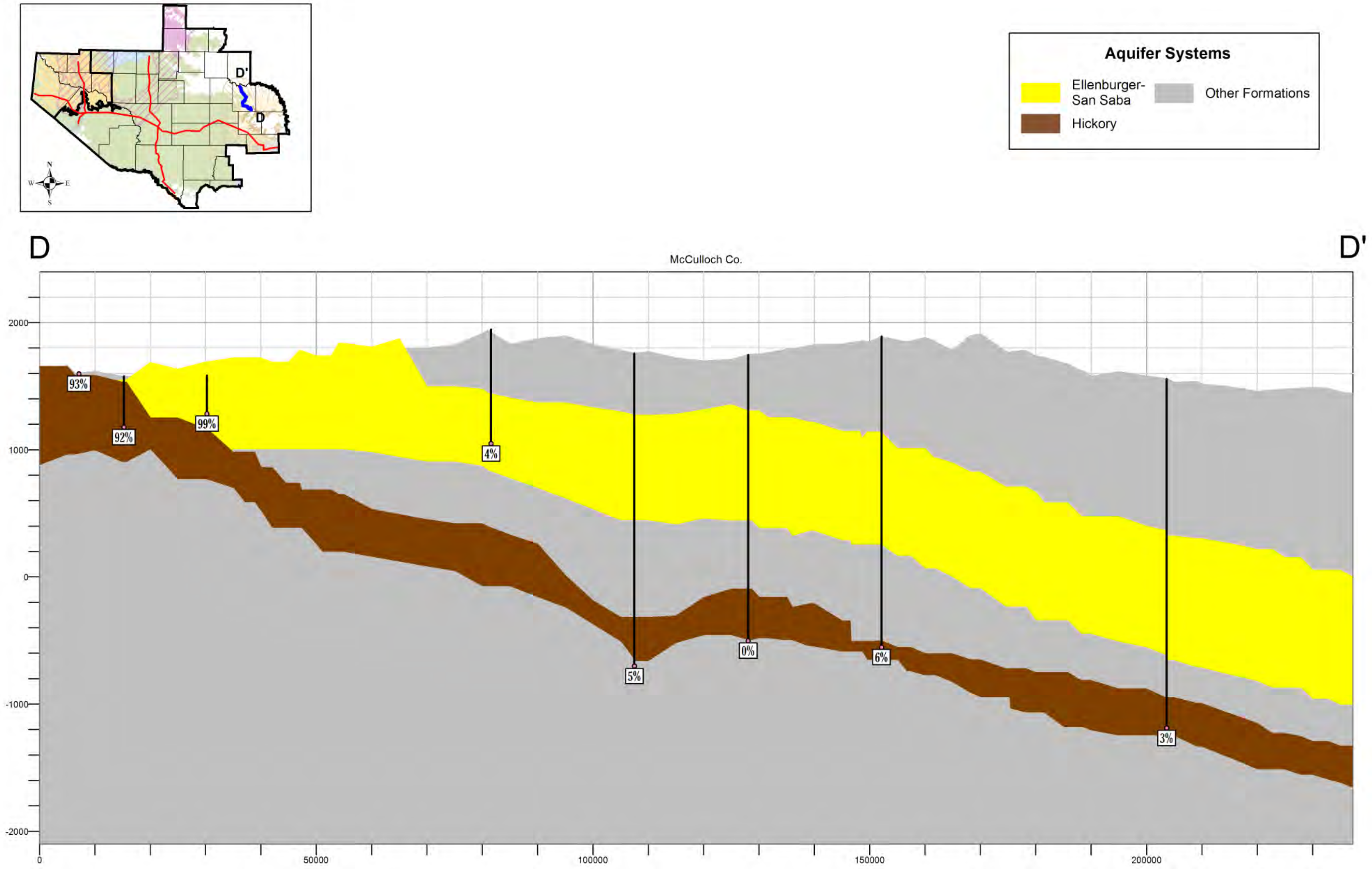


Figure 6-30. Southeast to northwest profile D-D’ showing carbon-14 percent modern at depth for Llano Uplift Aquifers in GMA 7.

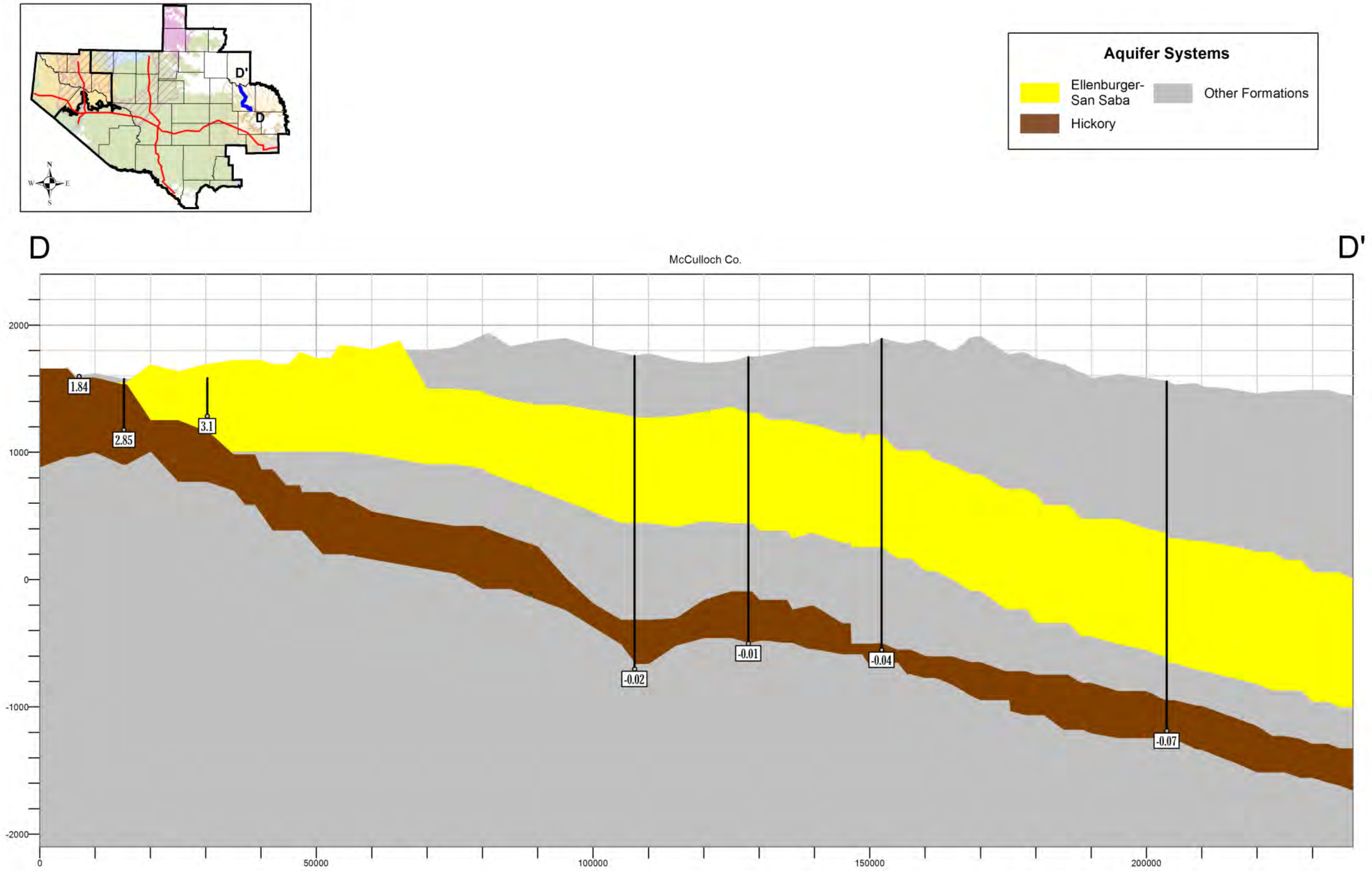


Figure 6-31. **Southeast to northwest profile (D-D') showing tritium activity at depth for the Llano Uplift aquifers in GMA 7.**

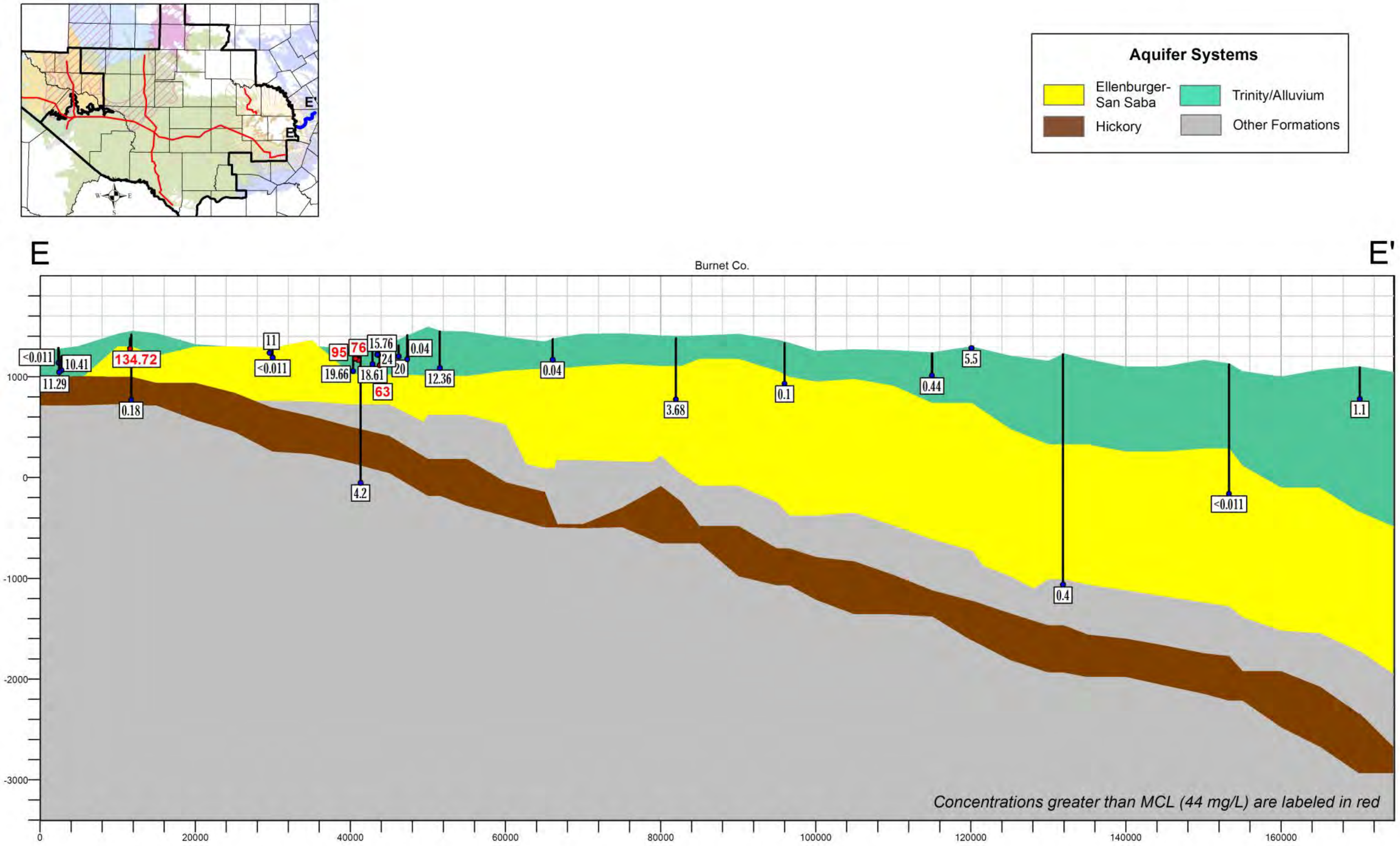


Figure 6-32. Southwest to northeast profile (E-E') showing nitrate concentration at depth for the Llano Uplift aquifers and the Trinity Aquifer in GMA 7.

6.4 Discussion

All the aquifers in the GMA 3 and 7 regions contain some old water. A higher percentage of old water is found in the aquifers farthest to the west. For the Ellenburger-San Saba Aquifer and the Hickory Aquifer, the outcrop areas are being actively recharged and contain young water. The downdip sections, however, contain old water. The Edwards Group in the Edwards-Trinity (Plateau) Aquifer appears to be actively recharging across the entire east to west extent of the plateau. In contrast, the Antlers Formation receives far less current recharge as evidenced by predominance of old water. The Edwards-Trinity (Plateau) Aquifer (Trans-Pecos region), Pecos Valley Aquifer, and Rustler Aquifer appear to have very limited recharge today. Another important factor other than the aridity of the recharge zones of the aquifers is the aquifer lithology. Lithified, fractured or karstic aquifers appear to have a much greater potential for being actively recharged than those aquifers, which are composed of porous lithologies. The recharging aquifers are the fractured Hickory Aquifer and the karstic Ellenburger-San Saba Aquifer and the Edwards Group. The non-recharging porous aquifers are the Antlers Formation and the Pecos Valley Aquifer.

Review of the isotopic data indicates three different aquifer groups: 1) Paleozoic (the Hickory Aquifer and the Ellenburger-San Saba Aquifer) aquifers in the Llano Uplift area, 2) the Trinity Group and Edwards Group in the Edwards-Trinity (Plateau) Aquifer and 3) the aquifers in the arid Trans-Pecos region. Further evaluation of each of these aquifer groups was conducted to develop conceptual models for each aquifer system in each sub region. Other aquifers occur in these three regions, but have limited isotopic and chemical data (e.g., the Capitan Reef Complex Aquifer, the Lipan Aquifer and the Marble Falls Aquifers). The focus therefore was on those aquifers with larger data sets and considered more representative for the region. Better understanding of conceptual models could be developed where more data is already available. Collectively the three sub regions contain most of the major and minor aquifers in GMA 3 and 7. The following sections address each of these three regions.

7 Llano Uplift Aquifers

7.1 General Review of the Llano Uplift Aquifers

TWDB is currently developing a groundwater availability model (GAM) for the aquifers in Llano Uplift region. A conceptual groundwater flow model is needed for the aquifers. The aquifers are the Paleozoic Hickory Aquifer and the Ellenburger-San Saba Aquifer. They ring the Llano Uplift area (Figure 7-1). Other Paleozoic aquifers, (e.g., the Marble Falls Aquifer) are present in the Llano Uplift area, but have either limited outcrop area or limited groundwater production in comparison to the Hickory Aquifer and the Ellenburger-San Saba Aquifer and therefore were not investigated. The Hickory Aquifer and the Ellenburger-San Saba Aquifer crop out in the Llano Uplift area and then radially dip away from the core into the subsurface. The Hickory Aquifer and the Ellenburger-San Saba Aquifer are faulted at multiple locations around the Llano Uplift area, creating a complex network of fault blocks and hydrologic isolated aquifers within discrete fault blocks. At some locations the Edwards-Trinity (Plateau) Aquifer overlies the Paleozoic aquifers (e.g., Gillespie County, south of the Llano Uplift area).

In some locations the Hickory Aquifer and the Ellenburger-San Saba Aquifer subcrop immediately beneath the Edwards-Trinity (Plateau) and be in hydrologic communication with the Edwards-Trinity (Plateau). In other areas, such as Burnet County, the Pennsylvania Smithwick Formation may function as a regional aquitard preventing leakage between the Paleozoic strata and the Cretaceous strata. The Smithwick is characterized as a black, slightly fissile shale with lesser amounts of siltstone and sandstone (Kier and others, 1979). A review of the hydrochemical data for the Hickory Aquifer and the Ellenburger-San Saba Aquifer indicated a general lack of an evolving chemical composition from recharge zone to downdip sections based on standard approaches of using the major and minor inorganic chemistry. There is no chemical evolution of "sodium-bicarbonate" water in the Llano Uplift Aquifers as observed in the Carrizo-Wilcox Aquifer or Gulf Coast Aquifer systems. An observed chemical evolution with an aquifer provides an analogue to groundwater flow direction and rates of flow. If traditional analysis of major anions and cations does not show chemical evolution", other approaches are needed. The important chemical isotopic parameters that appear to have regional trends are the presence of tritium, high carbon-14 activities, high chlorine-36 values and nitrate in groundwater within shallow depths, and the presence of low carbon-14 activities, low tritium values, low chlorine-36 and depleted isotopes of oxygen-18 and deuterium for the waters in the deepest parts of these aquifers. Some of the aquifers also contain elevated activities of radium-226 and radium-228, and possibly basement derived strontium isotopic compositions ratios. A review of the strontium isotopic compositions data that are available for the three regions is included after the descriptions of the three sub-regions. The strontium data provides some interesting observations, but specific conclusions are difficult to make on the conceptual models for each region. Grabens close to the Llano Uplift area appear to contain young water, whereas the downdip, confined portions appear to contain old water. The updip fault blocks are active flow systems. In the McCulloch County area, groundwater in the outcrop of the Hickory Aquifer and Ellenburger-San Saba Aquifer appears to be flowing toward the San Saba River. The downdip parts of the aquifer farther from the Llano Uplift area contain relatively stagnant groundwater. South of the Llano Uplift area in Gillespie County, head data may indicate leakage from the Cretaceous into the Paleozoic aquifers. Head data also indicates that groundwater from both the Paleozoic and Cretaceous aquifers discharge to the Pedernales River. East of the Llano

Uplift area in Burnet County, the Ellenburger-San Saba Aquifer is the major groundwater producer. Tectonics associated with the Llano Uplift area has separated the Ellenburger-San Saba Aquifer into at least three subaquifers. Flow systems appear to be isolated in northern, middle and southern sections. Recharge for each section is considered to be within the outcrop of the Ellenburger-San Saba Aquifer and discharge is to adjacent rivers, creeks or springs for each subaquifer. Most of the water appears young. Based on these differences, three different aquifer regions around the Llano Uplift area were selected for study to determine hydrogeologic and hydrochemical similarities and differences. These include a region north of the Llano Uplift area in northern Mason and McCulloch counties, a region south of the Llano Uplift area in Gillespie County and a region east of the Llano Uplift area in Burnet County. Although the Burnet County area was not in GMA 7, it was considered a good area to test in that the inclusion of Burnet County provided a more detailed evaluation for areas north, south and east of the Uplift. A transect in Mason and McCulloch counties was selected in preference to Lampasas County because previously sampled wells and chemical analyses were available for both the Hickory Aquifer and the Ellenburger-San Saba Aquifer than in Lampasas County. The southern Gillespie County transect was selected because of the isolation of the Hickory Aquifer and the Ellenburger-San Saba Aquifer in separate grabens as well as being overlain by the Cretaceous Edwards-Trinity (Plateau) Aquifer. The eastern transect in Burnet County was chosen because the Llano Uplift area structures appeared to divide the Hickory Aquifer and the Ellenburger-San Saba Aquifer geographically into three subaquifers. The presence of groundwater conservation districts in both Gillespie and Burnet counties (Hill Country Underground Water Conservation District and Central Texas Groundwater Conservation District, respectively) facilitated sampling.

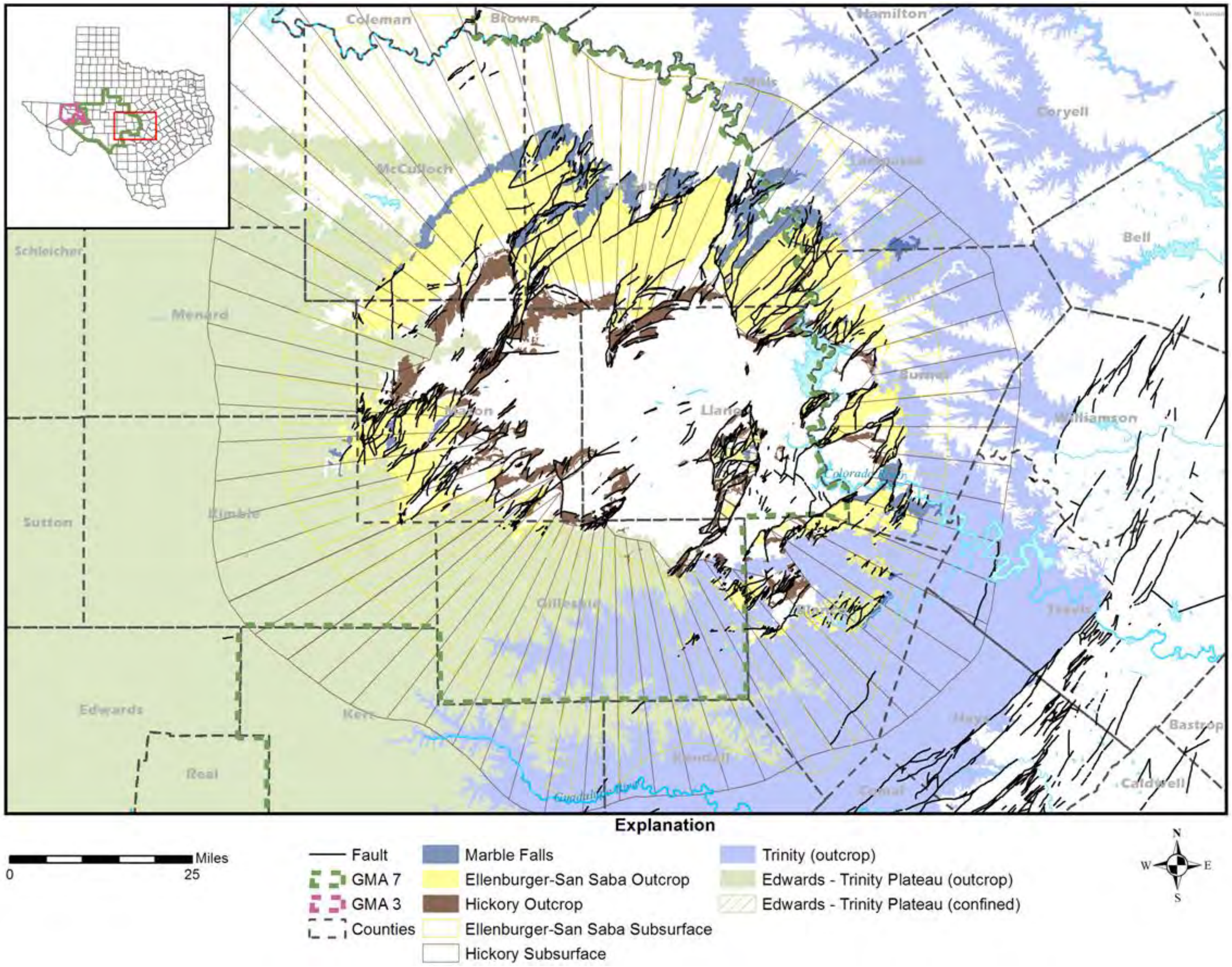


Figure 7-1. **Llano Uplift hydrogeology.**

7.2 Northern Sub-Region (Mason and McCulloch Counties)

7.2.1 Data Reviewed

New data was not collected in the Northern Sub-Region because it there was a good dataset in the TWDB database in Mason and McCulloch Counties. It was also assumed that the downdip section in in San Saba County would be similar to the downdip section in Mason and McCulloch Counties. The data that was evaluated from the TWDB dataset included:

1. Chemistry and isotope data from the Hickory Aquifer and the Ellenburger-San Saba Aquifer in Mason and McCulloch counties (north of the Llano Uplift area). These data sets represent data from the Hickory Aquifer and the Ellenburger-San Saba Aquifer wells or groundwater in their respective outcrops to as far down dip as data were available. Data were from TWDB groundwater database. Because there was a reasonable amount of isotopic data from this region, additional new samples were not collected.
2. Data were from the TWDB groundwater database. Potentiometric surface maps are based on available data from 2005-2010. Contouring is based on a kriging algorithm in Surfer.
3. Geologic evaluation is based on:
    a. Texas Bureau of Economic Geology Geologic Atlas of Texas Llano Sheet (1981 and Brownwood Sheet (1976).
    b. Published geologic cross section (McCulloch C-C') from northern Mason into McCulloch County. (Mason, 1961).
    c. Geologic cross section from southern McCulloch County northwest to the deepest occurrence of Hickory Aquifer in northern McCulloch County. Cross section is based on available geographical logs and drillers logs from TWDB.

7.2.2 Results for Hickory Aquifer

The Hickory Aquifer is a faulted monocline structure dipping to the northwest. Depths of water wells increase from the outcrop in Mason and southern McCulloch counties (shallow wells) to deeper wells in McCulloch County with depths greater than 2,000 feet (Figure 7-2). The Hickory Aquifer crops out along a northeast, trending, three-mile wide corridor extending across the Mason and McCulloch county line for approximately 27 miles (Figure 7-3 through Figure 7-6 and Table 7-1). Within this corridor the sandstone overlaps the Precambrian granite and metamorphic rocks along the southeast edge of the outcrop. It is bound by a graben fault plane that juxtaposes younger non water-bearing units along its northwest extent, thus forming a compartmentalized hydrologic unit. Northwest of the Hickory Aquifer, the outcrop corridor, a relatively narrow down faulted (graben) system represents the last structural impediment to natural groundwater flow in subsurface dipping beds. The outcrop may be isolated from downdip confined sections of the Hickory Aquifer. The Ellenburger-San Saba Aquifer may not be impacted by this faulting and therefore not exhibit compartmentalization.

The Hickory Aquifer and the Ellenburger-San Saba Aquifer in this area probably do not have a hydrologic interaction with any overlying Edwards- Trinity (Plateau) Aquifer waters because of the thick vertical separation of Pennsylvanian strata. Water levels were interpolated taking into account only the most recent water level data in the region; although prevalent throughout the outcrop of both the Ellenburger/San Saba and Hickory aquifers, faults were not taken into consideration when contouring. Water levels are highest in the southwest section of the Hickory

Aquifer outcrop in Mason County and decline toward the northeast in southern McCulloch County (Figure 7-7). Groundwater flow appears to be to the northeast in the outcrop toward the San Saba River as the river crosses the northern Hickory Aquifer outcrop in southern McCulloch County. Water levels are lower in the confined section of the Hickory Aquifer in comparison to outcrop water levels. There may be a small component of flow down the structural dip.

Table 7-1. **Location of dip and strike section shown on Figure 7-4. Cross sections for dip and strike sections shown on Figure 7-5 and 7-6.**

Sample No.	State Well No.	Owner	Latitude	Longitude	Use	Land Surface Elev.	Year drilled	Depth	Casing (blank)	Casing (slot)	Casing (open hole)	Production rate (gpm)	Static water level	Water Level Elevation (amsl) (ft)	Aquifer	Geophysical log available
1	56-06-311	Wau-Ban-See Ranch	30 59 03	99 15 11	Stock	1590		300					10	1580	Hickory	N
2	42-63-908	Edward Spiller	31 00 09	99 09 27	Dom	1555	1969	226	0 - 12		12 - 226	20	76	1479	Hickory	N
3	42-63-820	Larry Henderson	31 00 26	99 12 24	Dom	1578	2001	400	0 - 320	320 - 400				1578	Hickory	N
4	56-06-505	Bill Hall	30 56 41	99 17 57	PS	1808	1979	500	0 - 7		7 - 500	20	189	1619	Hickory	N
5	42-54-202	Brady System Richland SUD# 1, Owner #2	31 12 51	99 18 21	PS	1894	1982	2445*	0 - 2445		2445 - 2650*	297	426	1468	Hickory	N
6	42-61-303	City of Brady Well# 8	31 07 23	99 23 04	PS	1776	1985	2460	0 - 2127		2127 - 2460	445	246	1530	Hickory	Y
7	42-52-504	Millersview-Doole Well# 3	31 12 03	99 32 54	PS	1829	1984	3295	0 - 2972		2972 - 3295	400	360	1469	Hickory	Y
8	42-45-601	Lohn WSC	31 19 29	99 24 37	PS	1561	1963	2746					79	1482	Hickory	Y

**Note well depth discrepancy in TWDB database.*

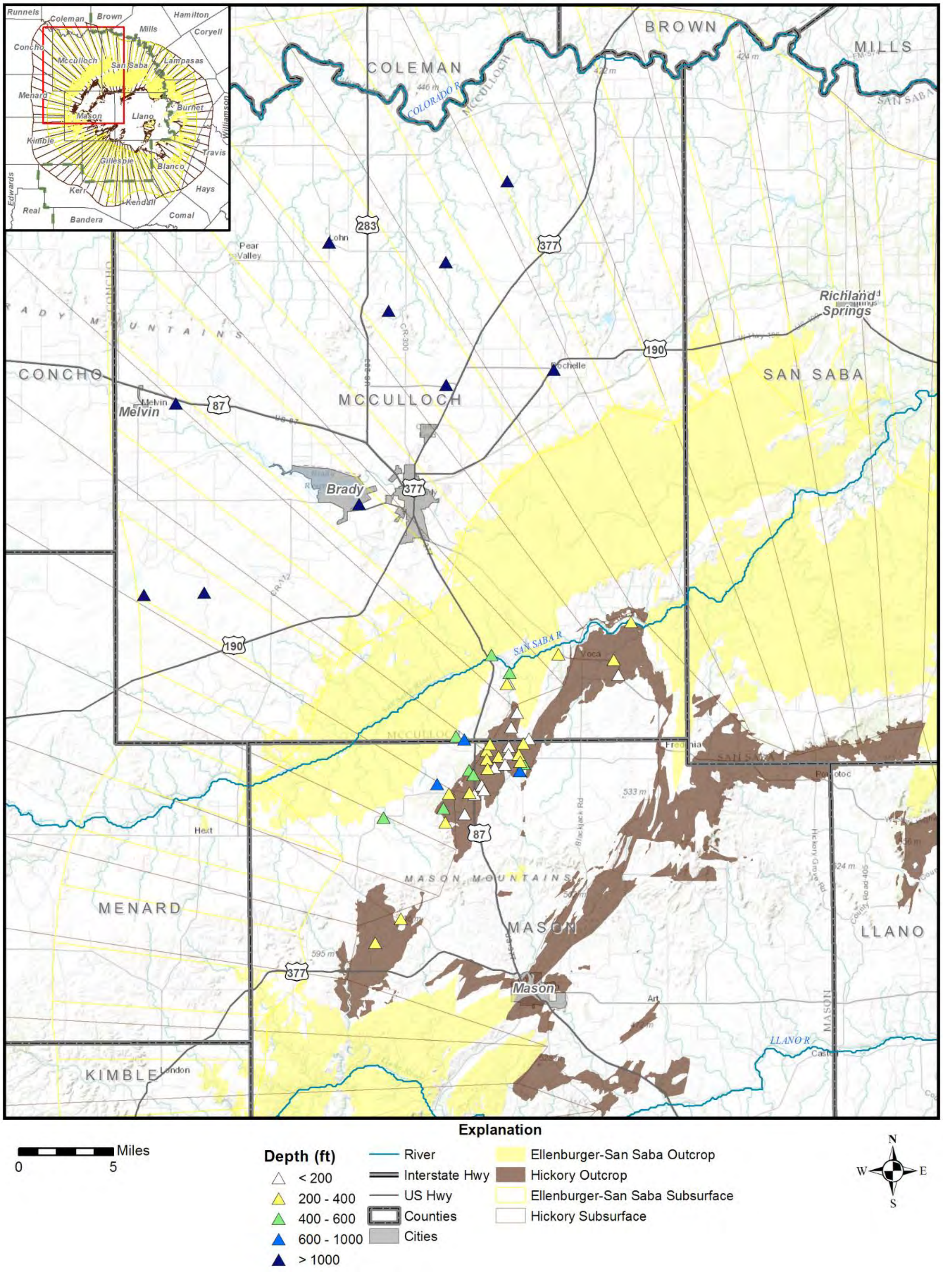


Figure 7-2. The Hickory Aquifer well locations and well depth map.

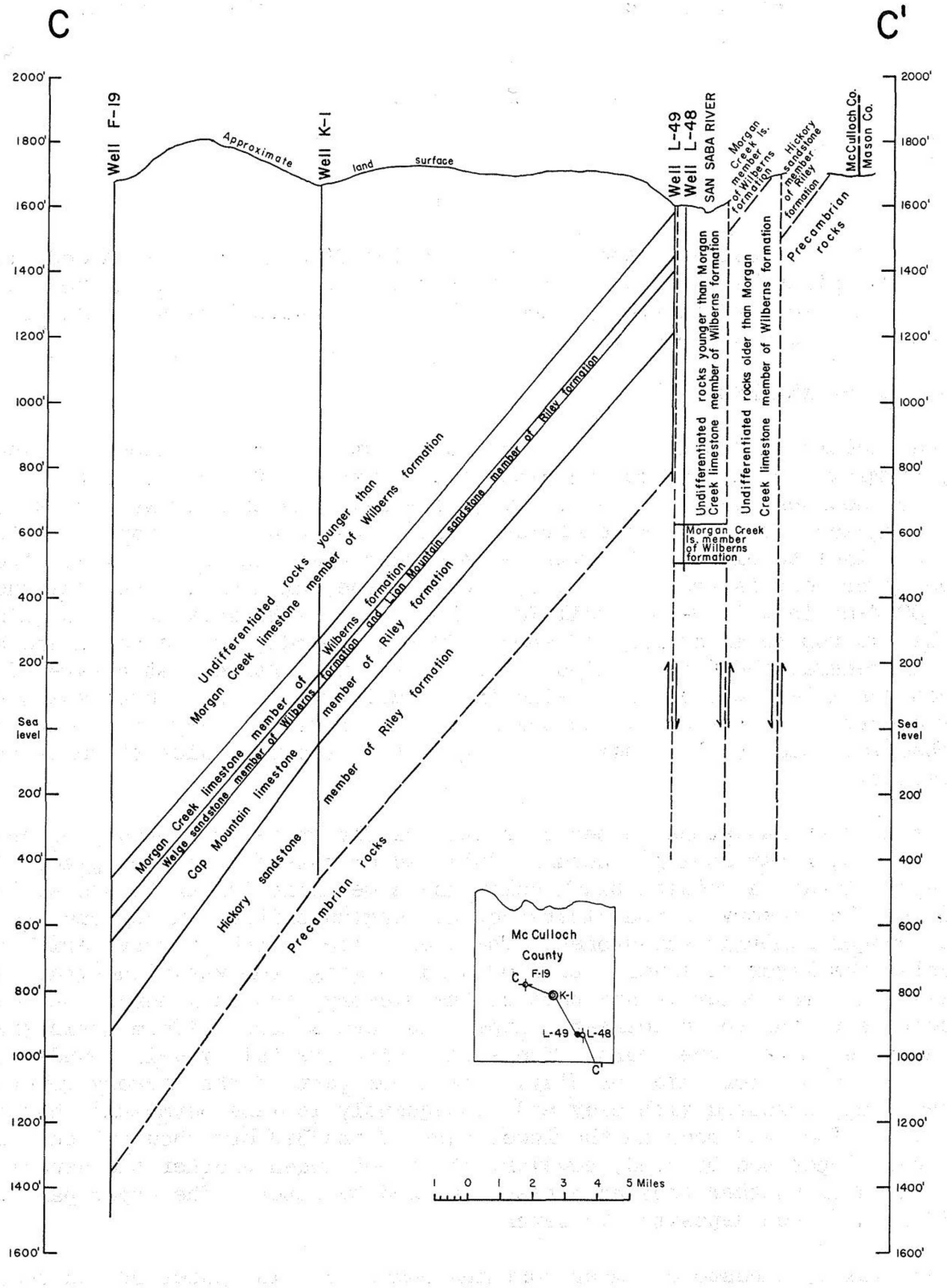


Figure 7-3. Dip oriented cross section, McCulloch County (after Mason, 1961).

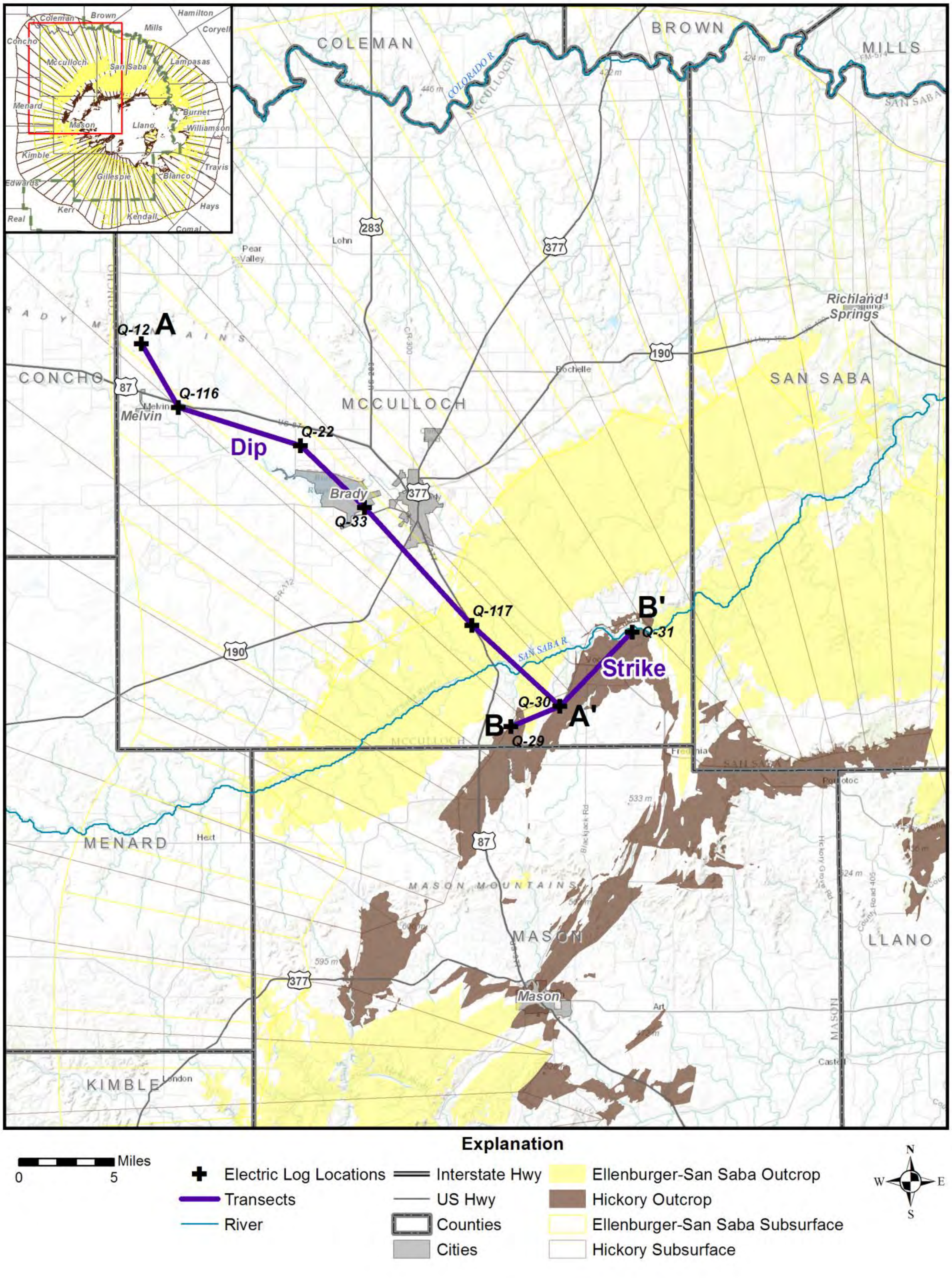
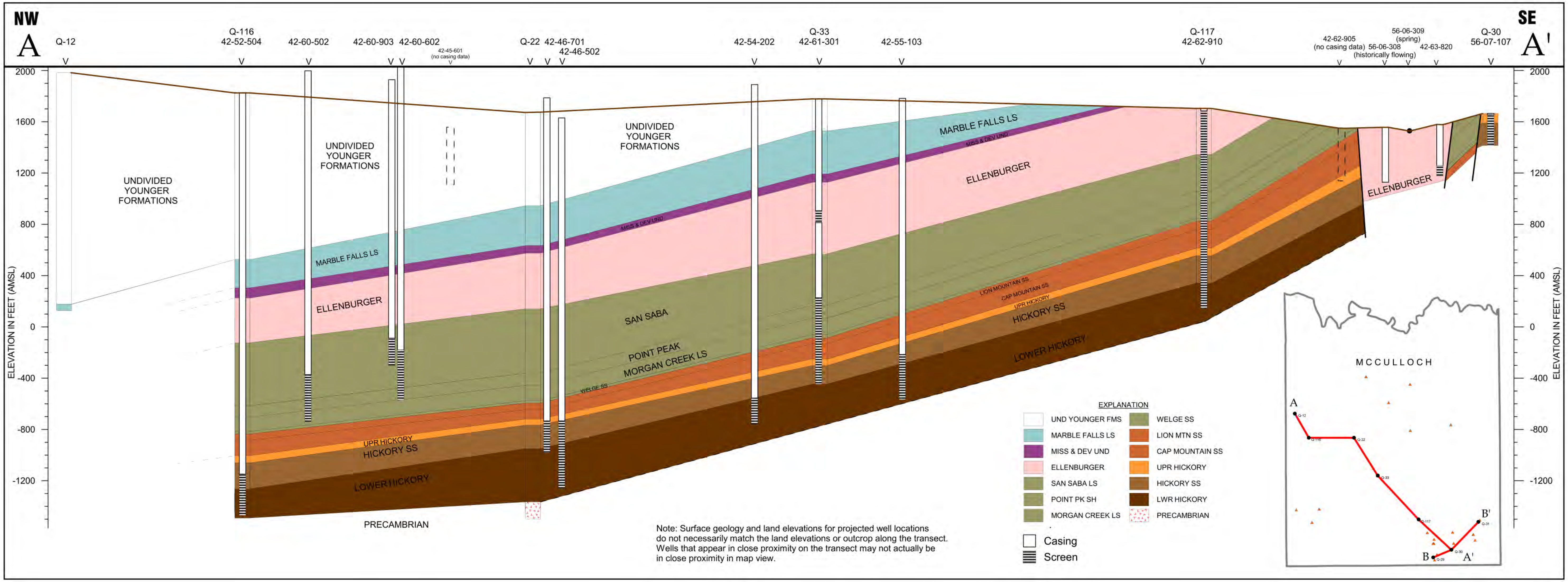


Figure 7-4. Location of strike and dip transects for carbon-14 geochemical modeling.



Note: Surface geology and land elevations for projected well locations do not necessarily match the land elevations or outcrop along the transect. Wells that appear in close proximity on the transect may not actually be in close proximity in map view.

Figure 7-5. Dip geologic cross section, A-A', through McCulloch County, Texas.

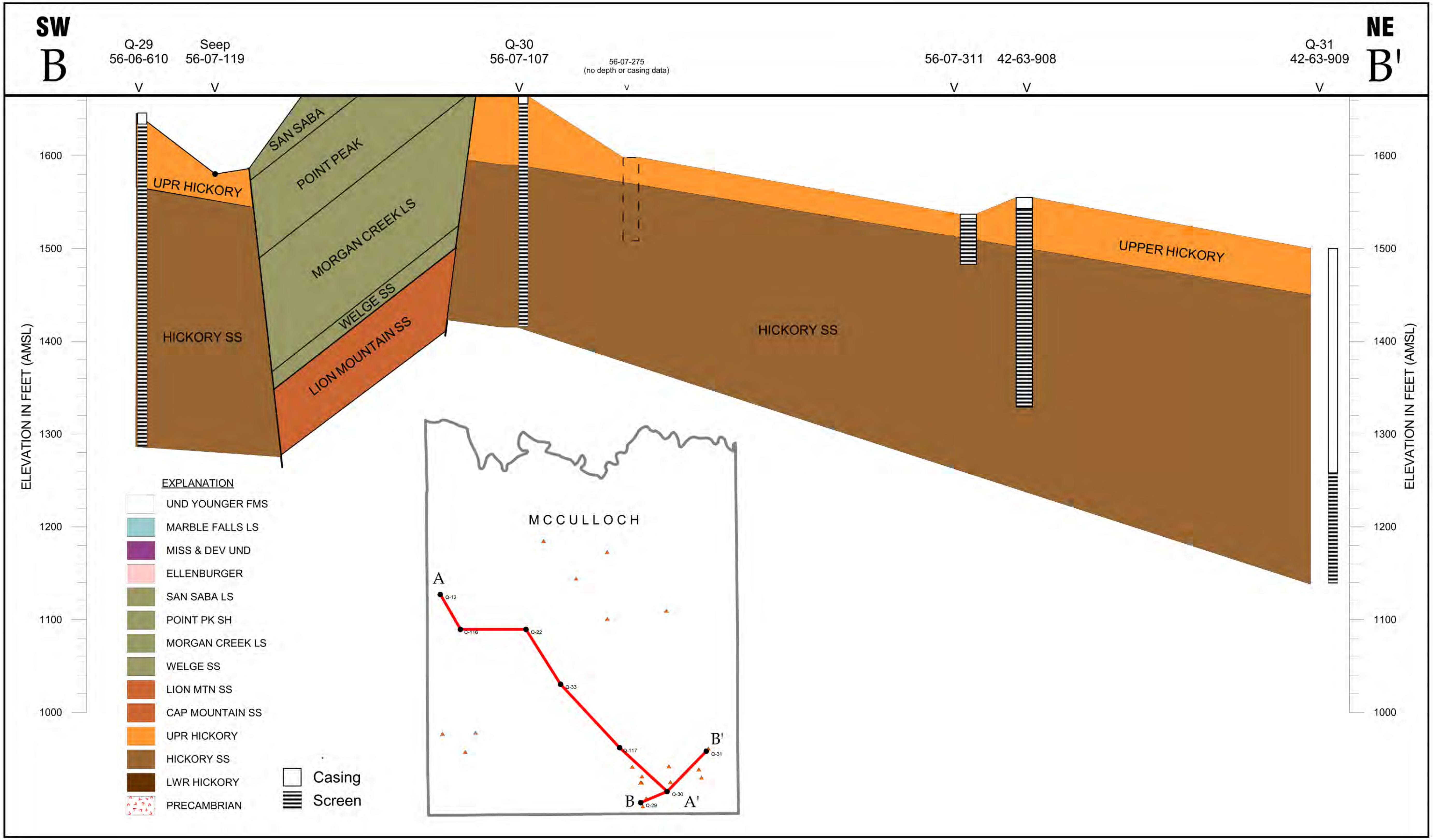


Figure 7-6. Strike geologic cross section, B-B', through outcrop area of the Hickory Aquifer, McCulloch County, Texas.

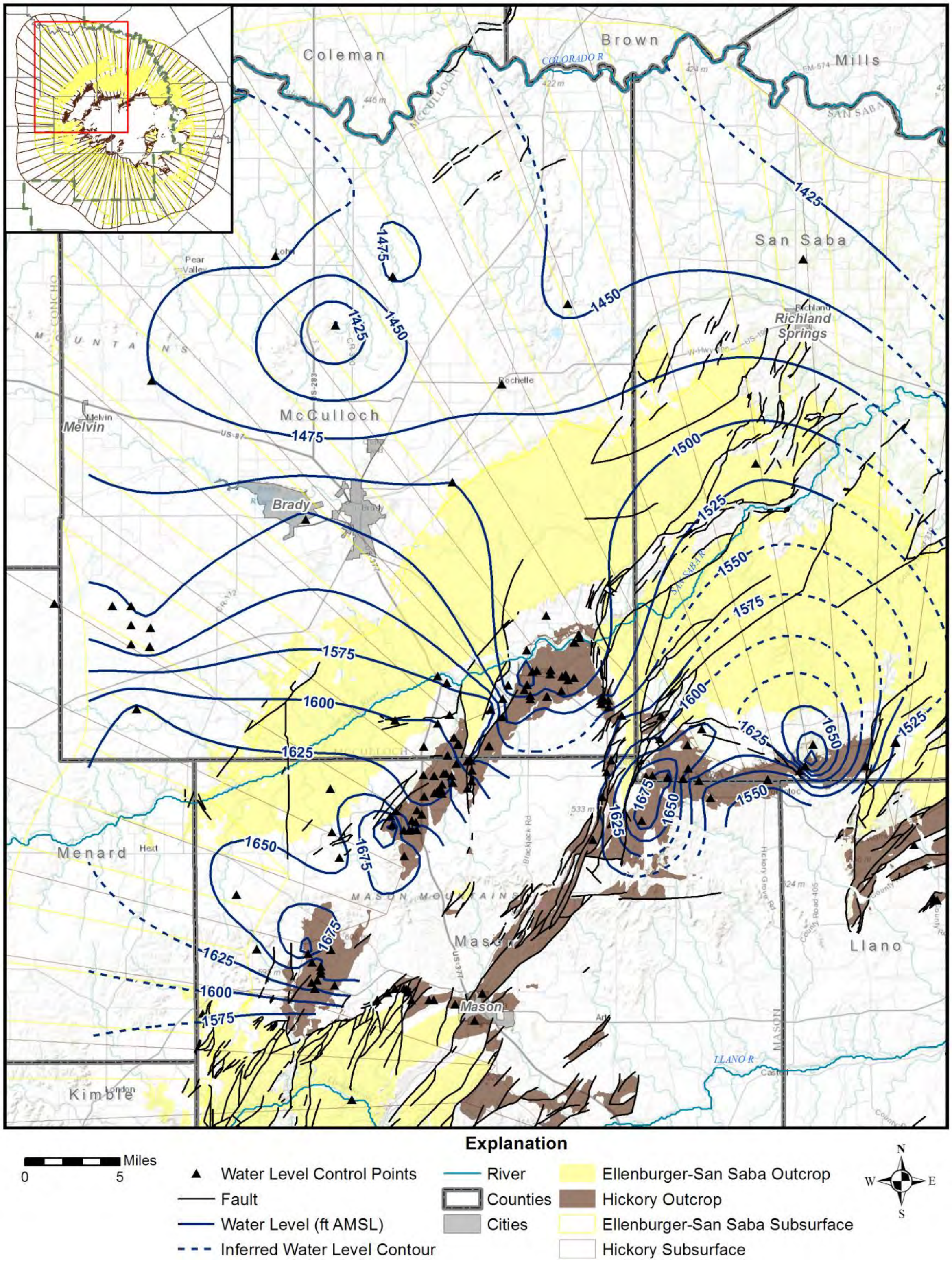


Figure 7-7. **The Hickory Aquifer water level map (based on 2005-2011 data).**

7.2.3 Critical Chemical Parameters

Piper diagram data are plotted for wells less than 1,000 feet depth and wells with depths greater than 1,000 feet (Figure 7-8). In the cation and anion triangles and diamonds the two data sets occupy different locations. For the shallower groundwaters, the cation chemistry is dominated by calcium and magnesium. For the deeper waters, there is an inverse correlation between sodium and calcium-magnesium suggesting cation exchange. In the cation triangle, the chemistry of the deeper waters does not appear to have evolved from the general chemistry of the shallower waters. Sodium and chloride increase linearly and then sodium increases independent of chloride (Figure 7-10). These higher sodium waters are the waters whose chemistry potentially is affected by cation exchange (Figure 7-9). Chloride is high in the deepest section of the aquifer, suggesting possible upwelling of deeper more saline waters (Figure 7-11).

High nitrate in shallow wells (less than 500 feet); suggest anthropogenic sources and therefore recent recharge to depths of 500 feet. This is primarily in outcrop areas of the Hickory Aquifer (Figure 7-12 and Figure 7-13). High potassium concentrations in deeper wells may be related to chemical reactions with feldspar (Figure 7-14 and Figure 7-15). Radium-226 and radium-228s elevated activities occur in the Hickory Aquifer (Figure 7-16). This Cambrian sandstone is derived from the Llano Uplift area's igneous basement rocks (e.g. granite). High radium values should be expected in the Hickory Aquifer in the Llano Uplift area. There is a linear correlation between radium-226 and radium-228. The highest radium-226 and radium-228 activities are in the deep Hickory Aquifer wells (Figure 7-17 through Figure 7-20). These high activities may be related to their long residence times considering the short half-life of radium-228 (5.75 years), these high activities have to be generated *in situ*. There are high carbon-14 percent modern values in wells shallower than 500 feet. There are low carbon-14 percent modern values in wells deeper than 1,000 feet (Figure 7-21 and Figure 7-22). High tritium activities (greater than .5 TU) occur in the shallow wells and low tritium (0.0 TU) in the deep wells (Figure 7-23 and Figure 7-24). High chlorine-36 (greater than 400 feet) occurs in the shallow wells and low chlorine-36 (less than 200 feet) in deeper wells (Figure 7-25 and Figure 7-26). Oxygen-18 and deuterium values follow the GMWL (Figure 6-1). Heavier isotopes are from shallower, younger waters. Lighter waters are from deeper part of the Hickory Aquifer (Figure 7-27 and Figure 7-28) and may represent cooler climate conditions in an earlier time period.

Geochemical modeling of the aquifer indicates that ages range from recent to a corrected 21,000 years before present. The age of the groundwater at a particular well location investigated in this study was assumed to be best indicated by radiocarbon (^{14}C) analysis of dissolved inorganic carbon. However, because of addition and removal of carbon in the groundwater through reactions with mineral and hydrocarbon sources, the measured or observed ($^{14}C_{OBS}$) ages are often referred to as "apparent ages" and must be corrected or adjusted ($^{14}C_{ADJ}$) for the carbon transfer to a realistic age. Corrections to the $^{14}C_{OBS}$ as the result of carbon transfer are done by first using the stable carbon isotopic values ($\delta^{13}C$) of the soil carbon dioxide in the recharge environment. The soil and shallow vadose zone is where the ^{14}C is first incorporated into the groundwater; subsequently, and further adjustments are required for reactions along the groundwater flowpath. As groundwater migrates from recharge to locations further downgradient, the dissolved inorganic carbon is changed by carbon mass transfer from reactions, such as, carbonate mineral dissolution, carbon dioxide gain or loss, and oxidation of organic material.

The presence of tritium in groundwater is also useful primarily as an indicator that some portion of the recharged water has been recently exposed to the atmosphere. Tritium is naturally occurring and is of cosmogenic origin, e.g., derived from reactions in the upper atmosphere, but tritium was also generated in abnormally high concentration during atmospheric nuclear testing beginning in the early 1950s. The half-life of tritium is 12.3 years; decay to background levels below detection limits should occur within about six half-lives or within 70 to 80 years, and tritium should not be present in waters with carbon-14 ages of several thousand years, unless mixing of old and young water sources is occurring.

The use of chlorine-36 is most valuable if the chloride is derived from different points of origin in the flow system; in this way the chlorine-36 content can be used as a label of the source rather than an age dating isotopic measurement. Chlorine-36 is generated in the upper atmosphere (cosmogenic) as well, within the subsurface *(in situ* production) or by atmospheric nuclear testing. The half-life of chlorine-36 is 301,000 years, so the decay rate is not generally applicable to the groundwater flow rates, especially for this region in which travel times are seldom older than a few thousand years. The chlorine-36 values are reported as ratios to total chloride in water, which is predominantly chlorine-35 and chlorine-37.

The natural atmospheric production for chlorine-36 is such that the shallow groundwater should have a concentration in the range of 100 to 200 δ^{36}Cl x 10^{15} (Bentley and others, 1986; Davis and others, 2003), thus the more elevated values greater than 400 indicate some contribution from nuclear testing was present in recently recharged water, and values less than100 are potentially indicative of old groundwater beyond the ages measured by carbon-14 (e.g., greater than 40,000 years before present). The value of the chlorine-36 signature for this data set is in detecting: 1) recent recharge which would have large concentration derived from nuclear testing (greater than 400), 2) intermediate and regionally determined values that indicated pre-bomb testing and water of only a few thousand years (100 to 300) and 3) very old water sources (less than 50) beyond the age dating range ofcarbon-14.

The groundwater hydraulic gradient for the Hickory Aquifer and the Ellenburger-San Saba Aquifer north of the Llano Uplift area is toward the north and northeast. Only the Hickory Aquifer has sufficient carbon-14 values to use them to corroborate direction of flow; the Ellenburger-San Saba Aquifer has only two measurements of carbon-14 for this area in the TWDB database. The conceptual model assumed for this area is that aquifers are recharged in regions where formations crop out, with confined intra-formational flow continuing down dip (Mason, 1961). Fault bounded grabens associated with the Llano Uplift area may have local effects on flow especially for shallow groundwater that may be diverted to surface discharge in the San Saba River (Figure 7-7).

The down dip flow through the Hickory Aquifer is constrained by aquitards above and below the formation boundaries; consequently flow is relatively well-defined (Figure 7-3). If flow does follow this lithologic pathway, then the carbon-14 data and other supporting isotopic analyses could be used to corroborate that flow path.

There are 12 water chemistry samples from the Hickory Aquifer in the TWDB database that contain carbon-14 measurements in Mason and McCulloch counties. These uncorrected or apparent ages range from: 1) the youngest, which is modern to 2) the oldest which is 27,750 years before present (0.03 percent modern carbon). The remaining ten samples have measured ages that separate into three distinct groups with respect to age, depth, and carbon-13 (Figure

7-21, Figure 7-29 and Figure 7-30). Shallow wells near the Hickory Aquifer outcrop 400 feet or less in depth have $^{14}C_{OBS}$ ages from modern to 610 years before present; a deeper well near the outcrop 500 feet in depth has a $^{14}C_{OBS}$ of 6,400 years before present; and seven deep wells from 2,350 to 2,746 feet in depth have $^{14}C_{OBS}$ ages from 22,510 to 27,750 years before present. The graph of carbon-14 versus carbon-13 (Figure 7-29) indicates that reaction with carbonate minerals has altered the carbon-13 of the dissolved inorganic carbon by the addition of heavier carbon-13 bicarbonate. This addition of bicarbonate is assumed as dead carbon (i.e., no carbon-14 percent modern activity), which makes the $^{14}C_{OBS}$ age greater than the actual age of the groundwater at that point in the aquifer.

The corresponding stable carbon ($\delta^{13}C$) isotopic values for each of these groups when plotted versus ^{14}C are not defined by distinct ranges of stable isotope signature but do separate into at least two groups above and below 0.50 pMC when the ^{14}C is considered (Figure 7-29). Similarly, shallow wells range from $\delta^{13}C$ of -13.8 to -7.9 ‰, deep wells from $\delta^{13}C$ of -7.6 to -5.9 ‰, and two wells which range from $\delta^{13}C$ of -11.10 to -8.80 ‰ (Figure 7-21, Figure 7-29, and Figure 7-30). These groupings of $\delta^{13}C$ and carbon-14 percent modern infer two flow systems in the aquifer, a shallow system in the outcrop and a deeper zone in the confined section (Figure 7-30).

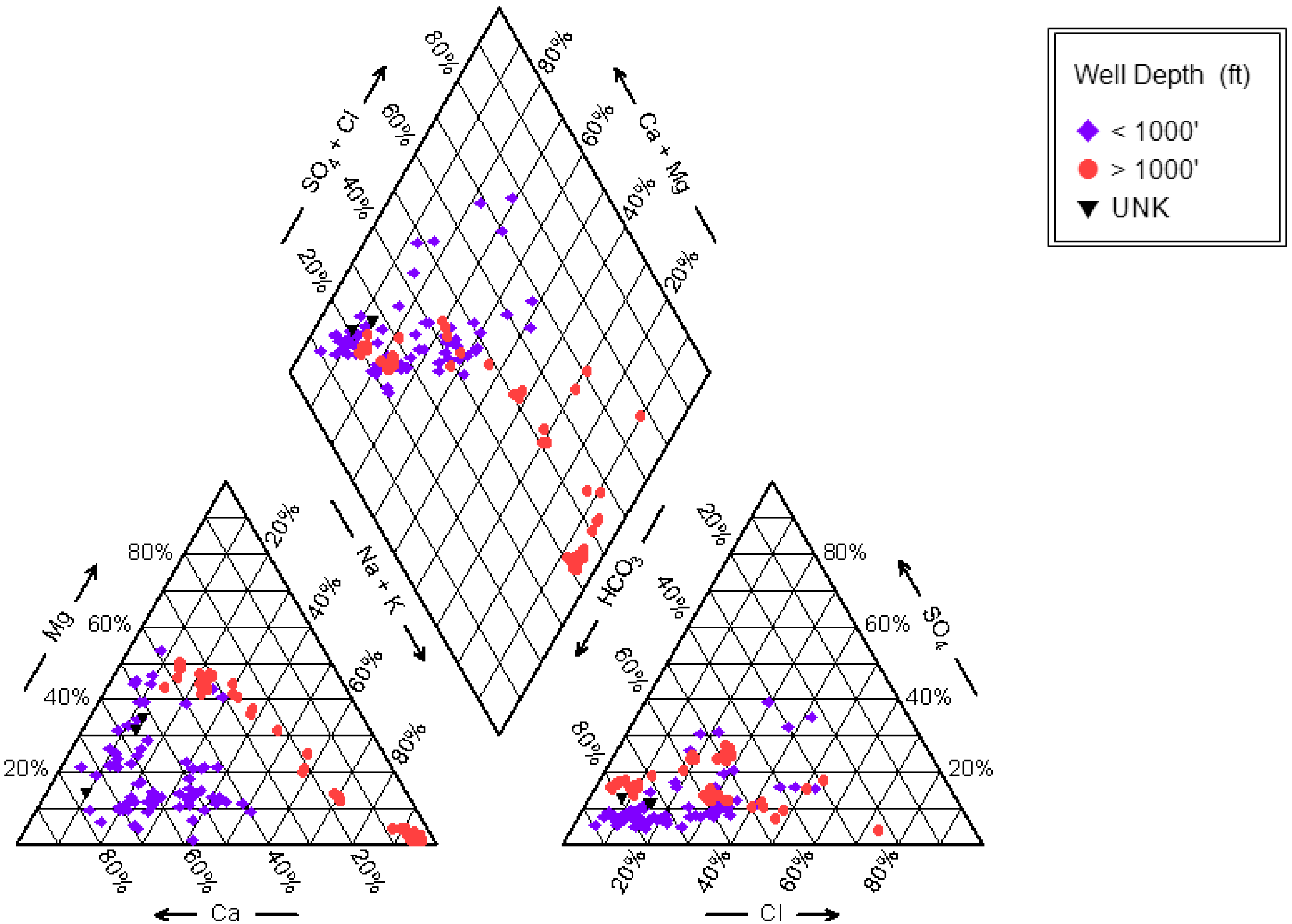


Figure 7-8. Piper diagram for the Hickory Aquifer, McCulloch and Mason Counties, Texas.

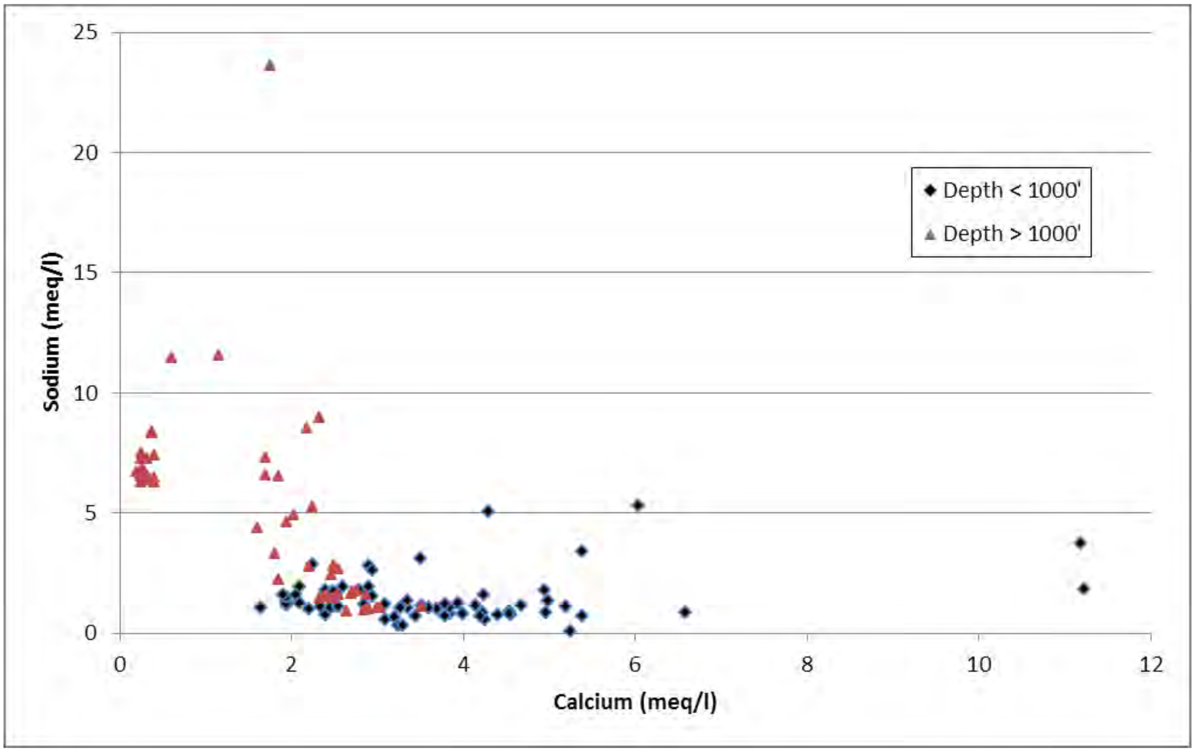


Figure 7-9. Calcium vs Sodium for the Hickory Aquifer, McCulloch and Mason Counties, Texas.

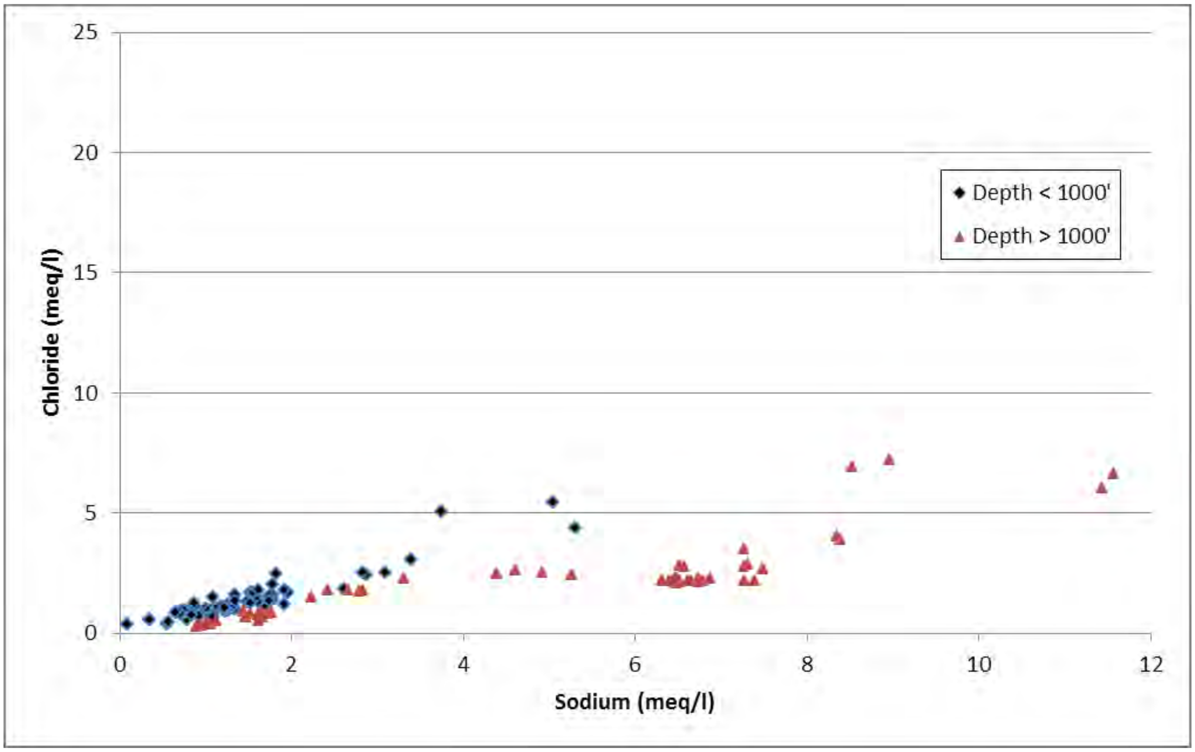


Figure 7-10. Sodium vs Chloride for the Hickory Aquifer, McCulloch and Mason Counties, Texas.

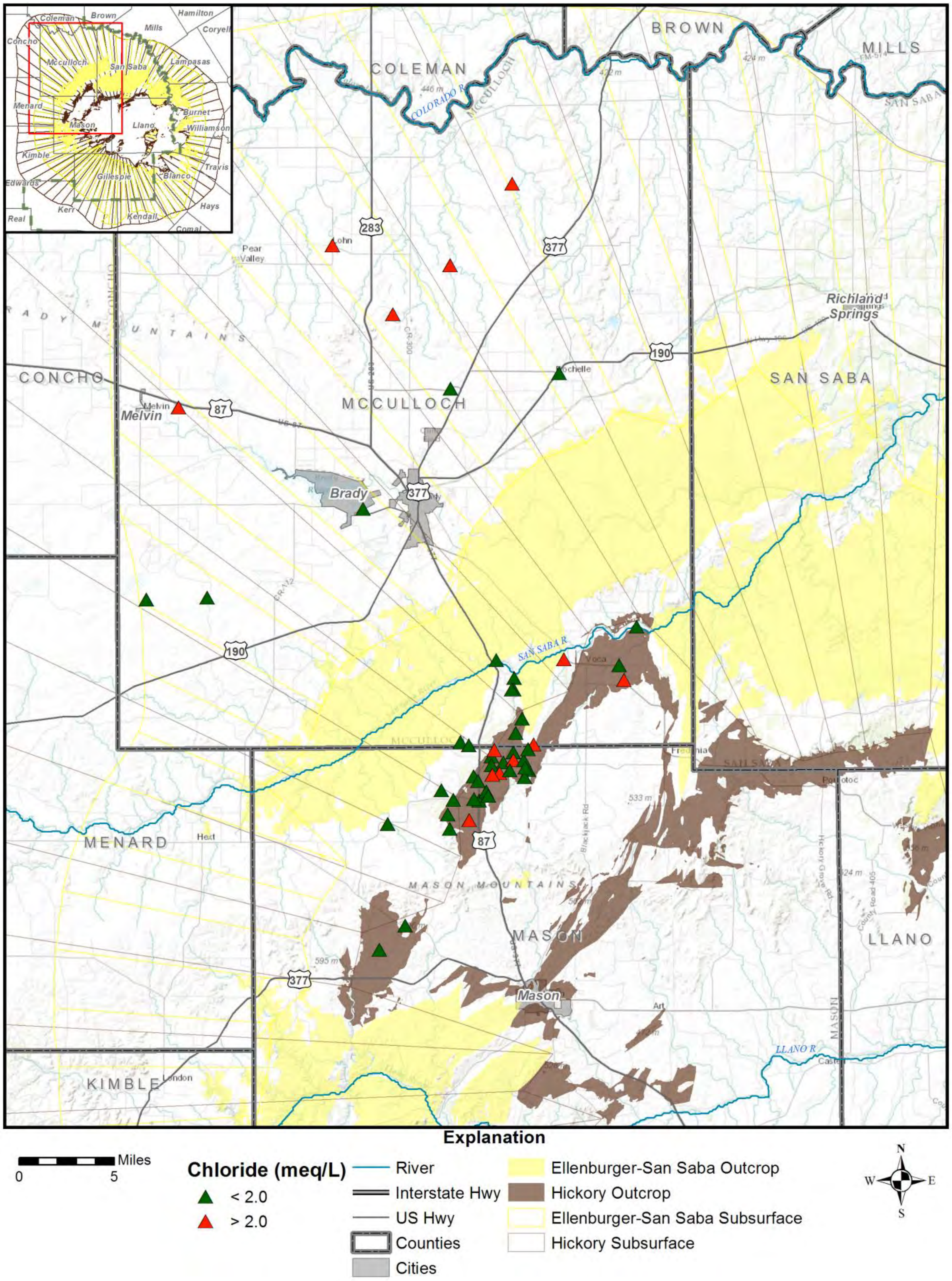


Figure 7-11. Chloride concentration for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

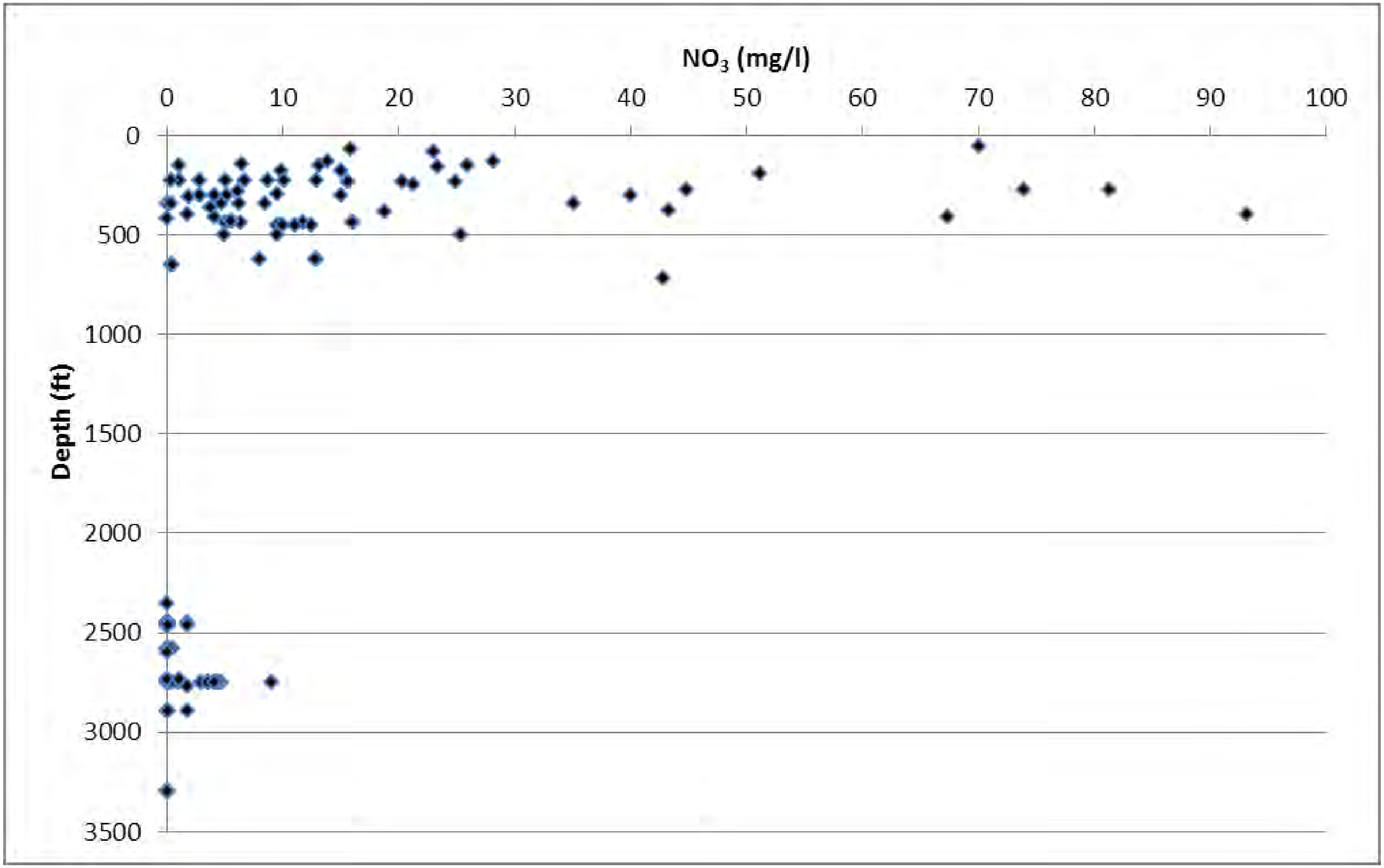


Figure 7-12. **Nitrate (NO_3) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.**

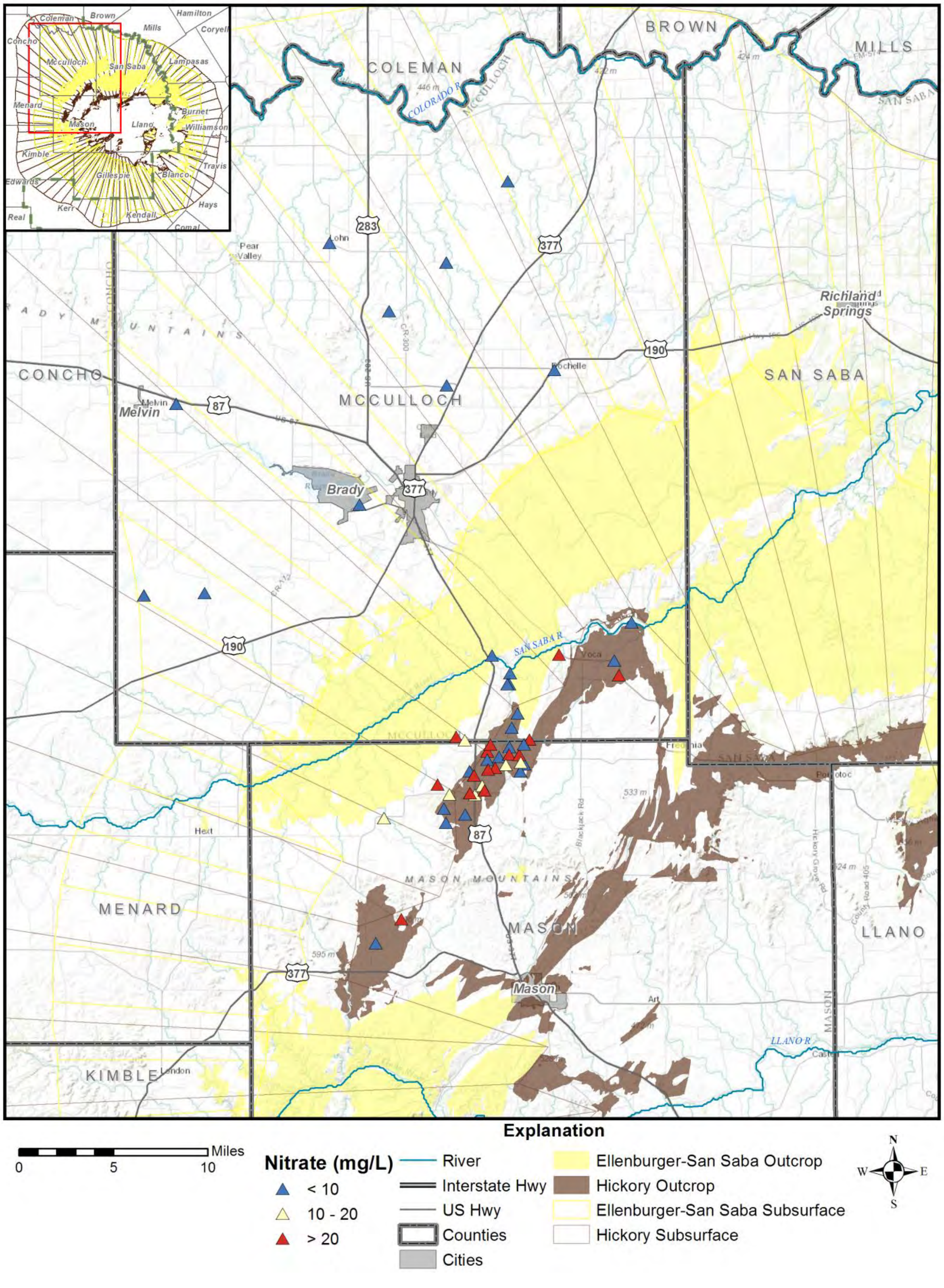


Figure 7-13. Map of nitrate concentrations for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

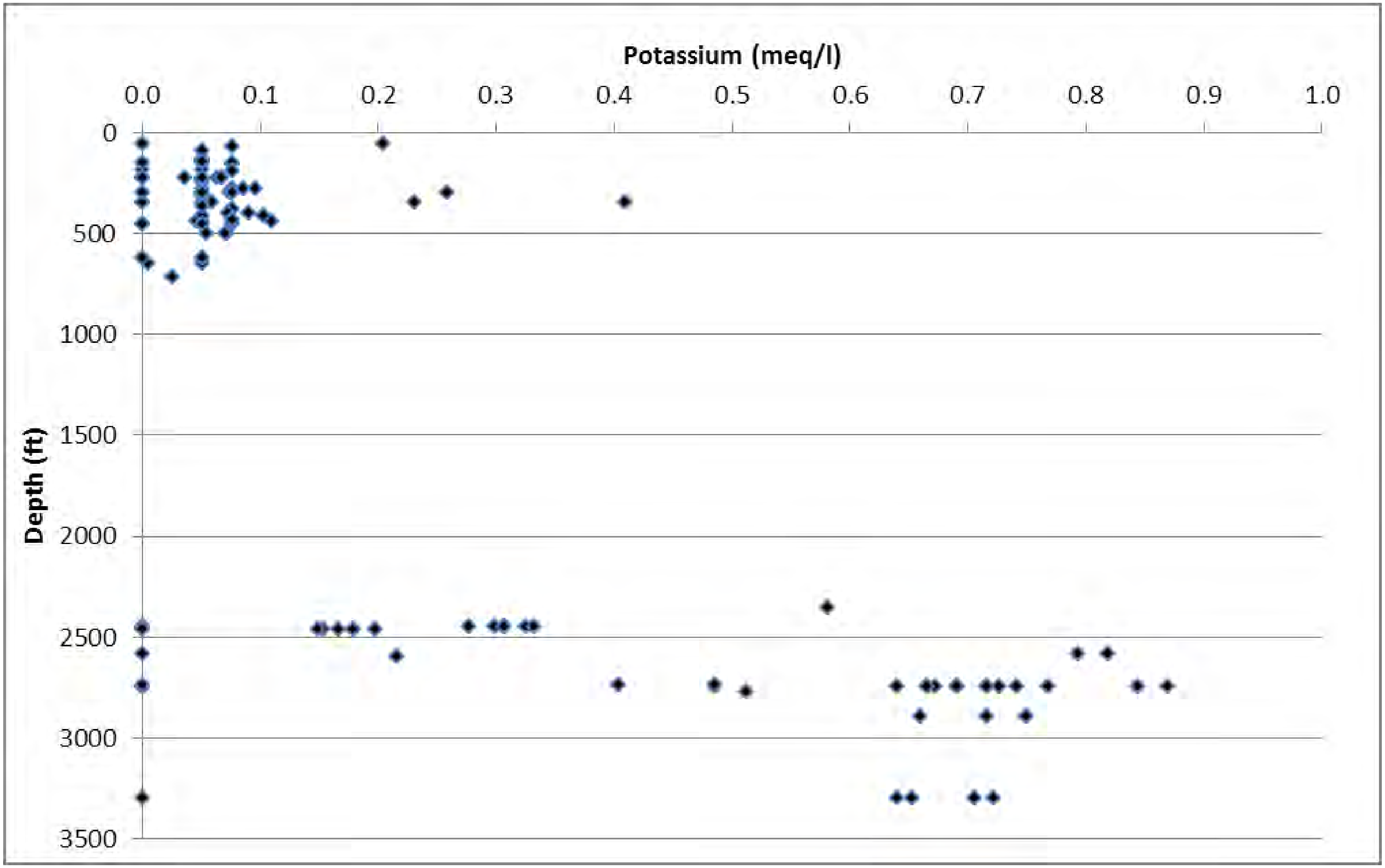


Figure 7-14. Potassium vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

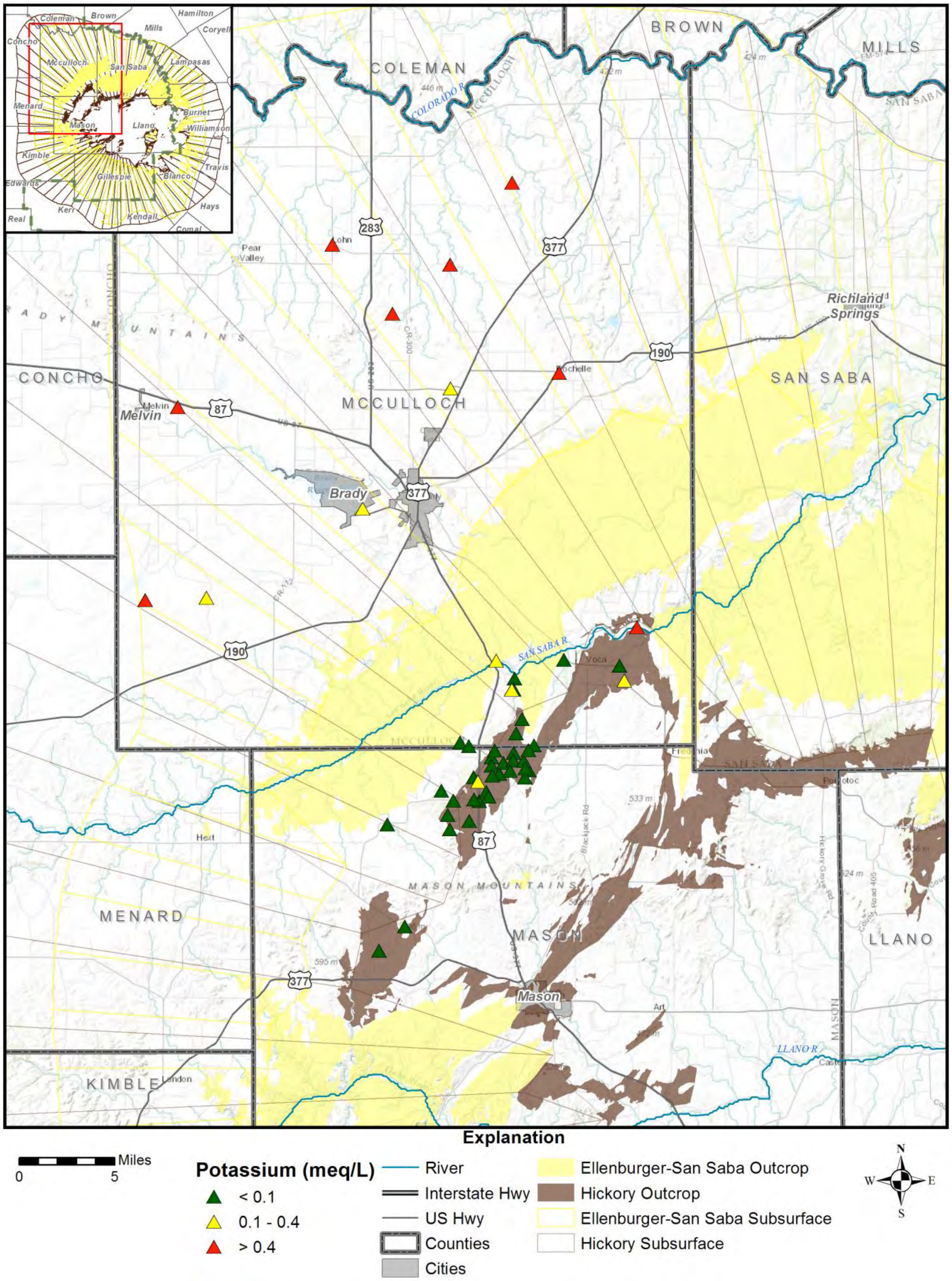


Figure 7-15. Map of potassium for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

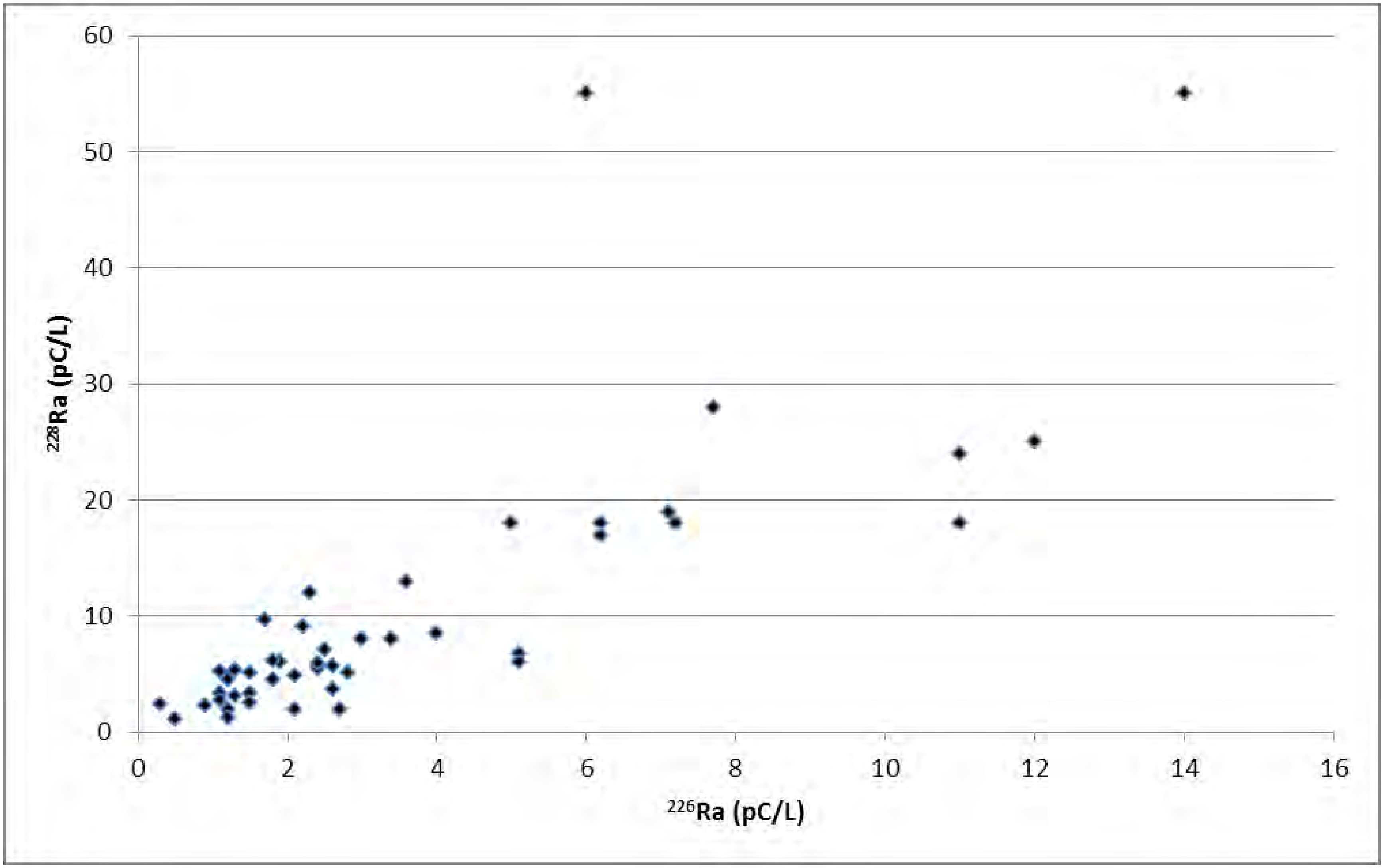


Figure 7-16. **Radium-226 (^{226}Ra) vs radium-228 (^{228}Ra) for the Hickory Aquifer, Mason and McCulloch Counties, Texas.**

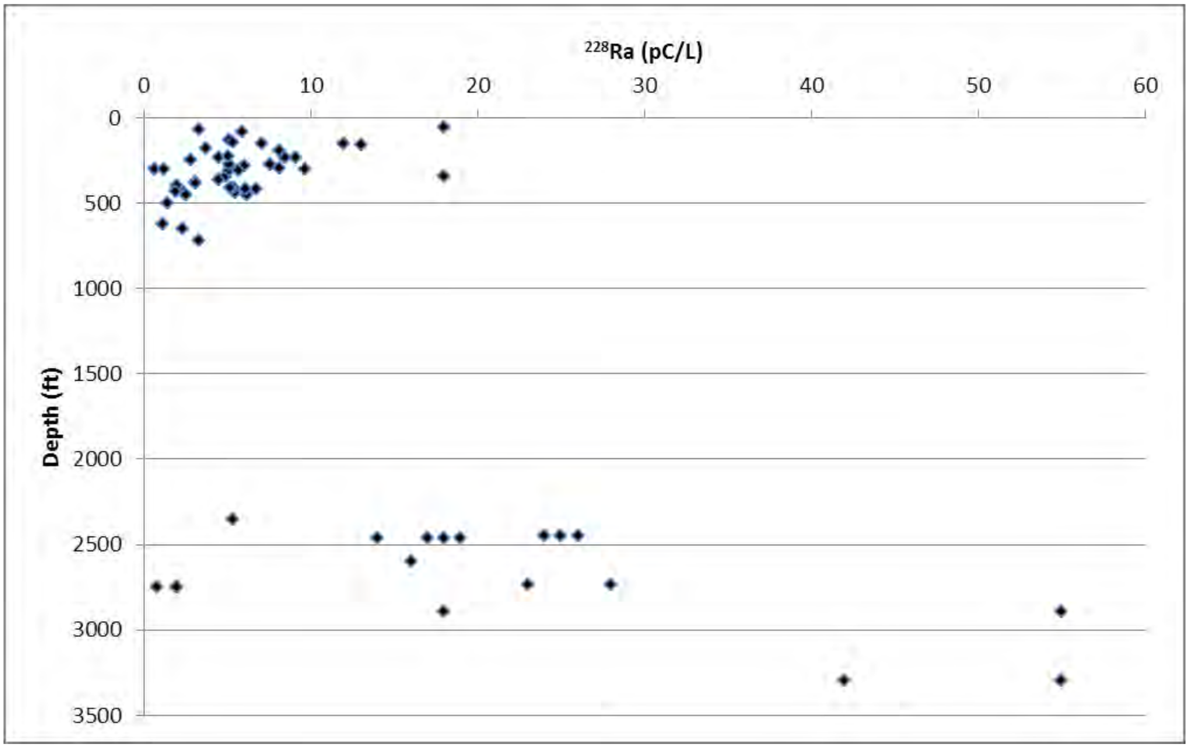


Figure 7-17. Radium-228 (^{228}Ra) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

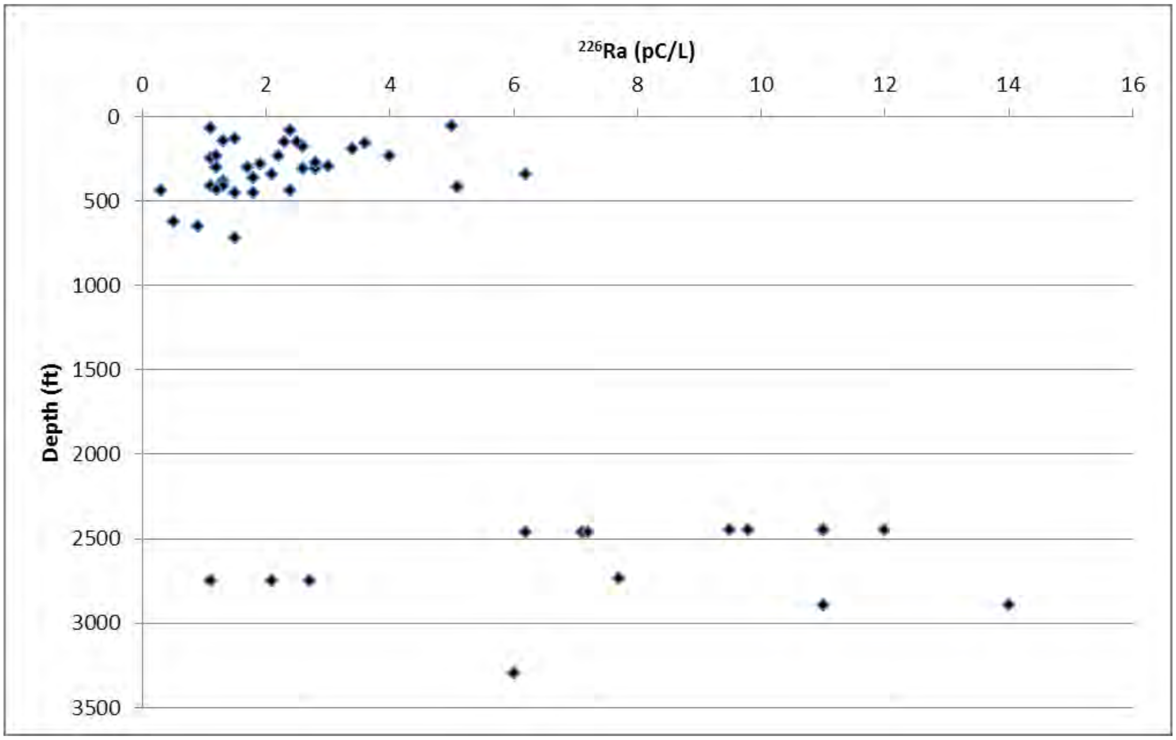


Figure 7-18. Radium-226 (^{226}Ra) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

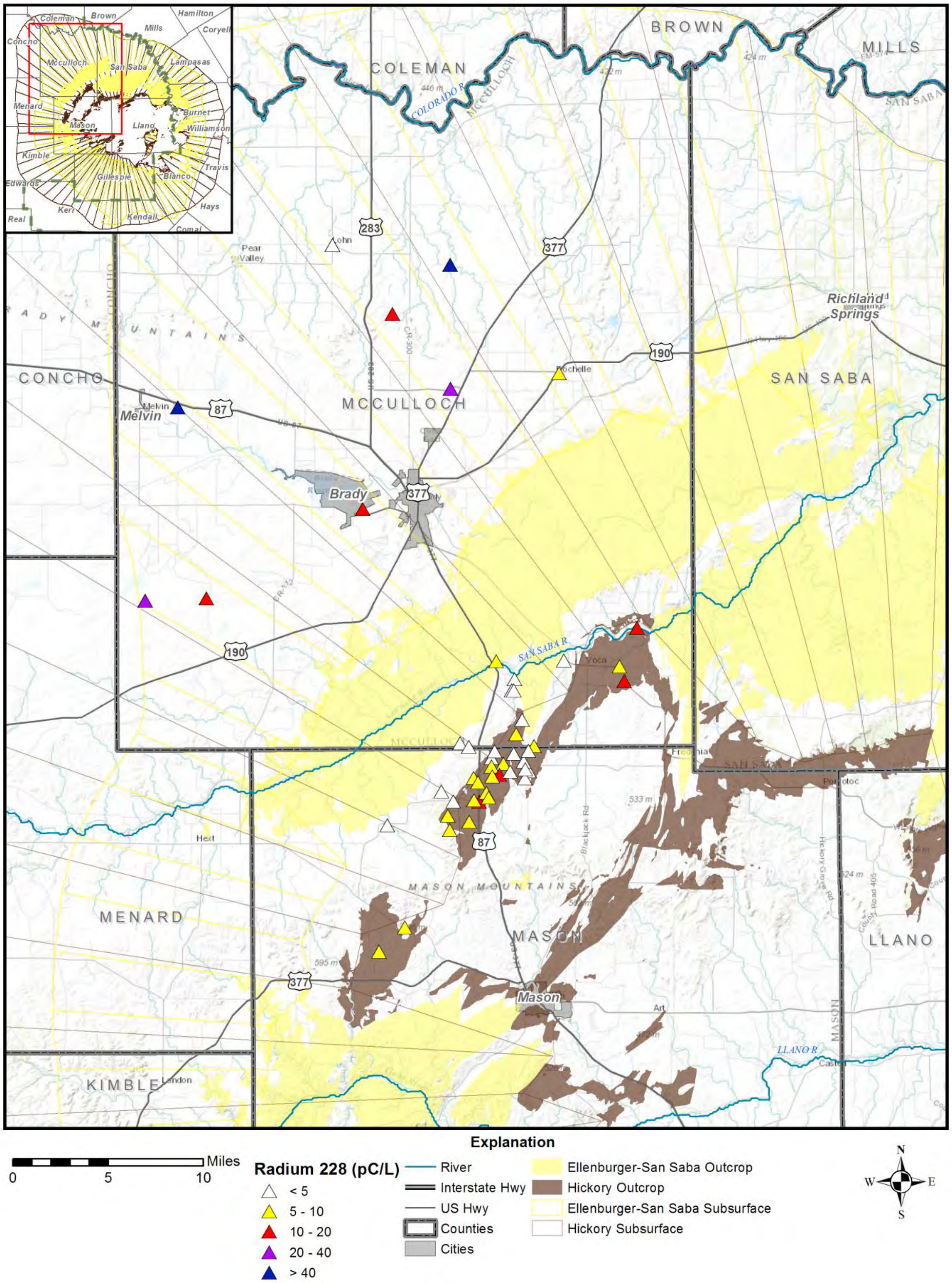


Figure 7-19. **Map of radium-228 for the Hickory Aquifer, Mason and McCulloch Counties, Texas.**

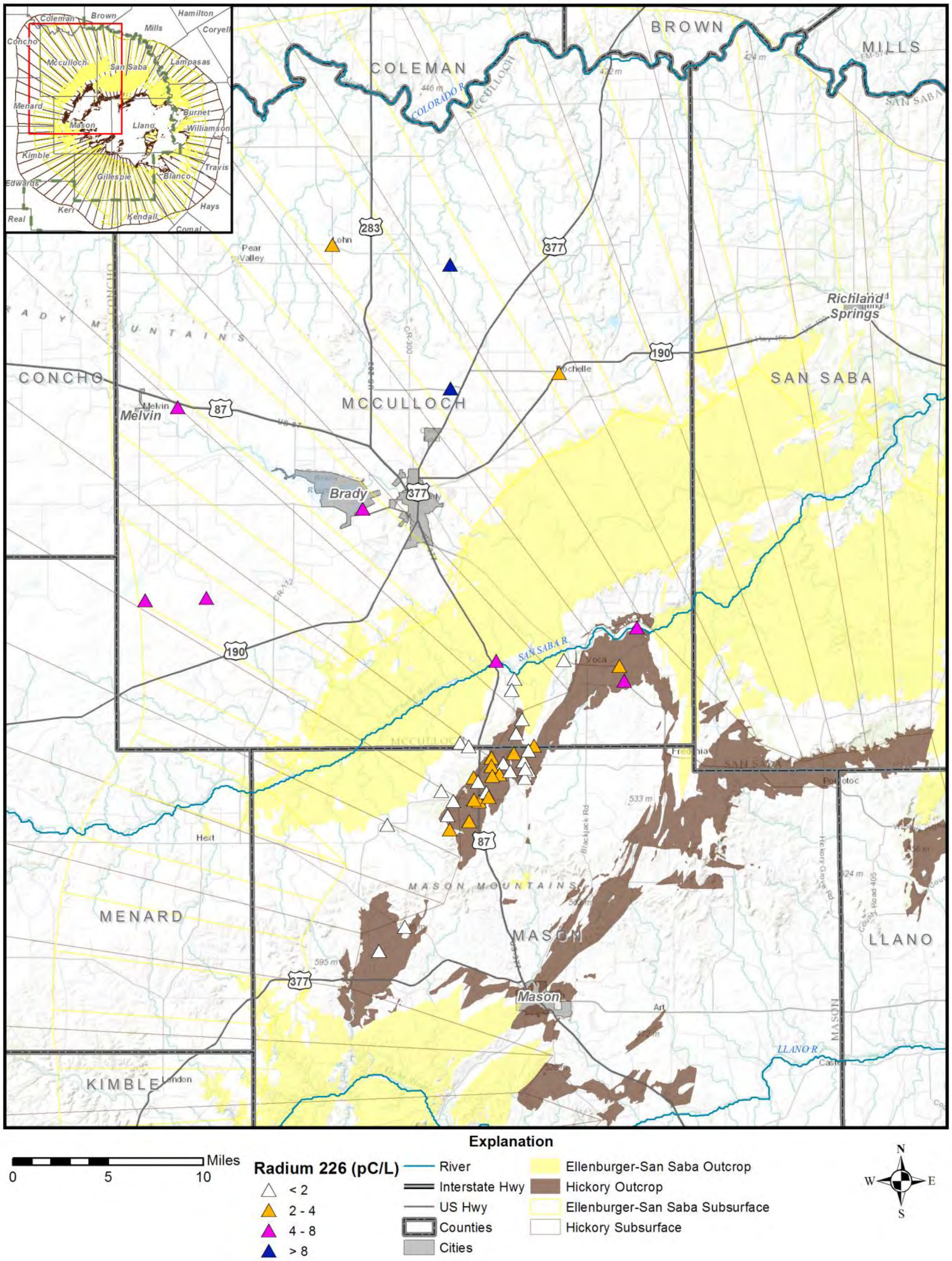


Figure 7-20. Map of radium-226 for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

