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# Using Electric Logs to Estimate Groundwater Salinity and Map Brackish Groundwater Resources in the Carrizo-Wilcox Aquifer in South Texas

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## ABSTRACT

**In South Texas, brackish groundwater is a potentially important resource for oil field and agricultural uses. However, it is difficult to distinguish and quantify because few direct salinity measurements are available. In this paper, methods are presented for using resistivity logs to estimate groundwater salinity and to map brackish groundwater resources in the Carrizo-Wilcox Aquifer in South Texas. Electric logs were used to correlate and map stratigraphy and to estimate groundwater salinity. Salinity estimations were based on two methods: (1) empirical relationship between deep resistivity ($R_0$) and formation water salinity; and (2) calculation of formation water resistivity ($R_w$) using a modified version of the Archie equation. Both methods provide cutoff values of $R_0$ to distinguish broad categories of groundwater salinity: fresh (<1000 mg/L total dissolved solids [TDS]), slightly saline (1000–3000 mg/L TDS), moderately saline (3000–10,000 mg/L TDS), and very saline (>10,000 mg/L TDS). Brackish groundwater includes both slightly saline and moderately saline waters. Each significant (>10 ft thick) sand in the Carrizo-Wilcox Aquifer was assigned to one of these categories, and then cross sections and thickness maps were constructed to locate and quantify the resource. The Carrizo–upper Wilcox interval contains most of the fresh groundwater in the aquifer, whereas the lower Wilcox interval contains mainly brackish and saline groundwater. Within Carrizo–upper Wilcox sands, fresh groundwater grades downdip into brackish groundwater without intervening flow barriers. Brackish groundwater in lower Wilcox sands, however, is hydraulically separated from fresh groundwater in overlying sands. Therefore, the lower Wilcox interval is the most favorable target for brackish groundwater production without impacting fresh groundwater resources. Lower Wilcox brackish groundwater sands are thickest in the north and northeast parts of the study area. The lower Wilcox interval contains roughly 423 million acre-ft of brackish groundwater in place in the confined part of the aquifer in South Texas.**

## INTRODUCTION

Brackish groundwater is becoming increasingly important as fresh groundwater resources diminish. Brackish groundwater is defined as water containing between 1000 mg/L and 10,000 mg/L total dissolved solids (TDS) (LBG-Guyton Associates, 2003). The Texas Water Development Board divides brackish groundwater into two categories: slightly saline (1000–3000 mg/L TDS) and moderately saline (3000–10,000 mg/L TDS) (LBG-Guyton Associates, 2003). Brackish groundwater is usable with minimal treatment for many purposes in agricultural and oil field operations and may be better suited than sea water (35,000 mg/L TDS) for desalination. In South Texas, brackish groundwater in the Carrizo-Wilcox Aquifer is a potential source of water for hydraulic fracturing in the Eagle Ford Shale play (Scanlon et al., 2014). Brackish groundwater, however, is difficult to distinguish and quantify because few direct salinity measurements are available. Most chemical analyses of formation water samples are either from freshwater aquifers or from oil field brines. In this study, electric logs were used to quantify and map brackish groundwater in the Carrizo-Wilcox Aquifer in South Texas (Fig. 1). Water sample analyses provide only point-sourced data, whereas electric logs provide continuous vertical records of the electrical properties of both rocks and fluids in wells.

## GEOLOGIC SETTING

The Wilcox Group is a thick succession of fluvial-deltaic sandstone and shale that was deposited during the Late Paleocene and Early Eocene in the first major Cenozoic progradational episode into the Gulf of Mexico Basin (Fisher and McGowen, 1967; Galloway et al., 2000, 2011). The onshore Texas Wilcox Group is divided into three intervals (Fig. 2). Lower and middle Wilcox sandstones are thickest along the upper Texas coast (Houston Embayment), whereas upper Wilcox sandstones are thickest in