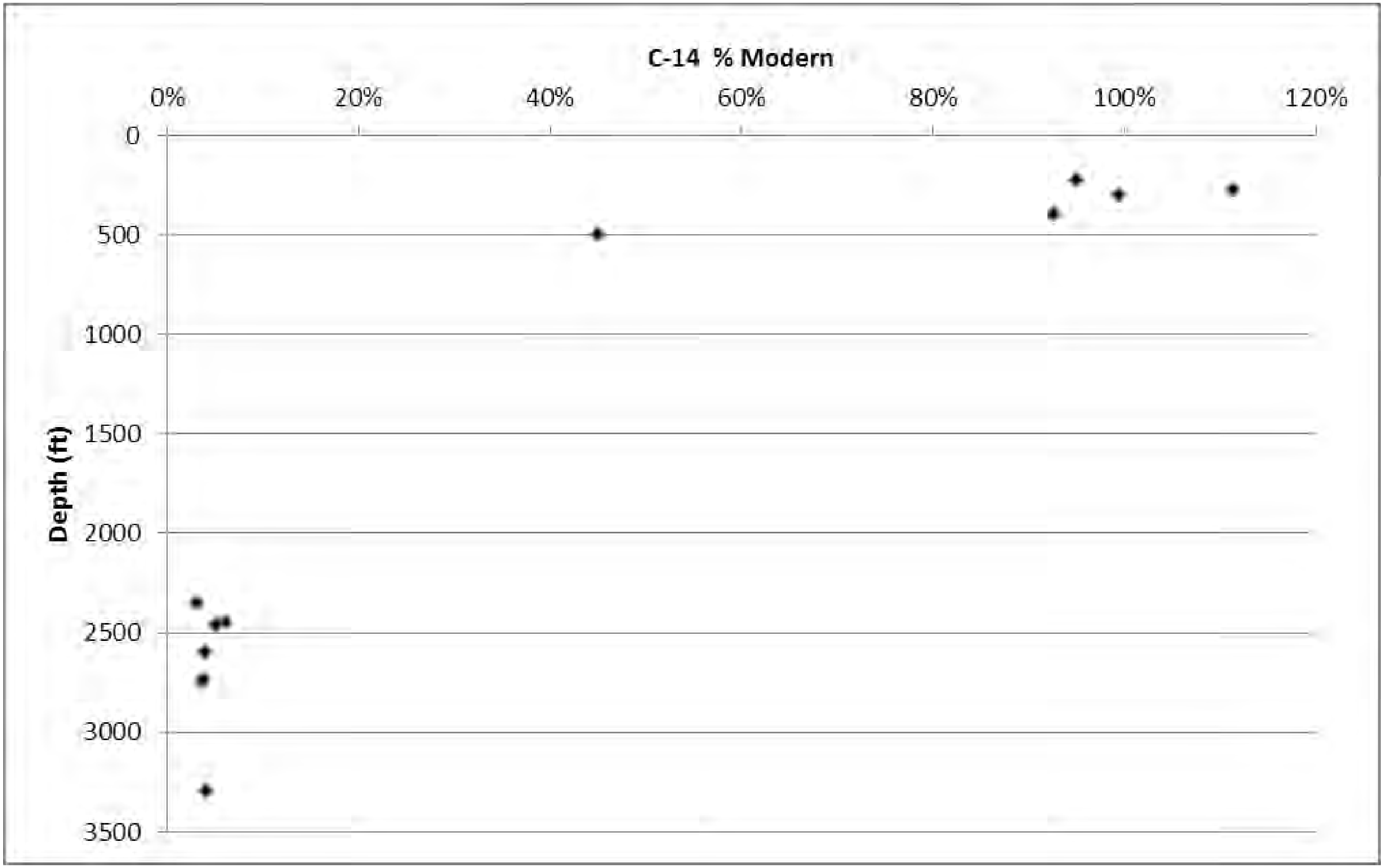


Figure 7-21. **Carbon-14 percent modern (C-14%) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.**

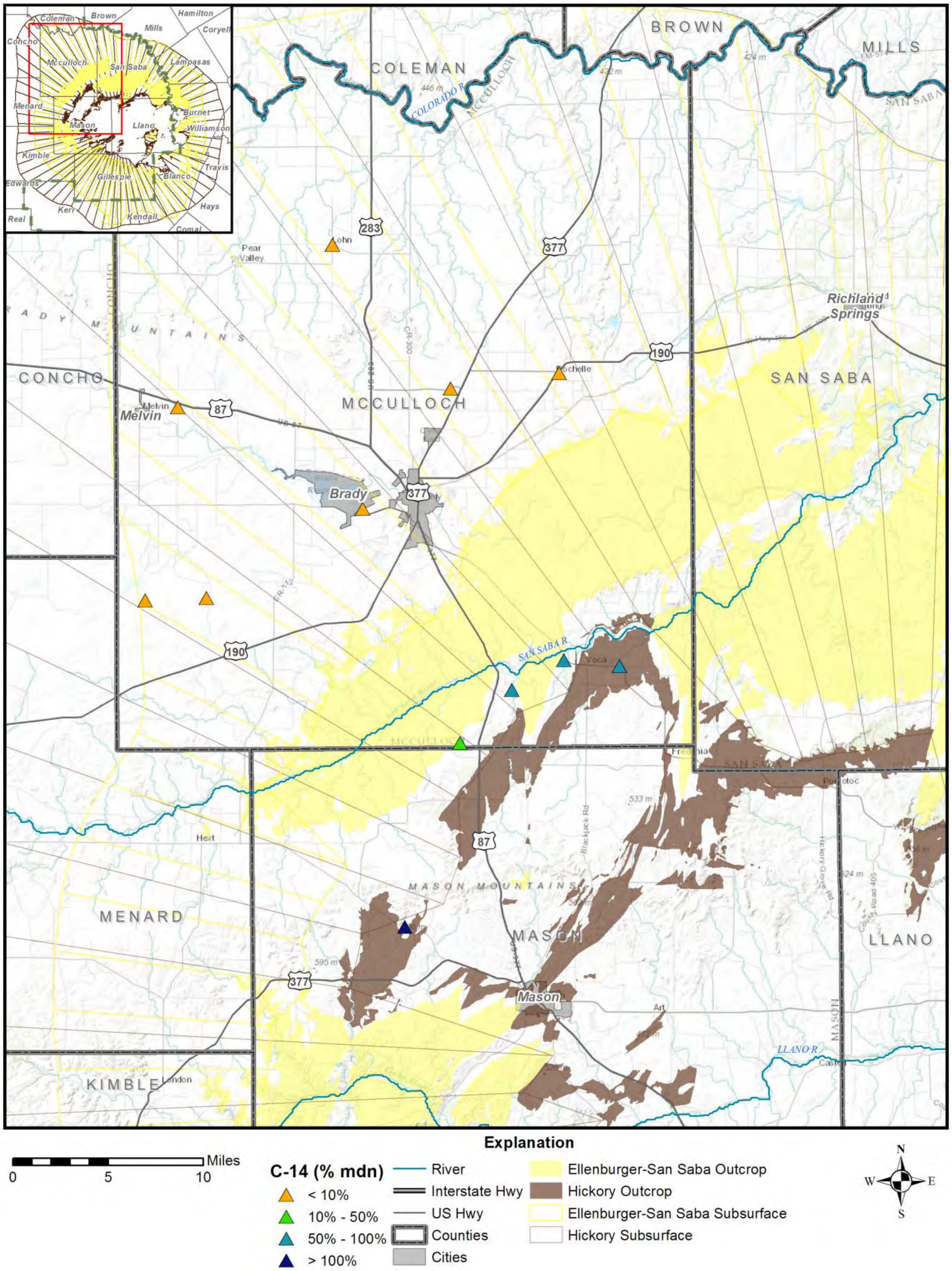


Figure 7-22. **Carbon-14 percent modern (C-14%) for the Hickory Aquifer, Mason and McCulloch Counties, Texas.**

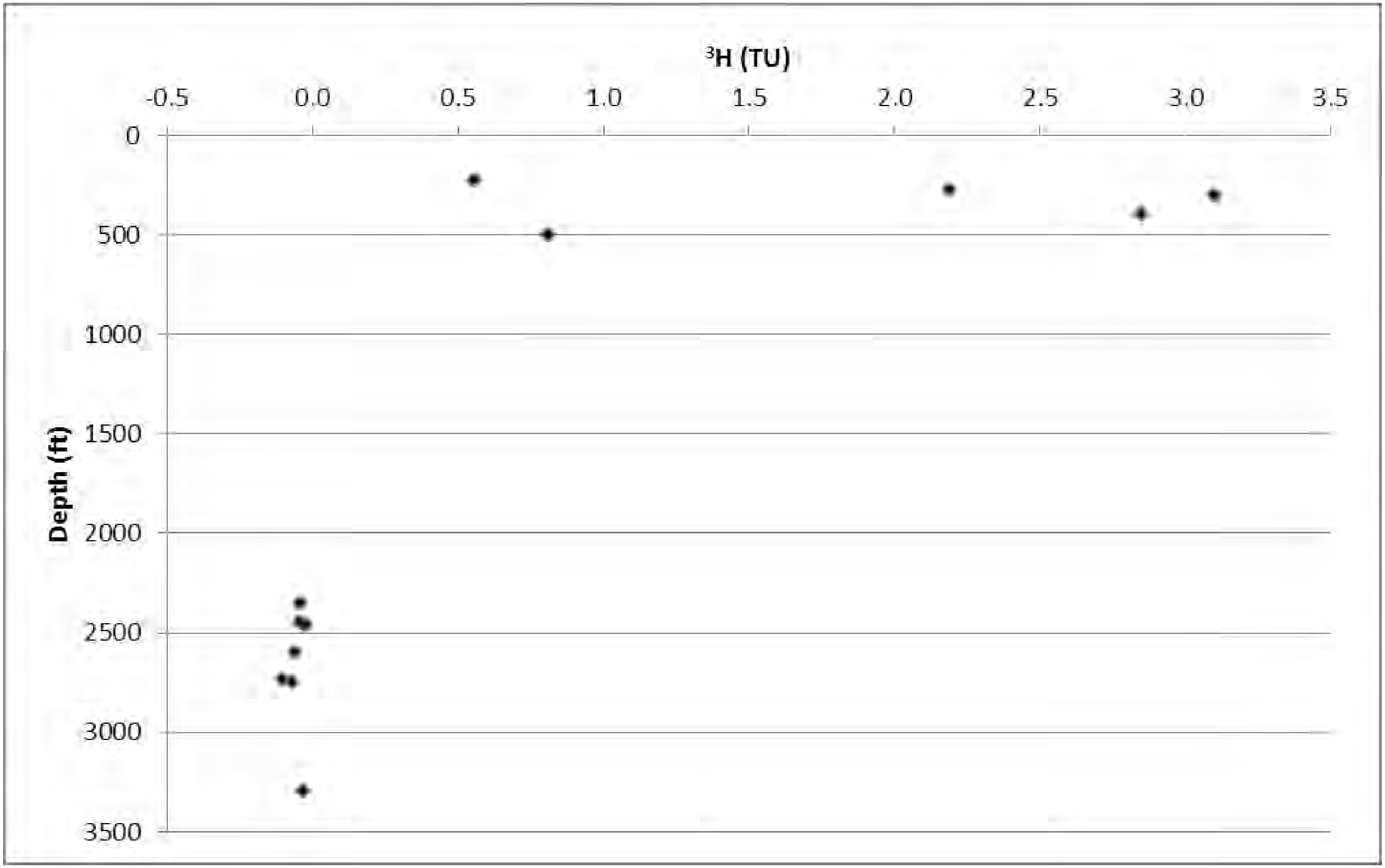


Figure 7-23. **Tritium (^{3}H) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.**

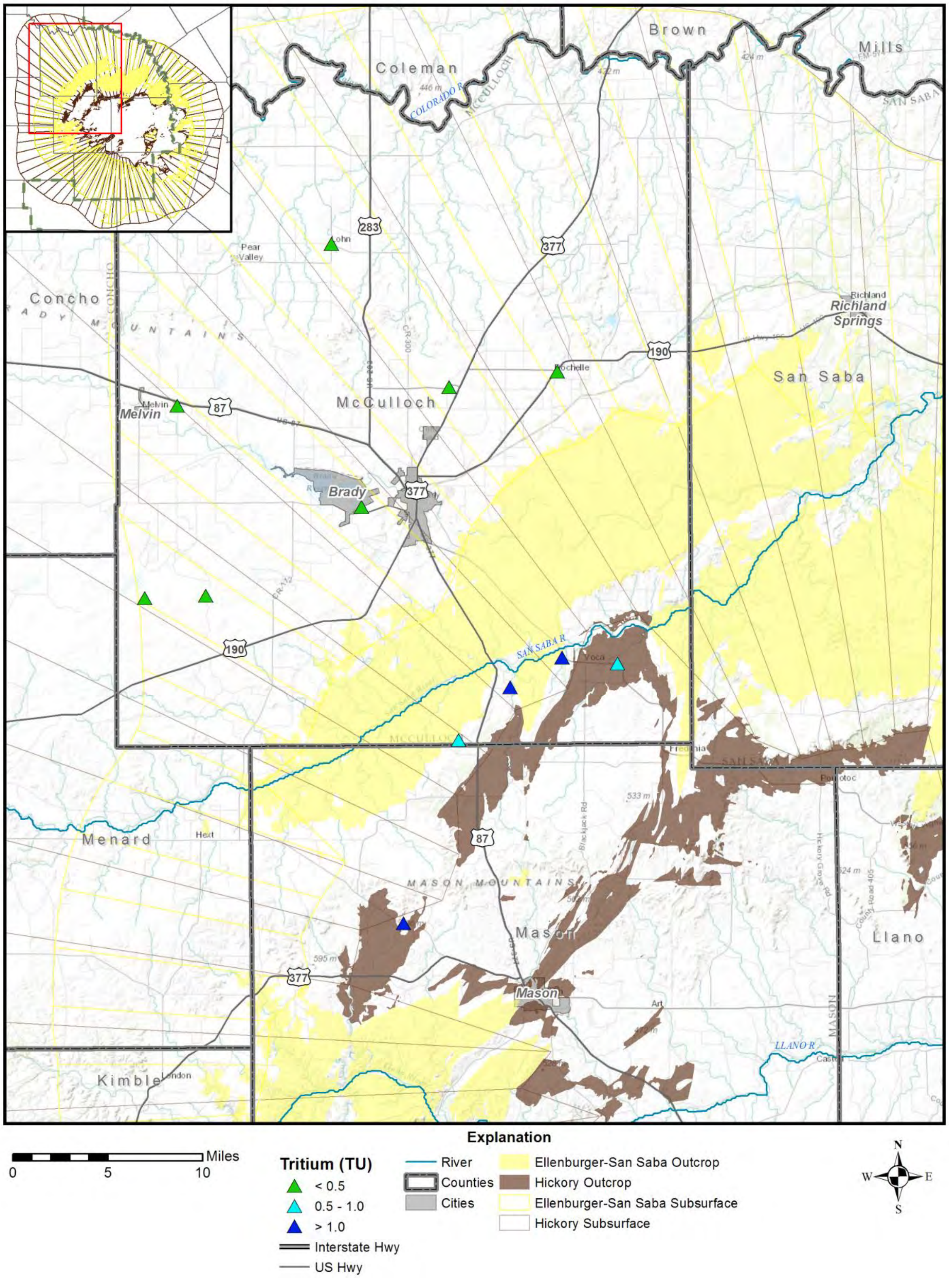


Figure 7-24. Map of tritium for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

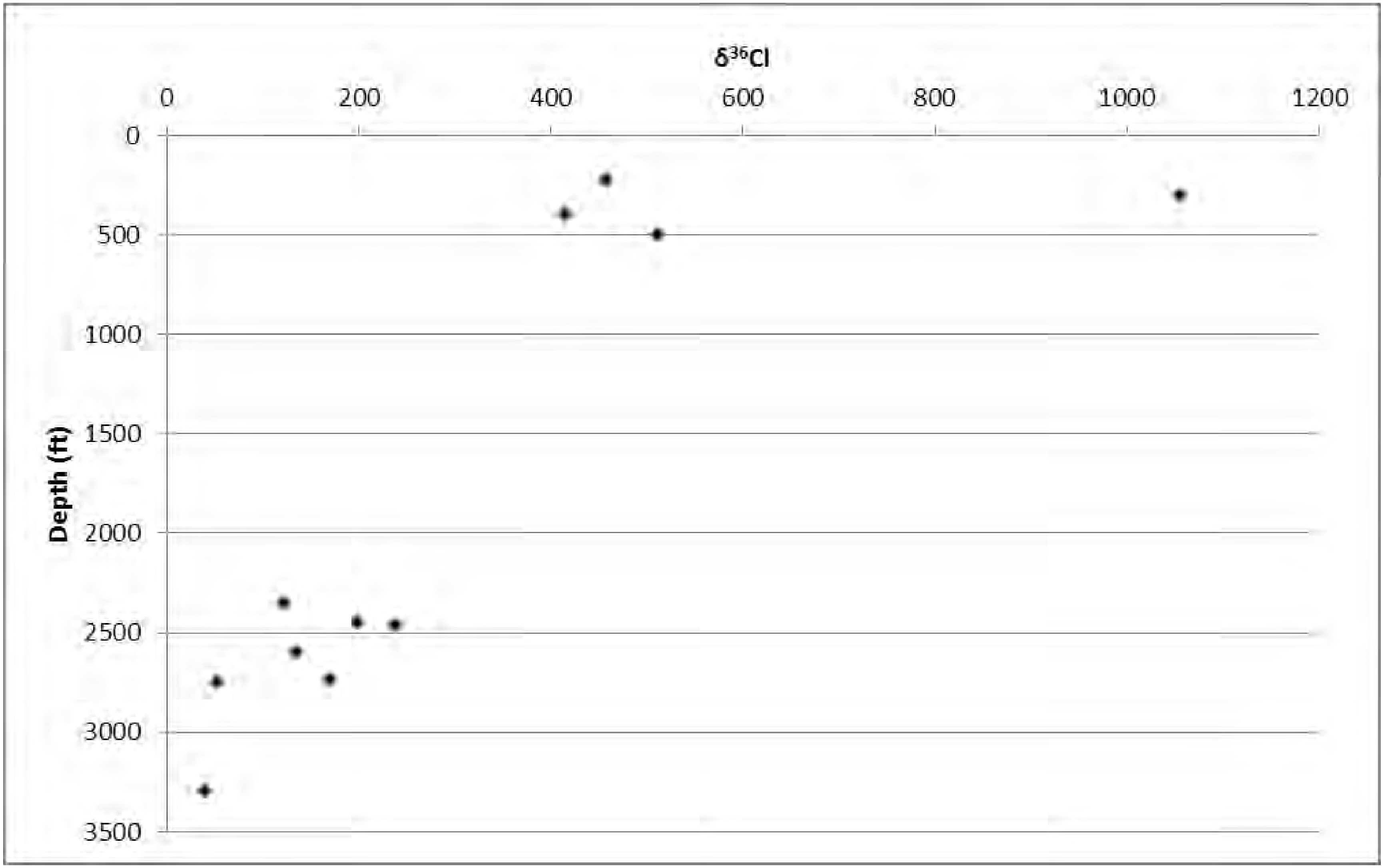


Figure 7-25. Chlorine-36 ($\delta^{36}Cl$) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

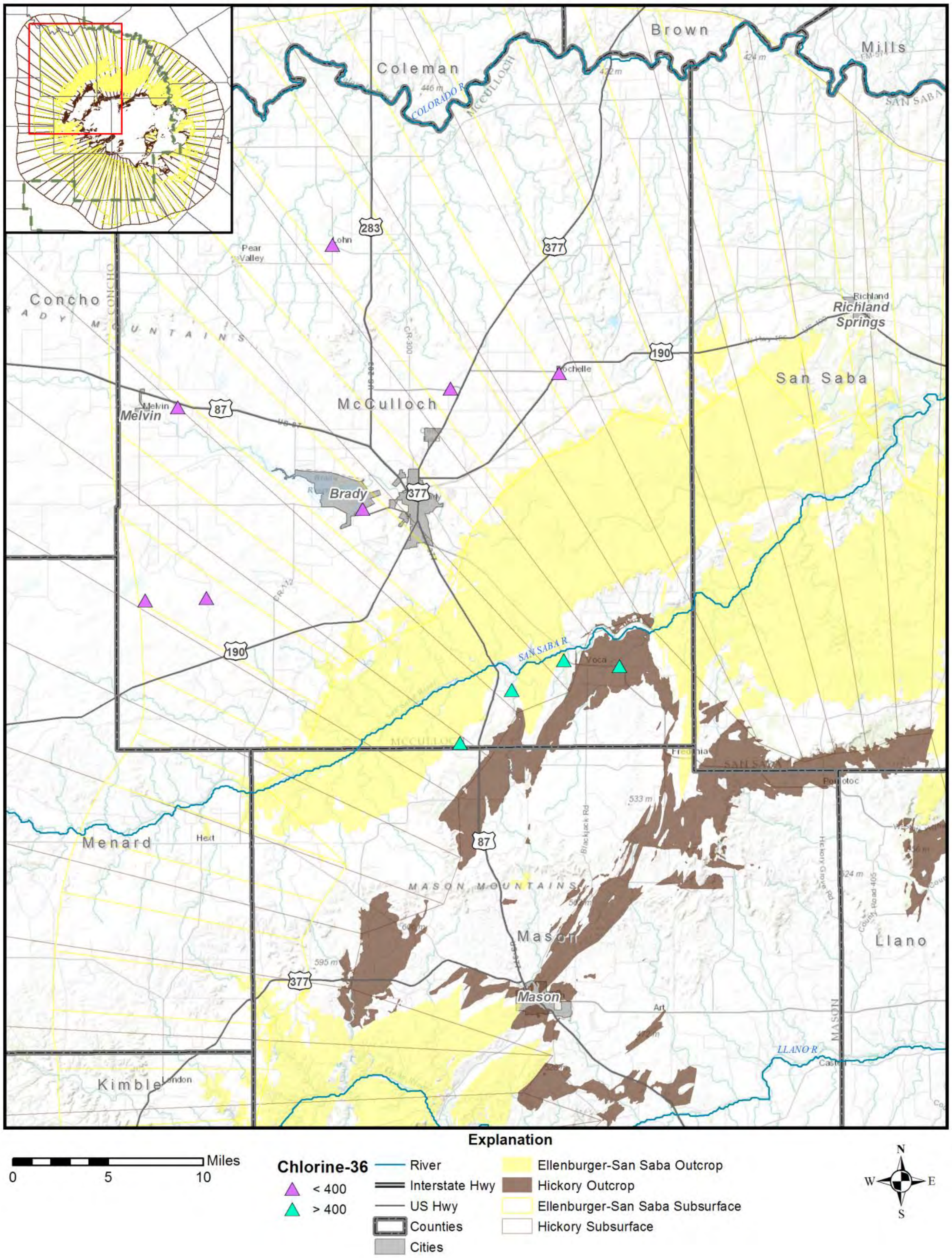


Figure 7-26. Map of δ^{36}Cl for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

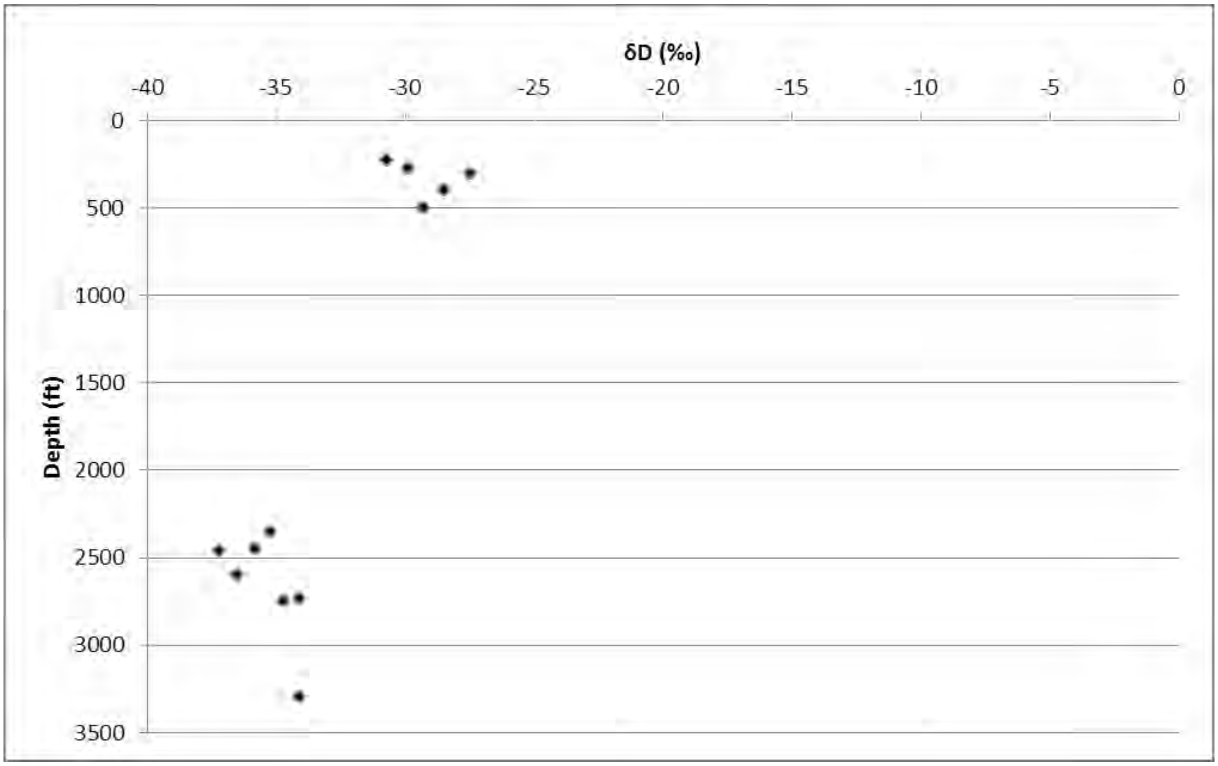


Figure 7-27. Deuterium (δD) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

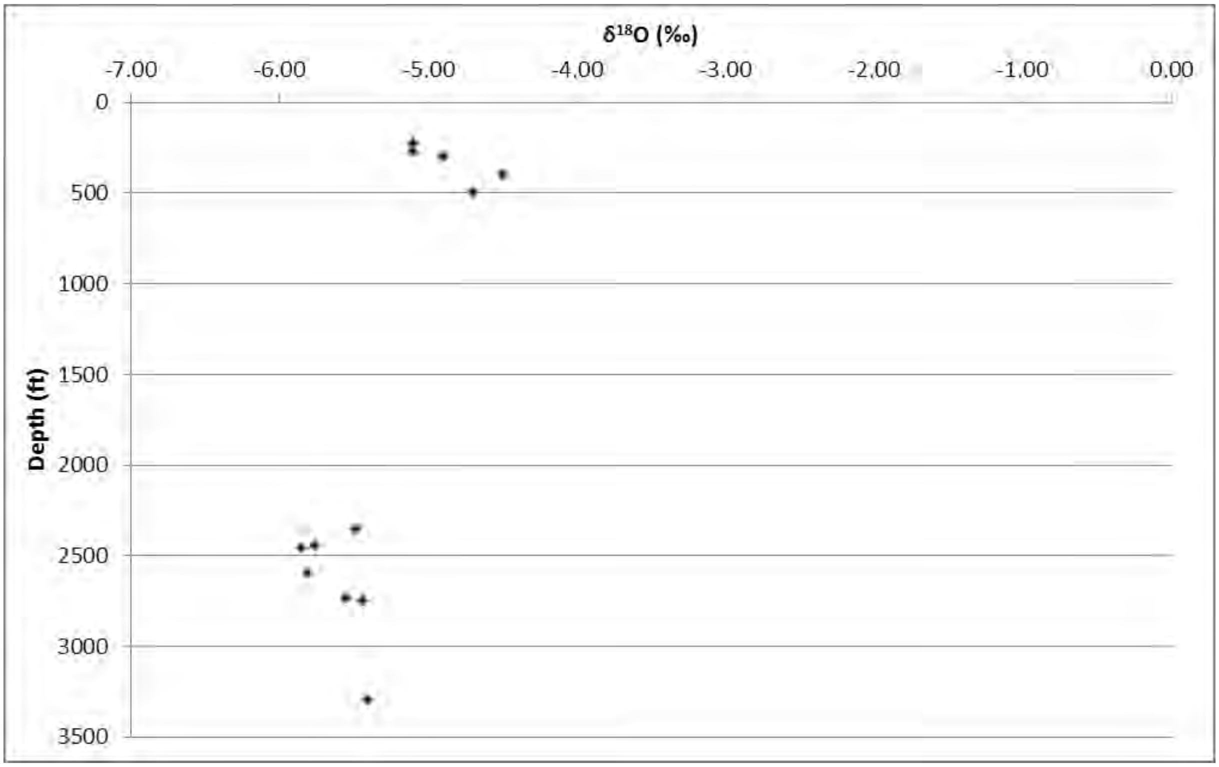


Figure 7-28. Oxygen-18 ($\delta^{18}O$) vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

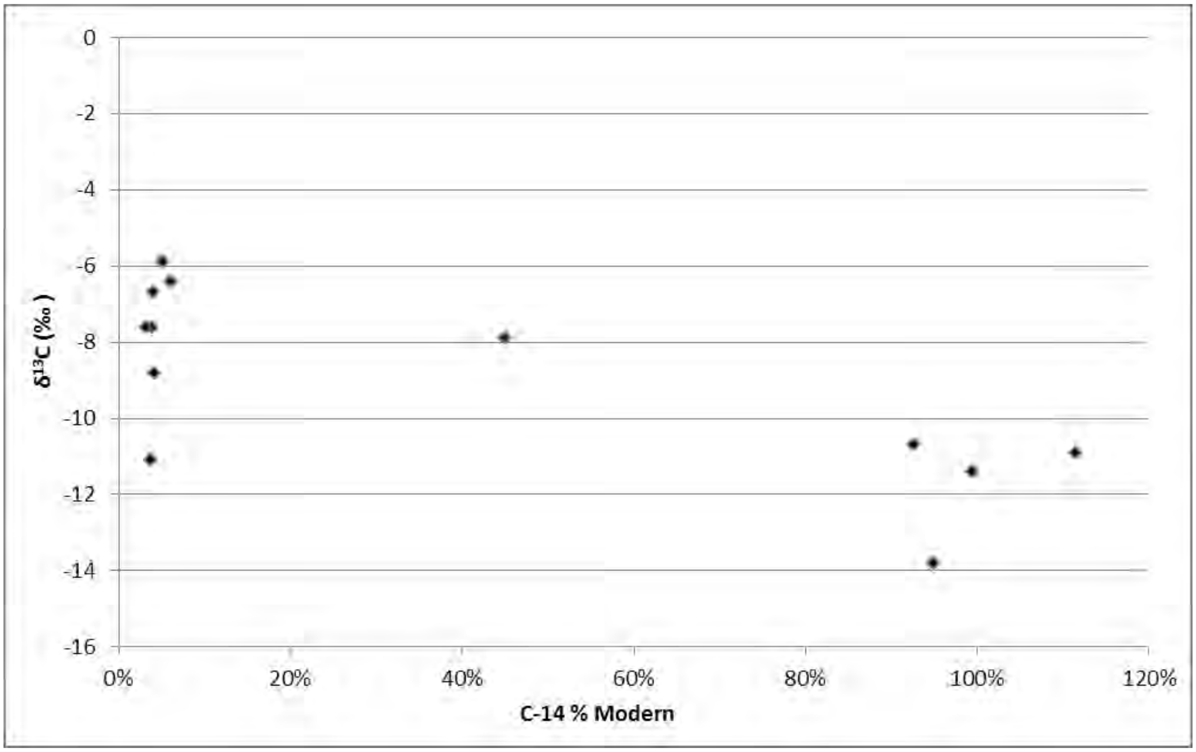


Figure 7-29. Carbon-14 percent modern (C-14%) vs $\delta^{13}C$ for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

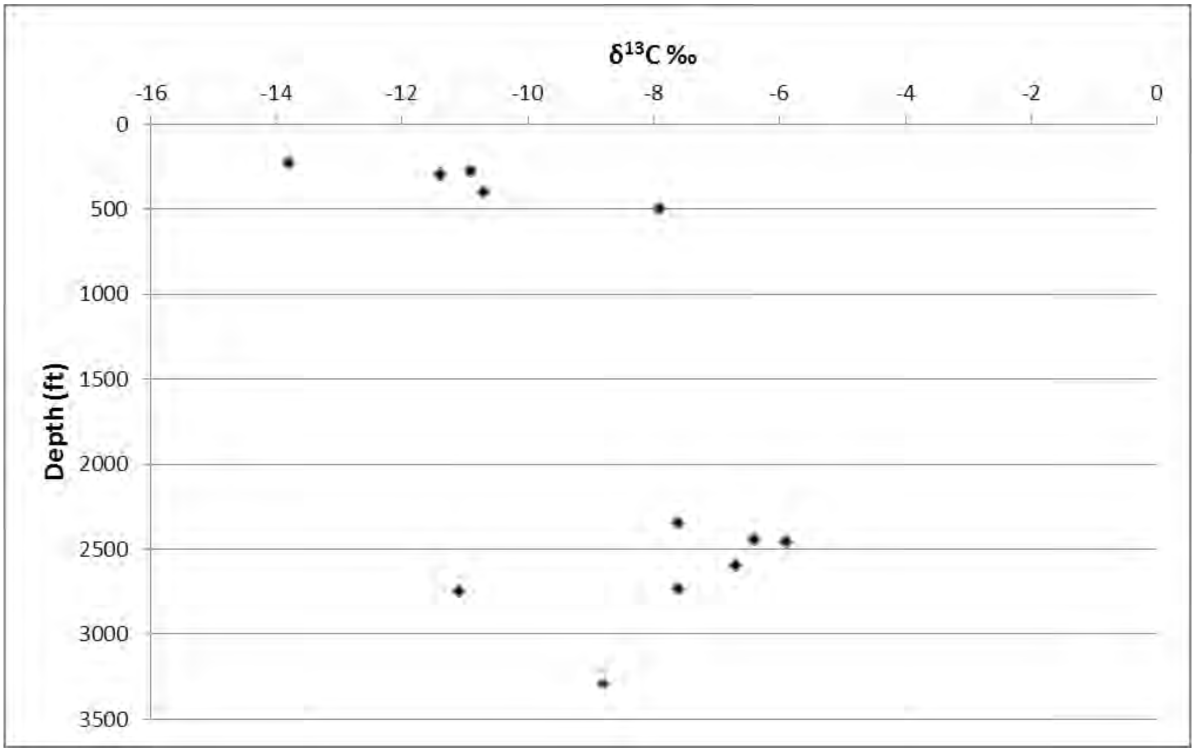


Figure 7-30. $\delta^{13}C$ vs depth for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

7.2.4 Radiocarbon Age Corrections

Computer simulation of the evolution of water composition between wells by considering both chemical and isotopic differences is a standard method for attempting to evaluate the plausibility of a flowpath and to correct the measured carbon-14 age after accounting for the carbon changes in the solution. The computer code NETPATH is used for these calculations and the procedure is described in detail in Plummer and others (1994). The available samples do not align on a well-defined groundwater flow path (Figure 7-7 and Figure 7-31), but because the carbon-14 data cluster into 3 groups of data that correspond to widely different depths (Figure 7-21, Figure 7-29, and Figure 7-30), but still potentially along segments of hypothetical flow pathways (Figure 7-31), the simulation for corrected carbon-14 ages was done where plausible using the following assumptions:

- The shallow well sample 5614410 is 275 feet in depth, is the most upgradient of the five shallow wells, has a depleted carbon-13, and has a measured carbon-14 content that is modern. For this study, this well is considered representative of a location upgradient from the other shallow wells, and is the best example of a recharge well composition.
- Well 5606505 (Table 7-1) has a depth of 500 feet, enriched $\delta^{13}C$ (Figure 7-31), and based on the water levels is representative of a well down gradient from the recharge well.
- Well 4263820 is also a shallow well down gradient from the recharge well, but has a total dissolved solid of approximately three times that of the other shallow wells. This well may be influenced by anthropogenic activities, and is not considered representative of the Hickory Aquifer.
- The remaining two shallow wells 5606311 and 4263908 are 300 feet in depth which is equivalent to the recharge well depth; similar total dissolved solids to the recharge well, but have more depleted $\delta^{13}C$ values. Modeling between the recharge well and these wells was unsuccessful and indicates that they are not on the flow path and may represent wells close to a different recharge location in the Hickory Aquifer outcrop.
- Similarly simulation of a reaction path from the recharge well to the westernmost deep well does not provide a solution, and is not considered a viable flowpath.
- The two wells furthest northwest (4252504 and 4245601) have isotopic and chemical compositions that are different from the other five deep samples, and the groundwater gradient near those wells clearly infers water sources from the west and northwest and not from the direction of the Hickory Aquifer outcrop (Figure 7-7). These wells cannot be assumed representative of flow from outcrop to deep aquifer.
- All other wells sampled in the deeper Hickory Aquifer are similar to each other in water composition and $\delta^{13}C$, but neither the chemical composition nor the isotopic values change in a uniform way that implies a unique flow line from westernmost to easternmost deep well, or from the recharge well to any of the deep aquifer wells.

The NETPATH modeling is an inverse method that assumes the change in chemical and isotopic composition between two wells can be attributed to reactions with minerals, organic material, or dissolved gas. If the model cannot obtain a solution, then the system is improperly characterized and may need adjustment for reasons such as: 1) the designated flow path is incorrect, 2) mixing is occurring with other water sources, 3) some reactive minerals or phases are not being considered and 4) errors in the analyses. For this study many efforts were made to simulate plausible reaction paths that explained that evolution of chemical and isotopic composition but the locations of these wells do not support unique flowpaths between them. Three pathways were successfully simulated as segments of the flow represented by the potentiometric surface shown in Figure 7-7.

The analytical data available from the TWDB was obtained historically for other projects and consequently was not part of a designed sampling scheme to support this project. Wells are not ideally located for the modeling but do provide a reconnaissance level assessment of the comparison of measured carbon-14 ages and the probable correction needed to make these measurements useful for corroboration of flow simulations. The results indicate that there are solutions for three selected flow pathways and that the change in water chemistry and isotopic composition can be explained by reactions with respect to the minerals listed.

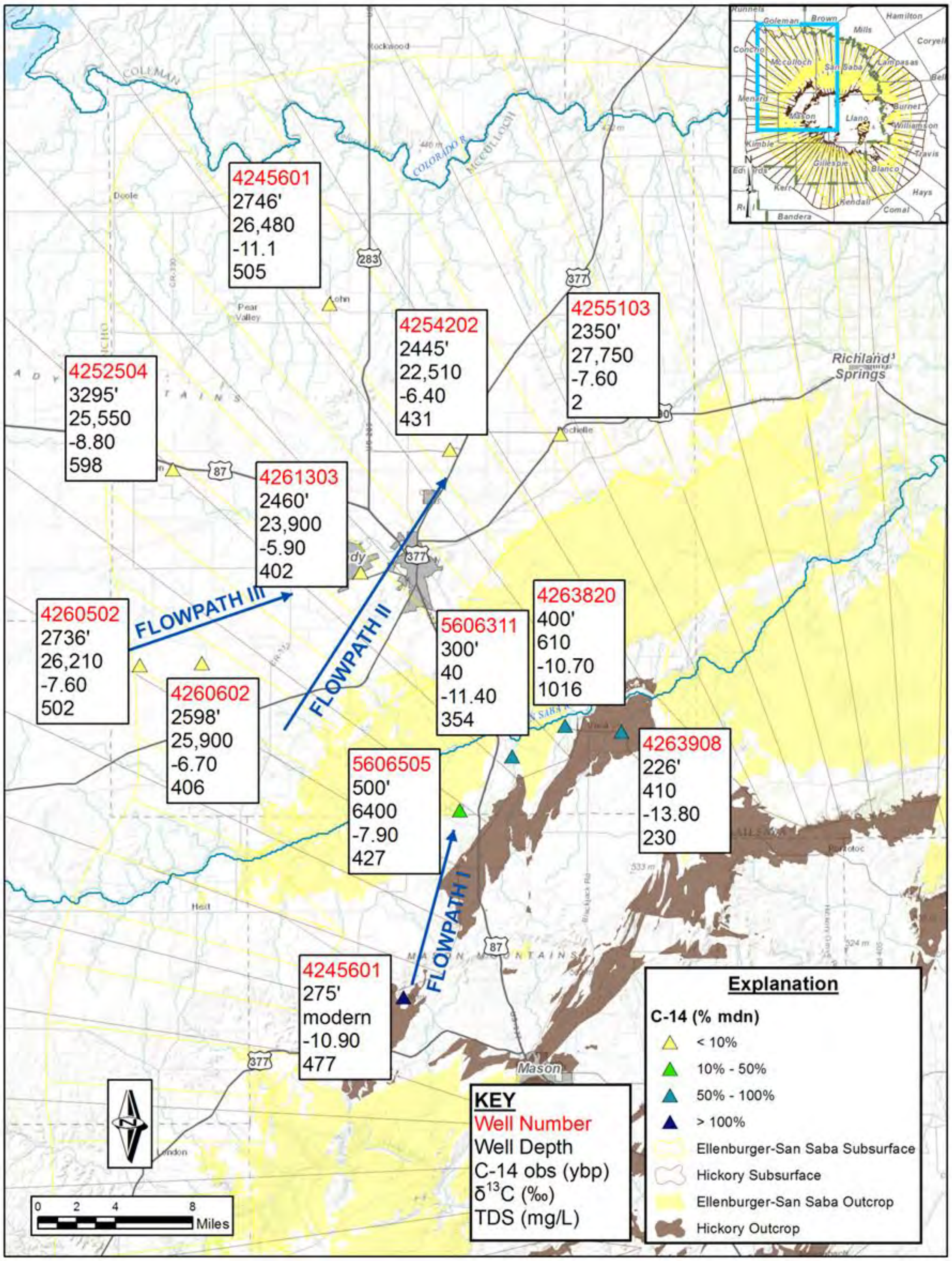


Figure 7-31. Key reference indications for wells with modeled flow paths indicated for the Hickory Aquifer, Mason and McCulloch Counties, Texas.

Shallow Flowpath I: Well 5614410 to Well 5606505

This pathway is representative of flow from recharge in the Hickory Aquifer outcrop to the well with a depth of 500 feet directly downgradient according to the Hickory Aquifer potentiometric surface (Figure 7-7). The total dissolved solids increase from 220 to 427 mg/L and the $\delta^{13}C$ becomes more enriched from -10.90 to -7.90 ‰. The mass changes can be accounted for by reaction with minerals and carbon dioxide; and the computed $\delta^{13}C$ after reaction matches the $\delta^{13}C$ of the down gradient well. Measured carbon-14 changes from modern to $^{14}C_{OBS}$ of 6,400 years before present; after accounting for carbon changes from reaction with minerals the $^{14}C_{ADJ}$ is a much younger 2,685 years before present. No other reaction pathway from recharge to other shallow wells can be simulated with existing data principally because the wells depicted as down gradient have much more depleted $\delta^{13}C$ values indicating they are closer to a different recharge location. Similarly, simulations from the recharge well to the deeper wells do not result in solutions. This was not unexpected because the potentiometric surface does not support a flow line between those locations. This would indicate that the groundwater source for the deeper wells is possibly further west and south. Additionally, the presence of faults that bound the grabens in which the shallow wells are positioned may also prevent flow directly north to the locations of the deeper wells.

Deep Aquifer Flowpath II: Well 4261303 to Well 4254202

The wells sampled from the deeper Hickory Aquifer do not yield plausible reaction pathways if available data from the shallow wells is used as the source. Additionally the deeper wells have similar water compositions and isotopic values (Figure 7-7 and Figure 7-31; Table 7-2). Flowpath II was constructed assuming flow from some unknown upgradient recharge location that passed through the deep aquifer well 4261303 and terminates at well 4254202 (Figure 7-31). The results of the mass balance are given in Table 7-2; the $\delta^{13}C$ matches well and the measured $^{14}C_{OBS}$ of 22,510 years before present corrects to $^{14}C_{ADJ}$ of 20,939 years before present.

Deep Aquifer Flowpath III: Well 4260502 to Well 4261303

Flowpath III was constructed assuming flow from some unknown upgradient recharge location that passed through the deep aquifer well 4260502 and terminates at well 4261303 (Figure 7-31). The results of the mass balance are given in Table 7-2; the $\delta^{13}C$ matches well and the measured $^{14}C_{OBS}$ of 23,900 years before present corrects to $^{14}C_{ADJ}$ of 21,431 years before present. This simulation is given as an example of the plausibility of the reaction path but cannot be accepted as a successful simulation for these two wells because the sodium and chloride are not consistent as a flowpath because the second well concentrations of both constituents are lower. No reasonable mechanism would explain the loss of chloride other than dilution by mixing but a rigorous accounting of mixing cannot be done without an identified second water source. As an example of the carbonate system changes, this pathway at least generally indicates a correction to the $^{14}C_{OBS}$ is required.

Without a defined flowpath from recharge to sampled well the accounting for carbon gain or loss to the dissolved inorganic carbon cannot be rigorously done; where the pathway is indicated the corrections seem plausible.

The presence of tritium and chlorine-36 in these groundwater samples is consistent with the $^{14}C_{OBS}$; where ages are modern to a few hundred years, the tritium and chlorine-36 are present. In deeper waters these isotopic signatures corroborate older water based on the carbon-14 evaluation.

Table 7-2. Reaction pathways for correction of carbon-14 for three plausible segments.

Phases	Pathway I	Pathway II	Pathway III
	5614410 to 5606505	**4261303 to 4254202**	**4260502 to 4261303**
Biotite			0.167
Mg/Na Exchange	-0.243	0.049	0.209
NaCl	0.019	0.605	Na & Cl
K/Na Exchange	0.031	-0.133	
CO_2 (g)	0.205	0.2	-0.063
Pyrite		0.036	
Gypsum	-1.021		
Calcite	1.37	-0.2	0.2
Siderite	0.556	-0.133	
$\delta^{13}C$ (measured)	-7.9	-6.4	-5.9
$\delta^{13}C$ (computed)	-7.9	-6.2	-5.9
$^{14}C_{OBS}$ years before present	6,400	22,510	23,900
$^{14}C_{ADJ}$ years before present	2,685	20,939	21,431

Notes: All units are millimoles. Sodium and chloride omitted.

7.2.5 Discussion of the Hickory Aquifer Results

Based on the potentiometric surface map in Mason and McCulloch counties, there are two different groundwater flow systems, 1) an active shallow system in the outcrop and 2) a deeper more stagnant flow system in the downdip confined section. In the shallow flow system in Mason and McCulloch counties there is recharge in outcrop and then discharge to the San Saba River. Although the potentiometric surface for the Hickory Aquifer would indicate potential flow from the outcrop to the downdip section, the Piper diagram for the Hickory Aquifer shows two different water chemistry populations inferring limited connections between the two. The isotope data further substantiates this conceptual model of two flow systems. Outcrop groundwater is young (high activities ofcarbon-14, tritium and chlorine-36) and heavier deuterium and oxygen-18 values. The high activities for carbon-14 and chlorine-36 suggest that their origin is from atmospheric nuclear testing, therefore their waters have been recharged post 1950's. Downdip waters are old. They have low carbon-14 percent modern, no tritium, low chlorine-36 and lighter deuterium and oxygen-18 values. If groundwater in the Hickory Aquifer outcrop is given the option of flowing into the deep subsurface or flowing along the strike of the outcrop to regional points of discharge such as the San Saba River, it appears to follow the second option of discharge to local streams rather than flowing into the deeper subsurface with no obvious points of discharge.

7.2.6 Results for Ellenburger-San Saba Aquifer

Depths of water wells increase from outcrop in Mason County and southern McCulloch County (shallow wells) to wells in McCulloch County with depths greater than 1000 feet (Figure 7-32). Wells can be grouped into 1) outcrop wells, slightly downdip wells and less than 1,000 feet and 2) “highly confined” wells and greater than 1,000 feet.

Groundwater elevations are highest in the southwest section of the outcrop of the Ellenburger-San Saba Aquifer and decline toward the northwest in McCulloch County and San Saba County (Figure 7-33). Groundwater flow direction in the outcrop is considered to be towards the northeast as it crosses the northern edge of the outcrop (note: the San Saba River and other similar areas of assumed groundwater flow control were not considered when interpolating potentiometric surface for contouring). The active flow system for the Ellenburger-San Saba Aquifer is in its outcrop. Water levels are similar in the confined section of the Ellenburger-San Saba Aquifer in northern McCulloch County when compared to outcrop water levels of the Ellenburger-San Saba Aquifer. Based on the potentiometric surface, there may be some flow from the outcrop into the confined section.

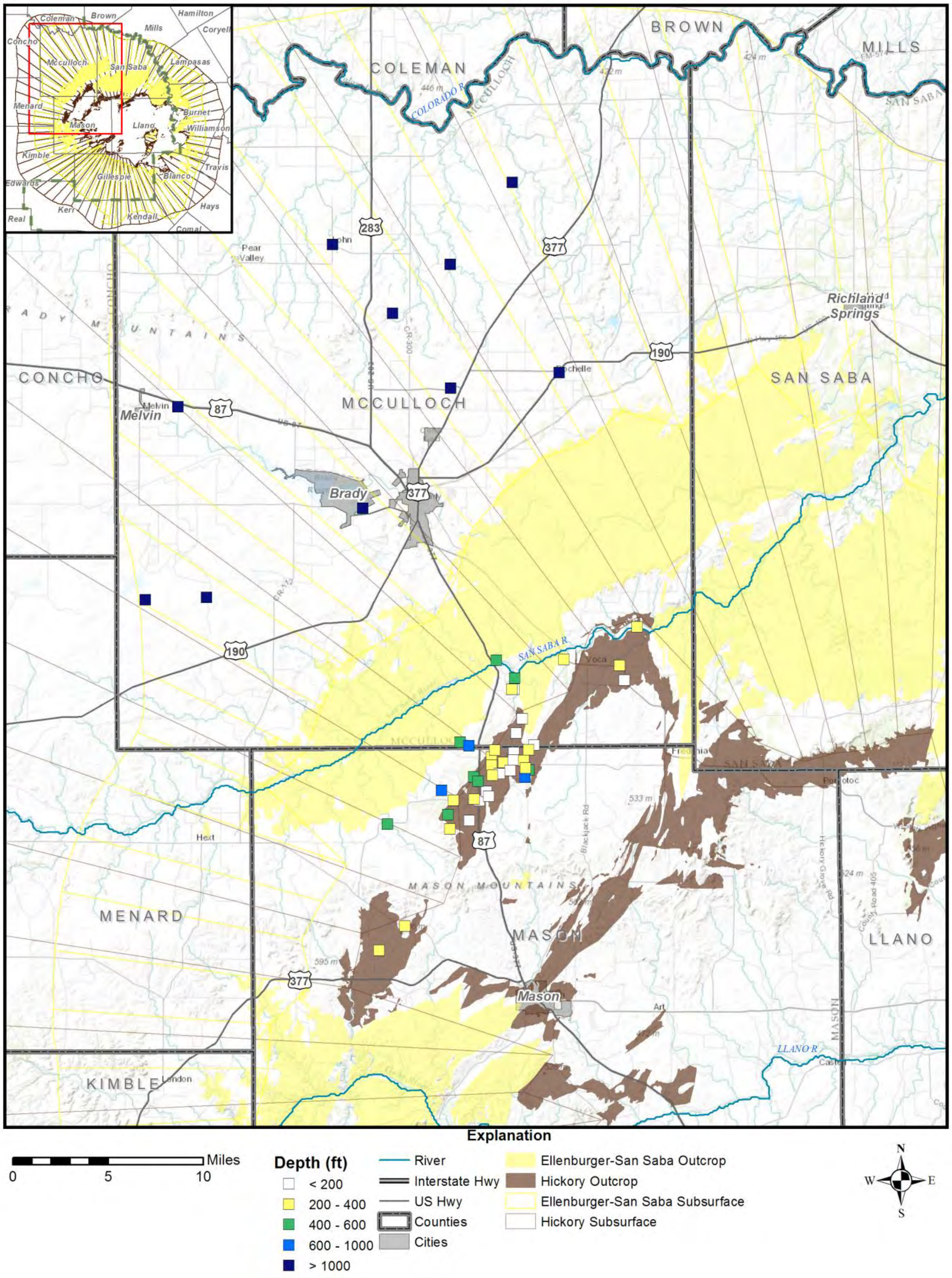


Figure 7-32. Ellenburger-San Saba Aquifer well locations and depths, McCulloch County, Texas.

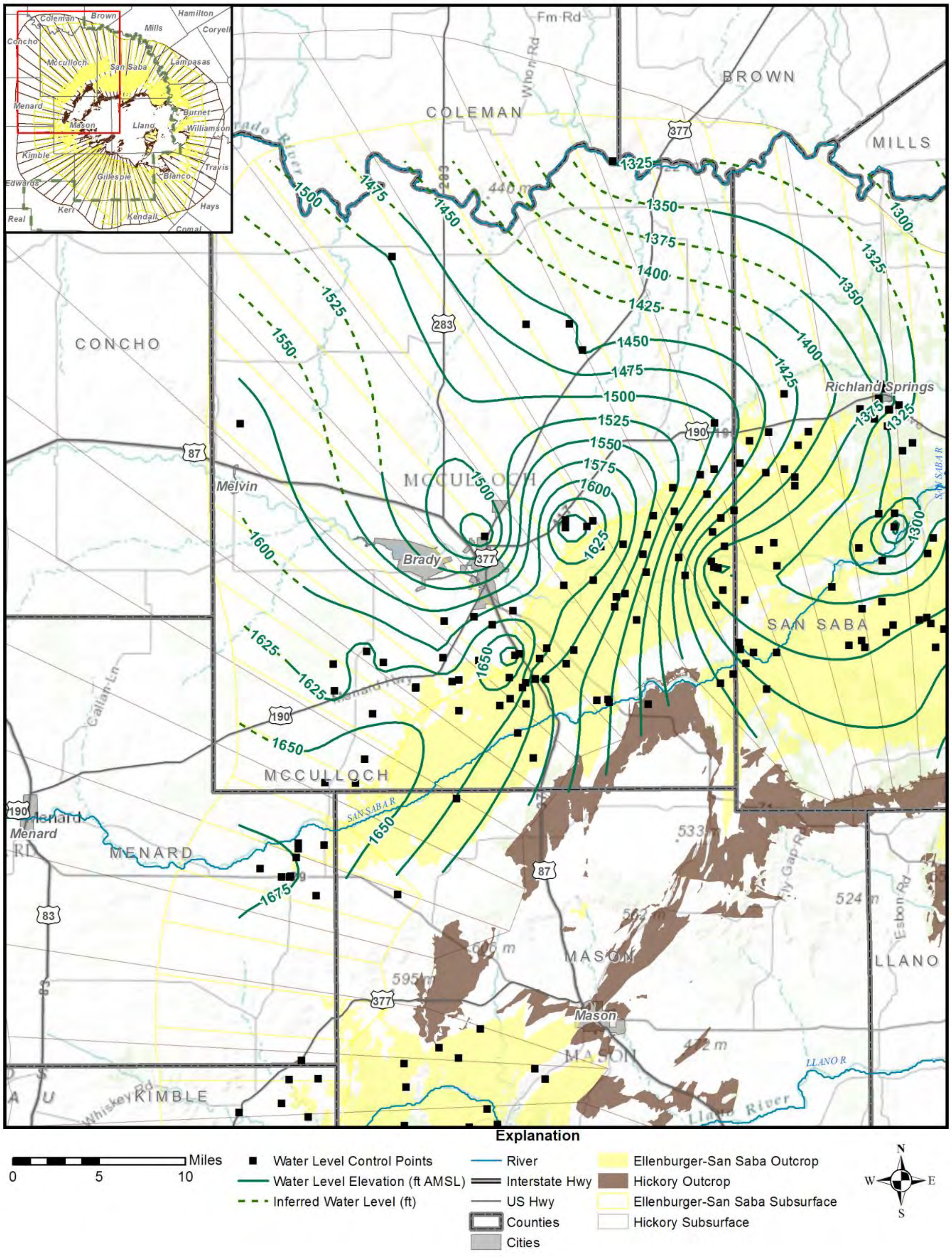


Figure 7-33. Ellenburger-San Saba Aquifer water level data (2005-2011), McCulloch County, Texas.

7.2.7 Critical Chemical Parameters

Less chemical data are available for the Ellenburger-San Saba Aquifer than for the Hickory Aquifer, especially isotopic data. The following geochemical observations are made with this limited data set. Piper diagram (Figure 7-34) shows that the general water composition is a calcium-magnesium-bicarbonate water. No obvious chemical evidence indicates upward leakage from the underlying Hickory Aquifer with its higher sodium, sulfate and chloride concentrations. There are high nitrate in shallow wells primarily in the outcrop (Figure 7-35). Much lower activities of radium-226 and radium-228 occur in the Ellenburger-San Saba Aquifer than in the deeper Hickory Aquifer waters. This suggests a lack of mixing between the Hickory Aquifer and the Ellenburger-San Saba Aquifer (Figure 7-36).

New data should be collected throughout McCulloch and San Saba counties. To the degree possible, wells should be screened (or open) to only a single formation. Ideally, the wells should be distributed from the outcrop to the downdip portions of the aquifer to assess potential age differences.

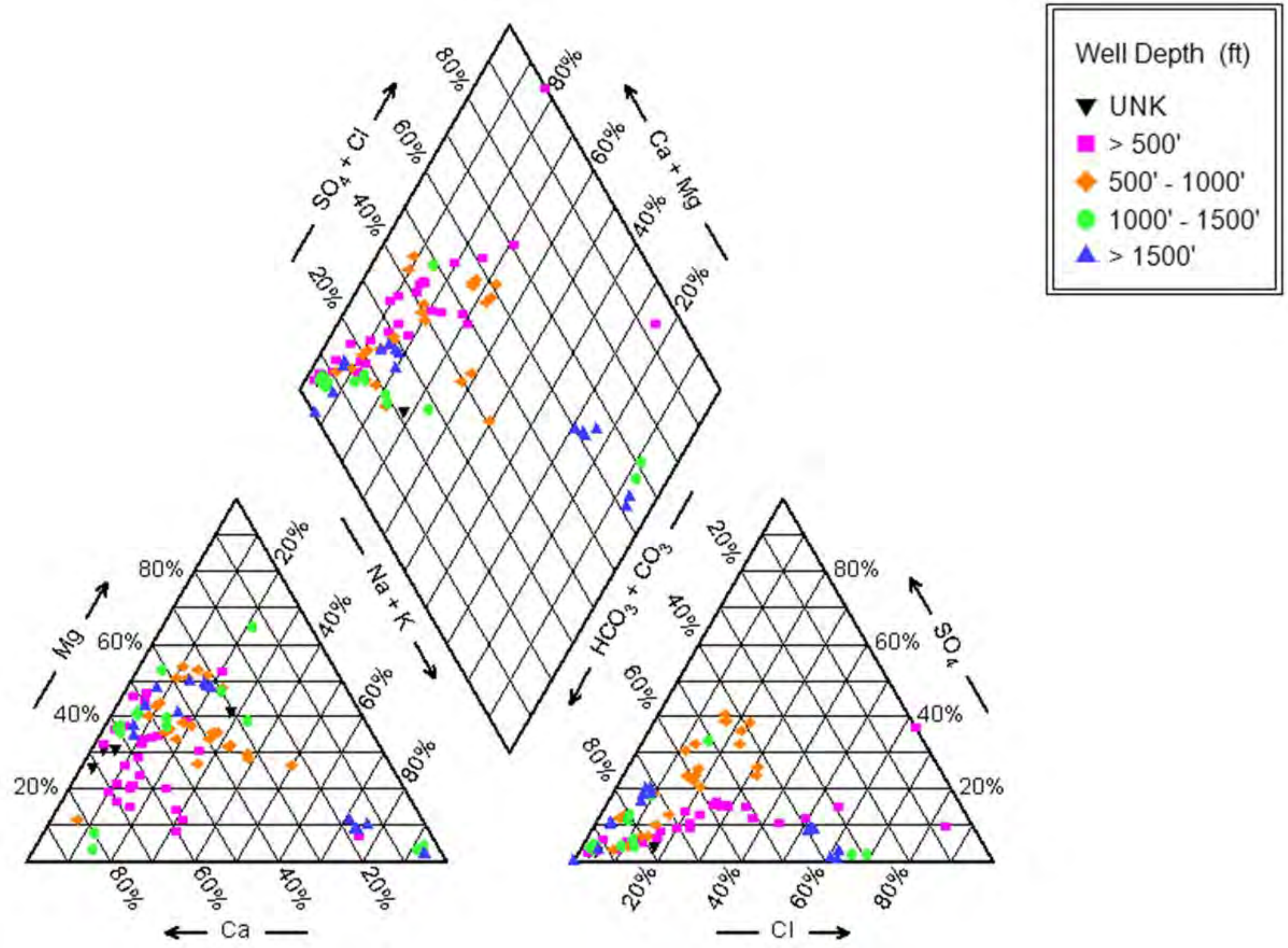


Figure 7-34. Piper diagram for the Ellenburger-San Saba Aquifer, McCulloch County, Texas.

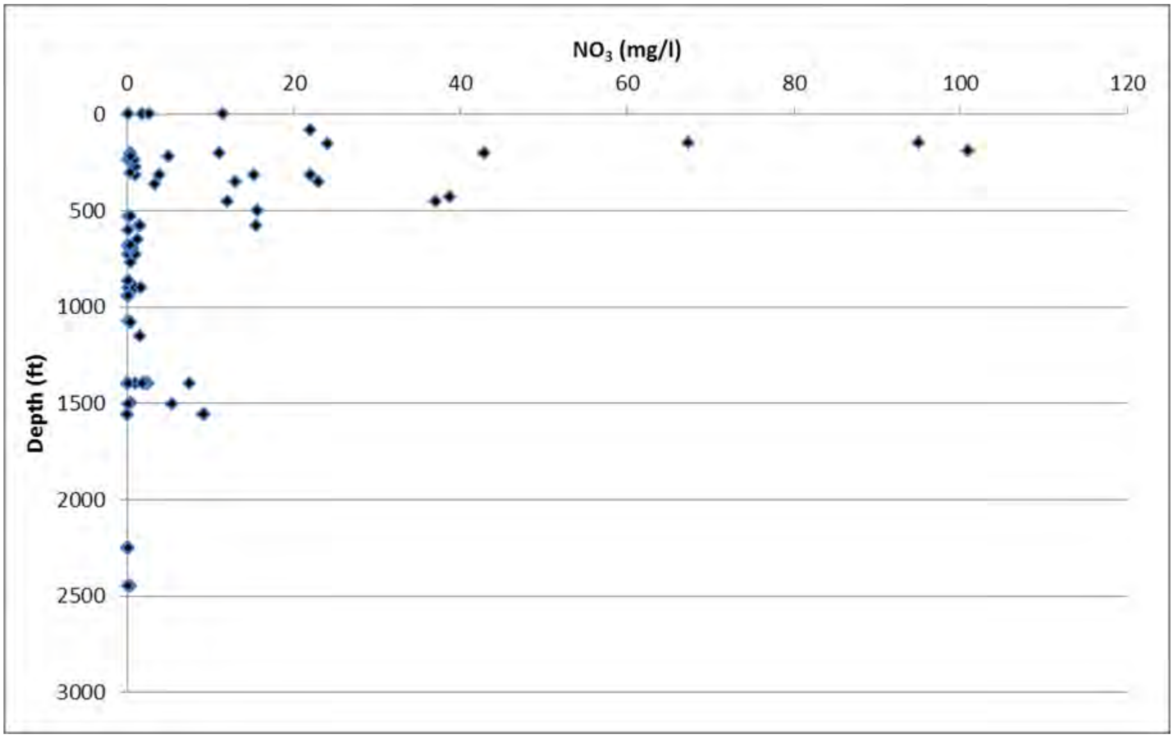


Figure 7-35. Nitrate (NO_3) vs depth for the Ellenburger-San Saba Aquifer, McCulloch County, Texas.

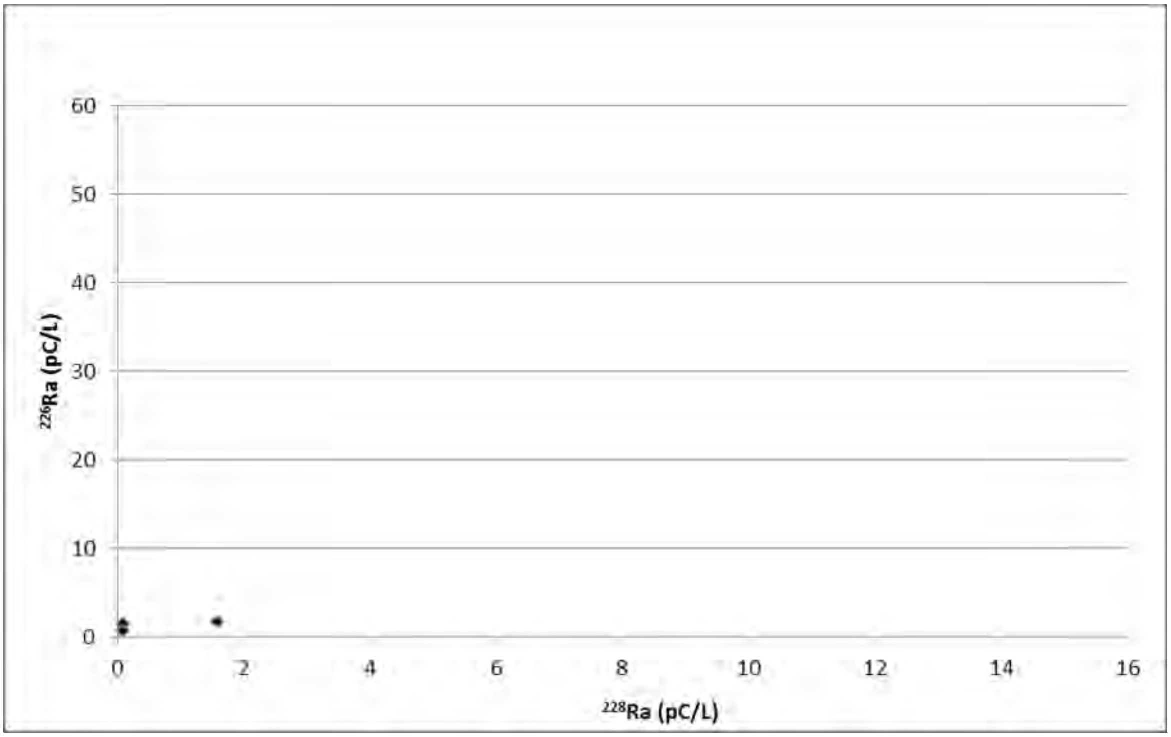


Figure 7-36. Radium-226 (^{226}Ra) vs radium-228 (^{228}Ra) for the Ellenburger-San Saba Aquifer, McCulloch County, Texas.

7.2.8 Discussion of the Ellenburger-San Saba Aquifer Results

The potentiometric surface suggests that much of groundwater in the Ellenburger-San Saba Aquifer outcrop flows toward the San Saba River and not into deeper subsurface. There is probably enough precipitation for recharge. Discharge is considered to be primarily to the San Saba River although there is no faulting to act as a barrier or partial barrier to down dip flow. The chemical composition of the Ellenburger-San Saba Aquifer groundwater from the Piper diagram does not indicate upward leakage from the Hickory Aquifer into the Ellenburger-San Saba Aquifer. Radium-226 and radium-228 activities for the Ellenburger-San Saba Aquifer are much lower than in the underlying Hickory Aquifer, also suggesting no significant or rapid leakage from the Hickory Aquifer into the Ellenburger-San Saba Aquifer. Additional wells are needed in both the outcrop and downdip with an emphasis in the confined section. The general inorganic chemistry should be collected and analyzed but carbon-14 and chlorine-36 will probably provide more information of flow dynamics.

7.3 Southern Sub-Region (Gillespie County)

7.3.1 Data Reviewed

Surface geologic interpretations are based on the Texas Bureau of Economic Geology, Geologic Atlas of Texas, Llano sheet (1981) for Gillespie County (Figure 7-37 and Figure 7-38). Two published geologic cross sections were available for eastern Gillespie County: Figure 7-39 from Bluntzer (1992) and Figure 7-40 from Standen and Ruggiero (2007).

Chemistry and isotope data from the Hensell Formation, the Hickory Aquifer and the Ellenburger-San Saba Aquifer in Gillespie County (south of the Llano Uplift area) were reviewed. These data sets represent data from the Hensell Formation, the Hickory Aquifer and the Ellenburger-San Saba Aquifer wells or groundwater data from wells in Gillespie County that are available from the TWDB groundwater database, plus groundwater samples collected in 2012.

The TWDB previously collected data for inorganic and isotopic constituents for Gillespie County for the Hensell Formation, the Hickory Aquifer and the Ellenburger-San Saba Aquifer. Wells with water chemistry data are shown in Figure 7-41.

The TWDB data plus recently collected (2012) data in Gillespie County are merged into Table 7-3.

Ten new samples were collected in 2012 in Gillespie County (Table 7-3). Paul Tybor, Manager of the Hill Country Underground Water District (Gillespie County) recommended well locations and helped in sampling. The new samples were collected from Hensell Formation wells and Ellenburger-San Saba Aquifer wells. No wells drilled solely to the Hickory Aquifer were sampled. Table 7-3 is the well information. Figure 7-42 is a location map for the sampled wells.

Water level data from the Edwards Group, the Hensell Formation, the Ellenburger-San Saba Aquifer and the Hickory Aquifer were used to construct potentiometric surface maps. The Cretaceous age aquifers (Edwards and the Hensell Formation) (Figure 7-43) and the Paleozoic age aquifers (the Ellenburger-San Saba Aquifer and the Hickory Aquifer) (Figure 7-44) are based on water level data from the TWDB groundwater database. Water level data for the integrated Edwards Group and Hensell Formation map is from 1970-2012. Water well data for the underlying Ellenburger-San Saba Aquifer and Hickory Aquifer map is from 1990-2012. The longer time period for Edwards Group and Hensell Formation map was used because less data were available for those aquifers in comparison to the Hickory Aquifer and the Ellenburger-San Saba Aquifer. Well location and well depth also from TWDB groundwater database.

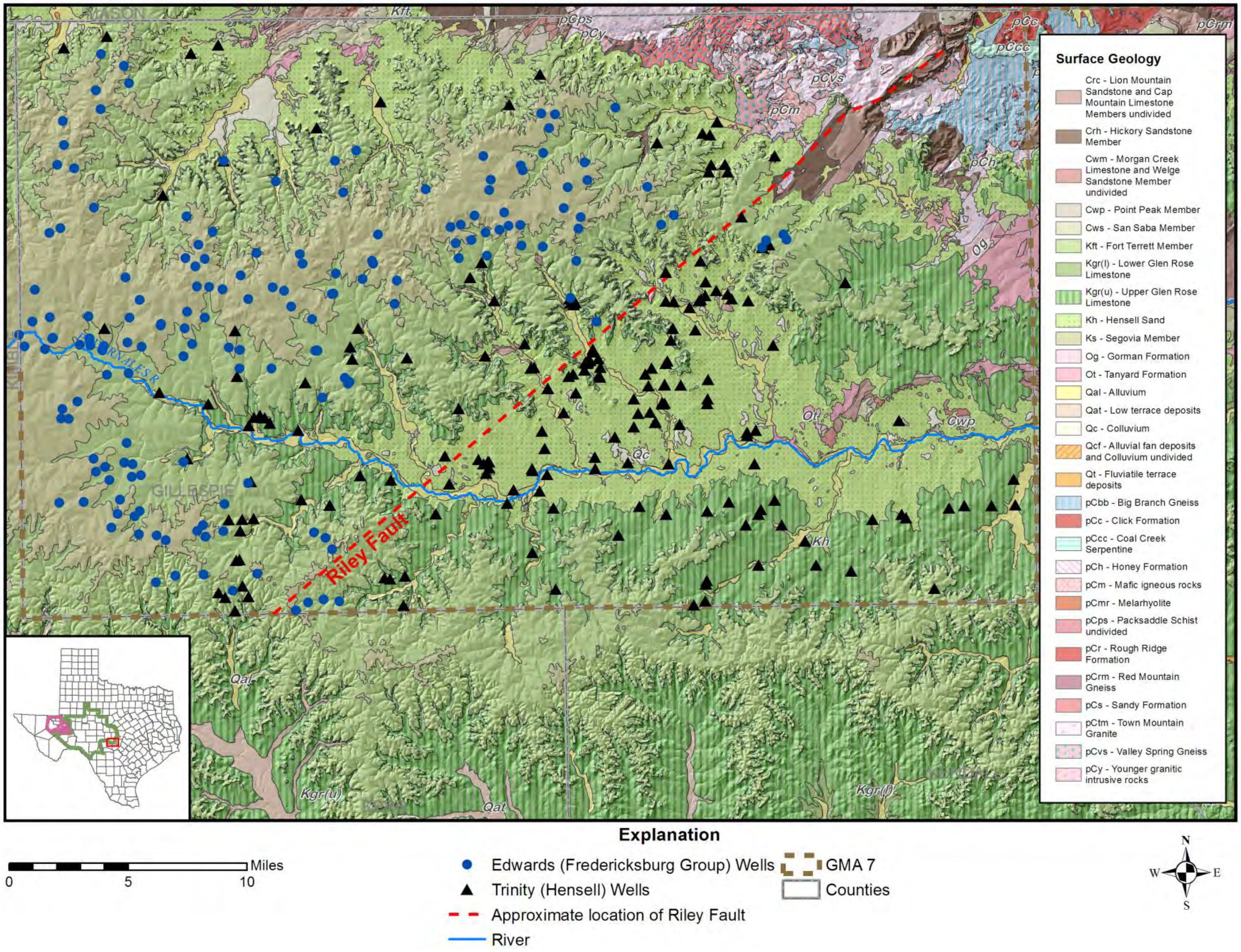


Figure 7-37. Geologic map of Gillespie County, Texas with Trinity (Hensell Formation) and Edwards well locations.

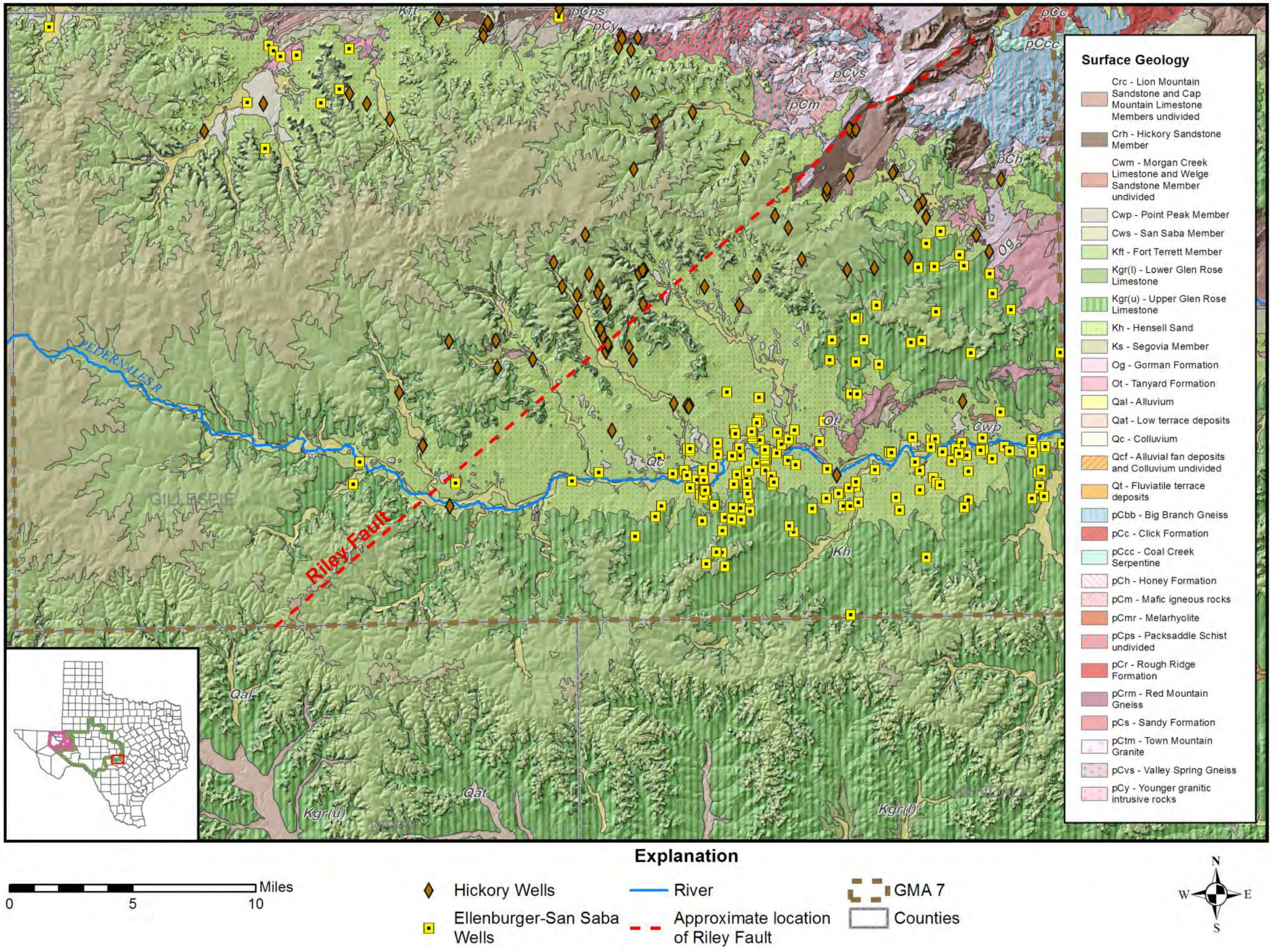


Figure 7-38. **Geologic map of Gillespie County, Texas with the Hickory Aquifer and the Ellenburger-San Saba Aquifer well locations.**

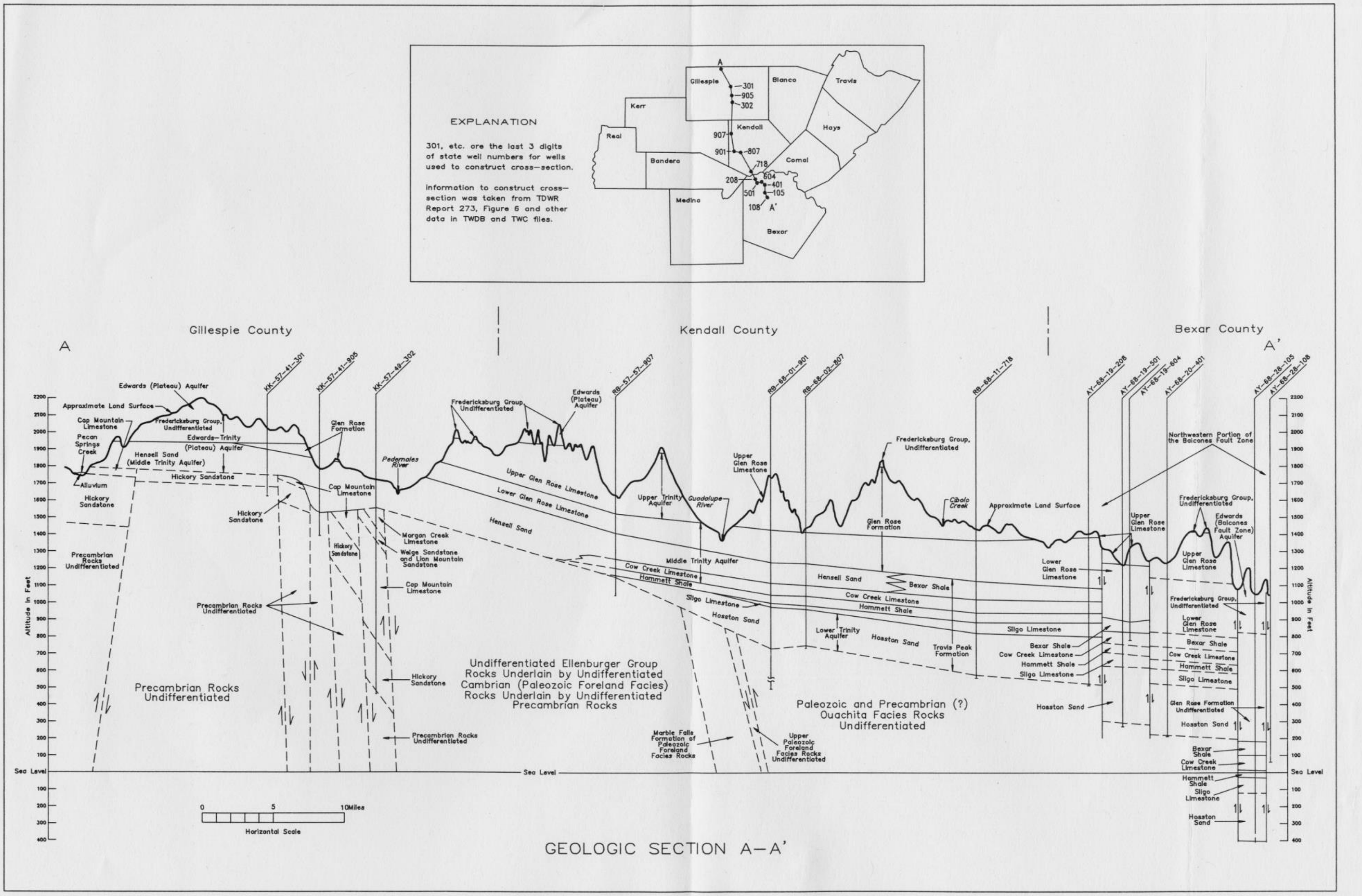


Figure 7-39. Regional geologic cross section A-A' in Gillespie County, (after Bluntzer, 1992).

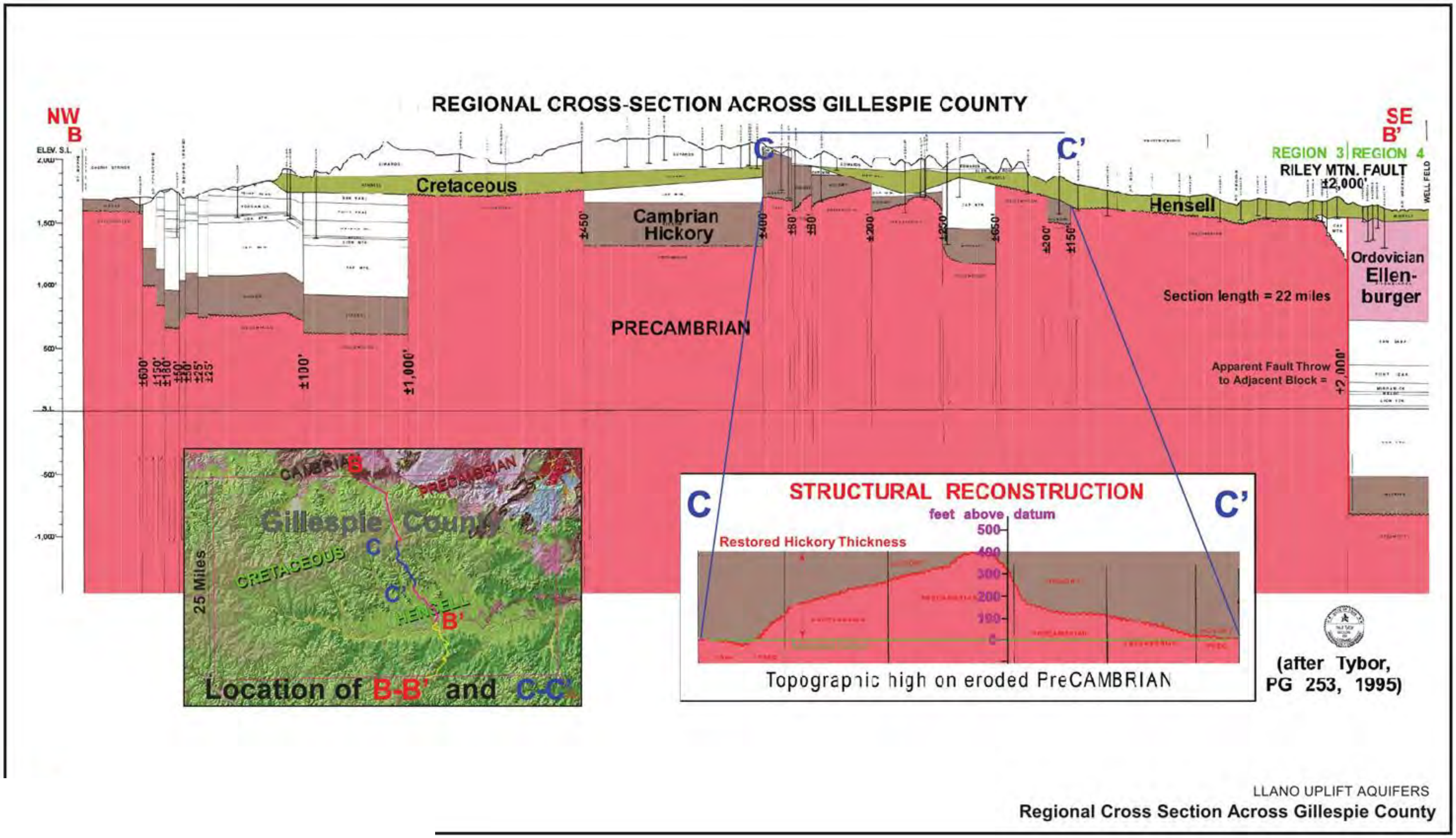


Figure 7-40. Regional geologic cross section B-B' in Gillespie County, (after Standen and Ruggiero, 2007).

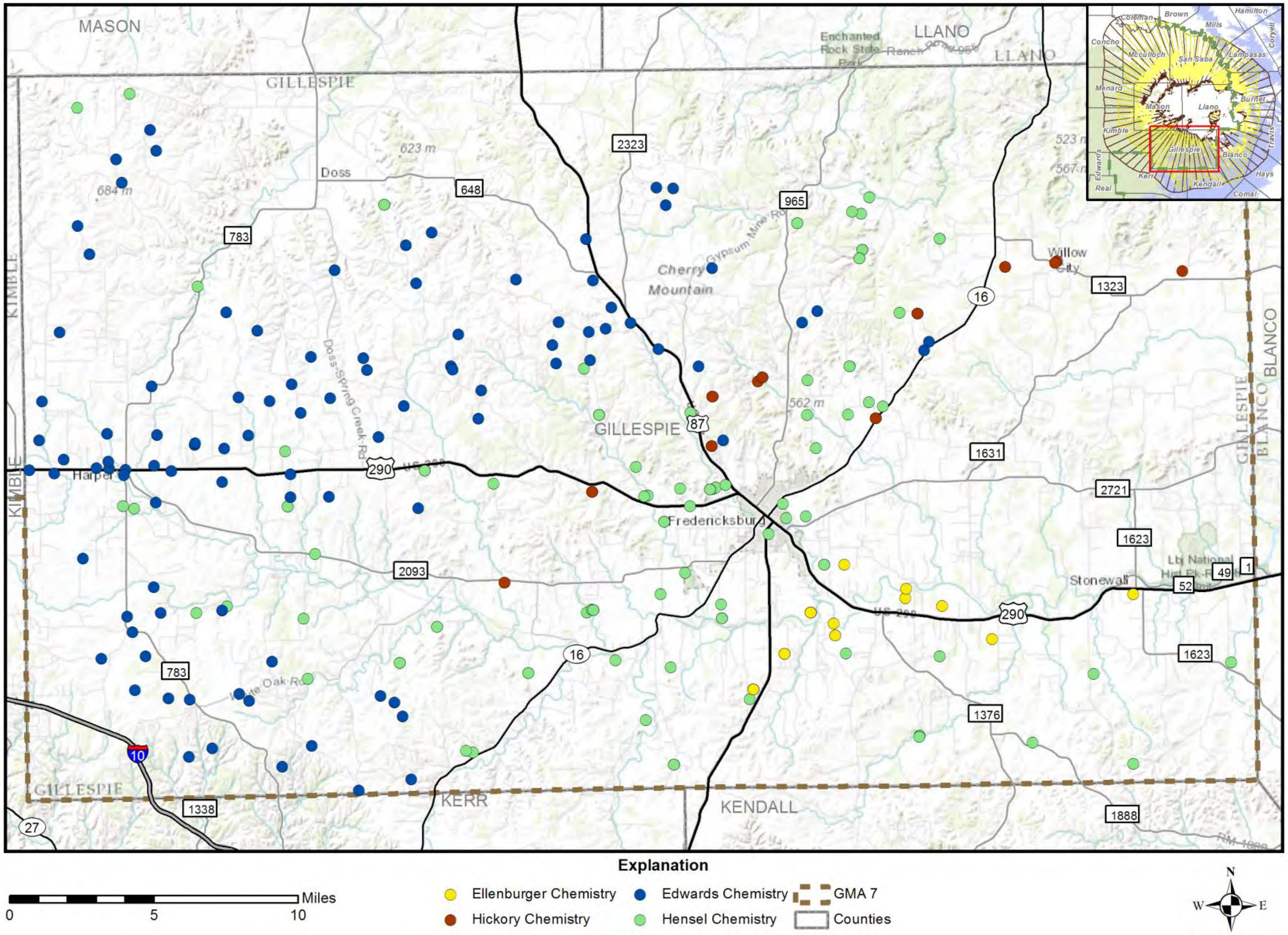


Figure 7-41. Water chemistry data map.

Table 7-3. Gillespie County sampled well data.

Sample No.	GCD No.	State Well No.	Owner	Lattitude	Longitude	Use	Land Surface Elev.	Year drilled	Depth	Casing (blank)	Casing (cement)	Casing (gravel pack)	Casing (slot)	Casing (open hole)	Production rate (gpm)	Static water level	Surface geology	Aquifer
1	R-02055	57-41-808	Lanny Maegden	30-17-18.1	98-55-16.2	Dom	1837	2000	153	0-133	0-50	50-153		133-153	25	110	Hensell	Mosly Hensell production with potential Hickory upward mixing.
2	R-00053	57-49-204	Mark Fikes	30-14-45.8	98-56-07.4	Dom	1742	1989	185	0-52 72-93	0-15	15-91	52-72 93-126	126-185	20	63	Hensell	Mix of Hensell and Hickory.
3	R-00238	57-49-503	Kenneth Hartwein	30-11-55.3	98-55-39.3	Dom	1742	1991	320	0-274 294-314	0-50	50-314	274-294	314-320	22	154	Hensell	Mosly Hensell production with potential Ellenburger upward mixing.
4	PI-00017		Joe Wieser	30-14-57.6	98-49-35.2	Irr		2001	345	0-116	0-50	50-115		116-345	700	108	Hensell	Ellenburger production with 104 feet of Hensell overburden. Static water level at He/Ell contact.
5	GI-00090	57-50-333	Wildseed Farm	30-13-41.0	98-46-11.0	Irr	1538	1995	243	0-52	0-50			52-243	37	38	Hensell	Ellenburger
6	GM-00043	57-51-316	Stonewall WCID #2	30-13-58.7	98-39-31.7	PS	1468	1995	100	0-60	0-60			60-100	60	57	Hensell	Ellenburger
7	GM-00025	57-50-329	City of Fredericksburg Well# 6 (Knauth #6)	30-14-12.9	98-47-26.5	PS	1543	1993	280	0-75				75-280	200	67	Hensell	Ellenburger production with 45 feet of Hensell overburden. Static water level about 10 feet below He/Ell contact.
8	GM-00014	57-50-204	City of Fredericksburg Well# 3 (Hahn #1 prod. well)	30-13-11.8	98-49-58.3	PS	1563	1963	216	0-123				123-216	1500	49	Hensell	Ellenburger production with 123 feet of Hensell overburden. Static water level is well up into the Hensell zone.
9	ER-02608	57-50-901	Clayton Klinksiek	30-09-45.2	98-47-02.4	Dom	1623	1980	288	0-208 268-288	0-13	13-288	208-268		45	141	Glen Rose	Hensell production with potential Ellenburger upward mixing.
10	ER-00775	57-50-514	Jim Wright	30-12-17.5	98-49-33.2	Stock	1705	1975	300	0-225				225-300	30	144	Glen Rose	Hensell production with potential Ellenburger upward mixing.

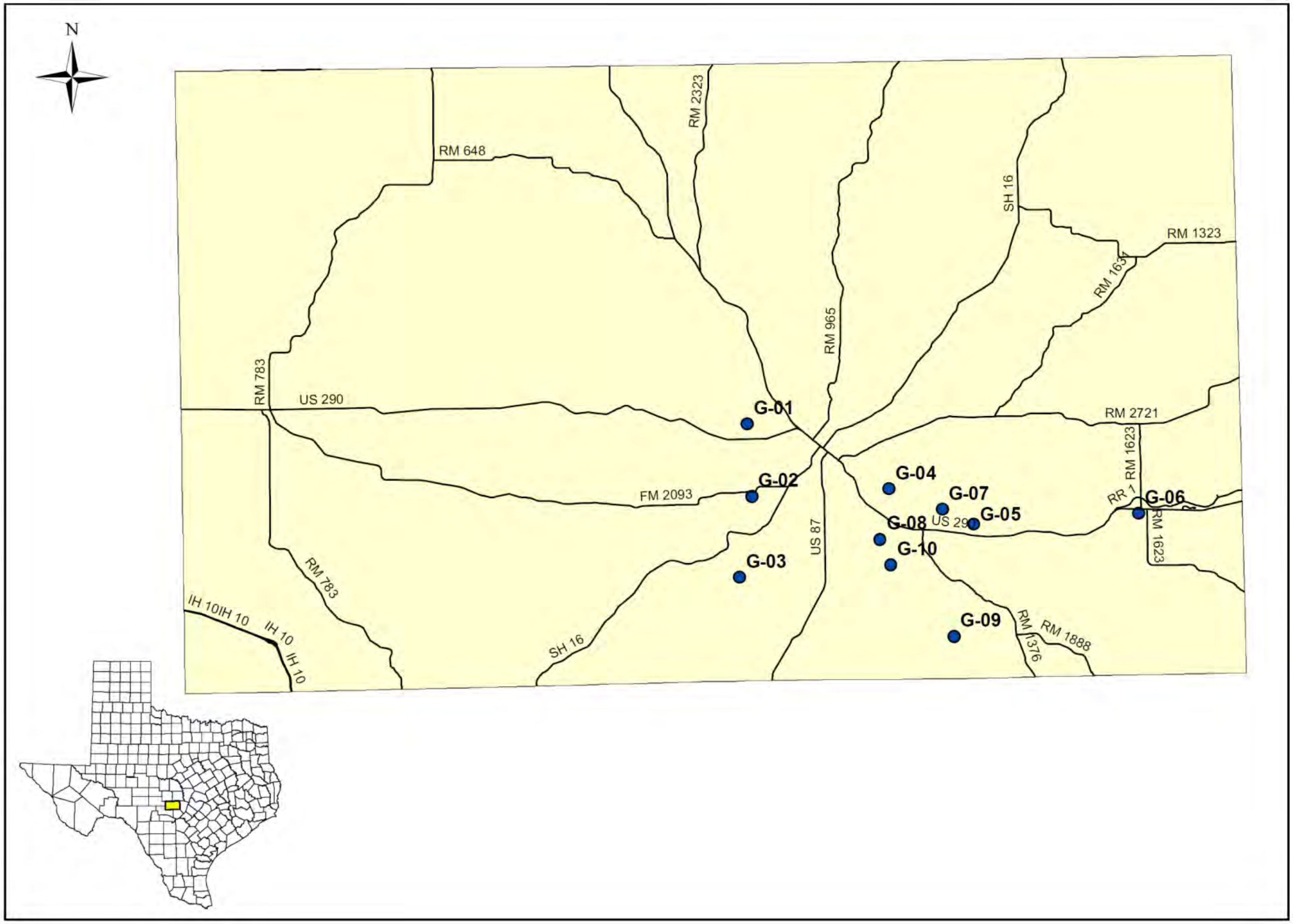


Figure 7-42. Location map for water wells sampled in Gillespie County (2012).

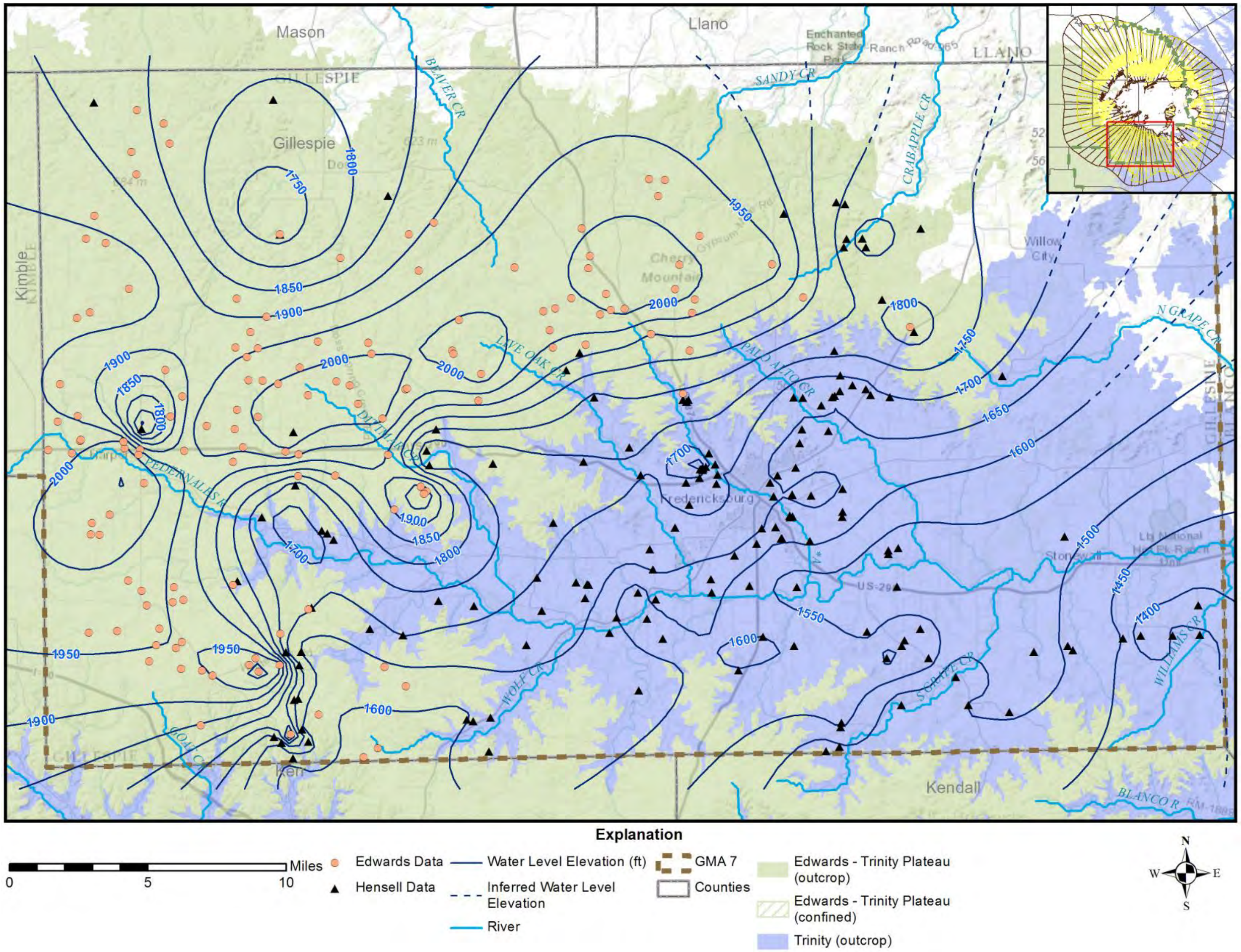


Figure 7-43. Integrated water level map for the Edwards Group and the Hensell Formation (Trinity Group), Gillespie County, Texas (1970-2012).