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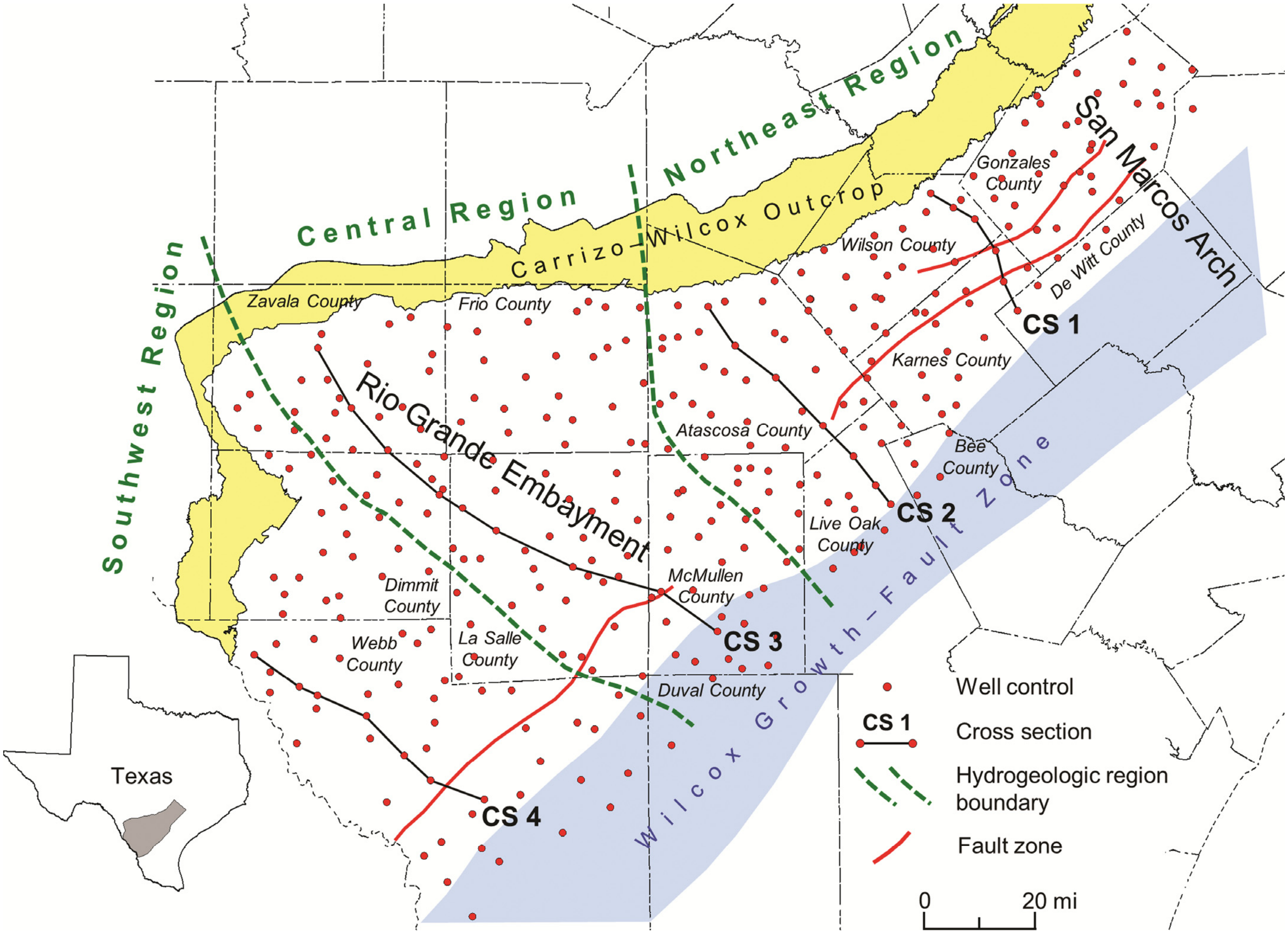


**Figure 1. Location of study area showing electric log well control, cross-section lines, and Carrizo-Wilcox outcrop. The Wilcox growth-fault zone and selected updip fault zones are also shown (Ewing, 1990). The area was divided into hydrogeologic regions (Hamlin, 1988) for separate $R_0$/TDS regressions.**

South Texas (Rio Grande Embayment) (Bebout et al., 1982; Xue and Galloway, 1993, 1995). In South Texas the Carrizo Formation is the updip equivalent of the upper Wilcox interval (Hargis, 1985, 1986). Carrizo fluvial facies updip are contiguous with upper Wilcox deltaic facies downdip (Hamlin, 1988). The middle and lower Wilcox intervals were deposited in a variety of coastal plain and marine environments and are generally less sandy than the Carrizo–upper Wilcox interval. The study area covers the Rio Grande Embayment and the southern flank of the San Marcos Arch, updip from the Wilcox growth-fault zone (Fig. 1). The Wilcox Group dips to the southeast at 50 to 150 ft/mi from outcrop to the Wilcox growth-fault zone.

Carrizo-Wilcox sands are one of the most extensive and productive aquifers in Texas. In South Texas almost the entire fresh groundwater resource is located in Carrizo–upper Wilcox sands. Fresh groundwater extends as far as 50 mi downdip from the outcrop to as deep as 5000 ft below sea level (Klemt et al., 1976; Hamlin, 1988). Middle and lower Wilcox sands contain primarily brackish and saline groundwater. The middle Wilcox interval is shale-dominated and generally forms an aquitard between the lower Wilcox interval and the Carrizo–upper Wilcox interval (Fig. 2). In this study, middle and lower Wilcox sands were mapped as one undifferentiated unit, which will be referred to as the lower Wilcox interval. The Carrizo-Wilcox Aquifer is variably consolidated and includes sands and sandstones, both of which are referred to as sands in this paper.

## METHODS

Electric logs from 327 wells were used to correlate and map stratigraphy and to estimate groundwater salinity (Fig. 1). Digital logs were used to display lithology and groundwater salinity on cross sections. Petra software (IHS, Inc.) was used for data management, interpretation, and visualization. Stratigraphic correlations were guided by type logs published in regional studies (Bebout et al., 1982; Hargis, 1986; Hamlin, 1988). The depositional framework is also based on previous regional studies (Hargis, 1985, 1986; Fisher and McGowen, 1967; Bebout et al., 1982; Hamlin, 1988; Xue and Galloway, 1993, 1995). In Gulf Coast Tertiary sand/shale sequences, lithologies can be distinguished with confidence on electric logs (spontaneous potential [SP] and resistivity curves) (Fig. 2). Standard subsurface mapping techniques were applied to construct net sand thickness maps separately for sands containing fresh groundwater and those containing brackish groundwater. Depth maps to important salinity boundaries were also constructed. Net sand thickness multiplied by estimated porosity allowed volumetric quantification of groundwater in place.

Groundwater salinity estimations are based on two methods: (1) empirical relationship between the resistivity of a water-filled formation ($R_0$) and formation water salinity; and (2) calculation of formation water resistivity ($R_w$) using a modified version of the Archie equation (Jones and Buford, 1951; Estepp, 1998).