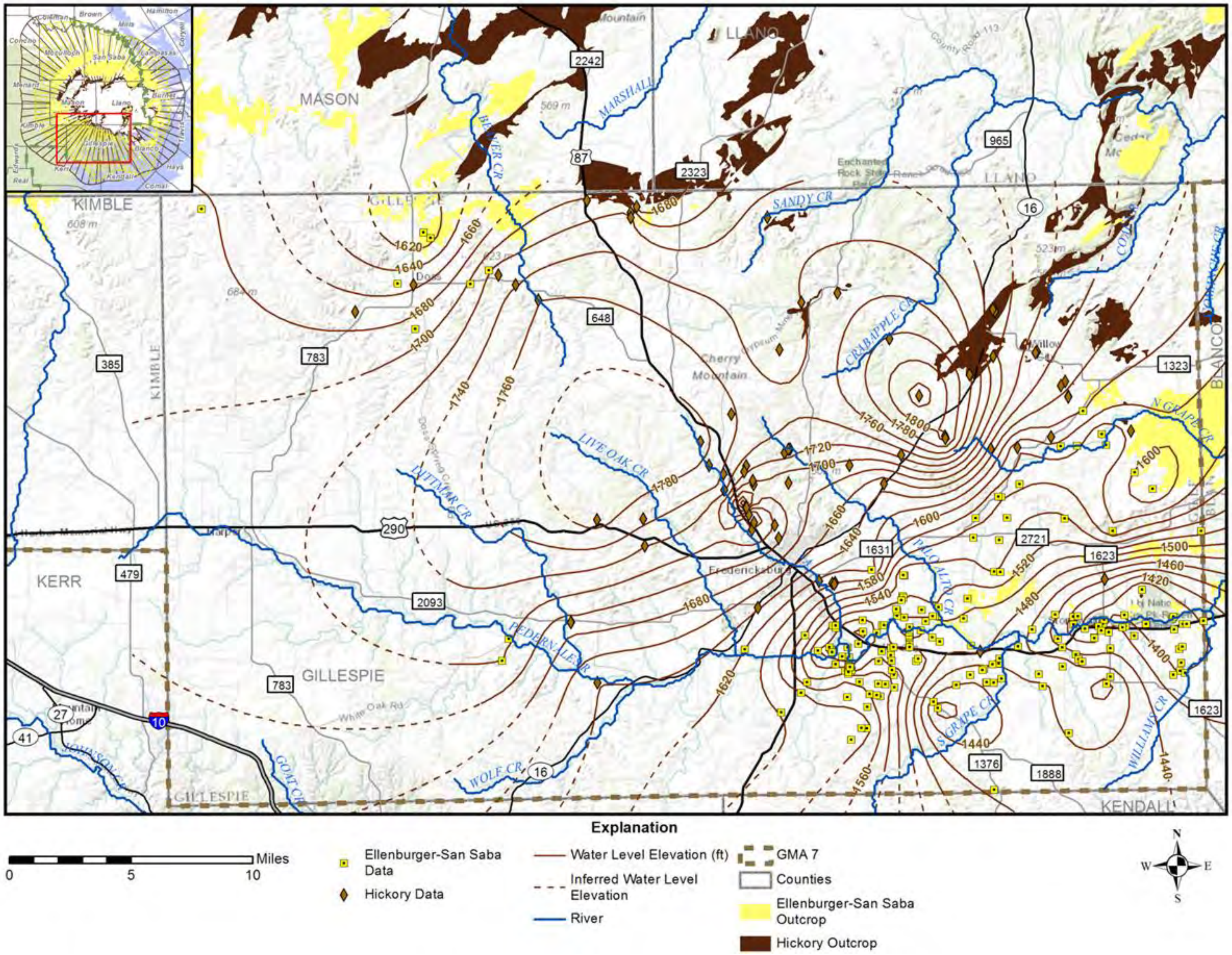


Figure 7-44. Integrated water level map for the Ellenburger-San Saba Aquifer and the Hickory Aquifer, Gillespie County, Texas (1990-2012).

7.3.2 Groundwater Hydrology

South of the Llano Uplift area in Gillespie County, the Ellenburger-San Saba Aquifer and the Hickory Aquifer dip to the south (Figure 7-39) (Bluntzer, 1992). The Ellenburger-San Saba Aquifer and the Hickory Aquifer, however, appear to be in separate grabens in the Precambrian granite and metamorphic rocks (Figure 7-38 and Figure 7-40). The Ellenburger-San Saba Aquifer wells are located primarily in a graben to the east of the Riley Fault (Figure 7-38 and Figure 7-40). Hickory Aquifer wells are located primarily in a graben to the west of the Riley Fault (Figure 7-38 and Figure 7-40). Both the Ellenburger-San Saba Aquifer and Hickory Aquifer outcrop are in north eastern Gillespie County. More importantly the Ellenburger-San Saba Aquifer and Hickory Aquifer subcrop is immediately beneath the Hensell Formation aquifer. The Hensell Formation therefore, may be an important recharge source for the Ellenburger-San Saba Aquifer and the Hickory Aquifer. The Ellenburger-San Saba Aquifer also crop out beneath the Pedernales River and may be an important point of discharge for this flow system.

In both the Hensell Formation and Ellenburger-San Saba Aquifer section of their respective potentiometric surface maps, the contours "v" upstream along the Pedernales River, indicating groundwater discharge to the river (Figure 7-43 and Figure 7-44). Groundwater elevations appear higher in the Hensell Formation than in the Hickory Aquifer or Ellenburger-San Saba Aquifer, indicating a potential for downward flow from the Hensell Formation (Cretaceous) into the Paleozoic aquifers, especially where the Hickory Aquifer and Ellenburger-San Saba Aquifer subcrop immediately beneath the Hensell Formation.

7.3.3 Hydrochemical Results

The Piper diagram for the Hensell Formation (Figure 7-45) indicates a general calcium-magnesium-bicarbonate water with some increasing sodium, chloride and sulfate concentrations (Figure 7-45). Chloride and sulfate increase independent of each other (Figure 7-46) and the increase probably represent independent geochemical processes. Mapping of the two parameters indicate a random occurrence. A plot of chloride versus depth (Figure 7-47) indicates that the high chloride concentrations appear to be more common at shallow depths. Higher nitrate also appear more common at depths less than 200 feet (Figure 7-48). The occurrences of both chloride and nitrate at shallow depths suggest an anthropogenic source and therefore recent recharge.

The Piper diagram for the Ellenburger-San Saba Aquifer (Figure 7-49) shows relatively consistent calcium-magnesium-bicarbonate waters. There are two samples with increased chloride and sulfate; however, they occur at random locations. The inorganic chemistry of the Ellenburger-San Saba Aquifer is similar to the overlying Hensell Formation.

The relationship between radium-226 and radium-228 (Figure 7-50) indicates that activities are low in comparison to the values seen in the Hickory Aquifer (Figure 7-54) in Gillespie County.

The Piper diagram for the Hickory Aquifer (Figure 7-51) indicates a calcium-magnesium-bicarbonate water, similar to the chemistry observed for the Hensell Formation and the Ellenburger-San Saba Aquifer. Figure 7-52 shows the relationship between chloride and carbon-14 percent modern and shows two groupings:

- High carbon-14 percent modern and high chlorine-36 indicating young waters.
- Low chlorine-36 and low carbon-14 percent modern indicating old waters. The locations of the old and young waters are shown on Figure 6-8.

A plot of radium-226 and radium-228 indicates some high values but lower than observed for the Hickory Aquifer in McCulloch County (Figure 7-53).

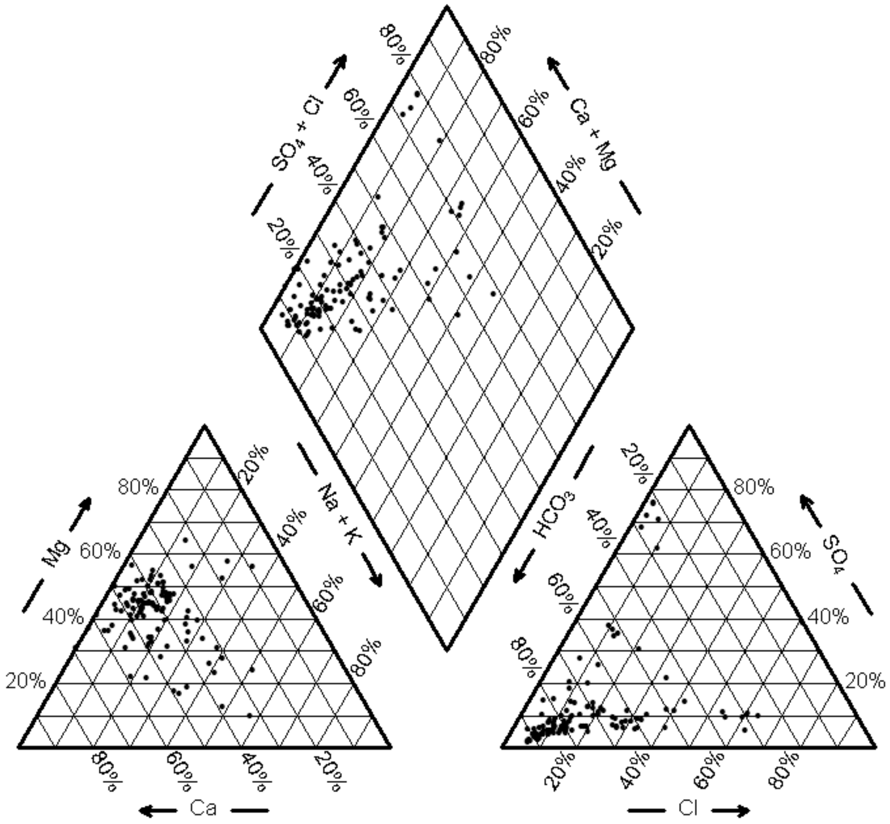


Figure 7-45. Piper diagram for the Hensell Formation, Gillespie County, Texas.

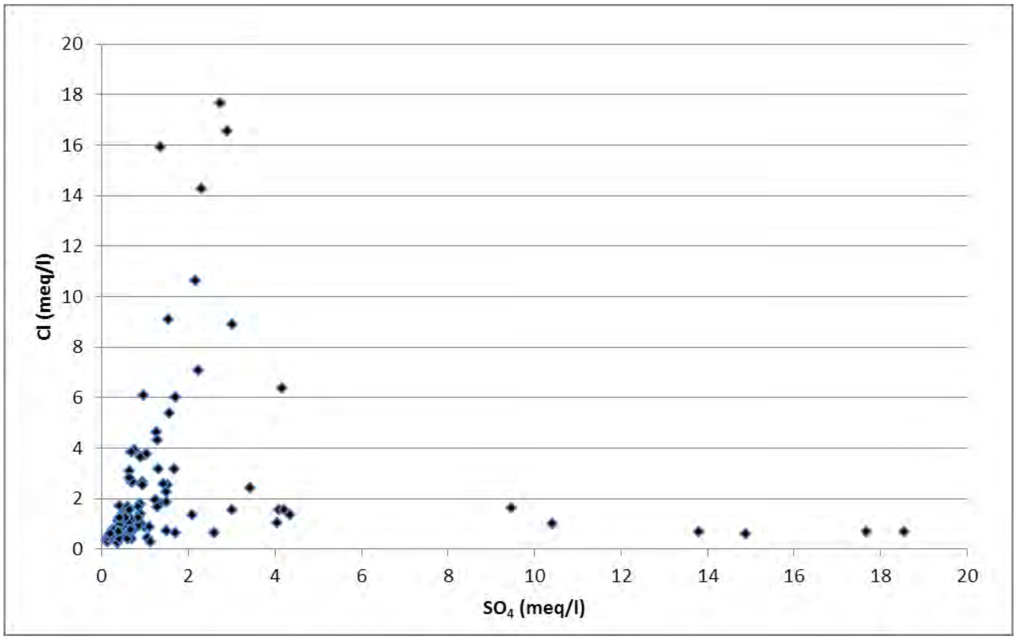


Figure 7-46. Chloride (Cl) vs sulfate (SO_4) for the Hensell Formation, Gillespie County, Texas.

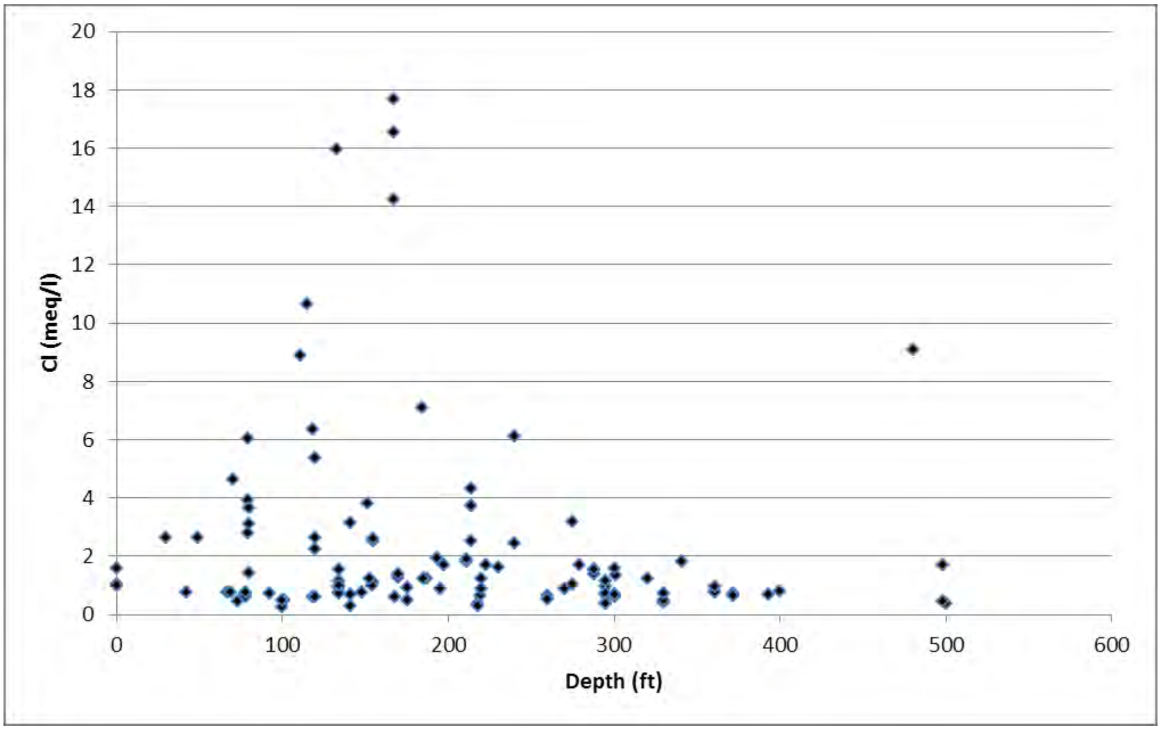


Figure 7-47. Chloride (Cl) vs depth for the Hensell Formation, Gillespie County, Texas.

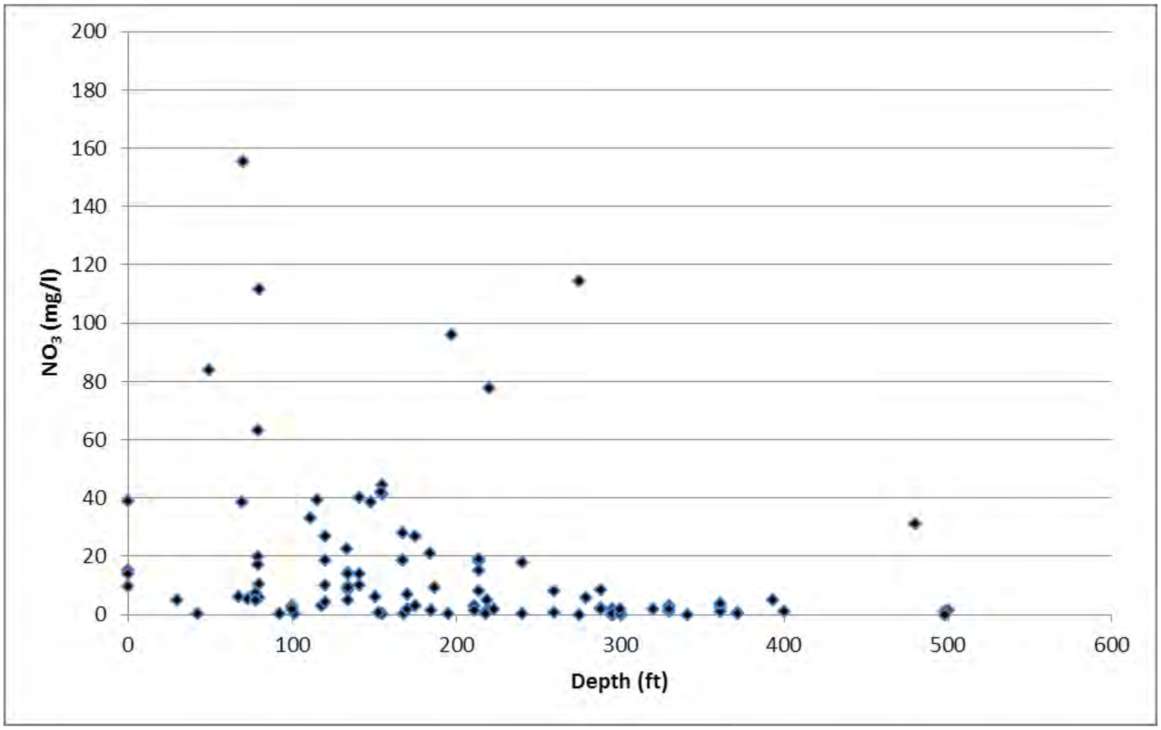


Figure 7-48. Nitrate (NO_3) vs depth for the Hensell Formation, Gillespie County, Texas.

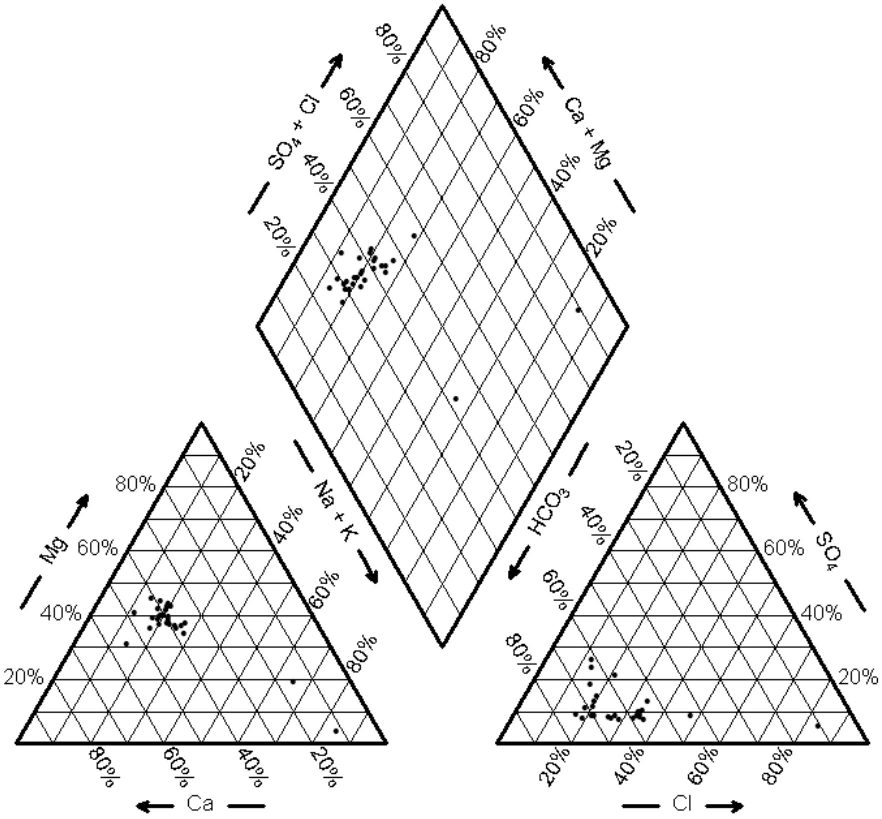


Figure 7-49. Piper diagram for the Ellenburger-San Saba Aquifer, Gillespie County, Texas.

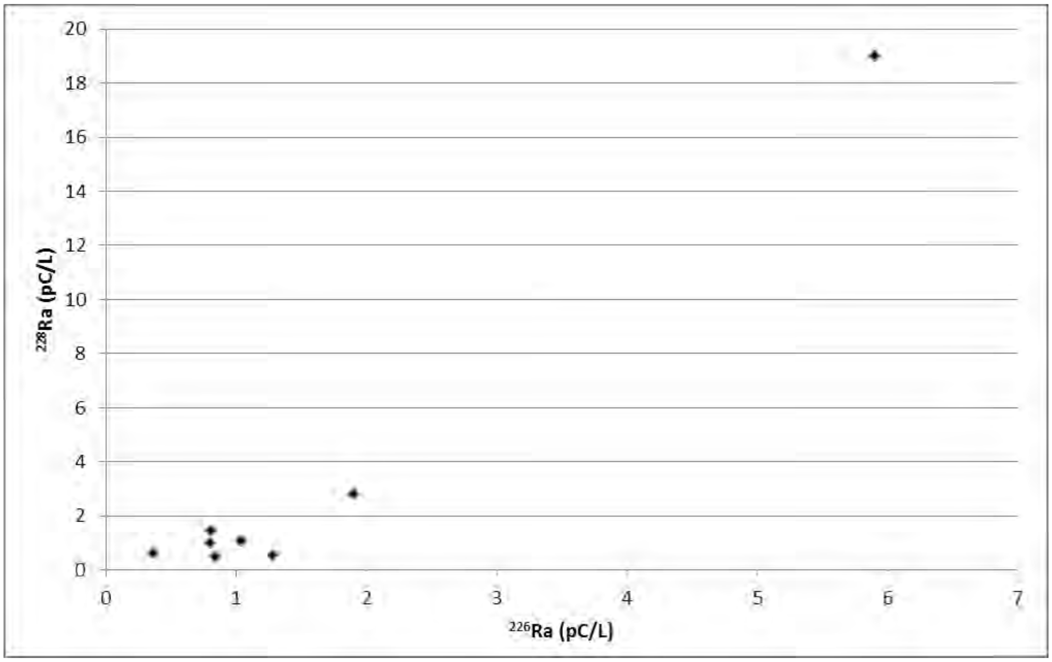


Figure 7-50. Radium-226 (^{226}Ra) vs radium-228 (^{228}Ra) for the Ellenburger-San Saba Aquifer, Gillespie County, Texas.

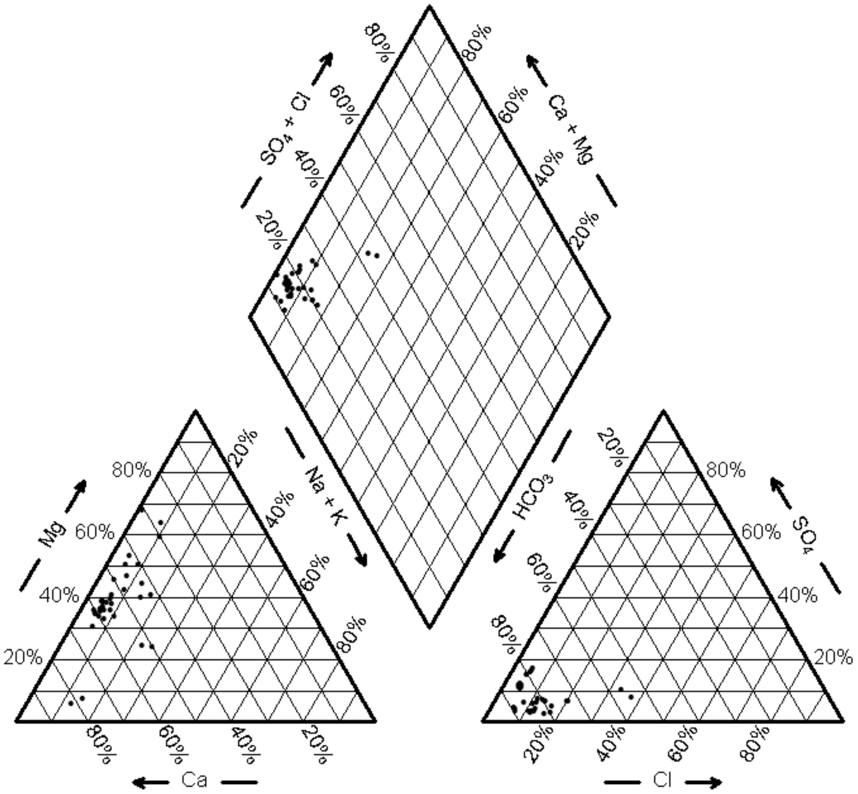


Figure 7-51. Piper diagram for the Hickory Aquifer, Gillespie County, Texas.

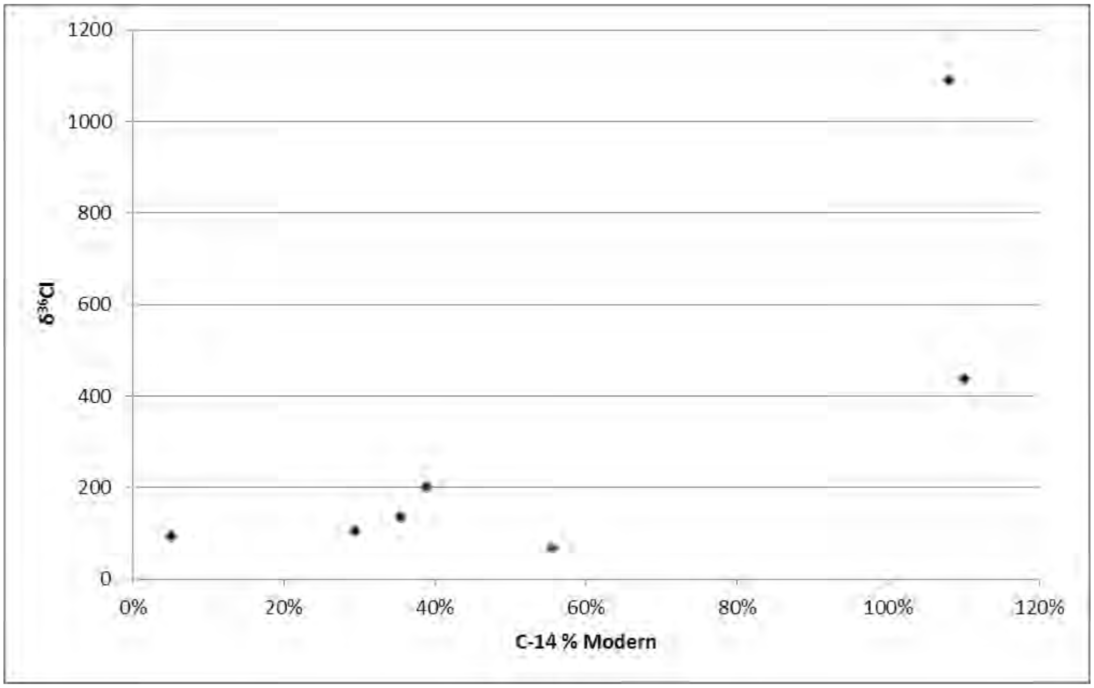


Figure 7-52. Chloride (^{36}Cl) vs carbon-14 percent modern (C-14%) for the Hickory Aquifer, Gillespie County, Texas.

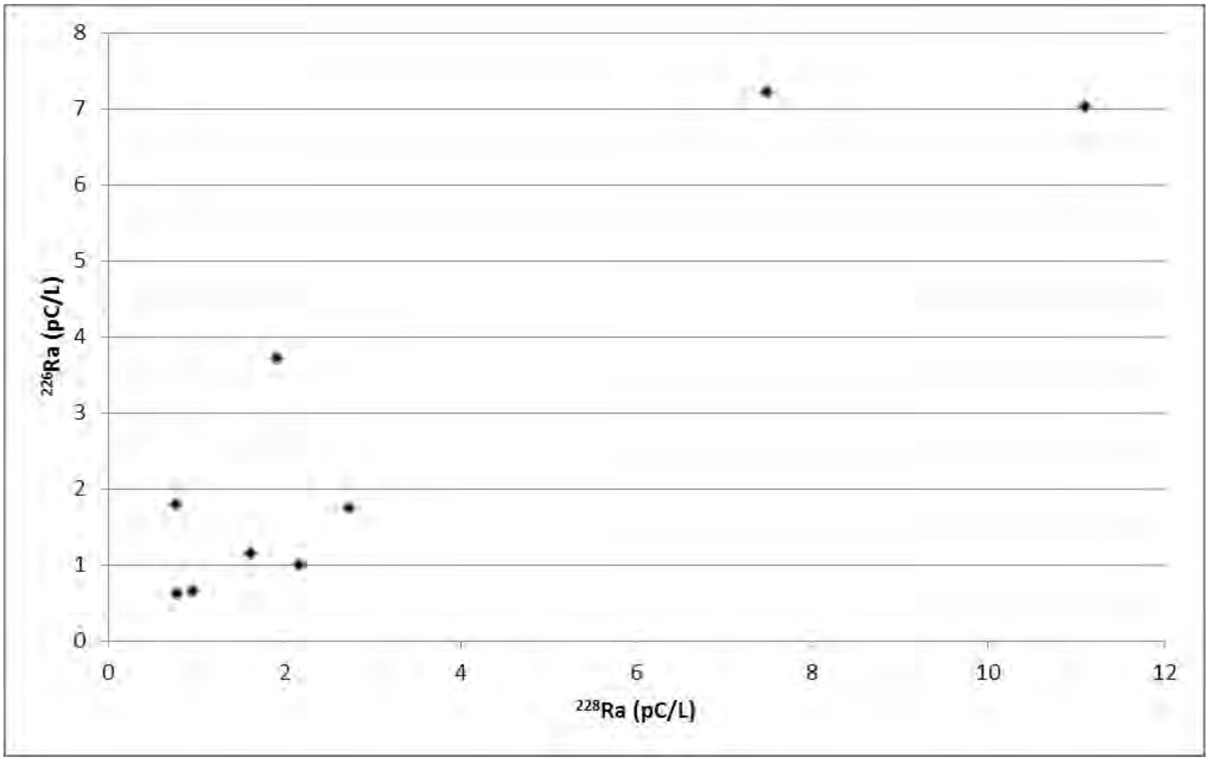


Figure 7-53. **Radium-226 (^{226}Ra) vs radium-228 (^{228}Ra) for the Hickory Aquifer, Gillespie County, Texas.**

7.3.4 Discussion of Results

Located on the southern flank of the Llano Uplift area (Gillespie County) is a groundwater flow system differing from the hydrogeology of the aquifers on the northern flank (Mason and McCulloch counties). Except for the northeast corner, Cretaceous-age Edwards and Trinity formations are exposed at the land surface throughout most of the county. Two higher elevation ridges capped by Edwards Limestone flank the headwater tributaries of the eastward flowing Pedernales River. Closely-spaced water-level contours descending off the flank of these ridges suggest that rainfall recharge entering the Edwards-Trinity outcrop rapidly moves through these formations and exits laterally as springflow into the river and its tributaries. The Pedernales River has eroded through Edwards and Glen Rose limestone formations to expose the Hensell Formation sand throughout most of the wide river floodplain. The Ellenburger-San Saba Aquifer and older units are also exposed in the river bottom near the eastern county border.

There are several late Paleozoic northeast-southwest trending faults that create a complex set of localized flow systems (Figure 7-39 and Figure 7-40). The most prominent of these faults is the Riley Mountain Fault with approximately 2,000 feet of displacement (Figure 7-40) which runs from the northeast corner of the county southwestward passing slightly south and east of the City of Fredericksburg. The Hickory Aquifer strata underlie Cretaceous Edwards-Trinity units on the northwest side of the fault, while Ellenburger-San Saba Aquifer strata directly underlie Edwards-Trinity on the downthrown southeastern side of the fault. Thus, Gillespie County can generally be classified as having two principal aquifer systems, the Edwards/Trinity - Hickory Aquifer to the west and the Edwards/Trinity – Ellenburger-San Saba Aquifer to the east.

The western half of Gillespie County is predominantly rural ranchland and water supplies are mostly sourced from relatively shallow wells completed in the Edwards-Trinity (Plateau) Aquifer, while a few deeper wells completed in the underlying Hickory Aquifer have low to medium yields. The Cap Mountain Limestone locally separates the Hickory Aquifer from the overlying Trinity Hensell Formation, which may permit only a small percent of the Trinity Group subsurface flow to migrate downward into the underlying Hickory. Hickory Aquifer water-level contours (Figure 7-44) demonstrate a generally southeasterly flow path through the county, although separate down-faulted blocks (grabens) may isolate Hickory Aquifer groundwater flow within the bounding fault.

Water-level elevation contours in the eastern half of the county "v" upstream, suggesting that the Cretaceous-Paleozoic aquifer system generally drains to the river (Figure 7-43 and Figure 7-44). The Piper diagram for the Hensell Formation, the Ellenburger-San Saba Aquifer and the Hickory Aquifer in Gillespie County are predominantly calcium-magnesium-bicarbonate waters (Figure 7-45, Figure 7-49 and Figure 7-51). From the major ion chemistry there is no obvious evidence of a chemical evolution along a flow path nor is there evidence of leakage from one aquifer to another. Each aquifer has a predominant chemistry of calcium-magnesium-bicarbonate.

The radiocarbon data in the TWDB database for the Ellenburger-San Saba Aquifer in Gillespie County consisted of only one well (5750102); consequently additional wells were sampled as part of this project. As is the case for the Hickory Aquifer, the TWDB water sample has an uncorrected carbon-14 value of 1630 years before present, but also contains tritium (1.54 TU) and δ^{36}Cl x 10^{15} of 208; these measurements are incompatible for a water from a single source and again must represent a mixed source groundwater.

Five additional samples were collected from the Ellenburger-San Saba Aquifer. Sample locations with carbon-14 values are shown on Figure 7-54. The carbon-14 samples shown range in apparent age from 300 to 9,440 years before present and the δ^{13}C values cover a narrow range of from -14.2 ‰ to -17.9 ‰. This could indicate that little reaction with carbonate minerals has occurred and thus the corrections to the carbon-14 age because of carbon transfer are not large; however, there are competing reactions that could be occurring such as oxidation of organic material and gains and losses of carbon dioxide that also affect the δ^{13}C value of dissolved inorganic carbon which cannot be evaluated. In the Ellenburger-San Saba Aquifer, no geochemical evolution of the water chemistry is evident, which makes it difficult to predict the amount of dead carbon that may be altering the carbon-14 activity. To use this approach for geochemical modeling requires a more detailed understanding of both the geochemistry and the flow dynamics of the aquifer. Availability of data may limit this type of interpretation. For the Ellenburger-San Saba Aquifer in Gillespie County, the Hill Country Underground Water District provided us access to the available wells. A more detailed study of the hydrogeology of a region is needed to provide basic groundwater hydrology for a region. The potentiometric surface (Figure 7-44) is complicated at these well locations along the Highway 290 corridor as the result of pumping; and because the samples are not aligned along a flow path, the evolution of water composition and the carbon accounting by reaction along the pathway cannot be done at present. A rigorous interpretation of the groundwater age with a corrected carbon-14 value that more represents a precise groundwater age for the Ellenburger-San Saba Aquifer has not been done.

The elevated carbon-14 percent modern values in the Ellenburger-San Saba Aquifer suggest, however, that these groundwaters are young (Figure 7-54). Their apparent young age may indicate leakage from the overlying Hensell Formation for several of the wells. The Ellenburger-

San Saba Aquifer functions as a local small hydrologic system rather than a large regional flow system.

The lower carbon-14 percent modern and lower chlorine-36 values for the Hickory Aquifer may indicate that these waters are older and isolated from active recharge. In general, the Hickory Aquifer wells in the northeast, where the Hickory Aquifer crops out have higher carbon-14 percent modern than the Hickory Aquifer wells to the southwest (Figure 7-54). The following comments are made on the eight carbon-14 measurements, tritium and chlorine-36 made on Hickory Aquifer samples.

The carbon-14 measurements of eight samples from the Hickory Aquifer in Gillespie County were available from the TWDB database. These uncorrected or apparent ages range from: 1) the two youngest which are modern meaning the ages are similar to the carbon-14 that was present in an National Bureau of Standards (NBS) standard from 1950, to 2) the oldest which is 23,920 years before present. A measurement of a modern date implies either that 100% of the sample is recently recharged, or alternatively, it may indicate the groundwater is a mixture of sources that includes older groundwater. If it is a mixture, most of the sample would be have been recently recharged containing carbon-14 from the era of atmospheric nuclear testing that created elevated carbon-14 beginning in the early 1950s. In either circumstance, the groundwater with a modern age is generally predominantly recent recharge. The remaining six samples have measured ages of at least 4,710 years before present or older.

The corresponding stable carbon ($\delta^{13}C$) isotopic value for each of these eight samples ranges from -15.1‰ to -6.9 ‰ respectively. A graph of the measured carbon-14 percent modern value of DIC in groundwater versus the $\delta^{13}C$ ‰ (Figure 7-55), yields a linear plot indicating the stable carbon isotopic value in the groundwater is changing toward the isotopic signature of the large reservoir of $\delta^{13}C$ in the aquifer matrix. The $\delta^{13}C$ of the limestone facies or carbonate cement in the Hickory Aquifer is not known for this area; but in general marine carbonate and carbonate cement should be close to 0 ‰. The Cambrian age carbonates like the Hickory Aquifer are known to have had large positive excursions of $\delta^{13}C$ from -1 ‰ to +5 ‰ (Saltzman and others, 2000) which is different enough from the groundwater composition to alter the total $\delta^{13}C$ of groundwater DIC as reaction with carbonates proceeds along the flow path. The two "modern" samples have DIC $\delta^{13}C$ values of -15.1 ‰ and -11.7 ‰ which changes in the samples progressively to a final measured $\delta^{13}C$ value of -6.9 ‰. This addition of more enriched $\delta^{13}C$ from the aquifer matrix into solution, is derived from carbonate without any remaining carbon-14, thus the net effect is to increase the DIC, enrich the $\delta^{13}C$, and proportionally decrease the percentage of carbon-14 in the dissolved inorganic carbon giving the appearance of an older age.

These eight wells with carbon-14 measurements are not aligned along a flow path, but rather are essentially along equipotential lines, so each sample has its own flowpath from the recharge location to the sampled well. This lack of data along a specific flowpath prevents assessment of carbon-14 changes from recharge nor does it provide information about reactions along the flow pathway. In addition, of the eight sample locations, all but one are complicated further by additional recharge from nearby Hickory Aquifer exposures away from the Llano Uplift area which would also be a source of additional modern carbon-14 yielding a mixed groundwater along a flow path already isolated and significantly down gradient from its initial recharge area.

The potentiometric surface as defined in Figure 7-44 does not indicate a direct flowpath from the assumed primary recharge at the Hickory Aquifer outcrop to any of the eight wells in the TWDB database. Without a defined flowpath from recharge to a sampled well, the accounting for carbon gain or loss to the DIC cannot be rigorously done; consequently a correction of the measured carbon-14 apparent age cannot be adjusted to a corrected age. Alternatively, by comparison to the corrections computed for the Hickory Aquifer in Mason and McCulloch counties it is reasonable to assume that the corrections to carbon-14 ages in Gillespie County will be somewhat similar. There the adjusted ages are at least 10 % younger than the measured ages. This is a smaller correction than that often observed in other regional aquifers (Busby and others, 1991; Plummer and Sprinkle, 2001) of coastal plain aquifers (Chappelle and McMahon, 1991); and this can be attributed to the minimal sources of carbon in the Hickory Aquifer.

Most carbonate is present only in the upper part of the Hickory Aquifer; however limestone is described as grayish in sections with glauconite, typically found in reducing environments indicating that some of the carbonate is probably siderite ($FeCO_3$) but no analytical work could have been easily done, when the section was described by Paige (1912).

The two samples in Gillespie County with modern carbon-14 also contain measurable tritium, which is consistent with very young water. Three other samples have measured tritium, but also have an older $^{14}C_{OBS}$, which implies they are comprised of mixed water sources, one component of which is young enough to contain modern water. This is incompatible with an interpretation of an age for groundwater of several thousand years without relying on a mixing scenario. The sample with the lowest % (23,920 years before present) has no detectable tritium, and also measures the most enriched $\delta^{13}C$ of -6.9 ‰; these data are consistent among all isotope values implying a long flow path or long reaction time in which tritium has decayed away, carbon-14 has decayed and additional carbon has been acquired from the limestone or carbonate after significant reaction. These data indicate a range of water ages that are young, old and mixed age composite waters. The flowpath and distance of travel cannot be defined, and thus the ages are not defined, and only relative ages result.

There are seven samples of chlorine-36 for the Hickory Aquifer in Gillespie County that range from 68 to 1088 $\delta^{36}Cl \times 10^{15}$. The two modern carbon-14 samples also have recent chlorine-36 which is consistent with young groundwater. Three chlorine-36 samples could be considered old, but within the range of carbon-14 measurements, and two that are clearly mixed samples.

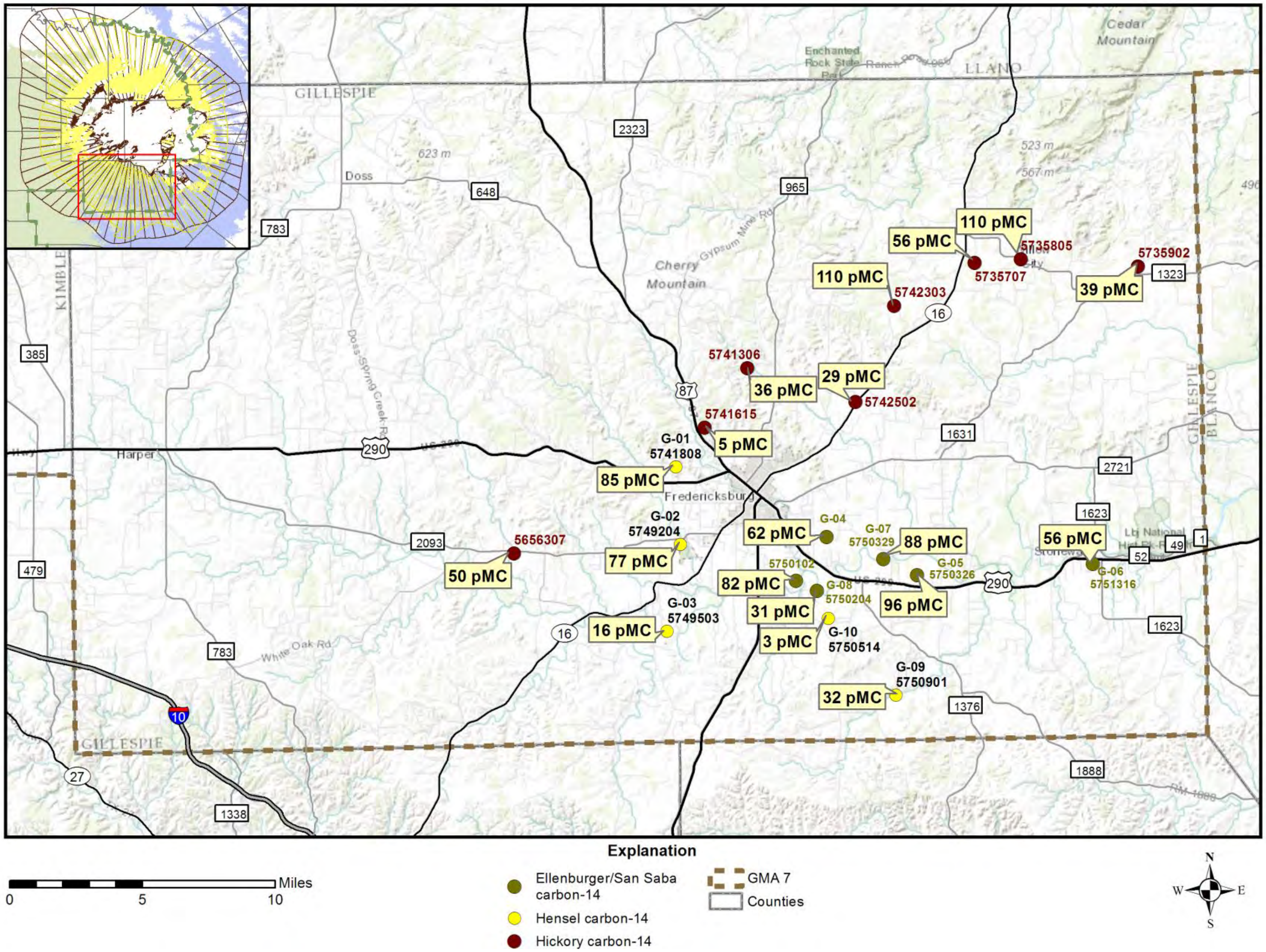


Figure 7-54. Carbon-14 percent modern for the Hensell Formation, Ellenburger-San Saba Aquifer and the Hickory Aquifer, Gillespie County, Texas.

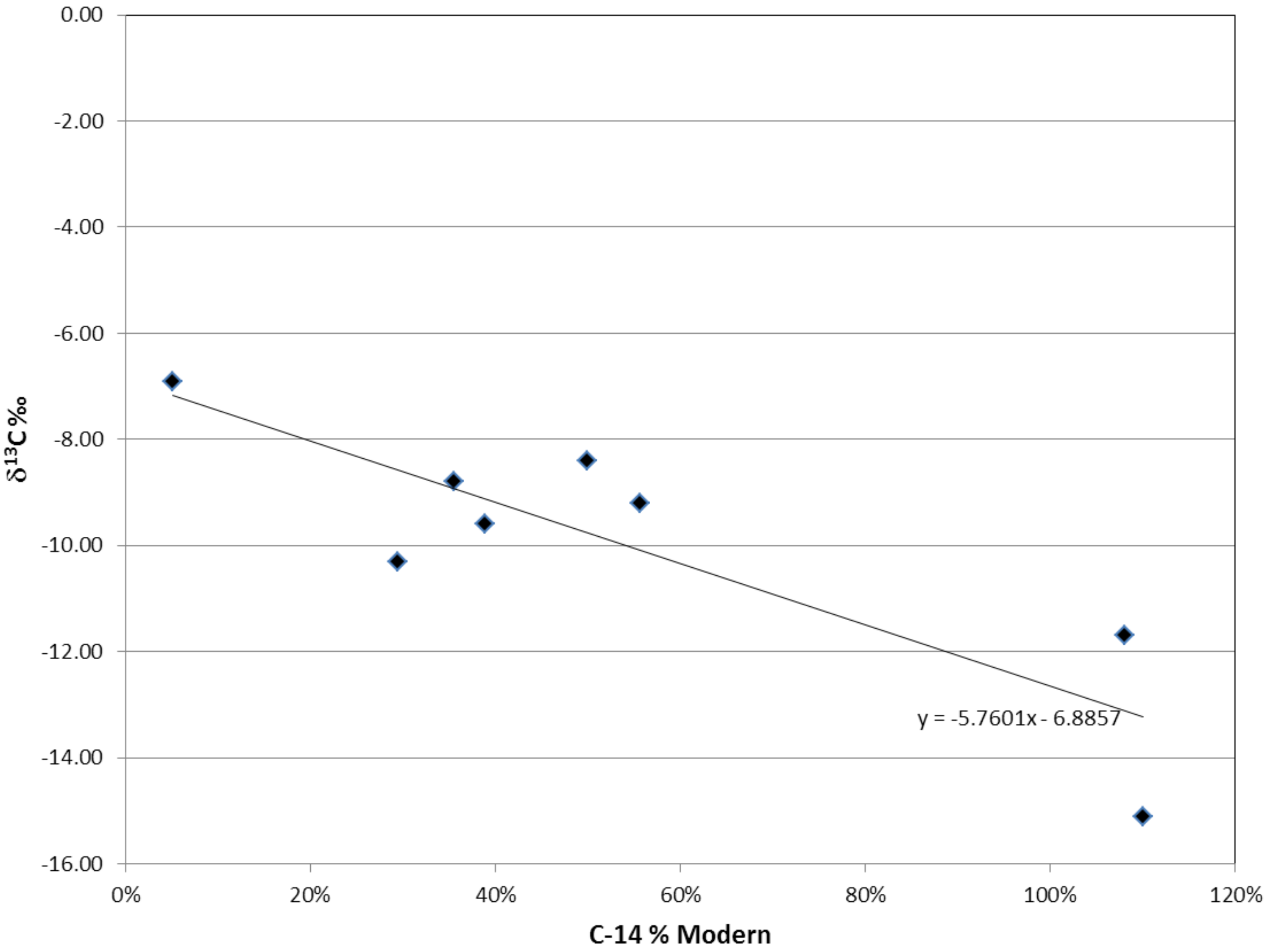


Figure 7-55. **Carbon-14 (C-14%) vs δ^{13}C for the Hickory Aquifer, Gillespie County, Texas.**

7.4 Eastern Sub-Region (Burnet County)

7.4.1 Data Reviewed

Geologic interpretations are based on the Texas Bureau of Economic Geology Geologic Atlas of Texas Llano sheet (1981). Water well locations, well depth and water level data are from TWDB groundwater database.

Chemistry data from Ellenburger-San Saba Aquifer in Burnet County, Texas (east of the Llano Uplift area) represent data from Ellenburger-San Saba Aquifer wells in the outcrops to as far downdip as available (Figure 7-56). Data are from the TWDB groundwater database plus Ellenburger-San Saba Aquifer samples collected in 2012. New samples were collected with help and direction of Mitchell Sodek, Central Texas Groundwater Conservation District. Figure 7-57 shows location of newly collected data. Table 7-4 provides well information for these samples. Most groundwater data for the Paleozoic aquifers in Burnet County is from the Ellenburger-San Saba Aquifer with a limited amount from the Hickory Aquifer. Data are available for the Cretaceous Hensell Formation and the Travis Peak, but these wells are located in eastern Burnet County. Because of the thick Pennsylvanian Smithwick Formation, the Cretaceous aquifers in Burnet County are not considered to be in hydrologic communication with the Ellenburger-San Saba Aquifer and therefore were not studied for this investigation.

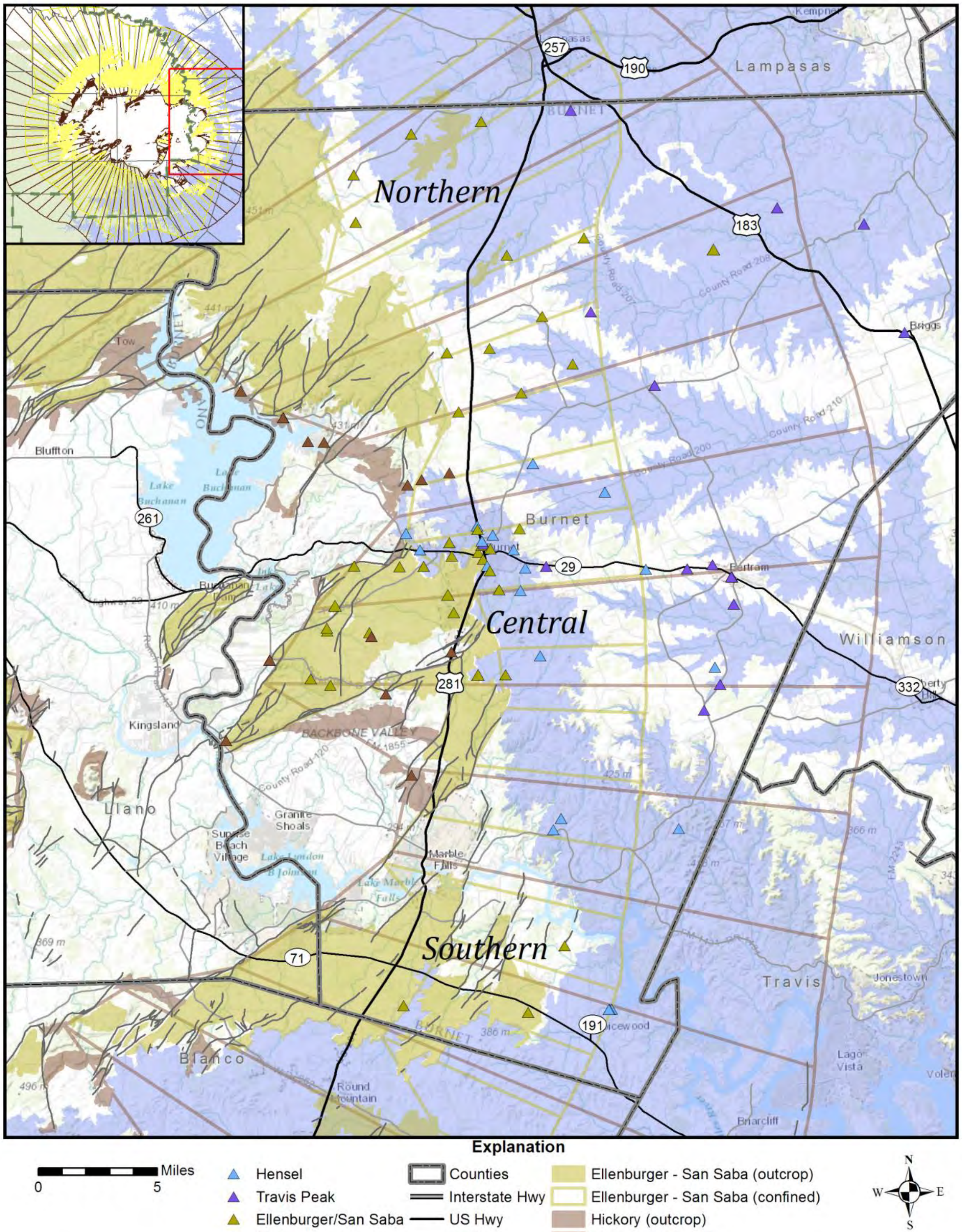


Figure 7-56. **Burnet County water quality well locations.**

Table 7-4. **Burnet County sampled well data.**

Sample No.	State Well No.	Owner	Latitude	Longitude	Use	Land Surface El.	Year drilled	Depth	Casing (blank)	Casing (open hole)	Static water level	Surface geology	Aquifer	Geophysical log avialable
1 and 2		Gurley Ellenburger	30 56 29	98 03 47		1130	2012	1285	0 - 344	344 - 1285	Flowing	Edwards	Ellenburger	Y, 1065'
3	57-22-106	FM 3509	30 43 42.75	98 20 4.95		1295					254	Welge SS.	Ellenburger	N
4	57-22-306	Oak Vista	30 44 2.88	98 15 17.25		1284		90			47	Welge SS.	Ellenburger	N
5		Simmons Irrigation Well	30 41 6.55	98 14 3.63	Irr.							Trinity - Hensel	Ellenburger	

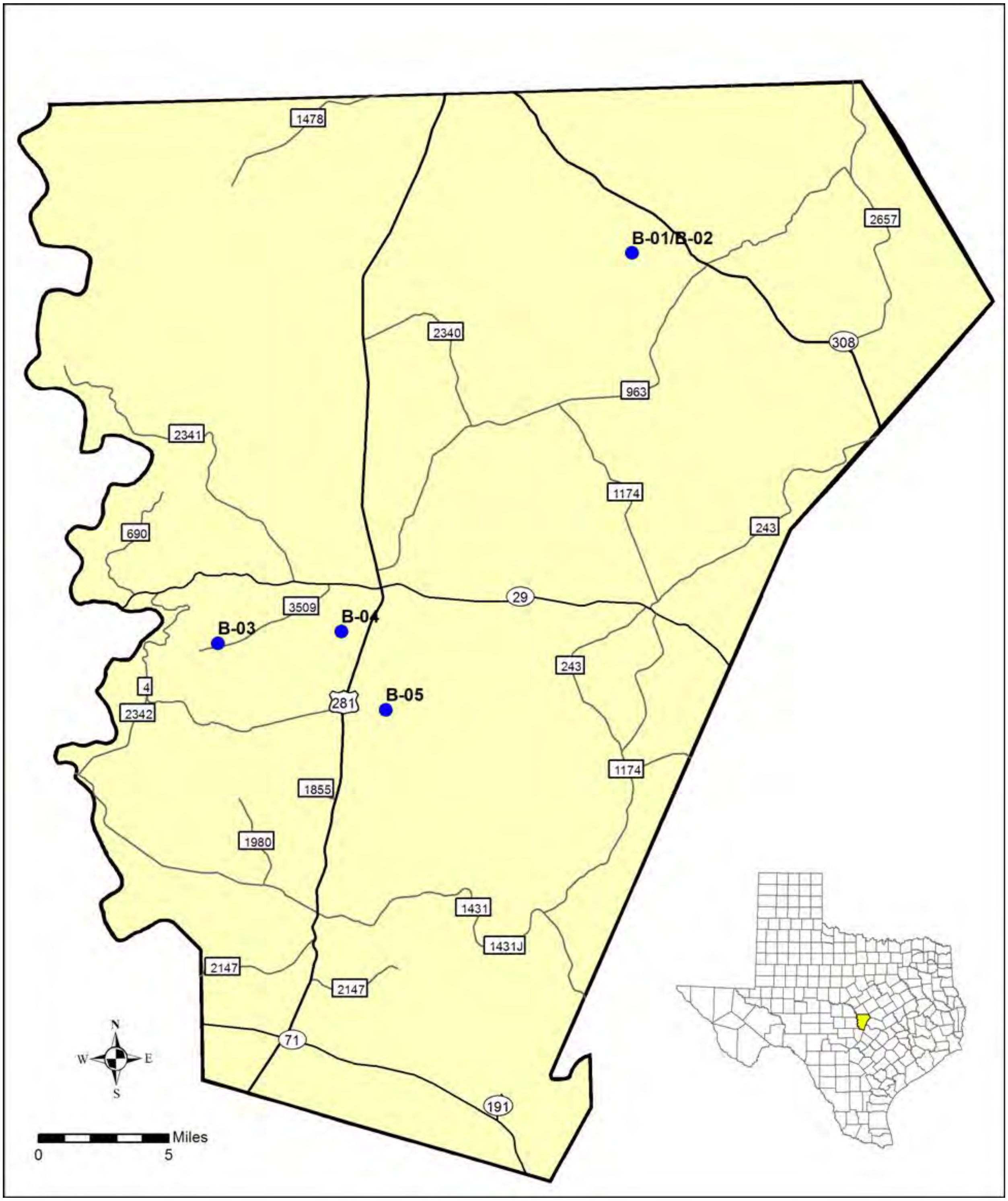


Figure 7-57. Location of wells sampled in 2012 for this study, Burnet County.

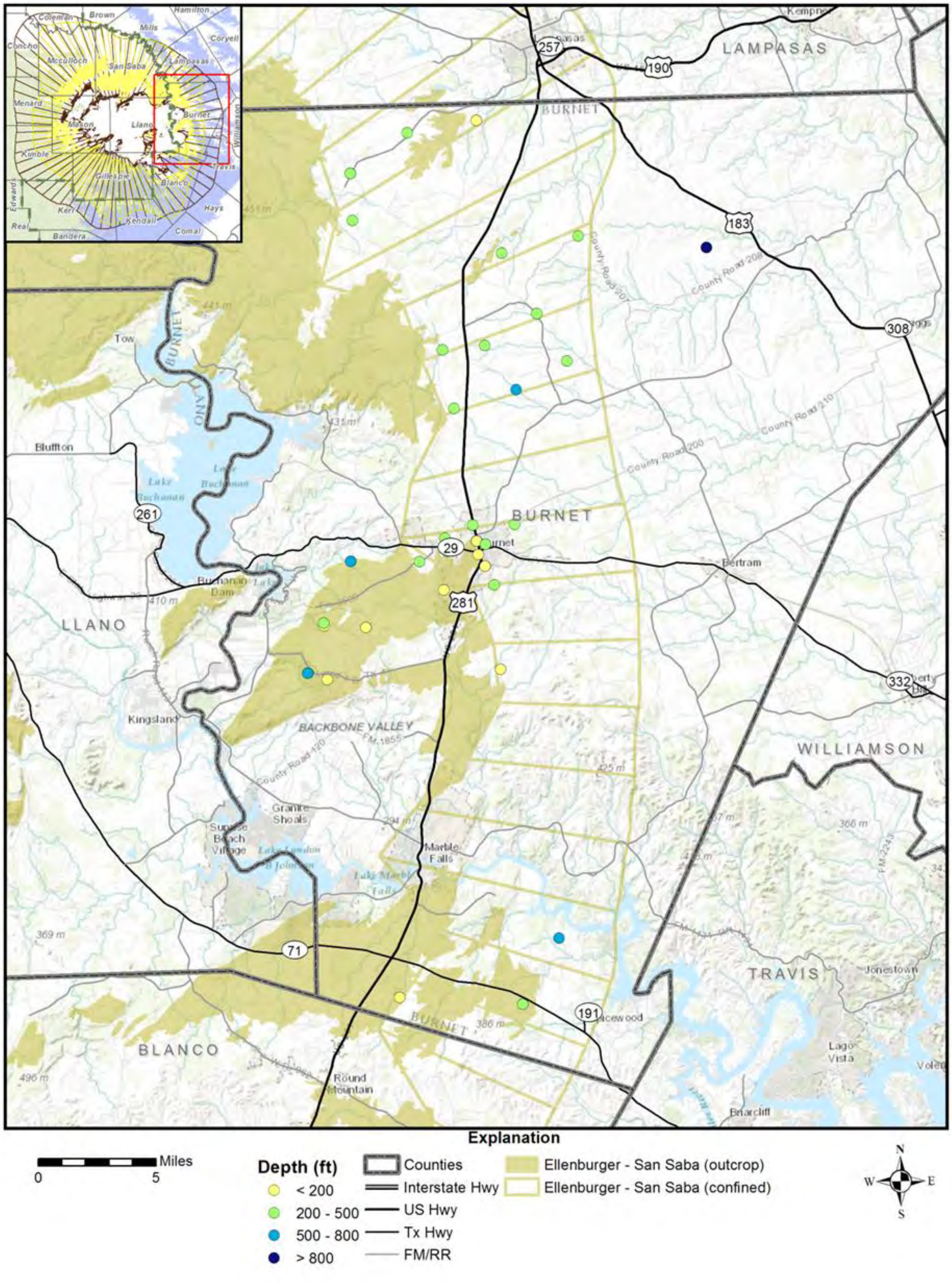


Figure 7-58. **Well depths for the Ellenburger-San Saba Aquifer, Burnet County,**

7.4.2 Hydrogeologic, Chemical and Isotopic Results

The Burnet County area was selected for hydrochemical evaluation to complete the review of the Paleozoic aquifers surrounding the Llano Uplift area. Previous sections of this report reviewed the hydrogeology of the Paleozoic aquifers northwest of the uplift in Mason and McCulloch counties, and the Paleozoic aquifer south of the Llano Uplift area in Gillespie County. Burnet County was selected to represent hydrogeology on the east side of the uplift. Data were reviewed for the Hickory Aquifer in Burnett County, but the availability of wells in the Hickory Aquifer was very limited. The Central Texas GCD recommended we focus on the Ellenburger and provided us access to Ellenburger wells.

Burnet County occupies the eastern edge of the Llano Uplift area with generally eastward dipping Paleozoic rocks, which are exposed at the surface on the western side of the county. Northeast-southwest trending faults have uplifted and exposed Precambrian non water-bearing zones that have hydrologically separated three sections of the Ellenburger-San Saba Aquifer. These are referred to in this report as the northern section in northern Burnet County, the central section (the City of Burnet region), and the southern section (south of the City of Marble Falls) and are considered as three separate sections of the Ellenburger-San Saba Aquifer, and therefore three hydrologically separate sub-aquifers (Figure 7-57).

The northern aquifer section located north of the town of Burnet contains a large area of Ellenburger formation outcrop, and a lesser amount of Hickory Aquifer exposed along the eastern and northern shoreline of Lake Buchanan. East of the Paleozoic outcrop, the Ellenburger-formation dips eastward into the subsurface and is separated from overlying Edwards-Trinity (Plateau) units by Pennsylvanian non water-bearing formations. An approximate three-mile wide corridor of Precambrian metamorphic rocks (Valley Spring Gneiss and Packsaddle Schist) separates the northern aquifer section from a middle aquifer section.

A southern Paleozoic aquifer section is separated from the middle section by a four- to seven-mile corridor of Town Mountain Granite to the west and non-water bearing Pennsylvanian units to the east. This section is mostly the Ellenburger-San Saba Aquifer outcrop with some Marble Falls Limestone in the northeastern part.

Water wells associated with the Paleozoic formations are located primarily in these three Ellenburger-San Saba Aquifer sub-aquifers and primarily in the outcrops, except for the northern section. Well depths are generally less than 800 feet though there is one well in northeastern Burnet County that has depth of 1,285 feet (Figure 7-58).

In the southern Ellenburger-San Saba Aquifer section water wells are primarily in the outcrop. In the middle Ellenburger-San Saba Aquifer section all wells are either in the outcrop or just downdip where the highest density of wells is near the city of Burnet. In the northern Ellenburger-San Saba Aquifer section wells are located along eastern edge of the outcrop or downdip, but not in outcrop area. Most of the wells are downdip from this outcrop area.

Figure 7-59 shows the potentiometric surface in this portion of the study area. In the southern section groundwater flows south to north towards the Colorado River, which appears as a primary discharge zone. There are no wells downdip, which possibly suggests there is no usable groundwater downdip. In the middle section there is a potentiometric high in the outcrop area. Groundwater flow is primarily to the east and south towards Hamilton Creek and the Colorado River. Hamilton Creek and the Colorado River may be the primary zones of discharge for this middle section. The lack of wells downdip from the outcrop suggests no usable groundwater is available because the groundwater discharges to Hamilton Creek and Colorado River. The lack of downdip wells in the southern and middle areas may also be caused by a lack of drilling to the deeper Ellenburger. Water may have been available in shallower horizons. It is interesting to note, however, that more downdip wells occur in the northern region. In the northern section there is a groundwater mound along eastern edge of the outcrop with some flow possibly west toward Lake Buchanan and Colorado River. Groundwater flows may be primarily east into the confined section. Most wells are located east of outcrop area. Groundwater flow in this northern section may be to Sulfur Creek and associated springs in the City of Lampasas. If discharge is through springs such as Hannah Springs and Hancock Springs it would explain why most of the groundwater production is in the confined part of the aquifer. In the case of the middle and southernmost geographic areas in Burnet County, possible pumping in the well south of the Colorado River may be a major discharge point.

Figure 7-56 shows the location hydrochemical data for the area. In the southern Ellenburger-San Saba Aquifer section there is limited data with only three data points. Most importantly, there are no downdip wells. In the middle Ellenburger-San Saba Aquifer section all water chemistry data is in the outcrop or slightly downdip. In the northern Ellenburger-San Saba Aquifer section, in contrast to the middle and southern sections, all well locations and water chemistry data are in the downdip confined section of the Ellenburger-San Saba Aquifer.

Figure 7-60 shows the Piper diagram for the Ellenburger-San Saba Aquifer. Data for the Piper diagrams is separated for the southern, the middle, and the northern and downdip well B-1. Most of the data are from the middle and northern sections of the aquifer. Most of the cation data appear in a zone between the calcium and magnesium corners of the cation triangle. From this calcium-magnesium line, sodium has been added. The increased sodium occurs in the outcrop in the middle aquifer section. In the anion triangle of the Piper diagram, the majority of the data are in the bicarbonate corner. The addition of chloride and sulfate in the Piper diagram has occurred in the outcrop in the middle aquifer section. A chloride and sulfate source has been added. In the diamond portion of the Piper diagram, data extend from the calcium-bicarbonate towards a sodium-chloride-sulfate corner. Increases in relative percentages of chloride, sulfate, and sodium occur primarily in the outcrop of the middle section aquifer.

Figure 7-61 shows the sodium versus chloride relationship. Sodium is increasing linearly with chloride. The addition of sodium and chloride may be as a possible surface contaminant. Figure 7-62 shows the depth versus total dissolved solids relationship and indicates that the higher total dissolved solid generally occurs for shallower wells less than 200 ft. Well B-1, which is greater than 1200 feet deep, has the highest total dissolved solid. Figure 7-63 and Figure 7-64 compare depth and chloride. The higher chloride concentrations generally occur in the shallower wells less than 200 feet deep and in the vicinity of the City of Burnet. The deepest well B-1 has the highest chloride concentrations. Figure 7-65 shows depth vs. sulfate. The higher sulfate concentrations are generally for wells shallower than about 200 ft. Figure 7-66 and Figure 7-67 show depth vs. nitrate. The shallowest wells have the highest nitrate. Most of these wells are in the City of Burnet region. The higher nitrate and chloride may be related to septic tank effluent in the City of Burnet area. The relationship between radium-226 and radium-228 is shown in Figure 7-68 and Figure 7-69. Radium-226 activities are higher than radium-228 with much higher activities of radium-226 than observed in other Ellenburger-San Saba Aquifer groundwater samples. The well with the highest radium-226 (B-1) also has the highest chloride, and the highest strontium isotopic compositions ratio. B-1 is from deeper confined sections in the northern section of the Ellenburger-San Saba Aquifer at depth (greater than 1,000 feet). This suggests either mixing with upward migrating from unidentified saline formation "brine" or from the underlying Hickory Aquifer.

The laboratory results for dissolved gases can be found in the Appendix. All the dissolved gases in the Burnet County region have the atmospheric ratio of nitrogen to oxygen (≈ 80%/20%). This is also true for the Ellenburger-San Saba Aquifer wells sampled in 2012 in Gillespie County where all wells have a relative gas ratio similar to atmospheric). Well B-1, however, had an oxygen content that was depleted relative to nitrogen. This well also contains dissolved methane. Figure 7-70 plots carbon-14 percent modern versus depth. All well samples less than 200 feet deep have higher carbon-14 percent modern (greater than 50%). Only the deepest Ellenburger-San Saba Aquifer well in northeast Burnet, well B-1, has a very low carbon-14 percent modern. The "shallower" waters are considered to be recently recharged. The deepest well is considered to be older water.

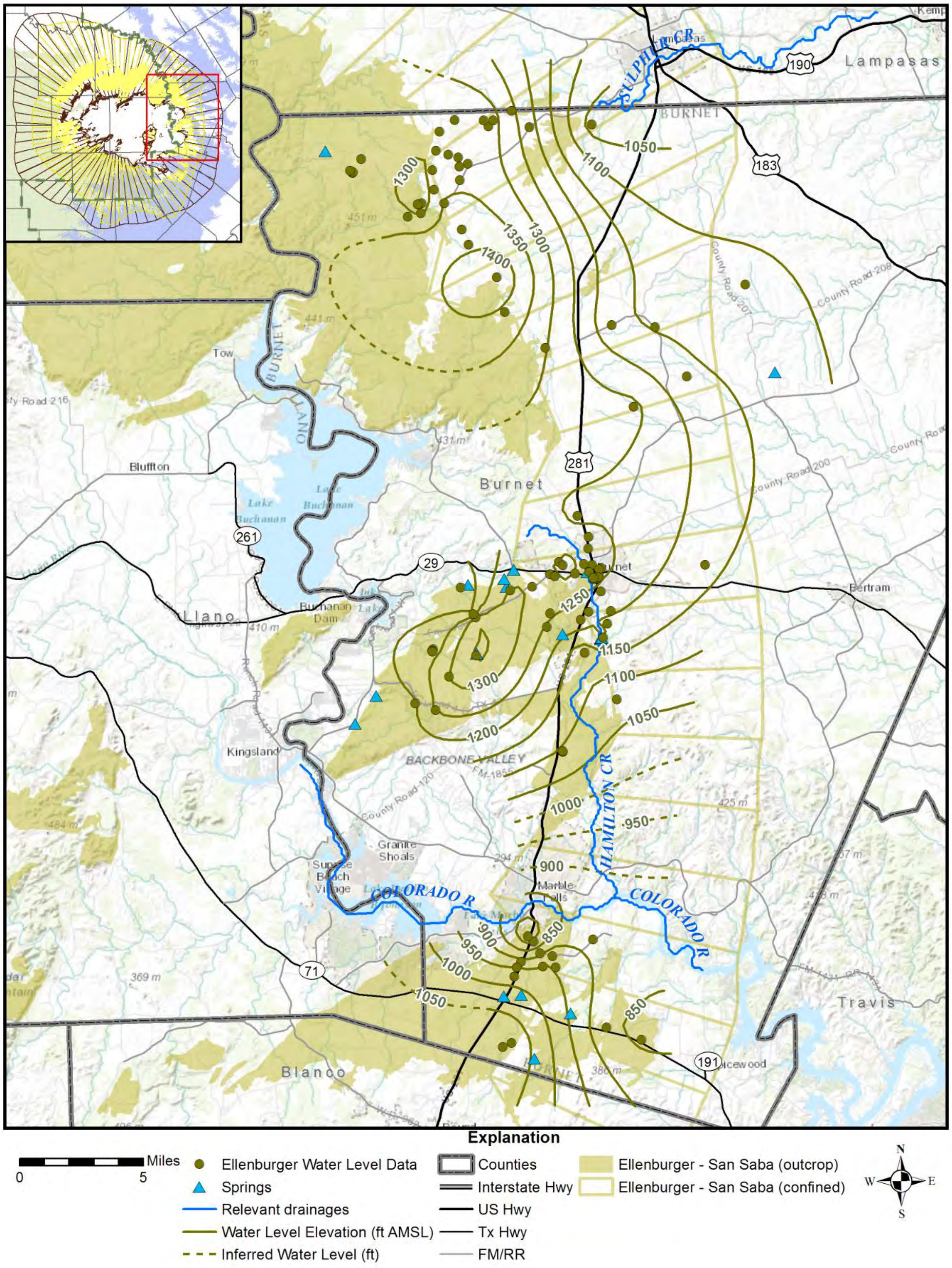


Figure 7-59. Water level map for the Ellenburger-San Saba Aquifer, Burnet County (2005-2011).

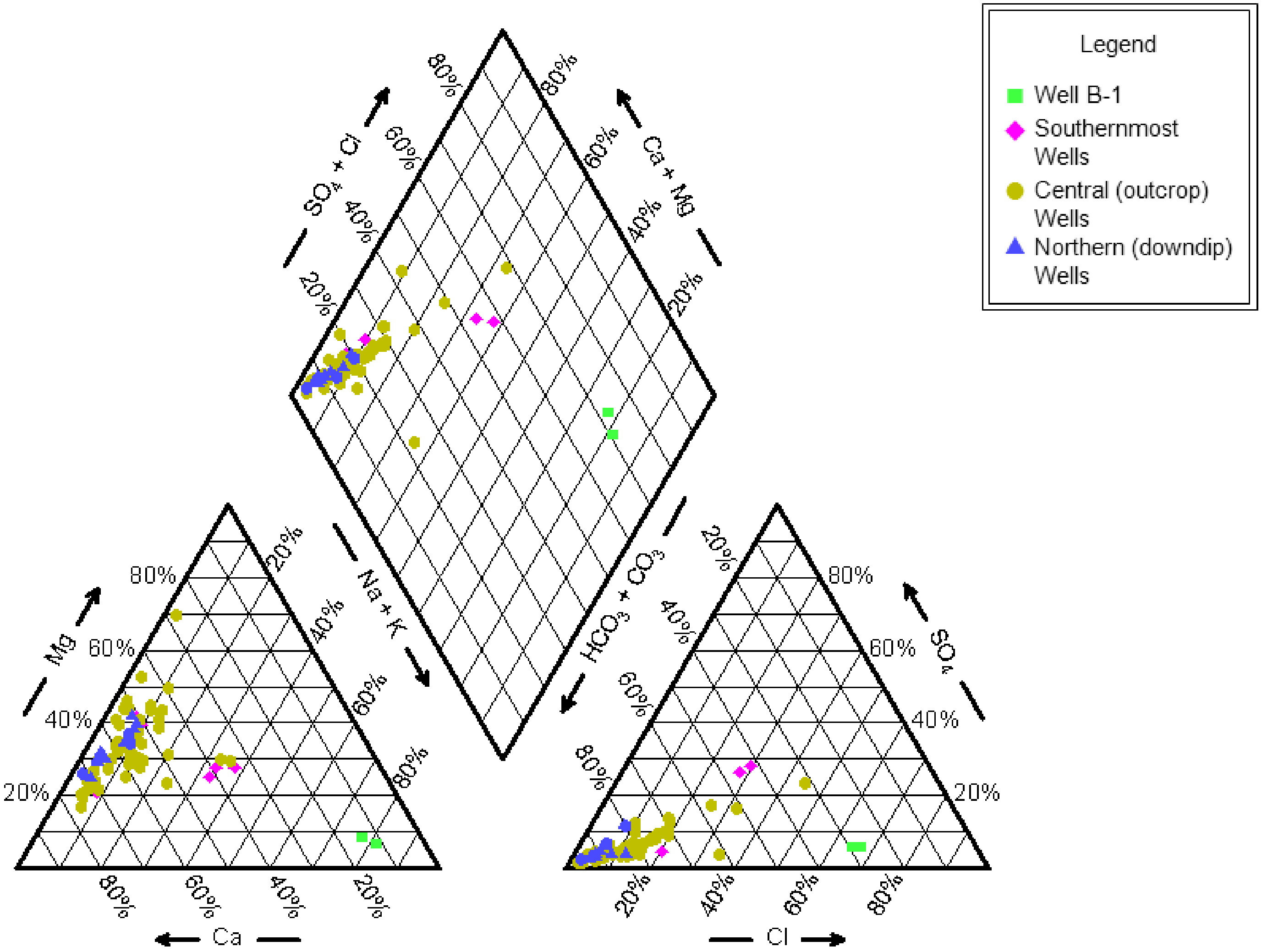


Figure 7-60. **Piper diagram for the Ellenburger-San Saba Aquifer, Burnet County, Texas.**

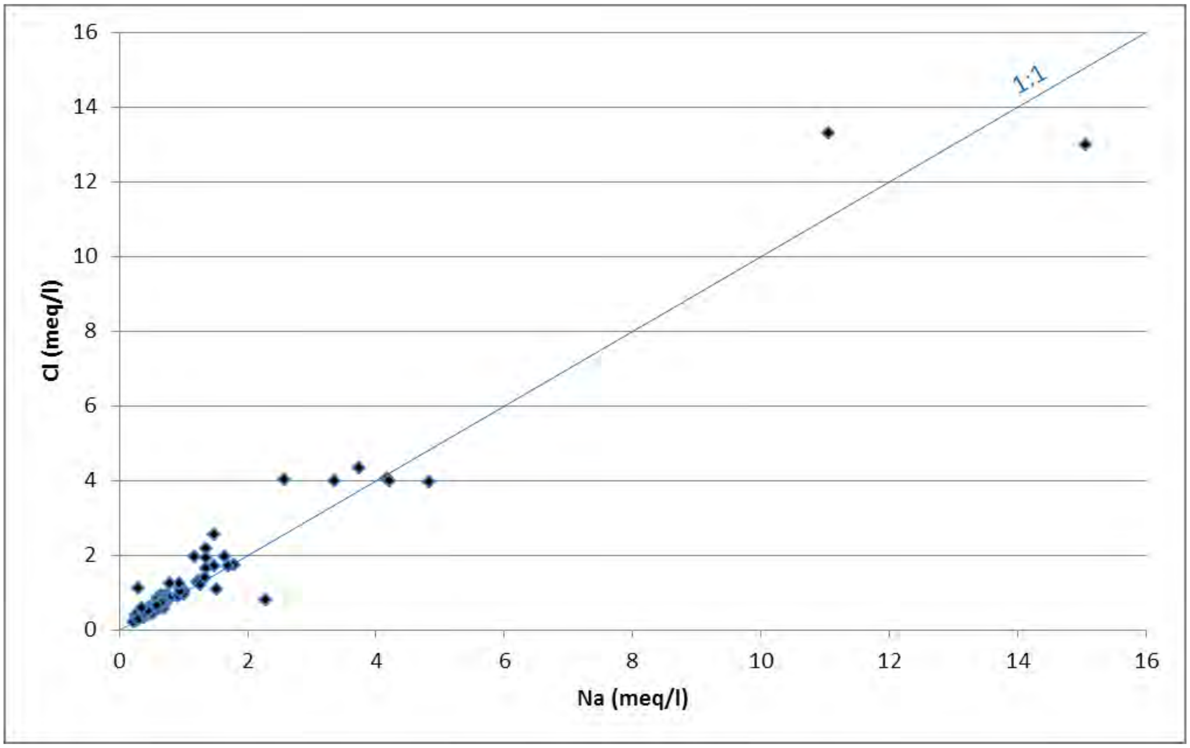


Figure 7-61. Sodium (Na) vs chloride (Cl) for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

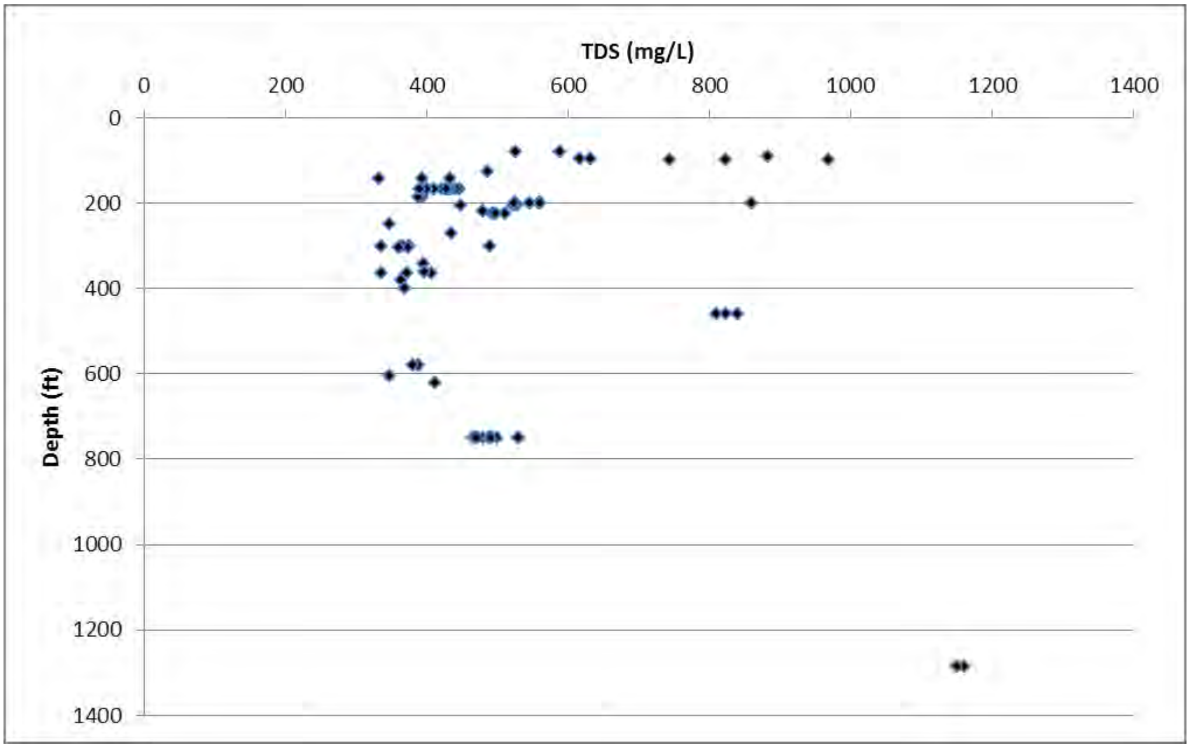


Figure 7-62. Depth vs total dissolved solid (TDS) for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

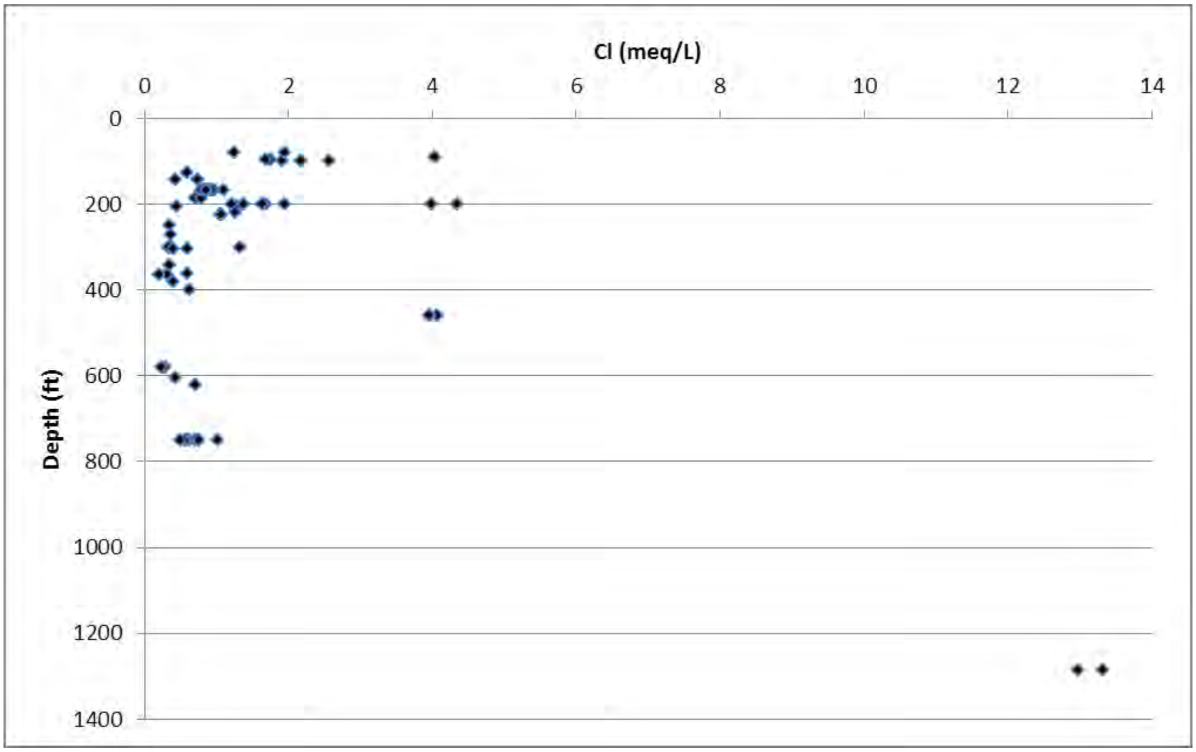


Figure 7-63. Chloride (Cl) vs depth for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

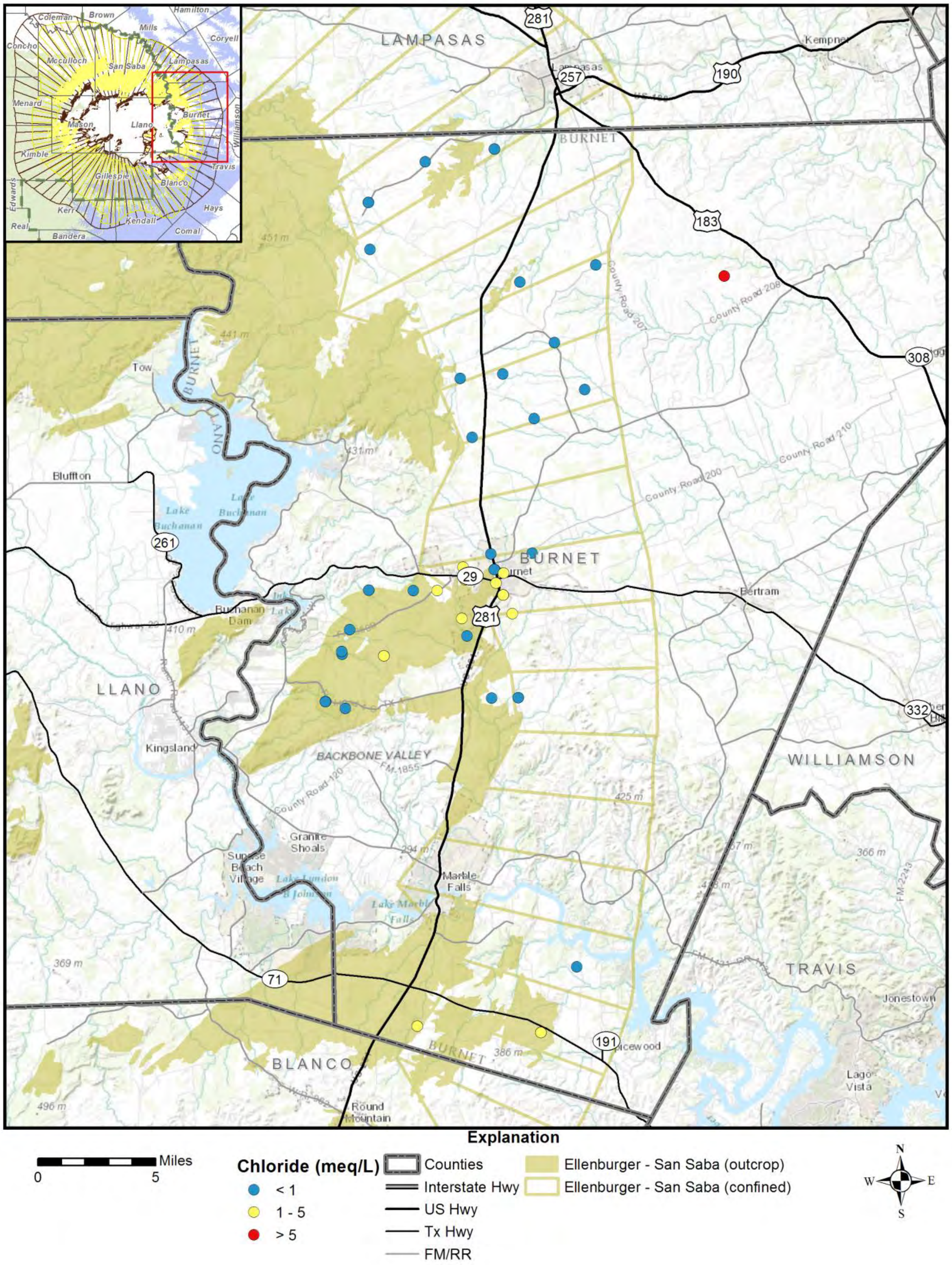


Figure 7-64. Chloride in the Ellenburger-San Saba Aquifer, Burnet County, Texas.

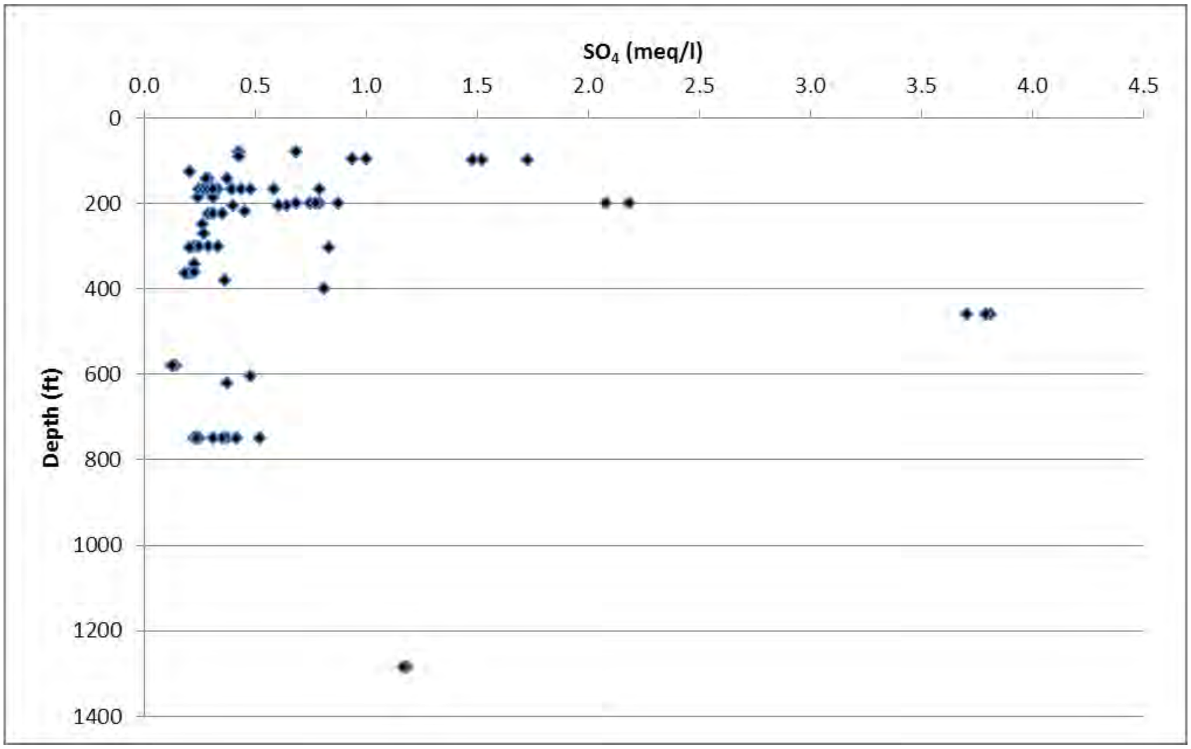


Figure 7-65. Sulfate (SO_4) vs depth for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

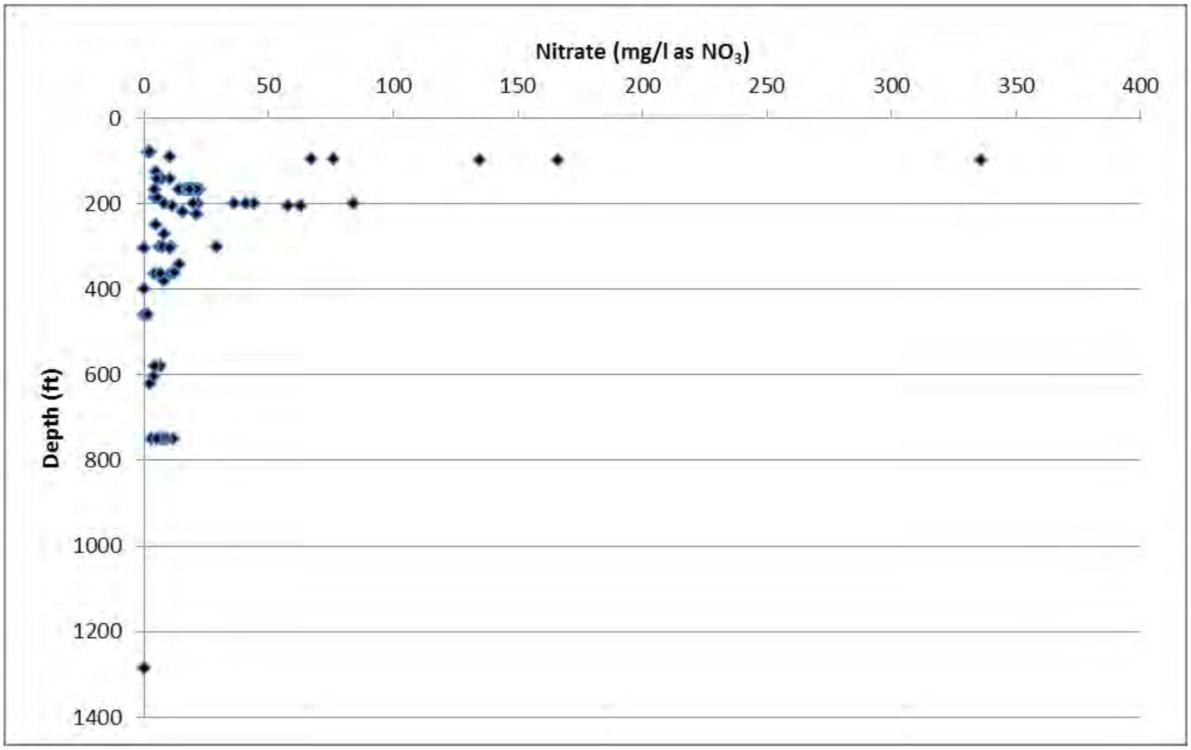


Figure 7-66. Nitrate (NO_3) vs depth for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

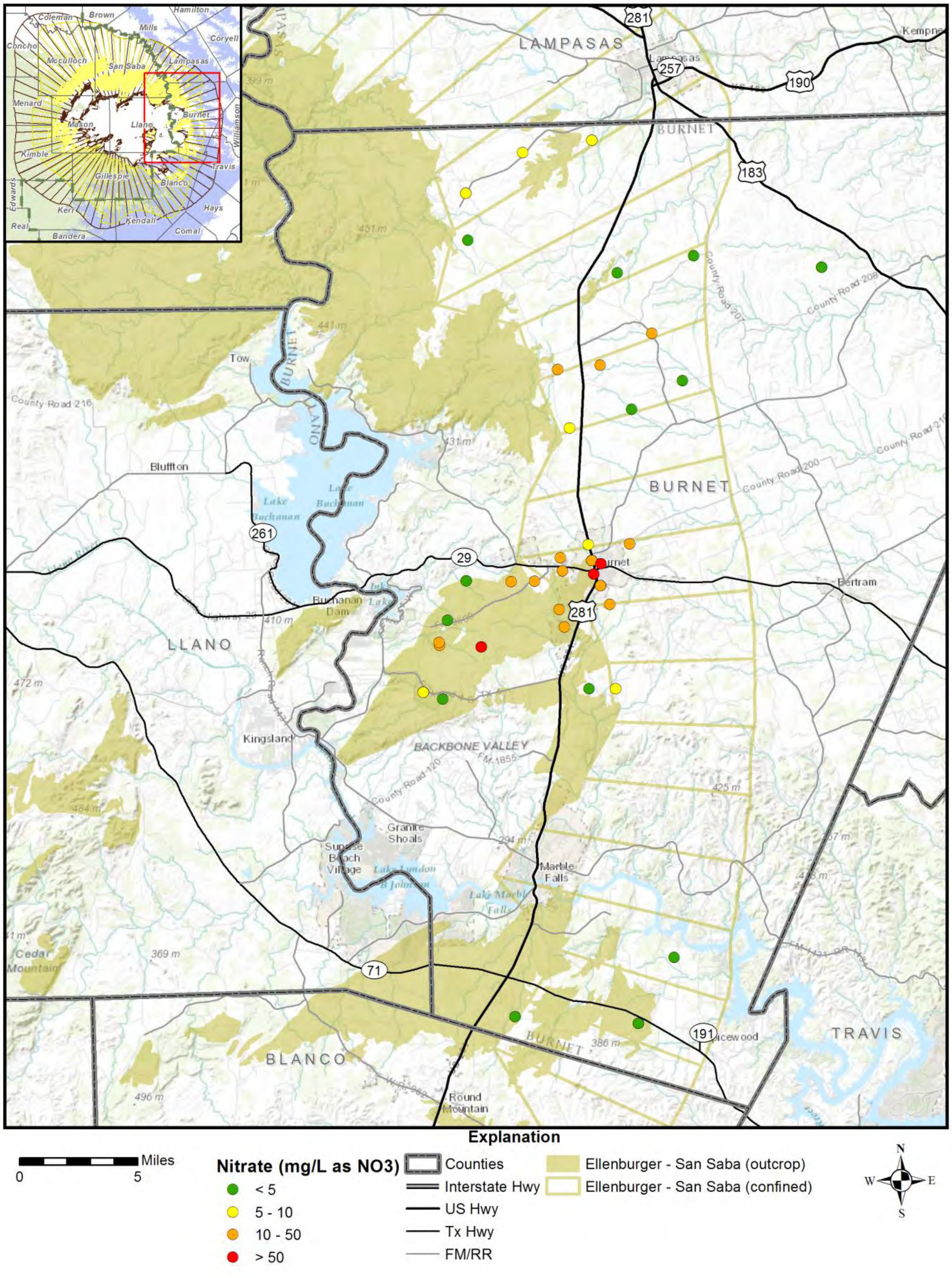


Figure 7-67. **Nitrate concentrations in the Ellenburger-San Saba Aquifer, Burnet County, Texas.**

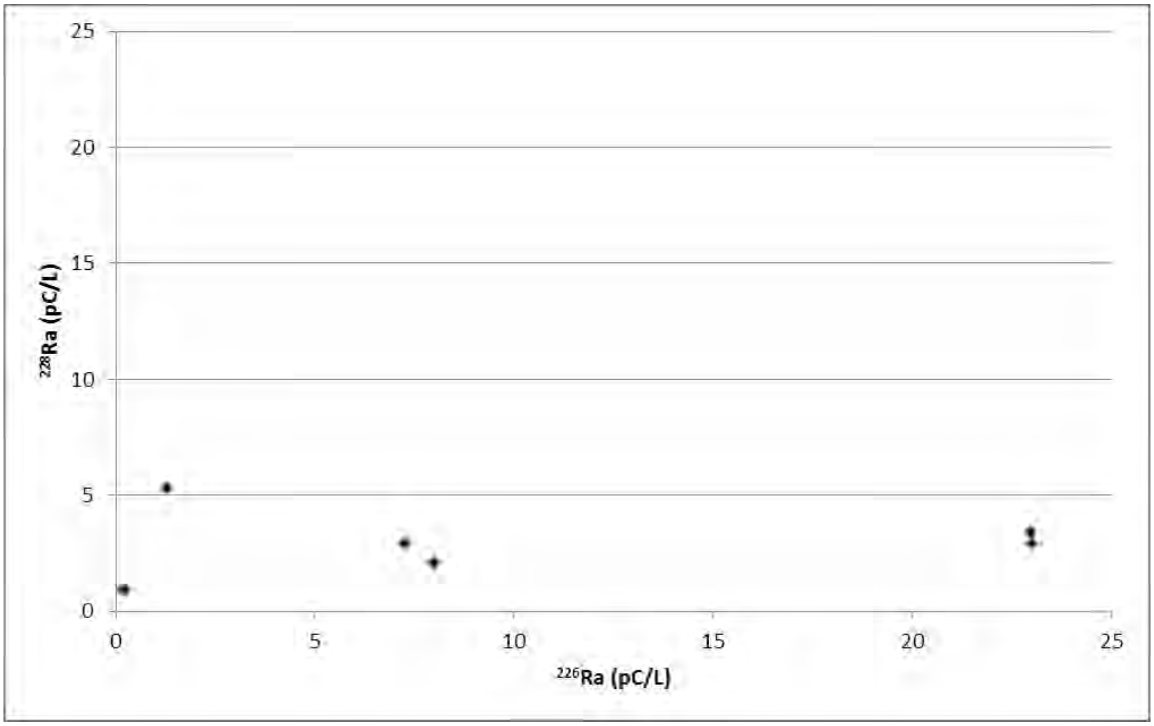


Figure 7-68. Radium-226 (^{226}Ra) vs radium-228 (^{228}Ra) for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

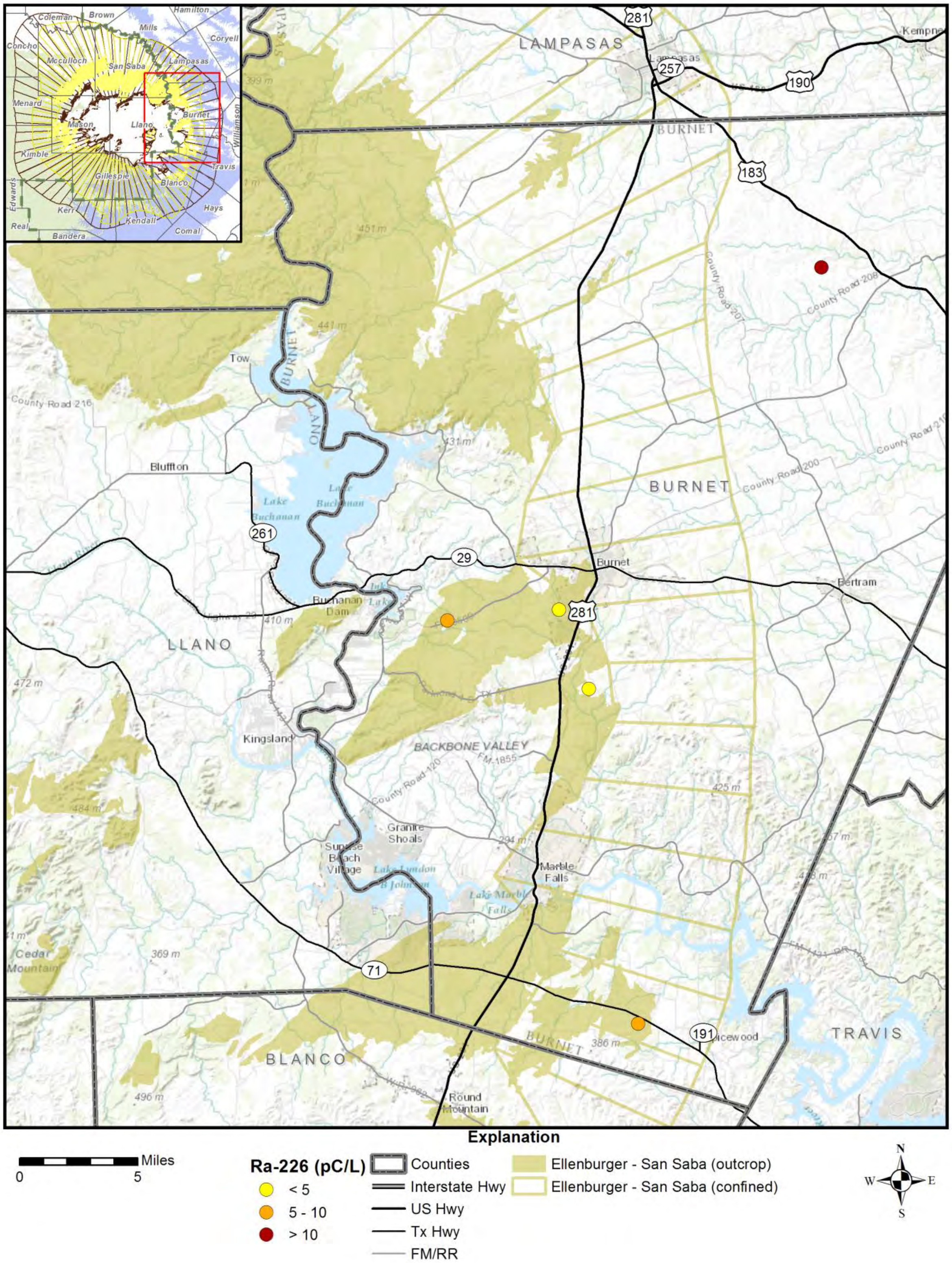


Figure 7-69. Radium-226 (^{226}Ra) in the Ellenburger-San Saba Aquifer, Burnet County, Texas.