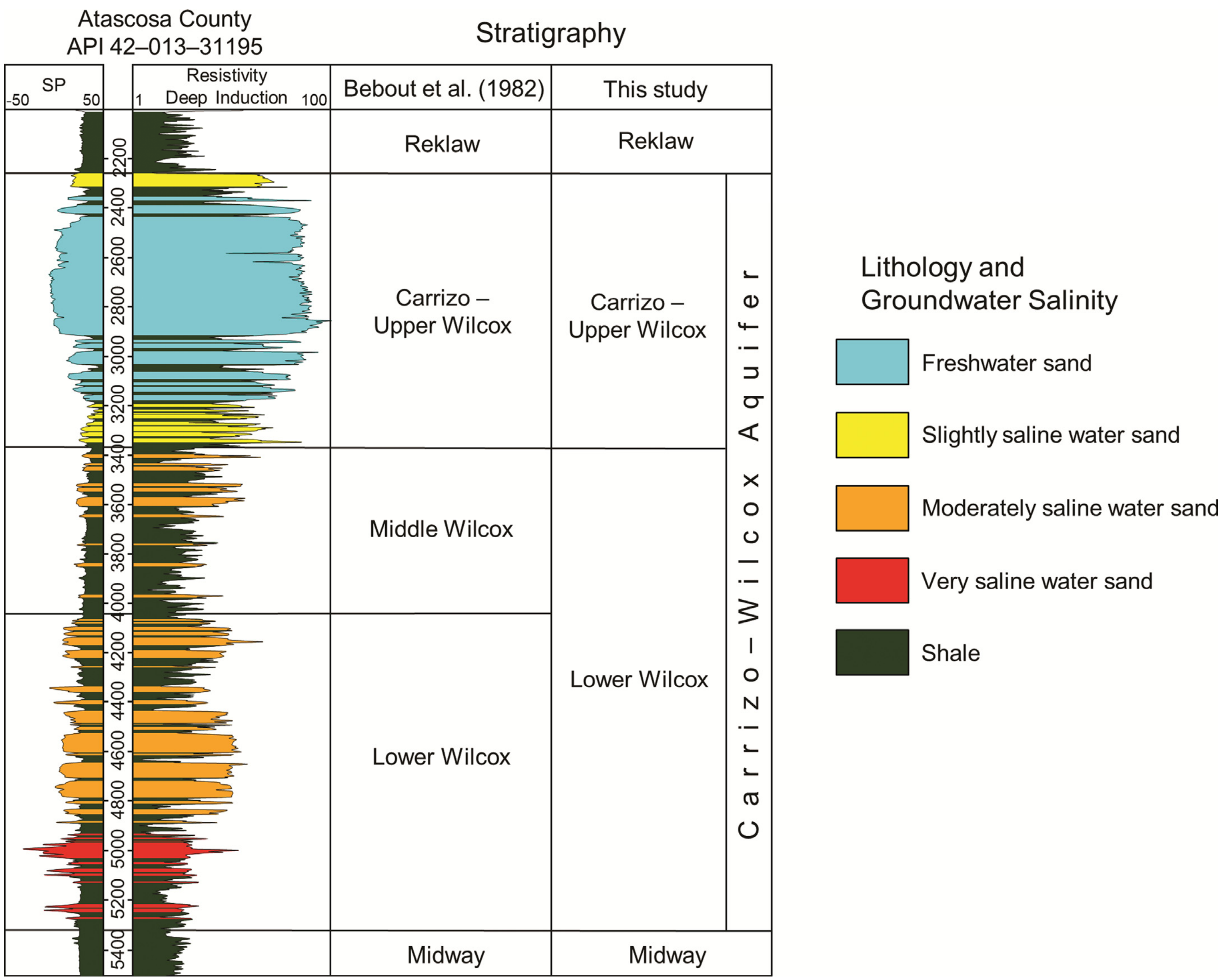


**Figure 2. Typical electric log showing spontaneous potential (SP) and resistivity curves through the Carrizo-Wilcox interval. In this study, the middle and lower Wilcox intervals were undifferentiated. Both lithology (sand/shale) and groundwater salinity were interpreted from the electric log (see text for details).**

The $R_0$ method involves correlating deep resistivity (long normal or deep induction) with chemical analyses of groundwater samples from the same zone (Fogg and Blanchard, 1986; Hamlin et al., 1988; Collier, 1993; Estepp, 1998). The deep resistivity curve is used to minimize the effects of mud filtrate invasion. Deep resistivity is assumed to be approximately equal to true formation resistivity ($R_t$). Bed thickness also affects the deep resistivity. For beds thinner than about twice the electrode spacing, the deep resistivity does not equal $R_t$ (Jones and Buford, 1951). Therefore, only sand layers greater than 10 ft thick are included in volume calculations. Where water saturation is 100% (no hydrocarbons), the deep resistivity is affected primarily by formation water salinity and hydrochemical composition, temperature, porosity, and lithology, and can be taken as a proxy for $R_0$, which is the $R_t$ value of a 100% water wet formation (Jones and Buford, 1951; Turcan, 1962; Alger, 1966). Hydraulic conductivity (permeability) also affects resistivity, and resistivity has been used to map recharge and groundwater flow paths (Fogg et al., 1983; Ayers and Lewis, 1985; Ayers et al., 1986). $R_0$ is most closely related to groundwater salinity in thick, clay-free sands having similar porosities, depositional facies, geographic area, and depth range. The $R_0$ method works best in unconsolidated to semi-consolidated, sand/shale sequences such as the Gulf Coast Tertiary.

To develop $R_0$/TDS regressions, TDS values from water well chemical analyses from 166 wells were paired with $R_0$ measurements in nearby petroleum wells, taking care to identify the same zone in both wells. Median distance between wells in the pairs is 8835 ft (Fig. 3; Appendix). Most of the water wells produce low TDS groundwater from the Carrizo–upper Wilcox interval; the lower Wilcox interval is poorly represented. A small set of lower Wilcox data (9 wells) was obtained from analyses of high TDS formation water produced in petroleum wells (Appendix). Graphing $R_0$ versus TDS for the entire dataset yielded a coefficient of determination ($R^2$) of 0.87 (Fig. 4). This relatively good correlation suggests that groundwater salinity is the dominant control on $R_0$ in shallow (<6000 ft) Carrizo-Wilcox sands in South Texas.

$R_0$/TDS correlations were refined by dividing the study area into three smaller regions, and developing separate $R_0$/TDS regressions for each region (Fig. 5). The regions coincide with hydrogeologic zones that have distinct lithologies, depositional facies, hydrochemical facies, and other aquifer properties (Hamlin, 1988) (Fig. 1). $R_0$/TDS correlations were used to de-

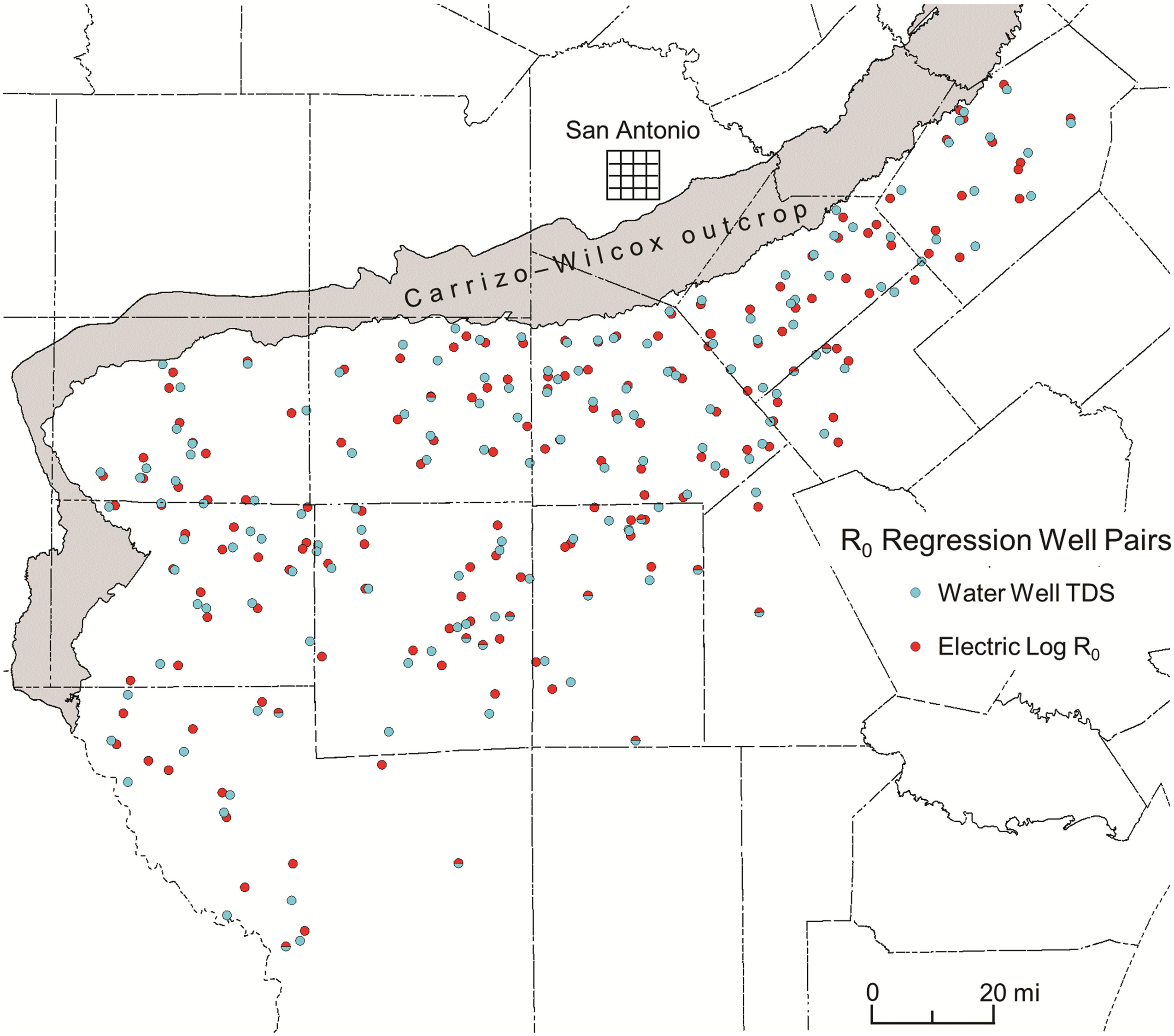


**Figure 3. Wells used to develop $R_0$/TDS regressions. Most TDS data (blue dots) come from water wells, whereas most resistivity data (red dots) come from petroleum wells. A few wells have both data types (red and blue dots).**

fine $R_0$ cutoff values in each region for freshwater (<1000 mg/L TDS), slightly saline water (1000–3000 mg/L TDS), moderately saline water (3000–10,000 mg/L TDS), and very saline water (>10,000 mg/L TDS) (Table 1). Brackish water includes both slightly saline and moderately saline waters.

The $R_w$ method was used to supplement and corroborate the $R_0$ method, especially in deeper intervals where water well chemical analyses are scarce. Parameters for the $R_w$ equation (Equation 1) are porosity (ϕ) and the cementation exponent (m), which is an empirical parameter related to compaction, cementation, and grain size (Jones and Buford, 1951; Asquith et al., 2004).

$$R_w = \phi^m \times R_0 \quad (1)$$

Values for ϕ and m are based primarily on previous studies of Wilcox porosity and petrography (Loucks et al., 1986; McBride et al., 1991; Dutton and Loucks, 2014) supported by water sample measurements of $R_w$ from petroleum wells (Gaither, 1986). Ranges of ϕ and m were tested for sensitivity and reasonable outcome. $R_w$ from Equation 1 was corrected to a standard surface temperature and then converted to TDS through a conductivity relationship that is specific to formation and region (Turcan, 1966; Estepp, 1998) (Equations 2 and 3).

$$C_w = 10{,}000/R_w \quad (2)$$

$$TDS = ct \times C_w \quad (3)$$

where $C_w$ is the formation water conductivity and ct is a proportionality constant that was determined by graphing TDS versus $C_w$, both of which were measured in groundwater samples from the Carrizo-Wilcox Aquifer in South Texas (Fig. 6). The $R_w$ method allows $R_0$/TDS cutoffs to be determined independently from water sample analysis (Table 2).