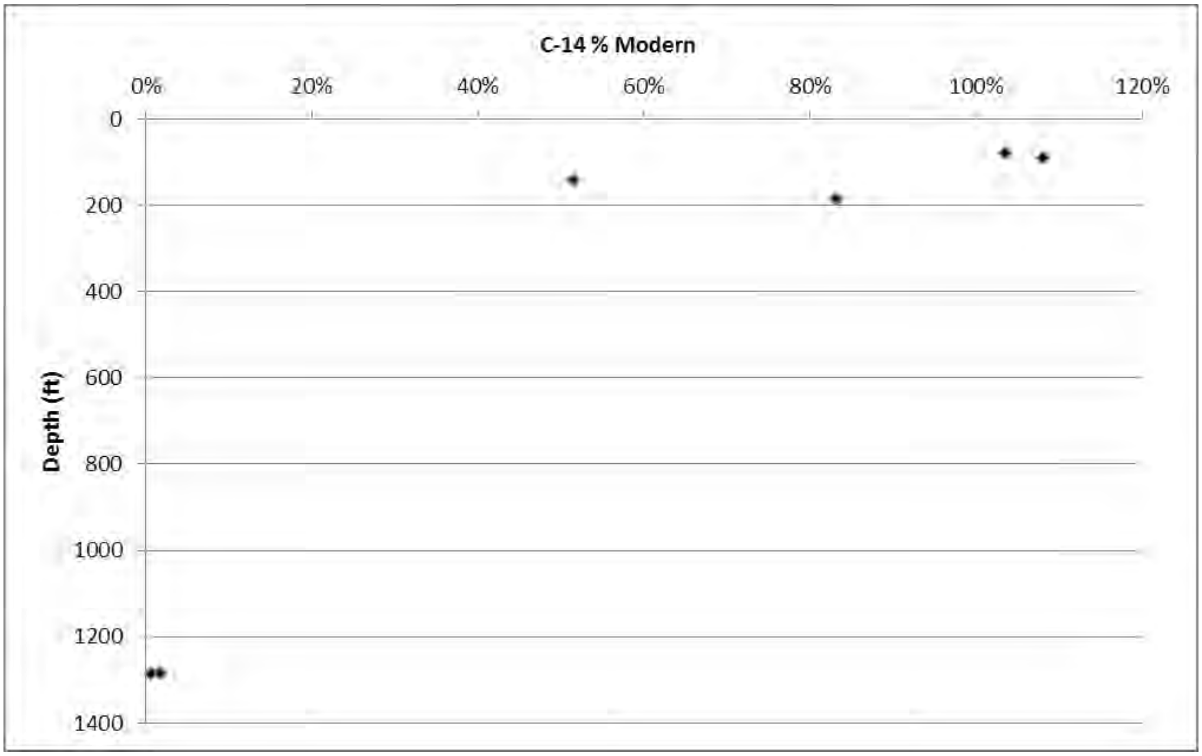


Figure 7-70. Carbon-14 percent modern (C-14%) vs depth for the Ellenburger-San Saba Aquifer, Burnet County, Texas.

7.4.3 Discussion of Results

There are three sub-aquifers for the Ellenburger-San Saba Aquifer in Burnet County: the southern, middle and northern sections. Groundwater production in southern and middle sub-aquifers is primarily from outcrop. In the northern section of the Ellenburger-San Saba Aquifer groundwater production is primarily from the downdip confined section.

Groundwater circulation for the middle and southern areas is considered to be from recharge in outcrop and then discharge to rivers (or creeks) either in the outcrop or close to the outcrop. For the northern section, some groundwater may flow west to the Colorado River/Lake Buchanan area. A majority of flow, however, may be to the east into the deeper subsurface of the confined section and discharge into Sulfur Creek and associated springs in Lampasas. The flow system in the northern section may be larger than the middle and southern.

Dominant water chemistry for the three Ellenburger-San Saba Aquifer sections is a calcium-magnesium-bicarbonate water.

Possible septic contamination in City of Burnet area may be causing the higher nitrate and chloride for this area.

In the “outcrop” groundwater ages appear “young” based on higher carbon-14 percent modern activities and presence of nitrate. The downdip sample, B-1, from northern section appears as an old water. B-1 is also the only sample with methane and reduced oxygen gas % relative to atmospheric ratios. Highest radium-226 activities for the Ellenburger-San Saba Aquifer for the three areas evaluated (McCulloch, Gillespie and Burnet counties) are in Ellenburger-San Saba Aquifer in the Burnet County where the radium-226 activities are higher than the radium-228 activities. For the other two aquifer settings in McCulloch and Gillespie the ratio is reversed. The high radium-226 and the high radium-228 suggests a mixing of water from either the underlying Hickory Aquifer or a deeper saline formation. Based on the hydrogeologic and hydrochemical data for the Ellenburger-San Saba Aquifer east of the Llano Uplift area, the conceptual flow model for this aquifer in this eastern area should be composed of three independent flow systems for which recharge occurs in the outcrop and discharge is to springs, creeks and rivers in the region. The Ellenburger-San Saba Aquifer on eastern side of the Llano Uplift area should be considered as a small, localized flow system.

7.5 Strontium Isotopic Compositions within Each Sub-Region

The data used in this review include samples collected in 2012 and data archived in the TWDB groundwater well database. Data were analyzed from the three following sub-regions within the study area:

1. North of the Llano Uplift area (Mason and McCulloch counties)
2. South of the Llano Uplift area (Gillespie County)
3. East of the Llano Uplift area (Burnet County)

The specific formations considered in this evaluation are:

1. The Cambrian Hickory Aquifer Formation/aquifer (present in all sub-regions)
2. The Ordovician Ellenburger-San Saba Aquifer system (present in all sub-regions)
3. The Cretaceous Hensell Formation Sandstone (present in Gillespie County)

The following strontium isotopic signatures are expected for the formations of interest within the Llano Uplift area. This is based on Figure 4-4 and the anticipated strontium isotopic compositions for the lithology in the local formations in the Llano Uplift area.

1. Precambrian: There are no known data for the minerals in the Precambrian rocks or for groundwaters that are dominated by a Precambrian signature. Based on the assumption presented in section 4.4.2, and from a Precambrian-dominated groundwater sample from Hudspeth County reported by Uliana and others, (2007), the Precambrian would be expected to have values above 0.7100 and possibly as high as 0.7140
2. Hickory Aquifer: strontium isotopic compositions should be greater than the typical Cambrian marine carbonate signatures; therefore, values expected should be greater than 0.7092.
3. Ellenburger-San Saba Aquifer: If no influence from other adjacent formations is assumed, then strontium isotopic compositions in the Ellenburger-San Saba Aquifer should reflect the typical range for late Cambrian and early Ordovician marine carbonates of 0.7085 to 0.7091.
4. Hensell Formation: The Hensell Formation consists of coarse-grained sandstone, shale, and sandy limestone containing pebbles at the base of the unit, with a gradational interbedded shale and limestone contact with the overlying Glen Rose Formation (Mancini and Scott, 2006). Assuming a relatively high content of late Permian/Cretaceous marine carbonate material in the sediments, with a significant fraction of older siliciclastics, the Hensell Formation should have strontium isotopic compositions at or slightly above the upper end of the Cretaceous range (0.7077) as indicated by Burke, and others. (1982).

Table 7-5 shows maximum, minimum, and average strontium isotopic compositions values for each formation and for each formation by county. Pages 155 through 177 include maps showing the distribution of strontium isotopic compositions values within each sub-region broken out by aquifer and graphs that show the relationships between strontium isotopic compositions and total dissolved solid, strontium concentrations, potassium concentrations, bicarbonate concentrations, and total well depth. The graphic representations of the data are then used to identify the specific processes controlling the strontium isotopic composition of the groundwaters within the study area and an attempt is then made to identify specific strontium isotopic signatures for each formation within each sub-region.

Table 7-5. **Ranges and averages of strontium isotopic compositions ($^{87}Sr/^{86}Sr$) values by formation and by formation within each county. All Hensell Formation results were from Gillespie County. The single well with an unknown completion interval is in Burnet County.**

	$^{87}Sr/^{86}Sr$ Ranges			
Aquifer and County	**Min**	**Average**	**Max**	**Count**
Hickory Aquifer	**0.7078**	**0.7103**	**0.7207**	**20**
Burnet	0.7086	0.7096	0.7106	2
Gillespie	0.7078	0.7091	0.7114	8
Mason	0.7112	0.7112	0.7112	1
McCulloch	0.7092	0.7114	0.7207	9
Ellenburger Aquifer	**0.7080**	**0.7096**	**0.7143**	**18**
Burnet	0.7084	0.7107	0.7143	7
Gillespie	0.7080	0.7086	0.7087	7
McCulloch	0.7094	0.7097	0.7101	4
Hensell Aq. (over Hickory)	**0.7085**	**0.7086**	**0.7087**	**2**
Hensell Aq. (over Ellenburger)	**0.7078**	**0.7079**	**0.7080**	**2**
Unknown completion interval	0.7112	0.7112	0.7112	1

7.5.1 North Sub-Region (Mason and McCulloch Counties)

Hickory Aquifer

Figure 7-71 shows the distribution of strontium isotopic compositions values within the North Sub-region separated by aquifer. The ten Hickory Aquifer samples from the north sub-region exhibit a broad range of strontium isotopic compositions values ranging from 0.7092 to 0.7207. These values are higher than those expected for Cambrian marine carbonates, but are consistent with values expected for siliciclastic rocks containing sediments of Precambrian provenance.

The highest value (0.7207), from well 42-63-908 located in southeast McCulloch County (Figure 7-72), is associated with the lowest total dissolved solids (288 mg/L), a very low strontium (0.0011 meq/L), and the shallowest well depth (226 feet). The strontium isotope composition for this sample was possibly controlled by soils, which are derived in part from weathered granite. This sample is considered an outlier that is not representative of the conditions deeper in the formation, and is therefore excluded from the remainder of the analysis.

The remainder of the samples, excluding the highest value, shows a positive correlation between total dissolved solids and strontium isotopic compositions with a correlation coefficient of 0.29 (Figure 7-72). The correlation is not considered to be statistically significant; however, it is still presented here because we believe that this relationship could be useful for future studies in the area. These samples also exhibit very little correlation between strontium concentration and the isotopic composition (Figure 7-73), suggesting that there are multiple sources of Sr with varying isotopic compositions. There appears to be a positive correlation (R^2=0.49) between the concentration of potassium and the strontium isotopic composition (Figure 7-74), especially at higher potassium concentrations, suggesting that the higher strontium isotopic compositions values may be controlled by interaction with weathered orthoclase feldspars from the granite intrusions or from clays that are ultimately derived from those feldspars. strontium isotopic compositions is negatively correlated with bicarbonate concentration (R^2=0.64) (Figure 7-75), suggesting that lower strontium isotopic compositions values are associated with dissolution of carbonates. There is very little correlation between strontium isotopic concentration and well depth (Figure 7-76).

Ellenburger-San Saba Aquifer

Strontium isotope compositions in the four Ellenburger-San Saba Aquifer samples from the north sub-region range from 0.7094 to 0.7101. These isotopic compositions are slightly higher than expected for only equilibration with late Cambrian and early Ordovician carbonates, suggesting that there may be some enriched strontium isotopic composition in the groundwater.

The strontium isotopic compositions of these samples show very little correlation between total dissolved solids and strontium concentrations (Figure 7-72). Potassium concentrations appear to have a positive correlation with strontium isotopic compositions (Figure 7-74), suggesting a similar connection between enriched strontium isotopic composition and weathering of the Precambrian granite intrusions; however, the R^2 for this correlation is 0.11, so the correlation is not considered to be statistically significant. Strontium isotopic composition is negatively correlated (R^2 = 0.88) with bicarbonate (Figure 7-75). The inverse correlation between depth and strontium isotopic composition is not statistically significant (R^2=0.20); however, the shallowest well appears to be associated with slightly enriched strontium isotopic composition while the deeper wells appear to have strontium isotopic compositions that are closer to those expected for late Cambrian and early Ordovician marine carbonates (Figure 7-76). The bicarbonate and depth trends suggest that the strontium isotopic composition of groundwater in the deeper parts of the aquifer are more strongly controlled by dissolution of the marine carbonate matrix rock.

Interformational Mixing

The spatial distribution of strontium isotopic compositions (Figure 7-71), and the previously discussed geochemical and isotopic data, do not show clear mixing relationships between the Hickory Aquifer and the Ellenburger-San Saba Aquifer in the north sub-region. There is a possibility that some mixing is occurring between the two aquifers, but based on the limited Ellenburger-San Saba Aquifer data, it appears that the enriched strontium isotopic composition in the formation is probably provided by interaction with weathered granites near the surface (e.g., in the soil zone) for the shallower wells in the outcrop zone and Precambrian-sourced detrital siliciclastic material in the Hickory Aquifer for the deeper wells.

It is difficult to evaluate mixing processes without data concerning the specific strontium isotopic composition of the mineral phases in the aquifers in questions. We therefore note that there is some uncertainty about the mixing relationships described in this section because the strontium isotopic compositions of the mineral phases in the aquifers were estimated from ranges of values in the literature and/or from general principles of strontium isotope occurrence in geologic materials.

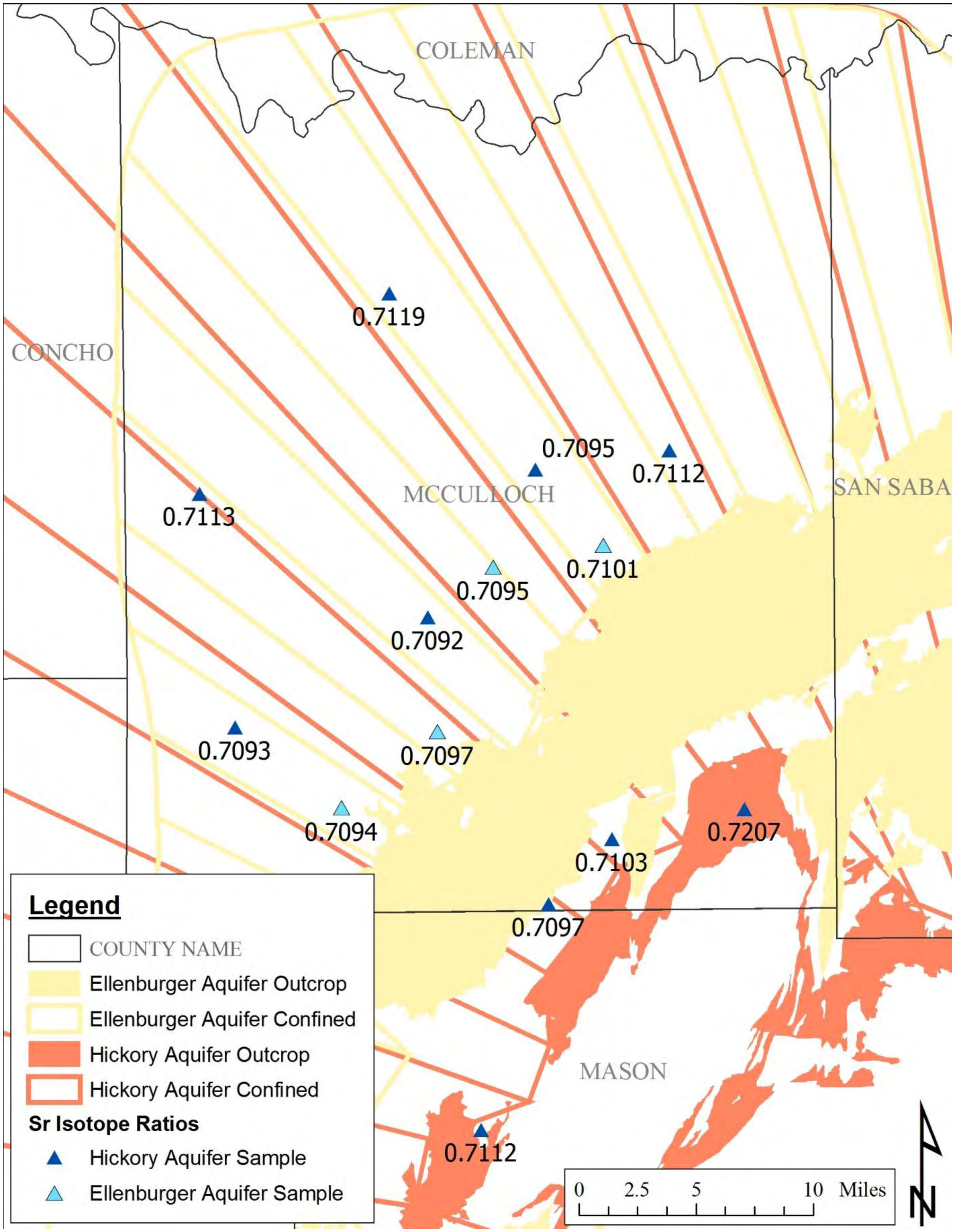


Figure 7-71. Map of strontium isotopic compositions ($^{87}Sr/^{86}Sr$) data for the north sub-region.

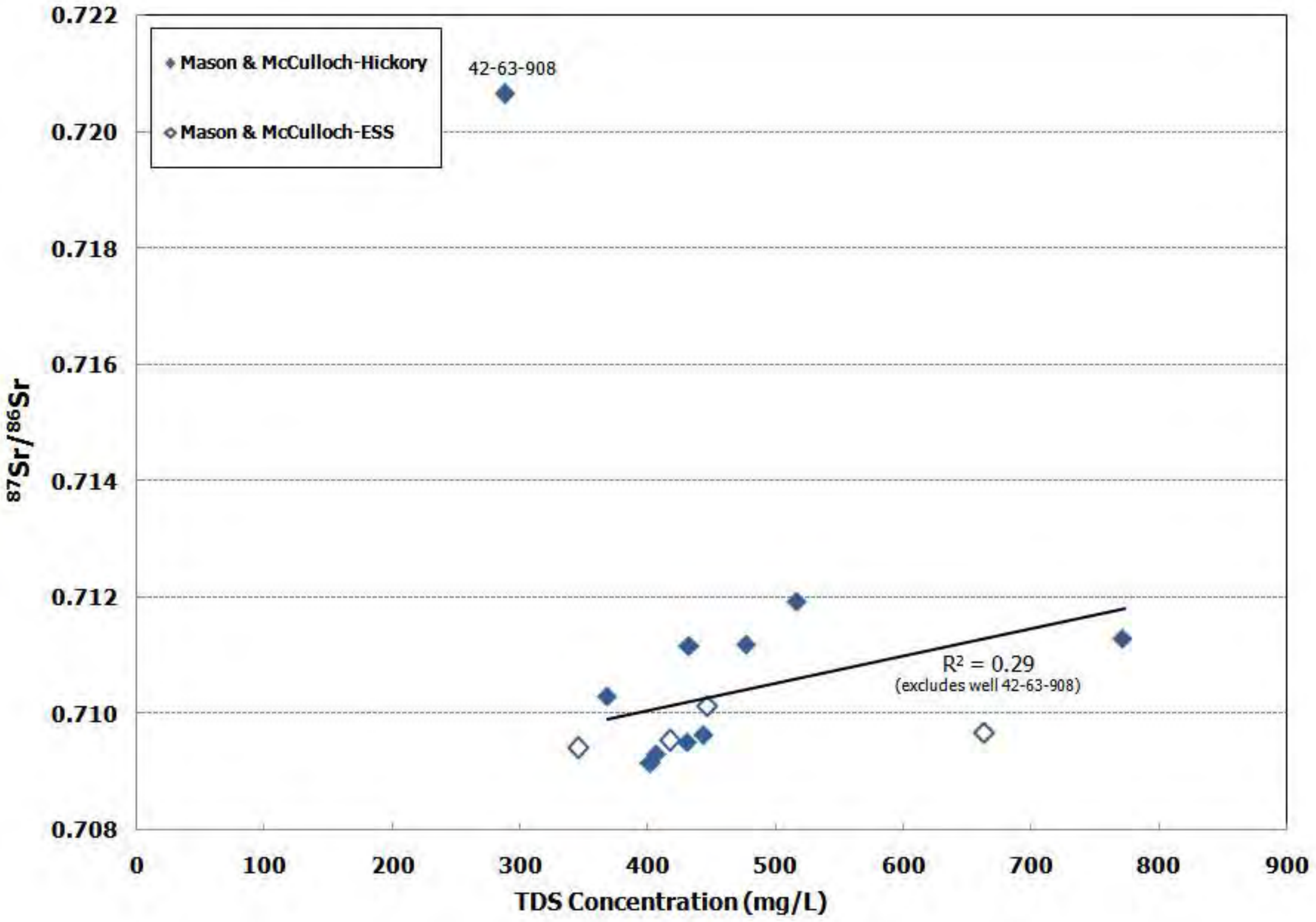


Figure 7-72. Total dissolved solids (TDS) concentration versus strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the north sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Hickory Aquifer samples excluding well 42-63-908.

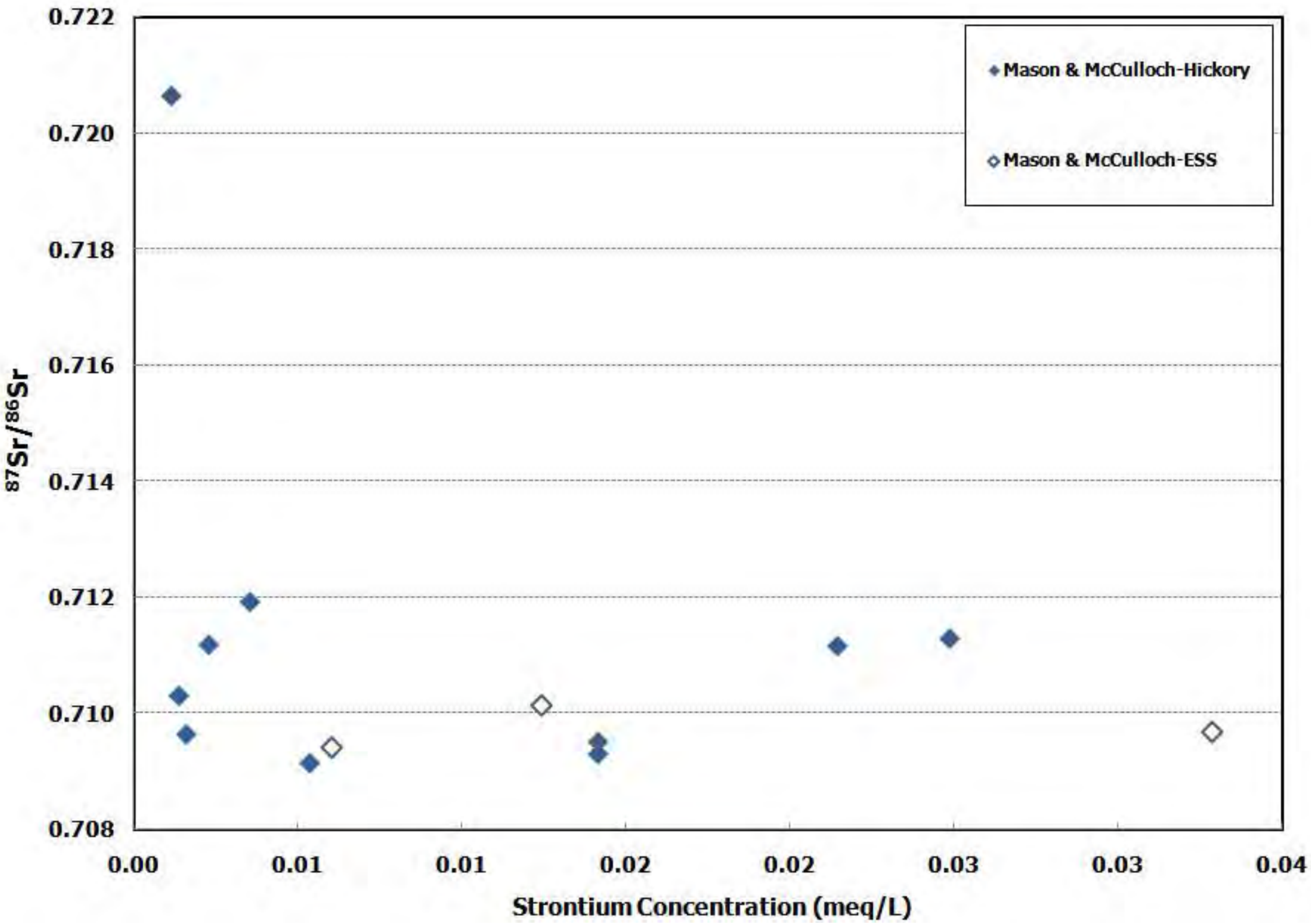


Figure 7-73. **Strontium isotopic compositions (^{87}Sr/^{86}Sr) for the north sub-region.**

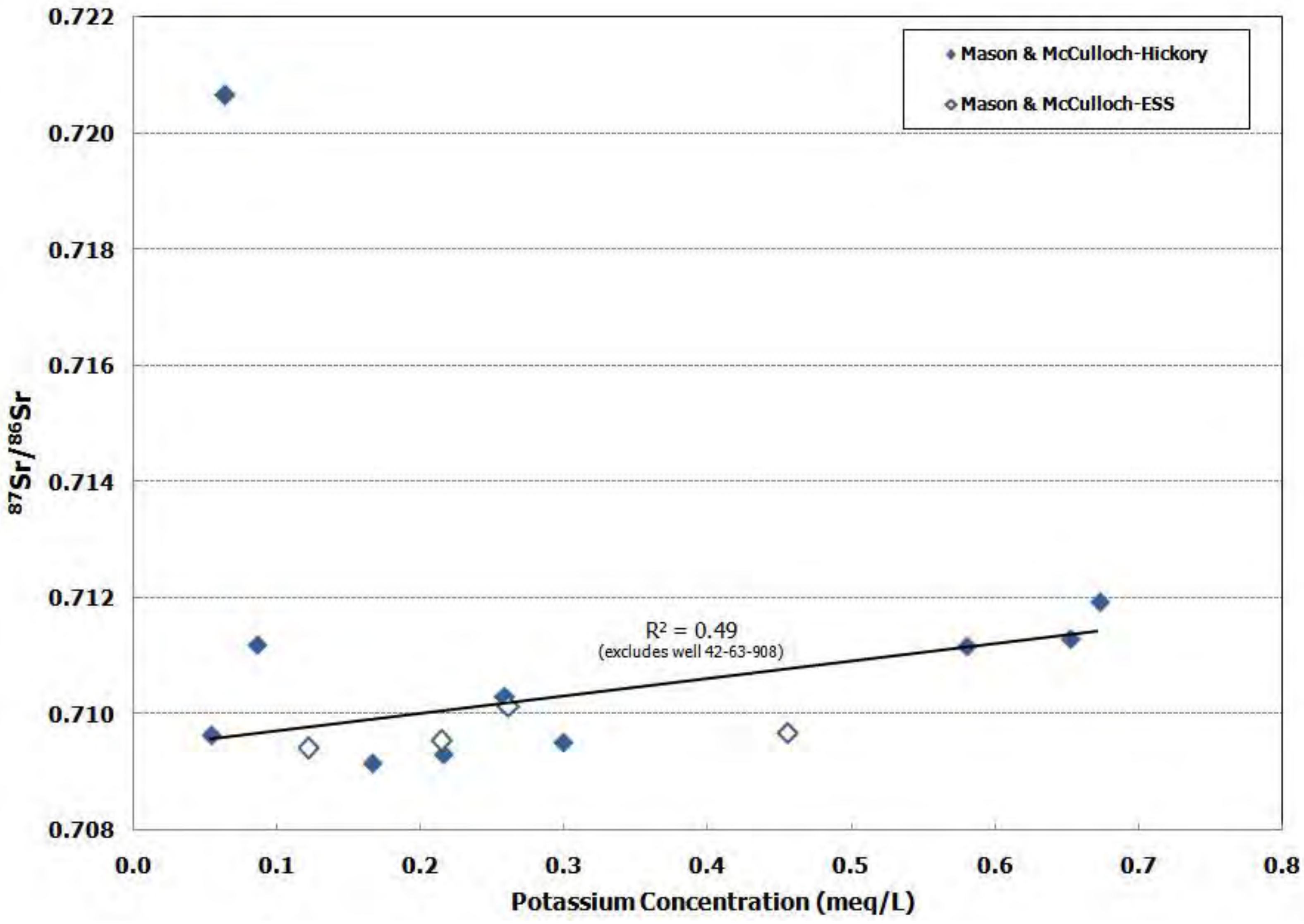


Figure 7-74. Potassium concentration vs strontium isotopic compositions (^{87}Sr/^{86}Sr) for the north sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Hickory Aquifer samples excluding well 42-63-908.

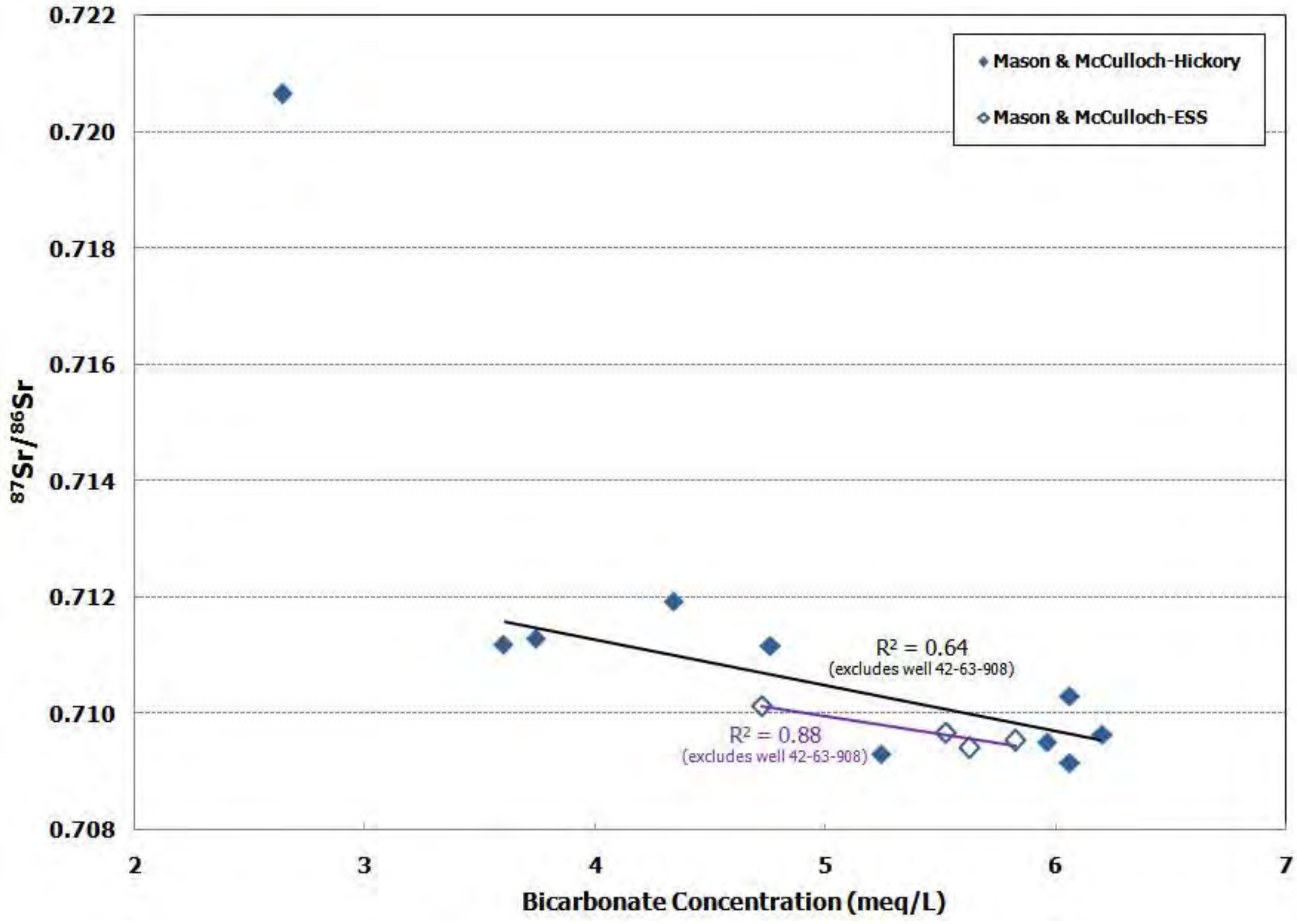


Figure 7-75. **Bicarbonate concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the North Sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Hickory Aquifer samples excluding well 42-63-908. The solid purple line is a linear least-squares regression, with the associated R^2, for the Ellenburger-San Saba Aquifer samples.**

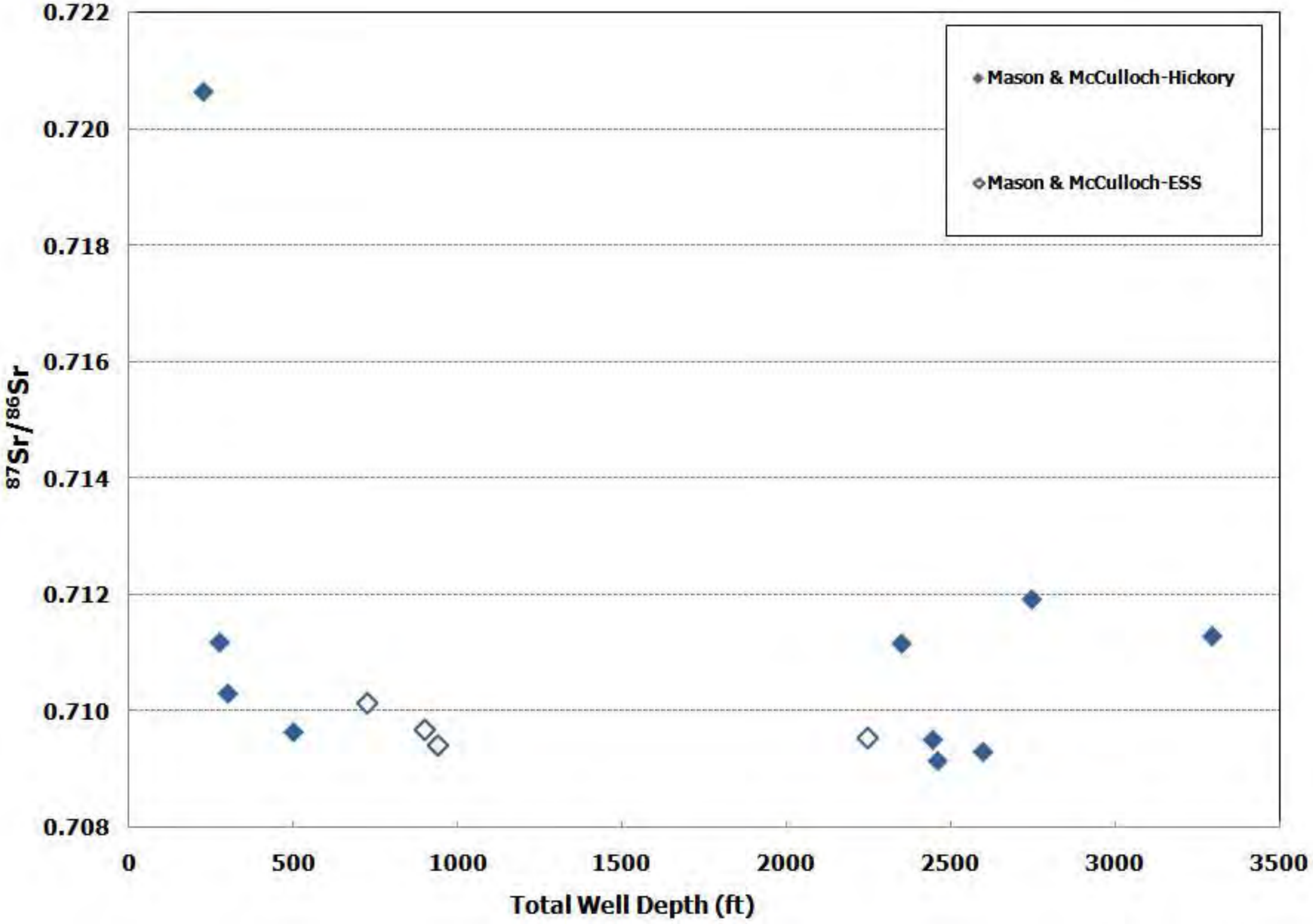


Figure 7-76. **Total well depth vs $^{87}Sr/^{86}Sr$ for the north sub-region.**

7.5.2 South Sub-Region (Gillespie County)

Hickory Aquifer

Figure 7-77 shows the distribution of strontium isotopic compositions values within the south sub-region separated by aquifer. Strontium isotopic ratios for the eight groundwater samples from the Hickory Aquifer in Gillespie County range from 0.7078 to 0.7114. These can be broken into three groups (Figure 7-78). Group 1 are samples below 0.7084, group 2 are samples between 0.7091 and 0.7092 and group 3 are samples above 0.7108. The group 1 samples are more consistent with influence from Cretaceous marine carbonates. Those in group 2 and 3 are consistent with the range of values observed in the north sub-region.

There is very little correlation between strontium isotopic composition and total dissolved solid (Figure 7-78). Low strontium concentrations show a large range of strontium isotopic compositions, with the higher strontium concentrations associated with the lowest strontium isotopic compositions values (Figure 7-79). Unlike in the north sub-region, the potassium concentrations appear to be negatively correlated ($R^2 = 0.79$) with strontium isotopic compositions values (Figure 7-80), suggesting that the isotopic compositions are not as strongly controlled by weathering of the granites. The strontium isotopic composition appears to have a negative correlation with bicarbonate (Figure 7-81), suggesting an influence of carbonate dissolution on strontium isotopic compositions values, although the correlation ($R^2 = 0.30$) is not statistically significant. These samples show a negative correlation ($R^2 = 0.79$) between strontium isotopic compositions value and depth (Figure 7-82), with higher strontium isotopic compositions values occurring in the shallower wells.

Ellenburger-San Saba Aquifer

Strontium isotope composition in the seven Ellenburger-San Saba Aquifer samples show very little variability. Strontium isotopic compositions values range from 0.7080 to 0.7087, with all but one between 0.7086 and 0.7087. The Ellenburger-San Saba Aquifer comprises the late Cambrian San Saba unit of the Wilberns Formation and the early Ordovician Ellenburger group. The isotopic ratios observed in these samples are consistent with the strontium isotopic composition of late Cambrian/early Ordovician marine carbonates (Figure 4-4).

These samples show a relatively broad range of strontium concentrations (0.007 to 0.09 meq/L; see Figure 7-79) that, when coupled with the low variability in Sr isotopic compositions, suggests that the Sr isotopic ratios are controlled by dissolution of the Ellenburger-San Saba Aquifer formation matrix. Strontium isotopic compositions values appear to show a negative correlation with bicarbonate (Figure 7-81), supporting the idea that carbonate dissolution is controlling the strontium isotopic composition; however, the correlation coefficient ($R^2 = 0.50$) indicates that the relationship is not statistically significant. There is insufficient well construction information to identify any trends relative to well depth (Figure 7-82).

Hensell Formation

Strontium isotopic compositions values in the four Hensell Formation samples range from 0.7078 to 0.7087. The two samples classified as "Hensell Formation over Ellenburger Aquifer" on Figure 7-77 to Figure 7-82 have strontium isotopic compositions values of 0.7078 and 0.7080, which are consistent with those expected for the Hensell Formation (see the discussion of expected isotopic signatures for the Hensell Formation on page 150). The two samples classified as "Hensell Formation over Hickory Aquifer" on Figure 7-77 to Figure 7-82 have strontium isotopic compositions values of 0.7085 and 0.7087, which are slightly higher than expected. The relationship between the strontium concentrations and the strontium isotopic composition (Figure 7-79) shows a pattern of decreasing strontium isotopic composition enrichment with increasing strontium concentration that indicates dissolution of Cretaceous marine carbonate material along the groundwater flow path. This pattern is consistent with the well depth relationship (Figure 7-82) and with the locations of the samples shown on Figure 7-78.

Interformational Mixing

Figure 7-79 shows the relationship between strontium concentrations and isotopic compositions for the samples from Gillespie County and helps to illustrated possible mixing and mineral-solution interactions in and between the various formations. The blue arrow indicates dissolution of the Ellenburger-San Saba Aquifer matrix and subsequent equilibration with the late Cambrian/early Ordovician strontium isotopic compositions signature between 0.7085 and 0.7091. This suggests that most of groundwater in the Ellenburger-San Saba Aquifer in the southeast corner of Gillespie County is relatively isolated from sources of enriched strontium isotopic composition.

Mixing Model 1 represents a hypothetical mixing model calculated using a sample from Hickory Aquifer well 57-35-805 as one end member and a sample from Hensell Formation well 57-50-901 as another end member. These samples were chosen as end-members because they represent the extreme endpoints of an apparent hypothetical mixing curve on the graph and because the Hensell sample is the best match to the expected strontium isotopic composition for the Hensell Formation Aquifer. This model indicates that the hypothetical addition of small amounts of Hensell water to Hickory Aquifer water results in drastic reductions in strontium isotopic compositions associated with relatively small increases in Strontium concentration. The overall pattern suggests that water in the Hickory Aquifer may be influenced by some infiltration of Hensell Formation; however, if this is the case, the actual volumes are probably not very large.

Mixing Model 2 indicates a hypothetical mixing model calculated using a sample from Ellenburger-San Saba Aquifer well 52-30-105 as one end member and a sample from Hensell Formation Sandstone well 57-49-503 as another end member. The objective of this model was to test if the Ellenburger-San Saba Aquifer sample with the lowest strontium isotopic composition and strontium isotopic composition value could represent a mixture between Hensell water and water dominated by Ellenburger-San Saba Aquifer matrix dissolution. The mixing model was calculated using each Ellenburger-San Saba Aquifer sample as an end-member, and the simulation using well 52-30-105 resulted in the best match for the Ellenburger-San Saba Aquifer well with the loweststrontium isotopic compositions. This model does not provide definitive evidence for mixing between the Hensell Formation and the Ellenburger-San Saba Aquifer; however, it does show that it is possible to produce the Strontium isotopic composition of the lowest strontium isotopic compositions Ellenburger-San Saba Aquifer well through mixing.

The Hensell Formation samples from the two wells located in the area where the Hensell Formation is in direct contact with the Ellenburger have strontium isotopic compositions values of 0.7078 and 0.7080. These values are slightly above the upper range for waters dominated by Cretaceous carbonates, and are consistent with groundwater influenced by some siliciclastics incorporated into the host rock matrix. The Hensell Formation samples from the wells located where the Hensell Formation is in direct contact with the Hickory Aquifer, however, have strontium isotopic compositions values ranging from 0.7085 to 0.7087. This could indicate some interformational flow from the Hickory Aquifer into the Hensell Formation.

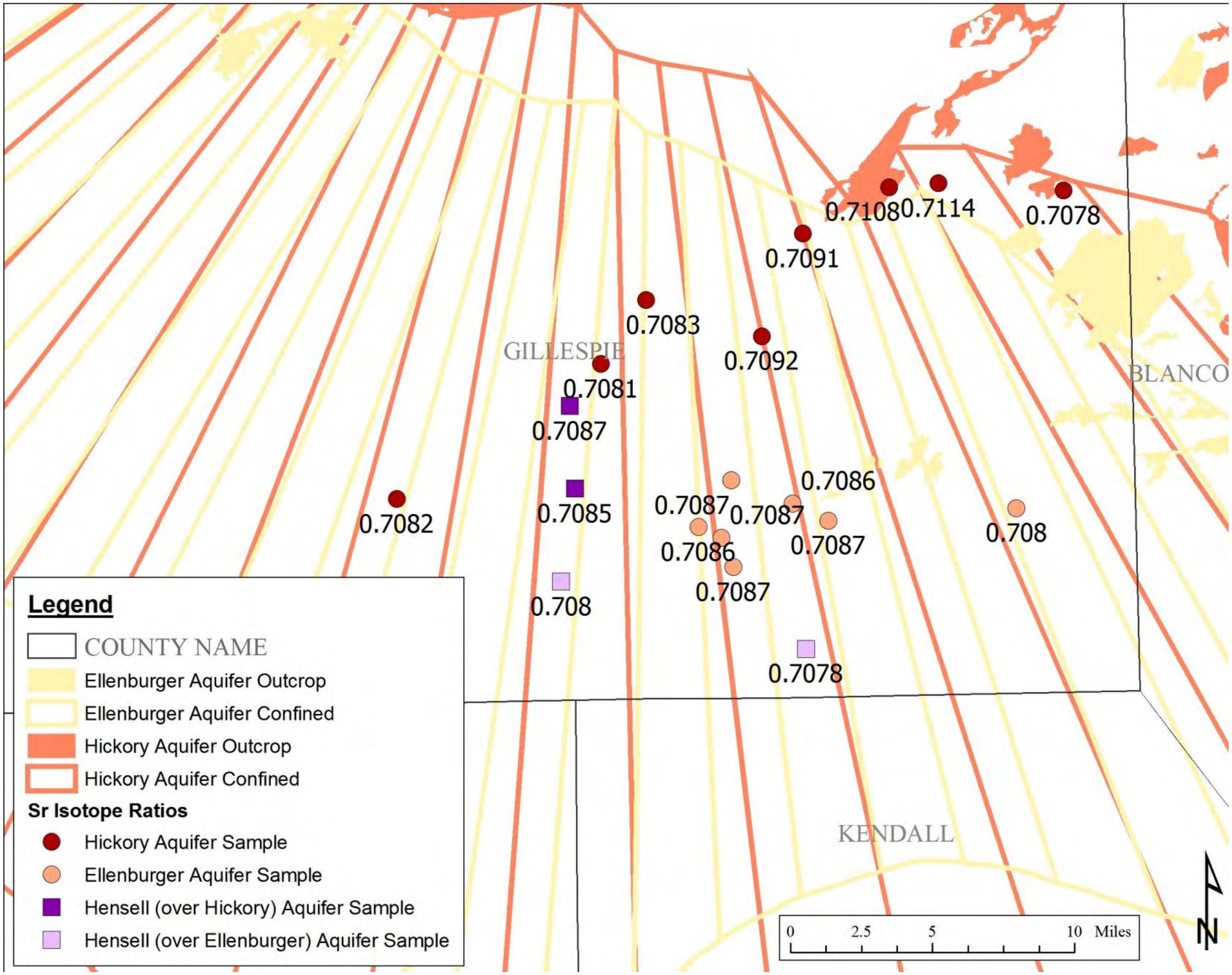


Figure 7-77. **Map of strontium isotopic compositions ($^{87}Sr/^{86}Sr$) data for the South Sub-Region.**

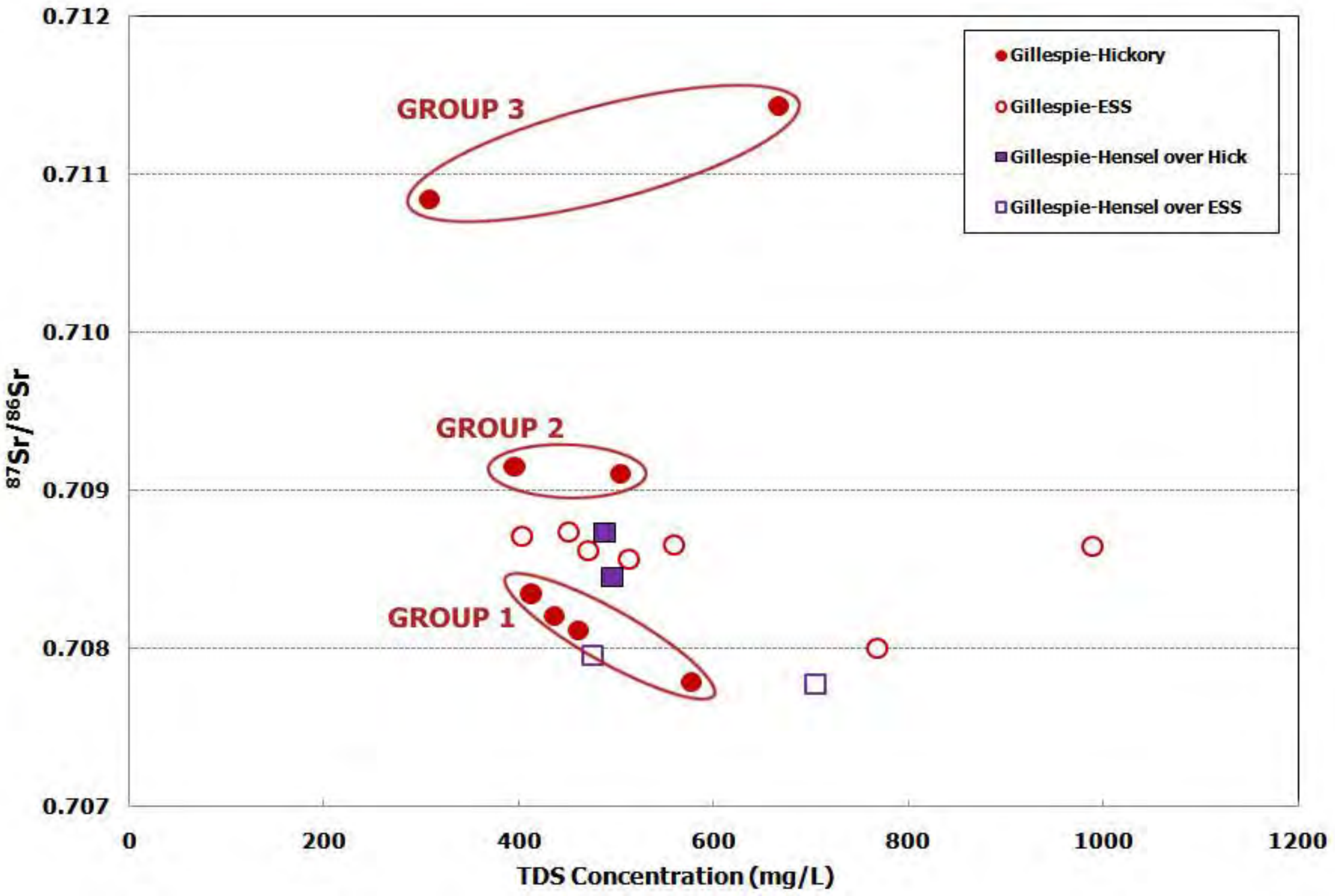


Figure 7-78. Total dissolved solids (TDS) concentration vs strontium isotopic compositions (^{87}Sr/^{86}Sr) for the South Sub-region

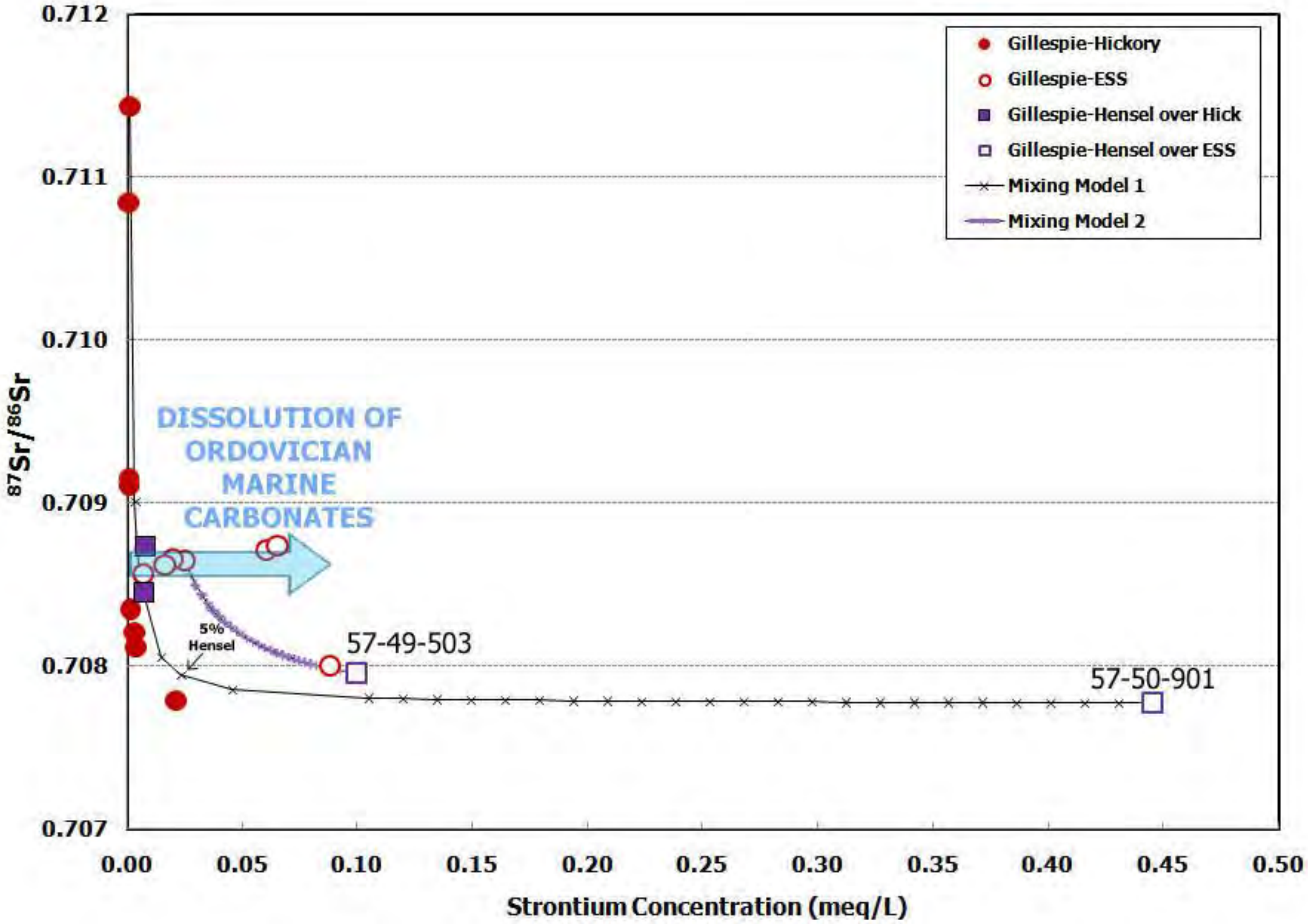


Figure 7-79. Strontium concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the South Sub-region including interformational mixing models.

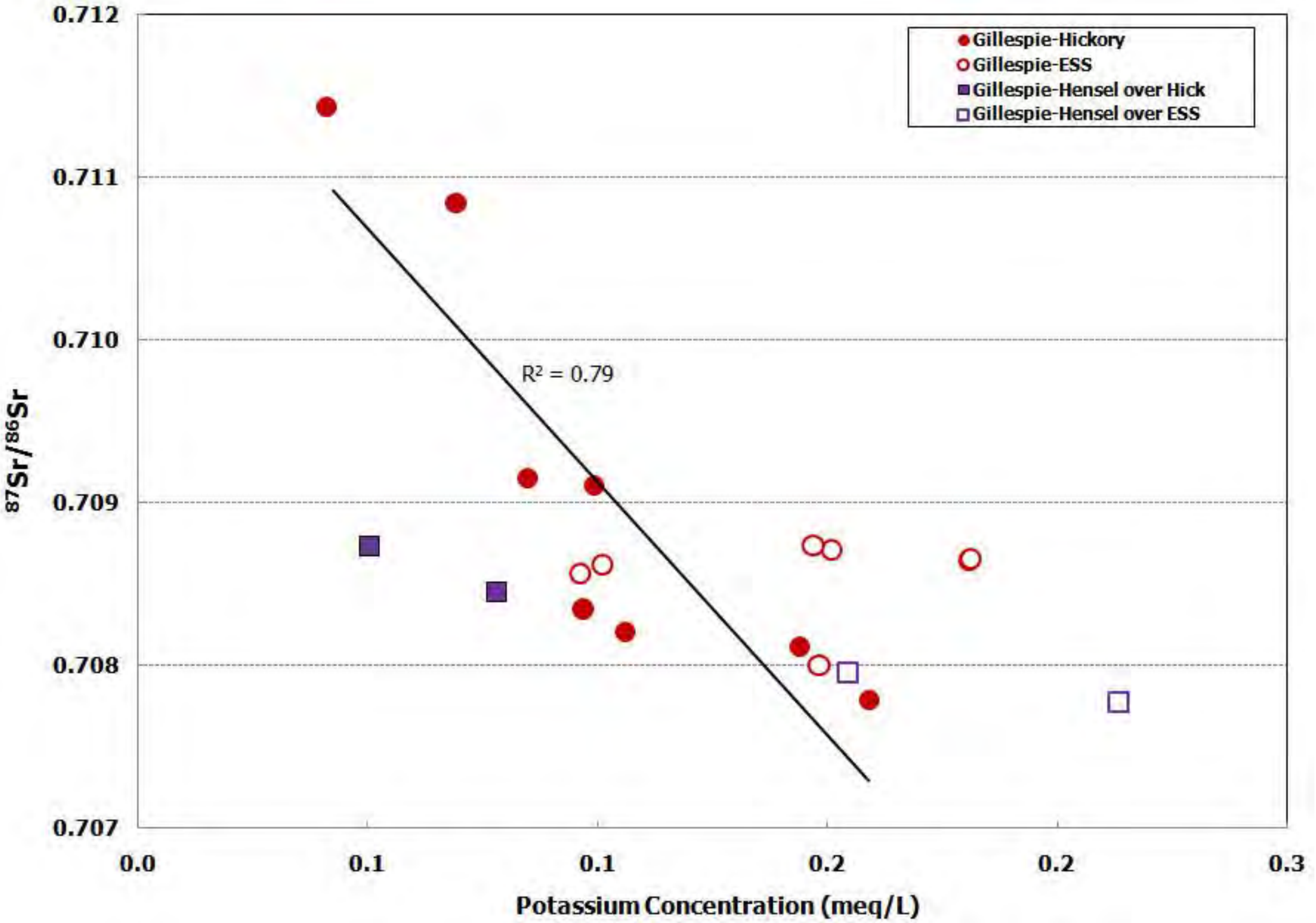


Figure 7-80. Potassium concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the South Sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Hickory Aquifer samples.

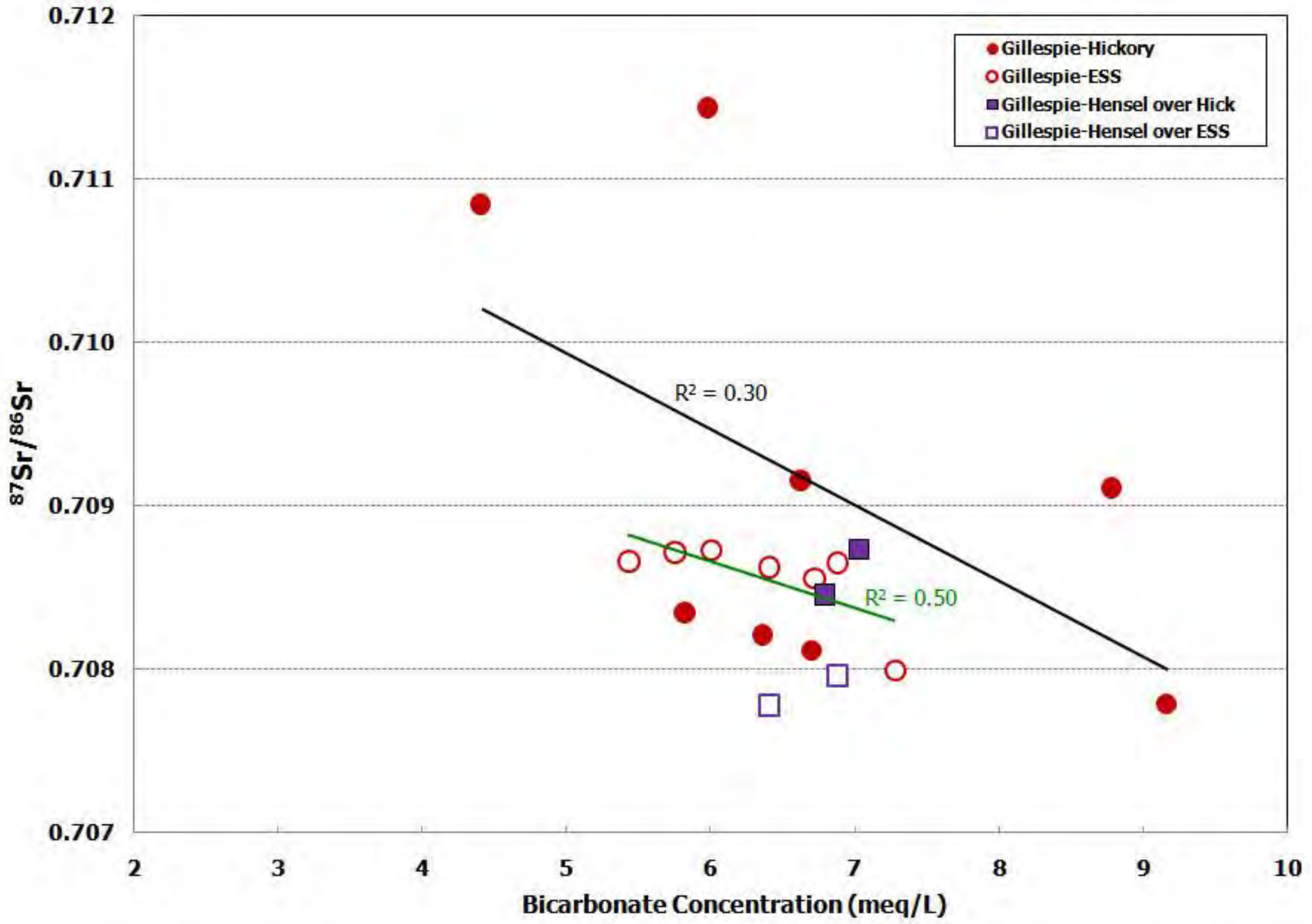


Figure 7-81. Bicarbonate concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the South Sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Hickory Aquifer samples excluding well 42-63-908. The solid green line is a linear least-squares regression, with the associated R^2, for the Ellenburger-San Saba Aquifer samples.

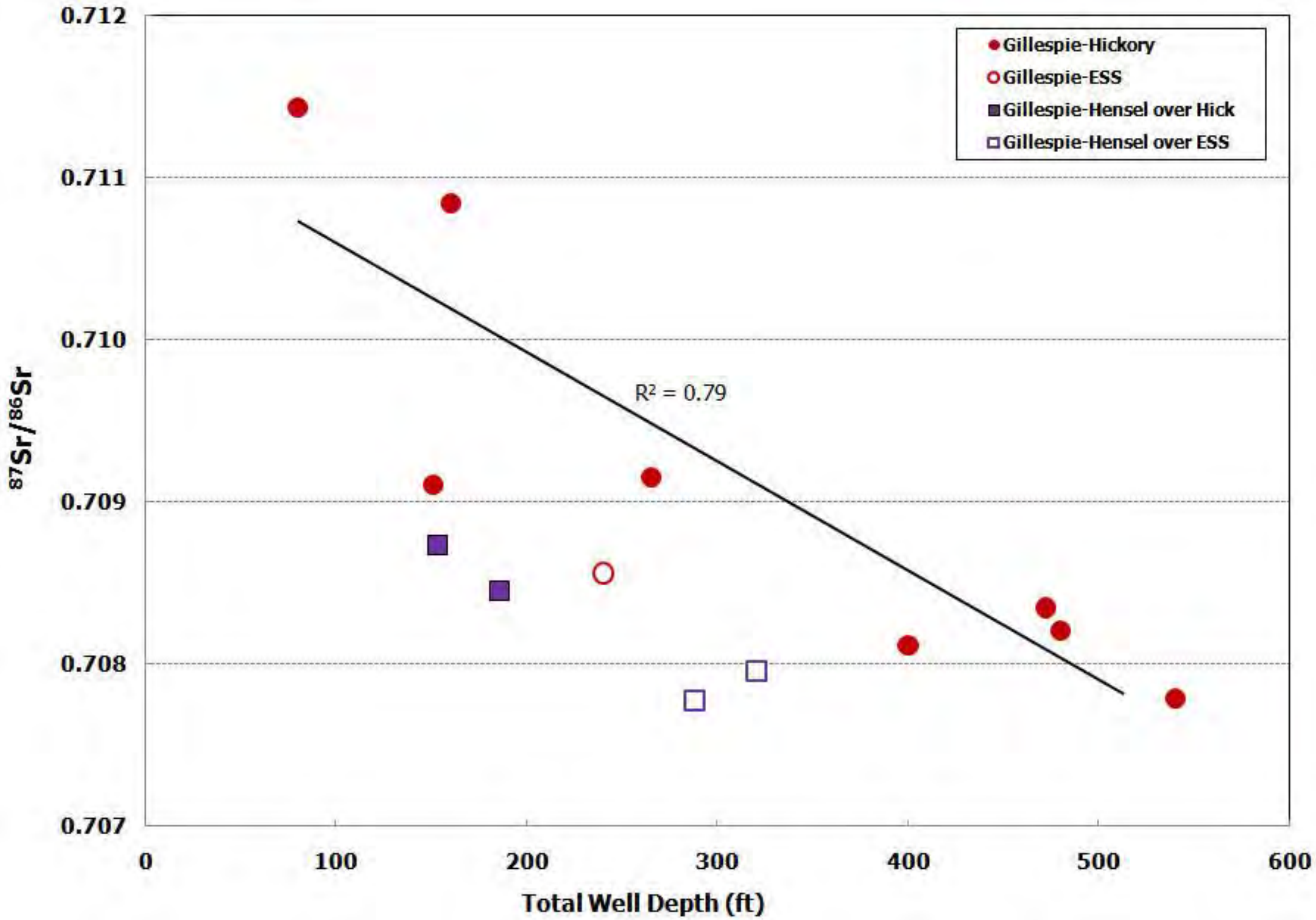


Figure 7-82. Total well depth vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the South Sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Hickory Aquifer samples.

7.5.3 East Sub-Region (Burnet County)

Hickory Aquifer

Figure 7-83 shows the distribution of strontium isotopic compositions values within the east sub-region separated by aquifer. The two Hickory Aquifer samples from Burnet County have strontium isotopic compositions values of 0.7086 to 0.7106. The lower value is consistent with the expected range of strontium isotopic compositions from a water that is controlled by dissolution of the Ellenburger-San Saba Aquifer, whereas the higher value could indicate influence from either siliciclastics in the formation matrix or mixing with groundwater that has interacted with the Precambrian.

Total dissolved solids (Figure 7-84), bicarbonate concentrations (Figure 7-85), and well depths (Figure 7-86) are almost identical for each sample. The sample with the higher strontium isotopic compositions value has higher concentrations of strontium (Figure 7-87) and K (Figure 7-88) than the other sample. This suggests that interaction with granite may be the source of the isotopic enrichment.

Ellenburger-San Saba Aquifer

Strontium isotopic compositions values in the seven samples from six Ellenburger-San Saba Aquifer wells in Burnet County range from 0.7084 to 0.7143. Only three of the samples are in a range that is consistent with interaction with late Cambrian/early Ordovician marine carbonates, suggesting that the remaining four wells are influenced by mixing with Hickory Aquifer groundwater or groundwater influenced by interaction with the granite intrusions or weathered granite at the surface. All samples show a positive correlation ($R^2 = 0.77$) between total dissolved solids and strontium isotopic composition and strontiuim-87 (Figure 7-84).

The samples with strontium isotopic compositions values <0.7100 show a negative correlation ($R^2 = 0.88$) between strontium isotopic compositions and Sr concentration (see “ESS Group 1” on Figure 7-87). This relationship could indicate control on strontium isotopic composition by dissolution of Ellenburger-San Saba Aquifer, which would cause water samples to approach strontium isotopic compositions between 0.7085 and 0.7091 as strontium concentration increased. As shown in Figure 7-88, there is very little variability in potassium concentration in these samples, suggesting that dissolution of granite, or siliciclastics derived from granite, is not a dominant process affecting strontium isotopic composition.

Within the “ESS Group 2” samples, the sample with the highest strontium isotopic compositions value has a much higher strontium concentration (Figure 7-87) and potassium concentration (Figure 7-88) than the “ESS Group 1” samples. The higher potassium concentration is consistent with the influence of dissolution of granite and/or siliciclastics in the groundwater. This sample is also much deeper than the other Ellenburger-San Saba Aquifer samples (Figure 7-86). The other sample in “Group 2” is from a well with an unknown completion interval; therefore, it is difficult to make any conclusions concerning the flow system from that sample.

Interformational Mixing

The information presented above suggests that the shallower parts of the Ellenburger-San Saba Aquifer (strontium isotopic compositions less than 0.710) are relatively isolated from the influence of mixing from sources of enriched strontium isotopic composition, while the deeper parts of the aquifer are influenced by a source of enriched strontium isotopic composition. This source could be associated with interformational flow from the Hickory Aquifer or a deeper unidentified saline formation. The existing data do not indicate that the Hickory Aquifer is the source; however, these data are limited and the Hickory Aquifer is the most logical source for enriched strontium isotopic composition in the aquifer system.

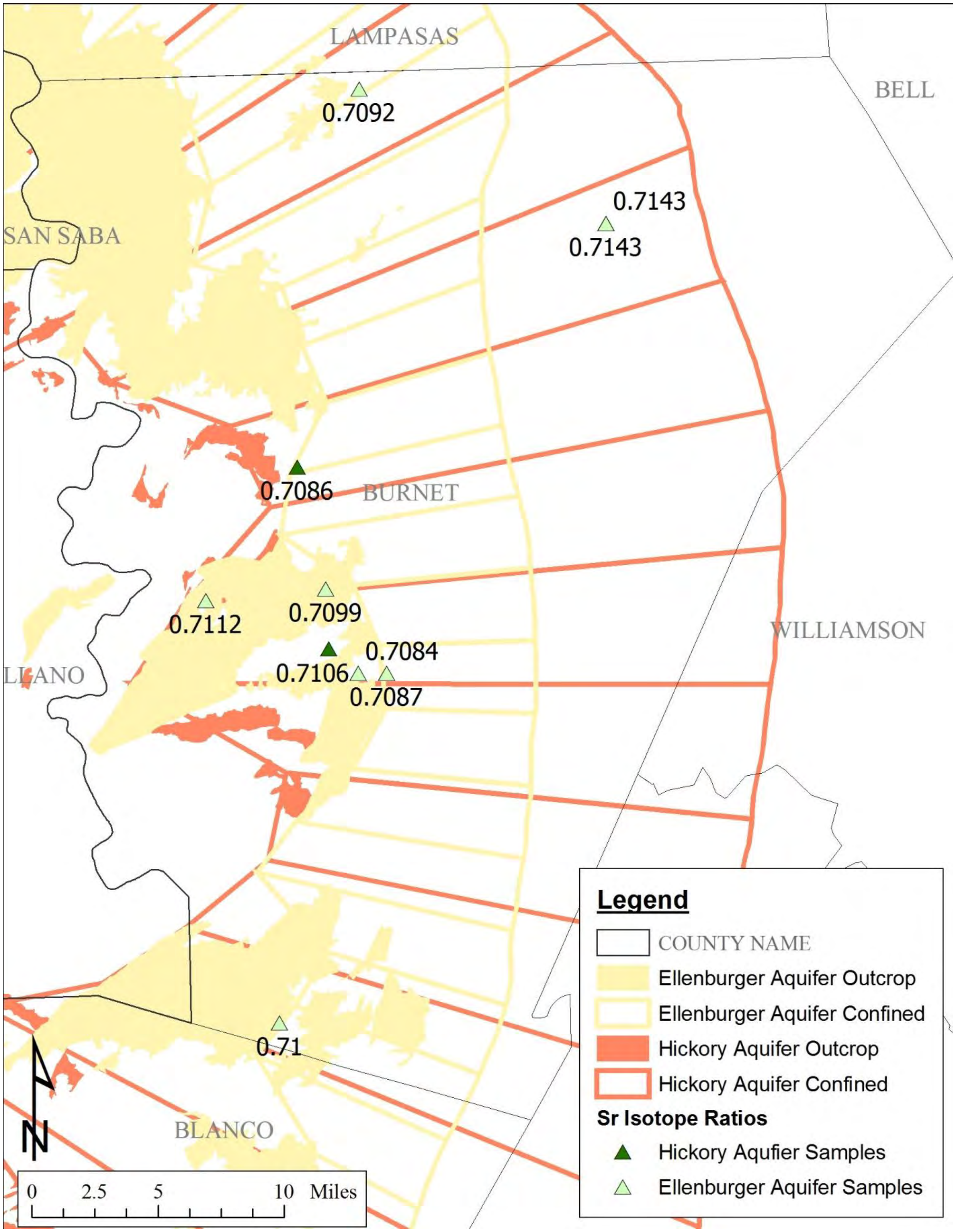


Figure 7-83. Map of strontium isotopic compositions ($^{87}Sr/^{86}Sr$) data for the east sub-region.

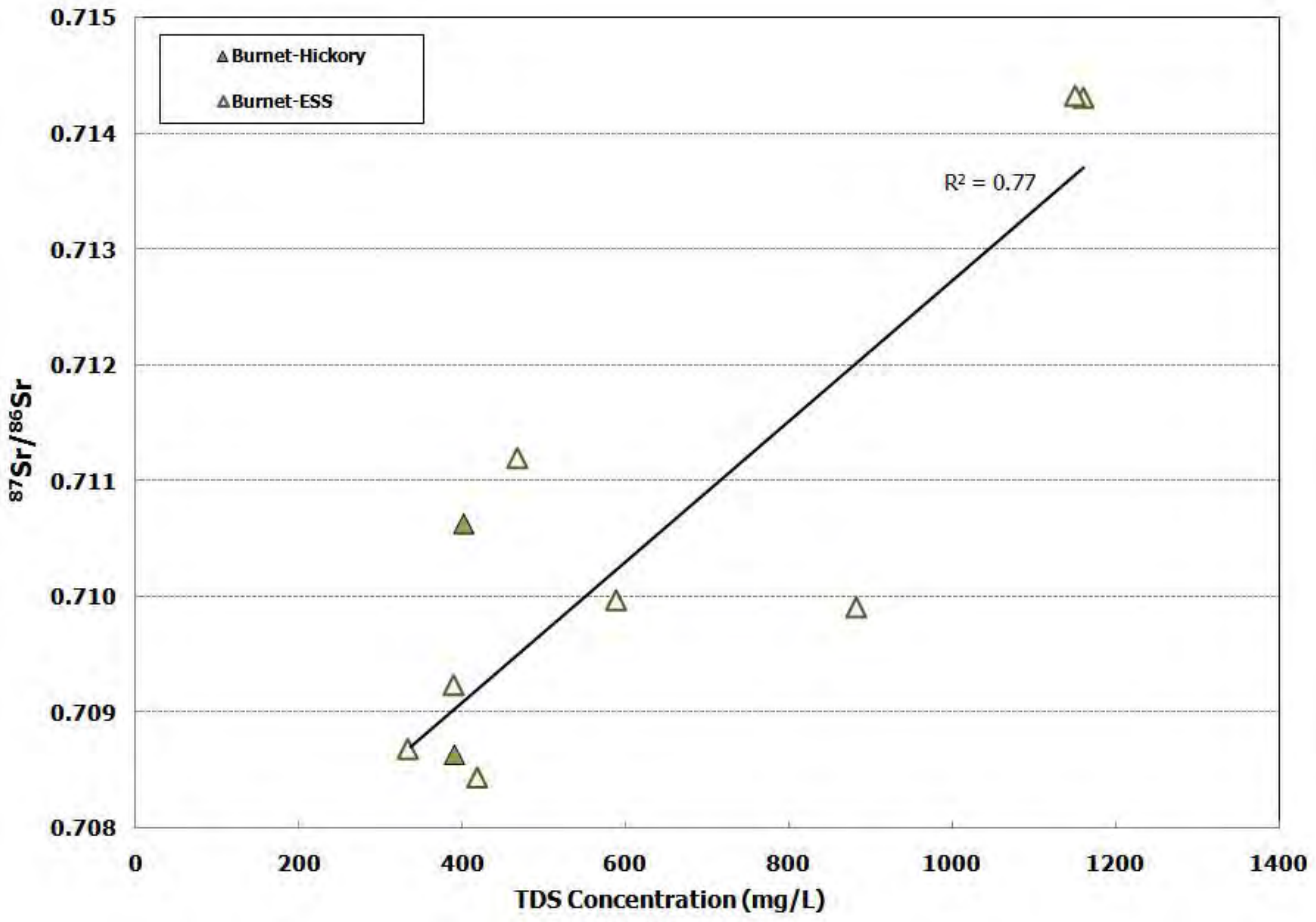


Figure 7-84. **Total dissolved solids (TDS) concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the east sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the Ellenburger-San Saba Aquifer samples.**

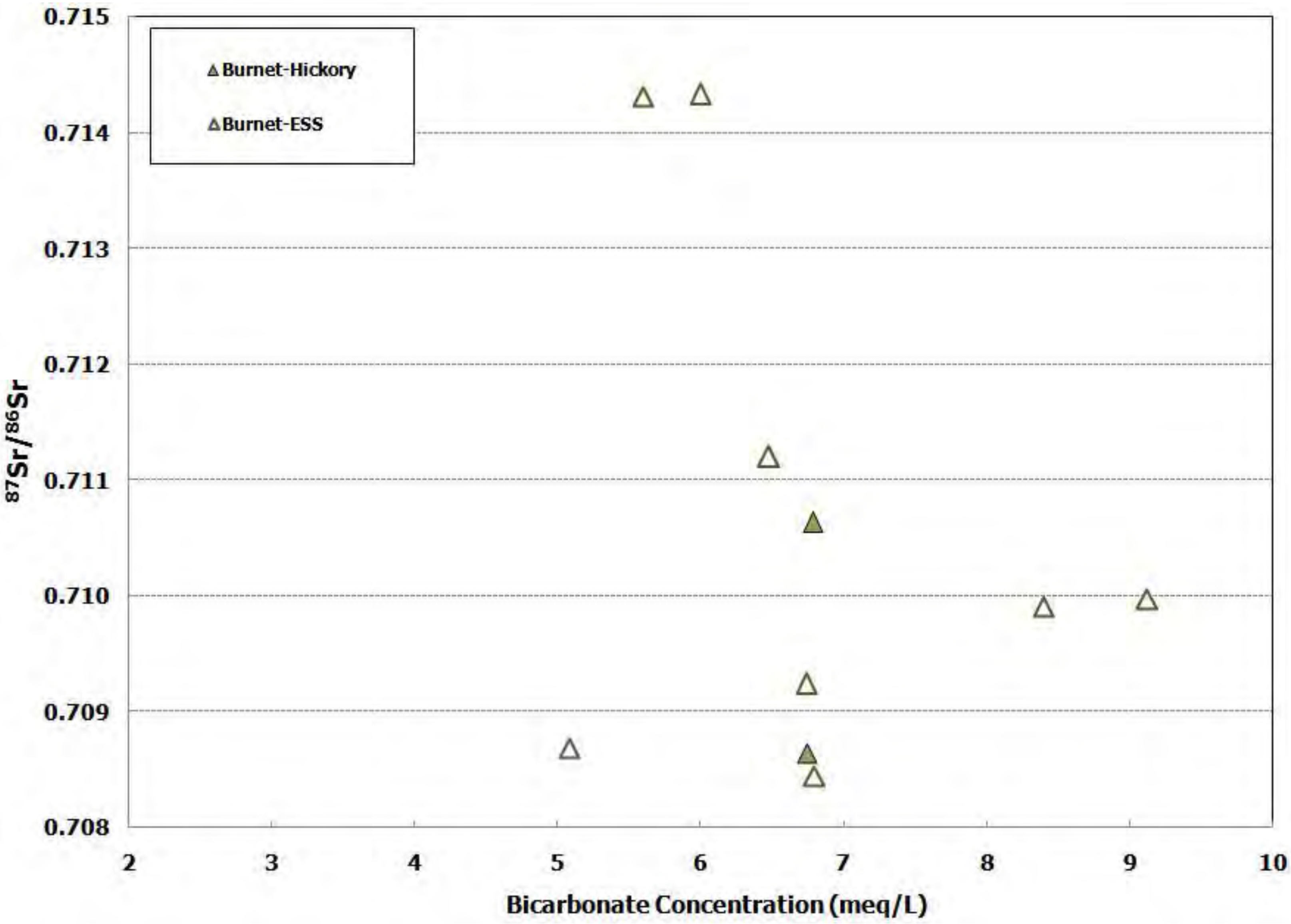


Figure 7-85. Bicarbonate concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the east sub-region.

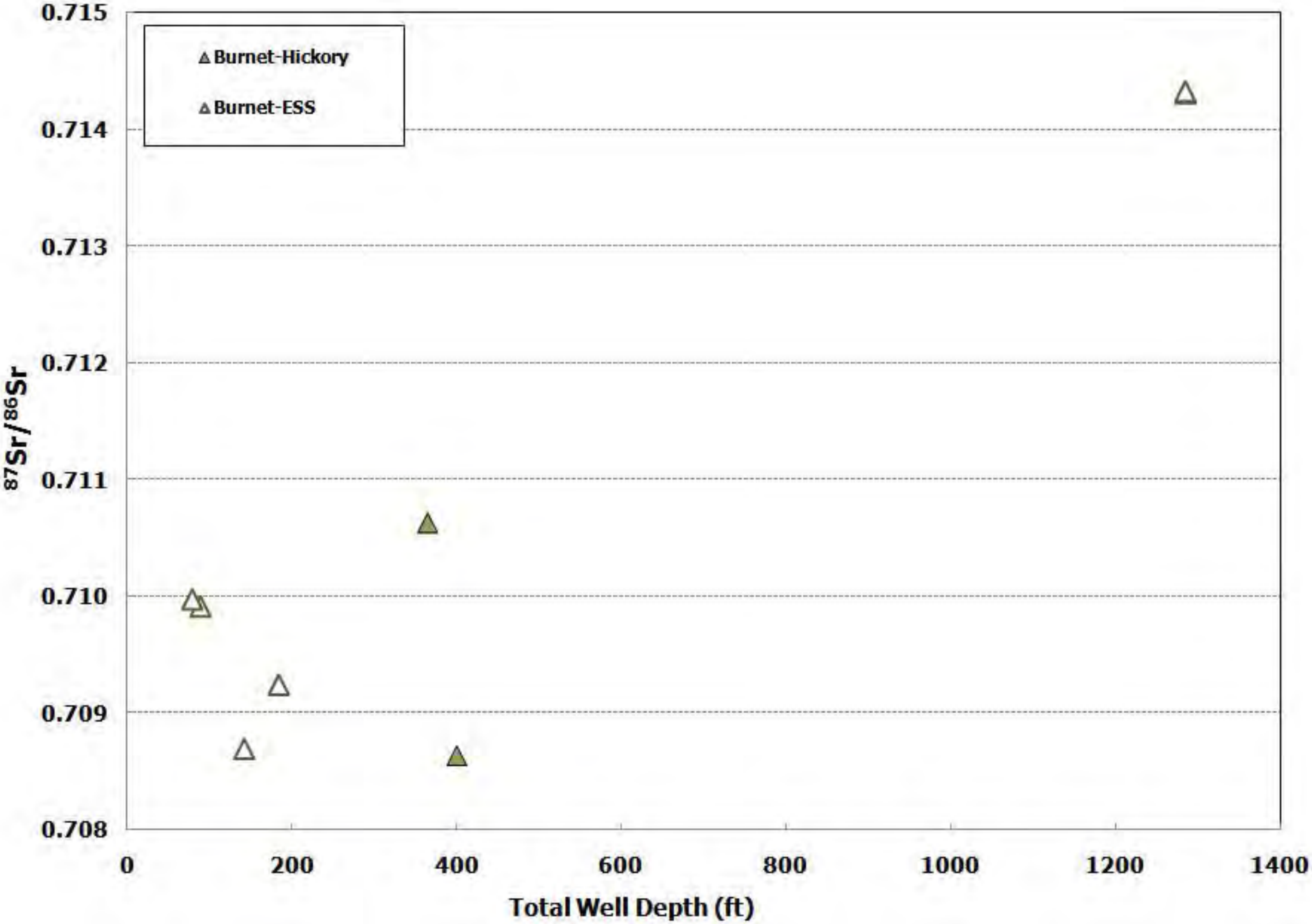


Figure 7-86. Total well depth vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the east sub-region

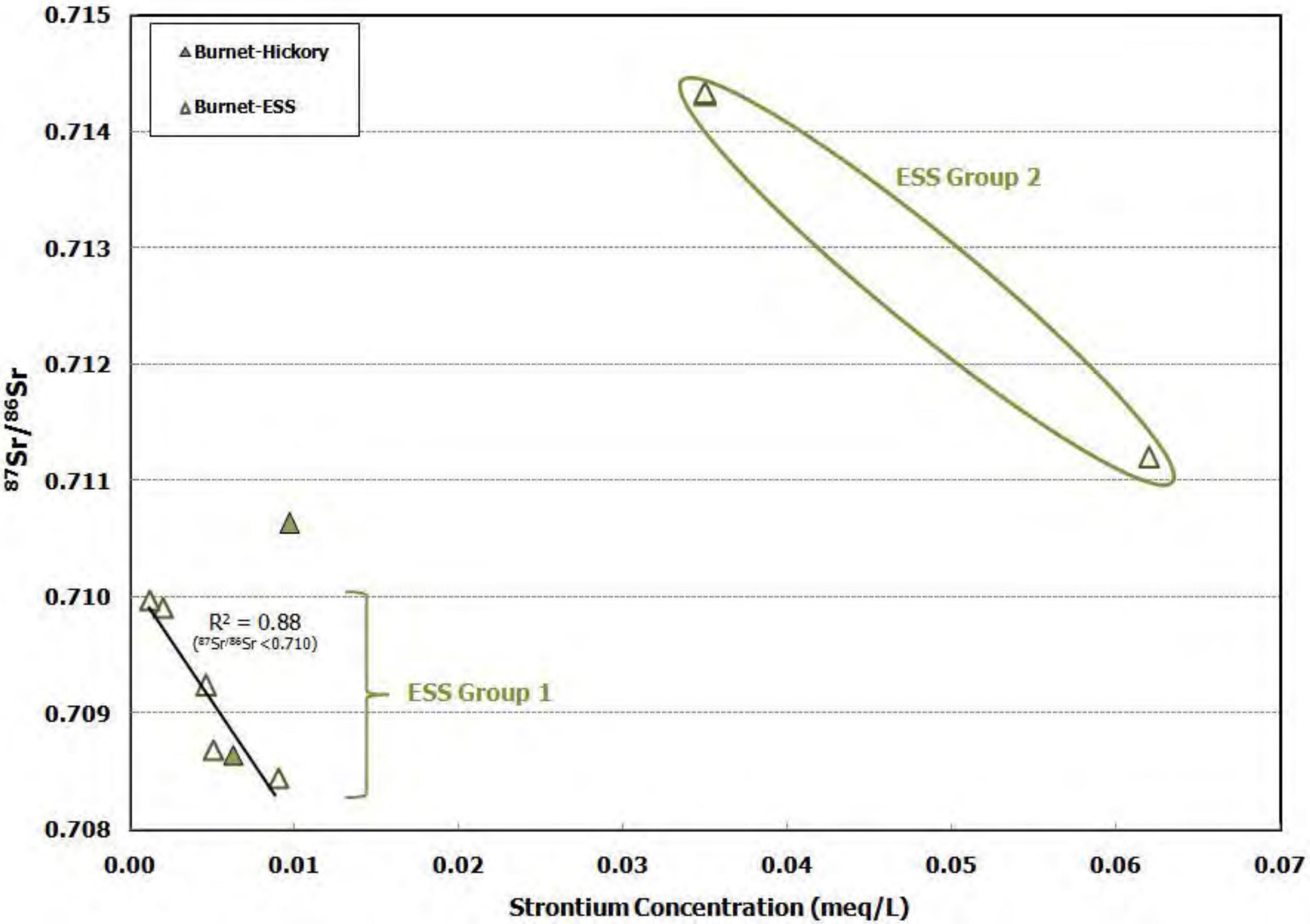


Figure 7-87. **Strontium concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the east sub-region. The solid black line is a linear least-squares regression, with the associated R^2, for the "Group 1" Ellenburger-San Saba Aquifer samples.**

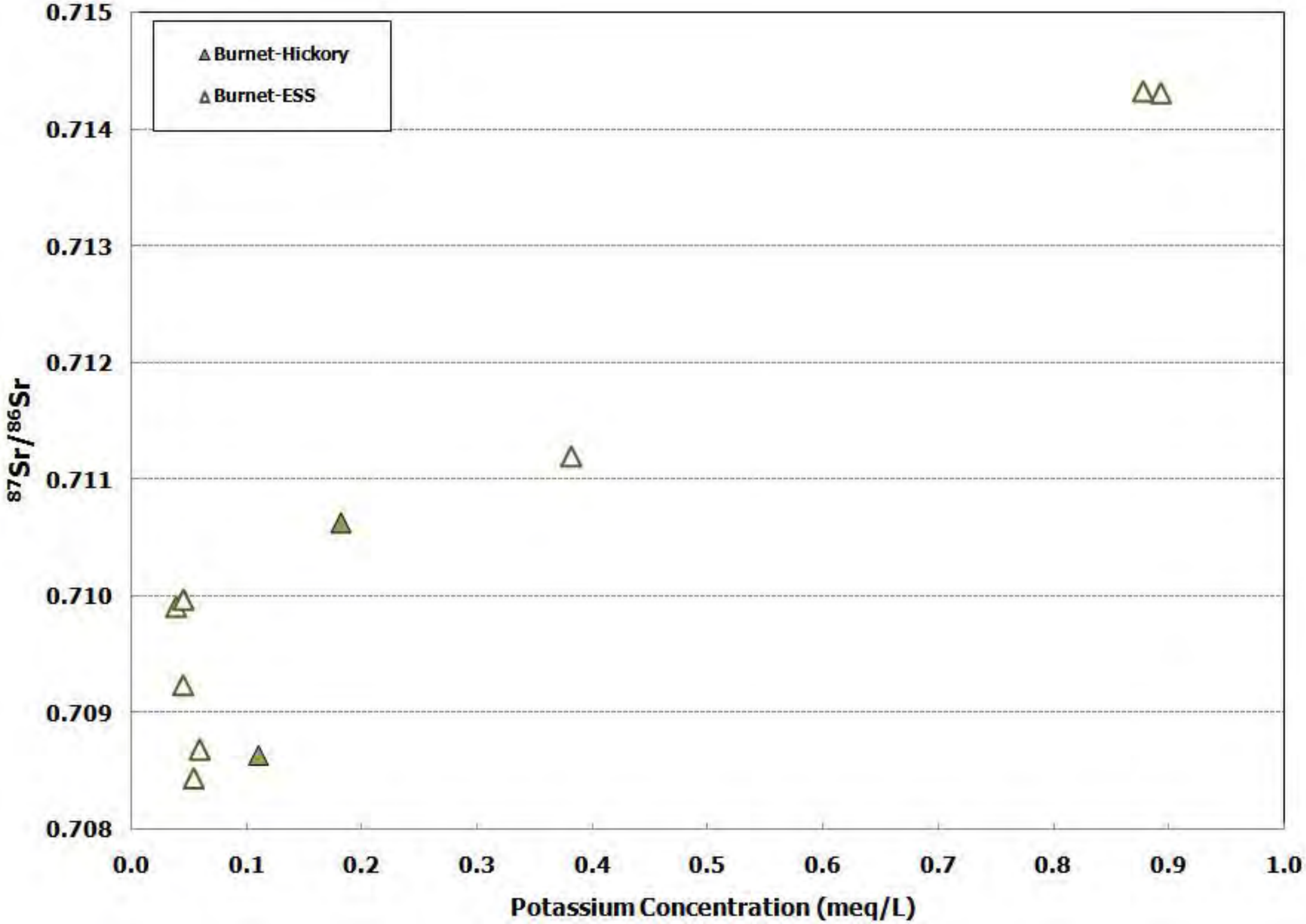


Figure 7-88. **Potassium concentration vs strontium isotopic compositions ($^{87}Sr/^{86}Sr$) for the East Sub-region.**

7.6 Conclusions

Three geographic areas were selected in the Llano Uplift area to develop conceptual models for the Hickory Aquifer and Ellenburger-San Saba Aquifers. The areas selected included McCulloch County (northern section), Gillespie County (southern section), and Burnet County (eastern section). Each area was anticipated to have a different conceptual model. Our investigation concluded:

- In the northern section, the Hickory Aquifer was the primary aquifer. There was an outcrop area and a downdip confined section of the aquifer. The outcrop area was an active recharge-discharge hydrogeologic setting. Groundwater in the downdip confined section of the aquifer was old and essentially stagnant. There was no evidence of upward leakage into the shallower Ellenburger-San Saba Aquifer. Based on this finding, it is assumed that the outcrop area of the Ellenburger-San Saba Aquifer is an active recharge-discharge setting, similar to the underlying Hickory. Although there is little downdip data to confirm that groundwater in this downdip section of the Ellenburger-San Saba Aquifer was older, the authors feel that a conceptual model incorporating this assumption is appropriate. Although there is no documentation available at the time when this report was finalized – verbal reports indicate a test well drilled near Brownwood, Texas in 2013 confirm this conceptual model. According to the verbal reports, laboratory analysis of the water in the Hickory Aquifer was saline and the Ellenburger water was brackish. This data should be evaluated further to develop a final conceptual model for the Ellenburger-San Saba Aquifer.
- In the southern section, both the Ellenburger-San Saba Aquifer and Hickory Aquifer were present but as isolated aquifers within separate faulted grabens. Both aquifers were overlain by the Cretaceous Hensell Formation and may be receiving significant leakage from the overlying Hensell Formation. Groundwater discharge is generally to the Pedernales River, which serves as a regional sink in the section of the aquifer. This hydrogeologic setting was considered to be a small localized system.
- In Burnet County (eastern section), the Ellenburger-San Saba Aquifer was the primary aquifer. Based on this study, it is assumed that the outcrop area of the Ellenburger-San Saba Aquifer is an active recharge-discharge setting with some recharge moving to deeper portions of the aquifer. The magnitude of the groundwater moving downdip is assumed to be controlled by downdip boundaries, for which there is limited data at this time. The regional tectonics of the Llano Uplift area had created three smaller localized aquifers for which recharge occurred in the outcrop and discharge was to local springs, streams and rivers. The Ellenburger-San Saba Aquifer was not a large regional flow system.

8 Edwards–Trinity (Plateau) Aquifer

8.1 Conceptual Groundwater Model

The Edwards Group on the Edwards-Trinity (Plateau) Aquifer is one of the most extensive aquifers in the state of Texas. It stretches approximately 300 miles across both GMA 3 and GMA 7 from Gillespie County on the east to Ector and Reeves counties on the northwest, and covers approximately three-quarters of GMA 7. This study area region is shown as the Edwards-Trinity (Plateau) Region on Figure 3-1 and includes only the eastern portion of the Edwards-Trinity (Plateau) Aquifer; the remainder of the aquifer is discussed in Chapter 9 of this study. Groundwater is extensively produced from this thinly layered aquifer system composed of the Cretaceous Edwards Group and the underlying Cretaceous Trinity Formation (Figure 8-1).

The shallower Edwards Group is a karstic unconfined limestone aquifer and is the primary producer in central and eastern portion of the plateau. In the northwest third of the plateau, the lower Trinity Group, referred to as the Antlers Formation, is the primary producer (Figure 8-2). The Antlers Formation is a slightly lithified sand which forms a confined aquifer in most areas (Figure 8-3). It is overlain by the Edwards Group and occasionally is exposed in streams cutting deeply into the Edwards-Trinity (Plateau) Aquifer. In the central section, very few wells are completed in the Trinity Group because the shallower Edwards Group generally provides sufficient water for the domestic and livestock demands in the region. In the eastern section, the Trinity Group is referred to as the Hensell Formation and is an important aquifer in central Texas counties such as Gillespie County. Between the Edwards Group area of production and the Antlers Formation area of production there is a transition zone of wells with dual completion from both the Edwards Group and the Trinity Group.

Topographically, the Edwards-Trinity (Plateau) Aquifer ranges from smooth to highly dissected surface that ranges in elevation from about 3,500 feet above mean sea level in the northwest to about 1,600 feet above mean sea level along the eastern and about 1,000 feet above mean sea level along the southern extent of the Edwards-Trinity (Plateau) Aquifer (the Rio Grande) as shown in Figure 8-4. Annual precipitation increases from about 12 inches at the highest elevation in the northwest to about 28-30 inches along the eastern boundary (Figure 8-5). It should be noted that this figure as well as others in this section were adapted from a previous study and will not be an exact representation of the GMAs 3 and 7 study area.

The potentiometric surface for the Edwards-Trinity (Plateau) Aquifer has been mapped for the Edwards Group and the Trinity Group as separate aquifers within the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) (Figure 8-6 and Figure 8-7) and by Nance (2010) as a composite water level map for both the Edwards and Trinity Groups (Figure 8-8). Both Anaya and Jones (2009) and Nance (2010) show a gently-dipping surface with the highest elevation (about 3,000 feet above mean sea level) in the northwest to about 1,600 feet at the eastern edge and about 1,000 feet along the southern edge (the Rio Grande). Inferred direction of lateral groundwater flow is down the gently-dipping potentiometric surface, that is, from northwest to south or east. This is true for overlying Edwards Group and underlying Trinity Group. Potentiometric maps in Anaya and Jones (2009) indicate that water levels in the Edwards Group are higher than water levels for the underlying Trinity Group and therefore there is generally potential for downward leakage from Edwards Group to Trinity Group.

Recharge to the unconfined Edwards Group is via percolation of rainfall through the unsaturated zone to the water table. The amount of recharge is estimated to be about 4% or less of annual precipitation (Anaya and Jones, 2009). Based on this assumption, recharge therefore increases from northwest to east as the amount of annual precipitation increases from northwest to the eastern areas of the Edwards-Trinity (Plateau) Aquifer (Figure 8-5). Green and Bertetti (2012) argue that there is a threshold of no recharge when annual precipitation declines to about 16-18 inches per year. The geographic area for 16-18 inches per year or less, i.e., the area of no recharge, is the northwest third of the Edwards-Trinity (Plateau) Aquifer. Nance (2010) makes a convincing argument that most recharge to the Edwards Group is through the ephemeral stream beds that have downcut into the plateau and not as diffuse recharge through the upland arid soils.

The groundwater flow in the Edwards-Trinity (Plateau) Aquifer is regional in nature due to the gently dipping, continuous potentiometric surface, its unconfined nature and the high transmissivity of the Edwards Group. A single flow tube might extend across the entire aquifer but with the continual addition of precipitation enhanced recharge through the overlying unsaturated section.

The hydrochemistry of the Edwards Group and Trinity Group, in the Edwards-Trinity (Plateau) Aquifer, has been studied by Nance (2010). His important geochemical observations are as follows:

1. The chemical composition of the Edwards Group groundwater in the central and eastern region of the Edwards-Trinity (Plateau) is a low total dissolved solids (less than 500 mg/l) and predominantly bicarbonate water. That finding is confirmed in this study, as illustrated in Figure 8-9, Figure 8-10 and Figure 8-11.
2. The chemical composition of the Antlers Formation groundwater is dominated by high total dissolved solids ranging from 500 mg/l to over 2,000 mg/l, high sulfate water or a mixture of sulfate and bicarbonate. This conclusion is confirmed in this study as shown in Figure 8-10, Figure 8-12 and Figure 8-13.
3. The area of higher total dissolved solids, sulfate-chloride waters in the Antlers Formation (northwest plateau) directly overlies subcrops of the Dockum Aquifer and Permian strata Figure 8-14. The poorer water quality in the Antlers Formation may result from long-term upward discharge from these underlying brackish to saline formations.
4. The majority of the Antlers Formation waters, based on carbon-14 percent modern and tritium values (with tritium less than 0.5 and carbon-14 percent modern less than 0.4), are older than the majority of Edwards Group waters (from tritium greater than 0.5 and carbon-14 percent modern greater than 0.4). This study finds the same conclusion and that shows the majority of the Antlers Formation waters are old and non-recharging as shown in Figure 6-11. In contrast, a majority of the Edwards Group waters are relatively younger and have been recharged more recently (Figure 6-9 and Figure 6-10). Young water in the Edwards Group extends to the western arid extent of the plateau (Figure 6-10). This conclusion is not in agreement with Green and Bertetti (2012), that there should be a zone of minimal recharge in this western region of limited precipitation.
5. There is a higher total dissolved solids zone in the Edwards Group in Crockett County, which may indicate leakage of underlying Antler Formation waters into the

Edwards Group (Figure 6-10). An alternate source may be from salt water contamination from oil and gas production.