Resistivity cutoffs from the $R_0$ method (Table 1) were used to estimate groundwater salinity mainly in Carrizo–upper Wilcox sands, whereas cutoffs from the $R_w$ method (Table 2) were used

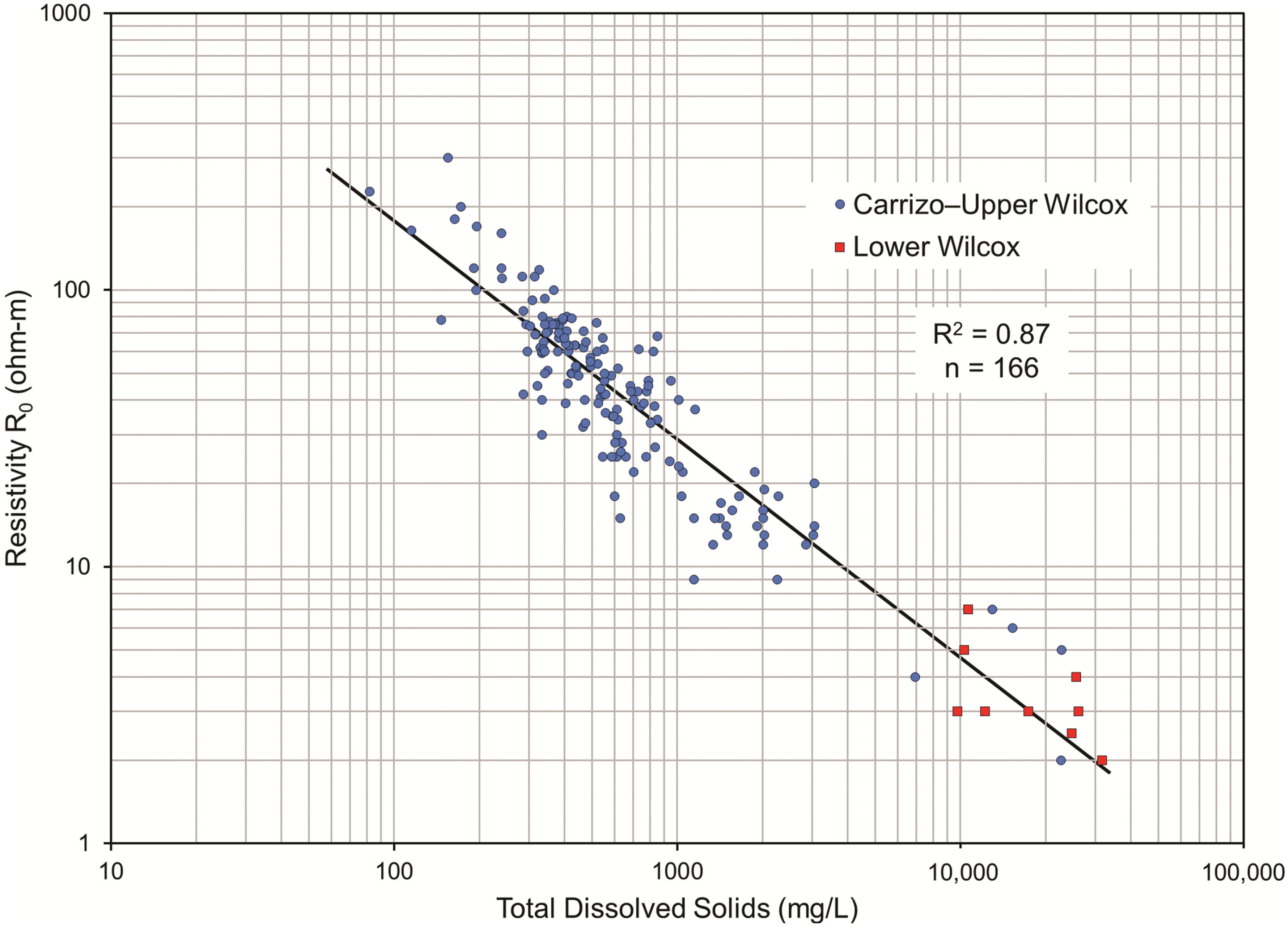


**Figure 4. Deep resistivity (proxy for $R_0$) versus total dissolved solids (TDS) versus for all well pairs in the study area. See Figure 3 for well locations and Appendix for data used to construct graph.**

mainly in lower Wilcox sands. For similar groundwater salinities, resistivities in Carrizo-Wilcox sands increase from northeast to southwest (Fig. 5). Reasons for southwest-increasing resistivities have not been documented, but decreasing porosity and permeability are probably important factors. Similar resistivity increases are present in the lower Wilcox interval relative to the Carrizo–upper Wilcox interval. However, in the southwest region (Fig. 1), lithologies and aquifer properties are similar for both the Carrizo–upper Wilcox and the lower Wilcox, and $R_0$ cutoffs are similar there as well (compare Tables 1 and 2) .