These five geochemical observations are important in refining the conceptual model as developed by Anaya and Jones (2009).

1. Based on the finding of some younger water in the Edwards Group all the way to the western extent of the Edwards-Trinity (Plateau) Aquifer (Figure 6-9 and Figure 6-10), recharge is actively occurring all across the outcrops. It is likely that recharge occurs mainly during very wet periods or during extended and high precipitation events and when evapotranspiration is low (Beach and others, 2006). The assumption that the recharge is linearly related to annual precipitation is sufficient for the regional model and over long periods of time.
2. The higher total dissolved solids, chloride-sulfate waters in the Antlers Formation strongly suggest that there is upward leakage of some saline water from the underlying Triassic or Paleozoic. The conceptual model developed by Anaya and Jones (2009) assumes a no flow boundary across the base of the Edwards-Trinity (Plateau) Aquifer system, except for this northwest region of their Edwards-Trinity (Plateau) Aquifer model.
3. There is a marked change in water chemistry from the Antlers Formation (northwest) to the Edwards Group (central, south and east). If there is significant flow from the northwest plateau to the east and central parts of the aquifer the poorer water quality of the Antlers Formation should also be present in the Edwards Group. The water chemistry in the Edwards Group is low total dissolved solids calcium-bicarbonate water. In contrast, the Antler Formation water is a high total dissolved solids sodium-sulfate water. This suggests that either; 1) there is no substantial regional groundwater flow from the northwest section of the Edwards-Trinity (Plateau) to the rest of the aquifer or 2) recharge from precipitation to the unconfined Edwards Group overwhelms any chemical signature from the Antlers Formation, which is located hydraulically upgradient. Two exceptions to this trend is a zone of higher total dissolved solids waters in the Edwards Group in Reagan and Crockett counties, which may represent some mixing of Antlers Formation and Edwards Group waters and a second saline zone in the Edwards Group along the Rio Grande. Heavy pumping in the Glasscock, Midland, Reagan and Upton counties area may have resulted in upwelling of groundwater from the Trinity Group. Similarly the Edwards Group along the Rio Grande may be receiving discharge from more saline deeper formations. Depending on modeling objectives, it might be more appropriate to develop two models to represent the Edwards-Trinity (Plateau) Aquifer based on what appears to be two relatively separate flow systems.
4. The lack of the Trinity Group wells in the central, southern and eastern sections suggests either there is no productive Trinity Group beneath the Edwards Group in this region, caused by poor water quality or lack of transmissivity, or that drillers never tested the deeper Trinity Group because sufficient productivity could be found in the overlying Edwards Group. The GAM for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) indicates 150,000 acre-feet per year of leakage from the Edwards Group down to the Trinity Group. If this actually occurs in the aquifer system, the Trinity Group should be a productive aquifer. In the area of Antler's

Formation production in the northwest, the Antlers Formation waters are old and of poor water quality which suggests limited recharge is coming through the overlying Edwards Group. This suggests that the Edwards Group and Trinity Group elsewhere may be two largely separate aquifers with minimal leakage between them.

To address these questions the GAM models for the Edwards-Trinity (Plateau) Aquifer, the Dockum Aquifer and the Rustler Aquifer were run to:

1. Estimate the leakage from the Rustler Aquifer and the Dockum Aquifer into the base of the Edwards-Trinity (Plateau) Aquifer.
2. Estimate the water budget for lateral flow for the Edwards Group and Trinity Group between sub regions.
3. Estimate the water budget for vertical flow between the Edwards Group and Trinity Group.
4. Simulate particle tracking of groundwater in a single flow tube from the northwest part of the Edwards-Trinity (Plateau) Aquifer to a point of discharge along the Rio Grande.

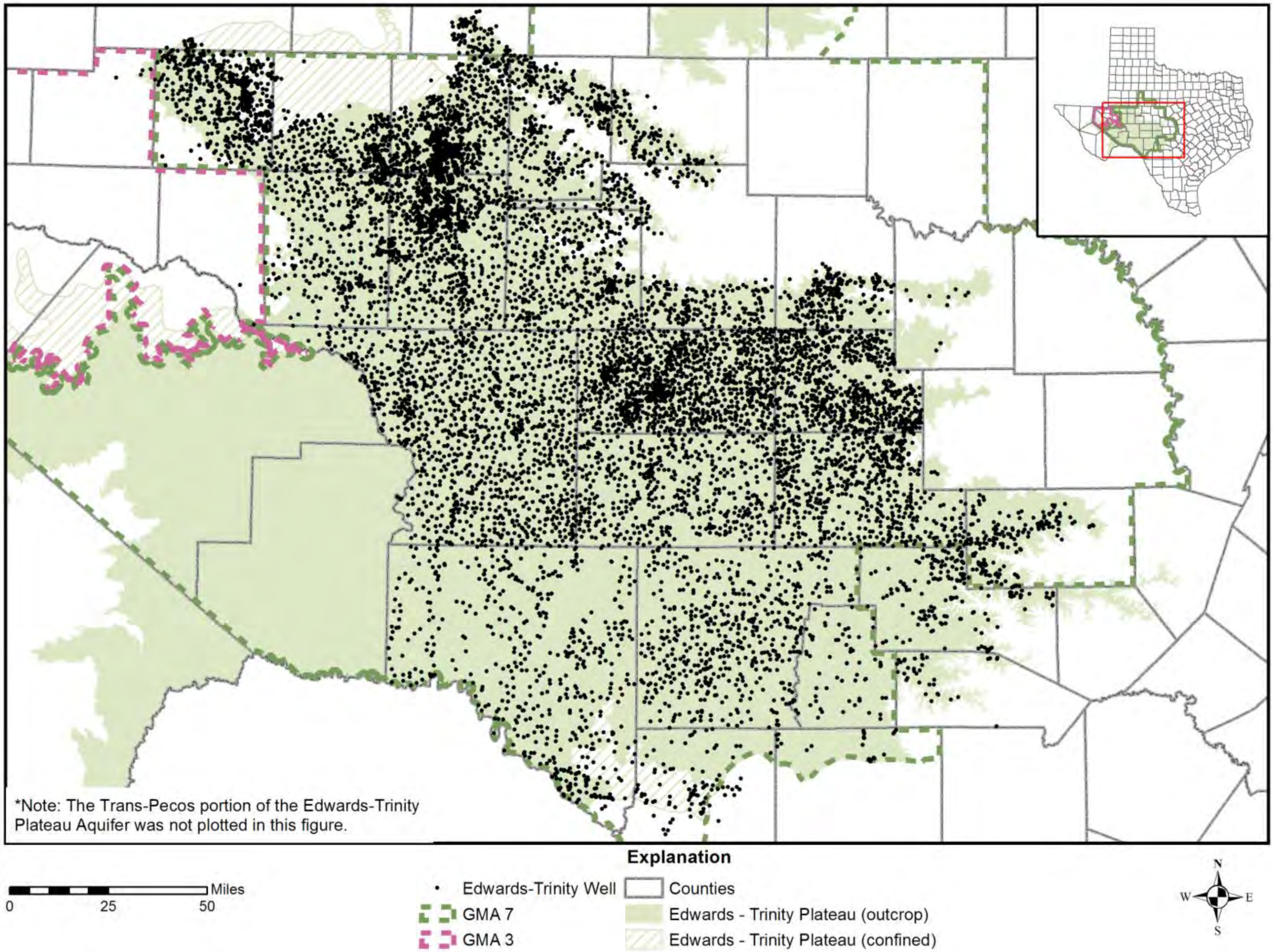
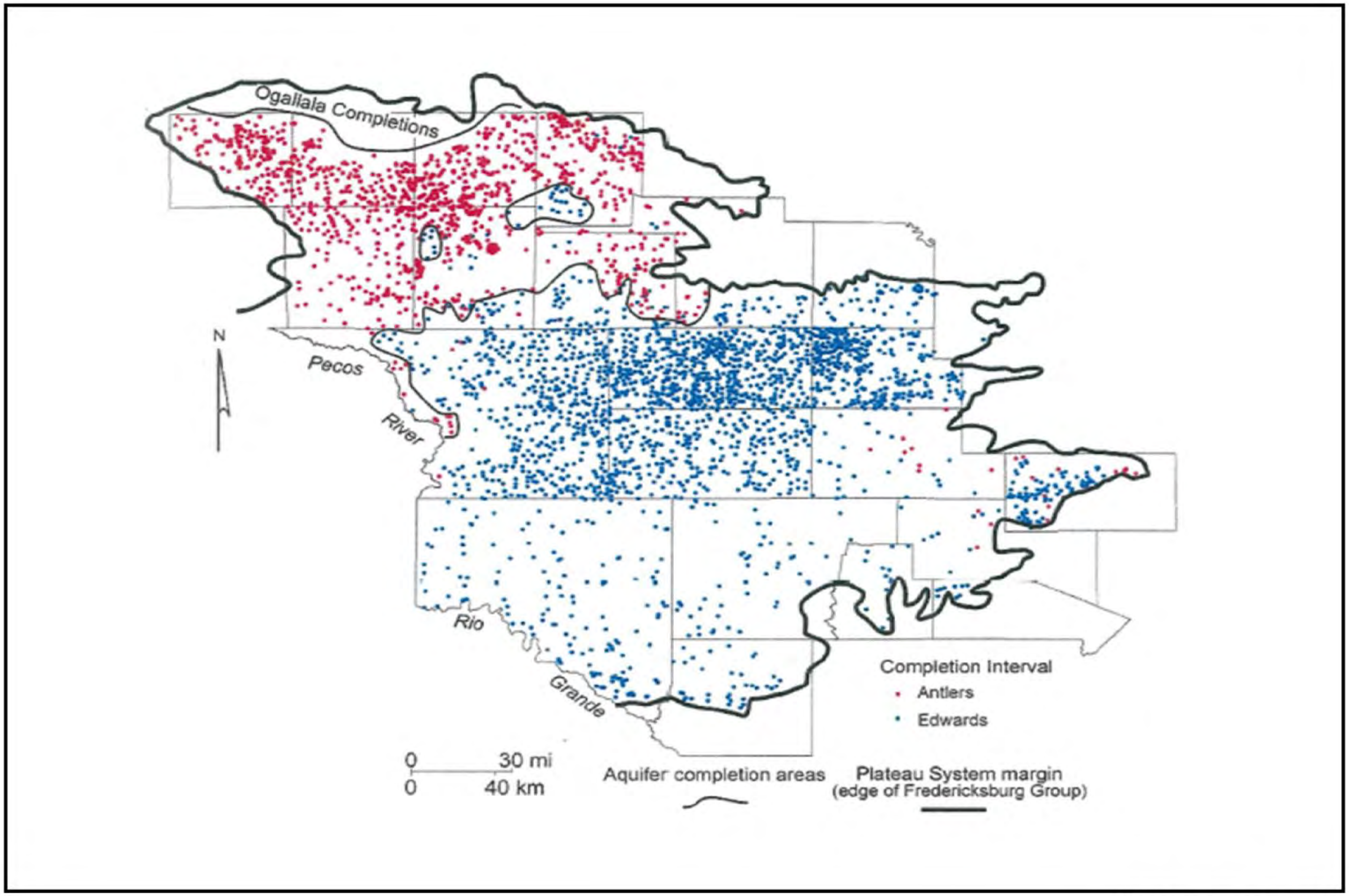


Figure 8-1. **Location of both Edwards Group and Trinity Group (Antlers Formation) water wells used in chemistry analysis, Edwards-Trinity (Plateau) Aquifer.**



(Modified from: Nance, 2010)

Figure 8-2. **Distribution of Edwards Group wells and Antler Formation wells, Edwards-Trinity (Plateau) Aquifer generalized topography of GMAs 3 and 7.**

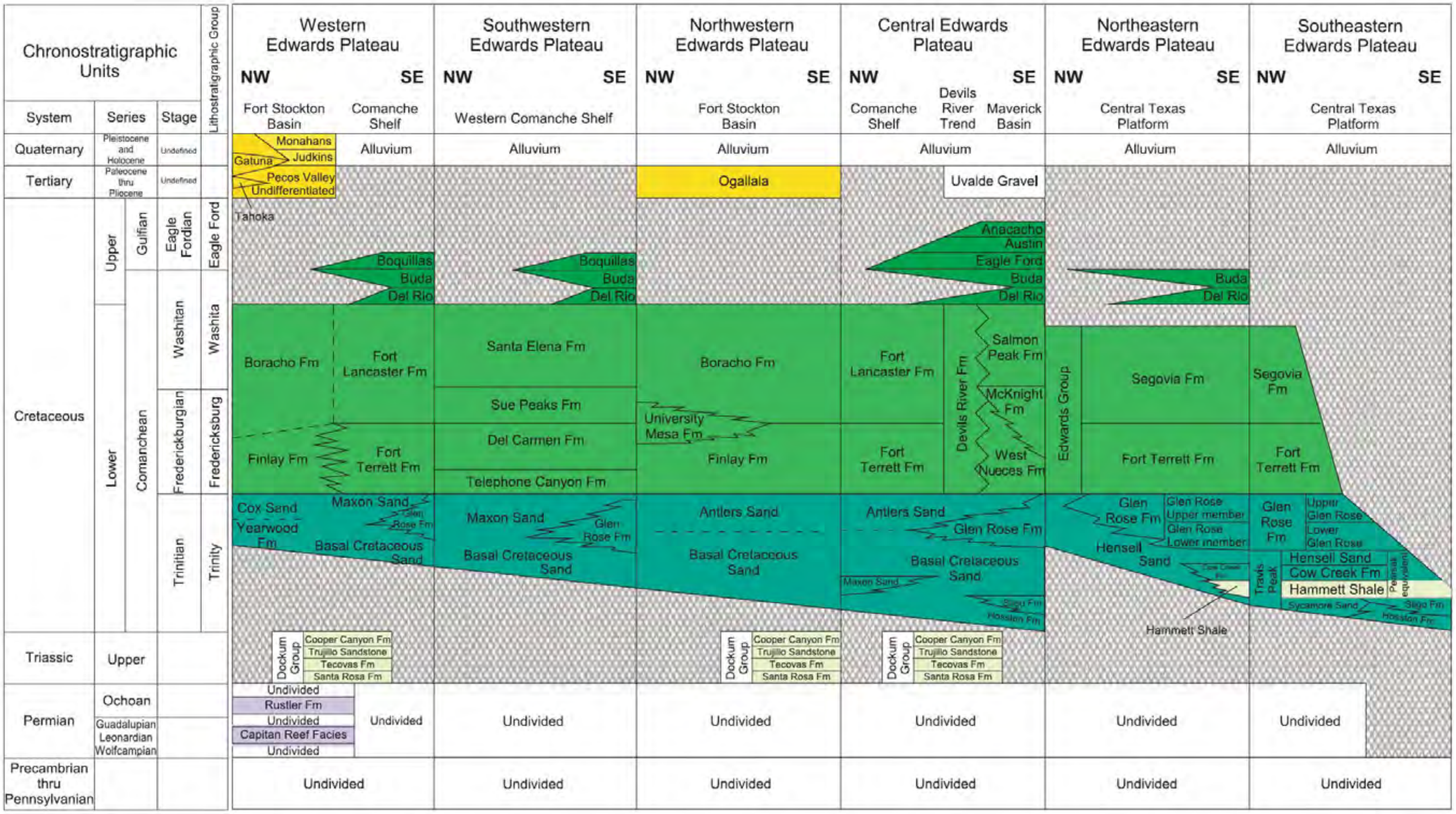


Figure 8-3. Stratigraphic column representing sections of the Edwards-Trinity (Plateau) Aquifer (from Anaya and Jones, 2009)

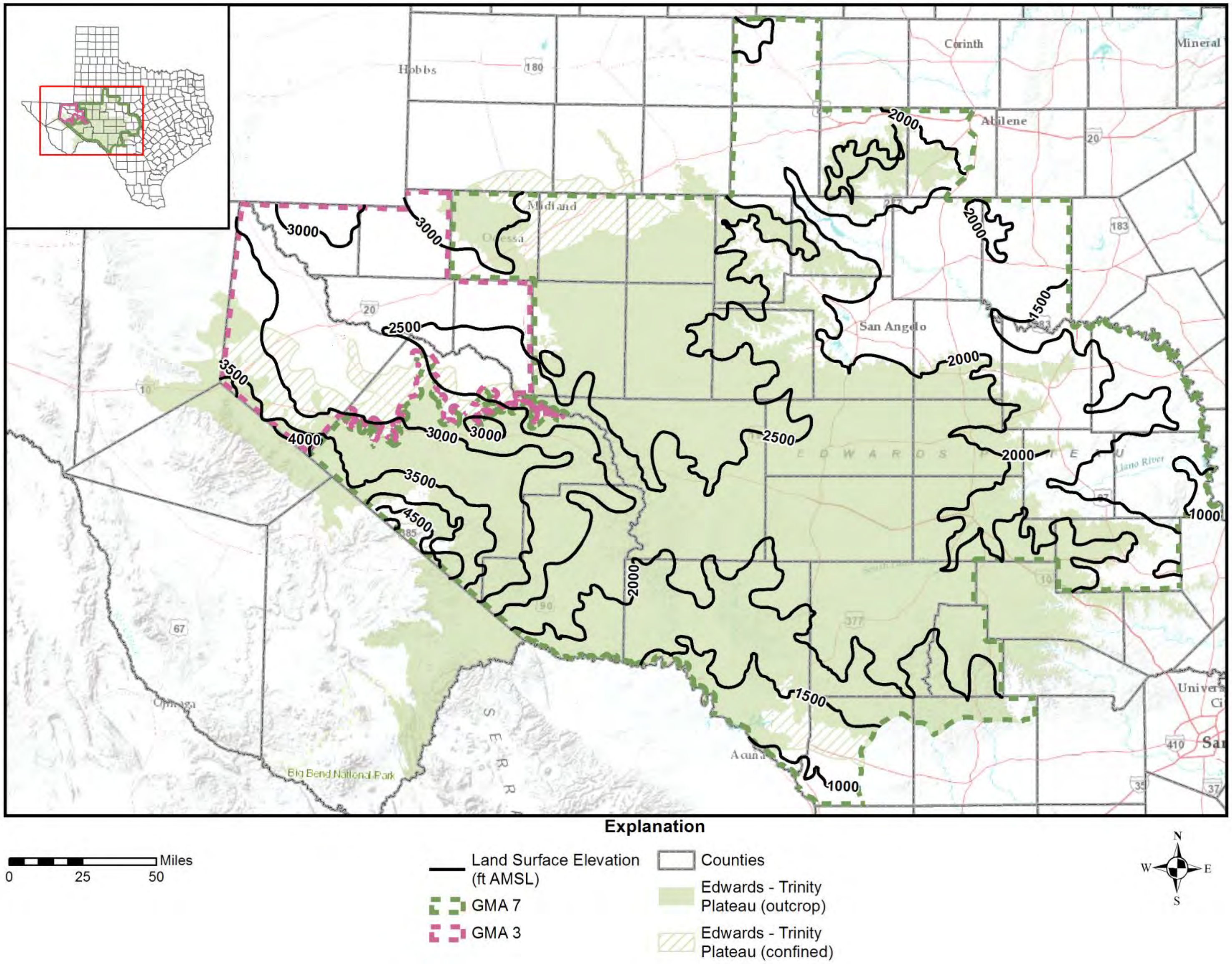
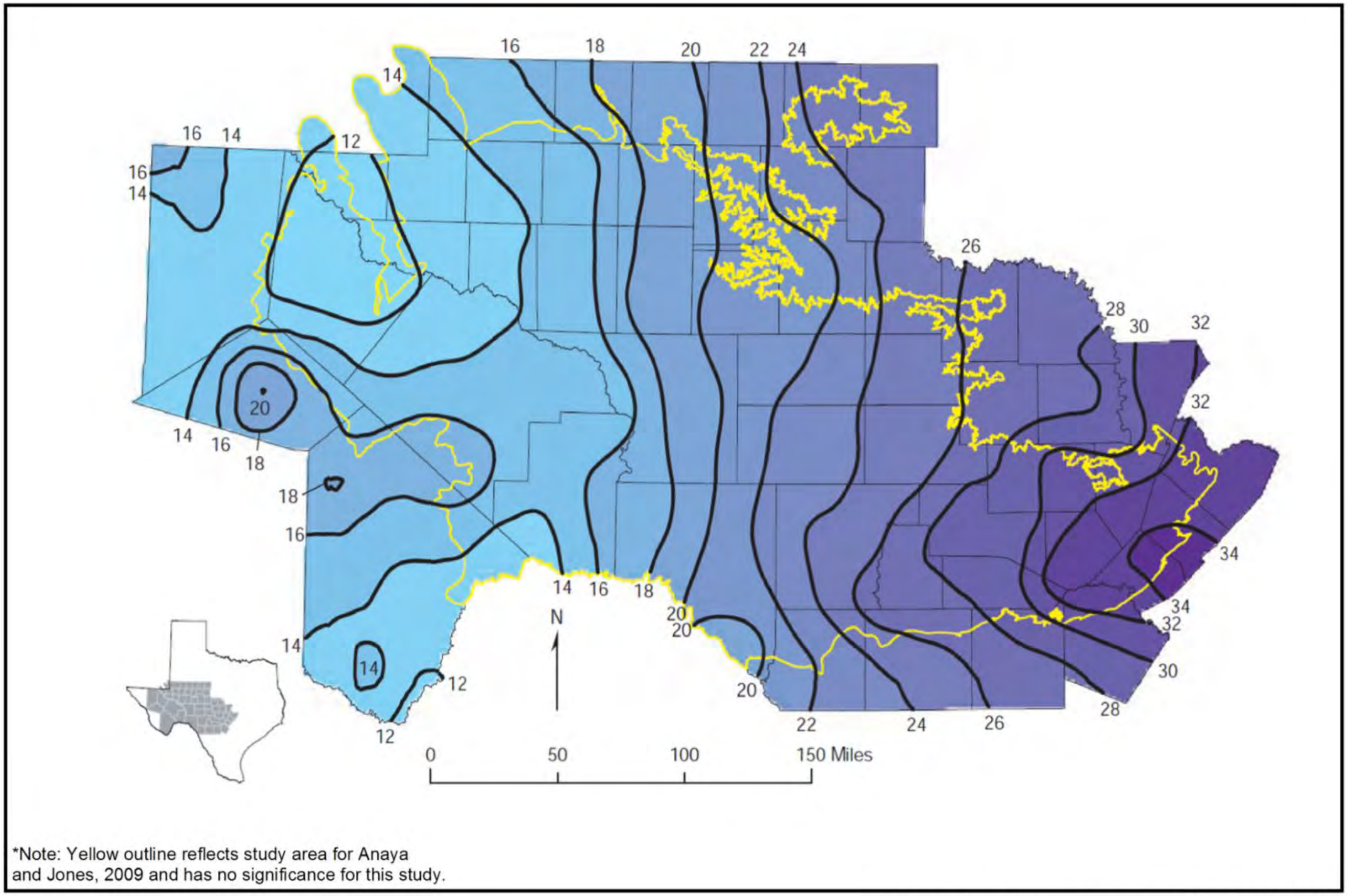


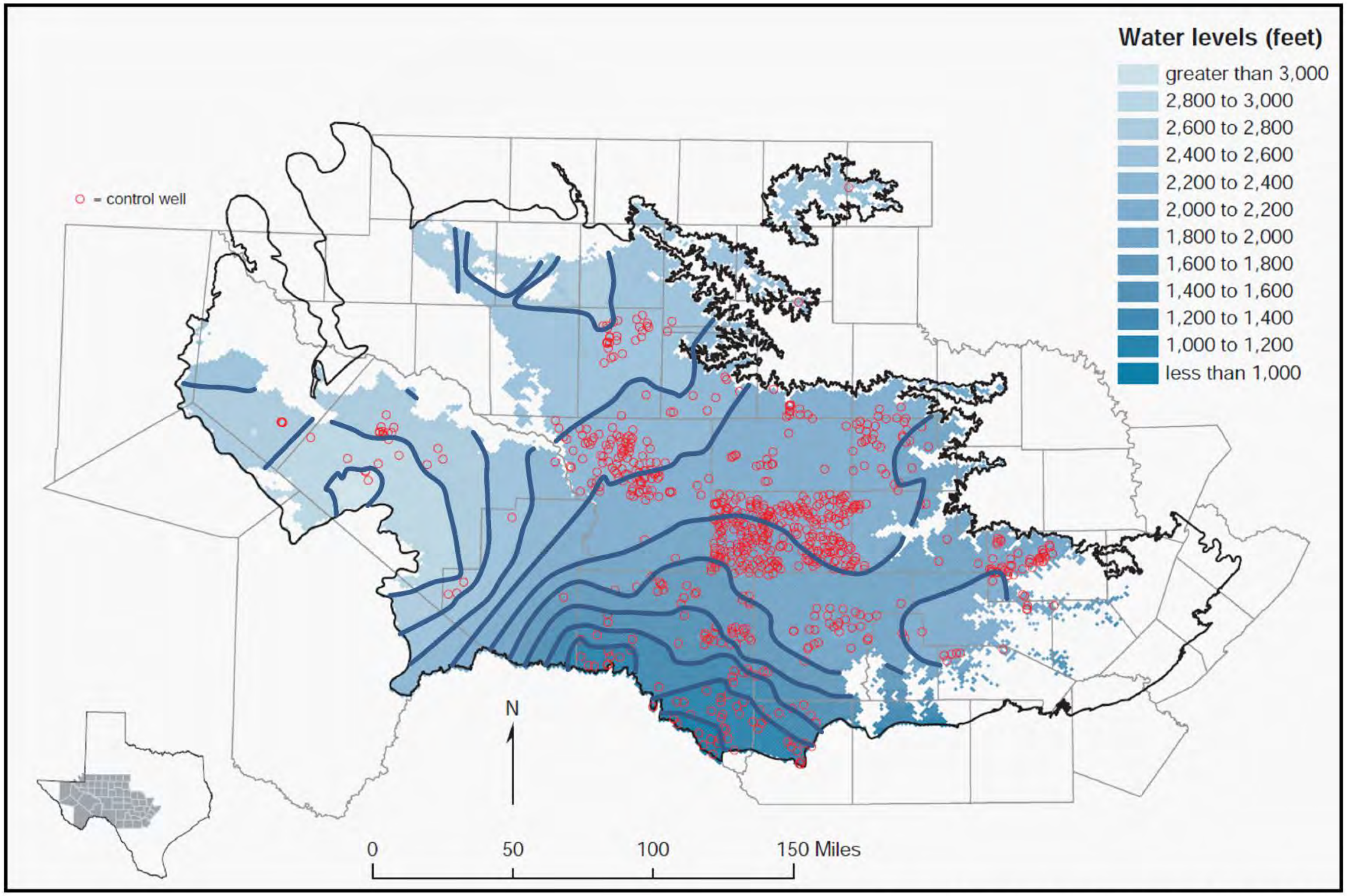
Figure 8-4. **Generalized topography of GMAs 3 and 7.**



*Note: Yellow outline reflects study area for Anaya and Jones, 2009 and has no significance for this study.

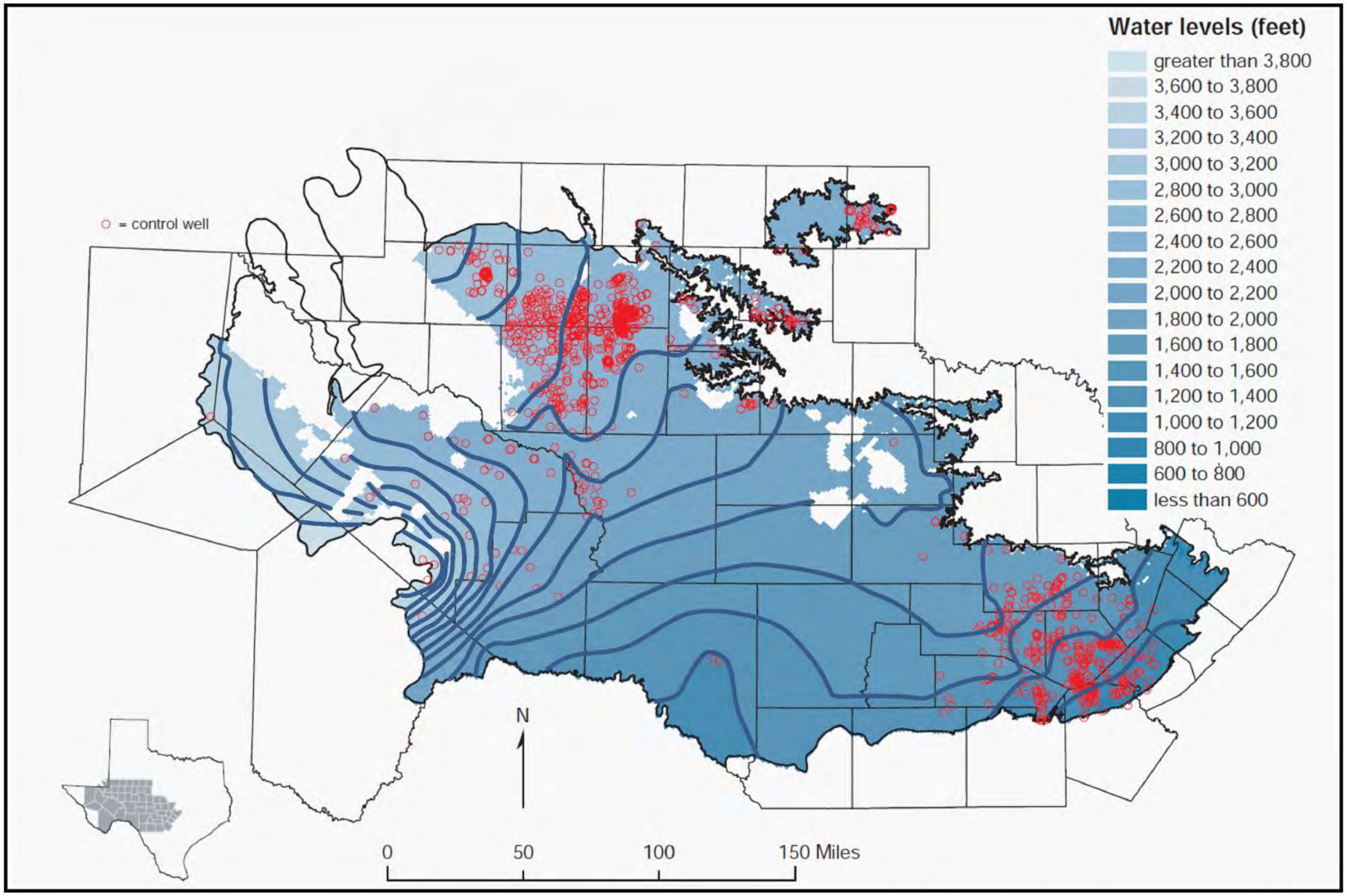
(Modified from: Anaya and Jones, TWDB Rept 373, 2009)

Figure 8-5. **Average annual precipitation.**



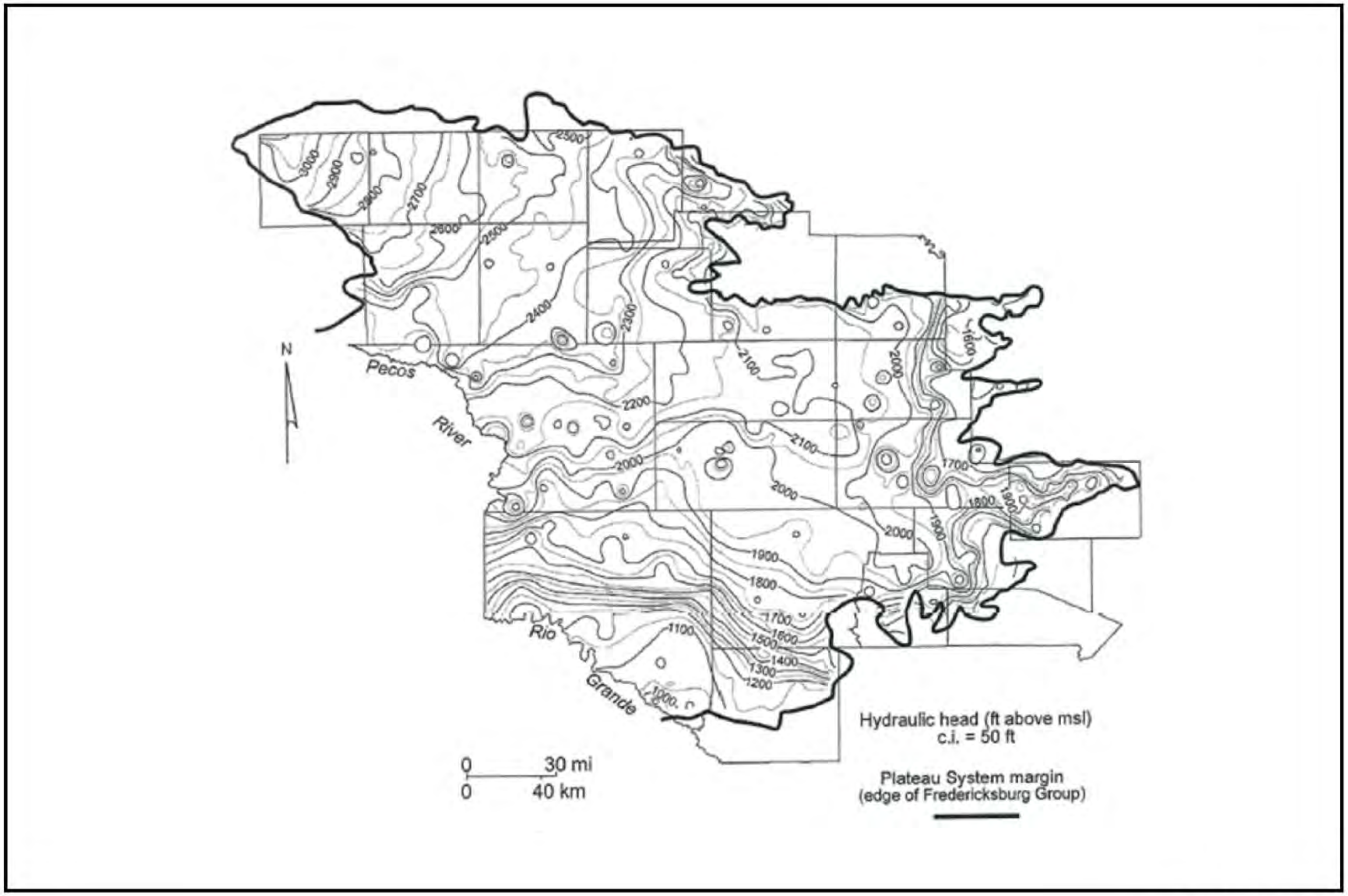
(Modified from: Anaya and Jones, TWDB Rept 373, 2009)

Figure 8-6. Potentiometric surface of both the Edwards Group and Trinity Group of the Edwards-Trinity (Plateau) Aquifer.



(Modified from: Anaya and Jones, TWDB Rept 373, 2009)

Figure 8-7. **Potentiometric surface of the Trinity Group of the Edwards-Trinity (Plateau) Aquifer.**



(From: Nance, 2010)

Figure 8-8. **Potentiometric surface of composite Edwards Group and Trinity Group (Antlers Formation) of the Edwards-Trinity (Plateau) Aquifer.**

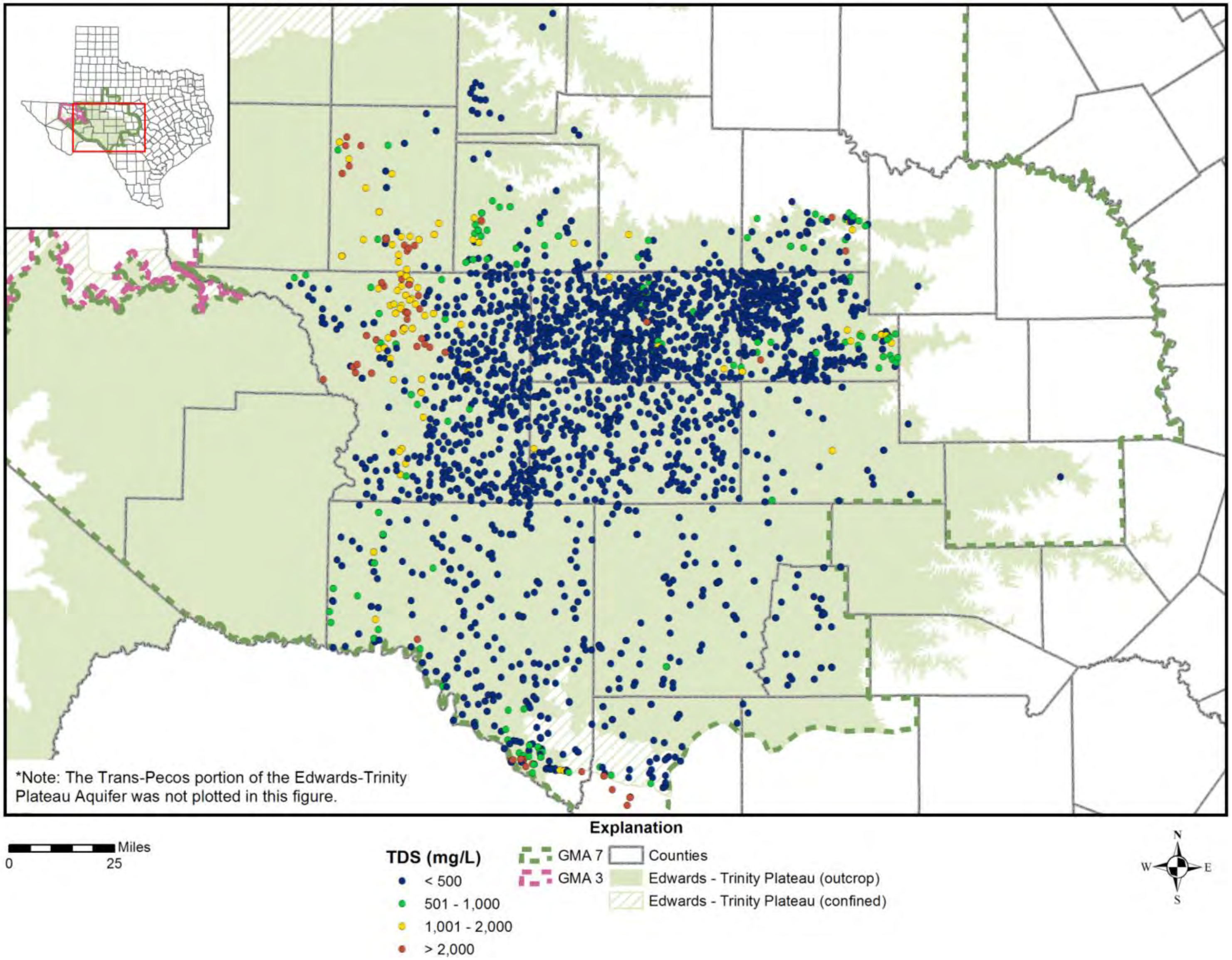


Figure 8-9. **Total dissolved solids (TDS) of the Edwards Group water samples from Edwards-Trinity (Plateau) Aquifer.**

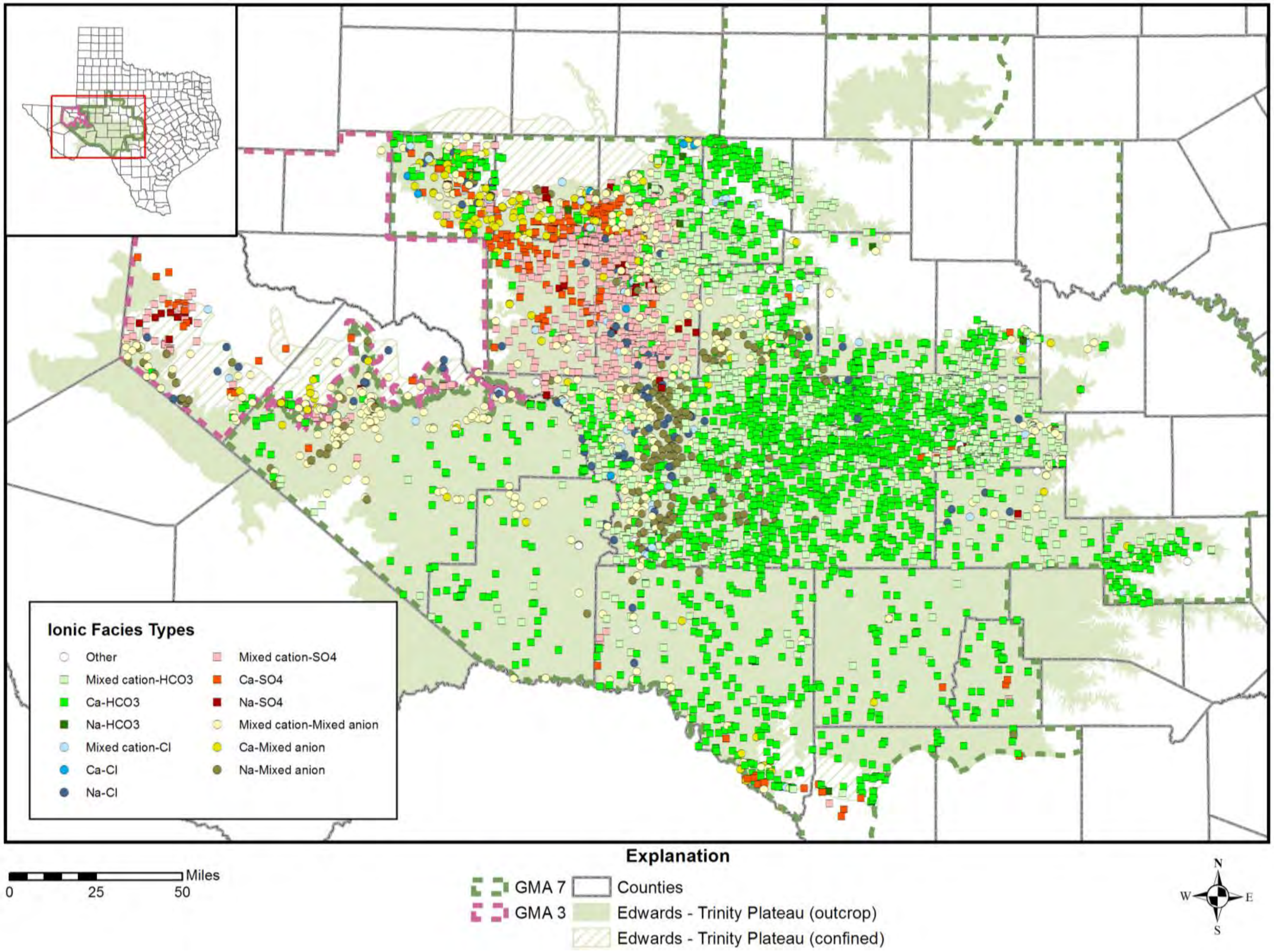


Figure 8-10. **Major chemical composition of groundwater in the Edwards-Trinity (Plateau) Aquifer.**

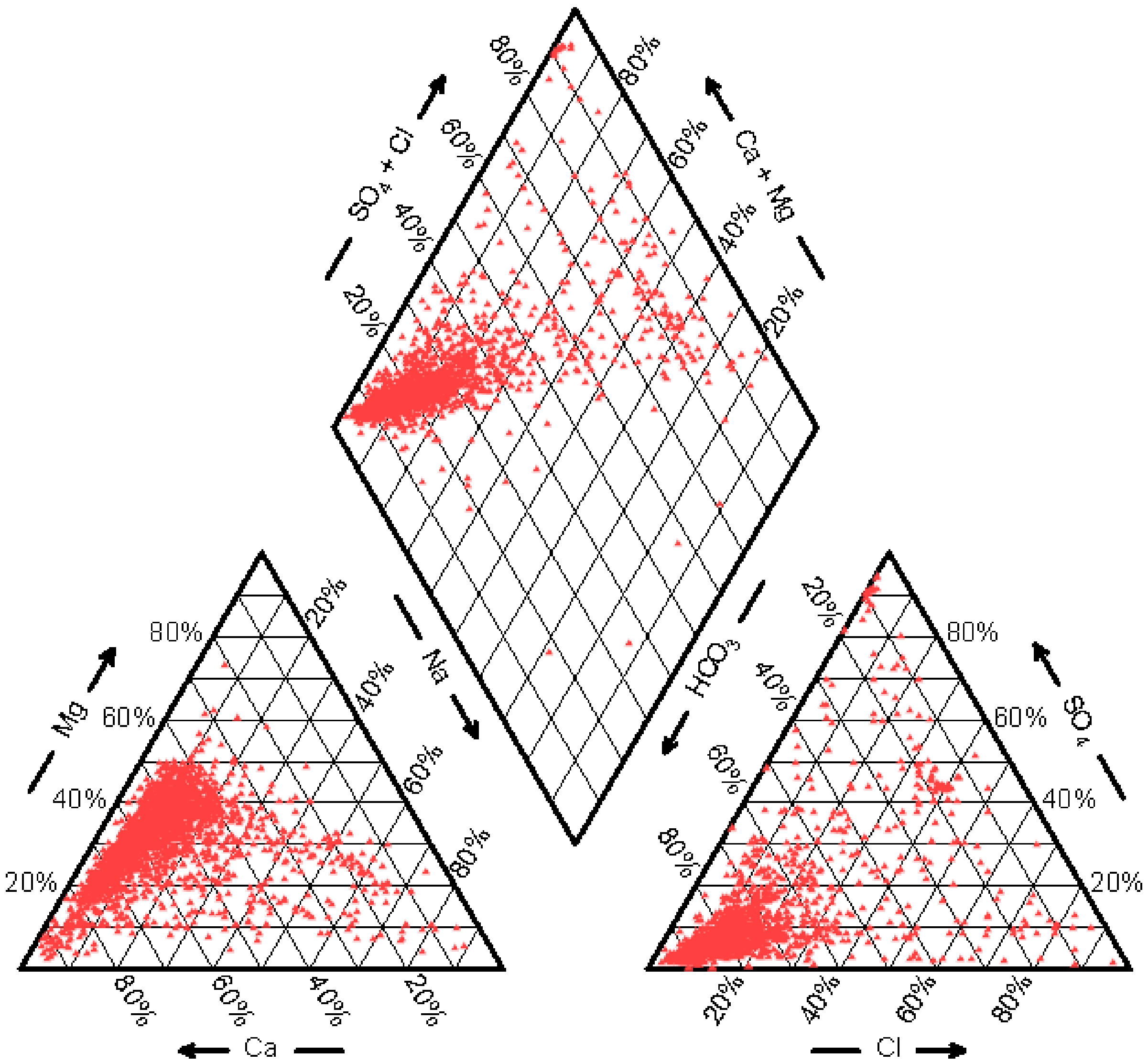


Figure 8-11. **Piper diagram for the Edwards Group groundwater, Edwards-Trinity (Plateau) Aquifer.**

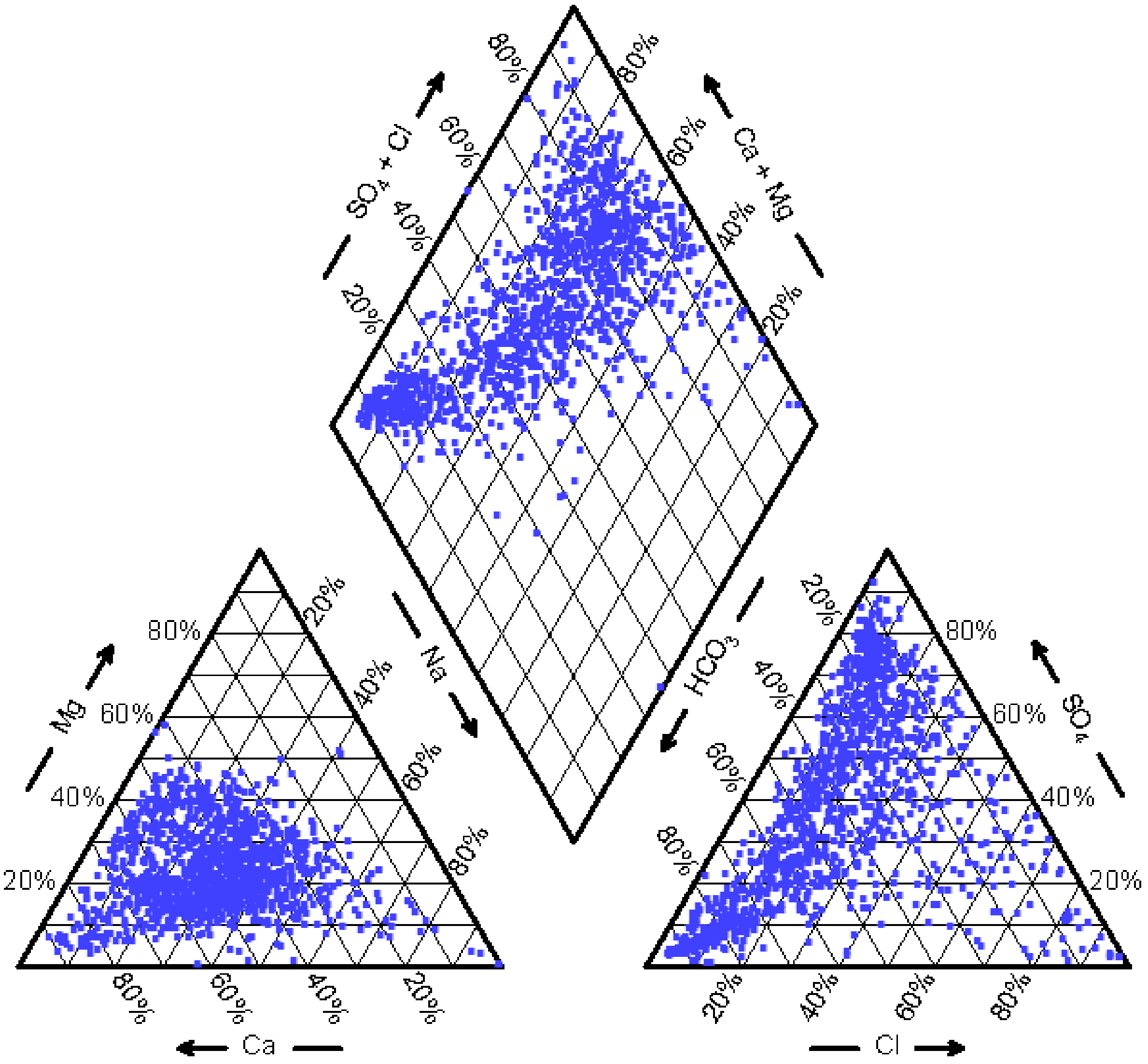


Figure 8-12. Piper diagram for Antlers Formation groundwater, Edwards-Trinity (Plateau) Aquifer.

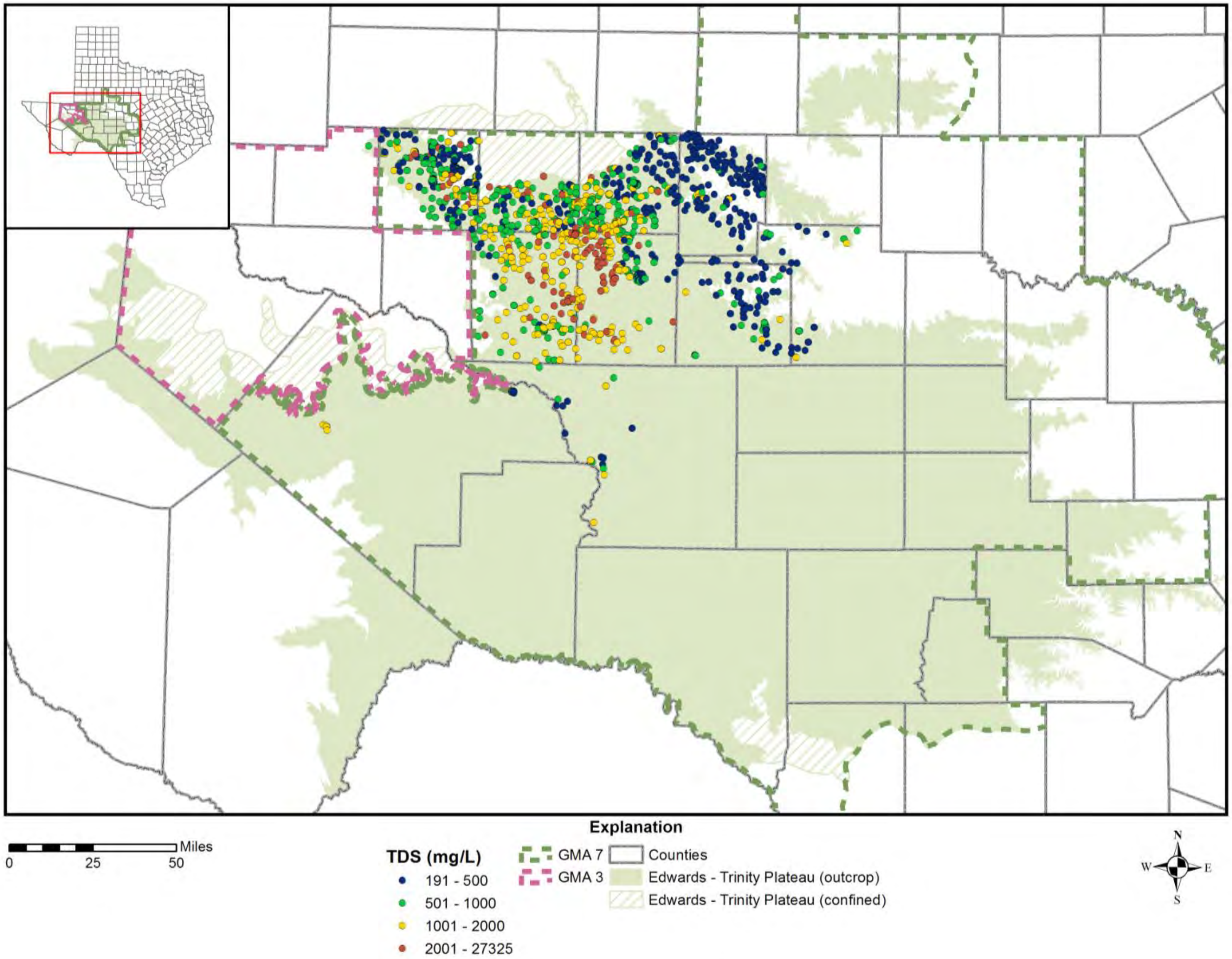
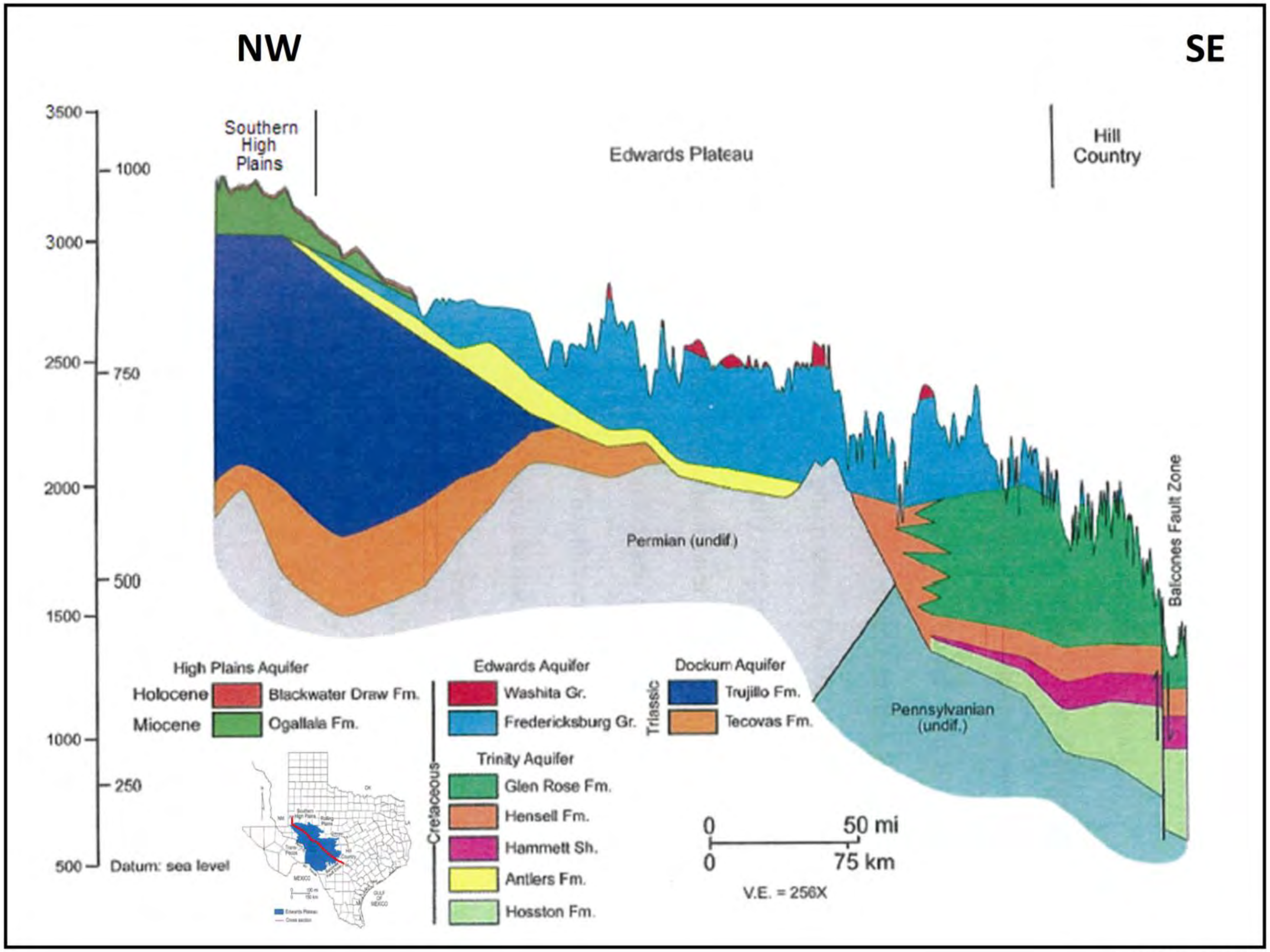


Figure 8-13. **Total dissolved solids in the Antlers Formation groundwater samples, Edwards-Trinity (Plateau) Aquifer.**



From: Nance, 2010)

Figure 8-14. Geologic cross section of Edwards-Trinity (Plateau) Aquifer that shows Triassic and Permian strata subcroping beneath the Cretaceous formations.

8.2 GAM Conceptual Model

A brief summary of the conceptual model for each of the three GAMs – the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer GAM (Anaya and Jones, 2009), the Dockum Aquifer GAM (Ewing and others, 2008), and the Rustler Aquifer GAM (Ewing and others, 2012) – being used will be discussed below. The discussion will focus on issues of hydrostratigraphy, recharge and cross-formational flow as described in the original GAM reports. The summaries are, in large part, derived from the original TWDB GAM reports and use many of the original figures from these reports.

8.2.1 Edwards-Trinity (Plateau) and Pecos Valley Aquifer

The hydrostratigraphy of the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer is very complex and Anaya and Jones (2009) divided the aquifer into eight stratigraphic nomenclature zones (Figure 8-15). Seven of the eight zones have to do with the stratigraphy of the Edwards-Trinity (Plateau) Aquifer system and one represents the extent of the Pecos Valley Alluvial Aquifer as it was modeled in the GAM. Anaya and Jones (2009) conceptualized the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer GAM as being comprised of two hydrostratigraphic units (Figure 8-15 and Figure 8-16). These two hydrostratigraphic units are the basis for the model possessing two layers. The lowermost hydrostratigraphic unit represents the partially confined Trinity Group unit and is contiguously extended to the southeast to include the Hill Country part of the Trinity Group. The upper hydrostratigraphic unit represents the mostly unconfined Edwards Group unit and also the Pecos Valley Aquifer in the Trans-Pecos region.

Key aspects of the conceptual model as reported in Anaya and Jones (2009) are summarized below in a bulleted format.

- The conceptual model for recharge is one of diffuse recharge in aquifer outcrops or as direct recharge from losing streams on the aquifer outcrops.
- Anaya and Jones (2009) estimated that the average recharge rate in the Edwards Group was approximately 4 percent of annual precipitation with recharge ranging from 1 to 8 percent of precipitation. Some of the recharge that occurs over the Edwards Group outcrop flows downward into the underlying Trinity Group unit. The authors conceptualize that most of the recharge enters into the Edwards Group eventually exiting that aquifer as seeps and springs along the plateau margins, baseflow to the gaining reaches of major perennial streams (at lower elevations), and evapotranspiration in riparian areas. In post-development, this recharge also discharges through direct extraction through pumping.
- Anaya and Jones (2009) report that the Edwards-Trinity (Plateau) Aquifer has few outcrops exposed for recharge and receives much of its water from the overlying Edwards Group except in the Hill Country where the Edwards Group has been removed by erosion. In the Hill Country area, Anaya and Jones (2009) estimate that recharge over the Trinity Group outcrop is about 4 to 6 percent of average annual rainfall and a value of 4.7 percent was used in the model.
- Anaya and Jones (2009) report that the Pecos Valley Aquifer receives recharge over the outcrop as diffuse recharge. Ashworth (1990) estimated that approximately 60

percent of the Pecos River irrigation diversions seep back into the aquifer as recharge in post-development.

- Cross-formational flow occurs between the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer and to and from the many adjacent aquifers (Figure 8-15 and Figure 8-16). The Trinity Group may also receive some water from the adjacent Ogallala Aquifer in the northwest as cross-formational flow. In the Hill Country, water flows out of the Trinity Aquifer as springs and baseflow to gaining streams and as cross-formational flow to the Edwards (Balcones Fault Zone) Aquifer. In the Trans-Pecos region, water exits both the Edwards and Trinity Groups as cross-formational flow into the Pecos Valley aquifer.
- The Pecos Valley Aquifer receives cross-formational flow from the Edwards-Trinity (Plateau) Aquifer, mostly from the western Trans-Pecos uplands. The Pecos Valley Aquifer is discharged as baseflow to the Pecos River, as evapotranspiration from the riparian reaches of the Pecos River where the water table is near the surface, and by pumpage (mostly for irrigation). Except for local cones-of-depression caused by intense pumping, groundwater flow through the Pecos Valley Aquifer is generally towards the Pecos River.
- Anaya and Jones (2009) map continuous hydraulic head surfaces for both the Edwards Group and Trinity Group portions of the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifers across the entire extent of their model domain and where the aquifers exist and are saturated. They did not map vertical gradients through hydrograph analyses or by taking the differences of the two head maps. The steady-state flow balance (1980) simulates approximately 150,000 AFY of discharge from the Edwards to the Trinity and 9,640 AFY discharge from the Trinity to the Edwards Group. The steady-state simulation period is representative of 1980 and includes 376,000 AFY of pumping. Because the analysis of groundwater chemistry data relates to pre-development conditions the pumping in the model is incongruous to this analysis.

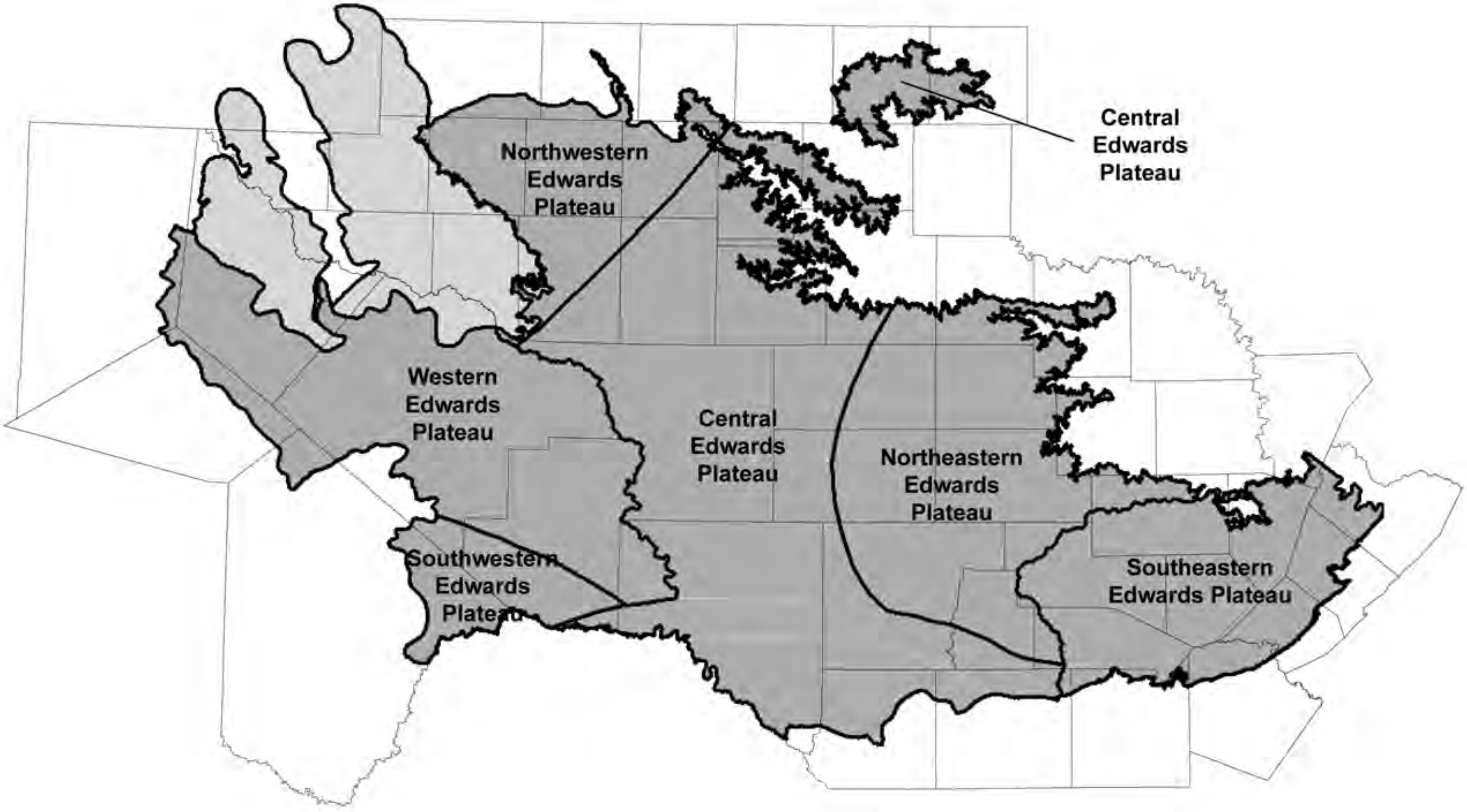


Figure 8-15. Regional extent of stratigraphic regions as defined by distinct nomenclature for the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer (Figure 5.1 of Anaya and Jones, 2009).

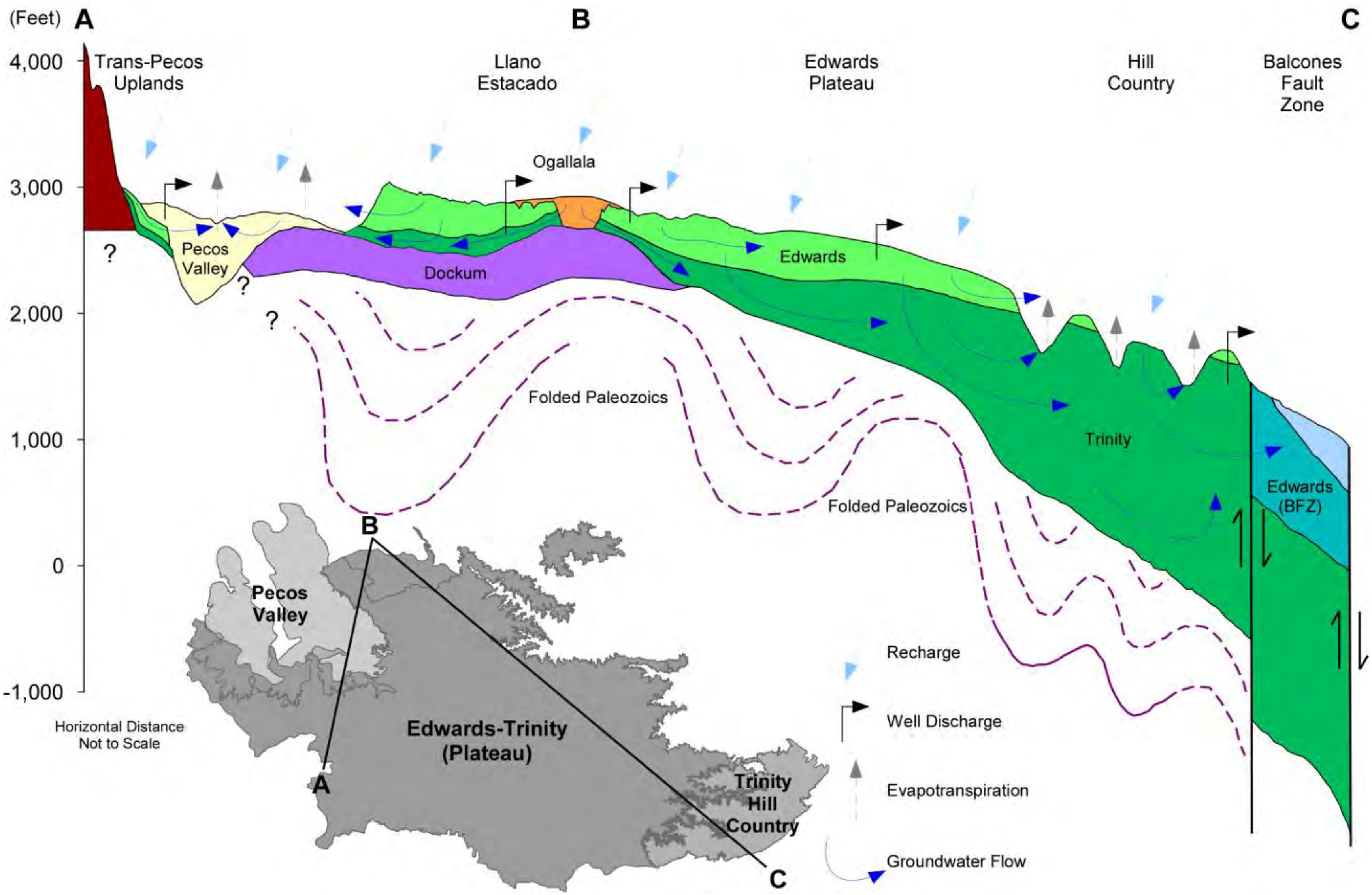


Figure 8-16. Schematic diagram of the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer conceptual model (Figure 6.1 of Anaya and Jones, 2009).

8.3 Hydrochemical Evaluation

Dockum Aquifer

The stratigraphic conceptual model for the Dockum Aquifer GAM (Ewing and others, 2008) defines three hydrostratigraphic layers: the younger units overlying the Dockum Aquifer, the upper portion of the Dockum Aquifer, and the lower portion of the Dockum Aquifer. Figure 8-17 is a schematic diagram representing a northwest-to-southeast cross-section through the active model area which depicts a simplified conceptualization of the hydrogeologic model describing groundwater flow in the Dockum Aquifer. The following discussion is based on the Dockum Aquifer GAM (Ewing and others, 2008).

- Because of the configuration and location of the outcrop areas in the Dockum Aquifer, all precipitation recharge to the Dockum Aquifer is considered to be shallow recharge with little expected to reach the deeper and confined portions of the aquifer.
- Except in its outcrop area, the Dockum Aquifer is overlain by the Ogallala, Rita Blanca, Edwards-Trinity (High Plains), Pecos Valley, or Edwards-Trinity (Plateau) aquifers. Interaction between the upper and lower portions of the Dockum Aquifer occurs via cross-formational flow. The Dockum Aquifer is underlain everywhere by Permian-age sediments. Vertical flow between the Dockum Aquifer and the underlying Permian was assumed to be negligible and a no-flow boundary was set at the base of the Dockum Aquifer in the GAM.
- The Dockum Aquifer obtains water from the overlying Pecos Valley Aquifer and, in some areas, from the overlying Ogallala Aquifer through cross-formational flow. The locations where the Ogallala and Dockum aquifers have significant hydraulic communication are generally limited to areas where the upper portion of the Dockum Aquifer is missing and where the lower portion of the Dockum Aquifer is relatively shallow along the eastern edge of the aquifer. In areas where the upper portion of the Dockum Aquifer is present, low permeability mudstone in the upper portion of the Dockum Aquifer likely restricts downward flow from the overlying Ogallala as well as from the overlying Edwards-Trinity (High Plains) Aquifer. Some groundwater is expected to flow vertically from the overlying Edwards-Trinity (Plateau) Aquifer to the Dockum Aquifer but the volume of this flow is expected to be small relative to that coming from the overlying Ogallala and Pecos Valley aquifers.
- The conceptual model defines very little movement of groundwater into or out of the Dockum Aquifer in the deeper parts of the depositional basin, which is also the part of the aquifer where the upper portion of the Dockum Aquifer is present. This portion of the Dockum Aquifer generally corresponds to the portion that is not included as part of the Dockum Aquifer by the TWDB (total dissolved solids concentration greater than 5,000 milligrams per liter). In this area, the potential exists for groundwater to flow vertically downward from the overlying aquifers to the Dockum Aquifer. However, due to large differences in water-level elevation, the time period for this flow is conceptualized as being very long due to the confining nature of the mud-rich upper portion of the Dockum Aquifer. For the portion of the Dockum Group defined as the Dockum Aquifer, fresh water enters the aquifer via precipitation in the outcrop or vertically downward from overlying aquifers. The groundwater then flows a relatively short distance and discharges to springs, streams,

the underlying Permian-age sediments, or the overlying Ogallala Aquifer along the eastern escarpment.

Rustler Aquifer

The Rustler Aquifer is located in the Trans-Pecos region of west Texas. The boundaries of the Rustler Aquifer defined by the TWDB consist of the portion of the Rustler Formation containing groundwater having a total dissolved solids concentration of less than 5,000 milligrams per liter (Boghici and Van Broekhoven, 2001). The following discussion is based on the Rustler Aquifer GAM (Ewing and others, 2012).

- The Permian-age Rustler Formation was deposited throughout the Delaware Basin, across the Central Basin Platform, and into the Midland Basin. In Texas, the Rustler Formation is locally subdivided into members that are regionally mappable. In Texas, the formation outcrops in eastern Culberson County where it has been mapped as six members, including (from youngest to oldest): the Forty-niner, the Magenta Dolomite, the Tamarisk, the Culebra Dolomite, a lower gypsum and mudstone, and a siltstone (Hentz and others, 1989). The lower two members appear to be equivalent to the Los Medoños Member of the formation in southeastern New Mexico as defined by Powers and Holt (1999). East into Pecos County and along the terminal edges of the Delaware Basin to the south in the Glass and Apache mountains, the lithology and contact relationships within the Rustler Formation change. South into the Glass Mountains, the Salado and Rustler formations are considered facies equivalents to the Tessey Limestone, which has been postulated to provide a recharge source to the Rustler Aquifer in Pecos County (Armstrong and McMillion, 1961; Ogilbee and others, 1962; Richey and others, 1985; Boghici, 1997; Boghici and Van Broekhoven, 2001; Bumgarner and others, 2012).
- The Rustler Formation is overlain by several formations/aquifers in the Delaware Basin including the Permian-age Dewey Lake Formation, the Triassic-age Dockum Aquifer, the Cretaceous-age Edwards-Trinity (Plateau) Aquifer, and the Cenozoic-age Pecos Valley Aquifer. In northeastern Culberson County and northwestern Reeves County, the Dewey Lake Formation is absent and the Pecos Valley Aquifer directly overlies the Rustler Aquifer to the north (Ogilbee and others, 1962) and the Edwards-Trinity (Plateau) Aquifer overlies the Rustler Aquifer to the south (Knowles and Lang, 1947). The Rustler Formation is overlain by the Edwards-Trinity (Plateau) Aquifer in northeastern Pecos County and by the Dockum Aquifer in the rest of the county (Boghici, 1997).
- The general structural character of the Rustler Formation, in addition to the aquifer data reviewed, provide a basis to subdivide the aquifer into hydrostructural domains that are significant for consideration of basin hydrogeology and construction of a GAM for the aquifer (i.e., properties, boundaries). A review of the available literature and data reviewed in this report provides a basis to integrate the hydrostructural domains broadly into two general flow systems occurring in the Rustler Aquifer in Texas; a western flow system and a southern flow system as shown on Figure 8-18.

There is potential that these two systems could be even further compartmentalized. Each of these is described below:

- The western flow system originates in the Rustler Hills in Culberson County, Texas and in southern Eddy County, New Mexico. Recharge in this system originates in the Rustler Aquifer outcrop areas and it is conceptualized to the degree that most flow discharges either through springs or evapotranspiration with some flow downdip that likely eventually discharges to the Pecos River or via cross-formational flow to overlying aquifers. From the outcrop area, flow in the aquifer is generally eastward and northeastward (White, 1971; Boghici and Van Broekhoven, 2001), but lack of water-level data east, northeast, and southeast of the outcrop area limits this assumption of flow direction. Water-quality data in the Pecos Valley and Edwards-Trinity (Plateau) aquifers suggest that the Rustler Aquifer discharges into these two aquifers east of the Rustler Aquifer outcrop and in the Toyah Basin, which is located in central Reeves County (Rees and Buckner, 1980; Texas Water Commission, 1989; Ashworth, 1990; Uliana and Sharp, 2001; Jones, 2001, 2004). The magnitude of this discharge is unknown, as is the amount of water that flows downdip into the aquifer subcrop. Research by Uliana (2000), Uliana and Sharp (2001), and Sharp and others (2003) have suggested that there may be a regional carbonate flow system originating at the southern edge of the Rustler Hills (outcrop) funneling groundwater from Wildhorse Flat and the Apache Mountains through the Stocks Fault/Rounsaville Syncline system into the Edwards-Trinity (Plateau) Aquifer and potentially the Rustler Aquifer. Their research has also shown that many Edwards-Trinity (Plateau) spring systems (Balmorhea, Phantom, San Solomon) at the border of Jeff Davis and Culberson counties are fed by this regional flow system. The evidence is generally based upon water quality analyses using Cretaceous groundwater samples and surface runoff from the Davis Mountains. It has been proposed that that the Rustler Aquifer receives a regional component of groundwater flow paralleling the Stocks Fault/Rounsaville Syncline system that could flow north and northeast into the Toyah Basin.

- The southern portion of the aquifer originates to the south of Pecos County and southeastern-most Reeves County through postulated recharge in the Glass Mountains (Figure 8-18). This recharge has been proposed to occur in the Tessey Limestone. It could also be originating in the Capitan Reef equivalent units and recharging the Rustler Aquifer in Pecos County through cross-formational flow. Both the total dissolved solids and carbon-14 data available for the Rustler Aquifer support the concept of a flow path originating in the Glass Mountains and flowing northward to Ft. Stockton and Diamond Y Springs (Ewing and others, 2012, Section 4.8.2).
- The Southern flow system in Pecos County has been demonstrated to be a prolific aquifer in the area of Belding and significant historical discharge has occurred in the vicinity of Diamond Y Springs, which at least in part must be attributed to the Rustler Aquifer. This flow system potentially extends into Reeves County from the south but little is known about the properties in this area. This area of the Rustler Formation is known to have a basal sandstone (Richey and others, 1985) and also has more carbonate facies compared to that in the north (Eager, 1984). The portion of the flow system extending through Belding and into the Fort Stockton area sits above the Capitan Reef and appears to terminate in the area of Diamond Y Springs, which coincides with the southernmost extension of the deepest portions of the graben.
- Cross-formational flow has been postulated to be an important discharge mechanism for this portion of the aquifer (Veni, 1991; Boghici, 1997; Harden and others, 2011). The source of brackish water in the Edwards-Trinity (Plateau) Aquifer in western Pecos County is considered to be due to the mixing of groundwater in the Rustler

Formation and the Edwards-Trinity (Plateau) Aquifer according to Boghici (1997) and Harden and others (2011). Harden and others (2011) saw a potential for diffuse mixing based upon water-quality data, and Boghici (1997) localized cross-formational flow from the Rustler Aquifer within the Belding Fault System. Veni (1991) hypothesized that discharge from the Capitan Reef Complex Aquifer into the Rustler Aquifer may occur north of the city of Fort Stockton in Pecos County at Diamond Y Springs. Through geochemical analyses, Boghici (1997) attributed flows at Diamond Y Springs to groundwater discharge from the Rustler Aquifer.

- The schematic diagram in Figure 8-19 shows a west to east cross-section through the study area along with a conceptual block diagram illustrating aquifer contact relationships and sources and sinks to groundwater. The Rustler Aquifer GAM was constructed using two model layers. The lowermost active model layer represents the Rustler Aquifer. Except in its outcrop area, the Rustler Aquifer is overlain by some combination of the Dewey Lake Formation and the Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers. The uppermost model layer typically represents the Dewey Lake Formation and Dockum Aquifer, where present. Including these formations as a model layer provides vertical resistance and storage that exists (in most places) between the Rustler Aquifer and the overlying Edwards-Trinity (Plateau) and Pecos Valley aquifers. In addition, some Dewey Lake Formation outcrop is present in the region north of the county line between Culberson and Reeves counties, where the Pecos Valley Aquifer is not present and the Rustler Aquifer is confined.

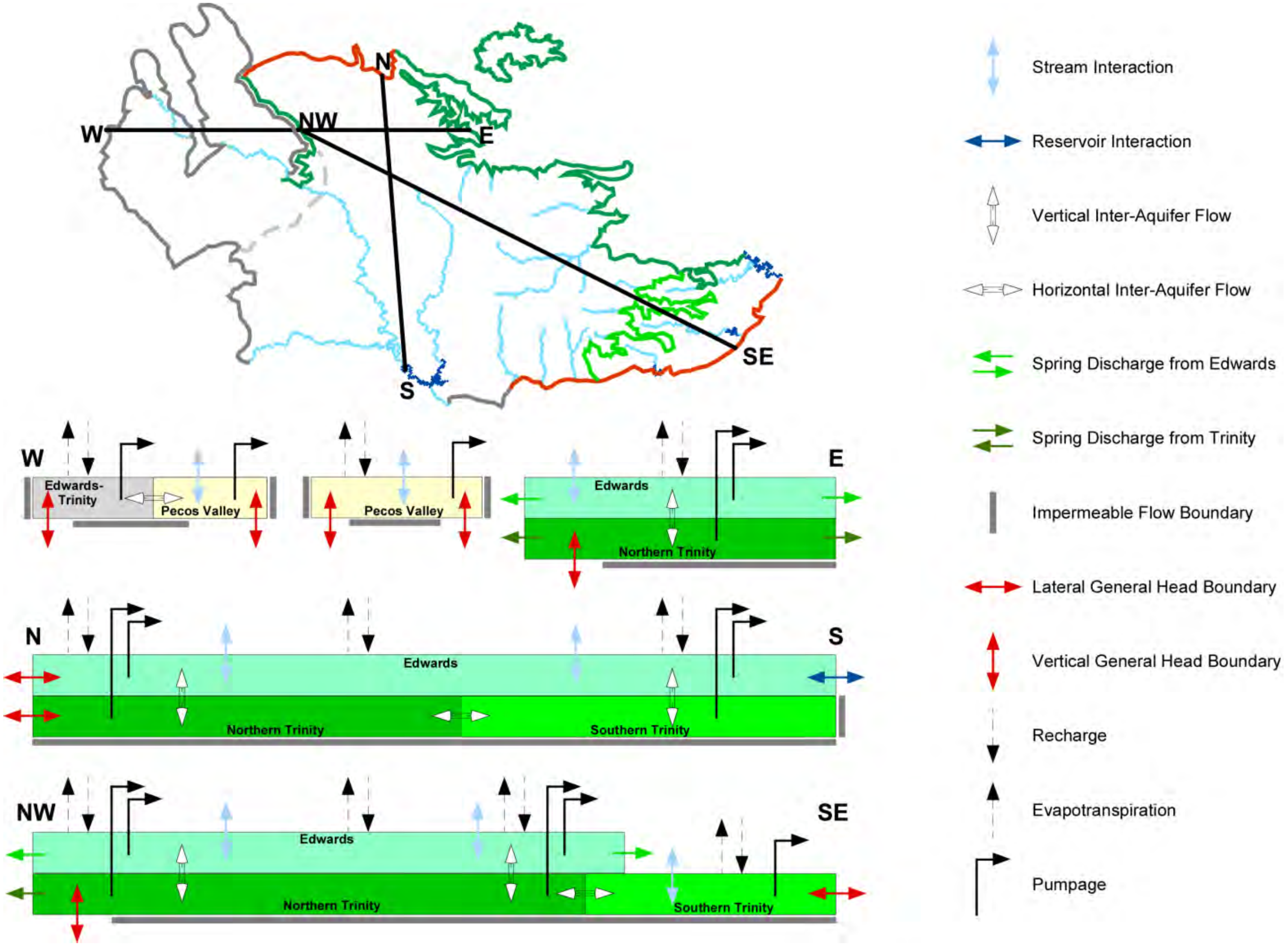


Figure 8-17. Block diagram of the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer (Figure 6.2 of Anaya and Jones, 2009).

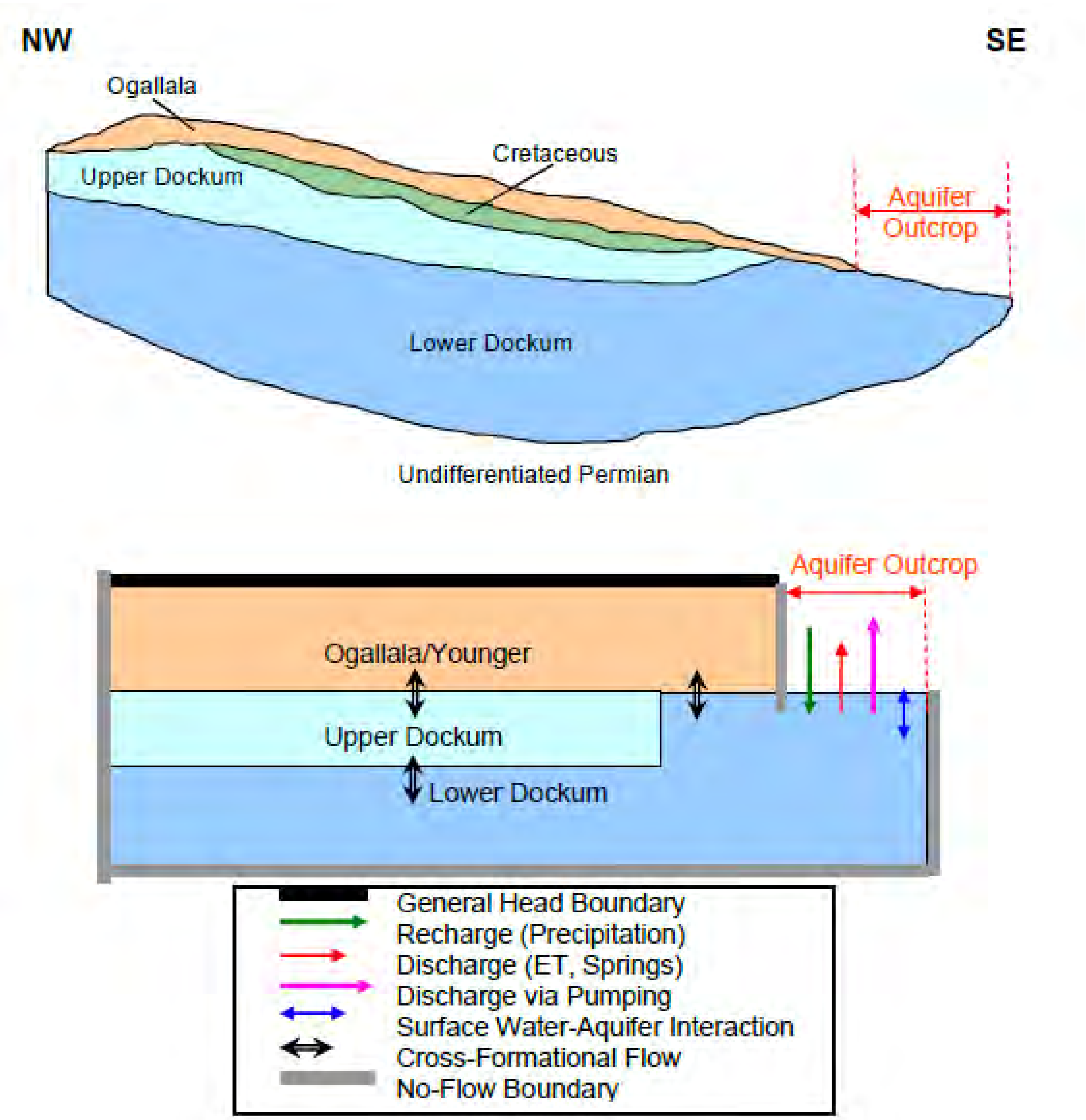


Figure 8-18. **Conceptual groundwater flow model (cross-sectional view) for the Dockum Aquifer GAM (Figure 5.0.1 of Ewing and others, 2008).**

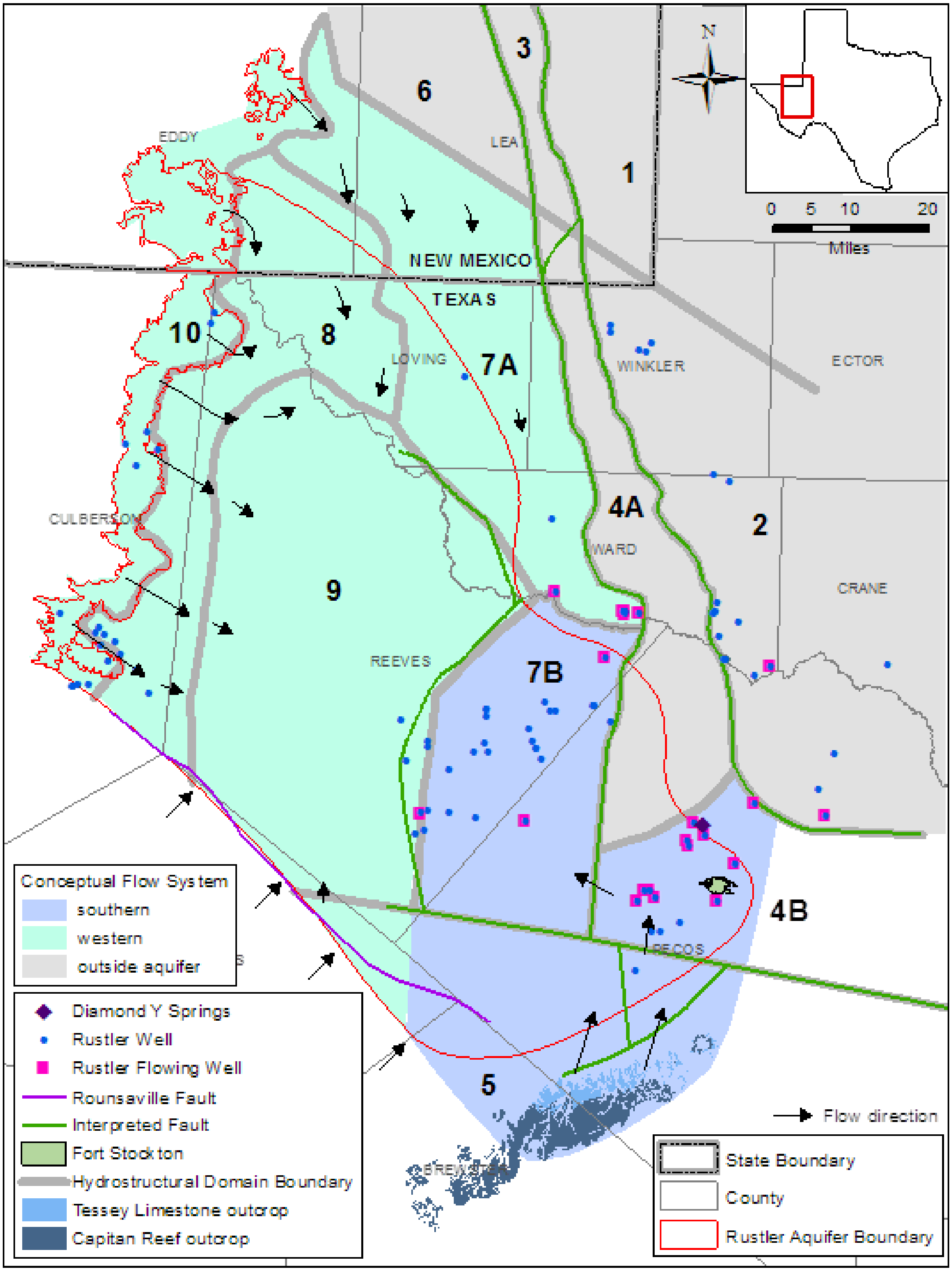


Figure 8-19. Conceptual groundwater flow model (cross-sectional view) for the Rustler Aquifer GAM (Figure 5.2 of Ewing and others, 2012).

8.4 Conceptual Issues to be Investigated

The project team identified several conceptual issues to be investigated with the current GAMs within the projects study region. These issues were identified through the review of the conceptual models summarized above and water quality data and the available literature (specifically a recent PhD Dissertation by Seay Nance (Nance, 2010)). Specifically, we will investigate through the use of the appropriate GAMs:

- Cross-formational flow between the Dockum Aquifer, the Rustler Aquifer and the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer;
- Groundwater flow-path continuity between the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer;

8.4.1 Cross-Formational Flow Bewteen Aquifers

Water chemistry studies have provided evidence for cross-formational flow in between the aquifers in the western portions of GMA 3 and 7. There is a definite trend of poorer water quality (greater than 1,000 mg/L total dissolved solids) in the far northwest portions of the Edwards-Trinity (Plateau) Aquifer (see Figure 1.8 of Nance 2010 reproduced here as Figure 8-8) which could possibly be derived from upward cross-formational groundwater flow from the underlying Dockum or Permian age sediments (which could include the Rustler Aquifer). This trend is particularly evident in Ector, Midland and Upton Counties. This would coincide with the northwestern Edwards-Trinity (Plateau) Aquifer (Figure 8-14) as defined by Anaya and Jones (2009).

Two important cross-formational flow issues to be considered for the Dockum Aquifer are the potential for flow from the Dockum to the Pecos Valley Aquifer and flow from the Dockum Aquifer to the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer. This potential was investigated by Ewing and others, (2008) and will be summarized below.

Garza and Wesselman (1959) state that the Pecos Valley Aquifer and the Dockum Aquifer are in hydraulic communication in some parts of Winkler County. In these areas, precipitation percolates into the Pecos Valley Aquifer and then flows into the Dockum Aquifer. The amount of cross-formational flow from the Pecos Valley Aquifer to the Dockum Aquifer will be less than the amount of recharge to the Pecos Valley Aquifer estimated to be approximately 1 percent of precipitation by Anaya and Jones (2009). Evidence suggests that the Dockum discharges to the Pecos Valley Aquifer in Monument Draw where the Dockum Aquifer subcrops to the Pecos Valley Aquifer (Ewing and others, 2008).

Garza and Wesselman (1959) state that, in some areas of Winkler County, the Chinle Formation of the upper portion of the Dockum Aquifer is present and hydraulically separates the Santa Rosa Formation of the lower portion of the Dockum Aquifer from the Pecos Valley Aquifer. Mudstones in the Chinle Formation likely act as a confining layer restricting downward flow.

Comparisons between heads in the Antlers Formation of the Trinity Group in the Edwards-Trinity (Plateau) Aquifer and the Dockum Aquifer can be made at several locations in Ewing and others, (2008). In Sterling and Upton counties, the water-level elevation in the Antlers Formation is about 10 to 125 feet higher than in the Dockum Aquifer. In Reagan County, the situation is reversed, with the water-level elevation in the Dockum Aquifer about 15 to 20 feet higher than in the Antlers Formation. In Ector County, one well-pair showed very similar water-level elevations in both aquifers.

The Rustler Aquifer also has evidence of cross-formational flow in the Western Edwards Plateau Region (after Anaya and Jones, 2009). The southern flow system (Figure 8-7) in Pecos County has been demonstrated to be a prolific aquifer in the area of Belding and significant historical discharge has occurred in the vicinity of Diamond Y Springs, which at least in part must be attributed to the Rustler Aquifer. The portion of the flow system extending through Belding and into the Fort Stockton area sits above the Capitan Reef and appears to terminate in the area of Diamond Y Springs, which coincides with the southernmost extension of the deepest portions of the graben. Cross-formational flow has been postulated to be an important discharge mechanism for this portion of the aquifer (Veni, 1991; Boghici, 1997; Harden and others, 2011). The source of brackish water in the Edwards-Trinity (Plateau) Aquifer in western Pecos County is considered to be due to the mixing of groundwater in the Rustler Formation and the Edwards-Trinity (Plateau) Aquifer according to Boghici (1997) and Harden and others (2011). Whereas Harden and others (2011) saw a potential for diffuse mixing based upon water-quality data, Boghici (1997) localized cross-formational flow from the Rustler Aquifer within the Belding Fault System. Veni (1991) hypothesized that discharge from the Capitan Reef Complex Aquifer into the Rustler Aquifer may occur north of the city of Fort Stockton in Pecos County at Diamond Y Springs. Through geochemical analyses, Boghici (1997) attributed flows at Diamond Y Springs to groundwater discharge from the Rustler Aquifer. Based upon a review of all of the data, there is significant evidence that cross-formational flow likely occurs in isolated regions between the Rustler Aquifer and the overlying Edwards-Trinity (Plateau) Aquifer. However, how much cross-formational flow occurs is less clear.

Figure 8-20 shows the areas of overlap of the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM, the Dockum Aquifer GAM and the Rustler Aquifer GAM in GMAs 3 and 7. To the degree possible, the issues of cross-formational flow summarized above will be investigated with the available GAMs.

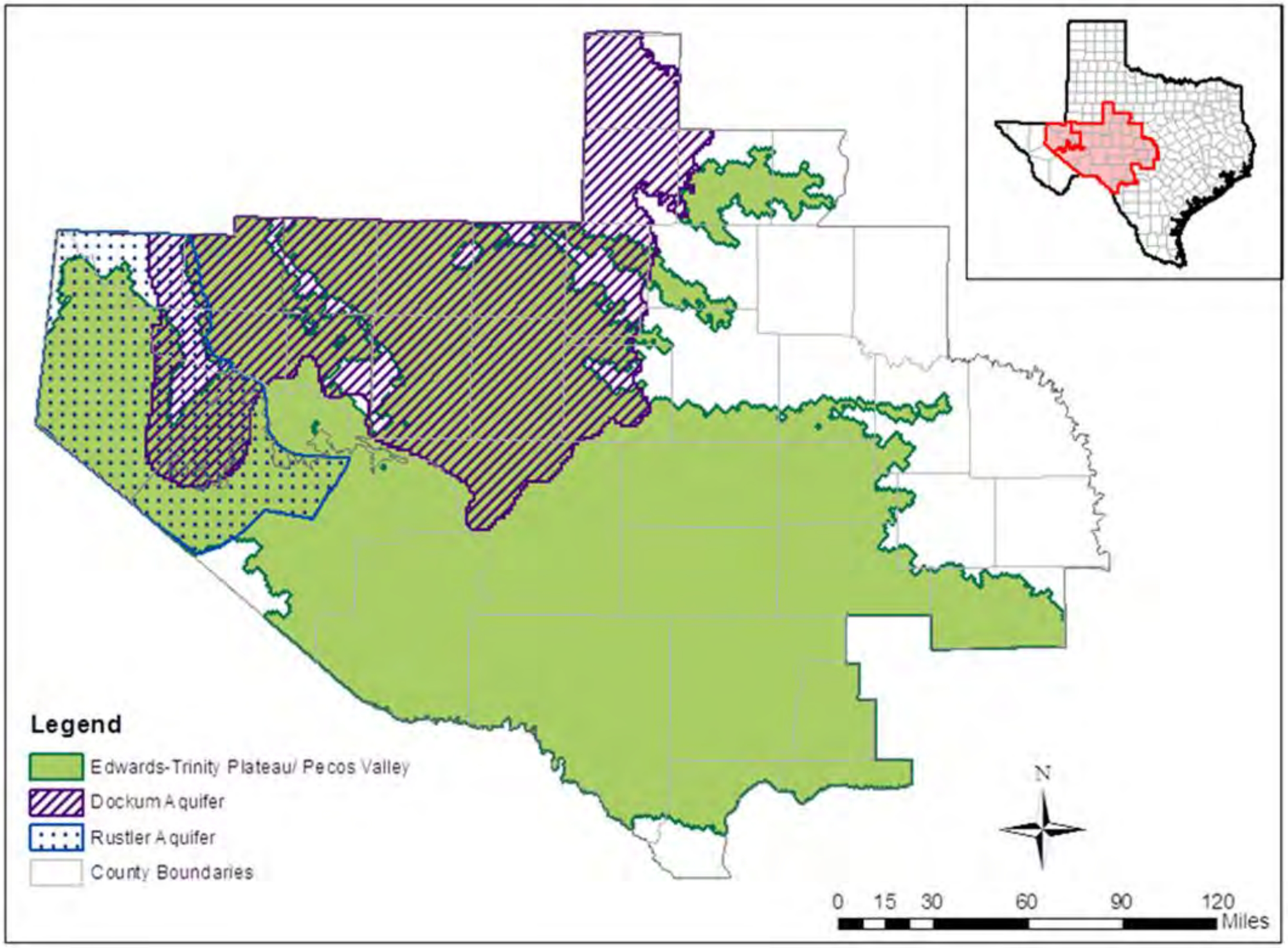


Figure 8-20. **Areas of overlap between the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM, the Dockum Aquifer GAM and the Rustler Aquifer GAM.**

8.4.2 Flow Path Continuity Between Aquifers

The original Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM is a two layer model allowing separation of flow between the Edwards Group and Trinity Group. The single-layer alternative groundwater flow model of Hutchinson, Jones and Anaya (2011) lumps flow processes between the aquifers and cannot be used to look at issues of cross-formational flow between the Edwards and Trinity Groups. Nance (2010) presents a combined Edwards-Trinity (Plateau) Aquifer head surface (Figure 8-7) which could be interpreted as defining Edwards Group flow paths that could originate in the northwestern Edwards Plateau Region and discharge in the southeastern Edwards Plateau Region east of the Balcones Fault Zone.

We used the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer GAM of Young and others (2010) and Anaya and Jones (2009) to review flow balance information such as cross-formational flow. Young and others (2010) is not an official TWDB GAM. We also used Young and others (2010) to look at a representative flow balance along a regional flow tube because it has a steady-state calibrated condition calibrated without pumping and it uses a similar recharge package and boundary conditions as were used in Anaya and Jones (2009). The pumping in the Anaya and Jones (2009) GAM representing relatively recent anthropogenic impacts on the aquifers is not consistent with the pre-development conditions necessary to compare to groundwater chemistry analyses meant to evaluate conditions in the aquifers that occurred thousands of years in the past.

8.5 Numerical Investigation of Conceptual Issues

Current GAM and alternative groundwater flow models were used to determine water budget and to look at the degree of cross-formational flow between the Edwards Group and the Trinity Group on a regional scale and the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer and the Rustler Aquifer and the Dockum Aquifer. While these models were never optimized to work together, they can be evaluated together. Modeling results were compared to the conceptual models to see whether there was agreement.

The GAMs that will be used to investigate these issues include the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM (Anaya and Jones, 2009); the Dockum Aquifer GAM (Ewing and others, 2008); and the Rustler Aquifer GAM (Ewing and others, 2012). There are alternative groundwater flow models for the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer (Hutchinson, Anaya and Jones, 2011 and Young and others, 2010) and the Dockum Aquifer (Oliver and Hutchison, 2010). Because the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer alternative groundwater flow model used to develop the managed available groundwater (Hutchinson, Anaya and Jones, 2011) is a single-layer model, it could not be used to investigate cross-formational flow. The alternate Dockum Aquifer groundwater flow model does not have significant differences with the original GAM in the project area so the original GAM was used. For flow-path continuity calculations, we opted to use the Young and others (2010) GAM because it had a steady-state calibration period that did not include pumping.

8.5.1 Interaction Between the Aquifers

The existing models from the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM (Anaya and Jones, 2009) and the alternative groundwater flow model (Young and others, 2010); the Dockum Aquifer GAM (Ewing and others, 2008); and the Rustler Aquifer GAM (Ewing and others 2012) were used to conduct a flow balance analysis to investigate cross-formational and cross-regional flow. The stratigraphic regions of the Edwards-Trinity (Plateau) Aquifer shown in Figure 8-14 were used to differentiate spatially between regions of the study area.

8.5.2 Vertical Flow Balance between Aquifers

The MODFLOW cell-by-cell budget file was used to extract the flow between model layers for the two steady-state Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer models, the steady-state Dockum Aquifer model, and the steady-state Rustler Aquifer model for each of the stratigraphic regions. Both Edwards-Trinity (Plateau) Aquifer models have two active layers and flow between them represents flow to or from the Trinity Group from the Edwards Group over the majority of the domain or the Pecos Valley Aquifer in the northwest. Both Edwards-Trinity (Plateau) Aquifer models account for the flow to or from underlying units through the use of general head boundary conditions; however this constitutes a relatively small portion of the water budget in those models. The flow between the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer (simulated using a model layer with general-head boundary conditions to represent the aquifers) and the Dockum Aquifer can be extracted from the Dockum Aquifer GAM. The Dockum model was used to estimate this cross-formational flow because it constitutes a significant portion othe water balance in the Dockum GAM and was a major focus of the modeling effort. The Dockum Aquifer model ignores the cross-formational flow between the Dockum and Rustler aquifers; however this flow can be extracted from the Rustler Aquifer GAM since it includes an upper layer with general-head boundary conditions representing the Dockum Aquifer. The cross-formational flows are summarized by stratigraphic region in Table 8-1. It should be noted that the cross-formational flows shown in Table 8-1 are net values representative of an entire stratigraphic region while flows between individual grid cell pairs can be either up or down within a single stratigraphic region.

Table 8-1. Cross-formational (vertical) flow by stratigraphic region in acre-feet per year (positive upward).

Region	Rustler to Dockum	Dockum to ETPV	Trinity to Edwards (Anaya and Jones)	Trinity to Edwards (Young and others)
Central Edwards Plateau		1,554	-57,566	-24,166
Northwestern Edwards Plateau		-6,554	-19,803	-7,823
Southeastern Edwards Plateau			-906	-2,634
Southwestern Edwards Plateau			-940	-4,191
Northeastern Edwards Plateau			-28,491	-30,944
Western Edwards Plateau	2,297	-798	-32,259	-22,909
Pecos Valley Alluvium	560	7,239		
Total	2,857	1,440	-139,965	-92,666

Both Edwards-Trinity (Plateau) Aquifer models exhibit similar flows by region which is expected since they both use the same recharge distribution with the Young and others, (2010) version using approximately 80% of the recharge in the Anaya and Jones (2009) model. Net flow in all regions is downward from the Edwards to the Trinity Groups where the two aquifers exist. The largest downward flow occurs in the central Edwards-Trinity (Plateau) Aquifer region in Anaya and Jones (2009). The Dockum Aquifer exhibits a net discharge to the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifers with the largest upward flow occurring into the Pecos Valley Aquifer. The Dockum Aquifer GAM predicts downward flow from the Trinity Group into the Dockum Aquifer occurring in the northwestern Edwards-Trinity (Plateau) Aquifer region, however. This appears to be in contrast to the higher levels of total dissolved solids and sulfate in Trinity Group (Antlers Formation) groundwater found in this region. The Rustler Aquifer has a net discharge upward into the Dockum Aquifer with the largest flow occurring in the western Edwards-Trinity (Plateau) Aquifer region.

8.5.3 Flow Balance by Stratigraphic Region

To better understand regional flows across each of the aquifers in the GMA 3 and GMA 7 boundaries, the net lateral flows were compiled between each of the stratigraphic regions depicted in Figure 8-14 and are summarized in Table 8-2. The flow directions and magnitudes between adjacent regions are the result of this analysis. A positive flow is "from to" and a negative flow is the reverse of that. For both of the Edwards-Trinity (Plateau) Aquifer models relatively large net lateral flows occur in the Edwards Group from the western to the southwestern region, from the southwestern to the central region, and from the northeastern to the central region. In the Trinity Group, both models have the largest flow from the northeastern to the central region. Both models maintain the same flow directions between hydrostratigraphic regions with the exception of flow between the Pecos and western regions in the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer and flow between the northeastern and the southeastern regions in the Trinity Group. Young and others, (2010) has a relatively large amount of flow to the Pecos Valley Aquifer from the western region in the Edwards Group and Pecos Valley Aquifer.

Table 8-2. Cross-regional (lateral) flows in acre-feet per year.

Direction	Edwards (Anaya & Jones, 2009)	Edwards (Young and others, 2010)	Trinity (Anaya & Jones, 2009)	Trinity (Young and others, 2010)	Dockum	Rustler
From Pecos to Western	2,114	-64,945			-801	-288
From Pecos to Northwestern	603	481			-3,730	
From Western to Central	7,565	10,006	-7,710	-271	-155	
From Western to Southwestern	25,406	32,277	12,180	7,360		
From Southwestern to Central	24,470	25,966	458	1,060		
From Northwestern to Central	4,580	4,280	6,780	2,813	2,512	
From Central to Northeastern	-25,435	-19,875	-23,270	-28,794		

From Northeastern to Southeastern	-8,311	-6,916	-4,953	1,762		

Color Flood of Vertical Flow within GMA 3 and 7

Where the Edwards Group overlies the Trinity Group, the flow between the two aquifers can be depicted for every model cell. There is non-zero flow between the two aquifers. Diffuse downward flow between zero and 0.3 inches per year tends to occur in the western, northern, and southeastern portions of the aquifer system with larger rates of downward flow up to 3 inches per year occurring at the western and eastern extremes of the Edwards Group and along the Pecos River. Diffuse upward flow between zero and 0.3 inches per year occurs in the south-central portion of the aquifer system where the Rio Grande acts as a regional discharge boundary.

The cross-formational flow between the Dockum Aquifer and the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer is shown in Figure 8-22. The majority of the flow is either diffuse downward flow or diffuse upward flow ranging between zero and 0.3 inches per year. There are no discernible regional patterns and downward flow occurs in proximity to upward flow.

The cross-formational flow between the Rustler Aquifer and overlying aquifers - the Dockum Aquifer in the north and the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer in the south is shown in Figure 8-23. The majority of the flow is diffuse upward flow ranging from zero to 0.3 inches per year. Diffuse downward flow ranging from zero to 0.3 inches per year occurs over a significant portion of the aquifer, however.

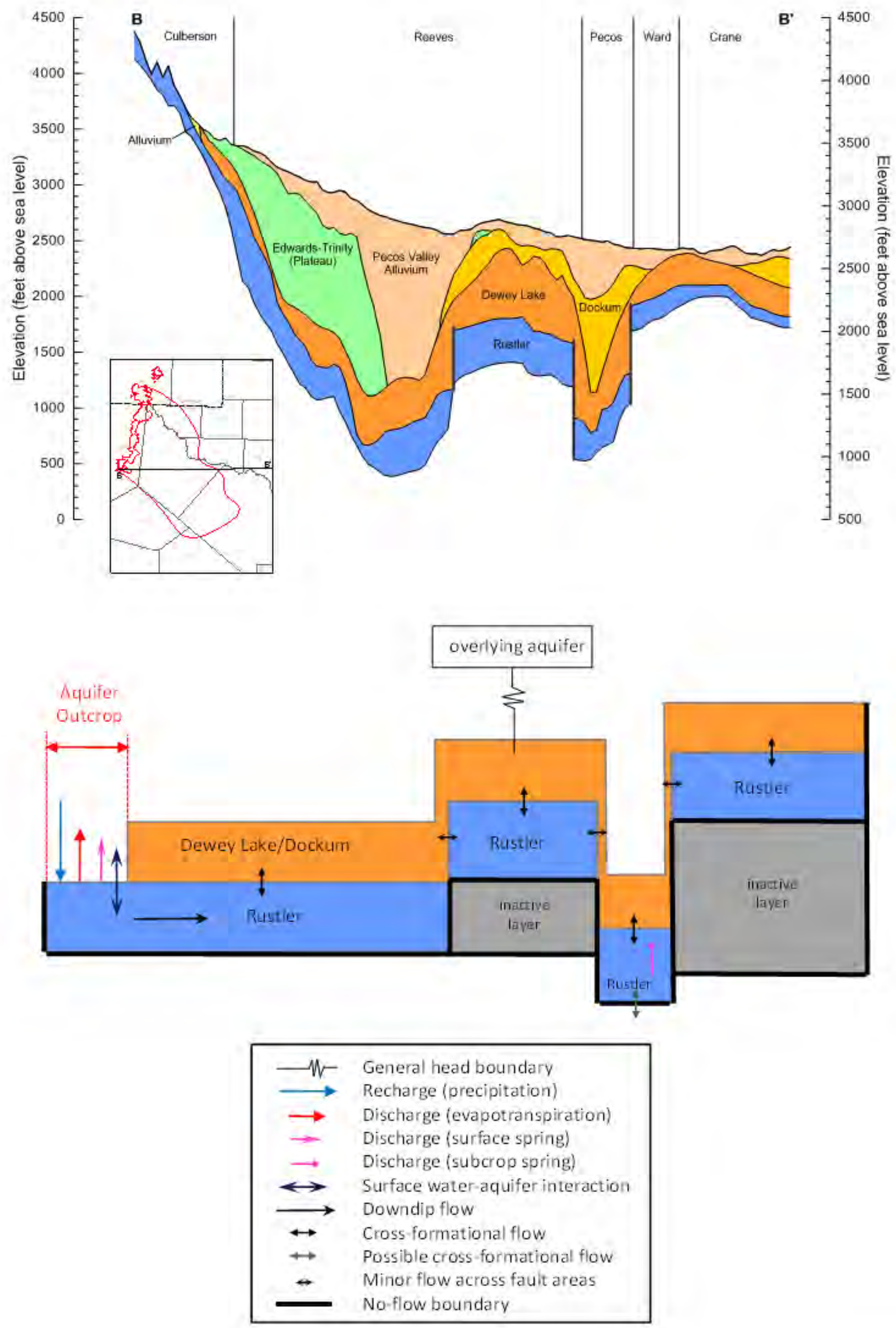


Figure 8-21. **Conceptual groundwater flow model (cross-sectional view) for the Rustler Aquifer GAM (Figure 5.2 of Ewing and others, 2012).**

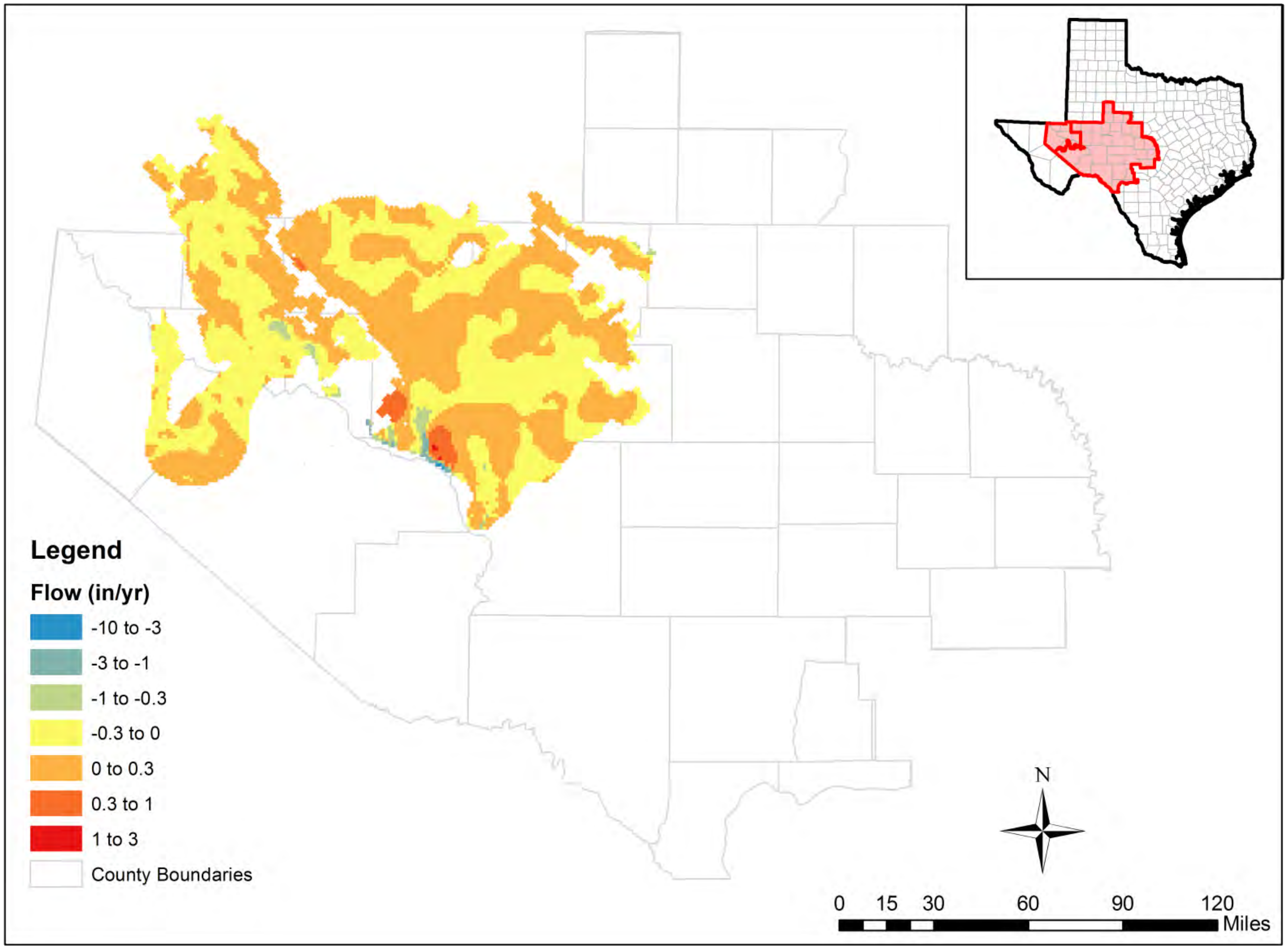


Figure 8-22. **Cross-formational flow between the Dockum Aquifer and Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer (positive flow is upwards).**

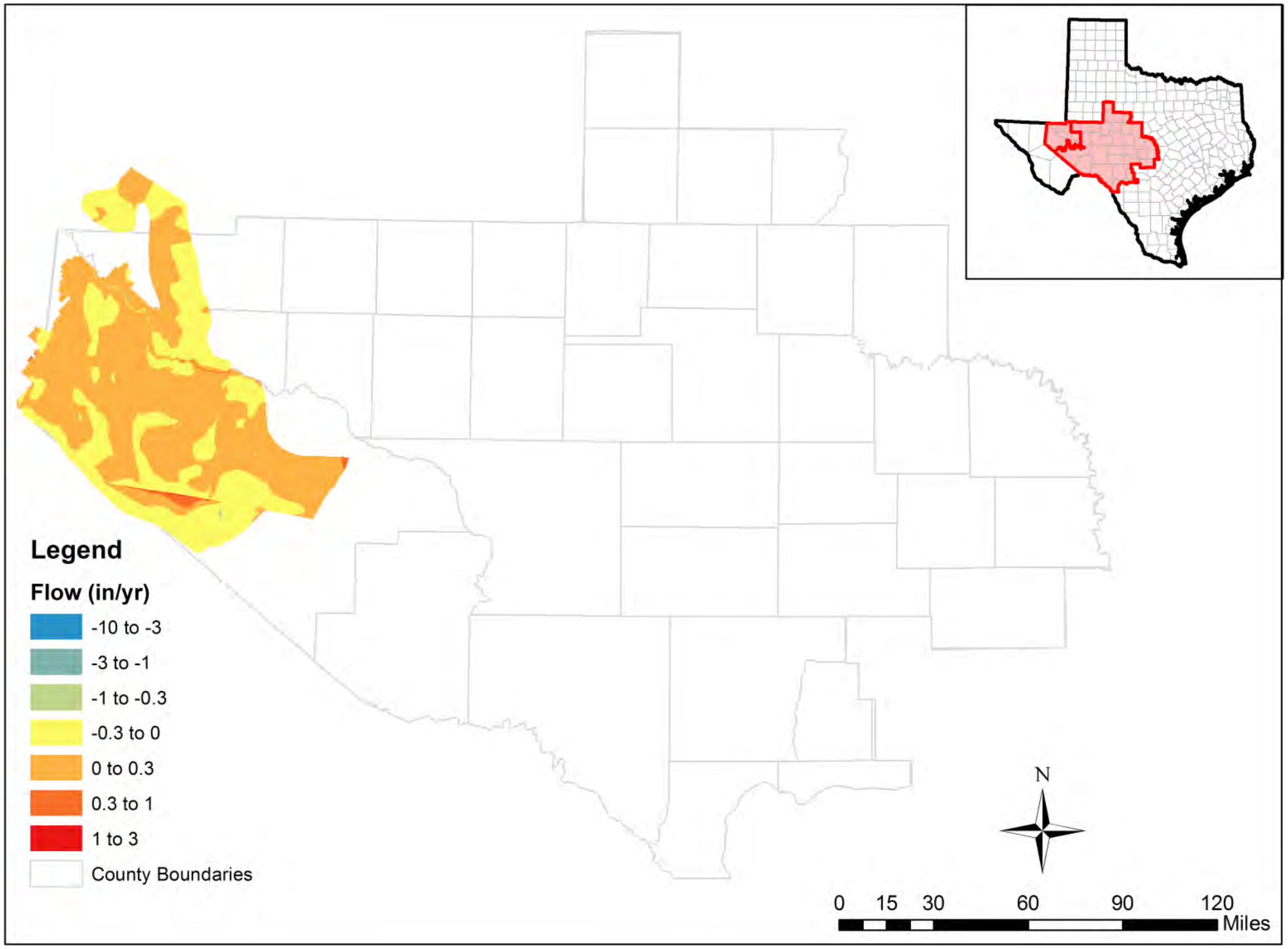


Figure 8-23. Cross-formational flow between the Rustler Aquifer and either the Dockum Aquifer or Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer (positive flow is upwards).

8.5.4 Flow Path Continuity Between the Aquifers

Nance (2010) presents a combined Edwards-Trinity (Plateau) Aquifer head surface (Figure 8-6) which could be interpreted as defining Edwards Group flow paths that could originate in the northwestern Edwards-Trinity (Plateau) Aquifer and discharge in the southeastern Edwards-Trinity (Plateau) Aquifer east of the Balcones Fault Zone.

8.5.5 Mass Balance along the Stream Tube

To evaluate the degree to which cross-formational flow adds to the mixing of groundwater flowing laterally along major flow lines, a stream tube mass balance analysis was conducted. The direction of the stream tube was based on the regional water-level contours presented in Figure 1.5 of Nance (2010). The width of the stream tube is arbitrary but was intended to incorporate multiple transverse model grid blocks while focusing on the longitudinal (in the direction of flow) aspect of the stream tube. The stream tube was discretized along the direction of flow into six blocks upon which mass balances could be analyzed.

The same stream tube location was used to compare longitudinal and cross-formational flow in both the Edwards Group (model layer 1) and the Trinity Group (model layer 2). The location of the stream tube is shown in Figure 8-24. The stream tube was divided into six mixing volumes to look at the relative magnitude of downstream flow versus vertical cross-formational flow. All flows were estimated across all faces and boundary conditions for each control volume. It should be noted that the flows from external boundary conditions and flows transverse to the stream line direction are ignored in this analysis and that these flows were significant. This is because the regions meant to roughtly follow the conceptual flow lines in Nance (2010) are approximate as are the flow lines. A flow tube without lateral inflows and out flow would be very difficult to produce. However, the purpose of this analysis is an attempt to estimate the degree of mixing between the Edwards and the Trinity Antlers

groups simulated by the groundwater models rather than the degree to which the conceptualized flow tubes are actually closed systems devoid of lateral inflows and outflows. The lateral flows were, therefore, excluded from the analysis to clarify the degree of vertical mixing relative to downstream flow since the transverse component of flow provides little value in the comparison of cross-formational and longitudinal flow. By analyzing the flow balance this way, we get a good picture of how important cross-formational flow is relative to lateral flow within each model layer. This is meant to provide a comparison to conclusions reached by the groundwater chemistry data.

The resulting flow vectors for downstream and cross-formational flow are plotted as a two layer stream tube in Figure 8-25. The analysis indicates that the cross-formational mixing component of groundwater flow is comparable to and, in some cases, larger than the downstream component of flow. The analysis shows that downward flow from the Edwards Group to the Trinity Group is the dominant cross-formational flow direction until you get to the southern discharge boundary (Rio Grande). The analysis shows that significant groundwater recharging the Edwards Group in the northwest and central regions moves to the Trinity Group through cross-formational flow. As one moves downgradient towards the regional sink (Rio Grande), the Edwards Group accumulates flow because of upstream flow. The Trinity Group continues to gain groundwater from the Edwards Group until the flow tube gets to the Rio Grande and groundwater must discharge through the Edwards Group to reach the discharge boundary. The amount of vertical leakage from Edwards Group to the Trinity Group as the stream tube approaches the Rio Grande is high relative to other cross-formational flows elsewhere in the model. The amount of recharge (as estimated in the flow tube) could potentially mask any higher total dissolved solids water that might be originating in the northwest region of the Edwards-Trinity (Plateau) Aquifer. The zone of increased salinity in the Edwards Group (Figure 8-9) is, however, abrupt, which does not suggest a gradual transition in chemistry as is evoked in dilution model caused by an ever increasing amount of recharge from precipitation. The flow from the Trinity Group to the underlying Dockum Aquifer (represented by general-head boundary conditions in the model) is primarily downward indicating that the Dockum Aquifer is not considered to be a source of the high total dissolved solids concentrations shown in Figure 8-9 and Figure 8-10 based on model results.

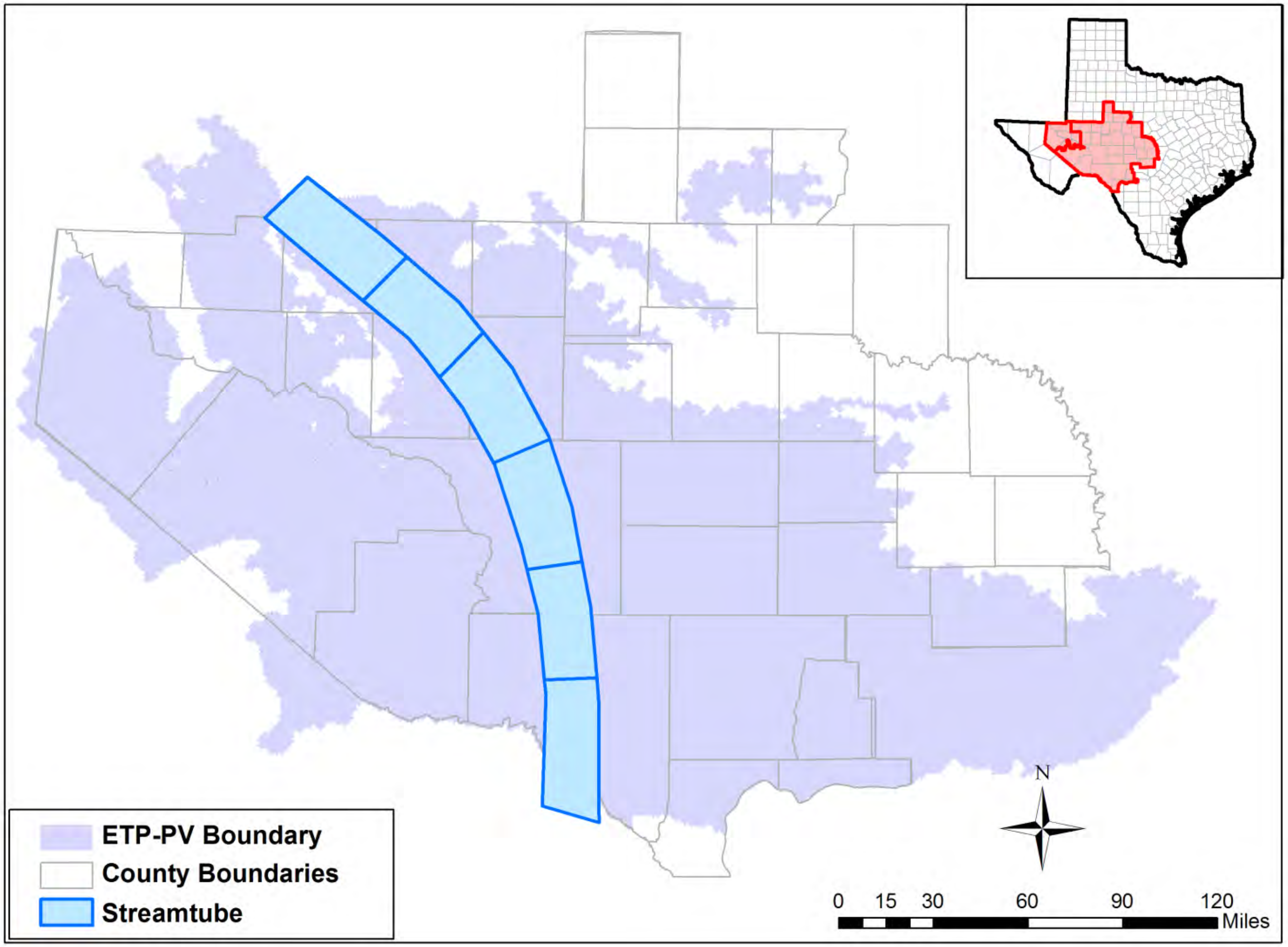


Figure 8-24. Location of the stream tube.

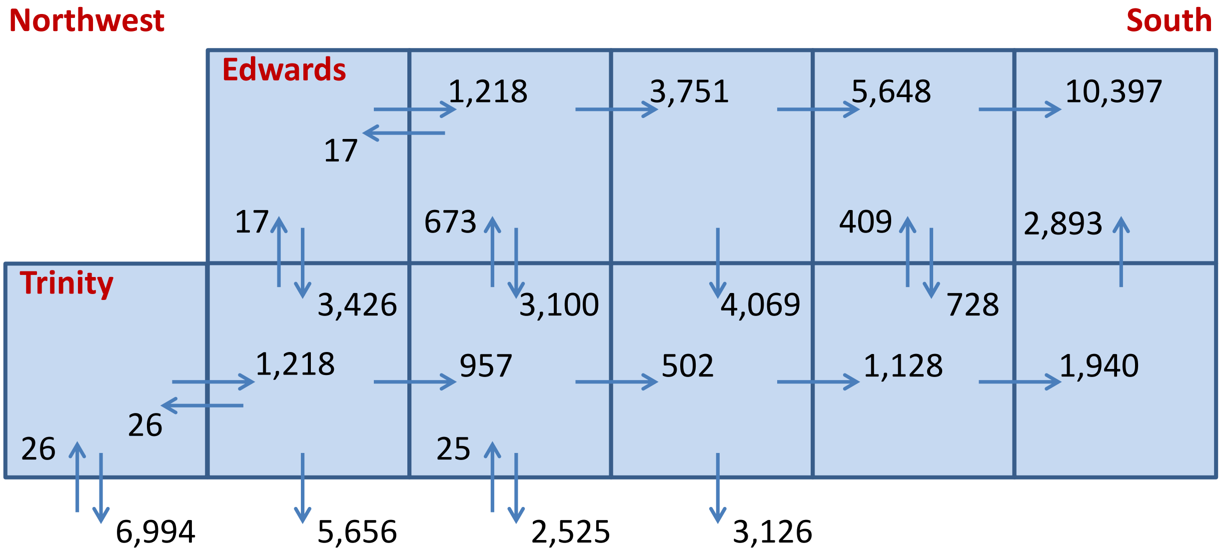


Figure 8-25. **Stream tube mass balance in the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer in acre-feet per year.**

8.6 Conclusions and Recommendations

The following will document some of the conclusions that can be reached based upon our analysis of the GAMs analyzed. In each case we will try to contrast the conceptual understanding or a particular flow component of the aquifer with the behavior quantified through analysis of the GAMs.

8.6.1 Interaction between Aquifers

Initially we looked at the vertical flow aspects of the Dockum Aquifer, the Rustler Aquifer, and the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer models where they are contiguous. The following is predicted by the GAMs analyzed.

- Net flow in all regions is downward from the Edwards Group to the Trinity Group in both the Anaya and Jones (2009) and Young and others, (2010) models.
- The largest net downward flow occurs in the central Edwards-Trinity (Plateau) Aquifer region in the Anaya and Jones (2009) model. In the Young and others, (2010) model the largest net downward flow component is in the northeastern plateau region.
- There is a significant region of the central Edwards-Trinity (Plateau) Aquifer region (southern-southwestern portion) where flow is upward from the Trinity Group to the Edwards Group as the Rio Grande is the regional sink.
- The Dockum Aquifer exhibits a net discharge to the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer with the largest upward flow occurring into the Pecos Valley Aquifer in the Dockum Aquifer GAM. Conversely, both the Anaya and Jones (2009) and Young and others (2010) exhibit a net downward flow from the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer to the Dockum Aquifer.

- The Dockum Aquifer GAM predicts downward flow from the Trinity Group into the Dockum Aquifer occurring in the northwestern Edwards-Trinity (Plateau) Aquifer region. This appears to be in contrast to the higher levels of total dissolved solids and sulfate in the Trinity Group (Antlers Formation) groundwater found in this region.
- The Rustler Aquifer has a net discharge upward into the Dockum Aquifer with the largest flow occurring in the western Edwards-Trinity (Plateau) Aquifer region. This is consistent with the Rustler Aquifer conceptual model for flow.
- Lateral flow in the Dockum Aquifer and the Rustler Aquifer in the region is dominated by flow to the Pecos Valley Aquifer with the exception of flow from the northwestern Edwards-Trinity (Plateau) Aquifer to the central plateau which is net flowing to the southeast across that regional boundary (Figure 8-14).
- Lateral flows in the Edwards-Trinity (Plateau) Aquifer are reasonable based upon head surfaces.
- The lateral flow magnitudes between the two models are very similar in the Edwards Group and the Trinity Group with the exception of one region. The Young and others, (2010) model has significantly more flow to the Pecos Valley Aquifer from the western region than in Anaya and Jones (2009) model.
- Both Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer models maintain the same flow directions between hydrostratigraphic regions with the exception of the southeastern to the northeastern regions in the Trinity Group. This may reflect the fact that the Anaya and Jones (2009) model steady-state period is representative of 1980 and has pumping in the model.
- All the models considered are deemed to have adequate vertical discretization; stratigraphic and water level data do not appear to warrant the inclusion of more model layers and aggregation of the current model layers would only preclude analysis of the cross-formational flow between aquifers currently available.

8.6.2 Flow Path Continuity Between the Aquifers

To evaluate the degree to which cross-formational flow adds to the mixing of groundwater flowing laterally along flow lines, a stream tube mass balance analysis was conducted. The direction of the stream tube was based on the regional water-level contours presented in Figure 8-7 in this report but originally from Nance (2010). Cross-formational flow represents flow between the Edwards Group and the Trinity Group or between the Trinity Group and general-head boundary conditions meant to represent the Dockum Aquifer. The following conclusions can be made from this analysis.

- Cross-formational mixing of groundwater flow is between the Edwards Group and Trinity Group is comparable to and, in some cases, larger than the downstream component of flow in the Edwards-Trinity (Plateau) Aquifer.
- Downward flow from the Edwards Group to the Trinity Group is the dominant cross-formational flow direction.
- Downward flow from the Trinity Group to the Dockum Aquifer is the dominant cross-formational flow direction in both Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer models.

- The current models are deemed to reasonably represent within and between the aquifers included in the models.

9 Aquifers of the Trans-Pecos Region

Historical geochemical and isotopic data for groundwater samples taken from wells and springs throughout the Trans-Pecos region of GMA 3 and 7 are used to develop conceptual models for the various aquifers in the area. End-member groundwater areas are first identified based on the general hydrogeology, established aquifer boundaries, and regional flow paths within the aquifers. The groundwater data are then used to identify geochemical and isotopic signatures for the end-member areas, and data about the mineralogy of the formations hosting the aquifers and the general hydrogeology of the aquifers are used to interpret the processes controlling groundwater chemistry. Finally, the hydrochemical processes are used to develop a set of conceptual models that primarily focus on cross-formational flows and identification of recharge areas.

For this part of the project, the Trans-Pecos region study area is defined as the westernmost area within GMA 3 and 7 with an emphasis on the aquifers located west of the Pecos River (Figure 3-1). This study area and the sub-divisions to be discussed in this chapter are detailed in Figure 9-1. The counties in GMA 4 are technically outside of the project study area; however, minor occurrences of several of the critical aquifers are located within GMA 4, and numerous researchers, including Couch (1978), Pearson (1985), LaFave and Sharp (1987), Uliana and Sharp (2001), Uliana and others. (2007), and Bumgarner and others, (2012) have concluded that the Cretaceous and Cenozoic aquifers of GMA 3 and the westernmost extent of GMA 7 are receiving local recharge from the Tertiary Volcanics and regional flow from the Permian aquifer systems in GMA 4. The easternmost parts of GMA 4 are, therefore, included in the development of the conceptual models described here.

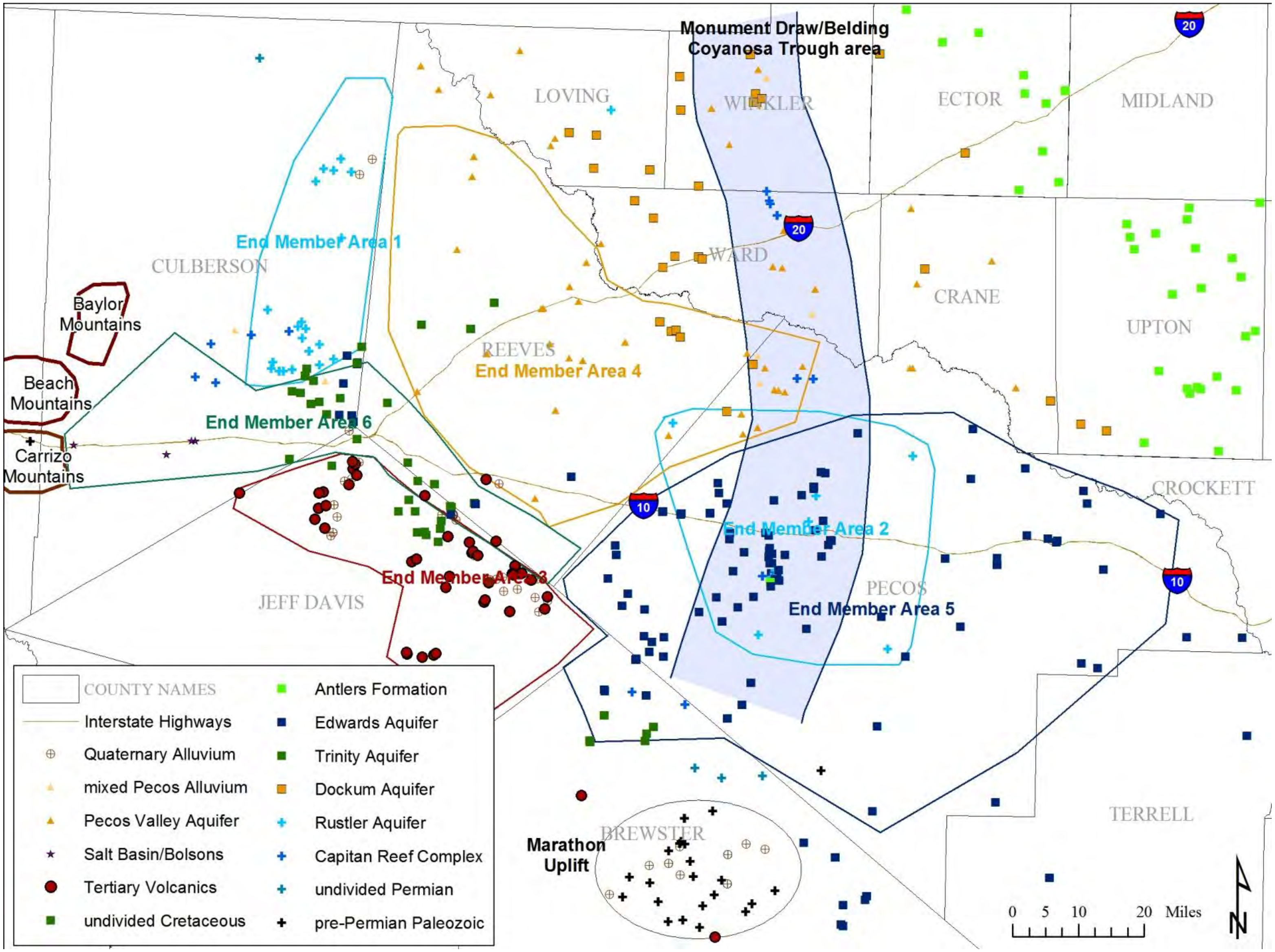


Figure 9-1. **Sub-divisions of Trans-Pecos region study area and location of individual aquifer data points.**

9.1 Description of Data Used

The analytical data used in the study include cation concentrations (calcium, magnesium, sodium, potassium, strontium), anion concentrations (chloride, sulfate, bicarbonate, nitrate), stable isotope ratios (oxygen-18, deuterium), and radiogenic isotope ratios and concentrations (carbon-14 percent modern, tritium, strontium isotopic compositions). The project database includes a total of 980 sample analyses from 421 wells and 13 springs (Figure 9-1). Eight hundred and eighty eight of those analytical records were obtained from the TWDB water well database in May of 2012. Eighty five analytical records were obtained from the USGS in June of 2012 (Pearson and others, 2012). The database was supplemented with 7 additional sample records with strontium isotopic compositions data from Uliana (2000). All but 21 samples have complete balanced ion concentrations (defined as charge balances of 5% or less). Nine of the 21 samples, with ion charge balances between 5% and 6.6%, are from wells located in critical parts of the study area and were therefore included in the analyses. The remaining 12 samples had isotope data that were used in the analyses, but any ion concentrations associated with those samples were deemed unreliable and were therefore not used in the study.

9.1.1 Identification of End Members and Description of Geochemical and Isotopic Signatures

Several end-member areas are identified based on the geochemical and isotopic signatures of the groundwaters in those areas. These areas, along with the sampling locations and the formations supplying the sampled wells and springs, are shown on Figure 9-1. Detailed descriptions of the end-member areas are provided in sections 9.1.2 through 9.1.7. The spatial distribution of the following select geochemical and isotopic parameters is also presented as: total dissolved solids (Figure 9-2), carbon-14 percent modern (Figure 9-3), oxygen-18 (Figure 9-4), and strontium isotopic compositions (Figure 9-5). A general discussion of the significance of each parameter is given below.

Total Dissolved Solids

Total dissolved solids are a general indicator of relative residence time, as longer residence times generally result in more mineralized waters. Total dissolved solids tend to increase along flow paths; therefore, maps of total dissolved solids distributions can often be used to infer groundwater flow paths. This is not an exact relationship, as total dissolved solids in groundwater is also a function of the type of minerals in the aquifer matrix, and aquifers with high percentages of soluble minerals (e.g., halite and gypsum) can contain relatively young waters with high salinities.

Carbon-14

Carbon-14, expressed as percent modern carbon dissolved in the groundwater, also provides an indication of time since the water recharged. No corrections for absolute age were performed on the data available for this project; therefore the data are only presented as relative indications of residence time.

Oxygen-18

Oxygen isotopes in groundwater provide an indication of climatic conditions present at the time meteoric water recharged the aquifer (Faure, 1986). The oxygen isotopic composition of groundwater is also dependent on other conditions in the recharge area, including latitude, distance from the moisture sources, elevation, and precipitation amounts. Based on precipitation data presented by Darling (1997), a review of data from the Global Network of Isotopes in Precipitation program (IAEA/WMO, 1998), and Uliana, and others, (2007), oxygen-18 values in precipitation throughout the study area should range from -7.5 to -5.5 ‰ SMOW. As discussed by Uliana, and others. (2007) and Nance (2010), groundwaters in the western areas of Texas with depleted oxygen-18 values relative to the values in current precipitation are interpreted to represent groundwaters that recharged during the cooler and wetter conditions present in the late Pleistocene and early Holocene rather than groundwaters that are affected by variations in latitude, altitude, location, or precipitation amount. Oxygen isotopes in this area, therefore, can be used to determine indirectly groundwater residence times.

Oxygen isotopes, in conjunction with the deuterium (ratio of ^{2}H/H (δD)), can also be used to identify waters that have been affected by evaporation. Figure 9-6 shows all oxygen-18 and deuterium data from the Trans-Pecos region study area relative to the meteoric water line, which represents the range of isotope values expected in precipitation throughout the world. Evaporation of meteoric water causes enrichment in the isotopes of oxygen and hydrogen at different rates, resulting in a deviation from the meteoric water line similar to the deviation indicated by the dark red arrow on Figure 9-6. The data indicate that a few Pecos Valley Aquifer samples, which are located near the Pecos River, and some of the samples from the Marathon Uplift area, have experienced evaporative enrichment. The overwhelming majority of the samples within the study area, however, have not experienced significant evaporation and, therefore, have oxygen-18 values that reflect conditions at the time of recharge.

Strontium isotopic compositions

Strontium readily substitutes into mineral crystal lattices for calcium-bearing minerals such as calcite, dolomite, anhydrite, and calcium-plagioclase feldspars, and is therefore a common trace element in those minerals (Banner, 2004). Since the isotopic composition of dissolved strontium experiences negligible fractionation during mineral-solution reactions, the isotopic composition of dissolved strontium in a water that is in equilibrium with a strontium-bearing mineral will be the same as the isotopic composition of the mineral (Banner and Kaufman, 1994; Banner, 2004). strontium isotopes, therefore, can be used to trace regional groundwater flow paths and identify groundwater mixing. The following is a list of expected ranges of strontium isotopic compositions values in the Trans-Pecos groundwaters based on the mineral contents of the various aquifers:

1. Marine carbonates and evaporites from the Permian and Cretaceous are common throughout the study area. Burke and others, (1982) reconstructed the historic strontium isotopic composition of the oceans throughout the Phanerozoic (Figure 4-4). Based on this curve, marine carbonates and evaporites deposited during the Permian and Cretaceous should have strontium isotopic compositions ranging from about 0.7068 to 0.7084.
2. Denison and others, (1998) determined strontium isotopic compositions values for anhydrite beds in the Late Permian (Ochoan) Rustler Formation ranging from 0.7069 to 0.7074. Rustler Aquifer samples should therefore have strontium isotopic compositions values within this range.
3. Strontium isotopic composition is a radiogenic daughter product of the decay of ^{87}Rb; therefore, the relative abundance of strontium isotopic composition in strontium-

bearing minerals is greater in older rocks and in siliciclastics composed of sediments derived from older rocks. Groundwaters in contact with early Paleozoic and Precambrian rocks will tend to be enriched in strontium isotopic composition. In addition, siliciclastic aquifers such as the Pecos Valley Aquifer can have enriched strontium isotopic composition values, depending on the age of the sediment source rocks, the amount of carbonate cements in the sediments, and the influence of cross-formational flow from adjacent carbonate terrains.

4. In addition, siliciclastic material entrained in marine carbonate or evaporite rocks will tend to result in enriched strontium isotopic composition relative to the marine minerals. The mudstones and clastic silts interbedded with the evaporites in the Rustler Formation, therefore, could result in slight enrichment of strontium isotopic composition in the Rustler Aquifer groundwaters relative to the measured ratios in the anhydrite beds.
5. Whole-rock analyses of igneous rock samples from the Davis Mountains presented by Cameron, and others, (1996) indicate an average strontium isotopic compositions value of 0.7067 with a range of values from 0.7030 to 0.7080.

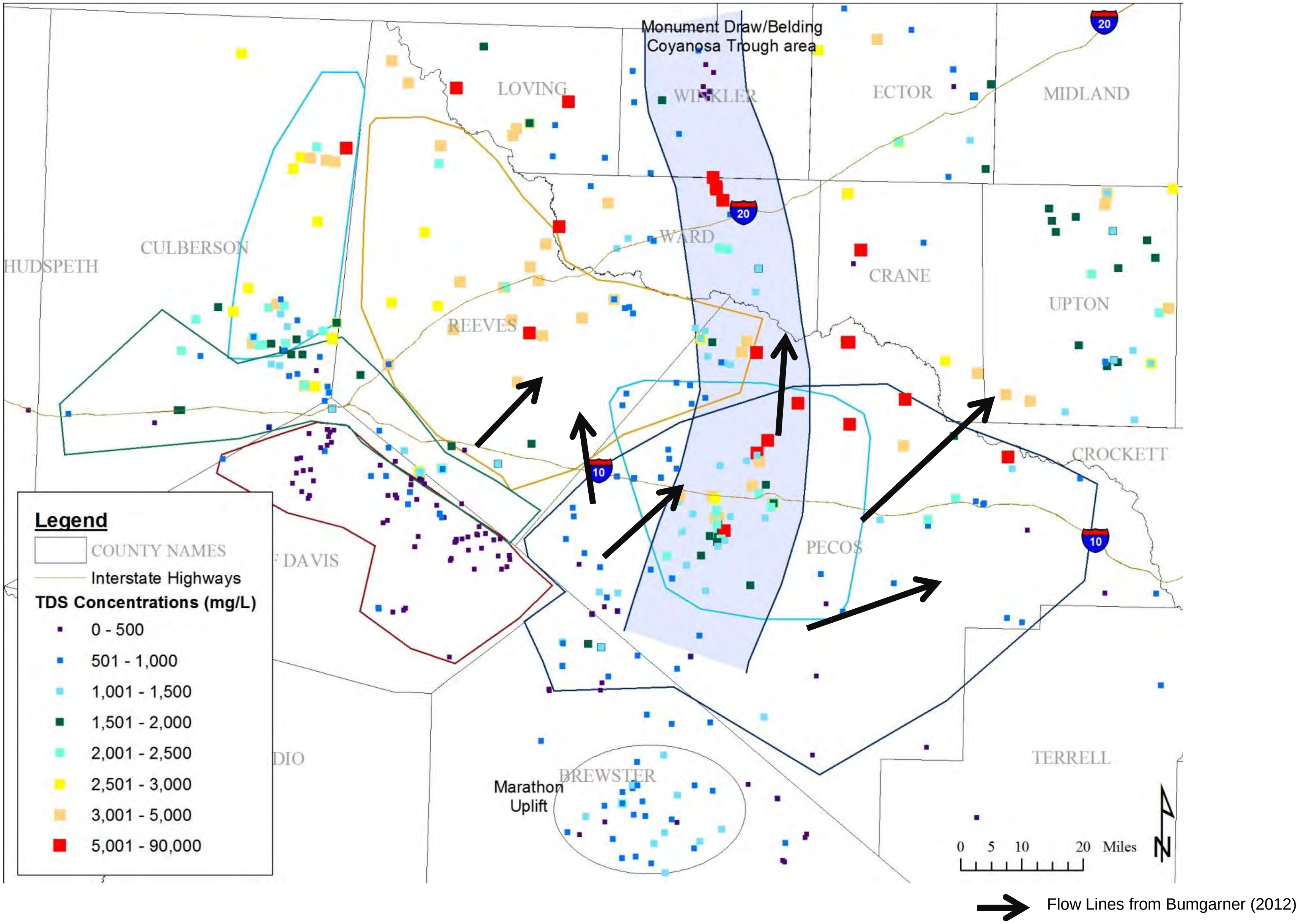


Figure 9-2. **Map of total dissolved solids (TDS) concentrations.**

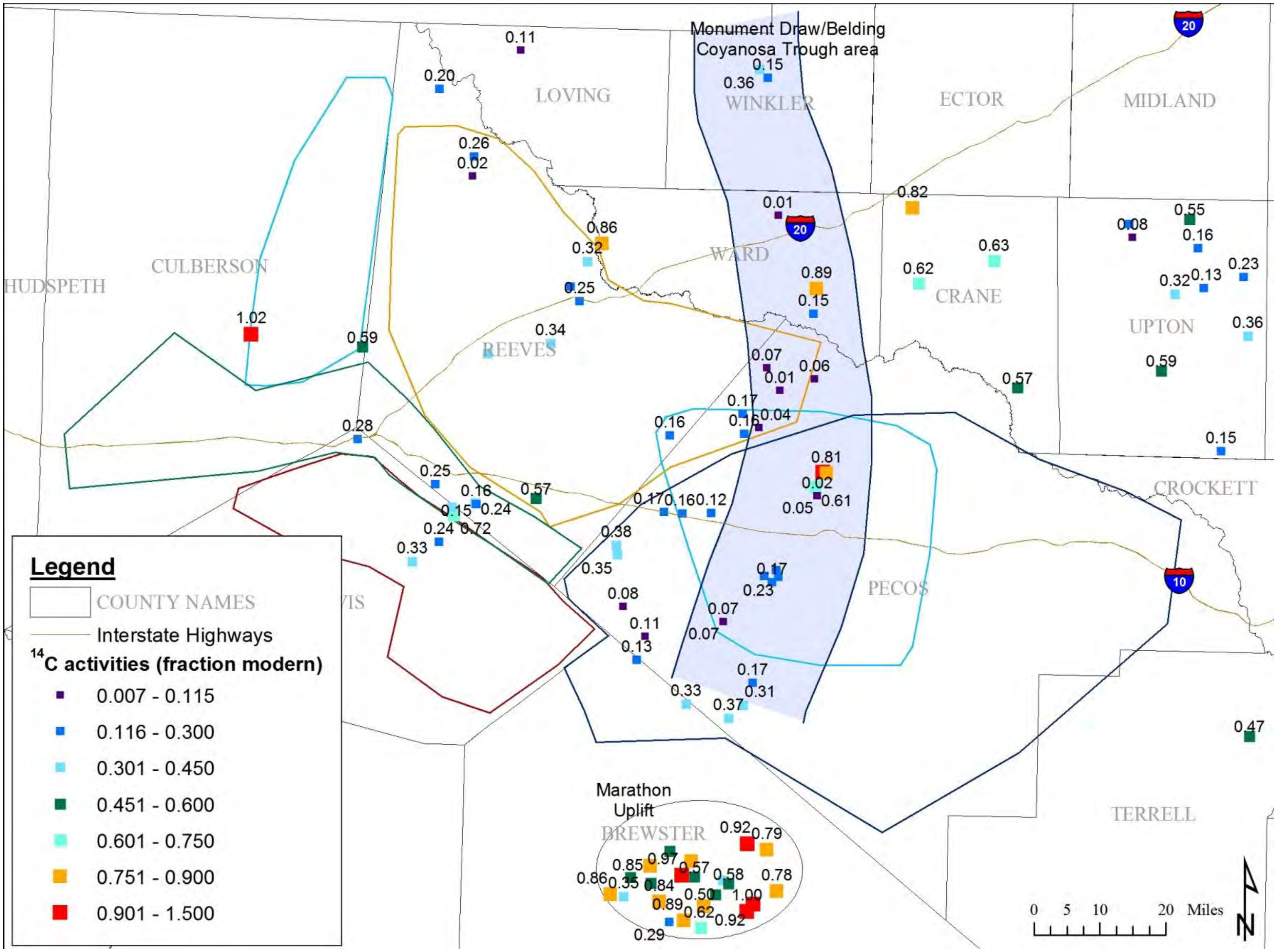


Figure 9-3. **Map of carbon-14 percent modern ($^{14}C\%$) values.**

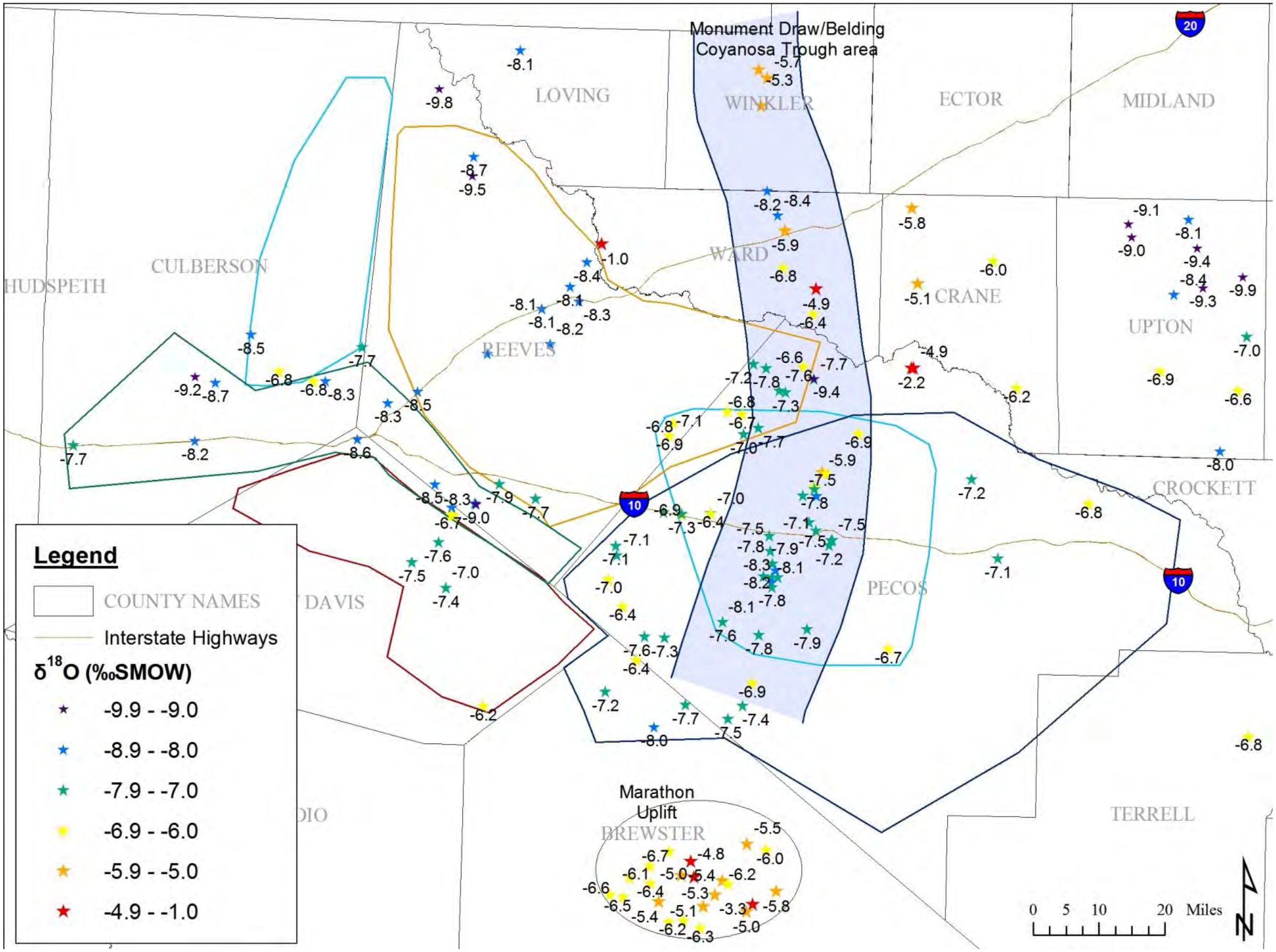


Figure 9-4. Map of oxygen-18 ($\delta^{18}O$) values.

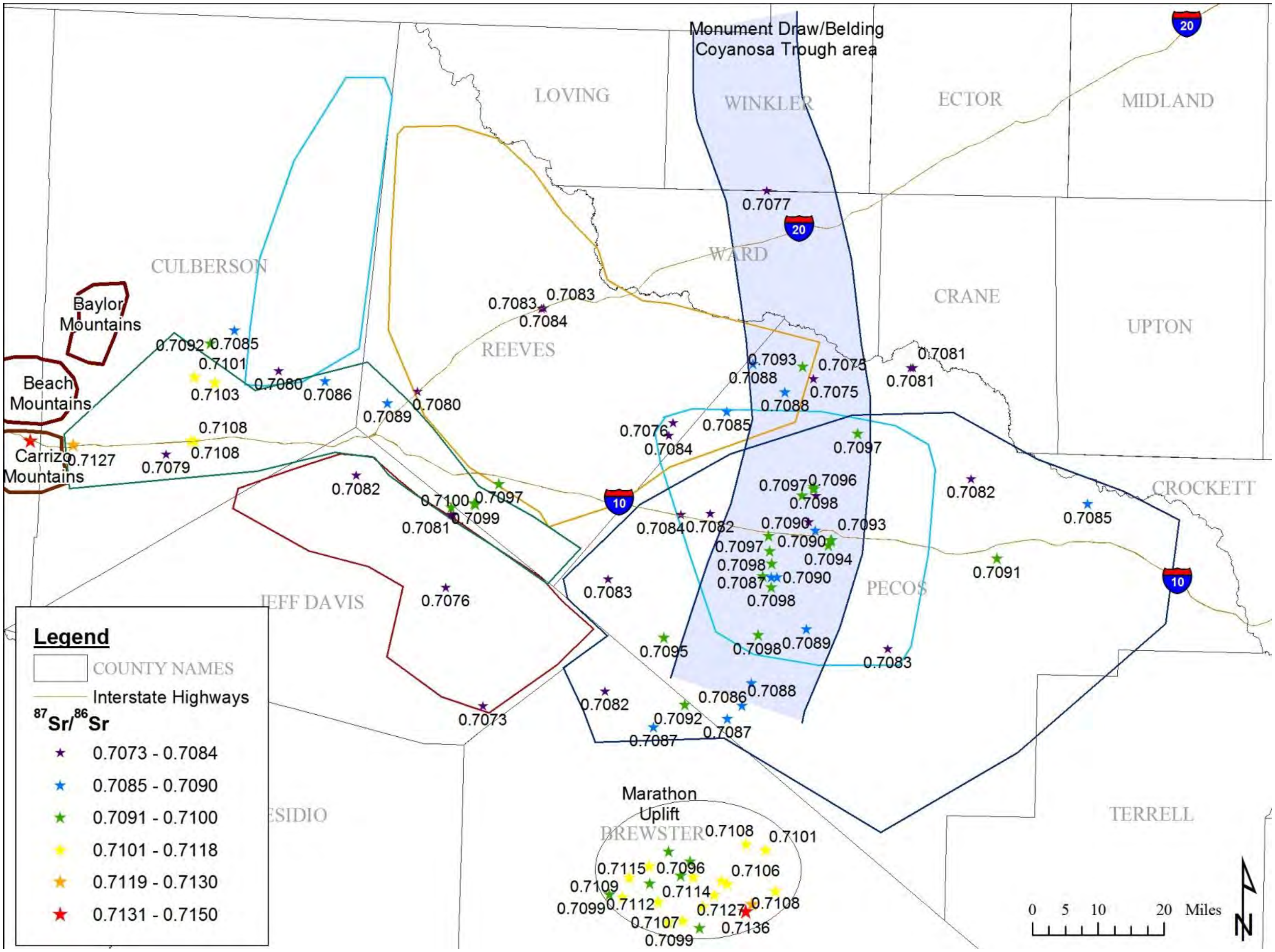


Figure 9-5. **Map of strontium isotopic compositions ($^{87}Sr/^{86}Sr$) values.**

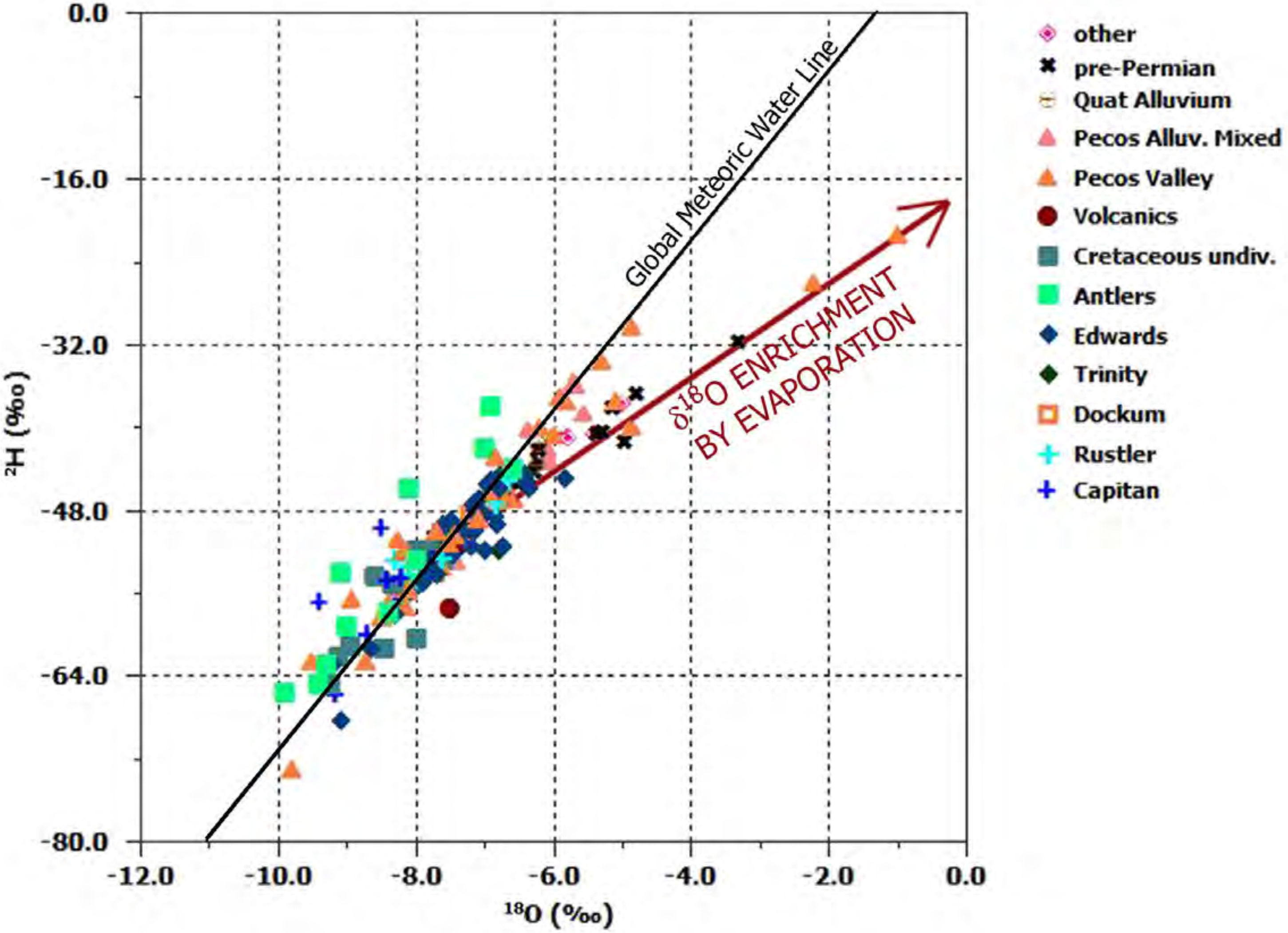


Figure 9-6. Oxygen-18 ($\delta^{18}O$) vs deuterium (δD) for all samples relative to the global meteoric water line (data are from the TWDB and USGS on-line water well databases).

9.1.2 End-Member Area 1: Rustler Aquifer Outcrop in Culberson County

The Rustler Aquifer, which occurs in the Permian (Ochoan) Rustler formation, is exposed at the surface in eastern Culberson County at the western edge of the study area (Figure 9-7). The mineralogy of the bedrock is primarily gypsum, anhydrite, and dolomite. The hydrochemical facies in groundwater samples from this area are predominantly calcium-sulfate and calcium-magnesium-sulfate facies (Figure 9-8) with low to moderately high (500-4,000 mg/L). Mineral saturation indices calculated using the geochemical modeling program PHREEQC version 2.15 (Parkhurst and Appelo, 1999) indicate that Rustler Aquifer waters are near saturation with gypsum and anhydrite and typically undersaturated to near saturation with respect to dolomite. The basic geochemical signature of the groundwaters in this area are interpreted as reflecting bedrock dissolution.

There are no carbon-14 percent modern or tritium values for Rustler Aquifer samples from the outcrop area. A single sample from a Rustler Aquifer outcrop area well has as oxygen-18 value of -6.8. This value is consistent with the expected values for current precipitation, which suggests that the groundwaters in the Rustler Aquifer outcrop area represent recharge that occurred under current climatic conditions.

A single sample from a Rustler Aquifer outcrop area well has a measured strontium isotopic compositions value of 0.7080. This value is slightly higher than the maximum expected strontium isotopic composition (0.7074) for the Rustler Formation anhydrites as determined by Denison and others, (1998), which suggests that the dissolved strontium is controlled by anhydrite dissolution with some slight enrichment from entrained siliciclastics. This value is also consistent with the overall range of values for Permian marine carbonates and evaporites as indicated by Figure 4-4.

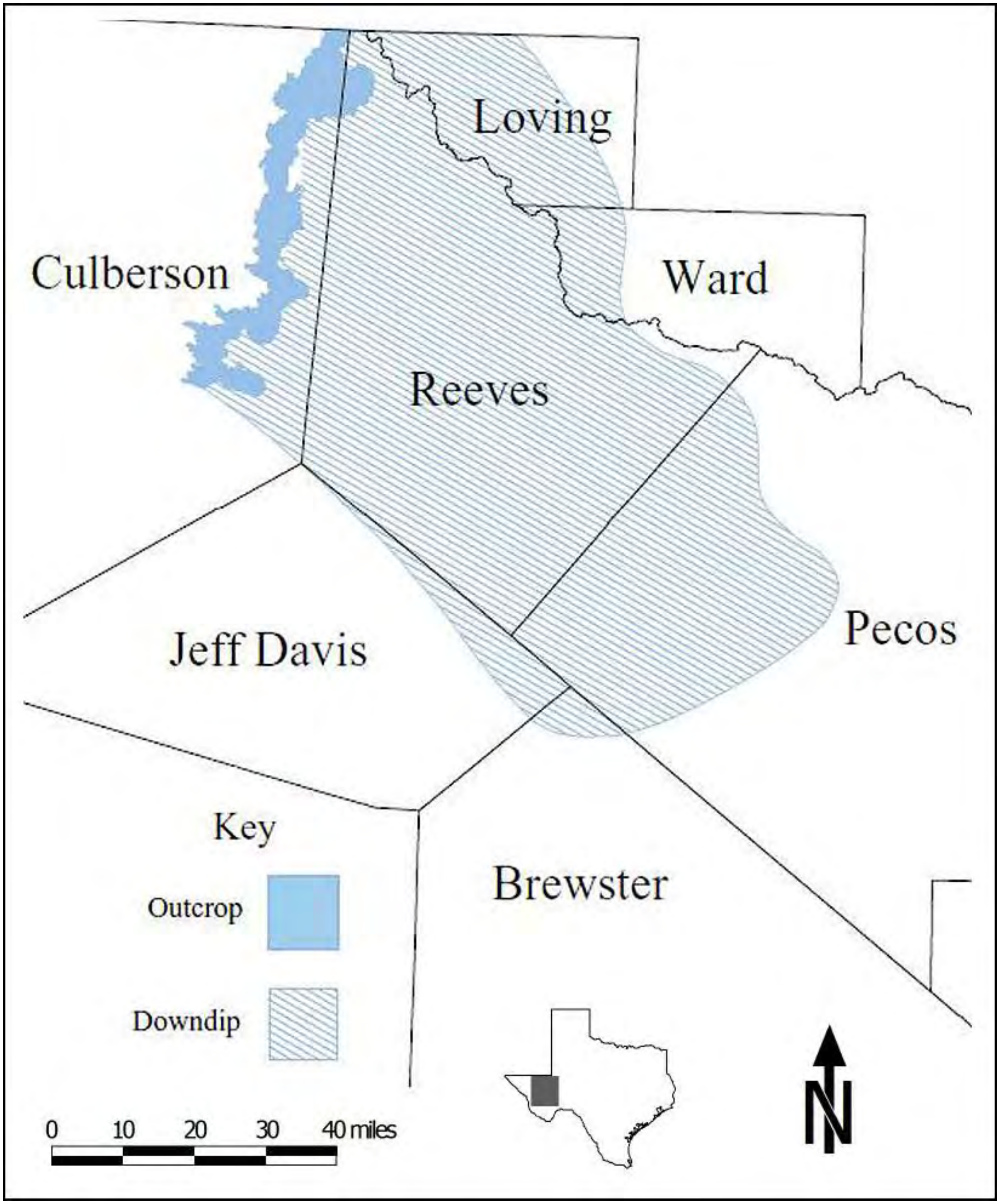


Figure 9-7. **Location of the Rustler Aquifer (from Ashworth and Hopkins, 1995).**

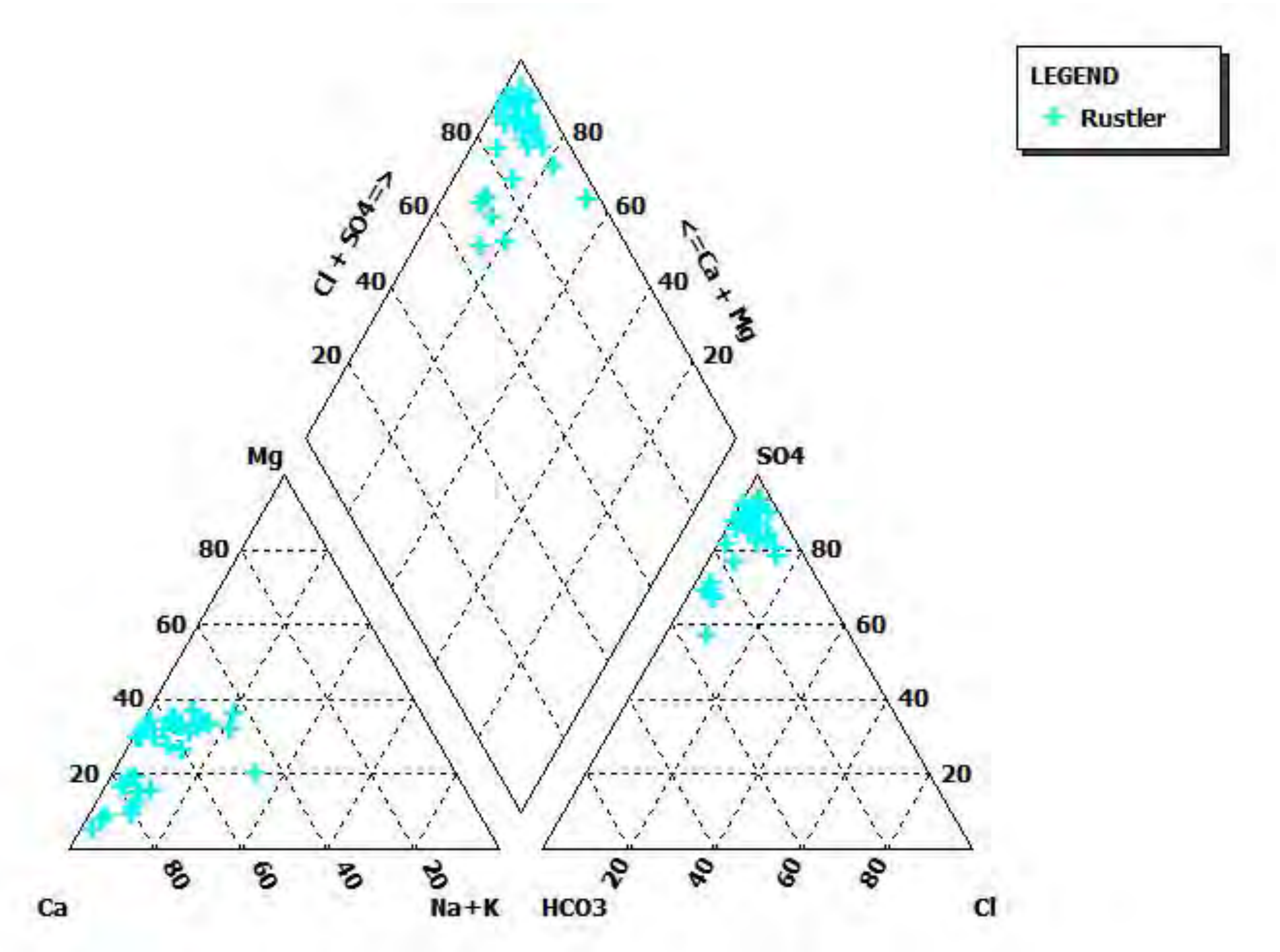


Figure 9-8. **Piper diagram showing analytical data from the Rustler Aquifer outcrop area. Data are from the TWDB and USGS on-line water well databases.**

9.1.3 End-Member Area 2: Rustler Aquifer in Subsurface in Reeves and Pecos Counties

The Rustler Aquifer also occurs in the subsurface beneath the Pecos Valley Aquifer, the Edwards-Trinity (Plateau) Aquifer, and the Dockum Aquifer in Reeves, Loving, and parts of Pecos counties (Figure 9-7). Total dissolved solids in Reeves and Pecos counties range from about 430 mg/L to 8,570 mg/L (Figure 9-2). The single sample from Loving County has a total dissolved solid of almost 90,000 mg/L and is predominantly sodium-chloride facies (symbol 1 on Figure 9-9); this sample is probably influenced by deep basin brines and is very different from the confined Rustler Aquifer waters in Reeves and Pecos counties. Hydrochemical facies in the subsurface in Reeves and Pecos counties are much more variable than those in the outcrop, ranging from a low-total dissolved solids calcium-bicarbonate water in easternmost Pecos County (symbol 2 on Figure 9-9), to mixed-cation facies with variable sulfate and chloride concentrations (symbols 3 and 4 on Figure 9-9), to a calcium-magnesium-sulfate facies typical of the outcrop zone water (symbol 5 on Figure 9-9).

Four available carbon-14 values from two wells range from 2 to 14 percent modern (Figure 9-3); these values are associated with relatively depleted oxygen-18 values of -8.1 to -8.3 (Figure 9-4) and tritium values < 0.1 TU. Five additional samples have oxygen-18 values that range from -7.9

to -6.7. These samples do not have carbon-14 or tritium data, so relative ages for these waters cannot be determined.

Most of the strontium isotopic compositions values are between 0.7074 and 0.7076, which is consistent with the expected values for the Rustler Aquifer and which suggests very little influence from interformational flow (Figure 9-5). The exceptions are the samples noted on Figure 9-4 as sample 2 (0.7083), sample 4 (0.7098), and a sample just north of sample 4 (0.7087).

End Member Area 2 is identified as a unique end member and distinguished from End Member Area 1 because, unlike the area 1 groundwater samples, those from area 2 exhibit a much wider range of geochemical and isotopic compositions. The area 1 groundwater samples have a fairly uniform chemistry that appears to be controlled by interaction with anhydrites in the Rustler Formation. The area 2 samples indicate considerable and variable influences from other sources, which are most likely associated with upwelling from underlying formations.

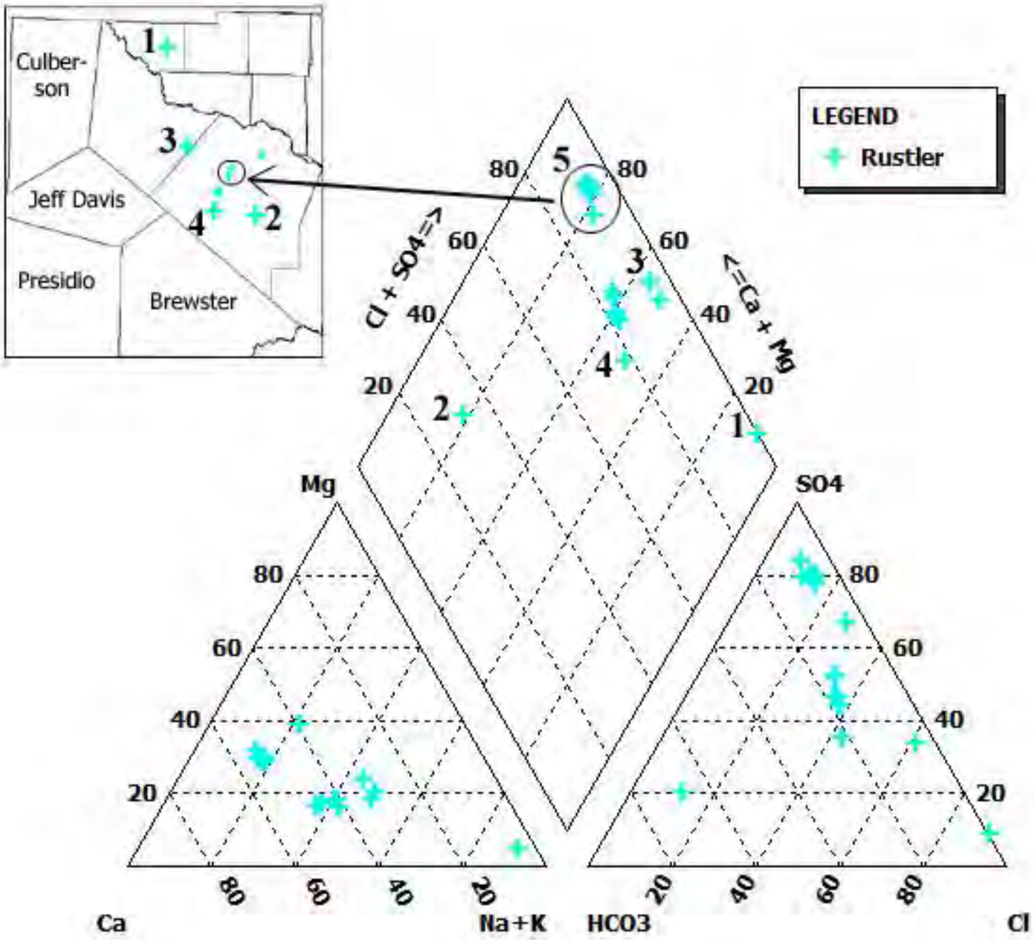


Figure 9-9. **Piper diagram showing analytical data from the Rustler Aquifer subcrop area. Data are from the TWDB and USGS on-line water well databases.**

9.1.4 End-Member Area 3: Tertiary Volcanics and Associated Alluvial Fill in Jeff Davis County

The Tertiary extrusive igneous rocks in northern Jeff Davis County, and the associated alluvial valley fill, is technically outside of the study area; however, previous studies (Couch, 1978; Pearson, 1985; LaFave and Sharp, 1987; Uliana and Sharp, 2001; Bumgarner and others, 2012) have demonstrated that runoff and groundwater flow from the Davis and Barilla Mountains is moving north into the Pecos Valley Aquifer and underlying Edwards-Trinity (Plateau) Aquifer and providing a significant amount of recharge to those aquifers. The groundwaters are predominantly calcium-bicarbonate and sodium-bicarbonate hydrochemical facies (Figure 9-10) with total dissolved solids generally less than 600 mg/L (Figure 9-2). The hydrochemical facies and low total dissolved solids are due to the relatively low amount of mineral-water interaction between meteoric recharge and the predominantly silicate bedrock and alluvial fill.

There are only three carbon-14 values available for this area (Figure 9-3). Two located in the volcanics have values ranging from 24 to 33 percent modern. The third sample is located in the alluvial fill and has a value of 72 percent modern. Measured oxygen-18 values range from -6.7 to -7.6 (Figure 9-4) and are assumed to be typical for local precipitation.

The strontium isotopic composition of groundwater samples from the volcanics and associated alluvial fill range from 0.7073 to 0.7082. These values are consistent with the whole-rock analyses of the volcanics discussed above.

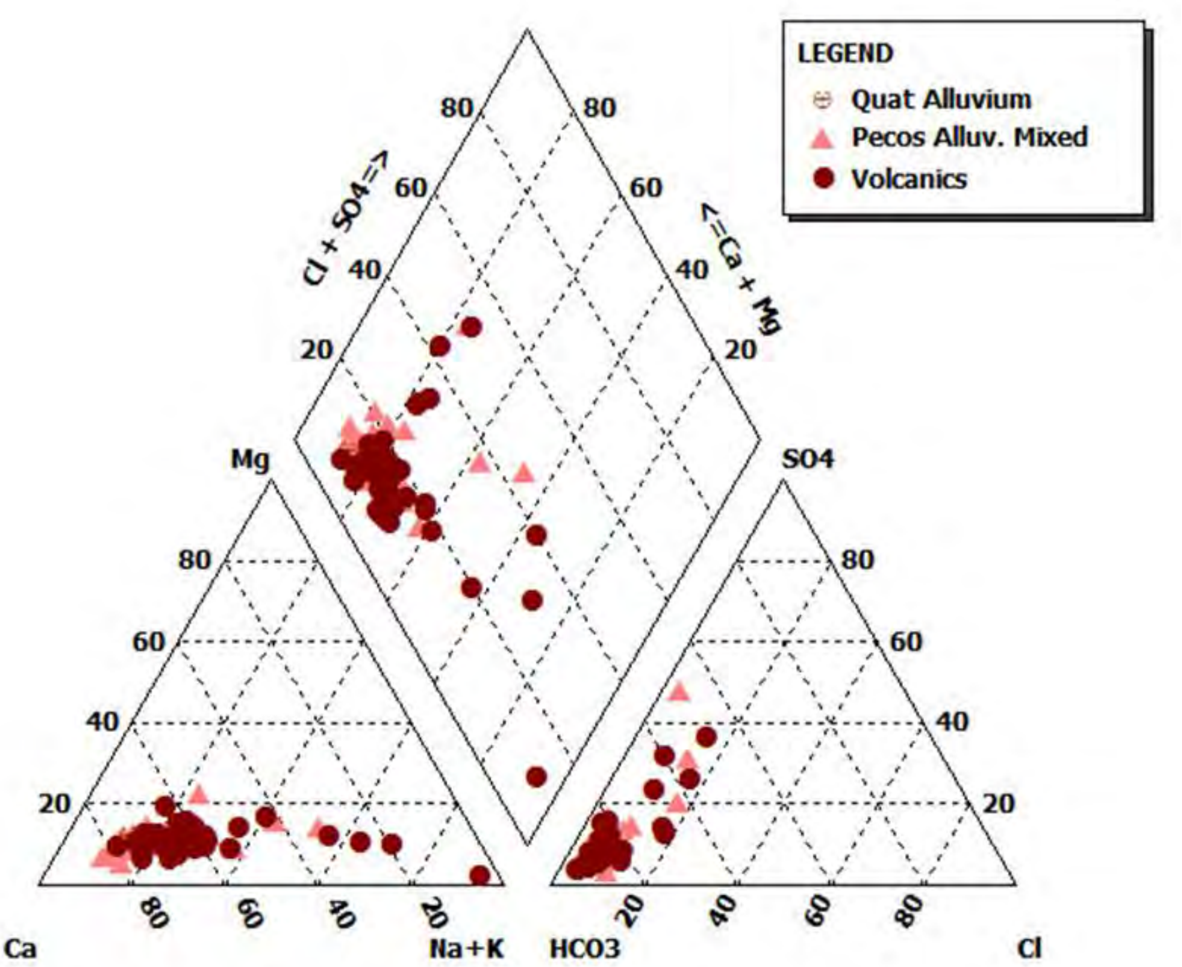


Figure 9-10. **Piper diagram showing analytical data from the igneous formations and associated alluvial fill, northeast part of Jeff Davis County, Texas. Data are from the TWDB and USGS on-line water well databases.**

9.1.5 End-Member Area 4: Pecos Valley Aquifer in Reeves and Northwest Pecos Counties

Groundwaters in the siliciclastic basin fill of the Pecos Valley Aquifer have highly variable hydrochemical facies (Figure 9-11). The northernmost wells in the county are calcium-magnesium-sulfate waters that are probably dominated by flow from the Rustler Aquifer in Culberson County. Pecos Valley Aquifer groundwater chemistry could also be influenced by surface runoff from the Delaware Mountains that crosses Permian Castile and Rustler outcrops and infiltrates into the basin fill. Groundwater in the western half of the county are predominantly sulfate-rich waters, while those in the central part of the county near the Pecos River are predominantly chloride-rich. Total dissolved solids range from about 600 to over 5,600 mg/L (Figure 9-2). The highest total dissolved solids values appear to be associated with the chloride-rich waters in the central part of the county and near the Pecos River.

Pecos Valley Aquifer samples from the central and western part of Reeves County have oxygen-18 values, ranging from -8.1 to -8.9 (Figure 9-4), that are depleted relative to current precipitation in the area. These are high-total dissolved solids (2,500 - 5,000 mg/L) waters with carbon-14 ranging from 22-34 percent modern (Figure 9-3). These samples also have low tritium (less than 0.44 TU). These isotopic data suggest very little recent recharge.

The strontium isotopic compositions of the Pecos Valley Aquifer samples range from 0.7080 to 0.7084. These values are consistent with Cretaceous marine carbonates, and are probably controlled by dissolution of carbonates in the underlying Edwards-Trinity (Plateau) Aquifer system. Two strontium isotopic compositions values in the Pecos Valley Aquifer in the northern corner of Pecos County are slightly higher with values ranging from 0.7088 to 0.7093. These higher values appear to be related to the high values in the Edwards-Trinity (Plateau) Aquifer system in the Monument Draw/Belding-Coyanosa Trough area (hereafter referred to as the "Monument-Belding Trough area") in central Pecos County, which will be discussed in the next section.

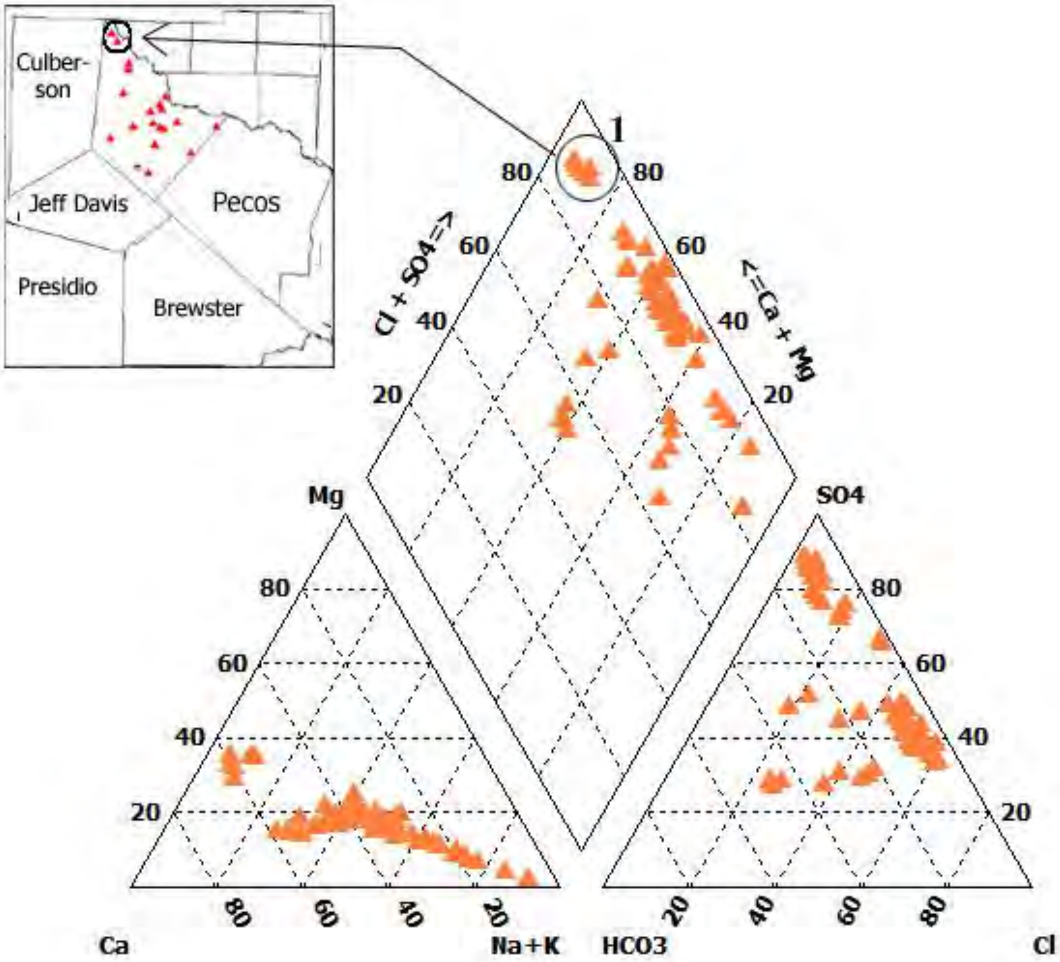


Figure 9-11. **Piper diagram showing analytical data from the Pecos Valley Aquifer, Reeves County, Texas. Data are from the TWDB and USGS on-line water well databases.**

9.1.6 End-Member Area 5: Edwards-Trinity (Plateau) Aquifer in Pecos and Northern Brewster Counties

The hydrochemical facies in the Cretaceous Carbonates of the Edwards-Trinity (Plateau) Aquifer system in Pecos County are also variable, ranging from calcium-bicarbonate and calcium-magnesium-bicarbonate to a few sodium-bicarbonate to a broad range of mixed cation and anion facies (Figure 9-12). Total dissolved solids concentrations are low (less than1,000 mg/L) along the border with Reeves County and in the easternmost part of the county near the Terrell County border (Figure 9-2); these samples are typically associated with bicarbonate or mixed anion waters. In the central part of the county, within the Monument-Belding Trough area, the facies are much more variable (including sulfate, chloride, and mixed-anion waters) and the total dissolved solids is much higher (1,000 to 5,000 mg/L) with a trend of increasing total dissolved solids towards the northeast along the flow paths identified by Bumgarner and others, (2012) (Figure 9-2).

The variable hydrochemical facies and total dissolved solids suggest an influx of water from several formations. The highest TDS values are found near the Pecos River.

Carbon-14 values for most of the area are relatively low (less than 40 percent modern) (Figure 9-3). Within the Monument-Belding Trough area, the values are less than 20 percent modern. The exception to the trend of low-carbon-14 waters in area 5 is a group of high-total dissolved solids (greater than 5,000 mg/L) wells on the north side of the area that have carbon-14 values of 0.81 to 1.08 percent modern. In addition, these samples and a few other nearby high-TDS samples have high tritium concentrations (Figure 9-13). These are young, chloride-rich waters and probably represent infiltration of Pecos River water applied for irrigation. A similar pattern is observed with the oxygen-18 data. Wells with higher ratios of modern carbon and higher tritium tend to have oxygen-18 values (-7.5 to -5.8‰ SMOW) that are consistent with values expected for local precipitation, while wells within the Monument-Belding Trough area that have low carbon-14 percent modern and low tritium tend to have slightly depleted oxygen-18 values ranging from -8.3 to -7.2‰ SMOW.

The fresher bicarbonate waters along the boundaries with Reeves and Terrell counties are associated with strontium isotopic compositions values that range from 0.7082 to 0.7088 (Figure 9-5) and are consistent with expected values for dissolution of Cretaceous marine carbonates with a slight enrichment of strontium isotopic composition, possibly from siliciclastics in the carbonate rock. Within the Monument-Belding Trough area, strontium isotopic compositions values are in the 0.7090 to 0.7098 range, and are considerably higher than expected for Cretaceous carbonates. The potential source of enriched strontium isotopic composition is discussed in a later section.

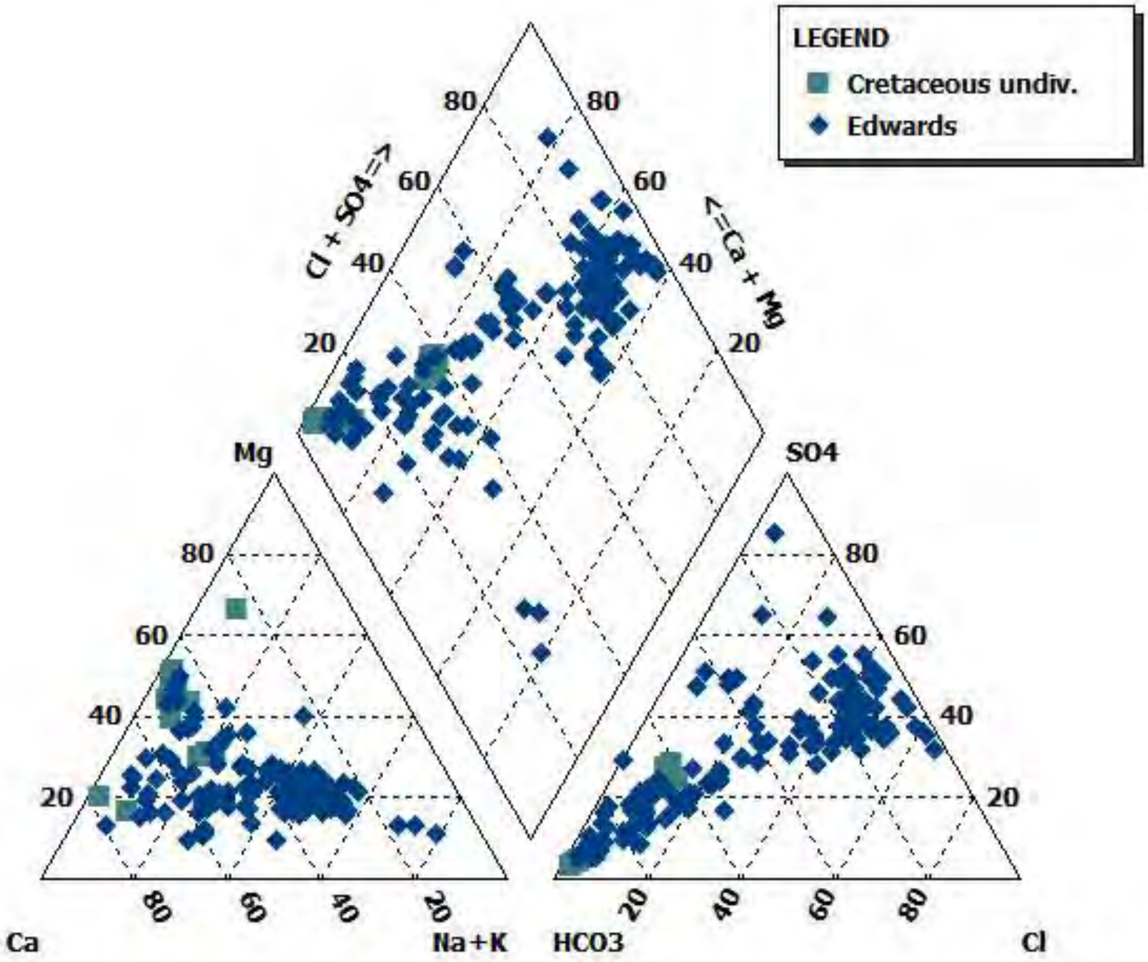


Figure 9-12. Piper diagram showing analytical data from the Edwards-Trinity (Plateau) Aquifer system, Pecos and northern Brewster counties, Texas. Data are from the TWDB and USGS on-line water well databases.

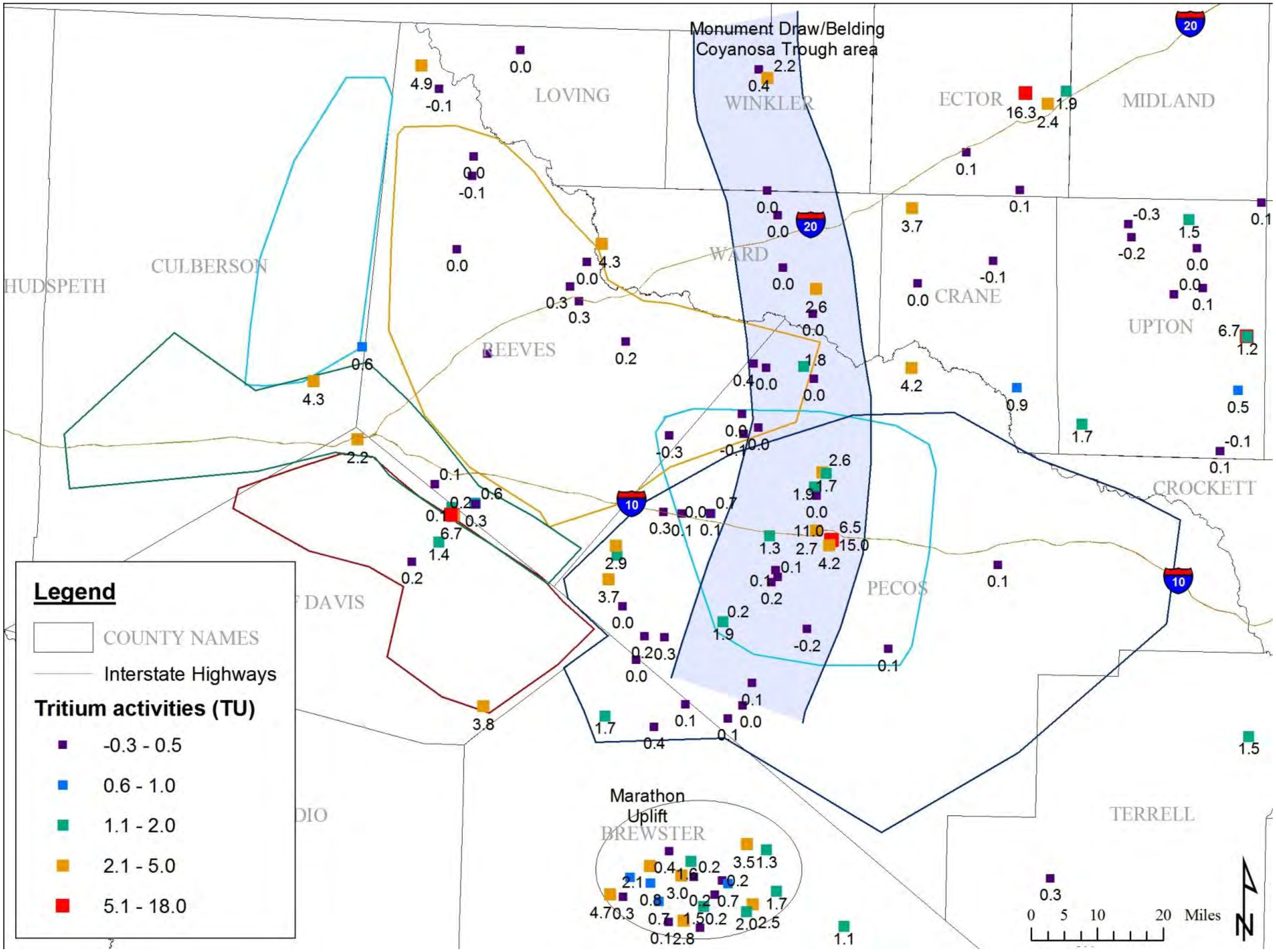


Figure 9-13. Map of tritium (^3H) values.

9.1.7 End-Member Area 6: Western Permian Regional Flow Path in Culberson, Reeves, and Jeff Davis Counties

Previous studies have hypothesized and presented data in support of a regional flow system, hereafter referred to as the western Permian regional flow path, that originates in the Tertiary and Quaternary alluvial fill in the Wild Horse Flat Bolson in Culberson County, then flows through the fractured siliciclastic basin fill facies associated with the Capitan Reef Complex under the Apache Mountains of Culberson County, then moves eastward into the westernmost extent of the Edwards-Trinity (Plateau) Aquifer at the boundary of Culberson, Jeff Davis, and Reeves counties. This flow system was first proposed by Neilson and Sharp (1985). LaFave and Sharp, (1987) studied the Balmorhea-area springs and used groundwater chemistry and geochemical modeling to differentiate between the western regional water source to the spring waters and the local source supplied by storm events in the Davis Mountains. Uliana and Sharp (2001) and Uliana et al. (2007) used stable and radiogenic isotopes in conjunction with geochemistry and a fracture trace analysis to delineate the hypothesized regional flow system west of the springs. Finally, Bumgarner and others, (2012) concluded that the western Permian regional flow path is influencing the Edwards-Trinity (Plateau) Aquifer system in Pecos County.