## RESULTS

Sand distribution and geometry are important aquifer properties, and mapping sand thicknesses is the first step in quantifying groundwater volumes. The Carrizo–upper Wilcox interval ranges from greater than 90% sand near outcrop in the northeastern part of the study area to about 50% sand along the Rio Grande in the southwestern part (Hamlin, 1988). Carrizo–upper Wilcox sand thickens into a large depocenter located south of San Antonio (Fig. 7). Coarse-grained, bed-load fluvial channel systems dominate the Carrizo updip from the sand depocenter (Hamlin, 1988). Along the downdip margin of the study area and in the Wilcox growth-fault zone, the upper Wilcox was deposited in wave-dominated delta and associated barrier/strandplain systems (Fisher, 1969; Edwards, 1980, 1981). Specific depositional environments within the sand depocenter are not well documented but probably comprise bed-load fluvial channel facies interfingering with coalesced delta front and shoreface facies.

The Carrizo–upper Wilcox interval contains fresh or brackish groundwater across most of the study area. The thickest freshwater zones are located in fluvial sands in the north and northeast parts of the study area (Fig. 8). Thickness of freshwater sands decreases abruptly along the downdip margin of the study area, coinciding locally with regional fault zones (Fig. 8). These normal faults are located updip from the Wilcox growth-fault zone (Fig. 1). In Gulf Coast Tertiary aquifers, groundwater salinity changes commonly occur near faults and result from the interaction between descending low-TDS meteoric water and expulsing high-TDS deep-basin formation water (Kreitler, 1979; Galloway, 1984; Hamlin, 1988). In Carrizo–upper Wilcox sands, fresh groundwater grades downdip into brackish groundwater. Sands containing brackish groundwater form a strike-aligned trend of maximum thickness near the downdip margin of the study area (Fig. 9).

In South Texas, the lower Wilcox interval is less sandy than the Carrizo–upper Wilcox interval. Percent sand in the lower Wilcox interval generally decreases from 60% sand near the outcrop and in the northeast to less than 10% sand locally in the southwest and downdip. The thickest sands in the lower Wilcox interval are in the northeast on the San Marcos Arch (Fig. 10). In the far northeast, the shale-filled Yoakum Canyon is expressed as a sand-poor, dip-oriented trend (Fig. 10) (Hoyt, 1959; Dingus and Galloway, 1990). In the Rio Grande Embayment, lower Wilcox