The hydrochemical facies for groundwaters in this area tend to be a broad range of mixed cation/anion facies with calcium-bicarbonate waters in the alluvium and volcanics and a range of calcium-sodium-sulfate-chloride waters for the Cretaceous strata (Figure 9-14). Total dissolved solids values typically range from about 2,000 to 3,000 mg/L (Figure 9-2). Relatively high sulfate concentrations in samples from the eastern extent of this area (up to 950 mg/L) suggest some influence from mixing with the Rustler Aquifer waters. There is very little carbon-14 or tritium data west of the Balmorhea-area springs along the flow path; one sample near the Culberson, Jeff Davis and Reeves counties boundary has a carbon-14 of 28 percent modern (Figure 9-3), which suggests a relatively old water, yet has a tritium value of 2.2 TU (Figure 9-13), which suggests recent recharge. The discrepancy between the relative ages suggested by the carbon-14 and tritium data in this single sample, if not related to sample contamination or analytical error, is possibly associated with mixing of younger and older waters. Oxygen isotope values are generally depleted (-9.1 to -8.2 ‰ SMOW) relative to current precipitation, suggesting that the waters are not recent (Figure 9-4). The variable total dissolved solids and hydrochemical facies, and the variable isotopic data, indicate that this is an area of active mixing between waters from the western extent of the flow path, waters from the volcanics of the Davis Mountains, and waters from the Rustler Aquifer outcrop area in Culberson County.

Sr isotopic compositions at the westernmost extent of the western flow path are very high (strontium isotopic compositions = 0.7148) and are related to interaction of the groundwater with Precambrian and early Paleozoic strata exposed in the Carrizo, Beach, and Baylor Mountains located along the boundary of Culberson and Hudspeth counties (Figure 9-5). Strontium isotopic compositions values throughout End Member Area 6, including the Balmorhea-area springs, are typically higher than 0.7100. This flow system is a potential source of high- strontium isotopic compositions waters throughout the study area (Uliana and others, 2007). This will be discussed in more detail in section 9.2.1.

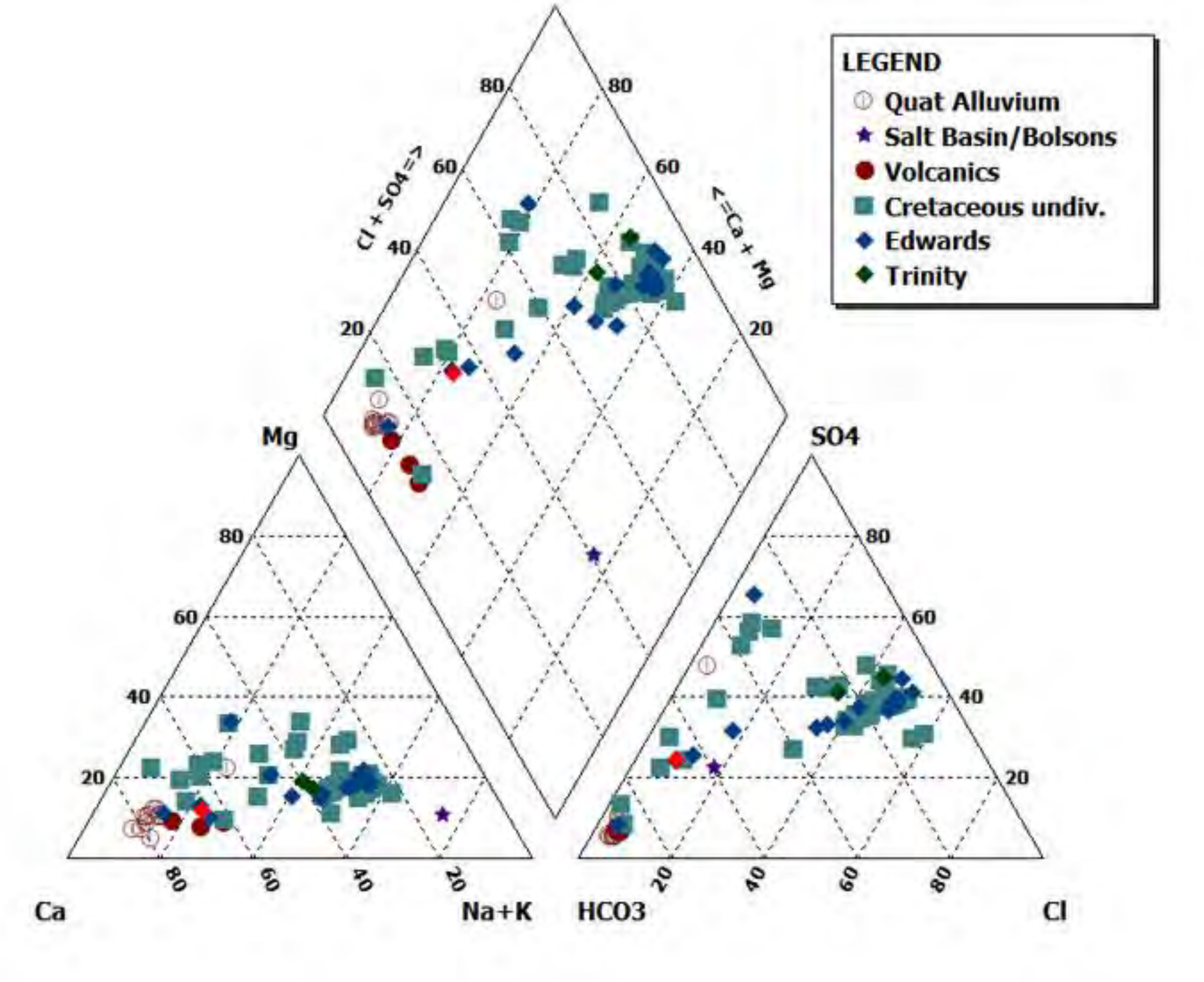


Figure 9-14. **Piper diagram showing analytical data from end member area 6. Data are from the TWDB and USGS on-line water well databases.**

9.2 Conceptual Model Interpretations

The geochemical and isotopic data presented above are used to develop a set of conceptual models that describe parts of the aquifers in the Trans-Pecos region of GMA 3 & 7. These conceptual models are focused primarily on interformational flows between the aquifers.

9.2.1 Conceptual Model 1: Lateral Flow from Western Permian Regional Flow Path (End Member Area 6) into the Edwards-Trinity and Pecos Valley Aquifers

This conceptual model deals with interactions between end member areas 1, 3, 4, 5, and 6. One of the key isotopic parameters that define the western Permian regional flow path is the high strontium isotopic compositions values that originate in the bolson aquifer in Culberson County. This parameter is especially useful because the strontium isotopic compositions values in the other end member areas are fairly consistent and clearly defined. Uliana and others, (2007) used major ion chemistry and strontium isotopic compositions to identify and delineate three end-member areas, called areas A, B, and C, that directly relate to end member areas 6, 3, and 1, respectively, that are defined in this report. A review of the larger and more detailed data set discussed in this report has confirmed that the end member areas defined by Uliana, and others. (2007) are correct and appropriate.

LaFave and Sharp, (1987), Uliana, and others, (2007) and Bumgarner and others, (2012) have provided geochemical and isotopic evidence that supports the hypothesis that the Balmorhea-area springs are sourced by the western Permian regional flow path, and Uliana, and others, (2007) hypothesized, based on limited data, that the flow system is controlled by fracture zones in the subsurface and that it may extend as far as Comanche Springs in central Pecos County. The current data set, which includes additional strontium isotopic compositions data as well as other geochemical parameters, indicates that the strontium isotopic compositions values in samples from the Monument-Belding Trough area are much higher than those expected for Cretaceous marine carbonates and that samples from wells outside of that area tend to have strontium isotopic compositions that are within the expected ranges (Figure 9-15). These samples also have oxygen-18 values that are slightly depleted with respect to current estimates of precipitation, but not as depleted as those at the Balmorhea-area springs or to the west of the springs. This is consistent with regional flow experiencing some partial dilution by a relatively minor amount of recent recharge and/or flow of fresher water from end member area 3. The sharp contrast between the high strontium isotopic compositions values along the flow path and the adjacent samples that are consistent with Cretaceous marine carbonates is consistent with the hypothesized controls on the flow system by regional scale fracture trends.

An alternate hypothesis for the high strontium isotopic compositions values in the Monument-Belding Trough area groundwaters is that they are the result of upwelling of deeper waters along the subsurface faults from pre-Permian formations. Groundwaters from samples taken from the early Paleozoic aquifers in the Marathon Basin area have high strontium isotopic compositions; if those or similar formations exist beneath the Capitan, they could be a possible source for enrichedstrontium isotopic composition. The problem with this hypothesis is that the project data set does not include any reliable samples from those formations that could be used for mixing calculations to test the hypothesis. If those deeper waters are highly saline, it could be that the mixing ratio required to raise the Sr isotopic composition to the observed values would make the waters much more saline than the data indicate. In addition, while there is evidence for some upwelling in the Monument-Belding Trough area (which will be discussed in a later section), the strontium isotopic compositions values in the underlying Rustler Aquifer are less than those in the Edwards-Trinity (Plateau) Aquifer. While it may be possible for upwelling flow from the early Paleozoic strata to bypass the Rustler and only discharge into the Edwards-Trinity (Plateau) Aquifer, it is highly unlikely. Until reliable data for the underlying formations are obtained, the western flow system is the most likely source for the enriched strontium isotopic composition.

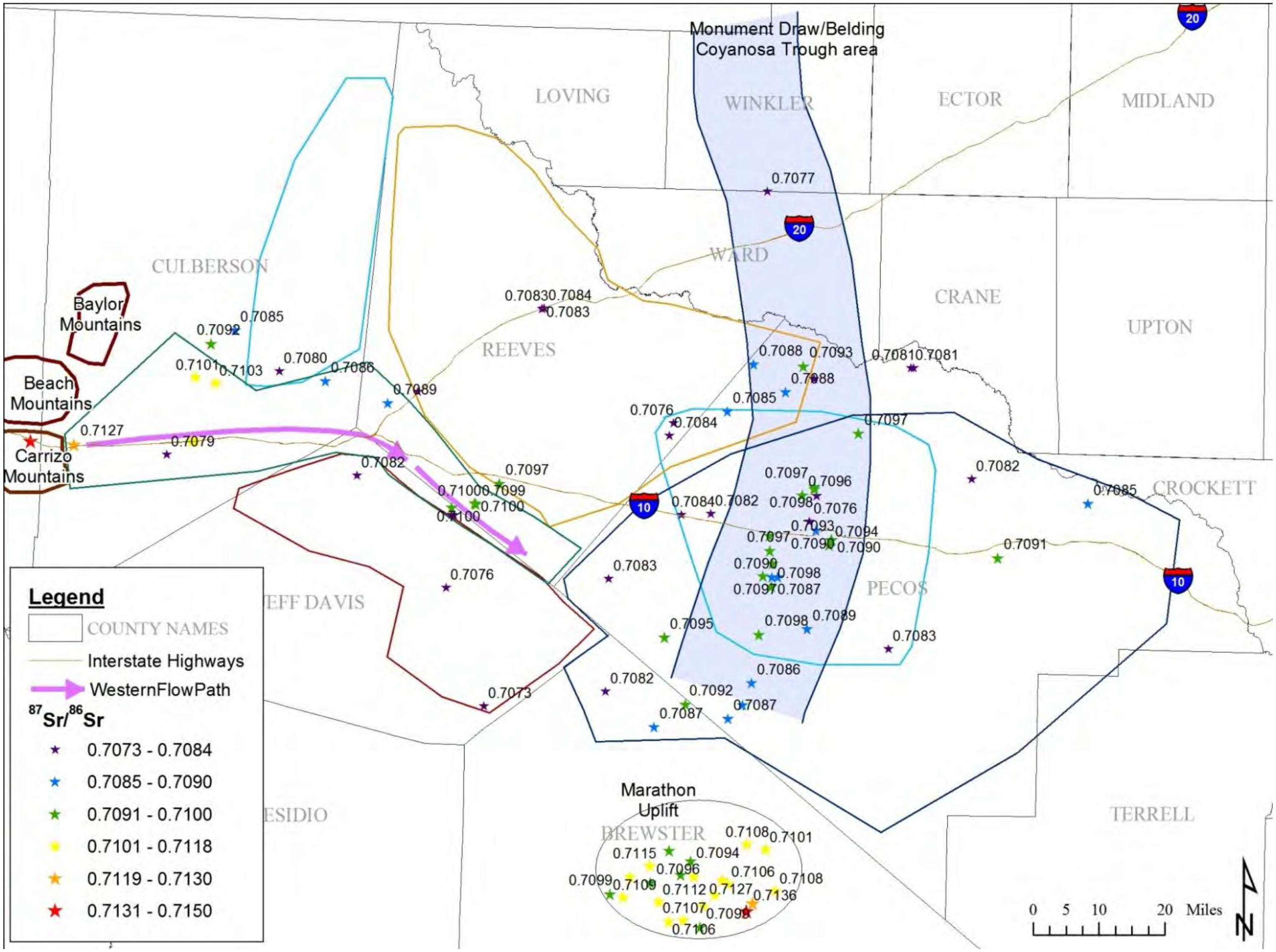


Figure 9-15. Map of strontium isotopic compositions ($^{87}Sr/^{86}Sr$) values with annotations describing conceptual model 1 (the blue arrows represent the main regional flow path).

9.2.2 Conceptual Model 2: Lateral flow from the Rustler Aquifer Outcrop Area (End Member Area 1) into the Pecos Valley Aquifer (End Member Area 4)

This conceptual model deals with groundwater flowing from the Rustler Aquifer outcrop area in eastern Culberson County laterally into the Pecos Valley Aquifer in Reeves County. As previously stated, the hydrochemical facies for End Member Area 1 is calcium-magnesium-sulfate, which reflects the predominance of gypsum, anhydrite, and dolomite in the bedrock. On a plot of total dissolved solids versus sulfate (Figure 9-16), the Rustler Aquifer samples fall on a least-squares regression line (Line A) with a slope of about 0.65 mg/l sulfate for every mg/L total dissolved solids. Samples from Pecos Valley Aquifer wells and mixed Pecos Alluvium – defined as any Quaternary alluvial fill that is not considered to be part of the Pecos Valley Aquifer system (e.g., recent river gravels) – from the western half of the county (Figure 9-17) follow the same trend; while samples from the eastern half of the county follow a different regression line (Line B) with a slope of about 0.4 mg/l sulfate for every mg/L total dissolved solids. The samples from the western half of the county are generally sulfate-rich waters, while those from the eastern half of the county are chloride-rich and mixed anion waters. In addition, as indicated on Figure 9-12, the Pecos Valley samples at the northern tip of the county are calcium-sulfate waters with very little other anions, indicating that they are directly impacted by flow from the Rustler Aquifer outcrop area.

These data suggests that a sufficient amount of water is flowing from End Member Area 1 into End Member Area 4 to control and/or significantly impact the major ion chemistry of the waters in the western half of End Member Area 4. Carbon-14 values in the western part of Reeves County range from 0.02 to 0.31 (Figure 9-3), suggesting that residence times in the aquifer are relatively high and that flow rates are slow. This is supported by oxygen-18 values (-9.8 to -8.1‰ SMOW) that are depleted relative to recent recharge (Figure 9-4) and generally low tritium values (less than 0.4 TU), with the exception of a value of 4.8 TU in the northernmost sample from Reeves County (Figure 9-13). The eastern half of End Member Area 4 is more controlled by either irrigation return flows or water from the western Permian regional flow path entering the Pecos Valley Aquifer and flowing north towards the river.

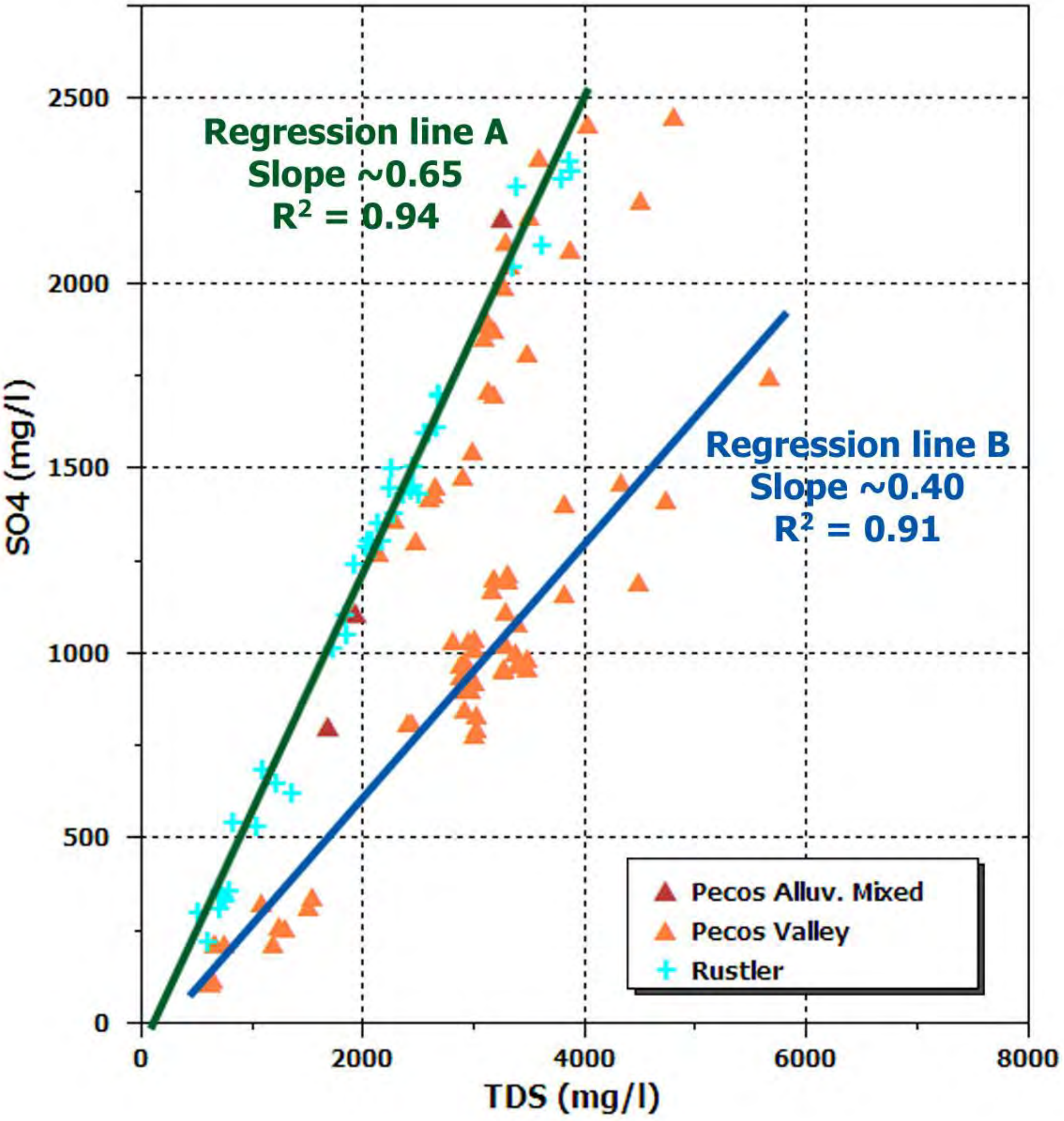


Figure 9-16. **Graph of total dissolved solids (TDS) vs sulfate ($SO_{4)}$ concentration for the Rustler Aquifer samples from End Member Area 1 and the Pecos Valley Aquifer samples from End Member Area 4.**

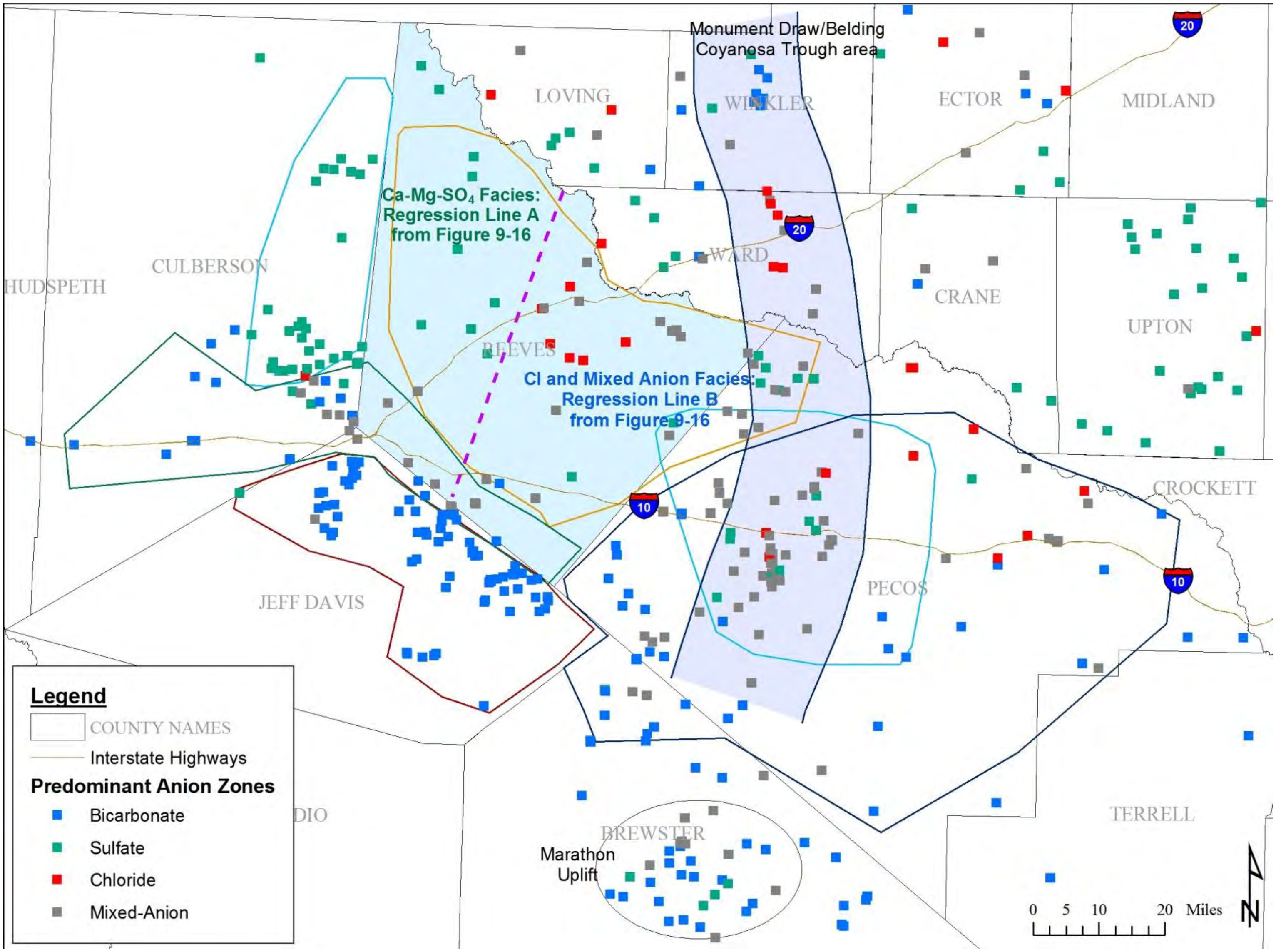


Figure 9-17. Map of study area showing sample locations and sample aquifers/formations. End-member area 4 is highlighted. The blue line separates the wells that fall on Regression Line A on Figure 9-15 from the wells that fall on Regression Line B.

9.2.3 Conceptual Model 3: Upwelling of Rustler Aquifer water (End Member Area 2) into the Edwards-Trinity and Pecos Valley Aquifers

This conceptual model deals with the potential for upwelling flow from the Rustler Aquifer subcrop into the overlying Edwards-Trinity (Plateau) aquifer and/or the Pecos Valley Aquifer in Pecos County.

As shown in Figure 9-2, waters from the Monument-Belding Trough area have much higher total dissolved solids concentration than those in the surrounding Edwards-Trinity (Plateau) Aquifer wells. Most surrounding wells are primarily bicarbonate waters. The Monument-Belding Trough area samples are variable hydrochemical facies; most are mixed-anion (sulfate-chloride) waters, with some sulfate-dominated samples and some chloride-dominated samples distributed within the group of mixed-anion samples. There is no systematic variation in the changes in water chemistry that would be expected from simple evolution of groundwater along a flow path (e.g., steadily increasing total dissolved solids, change from bicarbonate to sulfate to chloride dominated waters, etc.). This is illustrated using a map of the predominant anion for each sample similar to the method used in Uliana and Sharp, (2001) to develop predominant anion zones for the Trans-Pecos region (Figure 9-18). "Predominant anion" is defined as the anion in the sample that constitutes 50% (expressed as meq/L) of the three major anions in the sample; e.g., if a sample's anionic constituents are composed of 60 meq/L of sulfate, 30 meg/l of chloride, and 10 meq/l of bicarbonate, then sulfate would equal 60% of the total and would be assigned as the predominant anion. If no anion constitutes greater than 50% (e.g., 40% sulfate, 40% chloride, and 20% bicarbonate), then the sample is labeled "mixed-anion." This is useful in the Trans-Pecos region because it helps to distinguish between the sulfate-dominated waters of End Member Area 1 and 2 from the bicarbonate-dominated waters of End Member Area 3, and also distinguish the chloride-dominated waters associated with irrigation returns or with deeper, more saline waters.

As shown in Figure 9-18, samples outside of the Monument-Belding Trough within End Member Area 5 tend to be bicarbonate dominated waters, while those inside the area tend to be mixed-anion samples with some sulfate–dominated and chloride-dominated samples scattered throughout. The map of total dissolved solids value (Figure 9-2) shows a similar total dissolved solids distribution with some high (2,500-5,000 mg/L) total dissolved solids value scattered among more moderate (1,500-2,500 mg/L) values. A review of the carbon-14, oxygen-18, and bicarbonate data, however, indicates that the samples with high (greater than2,500 mg/L) total dissolved solids concentration within End Member Area 5 tend to have high carbon-14 percent modern values (Figure 9-3), oxygen-18 values that are consistent with modern precipitation values (Figure 9-4), and modern (greater than 1 TU) tritium signatures (Figure 9-13), suggesting that the very high total dissolved solids value within the Monument-Belding Trough in End Member Area 5 are possibly associated with flushing of concentrated salts in the surface from application of irrigation water recharging the aquifer rather than upwelling. The samples with moderate (1,500-2,500 mg/L) total dissolved solids value, low (less than30 percent modern) carbon-14 percent modern values, depleted (less than-7.5‰ SMOW) oxygen-18 values, and very little (less than 1 TU) tritium are probably related to upwelling flow from the Rustler Aquifer. In addition, samples from the northern part of Pecos County, within the area identified as within End Member Area 4, have predominantly sulfate facies, relatively high total dissolved solids, low carbon-14, and low tritium, which would indicate upwelling from the underlying Rustler Aquifer.

Within the Monument-Belding Trough area there appears to be a difference between the Rustler Aquifer samples from wells located south of IH-10 and those from wells north of the highway. The samples from the Rustler Aquifer wells north of the highway are very similar to those from the outcrop area-primarily calcium-magnesium-sulfate facies with very little chloride or bicarbonate (see symbol number 5 on Figure 9-9) with strontium isotopic compositions values (0.7074 to 0.7076) that are consistent with expected values for Rustler Formation-dominated waters. The sample with carbon-14, oxygen-18, and tritium data has low carbon-14, slightly depleted oxygen-18, and very little tritium, which is consistent with a long residence time in the Rustler since recharge in the outcrop zone. The samples south of the highway, however, have mixed-anion facies (see symbol number 4 on Figure 9-9) and higher strontium isotopic compositions values (0.7087 to 0.7098) that are more similar to the few Capitan Reef Complex Aquifer samples from the same area. This could indicate that more chloride-rich water from the Capitan Reef Complex Aquifer is upwelling and mixing with the Rustler Aquifer water in the area south of IH-10, resulting in mixed-anion more saline waters in both the Rustler Aquifer and in the overlying Edwards-Trinity (Plateau) Aquifer.

North of the Pecos River in Ward County chloride-rich groundwaters are also observed in a few Capitan Reef Complex Aquifer wells as well as in two Pecos Valley Aquifer wells located within the Monument-Belding Trough. There is no data from the Rustler Aquifer in this area to confirm the upwelling hypothesis; however, the Capitan Reef Complex Aquifer and Pecos Valley Aquifer data are consistent with upwelling flow in this part of the trough.

The overall conclusion for Conceptual Model 3 is that upwelling of both Rustler Aquifer and underlying Capitan Reef Complex Aquifer water is occurring within the Monument-Belding Trough area south of the interstate highway.

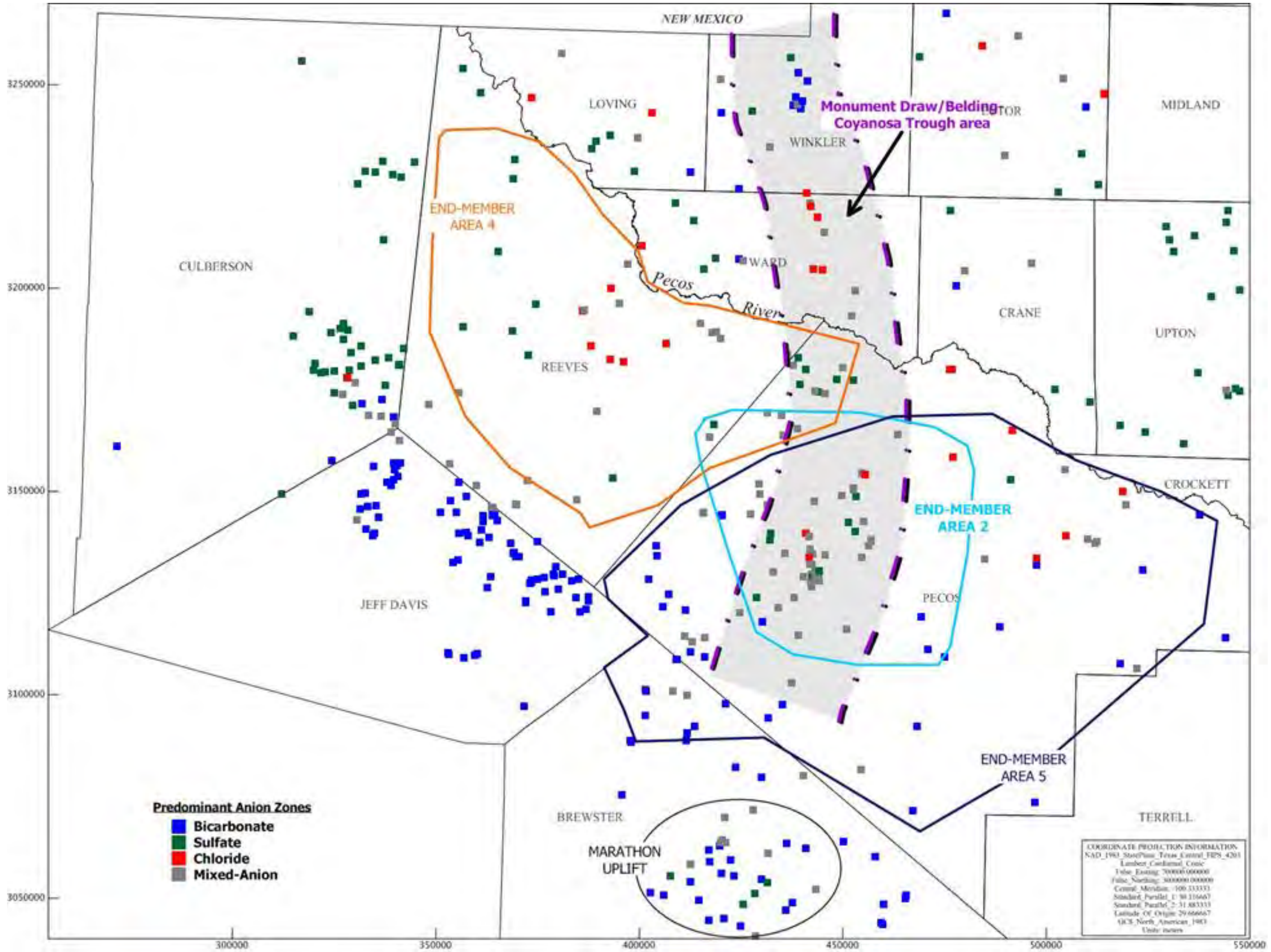


Figure 9-18. **Map of study area showing the predominant anion in each sample.**

9.3 Discussion of Results

Historical geochemical and isotopic data for groundwater samples taken from 421 wells and 13 springs throughout the Trans-Pecos region of GMA 3 and 7 are used to characterize regional and local groundwater chemistry trends, identify hydrochemical facies and geochemical signatures for the various aquifer, and develop conceptual models for the various aquifer systems in the Trans-Pecos region. Six end-member areas were established based on the general hydrogeology, established aquifer boundaries, and regional flow paths within the aquifers. Several geochemical and isotopic parameters, including total dissolved solids, carbon-14 percent modern, stable isotope (oxygen-18, deuterium), strontium isotopic compositions, tritium, and the major anions (chloride, sulfate, and bicarbonate), were used to determine the important chemical signatures for each end-member area and to infer the processes in each area that are controlling groundwater chemistry.

End-member area 1 is the outcrop of the Rustler Aquifer in the easternmost part of Culberson County. The samples from this area are calcium-sulfate and calcium-magnesium-sulfate facies with low to moderately high total dissolved solids (500-4,000 mg/l). The hydrochemical facies, saturation indices, and strontium isotopic compositions indicate that the geochemical signature is dominated by dissolution of gypsum/anhydrite and dolomite.

End-member area 2 is the sub-crop of the Rustler Aquifer beneath the Pecos Valley Aquifer and Edwards-Trinity (Plateau) Aquifers in Reeves and Pecos counties. Total dissolved solids values are low to moderately high (430 mg/L to 8,570 mg/l), and hydrochemical facies range from calcium-bicarbonate water in easternmost Pecos County, to mixed-cation facies with variable sulfate and chloride concentrations, to calcium-magnesium-sulfate facies similar to the outcrop zone waters. Limited carbon-14 percent modern and oxygen-18 data indicate that the water samples generally represent long residence times with some influx of more recent recharge.

End-member area 3 is the Tertiary volcanics and associated alluvial fill in the northern part of Jeff Davis County. The groundwaters are predominantly low-total dissolved solids (less than600 mg/l) calcium-bicarbonate hydrochemical facies that are interpreted to represent a relatively low amount of mineral-water interaction between meteoric recharge and the predominantly silicate bedrock and alluvial fill. Stable isotopes indicate that the samples represent relatively recent meteoric recharge. Strontium isotopes are consistent with whole-rock analyses of the volcanics.

End-member area 4 is the Pecos Valley Aquifer in Reeves County. The samples indicate highly variable hydrochemical facies, with calcium-magnesium-sulfate waters in the northernmost wells, sulfate-rich waters in the western half of the county, and more chloride-rich waters in the central part of the county and near the Pecos River. Total dissolved solids range from about 600 to over 5,600 mg/l. Oxygen-18 values are depleted relative to current precipitation in the area, carbon-14 percent modern values range from 22-34 percent modern, and tritium values are low (less than 0.44 TU), suggesting very little recent recharge. Strontium isotopes are generally consistent with Cretaceous marine carbonates, and are probably controlled by dissolution of carbonates in the underlying Edwards-Trinity (Plateau) Aquifer system.

End-member area 5 is the Edwards-Trinity (Plateau) Aquifer in Pecos County. Hydrochemical facies and total dissolved solids concentration are variable, ranging from low-total dissolved solids (less than1,000 mg/l) bicarbonate-rich waters along the border with Reeves County and in the easternmost part of the county near the Terrell County border and higher-total dissolved solids (1,000 to 5,000 mg/l) sulfate, chloride, and mixed-anion dominated waters within the

Monument-Belding Trough area. The fresher bicarbonate waters tend to have isotope compositions that indicate younger waters dominated by dissolution of Cretaceous marine carbonates. The higher total dissolved solids waters in the Monument-Belding Trough area appear to be older and have strontium isotopic compositions that are higher than expected for Cretaceous carbonates.

End-member area 6 is the western Permian regional flow path, originally described by LaFave and Sharp, (1987), and later defined by Uliana and others, (2007), in Culberson, Reeves, and Jeff Davis counties. Groundwaters in this area tend to be sulfate and chloride-rich mixed cation/anion facies with total dissolved solids values ranging from 2,000 to 3,000 mg/l. Tritium, carbon-14 percent modern, and oxygen-18 isotopes indicate long residence times for the waters in this area. Strontium isotopic compositions are enriched in strontium isotopic composition, which is from dissolution of minerals derived from Precambrian and early Paleozoic rocks exposed at the upgradient end of the flow system.

Three conceptual models that describe and characterize interformational flows between several of the important aquifers in the region are developed and discussed. The first conceptual model deals with the western Permian regional flow path and the extent of the influence of regional flow into end-member areas 4 and 5. The strontium isotopic data originally used to delineate the flow paths that are transmitting strontium isotopic composition-enriched waters eastward into GMA 3 and 7 (Uliana and others, 2007) were supplemented with additional TWDB and USGS data in the project database. These data, in conjunction with ion concentrations and other isotopic data, confirm the three end-member mixing system identified by previous researchers in the area and indicate that the flow system is influencing the groundwater as far east as the Fort Stockton area.

The second conceptual model identifies lateral interformational flow moving east from the Rustler Aquifer outcrop area in Culberson County into the Pecos Valley Aquifer in Reeves County. The results indicate that the groundwater chemistry in the western half of the county is influenced by the influx of sulfate-rich waters from the Rustler Aquifer outcrop area. The results also indicate that groundwater in the eastern half of the Pecos Valley Aquifer is probably affected by irrigation return flows or by infiltration of Pecos River water that was applied for irrigation.

The third conceptual model identifies localized upwelling of deeper waters from the Capitan Reef Complex Aquifer and Rustler Aquifer into the Edwards-Trinity (Plateau) Aquifer in the Monument-Belding Trough area south of Interstate Highway 10 in Pecos County. The water samples in Pecos County with the highest total dissolved solids have isotopic signatures that indicate recent recharge and are probably caused by infiltration of Pecos River irrigation water. Samples with moderately high total dissolved solids, low carbon-14 percent modern and tritium, and high strontium isotopic compositions are most likely influenced upwelling flows. This interformational upwelling is confined to the southern part of the end member area; north of IH-10 there is no evidence of upwelling flow from the Rustler.

In the study area the Capitan Reef Complex Aquifer coincides with the Monument Draw/Belding Coyanosa Trough area. Hydrochemical facies in the Capitan Reef Complex range from calcium-sodium-bicarbonate waters near the southern part of the aquifer in northern Brewster County to sodium-chloride-sulfate waters in central Pecos County to predominantly sodium-chloride waters in Ward County. Low to moderate total dissolved solid values ranging from 297 to 1,518 mg/L are observed in northern Brewster County (Figure 9-2). The measured total dissolved solid values increase moving northward through the aquifer, with slightly brackish waters in central Pecos County (approximately 1,259 to 1,907 mg/L); more saline waters in northern Pecos County (3,064 to 5,652 mg/L), and the highest measure of total dissolved solid values in Ward County (5,611 to 13,310 mg/L). Carbon-14 values for the same four areas decrease from 32 percent modern in northern Brewster, to 12 percent modern in central Pecos, to 6 and 1 percent in northern Pecos and Ward counties, respectively (Figure 9-3).

The total dissolved solids and carbon-14 data are interpreted to represent a northern flow path through the aquifer, with total dissolved solids increasing along the flow path and longer residence times at the end of the flow path. This is consistent with the conceptual model for the aquifer presented by Hiss (1980) and Uliana (2001), which describe recharge from the northern front of the Glass Mountains with groundwater flow from the south to the north with minor components of cross-formational flow along the length of the aquifer

Oxygen-18 values throughout the aquifer are depleted relative to local modern precipitation and range from just below the expected range for local precipitation (-7.70‰ SMOW) to approximately 2‰ depleted (-9.40‰ SMOW). Tritium values for all Capitan Reef Complex Aquifer samples range from 0.01 to 0.06 TU (Figure 9-13). The depleted oxygen-18 values and lack of post-bomb tritium are consistent with the longer residence times indicated by the carbon-14 data.

Strontium isotopic composition in the samples with the highest total dissolved solid values and longest interpreted residence times (i.e., from Ward and northern Pecos County; see Figure 9-5) have strontium isotopic composition values (0.707528 to 0.707682) that are consistent with expected values for waters in equilibrium with Permian marine carbonates as indicated by the historic seawater curve presented in Burke and others (1982). Samples from northern Brewster and central Pecos County have considerably higher strontium isotopic composition values that range from 0.709194 in Brewster to 0.709690 in central Pecos County. The source of enriched strontium-87 in these samples is not clearly defined by the available data. The samples have relatively low total dissolved solid values (497 mg/L and 1,480 mg/L, respectively), which suggests that they are probably not influenced by deep basin brines. A groundwater divide between the Belding Trough and the Marathon Uplift to the south (Smith, 2001) rules out the Marathon Uplift area as a source of enriched strontium-87. The western Permian regional flow path system described below in Section 9.2.1 could be the source of enriched strontium-87; however, there is insufficient data to definitively evaluate this option.

Valuable insights might be gained from developing a regional model in the western part of GMA 7 and GMA 3 that includes the Edwards-Trinity (Plateau) Aquifer, the Pecos Valley Aquifer, the Capitan Reef Complex Aquifer, the Dockum Aquifer and the Rustler Aquifer as well other pertinent formations. We recommend developing a preliminary model that combines each of the GAMs at a level of complexity similar to the existing GAMs, except perhaps having greater vertical discretization and possibly less discretization laterally. While this is a significant effort, it would be helpful in developing a better understanding of water budgets in separate GAMs (i.e., inflow and outflow, both vertically and laterally) that are not consistent on a regional basis. The findings from this model could be used to develop better constraints and overall water budgets for the independent GAMs. Both models would serve a purpose in advancing the state of the art for regional and county-level groundwater availability modeling.

The level of detail included in a combined model depends on the objectives of the model. The trend is not to use the GAMs for regional water planning only, but for estimating water budgets and impacts at a county and sub-county level. In addition, groundwater conservation districts often desire to assess permits and individual projects with GAMs. Therefore, models that combine hydrogeologically connected systems in higher resolution may be justified. Advantages of expanding the domain and adding more layers include potentially greater definition of flow components throughout the entire system and better understanding of the overall water budget throughout the area. However, there is always a trade-off for expanding the domain of groundwater models. Disadvantages may include more uncertainty in conceptual model components, boundary conditions, hydraulic properties, and other critical inputs. In addition to considering the overall objectives of the model, it is important to consider the relative importance of the uncertainties that are inherent in the existing GAMs in the region. If the uncertainties of the existing GAMs for a particular application are deemed too large and can be significantly decreased by developing a combined model, then it may be necessary or beneficial to develop a more integrated model.

10 Summary and Conclusions

GMA 3 and 7 extend from the Llano Uplift area to west Texas and contain a diverse set of aquifers. A review of hydrochemical and isotope data indicates a significant presence of older groundwater in the region and there is a higher percentage of older groundwater in the west. Old groundwater implies that minimal groundwater recharge is currently occurring and young groundwater implies that some recharge is occurring today and in the recent past. Lithology appears to play an important role in the recharge dynamics as the karstic Edwards Group and other fractured and lithified aquifers have a higher portion of young water than do formations composed of unconsolidated sediments, especially in GMA 3. The Ellenburger-San Saba Aquifer and the Hickory Aquifer in the Llano Uplift area and the Edwards Group in the Edwards-Trinity (Plateau) Aquifer are actively recharging. The Antlers Formation portion of the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer contain a higher portion of old water. On this basis, the aquifer systems selected for more detailed evaluation included the Hickory Aquifer and Ellenburger-San Saba Aquifer in the Llano Uplift area, the Edwards Group and the Trinity Group in the Edwards-Trinity (Plateau) Aquifer, and the Trans-Pecos region system.

Data from the Llano Uplift area aquifers has provided insight into those aquifers that encircle the Precambrian core. Specifically, the hydrogeology of the Ellenburger-San Saba Aquifer and the Hickory Aquifer varies based on their geologic and hydrologic setting. On the north side of the uplift, the Hickory Aquifer is the dominant aquifer. The active flow system is primarily in the outcrop region that receives recharge from precipitation and discharges to streams. Deep groundwater in the downdip section of the Hickory Aquifer is generally old and relatively stagnant compared to the outcrop groundwater. This is due to the limited potential for downdip groundwater movement due to the confined nature of the Hickory Aquifer in that area.

On the south side of the Llano Uplift area, the Hickory Aquifer and the Ellenburger-San Saba Aquifer are isolated in individual fault blocks. Leakage from the overlying Hensell Formation is likely the primary source of recharge. For the Ellenburger-San Saba Aquifer, groundwater discharge is generally toward the Pedernales River. The southern portion of the Hickory Aquifer and Ellenburger-San Saba Aquifer are largely hydraulically separate from the northern section due to faulting, structure, and proximity in the uplift region.

On the east side of the Llano Uplift area, the Ellenburger-San Saba Aquifer is the primary aquifer. Tectonics have isolated the Ellenburger-San Saba Aquifer into three sections; a northern, middle and southern section. Recharge appears to be largely on the outcrop and discharge is to the local streams, springs and rivers. Most of the active groundwater flow is considered to be local rather than regional due to structural control and limited potential for downdip movement into the confined section. In each area of the Llano Uplift area, it appears that the groundwater flow systems are characterized by local aquifer systems that are relatively isolated from other portions of the aquifer that share the same geologic name around the uplift.

Evaluation of the hydrochemical and isotope data for the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer confirms that recharge decreases significantly from east to west. Isotope data from the Edwards Group of the Edwards-Trinity (Plateau) Aquifer indicate young waters due to a higher rate of recharge to the karstic Edwards Group. On the other hand, groundwater in Trinity Group (Antlers Formation) and the Pecos Valley Aquifer is generally older water, which indicates that recharge from recent times has been much more limited than to the Edwards-

Trinity (Plateau) Aquifer. In addition, the hydrochemical and isotope data show a clear distinction between groundwater in the Trinity Group (Antlers Formation) and that in the Edwards Group to the east. Potentiometric surfaces and the existing Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM indicate consistent flow across the zone, which is not necessarily supported by the data. The Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer GAM should be reevaluated to assess whether it would be beneficial to separate the western portion of Edwards-Trinity (Plateau) Aquifer from the eastern portion.

In the Trans-Pecos region, three conceptual models were developed that describe and characterize interformational flows between several important aquifers in the region. The first conceptual model is a large, regional-scale flow system that is transmitting water from the bolson aquifers in Culberson County through fractured Permian basin fill strata associated with the Capitan Reef Complex Aquifer system and into the westernmost extent of the Cretaceous Edwards-Trinity (Plateau) Aquifer system.

The second conceptual model identifies lateral interformational flow moving east from the Rustler Aquifer outcrop area in Culberson County into the western half of the Pecos Valley Aquifer in Reeves County. The results also indicate that the groundwater chemistry in the eastern half of the Pecos Valley Aquifer is probably affected by irrigation return flows or by infiltration of Pecos River water that was applied for irrigation. The third conceptual model identifies localized upwelling of deeper waters from the Capitan Reef Complex Aquifer and Rustler Aquifer into the Edwards-Trinity (Plateau) Aquifer in the Monument-Belding Trough area south of IH-10 in Pecos County.

Overall, there appears to be a significant groundwater flow between various hydrogeologic units and aquifer systems on a regional scale in the Trans-Pecos region. This finding is not only supported by potentiometric data, but also by hydrochemical and isotope data reviewed in this report.

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TWDB Review of Responses to Comments from Draft Deliverable

The final report delivered was a vast improvement from the draft deliverable. TWDB appreciates the consultant responding to many of the TWDB draft deliverable review comments. It should be noted that the final report format was modified by TWDB to remove references to the report as a possible TWDB numbered report and logos were adjusted accordingly. The consultant reviewed the adjustments and re-sealed the work according to the guidelines of practicing geoscience and engineering in Texas. Italicized comments noted in the following document reflect TWDBs review of the final deliverables. For the record, the contract funding was reduced to reflect the project not encompassing the original scope of work.

Draft report comments:

General comments to be addressed

1. For clarification please use official aquifer and groundwater availability model names instead of colloquial or abbreviated ones; for example, using 'Uplift' and 'Ellenburger' instead of the 'Llano Uplift' and 'Ellenburger-San Saba Aquifer' or referring to Edwards, which may mean Edwards-Trinity (Plateau), Edwards (Balcones Fault Zone), or Edwards-Trinity (High Plains) aquifers. In addition, please differentiate between official aquifer names and physiographic designations; for example, "Edwards-Trinity (Plateau)" and the physiographical feature "Edwards Plateau". These– and others– appear to be used interchangeably in text and are confusing to the reader and reviewer (please see page 20, line 9, for one example). Where appropriate, consistently use aquifer nomenclature or please associate geologic formation names with the appropriate aquifer, for example, 'Hensell' and 'Edwards' should be identified properly as formations or groups and also associated with their corresponding aquifer or aquifers. Please refer to the subunits of the Edwards-Trinity (Plateau) Aquifer as the Edwards Group and Trinity Group or the appropriate formation name.

   Note: the proper identification of some of the current groundwater availability models is the "groundwater availability model for the"
   - Edwards-Trinity (Plateau) and Pecos Valley aquifers
   - southern portion of the Ogallala Aquifer and the Edwards-Trinity (High Plains) Aquifer
   - Hill Country portion of the Trinity Aquifer
   - Dockum Aquifer
   - Lipan Aquifer
   - Rustler Aquifer
   - West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat) and Igneous aquifers
   - San Antonio portion of the Edwards (Balcones Fault Zone) Aquifer

   Text revised.

Mention is still being made of Trinity Aquifer and Edwards Aquifer, referring to the components of the Edwards-Trinity (Aquifer) (see p. 176 and elsewhere). All occurrences should read "Group" instead of "Aquifer".

References to the Trinity Aquifer on pages 10 and 218 have been updated to reference the Trinity Group.

2. The writers mention repeatedly the lack of sample alignment along a flowline and it being an impediment to interpretation. The contract allowed additional sampling along flowlines to eliminate any impediment to interpretation. At a minimum please include suggestions, including maps, of where to sample for what constituent in which aquifer to gain insight into the various flow systems in Groundwater Management Areas 3 and 7.

   In many cases, the impediment was not a willingness or budget to sample, but rather identifying wells that were well documented, accessible, and screened at the appropriate depth that would be helpful for the interpretation. Sampling locations would include wells along an inferred flowpath at the appropriate depth, and that were accessible and well documented. Hopefully, there would be several wells nested with various screened intervals that would allow vertical assessment. We did not find wells meeting these criteria in the public databases and we suspect that they do not exist.
3. The pdf fails accessibility check per Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites). Please submit an accessible pdf version of the final report per contract Article III, subsection 5.

   Not addressed, most figures are not tagged.

   The figures have been tagged using their respective captions and made accessible.
4. Please include units with values that appear in the text and please update all graphs with units. The ^{87}Sr/^{86}Sr values in the text are expressed up to 4 decimal places; the standard is six decimal places as it appears in the cross-sections. Please adjust text as needed.

   In our experience, ^{87}Sr/^{86}Sr data are typically reported to 4 decimal places, and for the work presented here we do not see an advantage to reporting greater precision in the graphs and text. We have therefore not changed the precision of the Sr isotope data presented in the text.

   The response to Comment #4 was that in the contractor's experience typically strontium isotopic compositions are reported to 4 decimal places, however, the contractor's citations, such as Banner (2004) and Banner and Kaufman (1994) most likely use at least six decimal places. Note: references to strontium isotopic compositions should be expressed as "strontium isotopic composition(s)" instead of "strontium-87 and strontium-86".

   Any occurrences in the text to "strontium-87 and strontium-86" were changed to "strontium isotopic composition(s)". All of the specific ^{87}Sr/^{86}Sr values presented in the text were adjusted to six decimal places as requested. Any references to ^{87}Sr/^{86}Sr value ranges from the literature (e.g., ranges of values for specific geologic ages as presented on the historic seawater curve by Burke, et al., 1982) were kept in their current form to reflect the level of precision presented in the original literature sources.
5. Per Exhibit B, Scope of Work, Objectives: the objectives of this project, which includes the three dimensional interpretative maps, are to confirm, refine, and/or modify the conceptual model groundwater flow within **each** aquifer and possible interaction between aquifers for the study areas. Please explain the reasoning for excluding the Capitan Reef Complex, Lipan, and Marble Falls aquifers from this study (example page 54).

   The Capitan Reef Complex contains very few wells that are accessible, and very few of them are located in areas that would improve the hydrogeochemical understanding of the aquifer as it relates to identifying a conceptual model for a TWDB GAM. This was confirmed recently by the contractor and other entities that were trying to assess information for the City of Odessa to better understand the aquifer. Therefore, instead of expending considerable resources from a limited budget that would have yielded limited scientific data, we used available data to assess the hydrogeochemistry of the Capitan Reef Complex.

The Lipan Aquifer GAM was developed by the contractor, and we have done work for the Lipan-Kickapoo UWCD as well. We feel like the conceptual model for the TWDB Lipan GAM is reasonably solid compared to other aquifers in GMA 3 and 7. In addition, practically speaking, the current DFC for the Lipan Aquifer indicates that the aquifer will be used on a sustainable basis and that over the long-term planning horizon, all the groundwater that is in the aquifer will be used as it enters laterally or recharges vertically. Therefore, the conceptual model of the Lipan GAM seems relatively less critical than other aquifers that are being actively managed in GMA 3 and 7.

Because the Marble Falls aquifer is relatively local and shallow compared to the Ellenburger and Hickory, we felt that focusing on those aquifers would be more beneficial than getting a couple of scattered (and shallow) samples from the Marble Falls aquifer.

The TWDB groundwater database contains 27 Capitan Reef Complex Aquifer major element analyses in Groundwater Management Areas 3 and 7 out of a total of 117 analyses. The flow path on the eastern arm of the Capitan Reef Complex Aquifer through Brewster, Pecos, Ward, and Winkler counties has 8 isotope analyses out of a total of 23 samples. Considering the size of the Capitan Reef Complex Aquifer, this is enough to conduct at least a cursory evaluation, especially considering that locations outside of the study area were included in the sections on the other Trans-Pecos area and Llano Uplift aquifers. The model for the Lipan Aquifer included general head boundaries along the western boundary to account for flow from the Edwards-Trinity (Plateau) Aquifer (Antlers Formation). Logically, changes in geochemistry and increases in pumping would strongly influence the groundwater in the Lipan Aquifer. In addition, recharge for the Lipan Aquifer was applied using a percentage of average precipitation although this study suggests this is inappropriate for the Edwards-Trinity (Plateau) Aquifer. Understanding if recharge in the models for the Lipan and Edwards-Trinity (Plateau) aquifers should be re-evaluated and assessed in the same manner would have been valuable information from this study.

The following text has been added to Section 9.3 of the report:

In the study area the Capitan Reef Complex Aquifer coincides with the Monument Draw/Belding Coyanosa Trough area. Hydrochemical facies in the Capitan Reef Complex range from calcium-sodium-bicarbonate waters near the southern part of the aquifer in northern Brewster County to sodium-chloride-sulfate waters in central Pecos County to predominantly sodium-chloride waters in Ward County. Low to moderate total dissolved solid values ranging from 297 to 1,518 mg/L are observed in northern Brewster County (Figure 9-2). The measured total dissolved solid values increase moving northward through the aquifer, with slightly brackish waters in central Pecos County (approximately 1,259 to 1,907 mg/L); more saline waters in northern Pecos County (3,064 to 5,652 mg/L), and the highest measure of total dissolved solid values in Ward County (5,611 to 13,310 mg/L). Carbon-14 values for the same four areas decrease from 32 percent modern in northern Brewster, to 12 percent modern in central Pecos, to 6 and 1 percent in northern Pecos and Ward counties, respectively (Figure 9-3).

The total dissolved solids and carbon-14 data are interpreted to represent a northern flow path through the aquifer, with total dissolved solids increasing along the flow path and longer residence times at the end of the flow path. This is consistent with the conceptual model for the aquifer presented by Hiss (1980) and Uliana (2001), which describe recharge from the northern front of the Glass Mountains with groundwater flow from the south to the north with minor components of cross-formational flow along the length of the aquifer

Oxygen-18 values throughout the aquifer are depleted relative to local modern precipitation and range from just below the expected range for local precipitation (-7.70‰ SMOW) to approximately 2‰ depleted (-9.40‰ SMOW). Tritium values for all Capitan Reef Complex Aquifer samples range from 0.01 to 0.06 TU (Figure 9-13). The depleted oxygen-18 values and lack of post-bomb tritium are consistent with the longer residence times indicated by the carbon-14 data.

Strontium isotopic composition in the samples with the highest total dissolved solid values and longest interpreted residence times (i.e., from Ward and northern Pecos County; see Figure 9-5) have strontium isotopic composition values (0.707528 to 0.707682) that are consistent with expected values for waters in equilibrium with Permian marine carbonates as indicated by the historic seawater curve presented in Burke and others (1982). Samples from northern Brewster and central Pecos County have considerably higher strontium isotopic composition values that range from 0.709194 in Brewster to 0.709690 in central Pecos County. The source of enriched strontium-87 in these samples is not clearly defined by the available data. The samples have relatively low total dissolved solid values (497 mg/L and 1,480 mg/L, respectively), which suggests that they are probably not influenced by deep basin brines. A groundwater divide between the Belding Trough and the Marathon Uplift to the south (Smith, 2001) rules out the Marathon Uplift area as a source of enriched strontium-87. The western Permian regional flow path system described below in Section 9.2.1 could be the source of enriched strontium-87; however, there is insufficient data to definitively evaluate this option.

The recharge estimates for the Lipan Aquifer GAM might be improved by re-evaluating the assumption that recharge is a set percentage of the average precipitation. Beach and others (2004) indicate that recharge for the Edwards-Trinity (Plateau) and Lipan Aquifers might not be linearly correlated to precipitation, especially in very wet years or wet seasons.

6. The ‘Antlers Aquifer’ is not an official aquifer in Texas; please revise to be consistent with the official major and minor aquifers.
   All occurrences of “Antlers Aquifer” have been revised to read “Antlers formation”.
   Please clarify that the “Antlers Formation” is part of the Trinity Group of the Edwards-Trinity (Plateau) Aquifer. See figure in response to comment #20.
   Reference to Antlers has been clarified to mention that it is part of the Trinity Group of the Edwards-Trinity (Plateau) Aquifer.
7. The text in the legends of most figures is difficult to read. Please use a larger font.
   All figures have been adjusted so that the legend is in a larger font.
8. Please be consistent. If the writers choose to abbreviate chemical symbols, as opposed to

spelling out the element's name, please use the appropriate charge superscript for all ions (e.g., Ca^{2+} instead of just *Ca*) and please be consistent throughout the report in the text and graphics. For example, please change $^{87/86}Sr$ or $Sr^{87/86}$ to $^{87}Sr/^{86}Sr$ where it appears in the text; please express 14C pmc as a percentage, not a fraction; and/or please spell out chemical abbreviations in the text; for example, please change 'NO3' to 'nitrate'. Chemical notation is used throughout the report to represent quantitative and figure discussion, whereas for general discussion, chemical compounds are spelled out.

9. Please provide maps and plots with more descriptive titles; for example, please use something similar to "*Distribution of* $^{36}Cl/Cl$ *in the Hickory Aquifer*" as opposed to "*Hickory Del Cl-36*".
   All figures have been adjusted to remove map title in order to use figure caption as sole description of the figure.
10. It appears that no work was done in the Llano and San Saba county portions of the Llano Uplift aquifers located within Groundwater Management Area 7. Is this an assumption that flow is the same as McCulloch and Mason counties even though the previous study by Standen and Ruggiero (2007) suggested the flow system in these counties was isolated from the rest of the study area? Please discuss this omission.
    We don't disagree that the flow system in Llano and San Saba might be isolated from the rest of the study area. Our experience on other projects indicates that there may be significant isolation between many areas of the Llano Uplift aquifers. However, we had allocated budget to try to get samples in the western portion of GMA 3, and by the time the task of trying to identify willing landowners in that area was complete, time and budget were diminished. Therefore, we focused on the existing data in McCulloch and Mason counties, as well as the new data collection in Burnet and Gillespie counties.
    Some note of the omission of data collection and analysis San Saba and Llano counties should have been made in the text of the report, as well. Page 104 in the section discussing Hickory Aquifer states data needs to be collected in San Saba County for this aquifer although no mention was made in the section for collecting data for the Ellenburger-San Saba Aquifer. The Marble Falls Aquifer was not analyzed in any of the profiles.
    We have added the following text at the beginning of Section 7.2.1: New data was not collected in the Northern Sub-Region because it there was a good dataset in the TWDB database in Mason and McCulloch Counties. It was also assumed that the downdip section in in San Saba County would be similar to the downdip section in Mason and McCulloch Counties.
11. Please note in the text that it is difficult to use strontium isotopes as a tracer without information on the strontium isotopic compositions of the aquifer rocks.
    We agree that the use of strontium isotopes as tracers requires some knowledge of the strontium isotopic composition of the aquifer rocks, and have added text. In addition, please note that numerous references were made in the text to the strontium isotopic compositions of the various aquifer rocks, including references to direct measurements of Permian anhydrites in the Rustler by Dennison, et al., 1998 (see p. 224 in the draft report) and of Tertiary volcanics in the Davis Mountains area by Cameron, et al., 1996 (see p. 225 in the draft report); estimated values for Paleozoic and Mesozoic marine carbonates based on an extensive database of world-wide measurements as reported by Burke, et al., 1982 (see pp. 22, 150, and 224 in the draft report), and indirect assumptions for Precambrian rocks based

on general principles of Sr isotopes and on groundwater data reported by Uliana, et al., 2007 (see p. 150 in the draft report).

12. Please cite figure and table numbers as they appear in this report, and please exclude references to figures and tables from the reference cited unless included in this report.
    Figures and tables are now cited correctly and reference section has been updated.
13. A conceptual model for the Edwards Group of the Edwards-Trinity (Plateau) Aquifer—if present—is not clearly stated.
    Conceptual model text has been added.
14. The overall study area is subdivided into three zones; each evaluated using a different methodology. Please add discussion in the text on why this was done with a figure showing the zones and associated aquifers.
    Text added and reference made to Figure
15. Please note that the groundwater flow model by Young and others (2010) is not an official GAM. Please revise the text to reflect this.
    Text revised.
16. The data analyzed in this report come mostly from wells that do not have screen information or are open-hole. Therefore the data are representative of thick aquifer sections, some spanning multiple aquifers, and can rarely be assigned to individual water-bearing units. Data derived from wells that may span more than one aquifer should be flagged (in figures and the database) and/or analyzed separately as possible cross-formational mixing "zones".
    Because of the uncertainty that exist in well records and driller descriptions, we don't think it is practical or scientific to flag data in the figures or the database. Rather, we will add text to highlight the valid point the reviewer makes regarding the vertical averaging that may occur in most of the samples. For this same reason pointed out by the reviewer, we think it is of limited value to visualize the data from much of the Edwards-Trinity (Plateau) aquifer in three dimensions or even in vertical cross-section.
17. Please correct spelling of McCulloch County and the Hensell Formation in text, figures, captions.
    Text revised.

Specific comments to be addressed

18. Page 1, Paragraph 4: Please change 'the two major aquifers…' to 'the two main aquifers'. There is no mention of the Marble Falls Aquifer in the text. Please address why.
    Text revised to include discussion of the Marble Falls aquifer.
19. Page 2, Paragraph 1: Precipitation decreases east to west and therefore recharge does as well when using a percentage of precipitation approach, as was done in the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers. Please clarify statement that the concept of reducing the percentage of precipitation that becomes recharge form east to west should be assessed.
    Several recharge studies in arid areas (Beach and others, 2004; Nichols (2000); Stone and others (2000); Bennett and Finch (2002)) use an approach that better accounts for the complexity of the recharge process. These approaches generally incorporate some type of threshold approach that is more appropriate in arid climates. This approach may not be as critical in areas of relatively higher precipitation such as the eastern portions of GMA 7.

Comment #19 was not addressed in the report text. There is a discussion on page 10 (last bullet) on using a stream loss approach similar to one used in Edwards (Balcones Fault Zone) Aquifer. However, it was not clear on how this would be incorporated into Edwards-Trinity (Plateau) Aquifer where most streams are intermittent. In our experience using stream loss for applying recharge is sometimes difficult and challenging to use in predictive simulations because antecedent soil conditions, variations in precipitation duration/location, anthropogenic releases to the streams, and nearby groundwater pumping may all create different lag times for precipitation and recharge or loss of recharge to streams. Typically in numerical modeling using the simpler approaches based on the Occam's razor principle is preferred before adding more complicated approaches and additional uncertainty.

The following text was added to the paragraph to expand the discussion regarding recharge estimates: "The recharge estimates for the Edwards-Trinity (Plateau) GAM are based on percent of average annual precipitation, but do not incorporate a threshold approach as incorporated for other GAMs in west Texas, such as the Igneous and Bolson GAM (Beach and others, 2004). This approach may also be appropriate for the western portions of the Edwards-Trinity (Plateau) GAM."

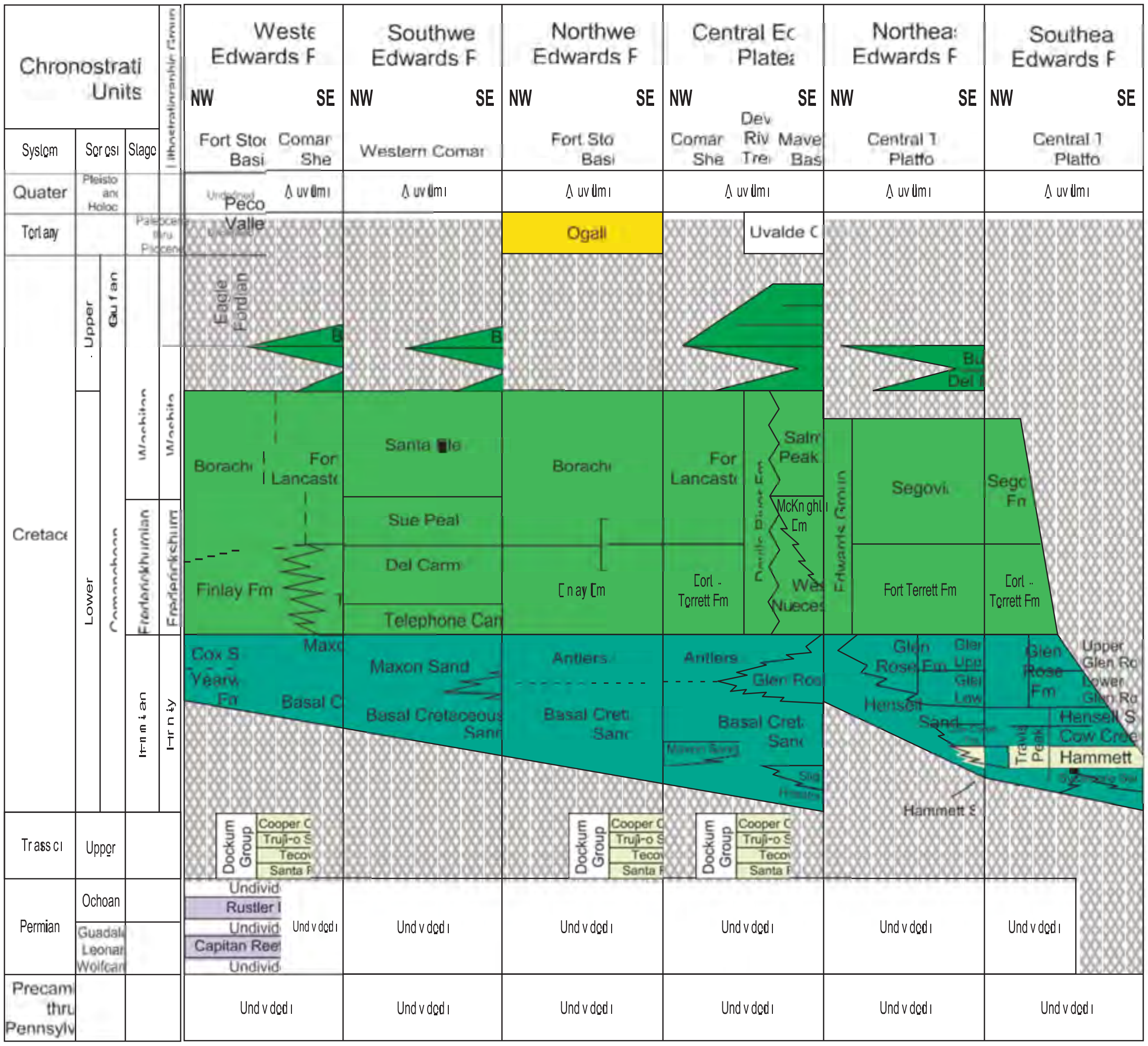
Regarding the second comment, the text was revised to remove the last sentence of the last bullet regarding the use of stream loss estimates for recharge calculations.

20. Page 2, Paragraph 1: Please clarify "the clear distinction between groundwater in the Trinity Aquifer (Antlers Formation) and that in the Edwards formation to the east". The next sentence discusses separating the Edwards-Trinity (Plateau) into a western and eastern model. Does the author mean the Trinity Group has different signatures?

    Yes, the Antlers Formation has a different chemistry than the Edwards Group to the south.

    It is still unclear if the facies changes in the Trinity Group was addressed or that the Antlers Formation and other clastic units of the Trinity Group in the study area (Maxon Sand, Cox Sand, basal Cretaceous Sand, and/or Hensell Sand) would have a different geochemical signature than the more karstic units of the Trinity Group (Glen Rose Formation) or even the Edwards Group that overlies the Antlers Formation (see figure below from Anaya and Jones, 2009).

    Due to the lack of wells that are screened only in distinct clastic units, it is impossible to say with certainty that the hydrochemical and isotope distinction is the same in each clastic unit. However, based on the data available, we would expect the clastic units to have a different geochemical signature than the karstic units.



Intuitively the separation would be the northern portion of the Trinity Group (Antlers Formation) is different from the southern portion, which does not contain the Antlers Formation. The Edwards Group is missing in the Hill County portion of the study area to the east. Does the author mean the Edwards (Balcones Fault Zone) Aquifer is different from the Trinity Group (Antlers Formation) portion of the Edwards-Trinity (Plateau) Aquifer?
No.

21. Page 3, Paragraph 2: Please add Trinity Aquifer to the list of major aquifers and please add and revise appropriate GAMs and references.
Aquifer added to list.
22. Page 3, Paragraph 3: Please add Lipan Aquifer to the list of minor aquifers.
Aquifer added to list.
23. Page 3, Paragraph 4: Please add reference for U.S. Geological Survey study.
Reference added.
24. Page 3, Paragraph 6: Please add justification for additional samples collected in Burnet County which lies outside the contract-specified study area.
The area contains Llano Uplift aquifers and very little data had been collected there. We felt it was critical to the development of the Llano Uplift GAM to better understand this area.
25. Figures 2-1 and 2-2 (pages 5 and 6) have gaps in the images between Llano, San Saba

counties and Burnet County. Please update figures and legends with an identifying line for Groundwater Management Area 8 and please outline Burnet County with this identifying line.
The figures and notes have been adjusted to show Burnet County as part of GMA 8.

26. Page 7, Paragraph 3: Please add a figure showing the three geographic/ hydrogeologic areas.
See response to #14.
Comment #26 was not directly addressed in the report text. The text now references figures 2-1, 2-2, and 2-3 of which the aquifers are depicted but not specifically the three geographic/hydrogeologic areas. A figure showing the extent of the 'Trans Pecos' region, instead of the subset shown in the U.S. Geological Survey study would have been helpful.
A figure addressing the study areas has been added as Figure 3-1 along with text reference.
27. Page 8, Paragraph 1: It is unclear why the writer picked sodium bicarbonate (Na-HCO3) as a "representative" hydrochemical groundwater facies for Texas, or even for Carrizo-Wilcox Aquifer – as opposed to any other facies occurring statewide, for example calcium bicarbonate (Ca-HCO3). Please clarify reasoning in text.
See addition. In some Texas aquifers, there are consistent chemical changes or trends as groundwater flows down the hydraulic gradient and therefore can be used as a proxy for groundwater flow directions. The Wilcox aquifer in East Texas is an example where the chemical composition of major anions and cations change with down gradient flow. Water chemistry in the Wilcox outcrop typically is a Ca-SO4-HCO3-Cl water where as down gradient water in a confined section, the water chemistry has the general composition of a Na-HCO3 water (Fogg and Kreitler, 1982).
28. Page 8, Paragraph 3: Please specify the type of head data—pump tests, relative heads, et cetera. Relative heads only suggest the potential for cross-formational flow; it is not evidence for actual flow.
We agree and that is why the sentence says head data indicate that leakage from the Cretaceous into the Paleozoic rocks might be occurring.
29. Page 8, Paragraph 6: The groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers is far more extensive than indicated in the first sentence in this paragraph. Please revise the sentence to reflect this. In this paragraph it is stated that the Trinity Aquifer does not crop out within the model. This is incorrect please correct text accordingly.
Text revised.
30. Page 9, Paragraph 2: Please cite the source of the information in the last sentence.
Text revised to indicate that water level data from the TWDB indicate that the Edwards is no longer saturated in some wells in Glasscock and Reagan counties.
Page 9, paragraph 2: "but according to recent water level measurements in the TWDB database, pumpage has caused water levels to decline…" Please note that the water level measurements in the TWDB do not indicate the reason for changes in water levels, only the depth to water.
Text revised to indicate that water level decline may be caused by pumping.
31. Page 11, Paragraph 1: Please include interaction with the Capitan Reef Complex Aquifer to the list.
Text revised.
32. Page 12, Paragraph 1: The implied definition of 'steady-state' and 'transient' conditions as natural and stressed hydrologic conditions is incorrect (see Glossary of Hydrology,

Compendium of Hydrogeology, Freeze and Cherry, et cetera).
Text revised.

33. Page 13, Paragraph 3: Please discuss the potential effects of irrigation return flow separate from natural recharge on nitrate (NO_3) and Chlorine (Cl).
See addition. Nitrate from "cultivation" can include downward percolation from "dry land" farming and irrigation. Lower nitrate concentrations in shallow groundwaters may occur in the naturally oxidizing conditions in these aquifers. Higher concentrations probably result from agriculture or animal wastes.
34. Page 14, Bullet 1: 'TDS-SO4' is not a recognized geochemical facies. Please revise.
Revised. Now reads, "The higher TDS and higher SO4 waters ..."
35. Page 14, Bullet 2: Please clarify if you are discussing the interaction of the Antlers Formation (Trinity Group) with the Edwards (Balcones Fault Zone) Aquifer located downdip or simply that the Antlers Formation is different from the rest of the Edwards-Trinity (Plateau) Aquifer or that the Antlers Formation (Trinity Group) does not interface with the overlying Edwards Group or the other units in the Trinity Group.
See addition. "in the central and eastern parts of the Edwards-Trinity (Plateau)"
36. Page 14, Bullet 4: Please clarify how the respective reactions would influence groundwater compositions. It is uncertain how calcite dissolution would influence changes from calcium bicarbonate (Ca-HCO3) to sodium bicarbonate (Na-HCO3) water compositions or even if the lithology or mineralogy of the Carrizo-Wilcox Aquifer would support such a reaction.
Bullet 4 has been deleted.
37. Page 16, Paragraph 1: Please add justification for the 0.5 TU boundary between old and new waters.
See addition. The age dating terms "recent" and "old" are used in a relative sense. Figures 4-1 and 4-2 show the correlation of 3H and 14C% and 3H and 14C apparent. On both graphs two limbs can be observed. The break between the two trends is considered to have a 3H value of about 0.5 t.u.. 3H measurements can be made such that old, pre 1950s bomb waters can have "0" values, depending on the method of analysis. Many of the analyses in the TWDB data have "0" values, but there are also several water samples with low 14C and some that have measureable but low 3H activities. A threshold of 0.5 t.u. was therefore assigned to define recently recharged waters. Clark and Fritz (1997) have used similar ranges such that modern waters (up to 10 years old) have 3H activities in the range of 5 to 10 t.u. while submodern aged water (recharged prior to 1952) have 3H activities of less than 0.8 t.u..
38. Page 16, Paragraph 1: In literature modern (up to 10 years old) recharge is evidenced by tritium activity of 5 to 15 TU. Activities less than 0.8 TU would be considered "submodern", i.e., recharged prior to 1952 (Clark and Fritz, 1997). Please adjust text accordingly.
See response to 37.
39. Page 17, Figures 4-1 and 4-2 and others: The Carbon-14 (^{14}C) versus Tritium (^{3}H), young versus old plots are not very informative as shown; the ^{14}C versus ^{3}H relationships depicted are universally valid and not specific to Groundwater Management Areas 3 and 7. Old waters everywhere have low percent modern carbon (pMC) and low ^{3}H. Please color-code dots by aquifer, county, or position relative to the recharge area in order to make the plots more meaningful and insightful.

The purpose of Figures 4-1 and 4-2 are to show the diverse relationship of “ages” (as indicated by Carbon-14 and Tritium). In the following sections there is a breakout of the major aquifers from east to west to show this relationship on an aquifer by aquifer basis. Several figures in each aquifer section illustrate there variations.

40. Page 20, Paragraph 1: Please revise this paragraph for clarity. Please discuss other processes influencing groundwater δdeuterium (δD) and δ^{18}oxygen (δ^{18}O) compositions, such as, temperature, altitude, and amount of precipitation.

    It should be noted that other physical processes affecting precipitation can also fractionate the isotopes of water. These include temperature, altitude, timing of a rainfall event and evaporation (Clark and Fritz, 1997). For example, rain water recharged in the Pleistocene period may have occurred under a cooler climate and may be isotopically lighter.

41. Page 20, Paragraph 1: Please replace “*curve*” with “*line*”, please replace “*MWL*” with “*GMWL*”, and please add “*‰ SMOW*” after the equation “$\delta D = 8\ x\ \delta 18O + 10$”. Please replace “*MWL*” with “*GMWL*” towards the end of the paragraph, or elaborate if it was meant to convey the existence of a local meteoric water line (MWL).

    “G” added to MWL.

42. Page 21, Figure 4-3: Please plot Craig’s global meteoric water line (GMWL) on the chart.

    GMWL line plotted on Figure 4-3.

43. Page 23, Figure 4-4: This figure shows that strontium isotope signatures in Groundwater Management Areas 3 and 7 would not be unique considering the wide age range of the rocks.

    The non-unique signature for Sr87 is acknowledged in the second paragraph of page 22 and stated tat Sr87 measurements were of value in Trans Pecos aquifer but not in Llano aquifers.

44. Page 25, Paragraph 4: Please include justification for excluding springs.

    Springs were excluded because of the source of the water discharging from a spring may differ form the surface formation where discharge is occurring.

45. Page 25, Section 5.1.2: Please clarify why data previously collected by Nance (2010) was excluded from your evaluation (as noted in Section 5.1) or please clarify that you used data housed in the TWDB groundwater database that includes data collected mainly by TWDB but also collected by other sources including Nance (2010), U.S. Geological Survey, other state agencies, et cetera.

    See addition. “or other sources including Nance (2010), U.S. Geological Survey and other state agencies.”

46. In Chapter 6 the thresholds of old/young water for Tritium and Carbon-14 change from aquifer to aquifer, so one cannot directly compare ages from one aquifer to another. Please be consistent or explain clearly why this approach was done.

    The following text has been added after Bullet 2 on page 29.In figures 6-2, 6-4, 6-7, 6-9, 6-11, 6-13 and 6-15 old waters have 3H activities of about 0.5 or less. Conversely, modern water had 3H activities greater than 0.5 as well as higher 14C% activities. Nance (2010) similarly had difficulty in assigning specific ages to Edwards waters in the Edwards in the Edwards Trinity Plateau, but preferred relative ages of the waters based on the 14C% activities.

    Comment #46 was partially addressed in the final report.

    This approach was used because the authors think that trying to develop a more quantitative approach is not warranted by the data.

47. Page 29, Paragraph 3: Reference is being made to Figure 4-7, non-existent. The writer

probably refers to Figure 6-1, page 30. The separation of aquifers based on their Deuterium and Oxygen-18 signatures is not that clear. Please discuss the overlap, e.g., the samples from the Pecos Valley Aquifer seem to plot along the entire range, Antlers Sand Formation, too.
aquifers from east to west and not to conclude that overlap did not exist. The overlap of the Pecos Valley wells with Edwards wells confirms (1) the complexity of the aquifer systems and (2) that many of the findings of the hydrogeochemical studies should be considered semi-quantitative in nature.

48. Page 30, Figure 6-1: If so, Please add the GMWL. Please use official aquifer names in the legend, where possible.
    GMWL line added.
    Comment #48 was not fully addressed as the legend contains a mix of formation and aquifer nomenclature.
    Legends and other text in the chart have been revised for clarity of aquifer and/or formation discussed.
49. Page 31, Section 6.2.1 and throughout Chapter 6, and elsewhere as applicable: Please plot Carbon-14 and/or Tritium (or other applicable data) activities against sample depth to illustrate changes in groundwater ages downdip, age stratification, et cetera. Heading 6.2.1: please correct the spelling of "*Ellenberger*".
    Additional figures of 14C or 3H vs depth have been added. In addition, graphs have been added showing the relationship of older waters verses slight decreases in δ^{18}O or δD.
50. Page 31, Paragraph 4: Please add a figure to show the relationship between ^{14}C and either δD or δ^{18}O.
    Figure for Ellenburger has been added.
    Comment #50 was not addressed in the report text or figures.
    A second Excel chart was added relating deuterium and carbon-14 for the Ellenburger Aquifer.
51. Page 34, Paragraph 3: Please add a figure to show the relationship between ^{14}C or ^{36}Cl and either δD or δ^{18}O.
    Figure for Hickory Aquifer has been added.
    Comment #51 was not addressed in the report text or figures.
    A third Excel chart was added relating δ^{18}O and carbon-14 for the Hickory.
52. Page 38, Paragraph 2: Considering the absence of data from Gillespie, Kerr, Kimble, and most of Menard counties, it is difficult to come to any conclusions with regards to the relative distributions of older and younger groundwater.
    Deleted the sentence that referenced geographic distribution of young water.
53. Page 38, Bullet 1: please discuss the "transition zone" between the two types of water. Please show plot of ^{14}C versus depth of sample.
    Deleted the reference to transition zone.
54. Page 41, Paragraph 4: Please add a figure showing relationship with δD or δ^{18}O.
    Figure for Antlers added.
    Comment #54 was not directly addressed in the report text (possibly figure 6-25 with one sample in Reagan County, one in Crockett County, and two in Val Verde County)
    A second Excel chart was added relating deuterium and carbon-14 for the Antlers Formation.
55. Page 42: Figure 6-9 caption indicates the graph shows a comparison between Antlers [Sand Formation] and ET-P [Edwards-Trinity (Plateau) Aquifer], not clear which is which.
    Figure caption incorrect and has been corrected.
56. Page 43: Figure 6-10 is a repeat of Figure 6-9. Please replace with proper graphic showing

sample locations taken in the Antlers Formation of the Trinity Group.
The correct figure has been inserted.

57. Page 44, Paragraph 1: Please revise the text to refer to the correct figure.
Text corrected to read Figure 6-11.
58. Page 44, Paragraph 4: Please revise the text to refer to the correct figure.
Text corrected to read Figure 6-12.
59. Page 44, Paragraph 5: Please revise the text to refer to the correct figure.
Text corrected to read Figure 6-11.
60. Page 46, Figure 6-12: A couple of the "old water" samples come from wells located in Glass Mountains, outside the [Edwards-Trinity (Plateau)] Aquifer. Please clarify and adjust as needed.
Corrected.
Comment #60 was not addressed in the report text and samples in the Glass Mountains still appear in Figure 6-12.
No changes were made to the report regarding this comment (mistakenly marked as corrected). Aquifer designations assigned to well records by TWDB were used, therefore the wells in question were defined as Edwards-Trinity wells.
61. Page 53, Paragraph 1: There is no mention of the karstic portion of the Trinity Group of the Edwards-Trinity (Plateau) Aquifer or the Trinity Aquifer that occurs in eastern Gillespie County, the Capitan Reef Complex Aquifer, the Marble Falls Aquifer, the Dockum Aquifer, and the Lipan Aquifer, please add text referring to these missing aquifers. About half of the water samples from the Pecos Valley Aquifer are classified as young but it is classified as a non-recharging aquifer. Please add justification for this. In addition, the aquifer lithology and recharge area climate appear to go in tandem. Suggest adding this to the discussion or quantify the impact – e.g., assigning numbers to each. If the Trans Pecos region experienced 34 inches of rain every year it will likely recharge and would have more evidence of "younger" water.
The following text has been added, "Other aquifers occur in these three regions, but have limited isotopic and chemical data (e.g. the Capitan Reef, the Lipan and the Marble Falls aquifers). The focus, therefore was on those aquifers with larger data sets and considered more representative for the region. Better understanding of conceptual models could be developed where more data is already available.
Comment #61: The response does not address issues related to the young water shown in Figure 6-14 in the Pecos Valley Aquifer, the relationship between climate and recharge, or the karstic portions of the Trinity Group of the Edwards-Trinity (Plateau) Aquifer or the Hill Country portion of the Trinity Aquifer.
The following text has been added to Section 6.2.6.
The four wells are 71, 94, 150, and 150 feet deep. These wells are relatively shallow wells compared to the total thickness of the Pecos Valley Aquifer, and may be subject to more recent recharge events than wells screened in deeper portions of the aquifer.
62. The section numbering in Section 7 is illogical and should be revised to flow in a more logical format. For example, discuss each aquifer separately and then add a section to discuss inter-aquifer relationships. All sections need to be numbered.
Sections have been renumbered.
63. Page 54, Paragraph 1: The TWDB well database has 93 wells attributed to the Marble Falls

Aquifer. One of the aims of this study was to locate more wells/data.
Please see response to Comment 5.

64. Page 56, Paragraph 1: Please indicate the rock type that makes up the Smithwick Formation. Please revise the last sentence for clarity. Please include reasoning for excluding the area west of the Uplift region (as the sentence states "…more detailed evaluation for areas north, south and east of the Uplift") or not sampling or analyzing data in model zone two of the four proposed model zones as suggested by the 2007 structure and stratigraphy study by Allan Standen and Robert Ruggiero.
    The Smithwick is characterized as a black, slightly fissile shale with lesser amounts of siltstone and sandstone (Kier and others, 1979).The following sentences have been added to the bottom of the paragraph on page 56: A transect in Mason and McCulloch counties was selected in preference to Lampassas County because previously sampled wells and chemical analyses were available for both the Hickory and the Ellenburger than in Lampassas County. The southern Gillespie County transect was selected because of the isolation of the Hickory and Ellenburger in separate grabens as well as being overlain by the Cretaceous Edwards-Trinity aquifers. The eastern transect in Burnet County was chosen because Llano Uplift structures appeared to divide the Ellenburger and Hickory geographically into three subaquifers. The presence of groundwater conservation districts in both Gillespie and Burnet counties (Hill Country Underground Water Conservation District and Central Texas Groundwater Conservation District, respectively) facilitated sampling.
65. Page 58, Table 7-1: The first sentence on page 57 suggests Table 7-1 includes chemistry and isotope data for the Hickory and Ellenburger-San Saba aquifers; however, Table 7-1 only provides basic well data for wells completed in the Hickory Aquifer. Only 8 wells appear in this table, however many more wells are implied in the first paragraph of page 57 and also appear in Figure 7-2 and Figure 7-32. Please adjust text and table as needed. In addition, highlight due to discrepancy in depth and casing information. Also owner information is not needed in report; please delete this column.
    Reference to Table 7-1 has been deleted. Caption for Table 7-1 has been modified. Table 7-1 has been corrected.
    Reference to Table 7-1 was not deleted in bullet 1 on page 64.
    Reference to Table 7-1 has been deleted in bullet 1.
66. Page 62, Figure 7-5: The cross-section shows the Marble Falls Limestone in direct contact with the Ellenburger Group. The geophysical logs for this area indicate there's an intervening section of Pennsylvanian (Barnett Formation and others) between the two units, which can amount to several hundreds of feet thick in places. Please adjust as needed. In addition, six wells extend below the Hickory "SS" of which only three appear to be possibly screened in Lower Hickory. Please extend dashed line to at least the fault block for the Ellenburger Formation or indicate what geologic unit for the well completions. Also many of the wells extend well past land surface, please adjust or clarify.
    The stratigraphic nomenclature was updated/modified from "Strawn" and "Caddo" to "Marble Falls Limestone" and "Mississippian & Devonian Undivided" to agree with the Llano GAT Sheet. The Miss & Dev Und was picked from geophysical logs Q-116 (erroneously labeled as Q-16 on the transect header), Q-22, and Q-33 and added to the transect above the Ellenburger. This undivided formation is only about 60 feet thick in this section of McCulloch County and is primarily Barnett.A note was added to the

transect to explain why the land elevations of projected sample locations and the transect centerline appear incongruous (an artifact of projecting).The estimated base of the Lower Hickory was extended to the Ellenburger fault block to better illustrate which formation the deepest wells on the transect are completed in.

67. Page 64, Paragraph 3: Please delete the first sentence in this paragraph and please revise the text to incorporate the figure reference. The deeper and shallower waters seem to have a common starting point (Ca-Mg-HCO_3) but may have different geochemical evolution paths. No clear relationship between Ca and Na is apparent in Figure 7-9. Authors state "*Ca in the outcrop is higher than down dip, Na in downdip section is generally higher than in outcrop*" to support the hypothesis of two unrelated waters. Could the Ca-Na chemistry be controlled, in part, by ion exchange reactions? "*Na and Cl increase linearly*" only at lower Na and Cl concentrations; in general, at concentrations ~5 meq/l or higher, Na is being predominantly added. Regarding the Piper diagram, there is some overlap between the two water groups (see the diamond and the anion triangle). The configuration of cation triangle suggests Ca/Na ion exchange reactions occur. Please delete the last sentence, based on Figure 7-11, which does not support statement concerning Cl as there are just as many downdip samples with high Cl concentrations, as there are those with low Cl.

    The text has been changed to read: "Piper diagram data are plotted for wells less than 1,000 feet depth and wells with depths greater than 1,000 foot (Figure 7-8). In the cation and anion triangles and diamonds the two data sets occupy different locations. For the shallower groundwaters, the cation chemistry is dominated by Ca and Mg. For the deeper waters, there is an inverse correlation between Na and Ca-Mg suggesting cation exchange. In the cation triangle, the chemistry of the deeper waters does not appear to have evolved from the general chemistry of the shallower waters. Na and Cl increase linearly and then Na increases independent of Cl (Figure 7-10). These higher Na waters are the waters whose chemistry is potentially affected by cation exchange (Figure 7-10). Cl is high in the deepest section of the aquifer, suggesting possible upwelling of deeper more saline waters (Figure 7-11)."

68. Page 64, Paragraph 4: Feldspar is generally insoluble. Please change 'feldspar dissolution' to 'chemical reactions with feldspar'. Please add an explanation for why the radium activity increases with depth. Please add a figure showing the relationship among δD, $\delta^{18}O$, and the global meteoric water line. Please add an explanation for the relationship between δD and $\delta^{18}O$ compositions and depth within the Hickory Aquifer.

    Revisions are in the text.

    Instead of correcting text to 'chemical reactions with feldspar' the text on page 73 states 'chemical reactions with field spaces'.

    Text has been revised.

69. Page 65, Figure 7-7: Please add in caption or legend that known faults were not considered during the development of water level contours. Please correct spelling of McCulloch County in legend. The water-level data coverage is sparse, so many of the contours in this figure should be shown with dashed lines to convey this uncertainty.

    Faults added, spelling error corrected, and dashed lines used to represent inferred water level contours.

    Faults were added in Figure 7-7 however the contour lines are unchanged. Maybe faults do not matter, but should be mentioned and explained in text. Some of the isolines are dashed where there are datapoints, and left solid in areas with data gaps.

Inferred and interpolated water level contours have been revised and text was added noting faults were not taken into consideration when contouring water levels.

70. Page 66, Figure 7-8: The symbols are too small and difficult to distinguish, please increase font size to no less than 6 point per Exhibit D, page 6, of the contract. The symbols in figure should be comparable to the symbols in the legend.
    Symbol point size increased to 6 pt.
71. Pages 67-68, Figures 7-9 and 7-10: Please use the symbols in Figure 7-8 to clearly indicate which waters are from shallower and deeper parts of the aquifer. Please provide correct units for ion concentrations on the axes' labels (i.e., meq/l).
    Symbology adjusted to show deep and shallow water data. Units corrected.
72. Page 69, Figure 7-11: Please provide the units of measure for Cl concentrations.
    Legend corrected to add Chloride concentration units.
73. Page 70, Figure 7-12: Please replace NO^3 with NO_3 in the Y-axis label. Is nitrate expressed as NO3 or as N on this plot? There's a sample showing nitrate-N near the MCL and other nitrate hits from deep wells—well head contamination or active flow system?
    NO_3 is expressed as NO_3, not as NO_3-N. The text states high nitrate concentrations probably related to anthropogenic sources.
74. Page 72, Figure 7-14: Please provide correct units for potassium concentrations on the axes'labels (i.e., meq/l).
    Units corrected.
75. Pages 74-76: Please provide units of measure for all radium data displayed in Figures 7-16 through 7-18.
    Units added.
76. Page 84, Figure 7-26: Please change the map title from "*Hickory Del Cl-36*" to "Hickory Aquifer *36Cl/Cl distribution*" or similarly descriptive.
    See response to #9.
77. Page 85, figure 7-27: Please be consistent in the use of Deuterium, and other such notations, in this figure and throughout text: either choose δ^2H or δD.
    After initial introduction in the report, all references to Deuterium have been changed to δD.
78. Page 87, Paragraph 1: The impact of the downthrown block of the Ellenburger Group on the Hickory Aquifer flow system is inconclusive. The head map in Figure 7-7 indicates flow of groundwater from the outcrop to the downdip portion, and no hydrologic divide or boundary between the shallow and the deep portions. Nor do the contours reflect discharge to the San Saba River. The "separation" is not at all clear on the Piper diagram, either. Rather, ion exchange reactions along a flowpath could be inferred from the Piper. The isotope data can just as well indicate communication between outcrop and downdip in an active, albeit slow-moving, groundwater system recharged during cooler, wetter times. Sampling several sites in between those outcrop and downdip ones would have been helpful in investigating the existence of a "transition zone". Could there be flow across faults bounding the graben and downdip through the Ellenburger Group block?
    If groundwater in the Hickory outcrop is given the option of flowing into the deep subsurface or flowing along the strike of the outcrop to regional points of discharge such as the San Saba River, it should follow the second option of discharge to local streams rather than flowing into the deeper subsurface with no obvious points of discharge.
    Heading 7.3 and first paragraph moved to page 95.
79. Page 87, Paragraph 2: Please specify whether the recent to 21,000 years range is observed or corrected.

The word “corrected” has been added to the text.

80. Page 88, Paragraph 1: Please update text to state that ^{36}Cl was elevated due to atmospheric nuclear testing.
The following sentence has been added to the text, “...or by atmospheric nuclear testing.”
81. Page 88, Paragraph 3: Please specify ‘groundwater hydraulic gradient’. Since the Ellenburger-San Saba Aquifer has only two Carbon-14 measurements, please expand text on where additional samples would be most beneficial.
The word “hydraulic” has been added.
82. Page 88, Paragraph 4: Please delete reference to the “Ellenb**er**ger” Formation and the association to Figure 7.7 (unless Figure 7.7 used water level information from wells completed in the Hickory Formation and Ellenburger Group and then please update all references to the figure to indicate this).
Reference and figure were deleted.
83. Page 88, Paragraph 5: The samples can only be broken into two groups with respect to depth—well depths are either less than 500 feet or more than 2,000 feet—and Carbon-13. The well depth range 400-500 feet is not distinct from the well depth range 0-400 feet considering that the well depth range for all of the data is 0-3,500 feet. Figure 7-30 is not related to Carbon-14 and therefore not relevant to the issues being discussed in this paragraph. Please clearly explain the reactions indicated in Figure 7-29.
Text has been modified to clarify the separation of two hydrological/hydrochemical settings that has also been observed in several other chemical constituents.
84. Page 88, last Paragraph, continued on page 91: This paragraph is hard to follow. Please add more detail on the use of Carbon-13 and Carbon-14 in delineating flow paths. Also, please annotate figures 7-29 and 7-30 (e.g., what does the arrow represent)?
Text has been modified to provide more clarification. Figures 7-29 and 7-30 have been modified without arrows, circles, etc.
85. Page 91, Paragraph 1: Please show the data in Figures 7-29 and 7-30 in map view with the well groupings and the arrow on that map. It is unclear what the author is trying to convey, please reword for clarification.
Notations on the charts have been deleted.
Map view is missing and text not changed for clarification.
Text was added in order to clarify the groupings in the chart. Since the notations were removed to avoid confusion a map view of the data was not added because it was deemed irrelevant to the text in question.
86. Page 91, Section 7.3.1: Considering that due to mixing, all groundwater radiocarbon ages are apparent—corrected and uncorrected—there is little gained in age correcting groundwater considering the amount of effort involved. Especially considering that the relative ages are unchanged at the end of the process.
Using the 14C model approach was not significantly different than using the δ13C correction approach. The 14C modeling approach does consider as many potential corrections factors as we know today and therefore provides “best” answer for the age of a groundwater sample.
87. Page 91, Section 7.3.1, Bullet 2: Refers to Figure 8-6 which does not seem related. Please adjust text to refer to correct corresponding figure—possibly Figure 7-31.
Figure number has been corrected to 7-31.
88. Page 92, Figure 7-31: Please increase font size to no less than 6 point per Exhibit D, page 6,

of the contract on the labels showing the well data. Please clarify if well identified as 421303 should be 4261303 and update figure as needed.
Font size has been increased. Well ID corrected.

89. Page 93, last Paragraph: Flowpath I (one) seems improbable, based on the water level map shown in Figure 7-7. It would require flow through a groundwater divide between wells 5614410 and 5606505.
It is recognized that the flow path (wells 5614410 to 5606505 may require flow over a hydrologic divide, but the pairing of these two wells provides the best geochemical fit to estimate and age of at well 5606505. Well 5614410 provides a generic well regardless of its location to estimate the age at well 5606505. The text has been changed to recognize the physical hydrogeology of the recharge zone.
90. Page 94, Paragraph 2: Well 4261303 not shown on Figure 7-31. Please adjust text or figure so they agree.
Well ID has been corrected to 4261303.
91. Page 95, Paragraph 1: Please define by drawing on Figure 7-32 or on a new figure the wells associated with areas discussed as 1) outcrop wells and slightly downdip wells and 2) “highly confined” wells.
Outcrop wells and slightly downdip wells are considered as those in the outcrop or slightly downdip from the northern extent of the outcrop that have wells depths less than 1,000 feet. High confined wells are considered as though wells in the downdip parts of the aquifer with well depths greater than 1,000 feet. Additional text has been added regarding well depths.
92. Page 98, Paragraph 1: The lack of data in the Ellenburger-San Saba Aquifer is justification to collect more data, please expand text on where additional samples would be most beneficial. Please provide as much detail as possible.
Text has been revised to add a discussion of future sampling.
93. Page 98, Section 7.4.2: The purpose of the paragraph seems to be to discuss the ESS recharge and discharge mechanisms. “*There is enough precipitation for recharge*” is not very meaningful. Please include a sentence or two on the location and configuration of the ESS recharge area instead. Also Figure 7-33 shows a stronger flow to the northeast than towards the San Saba River.
Additional text added. Annual precipitation is estimated at 26-30.” Sanford and Selnick (2013) estimated evapotranspiration to approximately 70% of precipitation. Considering the karstic nature and thin soils overlying the Ellenburger in outcrop, there is definitely a potential for recharge. The presence of high NO3 in the Ellenburger outcrop corroborates active recharge (Figure 7-35).
Comment #93: Figure 7-33 does not support the San Saba River as a main discharge area.
Agreed. Text has been modified in the report.
94. Page 98, Paragraph 4: Please delete “*These data include:*”. Please summarize the isotopic analyses available.
“These data include:” has been deleted.
95. Page 99, Figure 7-34: The symbols are too small and difficult to distinguish, please increase font size to no less than 6 point per Exhibit D, page 6, of the contract. The symbols in figure should be comparable to the symbols in the legend.
Symbol point size increased to 6 pt.
96. Page 100, Figure 7-35: Please replace NO^3 with NO_3 in the Y-axis label.
Label corrected.

97. Page 101, Figure 7-36: Please add units to the chart axes.
    Units added to labels.
98. Page 102: Please reword the map title and caption in Figure 7-37 to reflect the fact that the wells themselves are not Cretaceous, they are only completed in Cretaceous-period strata.
    See response to #9.
99. Page 103: Please reword the map title and caption in Figure 7-38 to reflect the fact that the wells themselves are not Paleozoic, they are only completed in Paleozoic-era strata.
    See response to #9.
100. Page 107, Paragraph 1: This paragraph states that no Hickory Aquifer wells were sampled but Table 7-3 indicates at least one well with mix of "Hensell and Hickory" and another with potential Hickory upward mixing. Please clarify in the text.
    Text is clarified. "No wells drilled solely to the Hickory were sampled."
101. Page 107, Paragraph 2: Please refer to figure numbers.
    Text has been revised to ass Figure 7-43 and Figure 7-44.
102. Page 110, Paragraph 1: Please refer to figures, please update spelling of Hensell, and please include features discussed on figures—Pedernales River and Riley Fault.
    This paragraph has been rewritten. The spelling of Hensel has been corrected. Pedernales River and Riley Fault have been added to Figure 7-38.
103. Pages 111 to 112, Figures 7-43 and 7-44: Please revise the figures so that the Pedernales River is easily identified.
    Figures revised to include Pedernales River.
104. Page 112, Figure 7-44: The water level contour lines in central-west Gillespie County for the Hickory Aquifer should be dashed, as there are not enough data points to justify solid lines.
    Dashed lines added to represent inferred water level contours.
105. Page 113, Paragraph 1: Figure 7-46 does not show an inverse relation between Cl and SO_4. Both Figures 7-45 and 7-46 show that increasing Cl and SO_4 is due to different, independent, unrelated processes. Please update text or figure so they agree.
    Text now reads, "Cl and SO4 increase independent of each other (Figure 7-46) and the increase probably represents independent geochemical processes.
106. Page 113, Paragraph 2: Sentence number 2 is unfinished. Please explain why the migration of high ^{228}Ra waters from the Hickory Aquifer is considered unlikely. At least two of the wells in Table 7-3 list production from both the Hickory Aquifer and Hensell Formation.
    This text has been deleted.
107. Pages 118 and 120: Figures 7-49 and 7-51: Please double-check the data to ensure that the the much longer lived Ra^{226} occurs in low concentrations than Ra^{228} and please add units for Radium-226 and -228 on the axes of these charts.
    Figure 7-49 and text referring to this figure have been deleted. Data were incorrectly plotted. pCi/l has been added to figures with radium values plotted.
108. Page 113, Paragraph 5: Figure 7-54 is cited before Figure 7-53 in the text. Please move and renumber these figures in the order that they appear in the text.
    Text associated with Figure 7-53 and Figure 7-54 is now in proper order.
109. Page 113, last Bullet: Figure 4-1 is referenced for location of old and young of the groundwater within the Hickory Aquifer in Gillespie County; however, Figure 4-1 refers to all of Groundwater Management Areas 3 and 7 and does not provide much insight. Please

adjust to possibly Figure 7-53 or provide appropriate figure.

The text now references Figure 6-6 which shows locations of wells at better scale.

110. Page 124: Most of data discussed in this section—Discussion of Results—does not previously appear in the text and does not appear in graphical form. Please show the data being discussed on tables and/or graphs. In addition, please add Riley Fault to Figures 7-37 and 7-38 and please cite associated figures in text; for example please list figures for piper diagrams referenced in paragraph 4.

Riley Fault and Pedernales River are located on Figure 7-38. Data plots (e.g. Piper diagrams and scatter graphs are referred to in Section “Hydrochemical Results” and “Discussion of Results.”

111. Page 124, Paragraph 4: The water level map (Figure 7-44) shows the Hickory and Ellenburger-San Saba aquifers contours transitioning seamlessly, possibly indicating communication between the two. Their chemistry is similar. Given the Hickory Formation is Precambrian-derived; perhaps looking at the silica could help differentiate between the two groundwaters?

Good point. Our previous work in looking at water chemistry in aquifers has shown that silica trends are often inconclusive. San Saba may also contain sandstone. Therefore SiO2 differences were not evaluated.

112. Page 125, Paragraph 2: There are seven sample locations identified in the Ellenburger Group in Figure 7-55; text suggests there should be a total of six. Please clarify and adjust text or figure as needed. Please revise the third sentence for clarity. It is difficult to identify wells referenced in Figure 7-55 in Figure 7-44 (sentence 5). Please identify these wells in Figure 7-44 or provide new figure with waters and wells sampled for Carbon-14.

Figure 7-55 has been corrected to show six samples.

Note figure 7-54 in the final report (was figure 7-55 in the draft report) does show the six samples. Figure 7-54 shows percent modern carbon that corresponds with figure 7-55.

Yes, Figure 7-55 was changed to Figure 7-54 in the final report. The third sentence in the second paragraph was revised for clarity and the reference made to Figure 7-44 has been updated to note that the area in question is along the Highway 290 corridor.

113. Pages 125 and 127: The writers mention repeatedly the lack of sample alignment along a flowline and it being an impediment to interpretation. The contract allowed additional sampling along flowlines to eliminate any impediment to interpretation. At a minimum please include suggestions, including maps, of where to sample for what constituent to gain insight into the flow system in Gillespie County and elsewhere in the report for other aquifers.

Additional clarification is provided. In the Ellenburger aquifer, no geochemical evolution of the water chemistry is evident, which makes it difficult to predict the amount of dead carbon that may be altering the 14C activity. To use this approach for geochemical modeling requires a more detailed understanding of both the geochemistry and the flow dynamics of the aquifer. Availability of data may limit this type of interpretation. For the Ellenburger aquifer in Gillespie County, the Hill Country Underground Water District provided us access to the available wells. A more detailed study of the hydrogeology of a region is needed to provide basic groundwater hydrology for a region.

114. Page 126, Figure 7-55: Please include units for Carbon-14 in the map legend.

Units for C-14 added to legend.

Note: labels on figure are percent modern carbon and should be noted as “pMC” on yellow labels instead of “%”. Also, map legend should use either “carbon-14” or “δ^{14}C” instead of

"C-14".

Figure 7-54 has been modified to note carbon-14 units as pMC in the data labeling.

115. Page 130, Paragraph 3: This area lies outside of the Groundwater Management Areas 3 and 7 study area. Please add justification here for why this work was done. In addition, please clarify in text that if the Hickory Aquifer had limited data why additional sampling in the Hickory Aquifer was not considered and investigated. Later in the "Eastern (Burnet County) section, the captions indicate the Ellenburger-San Saba Aquifer was analyzed; however the text just refers to the Ellenburger (Group?). Please clarify in this section and for the Gillespie County analysis if samples from the Cambrian age San Saba unit of the Wilberns Formation were included or not and why or why not.

The following paragraph has been inserted on page 130. The Burnett County area was selected for hydrochemical evaluation to complete the review of the Paleozoic aquifers surrounding the Llano Uplift. Previous sections of this report reviewed the hydrogeology of the Paleozoic aquifers northwest of the uplift in Mason and McCulloch counties, and the Paleozoic aquifer south of the uplift in Gillespie County. Burnett County was selected to represent hydrogeology on the east side of the uplift. Data were reviewed for the Hickory aquifer in Burnett County, but the availability of wells in the Hickory was very limited. The Central Texas GCD recommended we focus on the Ellenburger and provided us access to Ellenburger wells.

Comment #115: The last two sentences in the response were not included in the report text.

The last two sentences of the original comment response were added to the paragraph in the report text.

116. Page 130 Paragraph 4: Please show the three separate hydrologic areas, any major faults, and cities listed in text on map in Figure 7-57 or include a new figure with this information and cite accordingly in the text. Figure 7-61 (piper diagram) basically shows the same geochemistry trends for the southernmost and central wells and if downdip wells in these areas were sampled may very well have shown the same composition as the northernmost wells. West to east cross-sections of the three separate hydrologic areas would help to understand the possible and probable flow dynamics and differences between the three hydrologic areas.

"Northern," "Central" and "Southern" have been added to Figure 7-57.

Note: Figure 7-57 is now 7-56 in the final report. Only first part of TWDB comment was addressed and cross-sections of the three hydrologic areas were not provided.

Figure 7-56 has been properly annotated to show pertinent information discussed in the text, however, cross-sections were not developed because the TWDB and the contractor agreed to the number of cross-sections prior to completing the draft report.

117. Page 131: Of the four wells shown in Table 7-4, two do not have screen information, or depths. Therefore one can't be sure of the aquifer they're tapping. Please provide justification for selecting these wells.

The two wells (Table 7-4) were represented to us as Ellenburger wells by the Central Texas GCD. Guaranteeing production zones for many of these Paleozoic wells in the Llano region is difficult.

118. Page 135 Paragraph 4: The lack of downdip wells available for analysis is not necessarily suggestive of a lack of usable water. The TWDB database contains but a small number of wells (estimated 10 percent) relative to the total number of wells drilled statewide. Chances are, there are a lot more Burnet County wells that are off the beaten path, and have yet to be inventoried. Please revise text to note that the wells used were limited to

those with access granted. In areas where the Ellenburger Group is located downdip wells may have been completed in shallower, more productive aquifers; may not be part of the TWDB inventory; may not be cost effective to drill down to; and/or may indeed be of poorer water quality.

The following text has been added. "The lack of downdip wells in the southern and middle areas may also be caused by a lack of drilling to the deeper Ellenburger. Water may have been available in shallower horizons. It is interesting to note, however, that more downdip wells occur in the northern region."

119. Page 136, Figure 7-60: Please label the Colorado River, Hamilton Creek, Sulfur Creek, and any other features mentioned in text. Please dash or remove the 1,350 foot contour line through the outcrop of the Ellenburger-San Saba Aquifer as elevations of the terrain may not support the inferred gradient.

Suggested features labeled on map and dashed lines added to represent inferred water level contours.

Surface water features discussed in text are still hard to identify in the figure.

Figure has been modified to highlight and label the three relevant surface water features.

120. Page 137: The text in paragraph 1 is disorganized. Please re-arrange the sentences to indicate first what is being mapped on the Piper diagram, then the findings. Please provide some background and lab data on "the dissolved gases" mentioned in paragraph 2.

This paragraph has been reorganized.

***Comment #120: The second issue in this comment related to dissolved gases was not addressed in the text*.**

A new paragraph was initiated for the dissolved gases discussion and the first sentence indicates that the dissolved gas data can be found in the Appendix.

121. Page 138, Figure 7-61: Please discuss the significance of well 57-07-605. The text discusses well B-1 being an anomaly but no discussion concerning well 57-07-605.

Well 57-07-605 has been corrected to well B-1.

Comment #121 was not addressed in the report text; the Piper legend still shows well 57-07-605.

Any text addressing well B-1 as well 57-07-605 has been changed to avoid confusion.

122. Page 139, Figure 7-62: Please draw the 1:1 line on the chart.

1:1 line added.

123. Pages 143, 144, 145: Please use subscripts in the formulae for nitrate and sulfate on the y axes of Figures 7-67 and 7-66 and on map in Figure 7-68. Specify whether the nitrate is expressed as NO_3 or as N.

Notation adjusted/corrected as advised.

124. Pages 146, 147: Please include units of measure on chart in Figure 7-69 and on map in Figure 7-70. Please use proper notation and show the units for Radium-226 in the legend of map in Figure 7-70.

Units added to chart and map.

125. Page 149, Paragraph 1: Please see comment 119.

Corrected as requested in comment 119.

126. Page 149, Paragraph 2: It is hard to determine from Figure 7-60 if discharge is to streams (hard to locate streams in the figure). In the case of the middle and southernmost geographic areas in Burnet County, possible pumping in the well south of the Colorado River may be a major discharge point. In addition, in the northern section elevation maps may support the conclusion that some water may discharge toward Lake Buchanan.

Agreed. Rivers and streams are more clearly identified on Figure 7-57.

Comment #126 was not addressed in the report text.

Reviewer's comments have been added to the paragraph in appropriate locations.

127. Page 149, Paragraph 5: The water level map (Figure 7-60) suggests there could be a connection between the northern and the central flow systems. Please indicate on the Figure 7-60 where the discharge features are (the creeks, the streams, the springs, et cetera.).

Streams and creeks already in map, added springs.

Comment #127: There are no springs identified in Figure 7-59 except on the legend

Map has been corrected to show spring locations.

128. Page 150, Paragraph 2: Please briefly outline assumptions and/or refer back to Figure 4-4 (page number 23) since it is not close by in the text.

The following sentence has been added. "This is based on Figure 4-4 and the anticipated ^{87}Sr/^{86}Sr for the lithology in the local formations in the Llano Uplift area."

129. Page 150, last Paragraph: Table 7-5 is all the way at the end of the chapter and, therefore, hard to find when referenced on this page. Please add a page number, state explicitly the table is to be found at the end, or move the table near page 150.

Table moved to follow the paragraph.

130. Page 151, Paragraph 2: Please revise the first sentence for clarity and refer to a figure. The assumed well referred to in this paragraph is located far down dip. Please discuss why soil influence would be a factor in its Sr isotopic composition. Is the writer implying that the recharge has contact with the granitic soils a long enough time for the soils to impart their ^{87}Sr/^{86}Sr signature to the recharge water before it reaches the water table? Please elaborate.

The first sentence in paragraph 2 was changed. The well is relatively shallow (226 ft) and is located in southeast McCulloch County, which is in the Hickory Aquifer outcrop zone and not far down dip. Samples from the well have very low Sr concentrations (0.1 to 0.17 mg/L); therefore, the waters would not require a long period of equilibration with Sr-bearing minerals in the soil zone to have a Sr isotopic signature dominated by the soil signature. The high ^{87}Sr/^{86}Sr value, low Sr concentration, inconsistency with other Hickory Aquifer ^{87}Sr/^{86}Sr values in the area, shallow well depth, and location within the recharge zone all support the hypothesis that the Sr isotopic composition of the water in that well is controlled by interaction with soils derived from weathered Precambrian granite.

131. Page 151, Paragraph 3: Please specify the correlation coefficient for TDS and ^{87}Sr/^{86}Sr. The apparent correlations discussed in this paragraph are all unlikely to be statistically significant. Please either show that they are significant or delete. Rather than using "weakly positive correlation" and other similar language, please provide in the body of the text the coefficients of determination (R^2) for all the crossplots. Please include the R^2 values and the regression lines on all crossplots found on pages 153-157.

Paragraph 3 was extensively edited to address the specific comments. Figures 7-73, 7-75 and 7-76 were replaced with revised versions that now contain regression trendlines and the regression coefficients for the Hickory samples. The captions for those figures were also changed to describe the trendlines.

Comment #131: correlation coefficients were not added to Figures 7-73 or 7-76 as requested in the comment.

Correlation coefficients and linear regression lines were added to Figures 7-73 and 7-76. We would like to note that the reference to Figure 7-73 in paragraphs 3 on page 152 indicates that we acknowledge that the Sr concentration data show no apparent correlation to the isotopic data, which suggests multiple sources of Sr in the system. We also note in the reference to figure 7-76 in paragraph 3 and paragraph 5 on page 152 that the trend between well depth and isotopic composition is weak, but is still consistent with the interpretation based on the bicarbonate data. We had left out the correlation coefficients from the figures because we had concluded that stating the weak or non-existent nature of the relationships in the text would be sufficient and that there would be no reason to show them on the graphs. We acknowledge the error and have corrected the mistake.

132. Page 151, Paragraph 5: Please revise the first sentence to correct the figure number referenced. There is no apparent correlation in any of the figures discussed. Please revise the text to show this. There is no difference in the strontium isotopic composition of some of the shallower wells and the single deeper well, especially considering analytical error bars. Please revise the text to show this.

The first sentence was edited to reference the proper figure number (Figure 7-73). Other edits were made to the paragraph to address the concerns about the interpreted correlations depicted in the graphs, including the relationship between depth and Sr isotopic composition. In addition, Figure 7.76 was updated to include a linear least-squares regression line for the Ellenburger-San Saba data and the associated R^2 value.

133. Page 152, Figure 7-72: For additional clarity please include an aquifer basemap and/or color coded flowlines for each aquifer.

Figure 7-72 was changed to include a map of the outcrop and down-dip zones for the Ellenburger-San Saba and Hickory Aquifers.

134. Page 158, Paragraph 1: Please note that it is difficult to evaluate mixing processes without knowing aquifer rock strontium isotopic compositions.

A paragraph was inserted after paragraph 1.

135. Figure 7-72: Please add aquifer outlines to this figure.

Figure 7-72 was changed to include a map of the outcrop and down-dip zones for the Ellenburger-San Saba and Hickory Aquifers.

136. Figure 7-78: Please add aquifer outlines to this figure.

Figure 7-78 was changed to include a map of the outcrop and down-dip zones for the Ellenburger-San Saba and Hickory Aquifers.

137. Page 158, Paragraph 1: Is the writer implying that the recharge has contact with the granitic soils a long enough time for the soils to impart their ^{87}Sr/^{86}Sr signature to the recharge water before it reaches the water table? The cross-section A-A'(Figure 7-5) shows most of the land in McCulloch County dipping to the southwest towards the Uplift and only the fault block at the intersections of the cross-plots that would have any possible run-off or soil debris from the Precambrian pluton. Please elaborate.

We acknowledge that it is unlikely that interaction with soils can be responsible for the enriched ^{87}Sr in the wells outside of the outcrop zone. As discussed in Section 4.4.2 (see p.22 in the draft report), siliciclastic rocks derived from older source rocks, such as the Hickory Sandstone, typically have enriched ^{87}Sr contents. Therefore, a more appropriate interpretation is that the overall Sr isotopic composition of the water samples from the Hickory aquifer, with the exception of well 42-63-908 (see the response to comment 130), is dominated by interaction with Sr-bearing detrital mineral phases in the Hickory

Sandstone that were derived from Precambrian source rocks. We have amended this paragraph with the following text (the added text is in italics):

"…it appears that the enriched ^{87}Sr in the formation is probably provided by interaction with weathered granites near the surface (e.g., in the soil zone) *for the shallower wells in the outcrop zone and Precambrian-sourced detrital siliciclastic material in the Hickory Sandstone for the deeper wells.*"

138. Page 158, Paragraphs 2 and 3: Rather than using "weakly positive correlation" and other similar language please provide in the body of the text the coefficients of determination (R2) for all the crossplots. Please include the R2 values and the regression lines on all crossplots found on pages 162-164.

The text of paragraph 3 was updated to include correlation coefficients and to better reflect the significance of the interpreted relationships between Sr isotopic composition and the various chemical parameters. Figures 7-81 through 7-83 were replaced with revised versions that now contain regression trendlines and the regression coefficients for the Hickory samples. The captions for those figure were also changed to describe the trendlines.

139. Page 158, Ellenburger/San Saba Section: Please note here and elsewhere in the report that San Saba unit of the Wilberns Formation was deposited in the late Cambrian Period and the Ellenburger Group was deposited during the early Ordovician Period. These geologic units are the Ellenburger-San Saba Aquifer. Most the report only references the Ellenburger [Group] and the Ordovician Period. Therefore the $^{87}Sr/^{86}Sr$ results are indeed consistent with the Strontium isotopic composition of late Cambrian/early Ordovician marine carbonates. It would be interesting to see if the higher values of $^{87}Sr/^{86}Sr$ were screened in the San Saba unit of the Wilberns Formation which Figure 4-4 shows had slightly higher Strontium isotopic compositions.

Paragraph 4 on page 158 was edited to reflect the proper aquifer and formation names and to indicate the correct ages for those formations.

140. Page 165, Paragraph 1: Please revise the second sentence for clarity. The correlation between strontium isotopes and HCO_3 is not apparently statistically significant. Please either justify the statement with a correlation coefficient or delete it. Please delete the word 'strong' in the last sentence in this paragraph and please reference Figure 7-83.

The second sentence in paragraph 1 was changed to include a correlation coefficient for the Sr isotope/bicarbonate relationship and to state that the correlation is not statistically significant. Figure 7-82 was also edited to include a linear least-squares trendline for the Ellenburger-San Saba samples and the associated R^2 value. The word "strong does not appear in the last sentence of paragraph 1 on page 165. We have added a reference to Figure 7-83 at the end of the last sentence.

141. Page 165, Paragraph 2: The range of $^{87}Sr/^{76}Sr$ compositions of groundwater from the Hensell Formation is not consistent with Cretaceous age rocks but with Tertiary or Paleozoic age rocks. Please correct the figure references in this paragraph. Figure 7-72 shows no data related to the Hensell Formation. Figure 7-76 does not display the $^{87}Sr/^{76}Sr$ and total well depth relationship. Please re-label.

The part of the paragraph that describes the range of Sr isotopic compositions for the Hensell samples was edited to provide a more detailed interpretation of the values. The two samples presented as Hensell over ESS do have Sr isotopic compositions that are consistent with the expected isotopic signature (i.e., at or slightly above the upper end of the Cretaceous range; i.e., 0.7077), while the two other samples are higher than expected. This information was added to the paragraph. The figure references were changed so that they refer to the correct figures.

142. Page 165, Paragraph 4: Please add an explanation for the selection of the mixing end-members. For ease of following the text and Figure 7-80, please show wells 57-49-503 and 57-50-901 on Figure 7-80. Also, please use “*Mixing Model no 1*” and “*Mixing Model no. 2*” rather than the color of the mixing lines.

Explanations for the selection of mixing end-members for each mixing model was added to the text of paragraphs 4 and 5. The well numbers were added to Figure 7-80. The mixing model references were changed from mixing line colors to “Mixing Model 1” and “Mixing Model 2” as requested. Since paragraph 4 in the draft report deals with mix model 2 and paragraph 5 deals with mix model 1, the paragraphs were switched in the revised report.

143. Page 166, Paragraph about Ellenburger- San Saba: Please provide in the body of the text the coefficients of determination (R^2) for all the crossplots. Please include the R^2 values and the regression lines on the crossplots themselves. Can the authors provide any insight into the nature of the “strontium isotope ratio break” at 0.7100 based on the position of the samples in the flow system?

Correlation coefficients were added to statements in the text concerning the correlations between Sr isotopic composition and TDS and Sr concentration. Regression lines and coefficients were also added to the crossplots for TDS (Figure 7-85) and Sr concentration (Figure 7-88). The captions for those figures were also updated.

As stated in paragraph 3 under “Ellenburger/San Saba”on page 166 of the draft report, the “EES Group 2” sample with the highest $^{87}Sr/^{86}Sr$ value is much deeper than the other samples and has a much higher K concentration than the “EES Group 1” samples. The other Group 2 well has an unknown depth and completion interval. Other than general speculation about some form of separation/compartmentalization between the deeper Ellenburger-San Saba aquifer and the shallower parts of the formation, we are unable to provide any further insight into the nature of the difference between these two parts of the aquifer.

144. Page 166, Paragraph 2: Please specify evidence would indicate groundwater flow from the Ellenburger-San Saba Aquifer into the Hickory Aquifer.

Unfortunately, at this time we do not have direct evidence, other than suggestions deduced from the geochemical and isotopic data, that groundwater is flowing from the Ellenburger-San Saba into the Hickory.

145. Page 166, Paragraph 3: Please revise the second sentence. The statement with regard to strontium concentrations is incorrect.

Paragraph 3 on page 166 states that, of the two samples from Hickory Aquifer wells in Burnet County, the sample with the higher $^{87}Sr/^{86}Sr$ value also has the higher concentration of Sr. As indicated on Figure 7-88, this statement is true. We have therefore made no changes to this paragraph.

146. Page 166, Paragraph 4: In order to come to any conclusion with regard to groundwater strontium isotopic compositions one needs to know—not assume—the composition of the aquifer rock.

We agree that knowledge of the Sr isotopic composition of the mineral phase in the aquifer matrix is an important part of using groundwater Sr isotopes to trace flow paths and identify water sources and mixing relationships. However, we also believe that there is useful information in the groundwater Sr isotope data presented in this report, and we would like to point out the following:

- We did cite actual Sr isotopic composition data for Permian anhydrites in the Rustler Formation (Dennison, et al., 1998) and for Tertiary volcanics in the Davis Mountains (Cameron, et al., 1996).
- The general assumptions for compositions of marine carbonates deposited throughout the Phanerozoic are based on a large dataset of published measured values (Burke, et al., 1982) and are reasonable values when compared to $^{87}Sr/^{86}Sr$ values that are much higher or lower than expected (e.g., measured values >0.710 in Cretaceous carbonates, which have expected values <0.7082)
- There are published peer-reviewed articles that describe the use of Sr isotopes and basic groundwater chemistry to trace groundwater flow paths and mixing relationships that depended on the same basic assumptions about the Sr compositions of the aquifer matrix mineral phases as used in this report.
- We believe that it would not be responsible to simply discard a large amount of reliable groundwater Sr isotope data because there is some level of uncertainty about the Sr isotopic composition of the host rock, especially in light of the fact that we do have some direct data and that we do have some reasonable estimates.

147. Page 166, Paragraph 6: The first sentence is incorrect with regards to Strontium concentrations. Please revise.

That sentence was re-written to correctly describe the relationship between the Sr concentration in that well and the concentration in other samples.

148. Page 167, Figure 7-84: Please add aquifer outlines to this figure.

This figure was replace by a version with aquifer outlines.

149. Page 169, Figure 7-86: The graph axes are not consistent with the figure caption. Please correct.

The figure captions for Figures 7-86 through 7-89 are correctly numbered; and the graphs are correct; however, the graphs were added to the document in the wrong order. The correct graphs have been moved to be associated with the proper figure captions, so all graph axes are now consistent with the figure captions.

150. Page 170, Figure 7-87: The graph axes are not consistent with the figure caption. Please correct.

Please see the response to comment 149.

151. Page 171, Figure 7-88: The graph axes are not consistent with the figure caption. Please correct.

Please see the response to comment 149.

152. Page 172. Figure 7-89: The graph axes are not consistent with the figure caption. Please correct.

Please see the response to comment 149.

153. Page 173, Paragraph 1: There is not a Sabine Formation in Texas although according to the U.S. Geological Survey the Sabine Formation in Louisiana is equivalent to the Wilcox Formation. Please clarify and reword the sentence discussing flow from the Hickory Aquifer or a deeper unidentified Sabine [F]ormation.

"Sabine" was a typo and now reads "saline."

154. Page 174, Section 7.2: Please compare and contrast the results of this study and the previous study by Standen and Ruggiero (2007) for the framework of the Llano Uplift aquifers. Please include discussion if the aquifer should be modeled in four spatial zones and how overlying units should be modeled i.e. Smithwick Formation, Hensell of the Trinity

Group, and the Edwards Group. Should the Marble Falls be combined with the Ellenburger Group and San Saba unit of the Wilberns Formation, should they all be separate layers, or some combination? Please provide reasoning. How should the units between the San Saba unit of the Wilberns Formation and Hickory Sandstone unit of the Riley Formation be modeled? Should the base of the Hickory Sandstone unit of the Riley Formation be a combination of no-flow and general head boundary, if so where? Please provide recommendations for the model domain to avoid boundary conditions.

If the Llano Uplift GAM will be used by groundwater conservation districts to assess groundwater availability and to calculate Modeled Available Groundwater, then we believe that the GAM should address the distinct hydrogeologic zones. One approach would be to build different models and another approach might be to build a single model that is capable of accounting for the flow conditions between various areas by implementing appropriate boundary conditions. Either approach might be effective, but all the objectives and data limitations would need to be identified prior to determining a modeling approach. With regard to vertical discretization, this should be dependent on the objectives of the model, the relative importance of the cross-formational flow between the units (if that can be estimated), and the level of definition and amount of other hydrogeologic data available for those units. It was beyond the scope of this study to collect and assess all the hydrogeologic data so we could answer those questions. We can say that there was not enough vertical isolation of samples to draw conclusions about the vertical variation of hydrochemical and isotope between the units you listed. Generally this is the case because most wells are screened across multiple units. By “avoiding boundary conditions”, we assume you mean identifying locations where no-flow boundary conditions could be assumed. Again, it was beyond the scope of this study to collect and assess all the hydrogeologic data necessary to answer those questions.

155. Page 174, Paragraph 2: There is little mention of Ellenburger-San Saba Aquifer in this paragraph. Please include a conceptual model for the Ellenburger-San Saba Aquifer.

Text added.

No changes detected, other than replacing “Ellenburger” with “Ellenburger-San Saba” in paragraph 3.

Text added to describe the conceptual model in more detail.

156. Page 175, Paragraph 1: Please revise the sentence to state that the Edwards-Trinity (Plateau) Aquifer extends across both Groundwater Management Area 3 and Groundwater Management Area 7, from Gillespie County to Reeves County. Please indicate that this section only covers the eastern half of the Edwards-Trinity (Plateau) Aquifer and that the remainder of the aquifer is discussed elsewhere. It appears you are only referencing the geographic subarea called the Edwards Plateau (see USGS Water-Resources Investigations Report 94-4039 by Rene A. Barker, Peter W. Bush, and E.T. Baker, Jr.). Please reference the source of the information on the 40,000 wells producing from the aquifer. Please reference geologic units as the “…Cretaceous age formations of the Edwards Group and the underlying Trinity Group”.

“40,000” has been deleted. The sentence reads “Groundwater is extensively produced...”

Comment #156: Most of the issues in this comment were not addressed in the text or comment response.

This paragraph has been rewritten for clarity on the extent of the study area and geologic units involved.

157. Page 175, Paragraph 2: Please add a figure showing the Antlers, Glen Rose, and Hensell

referred to in this paragraph. Suggest moving and referencing Figure 8-12 and/or including a stratigraphic chart (please see report referenced in comment 157). The terms "Antlers Sand", "Glen Rose" and "Hensell" refer to individual formations of the Trinity Group. Please clarify in text. Please expand discussion on flow between the Antlers Sand Formation and other formations within the Trinity Group of the Edwards-Trinity (Plateau) Aquifer.
A figure showing the stratigraphic column for the Cretaceous formations on the Edwards Trinity Plateau has been added. A more complete discussion of the aquifers in the ETP is included in the pages following the initial discussion of the conceptual model for the aquifers of the ETP.
Comment #157: A figure showing a stratigraphic column for the Cretaceous formations was not located in the final report.
A stratigraphic column (Figure 8-3) has been added and referenced in the text.

158. Page 175, Paragraph 3: Please add a figure showing the topography of the area under discussion.
A figure showing generalized topography in GMAs 3 and 7 has been added as Figure 8-3.

159. Page 176, Figure 8-1: Please revise the figure to remove parts of the Edwards-Trinity (Plateau) Aquifer that lie outside of the area under discussion. Please use official aquifer/geological formation/physiographic nomenclature in the caption and title. No wells are plotted in the counties in the Trans Pecos geographic subregion.
Data points outside of contiguous Edwards Trinity Plateau have been deleted.
Comment #159: The response only partially addressed the comment.
A note has been added to the figure clarifying the data in the Trans-Pecos region was not plotted in the figure and aquifer nomenclature was updated.

160. Page 177, Figure 8-2: Please use official Texas geological formation nomenclature in the caption and map title. This seems to be a duplicate of Figure 8-1with fewer wells for the same counties—please clarify why.
Nomenclature adjusted as advised. Figure 8-2 includes data points used in a previous study by Nance (2010) and clarify the formation the wells are completed in.

161. Page 178, Figure 8-3: Please revise the figure to remove parts of the Edwards-Trinity (Plateau) Aquifer that lie outside of the area under discussion. This map is not an exact representation of Groundwater Management Areas 3 and 7, please adjust caption accordingly. The yellow "*study area boundary*" represents the study area for the TWDB groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers, please note that in the legend/explanation.
The figure's origin is referenced in the figure footnote. The "Study Area" label has been removed to eliminate confusion. The caption has been modified as advised.
Comment #161: The "study area" label has removed but without a legend that action adds to confusion about the significance of the yellow line in the figure. Most of the issues in this comment were not addressed.
A note has been added to this figure, which has been adapted from a previous report and therefore has not been altered further than necessary, clarifying the irrelevance of the yellow outline for this study.

162. Page 179, Paragraph 2: Please change 'unsaturated section' to 'vadose zone' or 'unsaturated one'.
Corrected.

163. Pages 180-181, Figures 8-4 and 8-5: The "*study area boundary*" in these figures

represents the study area for the TWDB groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers, please note that in the legend/explanation. Please use official aquifer/geological formation/physiographic nomenclature in the caption and title. Please label contour lines.

The “Study Area” label has been removed to eliminate confusion. The caption has been modified as advised. Water levels are quantified in the figure legend.

Captions, nomenclature, and labels not completely addressed.

This figure has been adapted from a previous report and therefore has not been altered further than necessary. Additional effort to add labels was not taken because this figure is meant to provide a general overview of the groundwater flow pattern and range of elevation for the Edwards and Trinity groups of the Edwards-Trinity (Plateau) Aquifer region.

164. Page 182, Figure 8-6: Please use official Texas geological formation/aquifer nomenclature in the caption and map title. This map is not an exact representation of Groundwater Management Areas 3 and 7, please adjust title accordingly.

The caption has been revised as advised.

Comment #164: The nomenclature used—Trinity Aquifer and Edwards Aquifer—in the figure caption is not consistent with Texas aquifer nomenclature.

The caption has been edited to be consistent with Texas aquifer nomenclature.

165. Page 183, Bullet 1: Please give range of observed total dissolved solids (TDS) concentrations.

The text “less than 500 mg/l” has been added.

166. Page 183, Bullet 2: Please give range of observed TDS concentrations. The range of groundwater compositions in the Edwards and Trinity groups are identical: however, Figure 8-10 shows that most groundwater for the Antlers [Sand (Trinity Group)] and Edwards [Group] is a mixture of SO_4 and HCO_3. Please revise the text to show this.

Text added. “with a TDS of greater than 500 to greater than 2,000 mg/l.”

Comment #166 was not addressed in the report text (should appear on page 177 of the final report).

Bullet 2 text was revised as stated previously (p. 180).

167. Page 183, Bullet 3: Please revise “*TDS-SO₄-Cl*” (improper facies nomenclature).

The text has been clarified.

168. Page 183, Bullet 4: Please re-word the first sentence for readability. Please use proper nomenclature and symbology for Carbon-14 and units of measure. Please show range of ^{14}C activities, rather than just stating “waters are old” or “*waters are relatively younger*”. Please add “*Group*” after “*Edwards*”. Figures 7-7, 7-8, and 7-9 refer to the Hickory Aquifer, please adjust text to refer to the appropriate figures in the report. If referring to a county in a figure, please label counties on the figure referenced. Please discuss whether these conclusions are in agreement with the conclusions of Green and Bertetti (2010).

The text for Bullet 4 has been modified.

Comment #168: Please change the units for carbon-14 isotopes from “percent modern” to “percent modern carbon” and express it as a percentage not as a fraction as appears in the text. Nomenclature changes not addressed in bullet 4.

The units have been changed in the text and the nomenclature has been addressed in bullet 4.

169. Page 183, Bullet 5: Please clarify the assumption that saline water in Crockett County can come only from the Antlers Formation. Previous studies indicate a history of oil and gas

drilling with an upward flow of brines in Crockett County (See McNeal, 1965).If referring to a county in a figure, please label counties on the figure referenced. Please change ‘Crockett County’ to ‘western Crockett County and southern Reagan County’.

A qualifying statement related to oil and gas production has been added.

“western Crockett…” suggested changes not implemented. Nomenclature problems.

The “western Crockett…” suggestion has been implemented and the nomenclature problems have been addressed in the text.

170. Page 184, Figure 8-7: Please revise the figure to remove parts of the Edwards-Trinity (Plateau) Aquifer that lie outside of the area under discussion and/or please clarify why wells in western part of the aquifer are not plotted. Please clarify if this figure refers to Edwards Group of the Edwards-Trinity (Plateau) Aquifer.

See comment 159.

Comment #170: The response was (1) not what was requested by the comment and (2) not appropriate.

This figure has been adapted from a previous report and therefore has not been altered further than necessary. Text was added to the first paragraph of section 8.1 to clarify the study area for this chapter and references to Edwards waters have been changed to reference Edwards Group of the Edwards-Trinity (Plateau) Aquifer.

171. Page 185, Figure 8-8: Please clarify if this figure refers to all geologic units of the Edwards-Trinity (Plateau) Aquifer. If so, please simplify caption to, “Major chemical composition of groundwater in the Edwards-Trinity (Plateau) Aquifer and add “aquifer” to title.

The caption has been revised.

172. Pages 186-187, Figures 8-9 and 8-10: Please indicate the source of data. Legend and captions do not agree. Please clarify if legends are correct and adjust caption accordingly.

The captions have been corrected.

Nomenclature problems with Pipers’ legends in Figure 8-10.

Legends have been removed and captions clarified for these figures.

173. Page 188, Figure 8-11: Please revise the figure to remove parts of the Edwards-Trinity (Plateau) Aquifer that lie outside of the area under discussion and/or adjust caption to refer to the Antlers Formation of the Trinity Group portion of the Edwards-Trinity (Plateau) Aquifer. Please identify (outline or highlight) the extent of the Antlers Formation.

The caption has been revised as advised. The extent of the Antlers formational waters is noted in Figure 8-2.

Comment #173: If data is for Antlers Sand Formation then sample locations do not agree with Figure 8-2.

We feel this is incorrect. The sample locations are in the same area(s) as outlined by the red wells in Figure 8-2.

174. Page 189, Figure 8-12: Please revise the index map to show the location of the cross- section. This figure can be simplified to just show the aquifers—Edwards, Trinity, Ogallala, et cetera., or alternatively, revise the colors used to better distinguish different stratigraphic units, for example, the Blackwater Draw Formation, Washita Group, and Hammett Shale all use the same color.

The transect has been highlighted in the index map. Since this figure was taken from a previous study, it was not modified, but referenced in the figure footnote.

175. Page 190, Bullet 1: The figure number cited is incorrect. Please revise. The

limitation of the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers is not appropriate at sub-regional scales is acknowledged in TWDB Report 373. Please delete the third sentence from this paragraph.
Figure 7-9 has been changed to Figure 6-7 and Figure 6-8. The sentence order for Bullet 1 has been reorganized. The sentence referring to use of the model for sub regional analysis has been deleted.

176. Page 190, Bullet 2: Please revise "*TDS- Cl-*SO_4" (improper facies nomenclature). Please add 'formations' to the end of the first sentence and after Antlers. The second sentence in this paragraph is untrue (see Figure 8-15) and should be deleted or clarified.
"TDS-Cl-SO4" has been reversed to read "TDS, Cl-SO4." "Formation" has been added. The statement in regards to the no-flow boundary has been clarified to read "except for this northeastern region of their ETP model."

177. Page 190, Bullet 3: The Trinity Group (Antlers Formation) underlies the Edwards Group and mixing of groundwater from the two aquifers requires vertical flow between the aquifers. Evidence of the vertical flow is apparent in the occurrence of high total dissolved solids found in the groundwater in the Edwards Group in Reagan and Crockett counties and along the Rio Grande (see Figure 8-7). These occurrences of saline groundwater in the Edwards Group are not surprising considering that the Rio Grande is a major discharge zone for the Edwards-Trinity (Plateau) Aquifer and heavy pumping in the Glasscock-Midland- Reagan-Upton counties area that would result in upward groundwater flow from the Trinity Group. Please revise the text to reflect to above statements. Please expand discussion on last sentence on developing two models including more on where, why, appropriate objectives (understanding the goals of the GAM program), layering, model assumptions, boundary conditions, et cetera. Please include a detailed figure with geologic units, groundwater flow, boundaries, et cetera.
Bullet 3 has been expanded with the additional text, "Heavy pumping in the Glasscock-Midland-Reagan-Upton Counties area may have resulted in upwelling of groundwater from the Trinity. Similarly the Edwards Group along the Rio Grande may be receiving discharge from more saline deeper formations."

178. Page 191, Bullet 4: Please revise this paragraph. The spatial distribution of wells in the Trinity Group is related to the availability of adequate water supply in the shallower Edwards Group and says nothing about the productivity of the Trinity Group.
The following text has been added, "or that drillers never tested the deeper Trinity because sufficient productivity could be found in the overlying Edwards."

179. Page 191, Paragraph 2: Please discuss and clarify why the models for the Lipan Aquifer and Ogallala Aquifer were not considered.
The study focused three different hydrogeologic settings (far west Texas, Edwards-Trinity Plateau and the aquifers in the Llano region) as being representative of the major aquifers in the GMA 3 & 7 region. It was considered to be more important to place over emphasis there than in a small section of the Ogallala Aquifer or the Lipan Aquifer.
Comment #179 was not addressed in the report text.
Text has been added in the Introduction (p.3) that clarifies the omission of these models.

180. Page 191, Paragraph 7: Please list the three groundwater availability models (GAMs)—please see comment 2 on how to reference the groundwater availability models.
Completed.

181. Page 192, Bullet 2: Please use official Texas geological formation/aquifer

nomenclature (e.g., revise the phrase "*Trinity Plateau aquifer*"). Recharge to the Edwards-Trinity (Plateau) Aquifer ranged from 1 to 8 percent. Please revise the text to reflect this.
Text revised.

Comment #181: The official Texas geological formation/aquifer nomenclature was not used.
The text has been revised to use official Texas geological formation/aquifer nomenclature.

182. Page 192, Bullet 3: Recharge in the Hill Country portion of the Trinity Aquifer model was 4.7 percent. Please revise the text to reflect this.
Text revised.

183. Page 196, third bullet: Please use official Texas geological formation/aquifer nomenclature (e.g., revise the phrase "*Edwards and the Trinity (Plateau) aquifer*"). Please clarify last sentence; the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers is a transient model.
Corrections made and clarification added.

184. Page 196, last bullet: Please clarify if the source of the Dockum Aquifer summary is from the groundwater availability model for the Dockum Aquifer and please cite related references.
Text added to reflect this.

185. Page 197, Figure 8-16: Please check year of model report for the Dockum Aquifer, and adjust citation and references as needed. Our records indicate the report was dated 2008. Per Exhibit D of the contract and for consistency, please replace "et al" with "and others" in citation.
Corrected.

186. Page 199: Rustler Aquifer Section: Please clarify the source of the Rustler Aquifer summary is from the groundwater availability model for the Rustler Aquifer and cite references as needed and appropriate.
Text added to reflect this.

187. Page 200, Figure 8-17: Per Exhibit D of the contract and for consistency, please replace "et al" with "and others.
Corrected.

188. Page 201, Bullet 2: Please cite figures and/or references Carbon-14 and total dissolved solids supporting the flow from the Glass Mountains to Fort Stockton and Diamond Y springs.
Citation added.

189. Page 202, last Paragraph: Please change the reference to Figure 8-18 in the text. Figure 8-18 does not show a cross-section or a conceptual block diagram.
Corrected.

190. Page 204, Bullet 1: The Lipan and Ogallala should be added to this list of aquifers and models.
This is a list of what aquifers and models were investigated rather than an exhaustive list of aquifers and models intersecting GMAs 3 and 7. No alterations made.

191. Page 204, Bullet 2: Please use official Texas geological formation/aquifer nomenclature (i.e., revise the phrase "*Edwards and the Trinity (Plateau) Aquifers*").
Corrected

192. Page 204, Paragraph 2: Please include a copy of Nance's Figure 1.8, or show the trend of poor water on one of the figures in this report. Please give TDS range in text for the "poorer water" in that area. Please change 'Figure 1.1' to 'Figure 8-13'.

Corrections made and clarification added.

193. Page 204, Paragraph 6: Recharge to the northern part of the Pecos Valley Aquifer was estimated to be about 1 percent. Please correct the text and associated reference.

Corrected.

194. Page 205, Paragraph 2: Please change ‘Figure 1.5’ to the figure number that appears in this report.

Corrected.

195. Page 205, Paragraph 3: Figure 8-19 shows the conceptual model for the Rustler Aquifer. Please revise the figure number used here.

Corrected.

196. Page 206, Figure 8-19: Per Exhibit D of the contract and for consistency, please replace “et al” with “and others.

Corrected.

197. Page 207, Paragraph 1: Please change ‘…single layer GAM…’ to ‘…single-layer alternative groundwater flow model…’ and revise the second sentence for clarity. Please refer to the Nance (2010) figure that appears in this report. The conclusion in the last sentence is incorrect and should be deleted.

Corrected.

198. Page 207, Paragraph 2: Please expand on the justification for using the model by Young and others (2010). Please note that the groundwater flow model by Young and others (2010) is not an official GAM and is considered an alternative groundwater flow model. Please revise the text to reflect this. Please clarify why having a steady-state stress period without pumping makes it better than the GAM by Anaya and Jones (2009).

Corrections made. Additional explanation for the rationale of chosen models added.

199. Page 208, Paragraph 1: Please expand on the explanation for using groundwater flow models to investigate cross-formational flow and include an explanation for ‘why are the models being used to develop a conceptual model of groundwater flow instead of the groundwater geochemistry being used to develop a conceptual model to be used in future updates to the models?’.

The models aren’t being used to develop a conceptual model of groundwater flow. Rather, the groundwater models are being reviewed to investigate the degree to which they conform with the groundwater chemistry data. We believe the text reflects this.

200. Page 208, Paragraph 2: Please see comment 2 for referencing groundwater availability models and update all references in this paragraph and Chapter 8.5 accordingly. Please delete ‘and Young et al. 2010’ where it appears in the first sentence and note this is an alternative groundwater flow model. Please change ‘alternative GAMs’ to ‘alternative groundwater flow models’.

Corrected.

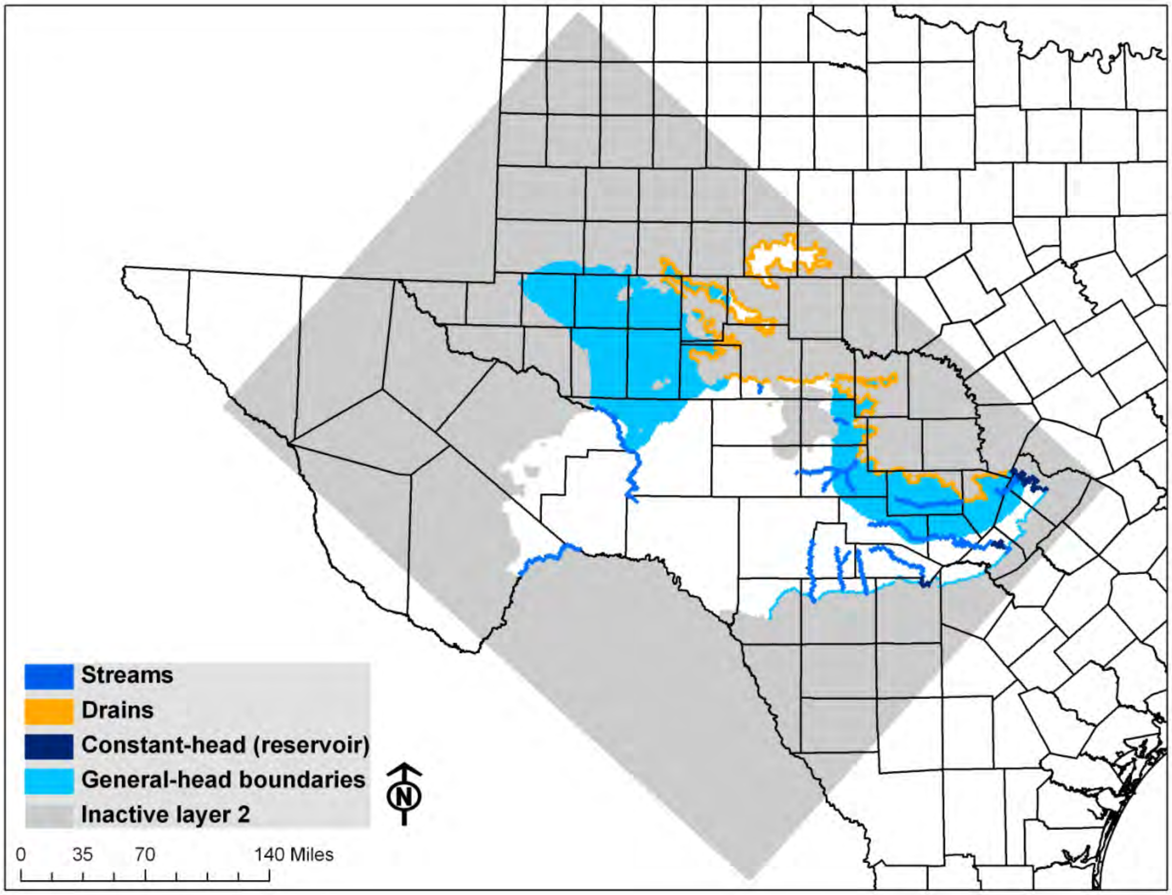
201. Page 208, Paragraph 4: Please note in the text that both models have general-head boundary cells simulating flow between the Edwards-Trinity (Plateau) Aquifer and underlying aquifers. Please revise the text to reflect this. Table 8-1 is a misleading misinterpretation of the data because it evaluates cross-formational flow averaged over a zone within the model. It also conflicts with data shown later in the report. Evaluation of cross-formational flow on a cell-by-cell basis (see Figures 8-20 and 8-22) is much better.

Additional text was added to clarify that general-head boundaries were used in simulating the cross-formational flow to overlying aquifers in the Dockum and Rustler GAMs. We believe that Table 8-1 is neither misleading nor a misinterpretation of the data; the summarizing of cross-formational flows over regions of the models is analogous to the TWDB requirements of summarizing water balances over county and GCD regions in GAM contracts. We feel that Table 8-1 provides an informative analysis of cross-formational flow that is complimentary to the individual cell-by-cell flows shown in Figure 8-20 and the summarized regional flows shown in Figure 8-22.

Comment #201 was not fully addressed in the report text. Text in paragraph 1, section 8.5.2, page 208 states neither Edwards-Trinity (Plateau) Aquifer models account for the flow to or from underlying units. The official groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers has general head boundaries in certain areas of the model to simulate flow between the Edwards-Trinity (Plateau) Aquifer and underlying aquifers (see figure below). It should be noted that flow leaving or entering the models was not a calibration factor and contains some uncertainty.

The reason for requesting water balances for counties and groundwater conservation districts for contracts that involve developing numerical flow models is to determine if the regional scale model can or should be used at this finer scale. When water budgets are not reasonable, additional model calibration may be needed and requested before accepting the model.

We had mistakenly interpreted "both models" in the original comment to refer to the Dockum and Rustler GAMs. Now that we understand "both models" to refer to the two Edwards-Trinity (Plateau) Aquifer models, we have corrected the text concerning the simulation of flow to underlying aquifers in those models. We have also added additional text to explain our rationale behind the choice of models used for each of the cross-formational flow calculations and how Table 8-1 compares to Figures 8-20 and 8-22 (now Figure 8-24).



202. Page 210, last Paragraph: This is an interesting analysis; however, given the differences between the assumptions of the individual numerical groundwater flow models analyzed, the fact that they were never optimized to work together, and the matter that cross-formational flow was not calibrated, the accuracy of the findings (rates of cross-formational flow) is questionable. Part of this study was to locate areas where cross-formational flow is significant to the flow system so future improvements to models could incorporate the results of this study. More discussion in the text may be needed to clarify reasoning and approach.

Additional discussion was included in this paragraph and at the beginning of Section 8.5 to clarify our rationale for using the models.

203. Page 211, Figure 8-20: Please add equivalent figures for the other models used in this analysis.

The equivalent figures and discussion were added for the Dockum and Rustler aquifers.

204. Page 212, Paragraph 1 and 2: Please change 'Figure 1.5' to the figure number that appears in this report. Please delete the last sentence in paragraph one as it is not conceptualized in any of the models or Nance (2010). Layer 1 (Edwards Group) in the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Figure 8-4) and Nance (2010)—Figure 8-6, which is a composite of the aquifers in the Edwards Plateau geographic subregion—shows a northwest to southwest flow across the Edwards Plateau geographic subarea. Figures 8-4, 8-5, and 8-6 all show another flow path

toward the Rio Grande.

Corrections made.

205. Page 212, Paragraph 3: It is unclear how ignoring certain significant flow components will not affect the relationship between vertical mixing and downstream flow. Please clarify.

Additional text was added in an attempt to clarify. The regions meant to roughly follow the conceptual flow lines in Nance (2010) are approximate as are the flow lines. A flow tube without lateral inflows and outflow would be very difficult to produce. However, the purpose of this analysis is an attempt to estimate the degree of mixing between the Edwards and the Trinity aquifers simulated by the groundwater models rather than the degree to which the conceptualized flow tubes are actually closed systems devoid of lateral inflows and outflows. We believe the chosen flow tubes represent the simulated cross-formational mixing between the Edwards and Trinity aquifers along what is conceptualized to be a major groundwater flow path. This is meant to provide a comparison to conclusions reached by the groundwater chemistry data.

While text was slightly modified on page 214, the above response is more descriptive than what was provided in the text of the report.

The majority of the above explanation has now been added to the report text to better clarify within the report itself.

206. Page 212, Paragraph 4: Please delete the last sentence on this page or include justification for why vertical leakage between the Edwards and Trinity groups is unrealistic. Figure 8-22 shows the upward flow from the Trinity Group indicated by groundwater chemistry. In addition, the groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Anaya and Jones, 2009) has a general head boundary at the base of Layer 2 where the Dockum Aquifer underlies the Edwards-Trinity (Plateau) and Pecos Valley aquifers. The stream tube analysis would be more robust if flow between Layer 2 and underlying units was included using this model. The results may support the source and pattern of the water quality observed in Figure 8-8.

The last sentence on page 212 was revised. The flow between Layer 2 and the underlying units was added to the analysis and Figure 8-21. Note that the Anaya and Jones (2009) GAM also shows primarily downward flow (to the GHBs representing the Dockum) and also does not support the high TDS levels observed in Figures 8-7 and 8-8.

207. Page 214, Section 8.6: Please expand section with recommendations for future studies and modeling recommendation from this study; for example:

- how many model layers,
- lump or split the model (where and why),
- combine which aquifers together for a regional flow model.

This section was expanded to provide our evaluation of the current vertical discretization of model layering with respect to either additional refinement or combining layers.

208. Page 214, Bullet 3: Please correct the figure number cited here.

Corrected.

Comment #208: The response to this comment was to delete erroneous figure citation without replacing it with an appropriate figure citation.

209. Page 215, Bullet 3: Please correct the figure number cited here. Please discuss whether this conclusion is supported by the groundwater chemistry. Please note, there has been no evaluation of the Capitan Reef Complex, Rustler, Dockum, Lipan, or Pecos Valley aquifer groundwater chemistry so far in the report.

Figure number corrected.

210. Page 215, Section 8.6.2: Please change ‘Figure 1.5’ to the figure number that appears in this report. Please clearly state that this section discusses how the models currently handle flow, and please expand section to how or if they should be modified in future updates to the model(s).

Figure number corrected. Additional bullets and clarification added.

211. Page 216, Paragraph 2: Please refer to a figure that outlines Trans-Pecos study area.

A reference to Figure 9-1 was added to the first sentence in paragraph 2. This figure shows the Trans-Pecos study area.

212. Page 218, Paragraph 1: Please briefly describe each of the end members shown in Figure 9-1.

End-member area 1 is described in the draft report in Section 9.1.2 on page 225. End-member areas 2 and 3 are described in the draft report in Sections 9.1.3 and 9.1.4 on page 228. End-member areas 4 and 5 are described in the draft report in Sections 9.1.5 and 9.1.6 on page 231. End member area 6 is described in Section 9.1.7 on page 234.

The following sentence was added to paragraph 1 on page 218 to alert the reader that descriptions of the end members are included in later sections. The exact text is as follows: “Detailed descriptions of the end-member areas are provided in sections 9.1.2 through 9.1.7.”

213. Figures 9-1 through 9-5: Please indicate the aquifers associated with the data. Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.

The aquifers associated with the data are presented on Figure 9-1. We decided to use symbol shapes and color-coding on the other figures based on the parameters depicted; therefore, it would be too busy to also include some sort of indication of the aquifers for each sample. The data were derived from the TWDB water well database or from the USGS database, with a handful of supplemental $^{87}Sr/^{86}Sr$ values from a published source. A description of the sources of data is provided in Section 9.1

214. Page 218, Paragraph 2: In this area, high total dissolved solids is quite often associated with the occurrence of soluble, evaporite minerals—halite and gypsum. Please include a statement to the effect that TDS, in addition to being a residence time indicator, is also greatly influenced by the solubility of the minerals comprising the aquifer rocks. One could find young, yet saline, waters in, say, evaporitic materials and old, low-TDS waters in quartzitic sandstones.

We agree with this statement and have added the following sentence to the end of paragraph 2: “This is not an exact relationship, as TDS in groundwater is also a function of the type of minerals in the aquifer matrix, and aquifers with high percentages of soluble minerals (e.g., halite and gypsum) can contain relatively young waters with high salinities.”

215. Page 218, Paragraph 4: Pleistocene recharge is not the only effect influencing stable oxygen isotopic compositions of groundwater in this area; effects such as the amount of precipitation and elevation of the recharge zone also play a role. Please clarify in text.

We agree that other processes affect the isotopic composition of rainwater in various locations; however, the GNIP database and work by several researchers in the study area, including Darling (1997), Nance (2010), and Uliana, et al. (2007) have shown that depleted oxygen isotopic compositions relative to current local precipitation are associated with groundwaters that recharged during the late Pleistocene. We have therefore amended the text of the paragraph.

216. Page 219, Figure 9-2: Please replace the legend title with "*TDS Concentrations (mg/L)*". Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.
The legend title was updated as requested. The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1 All text was updated to greater than 6-point as requested.

217. Page 220, Figure 9-3: It appears the values associated with each dot are shown as "fraction modern ^{14}C". Please either convert all values on the map to percentages and replace the legend title with "*^{14}C activities (pmC)*", or modify the legend to read "*^{14}C activities (fraction modern)*". Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.
The legend title was updated as requested. The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested.

218. Page 221, Figure 9-4: Please replace the legend title with "*$\delta^{18}O$ ($^{o}/_{oo}$ SMOW)*". [Some (many?) of these should be reported as VSMOW]. Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.
The legend title was updated as requested. The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested.

219. Page 222, Figure 9-5: Please use the proper notation for strontium isotopic ratio in the map legend and include units. Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.
The legend was updated as requested. The isotopic ratios are unitless, so no units were added to the legend.The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested.

220. Page 223, Figure 9-6: Please label Global Meteoric Water Line on graph. Please include reference for source of data.
The figure was updated with a label for the global meteoric water line. A statement concerning the source of the data was added to the figure caption.

221. Page 225, Paragraph 3: Please specify how the saturation indices were computed (e.g., Wateq, Netpath, by hand, etc).
The saturation indices were calculated using PHREEQC version 2. A reference to the program was added to paragraph 3.

222. Page 226, Figure 9-7: Please add Texas inset map, scale bar, and north arrow and please include reference for source of data.
Figure 9-7 has been updated with a state inset map, a scale bar, a north arrow, and a reference in the caption.

223. Pages 227,229, 230, 232, 233 Figures 9-8 to 9-12: Please include references for source of data.
All figure captions were updated with references to the source data.

224. Page 228, Paragraph 1: Please provide the state well number or identification information for the fresh water Rustler well in "easternmost Pecos County". End-member Area 2 total dissolved solids should be shown on a separate figure. Please explain why end-member area 2 should be separate from end-member area 1. The term 'end-member'

implies a closely packed cluster of groundwater compositions, end-member 2 has a fairly wide range of compositions (Ca-Mg-HCO_3 → Ca-Mg-SO_4 → Na-Cl). Please discuss this including justification for end-member status.

The fresh water Rustler well sample (symbol 2 on Figure 9-9) is from the USGS database and is listed as well US-53-19-7xx (USGS No. 303852102432902). Figure 9-2, which contains TDS values for area 2, was updated to be more readable. The reason that End Member Area 2 was distinguished from area 1 is related to the wide range of compositions in area 2 noted in the comment. The area 1 groundwater samples have a fairly uniform chemistry that appears to be controlled by interaction with anhydrites in the Rustler Formation. Area 2 appears to have a considerable and variable influence from other sources; most likely upwelling from underlying formations.

Comment #224 was not addressed in the report text on page 232.

We mistakenly assumed that addressing the comments in the comment responses would suffice, and have addressed the latest comment by making the following edits to the latest draft of the report:

- Identification information for the "fresh water Rustler well in easternmost Pecos County" was added to the first paragraph under section 9.1.3. The data for this well was obtained from the USGS well water quality database, so the USGS well number was included.
- The following paragraph was added to the end of Section 9.1.3: *"End Member Area 2 is identified as a unique end member and distinguished from End Member Area 1 because, unlike the area 1 groundwater samples, those from area 2 exhibit a much wider range of geochemical and isotopic compositions. The area 1 groundwater samples have a fairly uniform chemistry that appears to be controlled by interaction with anhydrites in the Rustler Formation. The area 2 samples indicate considerable and variable influences from other sources, which are most likely associated with upwelling from underlying formations."*

225. Page 228, Paragraph 2: It would be useful to show a table with all these analyses in each end member area, or individual figures for each end member area. Please discuss the available tritium data for this part of the Rustler aquifer. Please define 'recent recharge', Carbon-14 compositions less than 20 percent modern carbon imply Pleistocene recharge as does the low Tritium in these waters.

This paragraph was re-worded to address the tritium data for this part of the Rustler and to clarify the statement about "recent recharge".

Comment #225: The response to this comment only partially addresses the issues outlined in the comment (pages 232 to 233).

We inadvertently applied this comment to paragraph 2 in section 9.1.3 rather than paragraph 2 in section 9.1.2, as was intended by the comment, and we acknowledge that it was not fully addressed. The following responses to the comment are given:

- We attempted to generate a single table of values for each of the end-member areas; however, there are variations within each area that are described in the text which make it nearly impossible to put together a single table that would present all of the ranges of values in a way that would allow for effective comparisons of each area. The descriptions in the text are a much more effective way of presenting the information; therefore, we have not added an additional table.

- Figure 9-1 shows the boundaries of the end-member areas; Figures 9-2 through 9-5, 9-13, 9-15, and 9-17 show all relevant data and their relation to the boundaries of the end member areas. We decided that adding additional figures for each end member area would be redundant and would add a large number of unnecessary additional figures; therefore, we decided not to add those.
- As stated in the text, there is no available tritium data for this part of the aquifer. We were unable to make contact with any landowners and obtain permission to sample wells in this area, therefore, we were unable to collect any new data.
- Upon further review of this section of the report, we have decided that the use of the phrase "recent recharge" is not appropriate due to the lack of carbon-14 and tritium data. Paragraph 2 has therefore been amended as follows (edits are indicated by underlined text):
  "There are no carbon-14 percent modern or tritium values for Rustler Aquifer samples from the outcrop area. A single sample from a Rustler Aquifer outcrop area well has a oxygen-18 value of -6.8. This value is consistent with the expected values for current precipitation, which suggests that the groundwaters in the Rustler Aquifer outcrop area represent ~~recent~~ *recharge that occurred under current climatic conditions."*

226. Page 228, Paragraph 3: Figure 9-5 does not have enough detail to support this statement. Unable to identify which of the $^{87}Sr/^{86}Sr$ datapoints are derived from samples taken from the Rustler Aquifer, please provide figures with end-member areas and results. Figure 9-9 does not show Strontium isotopes. Please correct this figure reference.

All the $^{87}Sr/^{86}Sr$ data required to support the statement are depicted on Figure 9-5. This figure can be cross-referenced with Figure 9-1, which contains the aquifer designations for the samples, and with Figure 9-9, which shows locations of a few critical samples. A cleaner and more readable revised version of Figure 9-5 has been included as requested by comment 219.It is correct that Figure 9-9 does not show Sr isotope values; this is why the values were added in the text of paragraph 3 after each sample number. The reference to figure 9-9 is for sample location purposes.

227. Page 228, Paragraph 4: Please identify the mountains providing the groundwater flow. The authors listed have shown that the springflow emerging in the Balmorhea area is a mixture of fresh recharge from the Davis Mountains and older water supplied by a regional flow system. They hypothesized (not demonstrated, because the head data are sparse, and the well completions are uncertain) that the regional flow system carries water to the southeast through Limpia Creek, and then might veer north around Barilla Mountains towards Pecos County and into Pecos Valley Aquifer and Edwards-Trinity (Plateau) Aquifer. There are strontium isotope data in support of this hypothesis (same Sr data could support other hypotheses, too), but no smoking gun exists. Please re-word. Please indicate that the groundwater compositions range to Na-HCO_3 compositions.

The Davis and Barilla mountains are providing the groundwater flow. They have been added to the first sentence in the paragraph. A statement concerning Na-HCO_3 groundwater compositions in this part of the study area was added to this paragraph. We agree with the statement that the regional flow system is hypothetical at this point and not necessarily conclusively demonstrated by available data; however, paragraph 4 on page 228 is not discussing the regional flow system. This paragraph is only discussing flow from the Davis and Barilla Mountains north into the Pecos Valley – which we and others believe has been conclusively demonstrated – and does not refer to regional flow from any other areas. We have therefore made no other changes to this paragraph.

228. Page 231, Paragraph 2: Please add that the Pecos Valley Aquifer could also be influenced by runoff from the Delaware Mountains that crosses the outcrops of the Castile and Rustler formations (Jones, 2008). The data could also indicate mixing of old and recent waters. The section title should be changed to reflect that the end-member area extends into northern Pecos County. Please add the remainder of the Pecos Valley Aquifer to this end member or explain why it was excluded.

The following statement was added to paragraph 2 after the second sentence: "Pecos Valley Aquifer groundwater chemistry could also be influenced by surface runoff from the Delaware Mountains that crosses Permian Castile and Rustler outcrops and infiltrates into the basin fill." The title of the section was changed to "End-Member Area 4: Pecos Valley Aquifer in Reeves and Northwest Pecos Counties" to better describe the extent of the area.

229. Page 231, Paragraph 5: Please use official aquifer names, i.e., insert "*(Plateau)*" after "*Trinity*" in the sub-section title. Please draw on Figure 9-2 the flowpaths identified by Bumgarner (2012). This end-member area extends into Brewster County. Please revise the section title to reflect this.

The title of the section was changed to "End-Member Area 5: Edwards-Trinity (Plateau) Aquifer in Pecos and Northern Brewster Counties" to reflect the official aquifer name and the extend of the area.

Comment #229: The response to this comment does address the flowpaths identified by Bumgarner (2012)

Flow lines from Bumgarner (2012) have been added to Figure 9-2 in the report document.

230. Page 233, Figure 9-12: The Antlers Sand is not recognized in Pecos County.

The single data point on Figure 9-12 was incorrectly identified as Antlers Sand. The figure was corrected and replaced in the text.

231. Page 234, Paragraph 2: The Pecos River water, if applied for irrigation, should show some departure from the GMWL on the Deuterium versus Oxygen-18 plot due to evaporative effects. If not, one must look for another source of young water. Please re-word "*wells with greater pms of 14-carbon*" for readability, and replace "*pms*" with "*pmC*".

Figure 9-6 shows three Pecos Valley Alluvium samples that plot on the arrow indicating departure from the meteoric water line caused by evaporation. These are located Pecos and Crane Counties and have high TDS and high chlorides. Therefore, the available deuterium data for those samples are consistent with concentration of chlorides due to evaporation of river water applied for irrigation. The final paragraph was re-worded for better readability as requested.

232. Page 234, last Paragraph: See comment Page 228, Paragraph 4 above, the part regarding the regional flow path.

The last paragraph on page 234 has been re-worded to stress that the western regional flow system is hypothetical and has not been conclusively demonstrated.

233. Page 235, Figure 9-13: Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract. This data would be better displayed on separate maps for each 'end-member area'. Please revise.

The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested. The end member areas were added to the map so that the association between tritium values and end-member areas is more easily identified.

234. Page 236, Paragraph 1: Please add discussion of groundwater major element chemistry, including a Piper Diagram, consistent with the other end-member areas. Please discuss in more detail why groundwater could have low Carbon-14 but relatively high Tritium. Please discuss the range of modern precipitation stable oxygen and hydrogen isotopic compositions. Depleted isotopic compositions could result from recharge at high elevations,such as in the Guadalupe or Delaware mountains. Please elaborate on the basis for including the Rustler Aquifer as a contributor to the mixture described here.

A piper diagram for the analytical data from End Member Area 6 was added to the report as Figure 9-1x. The text was edited to include a discussion of the major element chemistry as requested .A discussion of the sample with low 14-carbon, yet high tritium, was also included. The range of modern precipitation stable oxygen and hydrogen isotopic compositions was already discussed elsewhere in the report (see page 218 in the draft report). Additional discussion concerning stable isotope values in modern precipitation was, therefore, not added to this section.The interpretation of contributions from the Rustler Aquifer is based on relatively high (up to 950 mg/L) concentrations of sulfate in some samples around the easternmost end of the area, including the major springs in the Balmorhea area. A sentence concerning this was added to the paragraph.

235. Page 236, Paragraph 2: Please add a figure showing the locations of the Carrizo, Beach, and Baylor mountains and the flow path extending from those mountains. Specify where high ^{87}Sr/^{86}Sr groundwater occurs.

The locations of the Carrizo, Beach, and Baylor mountains, the area with high ^{87}Sr/^{86}Sr values, and the flow path were added to Figure 9-5.

236. Page 237, Paragraph 1: This hypothesis does not address the ^{87}Sr/^{86}Sr anomaly in the Belding Trough. The trough fill is a mélange of materials, of which Cretaceous carbonates are probably a minority. In addition, close scrutiny of Figure 9-14 shows three separate clusters of high groundwater ^{87}Sr/^{86}Sr values located in Culberson County, Reeves County, and the Monument Draw-Belding Trough, respectively. Additionally, the arrows connecting the high groundwater ^{87}Sr/^{86}Sr values in Reeves County and the Monument Draw-Belding Trough are perpendicular to the regional flow system in the Edwards-Trinity (Plateau) and Pecos Valley aquifers. Discuss whether the alternative conceptual model is a better fit to the data.

We are not exactly sure what this comment means. The primary purpose of paragraph 1 is to directly address the ^{87}Sr/^{86}Sr anomaly in the Belding Trough and provide two alternate hypotheses that could explain the Sr isotopic composition in the trough. We agree that the trough fill is a mélange of materials; however, we have not found any references or other information that describes the mineralogy of the materials in the trough, and do not have any reason to think that Cretaceous carbonates are probably a minority. We also agree that the high ^{87}Sr/^{86}Sr groundwater samples fall into the three clusters; however, we believe that there is insufficient well coverage between those clusters to conclude that they are isolated zones of enriched ^{87}Sr rather than part of a larger connected zone.We believe that the alternate hypothesis does provide a reasonable explanation for the data in the Belding Trough, but until more extensive data for the geochemistry of the underlying formations is available, we cannot say that it is a better fit for the data.

237. Page 237, Paragraph 2: The Capitan Reef Complex Aquifer geochemistry should have previously been discussed in this report. A conceptual model cannot be discounted because of the absence of data. It is difficult to determine whether any of the End-Member Area 3

data fall within the Monument Draw-Belding Trough based on the jumbled data presented in the figures. Since the trough is a collapse structure, it potentially provides a pathway for upwelling of saline groundwater from the Capitan Reef Complex. Please evaluate the Capitan Reef Complex Aquifer groundwater data in the light of the proposed alternative conceptual model. One hypothesis to consider: ^{87}Sr-rich groundwaters from the Marathon uplift region flow northwest towards Acebuche Draw and Hovey Channel, where they are intercepted by these precursors to the collapse troughs further north, and funneled through the troughs and towards the Pecos River.

Conceptual models can only be evaluated if there is data; therefore, because of the lack of data on the Capitan Reef Complex Aquifer in GMA 3&7 we did not see any value in evaluating it. We are not sure what the specific problems are with the "…jumbled data presented in the figures", and we will address the issue when we receive clarification on the nature of the problem. We agree that the trough is a collapse feature that could potentially provide a pathway for upwelling of saline groundwater from the Capitan Reef Complex; in fact, this is a fundamental aspect of the alternative hypothesis that we presented in this paragraph. The potential for the presence of a pathway for upwelling saline fluids, however, does not address the lack of data for the Capitan Reef Complex Aquifer in this area, and we cannot use the concept of a potential pathway as evidence supporting the alternative hypothesis.The idea that the Marathon uplift region is the source of enriched ^{87}Sr in the Belding Trough was considered as an alternative hypothesis, but was discounted because flow paths in the Marathon as described in Smith (2001)[1] are towards the south and southeast.[1]Smith, R., 2001, Hydrogeology of the Marathon Basin Brewster County, Texas. In: Aquifers ofWest Texas (Eds. Mace, R.E., Mullican, W.F., and Angle, E.S.), Texas Water Development BoardReport 356, pp. 190-206.

238. Page 238, Figure 9-14: Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.

The figure number was changed to Figure 9-15 due to the addition of the piper diagram requested by comment 234.The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested.

239. Page 239, Paragraph 1: The problem with this model is the total lack of water quality data between the Rustler Aquifer outcrop and the southeast part of Reeves County. A good part of the flow line is "missing". This conceptual model was previously discussed in Jones (2008). Please reference that paper. Revise the fourth sentence to clarify which aquifer and county is being referenced. Please discuss how isotope data supports the conceptual model presented here.

We don't understand exactly what you mean by "total lack of water quality data between the Rustler Aquifer outcrop and the southeast part of Reeves County." There is fairly good well coverage throughout Reeves County, and there is sufficient major ion chemistry to support some influence of Rustler Aquifer water on groundwater chemistry in the western half of Reeves County. Jones (2008)[1] discusses recharge mechanisms and isotopic evolution of groundwaters in the Pecos Valley Aquifer, but does not address the conceptual model presented in this paragraph (lateral flows from the Rustler Aquifer into the Pecos Valley Aquifer). We therefore did not add a reference to this paper. The fourth sentence was clarified as requested. Additional text was added to paragraph 2 on this page to discuss the isotope data relative to this conceptual model. The exact text is as follows: "14-carbon values in the western part of Reeves County range from 0.02 to 0.31 (Figure 9-3), suggesting that residence times in the aquifer are relatively high and that flow rates are slow. This is supported by 18-oxygen values (-9.8 to -8.1‰ SMOW) that are depleted relative to recent recharge (Figure 9-4) and generally low tritium values (<0.4 TU), with the exception of a value of 4.8 TU in the northernmost sample from Reeves County (Figure 9-13)."

[1] Jones, I. C., 2008, Investigating recharge in arid alluvial basin aquifers: The Pecos Valley Aquifer, Texas: Gulf Coast Association of Geological Societies Transactions, v. 58, p. 489-500.

Comment #239: The contractor forgets that earlier in the report they discussed that recharge took place during the Pleistocene when the climate was wetter. Some runoff process had to have taken place that resulted in the hundreds of intermittent streams that we see today that extend from the Delaware Mountains to the Pecos River. Perennial streams are not a requirement for recharge. The contractor cited Darling's dissertation and therefore should know this.

The original comment discussed several issues, including a perceived lack of water quality data in Reeves County, a failure to cite that Jones (2008) previously discussed this conceptual model, a request for clarification concerning which aquifer and county is being discussed, and a request for additional language describing how the isotope data support the conceptual model. We addressed all of these issues in the response, and there is no indication in the follow-up comment that our responses did not adequately address the specific issues in the original comment – in fact, it appears that the follow-up comment was intended to address part of our response to comment #240 rather than comment #239. We will therefore assume that this follow-up comment is related to comment #240 and respond accordingly.

We agree that there are intermittent stream courses that drain the Delaware Mountains over the Rustler Outcrop onto exposures of the Pecos Valley Aquifer. The key component of our response to comment #240 is that we do not have any data, including flow rates, and/or analytical data, related to surface runoff from the Delaware Mountains across the Rustler outcrop; therefore, any attempts to address the possible effects of this mechanism would be purely speculative and would not provide any additional insight into understanding recharge mechanisms to the Pecos Valley Aquifer. This is why this recharge mechanism was not addressed. In addition, our response did not in any way state or imply that perennial streams are a requirement for recharge; in fact, our response directly addressed the potential for intermittent streams providing recharge in that we addressed a lack of data related to flow rates and persistence of flow related to storm events (i.e., intermittent flow events).

240. Page 239, Paragraph 2: This conceptual model does not take into consideration the presence of the Dockum Aquifer which directly underlies the Pecos Valley Aquifer in eastern Reeves County. Please evaluate Dockum Aquifer groundwater geochemistry and add it to the conceptual model. Also take into consideration the possible effects of recharge to the Pecos Valley Aquifer by surface water derived from the Delaware Mountains that had previously flowed over the Rustler Formation outcrop.

There are only a small number of samples from Dockum wells in eastern Reeves County, and these only have major ion chemistry with no isotope data. The Dockum samples are mixed-anion facies with low (<1,000 mg/L)) TDS, while the nearest Pecos Valley samples are predominantly chloride samples with TDS values >3,000 mg/L. Because of insufficient data, and a significant difference in chemistry implied by the limited data available, we did not include the Dockum in the conceptual model development, and we did not amend this section further to address the Dockum Aquifer. We are unaware of any perennial streams draining the Delaware Mountains that flow across the Rustler Formation outcrop and eventually reach the Pecos Valley Aquifer outcrop, nor do we have data to suggest that the flow rates from storm events are enough to a) carry a sufficient volume of surface runoff across a broad segment of Culberson County to significantly impact recharge to the Pecos Valley Aquifer, and b) persist long enough to dissolve enough of the Rustler outcrop to make a noticeable contribution to the chemistry of the surface runoff. In addition, we do not have any analytical data from surface runoff from the Delaware Mountains or from anywhere along the Rustler Formation outcrop, and can therefore not make any interpretations about the potential impact of Culberson County surface runoff that would amount to anything more than speculation. We have, therefore, not addressed the possible effects of the impact of surface runoff from Culberson County.

241. Page 239, Paragraph 3: Please delete the last sentence. It conflicts with statements made in the previous section.
Corrected.

242. Page 239, Paragraph 4: Conceptual model 1 is very weakly supported by the data and there are more defensible sources of saline groundwater close by, so please delete the second sentence and add the first to the next paragraph.
Corrected.

243. Page 240, Figure 9-15: Please revise, using different colors/symbols to represent the Pecos Valley Aquifer and Pecos Alluv. Mixed. The colors used are hard to differentiate. Please discuss Pecos [Alluvium] Mixed in the text. Please include reference for source of data and R^2 regression lines.
The color of the Pecos Alluvium Mixed was changed so that they can be differentiated from the Pecos Valley Aquifer. Pecos Alluvium mixed is described in the text. Correlation coefficients for the regression lines were added to the graph.

244. Page 241, Figure 9-16: Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.
The figure number was changed to Figure 9-17 due to the addition of the piper diagram requested by comment 234. The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested.

245. Page 242, Paragraph 2: There is no Figure 9-18, Figure 2 or Figure 3 in this report, please correct. The isotope-based conclusions discussed in this paragraph are difficult to discern from the figures. Irrigation using Pecos River water is restricted to areas adjacent to the river and thus cannot explain elevated groundwater salinity throughout the Monument Draw- Belding Trough. Furthermore, the Pecos River water is of such poor chemical quality, it’s hard to picture any farmer voluntarily applying it on his land. Please add a figure showing the areas identified as being affected by river water irrigation and areas affected by upwelling. Most of the samples within the trough area and located near the Pecos River have low (1-7 pmC) Carbon-14 activities and Tritium activities of 0 to 1.8 TU. Also, there are data available on the Capitan Reef Complex Aquifer that could have been used to evaluate the upwelling of water from the Capitan Reef Complex Aquifer into the Edwards-Trinity (Plateau) Aquifer. Please discuss why the Capitan Reef Complex Aquifer and other stratigraphic units below the Rustler Aquifer were not considered.

The figure numbers were corrected in the text. The correct figure numbers are Figure 9-17, Figure 9-2, and Figure 9-3. The figures containing maps of the isotope values throughout the study area were revised for better readability; therefore, the isotope-based interpretations should now be clearer. We agree that Pecos River water is probably unsuitable for irrigation in this area. References to application of Pecos River water for irrigation were removed and replaced with a discussion of possible irrigation return flow flushing salts concentrated in the soil from previous evaporation into the aquifer. We agree that the samples in the northern part of Pecos County (within the area identified as part of End Member Area 4) does show evidence for influence from upwelling flows – specifically, relatively high TDS, low ^{14}C, and low tritium – and therefore we have changed the text to reflect this.

246. Page 243, Figure 9-17: Please include reference for source of data and increase font size to no less than 6 point per Exhibit D, page 6, of the contract.

This figure called Figure 9-17 in the draft report was deleted because the necessary information on this figure was incorporated into the new Figure 9-17.

The data were derived from the TWDB water well database or from the USGS database. A description of the sources of data is provided in Section 9.1. All text was updated to greater than 6-point as requested.

247. Page 244, Paragraph 1: Please change ‘Figure 9-10’ to ‘Figure 9-9’.

Corrected.

248. Page 244, Paragraph 2: Please explain why upwelling from the Capitan Reef Complex Aquifer would not occur north of IH-10. Chloride groundwater occurs in Ward County.

Paragraph 2 addresses chloride concentrations in samples from wells identified as Rustler Aquifer wells within the trough. We observe that the few Rustler wells located north of IH-10 have major ion chemistry (primarily Ca-SO4) and Sr isotope values (0.7074 – 0.7076) that are consistent with the Rustler outcrop wells, while the Rustler wells south of the highway have higher chloride concentrations and higher ^{87}Sr/^{86}Sr values that are consistent with upwelling of more saline water from the Capitan Reef Complex. We find it hard to imagine that upwelling water from the Capitan would bypass the Rustler and not impact the Rustler wells while affecting the salinity and isotope values in the overlying Pecos Valley aquifer; therefore, we conclude that upwelling is likely south of the highway but not north of the highway. Chloride groundwaters do occur in Ward County in wells identified as either Capitan Reef Complex Aquifer wells or Pecos Valley Alluvium wells. We do not have data for the Rustler Aquifer north of the river; and can’t make exactly the same conclusions that we made south of the river; however, we agree that the presence of chloride-rich waters in the PVA with similar waters in the Capitan suggests upwelling flow. “North of the Pecos River in Ward County chloride-rich groundwaters are also observed in a few Capitan Reef Complex Aquifer wells as well as in two Pecos Valley Aquifer wells located within the Monument-Belding Trough. There is no data from the Rustler Aquifer in this area to confirm the upwelling hypothesis; however, the Capitan Reef Complex and Pecos Valley data are consistent with upwelling flow in this part of the trough.”

249. Pages 244-246, Section 9.3: Please expand section with recommendations for future studies and modeling recommendation from this study; for example:

- how many model layers,
- lump or split the model (where and why),
- combine which aquifers together for a regional flow model.

The answer to each of these questions depends on the objectives of the model. The trend is not to use the GAMs for regional water planning only, but for estimating water budgets and impacts at a county and sub-county level and for GCDs to assess permits. Therefore, models that combine hydrogeologically connected systems in higher resolution may be justified. Advantages of expanding the domain and adding more layers include potentially greater definition of flow components throughout the entire system and better understanding of the overall water budget throughout the area. However, there is always a trade-off for expanding the domain of groundwater models. Disadvantages may include more uncertainty in conceptual model components, boundary conditions, hydraulic properties, and other critical inputs.Valuable insights might be gained from developing a regional model in the western part of GMA 7 and GMA 3 that includes the Edwards-Trinity (Plateau), Pecos Valley, Capitan, Dockum and Rustler Aquifers. We recommend developing a preliminary model that combines each of the GAMs at a level of complexity similar to the existing GAMs. This is a significant effort, but would be helpful in developing a better understanding of water budgets in separate GAMs (inflow and outflow, both vertically and laterally) that are not consistent on a more regional basis. The findings from this model could be used to develop better constraints and overall water budgets for the independent GAMs. Both models would serve a purpose in advancing the state of the art for regional and county-level groundwater availability modeling. Text has been modified in report.

250. Pages 247-248, Chapter 10: Please adjust as needed to reflect review comments.

Sections of Chapter 10 have been revised.

251. Several references sited throughout text that do not in Section 11: References. Please update Section 11 with the following references cited in the text:

- Anaya and Jones, 2004 page 204
- Anaya and Jones, 2011 page 208
- Anaya 2010, page 208
- Brownwood Sheet 1976 page 57
- Beach and others 2006, page 190 (did you mean 2008?)
- Blanford and others, 200_ page 3
- Clark and Fritz 1997 page 13
- Fritz and Fontes 1986 page 13
- Hem 1985 page 13
- Richter and Kreitler 1993 page 13
- Pape and others 2010 page 20
- Chapman and other 1992 page 20
- USGS 2012 page 24
- Dutton and Simpkins 1986 page 29
- Chowdhury and others 2008 page 29
- Texas Bureau of Economic Geology Geologic Atlas of Texas Llano Sheet 1980 page 57
- Texas Bureau of Economic Geology Geologic Atlas of Texas Llano Sheet 1981 page 130
- Tybor in DBS 2007
- Plummer et al., 1991 page 127 (did you mean 1990 or should the 1990 reference be 1991?)

- Green and Bertetti 2010 page 179
- TWDB 2012 page 216
- Nance 2002 page 10
- Mancini and Scott 2006 page 150

References have been updated.

The following citations are incorrect or are not included in the list of references:

- ***Craig (1961),*** Added to References section
- ***DBS (2007) (should be changed to Standen and Ruggiero, 2007),*** ***Changed***
- ***Fogg and Kreitler (1982),*** Added to References section
- ***Kier and other (1979),*** Added to References section
- ***Oliver, Hutchison, and Anaya (2010) (should be Oliver and Hutchison, 2010),*** ***Changed***
- ***USGS, 2012.*** Corrected to cite Pearson and others, 2012 in text

252. Bumgarner and others 2012 is listed twice in the reference section. Please adjust.
Corrected.

253. Some reports that are cited in the text list years that do not match the References in Section 11, for example on page 197 there is a reference to Ewing et al., 2009, but the Dockum Aquifer GAM was 2008 in the references.
Text revised.

254. There is inconsistence when citing multiple authors. (example Ewing et al vs Ewing and others). Per Exhibit D of the contract and for consistency, please replace “et al” with “and others”.
Corrected.

Draft data comments to be addressed:

255. Screened intervals are not shown for any of the wells in the Appendix; many of the wells sampled by the contractor have no depths reported either, so they cannot be reliably assigned to an aquifer (see file Appendix-LU_BigTables.xlsx). Please update data spreadsheet with screened intervals and depths.
Depths of sampled wells have been included in analytical results table and LU_BigTables.xlsx has been revised to include this version. Screened intervals for new wells not already recorded in the TWDB groundwater database are not known.

256. As provided, the water quality data are not compatible with the TWDB database and cannot be uploaded without extensive manipulation.
    a. Please convert the data from meq/l to mg/l,
    b. Please add concentrations for HCO3;

The water quality data gathered for this project for submittal to TWDB has been revised and added to the electronic deliverables as “LBG_GMA37_AnalyticalResultsForTWDB_Final.xlsx”

The spreadsheet and documentation for sampling protocol are incomplete and therefore data from this study will not be incorporated into the TWDB groundwater database.

We have been sent the correct templates by TWDB and will be resubmitting the electronic water quality data with these responses for inclusion into the Groundwater Database.

257. Several matrix spikes are out of recovery range, mainly for fluoride (see file

labanalyses_1.pdf, the Quality Control section), please investigate, adjust, or note accordingly;

We previously requested San Antonio Test Laboratory to review their data. A few dilution errors were found and corrected. See comment 258.

258. Ten water quality samples do not meet TWDB standard on charge balance; they are off by more than +/- 5 percent (see file Appendix-LU_BigTables.xlsx). This and the precedent item should have prompted lab re-runs;

Charge balance issues were noted where analyses were received from San Antonio Testing Laboratory. San Antonio Testing Laboratory was requested to review these analyses. A few errors caused by dilution problem source were found and corrected. Their reevaluation of their data indicated no analyses problems.

259. The lab reports from Zymax (paper copy) are missing. Please provide the paper copies so we can scan the information into the TWDB WIID.

The reports have been included in deliverables.

Draft visualization cross-sections to be addressed

260. Please specify the units on each profile.

Profiles have been revised to include units in the title.

261. Please use the same color to represent specific aquifers consistently in the profiles; for example some shade of green for Cretaceous age formations, yellow for Quaternary, et cetera.

Colors have been modified to be consistent between profiles.

262. Please label all data points.

All points are now labeled.

263. Many of the labels overlap obscuring most of them. Please correct this.

Data in the profiles has been modified to show only most recent values and labels have been reorganized.

264. Nitrate profiles: The maximum contaminant level (MCL) for nitrate is 10 mg/l (expressed as nitrogen), which is equivalent to a nitrate concentration of approximately 44 mg/l. Please revise the profiles to correct this.

This error has been corrected.

265. Profile A-A’: The Pecos Valley Aquifer is apparently missing. In the δ^{18}O profile, there is an additional aquifer that does not appear on the legend, please correct this.

Pecos Valley Aquifer added to all relevant profiles and additional aquifer removed.

266. Profile B-B’: Please use different colors for the Edwards-Trinity (Plateau) and Pecos Valley aquifers. The Rustler Aquifer does not crop out in southern Pecos County, please correct. The wells on this profile do not match the wells on the profile map. The southern margin of the Dockum Aquifer is unrealistic, please revise.

Pecos Valley Aquifer added to all relevant profiles. The data used to create these profiles were taken from various GAMs, therefore any unrealistic surfaces are due to this and beyond scope to adjust for realistic profiles.

267. Profile C-C’: Many of the wells are located above the top of the Edwards Group. Please correct or explain. Please change the Deuterium profile to δ^{18}O to be consistent with other profiles.

Well data is taken from a distance of up to 1000ft from the transect line and may, therefore, have a higher or lower land surface elevation from which the depth is calculated. Deuterium changed to δ^{18}O profile.

268. Profile E-E': The profile is mislabeled in the index map. There seems to be enough data for isotope profiles.

Index map corrected.

Draft geodatabase comments to be addressed

269. Data in "commondata" folder is not in a geodatabase. Please update with geodatabase format including metadata.

All GIS data has been added to a comprehensive ArcGIS file geodatabase.

270. Please provide metadata for all geospatial data created.

Metadata has been added.

271. Please provide MXD figures in deliverables (including any new ones suggested in the report comments). MXD figures missing from GIS deliverables:

- 7-31
- 7-42
- 7-58
- 7-72
- 7-84
- 8-1
- 8-2
- 8-3
- 8-4
- 8-5
- 8-6
- 8-7
- 8-8
- 8-11
- 8-12
- 8-18
- 8-20
- 8-21
- 9-1
- 9-2
- 9-3
- 9-4
- 9-5
- 9-13
- 9-14
- 9-16
- 9-17

MXDs for the figures have been included in deliverables.

272. Some data is missing from basemap_features and gwdb_aug2012 causing broken links in the MXD files. Please investigate and correct as needed.

See response to comment #269

Suggestions for Report:

General suggestions

273. We recommend that a technical editor review the document to address issues such as the flow of logic (mixing of objectives, data results), grammar (e.g., fragmented, incomplete sentences), inconsistent/missing references, spelling and word consistency issues, and formatting (line spacing, fonts, etc.). Some figures appear to be reduced and scanned, rendering them difficult to read (e.g., Figure 7-31 and others). We also recommend that the Executive Summary be expanded to present the fundamental findings of the project. For example, the summaries of the Trans-Pecos conceptual models are insufficiently developed and do not help the reader understand the findings of the study. Please consider adding figures to the Executive Summary to aid the presentation.
Text revised to improve flow of logic, grammar, etc.

274. Suggest including a stratigraphic chart for the study area at the beginning of the report (or subregion) to assist with understanding formation names, ages, and geologic materials as it relates to the geochemical results.
A stratigraphic chart for each subregion has been developed.

275. Suggest including a glossary that includes aquifers, physiographic nomenclature, isotopes, and geochemistry terms and/or abbreviations.
A glossary has not been included.

276. Please check grammar and spelling and please avoid the use of abbreviations throughout the report.
Report has been reviewed for grammatical errors and spelling errors.

277. If an abbreviation is used please introduce first.
Report text was edited to introduce abbreviations first.

278. Please replace the symbols ‘<’ and ‘>’ with ‘less than’ and ‘greater than’, respectively.

279. Please use subscripts and superscripts where appropriate.
Text was corrected to use appropriate subscripts and superscripts.

280. Please use “*data have/are/show*” as opposed to “*data has/is/shows*” as data is plural for datum.
Report has been corrected.

281. Please change the x-y charts to show the x-axis intercepting the y-axis at the latter’s minimum value, even if negative.
Charts have been revised as advised.

282. Please use standard notations for isotopic ratios, delta, permils, et cetera. Also, colloquialisms should be avoided when discussing ion concentrations, radiogenic isotope activities, et cetera. For example “*Calcium is high*” is better interpreted as, “*Calcium concentrations are high*”.
The text has been adjusted for standard use of isotopic terms.

283. Please use the abbreviation ‘TU’ instead of ‘t.u’.
Corrected.

284. Please express concentrations in milligrams per liter.
Concentrations have been expressed in the units in which they were analyzed, including but not limited to milligrams per liter.

285. Please use a consistent format in the figures.
All figures have been revised for consistent format.
286. Please use consistent line spacing.
Corrected.
287. Please move location of source for figures where the font can be larger and readable.
Figure source formatting revised.

Specific suggestions

288. Page 1, Paragraph 3, right above bullet list: replace "*has provided insight*" with "*have provided insight*".
Corrected.
289. Page 1, first bullet: "The hydrogeology of the Ellenburger and the Hickory, the two major aquifers of the Uplift, vary based on their geologic and hydrologic setting" sounds like circular reasoning. (The hydrogeology varies based on hydrogeology). Please consider revising.
Text has been corrected
290. Page 1, Paragraph 4: The sentence "Isotope data on the eastern side of the Edwards-Trinity (Plateau) indicate much younger waters due to a higher rate of recharge to the Edwards Aquifer" is confusing. It is unclear what the Edwards Aquifer (Balcones Fault Zone?) Aquifer has to do with the recharge to the Edwards-Trinity (Plateau) Aquifer. Please reword.
The text of this paragraph has been modified.
291. 291. Page 8, Paragraph 2: Please reword "*Farther from the Uplift may be relatively stagnant*" – this is not a sentence.
Text has been modified to read, "Farther from the outcrop, groundwater may be relatively stagnant."
292. Page 10, Paragraph 4: Please change '100% ^{14}C' to '100 percent modern carbon ^{14}C'.
Corrected.
293. Page 10, Paragraph 5: please replace (2002) with (2010).
Corrected.
294. Page 10, last Paragraph: add the definite article "*the*" before "*Pecos Valley*".
Corrected.
295. Page 11, Paragraph 5: replace "*Balding*" with "*Belding*".
Corrected.
296. Page 12, Paragraph 3: Please change '…minor ion chemistry' to 'minor element chemistry'.
Corrected.
297. Page 13, Paragraph 2: Please check grammar in the last sentence.
Corrected.
298. Page 14, bullet 1: Please replace "*higher TDS-SO4*" with "*sulfate-rich, higher salinity*" or similar.
Corrected.
299. Page 19, Paragraph 1: Please revise the first sentence for clarification.
The first sentence has been modified to read, "Chlorine-36 is created in the upper atmosphere by naturally occurring processes as well as well within the subsurface (in situ production)."

300. Page 25: Please check the last line for formatting and add to the previous paragraph.
Corrected.

301. Page 28, Paragraph 1: Please review and revise the first sentence for clarity. The word ‘lithified’ is redundant and should be deleted. Please change ‘”’ to ‘inches’.
Text revised.

302. Page 28, Paragraph 5: Please add ‘respectively’ to the end of the first sentence.
Corrected.

303. Page 29, Paragraph 2: Please add ‘respectively’ to the end of the first sentence.
Corrected.

304. Page 29, Paragraph 3: Please check the grammar in this paragraph.
Corrected.

305. Page 57, Paragraph 2: Please delete the first sentence since it also appears in the previous paragraph.
Corrected.

306. Page 110, Paragraph 1: Check grammar and revise as appropriate.
Corrected.

307. Page 113, Paragraph 2: The first sentence is incomplete, please revise.
Corrected.

308. Page 124, Paragraph 1: Please revise the first sentence for clarity.
Corrected.

309. Page 124, Paragraph 4: Please use official aquifer nomenclature.
Corrected.

310. Page 125, Paragraph 5: Please change “may be” available from TWDB database to “are available” or cite where they are found i.e. report appendix or electronic appendix.
Corrected

311. Page 127, Paragraph 1: Please change ‘0‰ d13C’ to ‘0‰’.
Corrected.

312. Page 130, Paragraph 3: Please use official aquifer nomenclature.
Corrected.

313. Page 179, Paragraph 3: Please delete the last sentence in the paragraph.
Corrected.

314. Page 183, Paragraph 1: Please revise the first sentence to correct grammatical errors.
Corrected.

315. Page 183, Paragraph 4: Please change ‘…overlies subcrops…’ to ‘…directly overlies subcrops…’.
Corrected.

316. Page 215, Paragraph 6: Please revise the last sentence to correct a typographical error.
Corrected.

317. Page 216, Paragraph 1: Please change ‘interformational’ to ‘cross-formational’.
Corrected.

318. Page 224, Paragraph 5: Please change ‘interformational’ to ‘cross-formational’.
Corrected.

319. Page 20, Paragraph 1: Please replace “*this data*” with “*these data*”.
Corrected.

320. Page 22, Line 1: Please replace “$Sr^{87/86}$” with $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ here and throughout the text.

Corrected.

321. Page 24, Paragraph 1: Please delete "*and groundwater quality*".

Corrected.

322. Page 34, Section 6.2.2, Bullet 2: please replace "*collected 36Cl values*" with "*analyzed for* ^{36}Cl".

Corrected.

323. Page 38, Bullet 2: Please reword "there are fewer old waters".

Corrected.

324. Page 47, Bullet 3: Figure 7-1 not showing the stable isotope data referred to in the text.

Figure number has been corrected.

325. Page 49: Please modify legend to read "Old Pecos Valley Aquifer Waters" and "Young Pecos Aquifer Waters".

Legend modified.

326. Page 56: Some of the wording of this text is too tentative. For instance: "*head data may indicate leakage*", or "*updip fault blocks may contain an active flow system*". If data are available, what is the interpretation? Please include and discuss in more detail.

Page 56 has been modified to be less tentative.

327. Page 59, Figure 7-2 and other figures: "*McCulloch*" is misspelled in the map title. Please correct.

See response to comment #9

328. Page 64, Paragraph 2: please replace "*McClelland*" with "*McCulloch*".

Corrected.

329. Page 93, last Paragraph: Please replace "*compute*" in line 5 with "*computed*".

Corrected.

330. Page 95, last Paragraph: Please replace "*McClelland*" with "*McCulloch*". Also, correct "*McCullough*" in all the map titles.

Corrected.

331. Page 107, Paragraph 2: First sentence does not have a predicate.

Corrected.

332. Page 110, Paragraph 1: Please replace "The Hickory and Ellenburger does" with "The Hickory and Ellenburger do". Please clarify if discussing geologic formations, groups, or aquifers and correctly identify them.

Corrected.

333. Page 124, Paragraph 1: Please reword the first sentence. Please remove "*rapidly*" from the fourth sentence. (Closely-spaced water level contours are not necessarily indicative of high groundwater velocities).

First paragraph of page 124 has been revised for clarification. The word "rapidly" has been removed.

334. Page 132, Figure 7-57: Please capitalize "*with*" in the map title.

See response to comment #9

335. Page 133, Figure 7-58: Please re-word the figure caption to include the county name, and add a scale bar.

Figure and caption revised as advised.

336. Page 133, Figure 7-59: Please re-word the map title and the figure caption. Make them consistent. Avoid repeating the word "*Well*" and include the word "*Aquifer*".

See response to comment #9, caption revised.

337. Page 165, Paragraph 3: Please correct typo in line 2 ("*illustrate**d***").
Corrected.

338. Page 165, Paragraph 4: Page 166, Paragraph 2: Please replace "values that range from 0.7086 to 0.7106I" with "values of 0.7086 and .7106I".
Corrected.

339. Page 167, Figure 7-84: Please consider showing flow lines (arrows) and aquifers' outlines.
Aquifer outlines were added to this figure.

340. Pages 169-72: Please change the captions to match the content of the crossplots and ensure the text refers to the proper figure number.
Please see the response to comment 149.

341. Page 175, Paragraph 1: Please correct nomenclature in the section title. Please correct typo at the end of line 3 ("*And*").
Corrected.

342. Page 175, Paragraph 2: Please revise to correct grammatical errors.
Corrected.

343. Page 175, Paragraph 3: Please remove River when referring to the Rio Grande as Rio and River are redundant.
Corrected.

344. Page 190, Bullet 3: please erase "*in contrast*" after $Na\text{-}SO_4$ (repeated words).
Corrected.

345. Page 192, third Bullet: Page 196, first bullet: Please replace "*within*" with "*between*" in line 1.
Corrected.

346. Page 202, Bullet 2: Please reword sentence that begins with "Whereas"—second part of the sentence is missing a verb.
Corrected.

347. Page 215, Bullet 6: Please correct spelling of "stdeay-state".

348. Page 218, Paragraph 1: Please use correct and consistent notations for isotopes. If spelling out the name, use Carbon-14, Oxygen-18, etc. If abbreviating, use ^{14}C, $\delta^{18}O$, etc.
Corrected.

349. Page 218, Paragraph 4: Please avoid split infinitives. See "*can be used to indirectly determine*".
Corrected.

350. Page 224, Paragraph1: please spell out "Deuterium", in addition to using the symbols "$^{2}H/H\ (\delta D)$".
Corrected.

351. Page 225, last line: Please replace "*indicted*" with "*indicated*".
Corrected.

352. Page 231, Paragraph 2: Please revise the second sentence for clarity and grammatical errors. Please use correct and consistent notations for isotopes and their units of measure. If spelling out the name, use Carbon-14, Oxygen-18, etc. If abbreviating, use ^{14}C, $\delta^{18}O$, pmC, TU, etc.
Split infinitive has been corrected. Isotopic notation is consistent through the text.

353. Page 234, Line 1: Suggest replacing "*a different formation*" with "*several formations*".
Corrected.

354. Page 235, Figure 9-13: Please re-word the legend title to read "*Tritium activities*" and replace "*t.u.*" with "*TU*".
The legend title was re-worded to read "Tritium activities (TU)" as requested.

355. Page 239, Paragraph 4: Please revise for the first sentence to correct grammatical errors.
Corrected.

356. Page 242, Paragraph 1: Please delete 'potentially' from the last sentence.
Corrected.

Additional comments on new text:

357. ***Page 1, paragraph 5: "San Sab" should be "San Saba".***
Corrected.

358. ***Page 8, paragraph 1: It is unclear what chemical element was intended by author when referencing "hahnium".***
Corrected.

359. ***Page 11, Paragraph 2: Now states in the text "The TWDB has identified the Cretaceous aquifer in Pecos County to be the Edwards-Trinity (Plateau) Aquifer rather than just the Edwards Formation or Antlers Formation". This is a misleading statement. The TWDB recognizes that the groundwater within the geologic units of the Edwards Group and Antlers Formation as well as the other geologic units of the Trinity Group are collectively referred to as the Edwards-Trinity (Plateau) Aquifer.***
This text has been revised for clarity to read, "The TWDB has identified the Cretaceous aquifer in Pecos County collectively as the Edwards-Trinity (Plateau) Aquifer containing the Edwards Group, Antlers Formation, and the Trinity Group."

360. ***Page 12, Bullet 2 and elsewhere: The authors should have used superscripts to show isotopic delta values, where appropriate; for example, $\delta^{13}C$ instead of δ13C.***
Corrected.

361. ***Page 90, Figure 7-24. Spelling of tritium in map legend is incorrect.***
Legend corrected.

362. ***Page 92, Figure 7-26. In map legend, instead of "chloride-36" it should be "chlorine-36" and the delta symbol should be removed.***
Legend corrected.

363. ***Page 116, Figure 7-43: Hensell misspelled in the map legend.***
Legend corrected.

364. ***Page 167, paragraph 1: typo "enrichedstrontium-87".***
Corrected.

365. ***Page 177, bullet 1: Please correct "carbon-bicarbonate water".***
Corrected.

366. ***Page 177, bullet 2: please replace "chlorine" with "chloride".***
Corrected.

367. ***Page 180: "Formation" misspelled in Figure 8-1 caption.***
Caption corrected.

368. ***Page 194, paragraph 4: Change "Pecos Valley Aquifers" to "Pecos Valley Aquifer".***
Corrected.

369. ***Page 204, bullet 2: change in focus from first draft report (?): from continuity of flowpath between Edwards and Trinity changed to "flow-path continuity between the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer".***

Draft version was incorrect and was corrected in the final version as noted by the discussion in 8.4.2.

370. ***Page 221, figure 9-1: Please modify caption to reflect map contents***

Text and caption corrected.

371. ***There are several instances (for example section 9.2.3) where "chlorine" (the element) is used instead of "chloride" (the ion Cl^-). The latter should be used, unless the writers are referring to chlorine-36, the isotope.***

Corrected.

372. ***Figure 9-10: The figure caption is on a different page from the figure.***

Corrected.