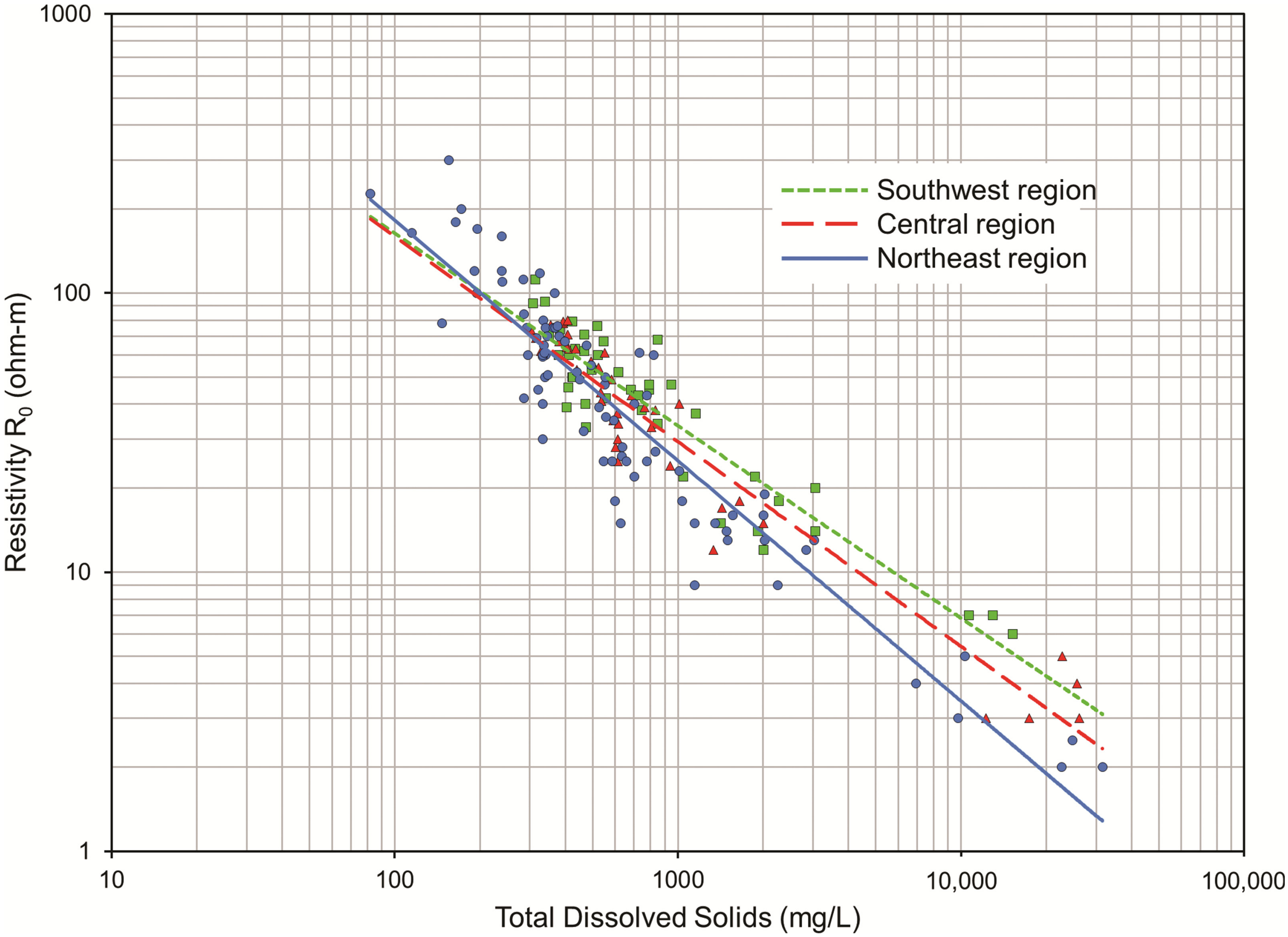


**Figure 5. Deep resistivity (proxy for $R_0$) versus total dissolved solids (TDS) showing separate regressions for each of the three hydrogeologic regions (Fig. 1). See Figure 3 for well locations and Appendix for data used to construct graph.**

**Table 1. $R_0$ cutoff values based on the $R_0$/TDS empirical relationships (Fig. 5).**

| Region | Freshwater | Slightly Saline Water | Moderately Saline Water | Very Saline Water |
|---|---|---|---|---|
| Southwest | > 34 | 16 – 34 | 7 – 16 | < 7 |
| Central | > 29 | 13 – 29 | 5 – 13 | < 5 |
| Northeast | > 25 | 10 – 25 | 4 – 10 | < 4 |

net sand patterns are strike aligned and decrease updip and downdip from an elongated depocenter (Fig. 10). Fisher and McGowen (1967) interpreted these sand thickness patterns to represent a delta system in the northeast flanked by a barrier-strandplain system to the southwest.

The lower Wilcox interval is dominated by brackish and saline groundwater, although minor fresh groundwater is present locally in outcrop and the shallow subsurface. Lower Wilcox brackish groundwater sands are thickest in the north and northeast (Fig. 11), where they underlie maximum fresh groundwater in the Carrizo–upper Wilcox interval (Figs. 12 and 13). The lower Wilcox interval contains mostly saline groundwater in the southwest (Webb County) and along the downdip margin of the study area (Figs. 14 and 15). Fault-related groundwater mixing probably controls distribution of brackish groundwater in the lower Wilcox interval in the northeast (Fig. 11). In the southwest poor sand development and low rainfall recharge in outcrop are probably the main controls on brackish groundwater distribution (Hamlin, 1988).

Fresh and brackish groundwater intervals extend to greater depths in the Carrizo-Wilcox Aquifer in South Texas than they do in other Texas aquifers (LBG-Guyton Associates, 2003). Base of fresh groundwater ranges from 500 ft below surface near the outcrop to greater than 5000 ft below surface locally downdip (Fig. 16). The base of brackish groundwater ranges from 1000 ft below surface near outcrop to greater than 6500 ft below surface downdip (Fig. 17). The deepest occurrences of both fresh and brackish groundwater are in the Carrizo–upper Wilcox interval.

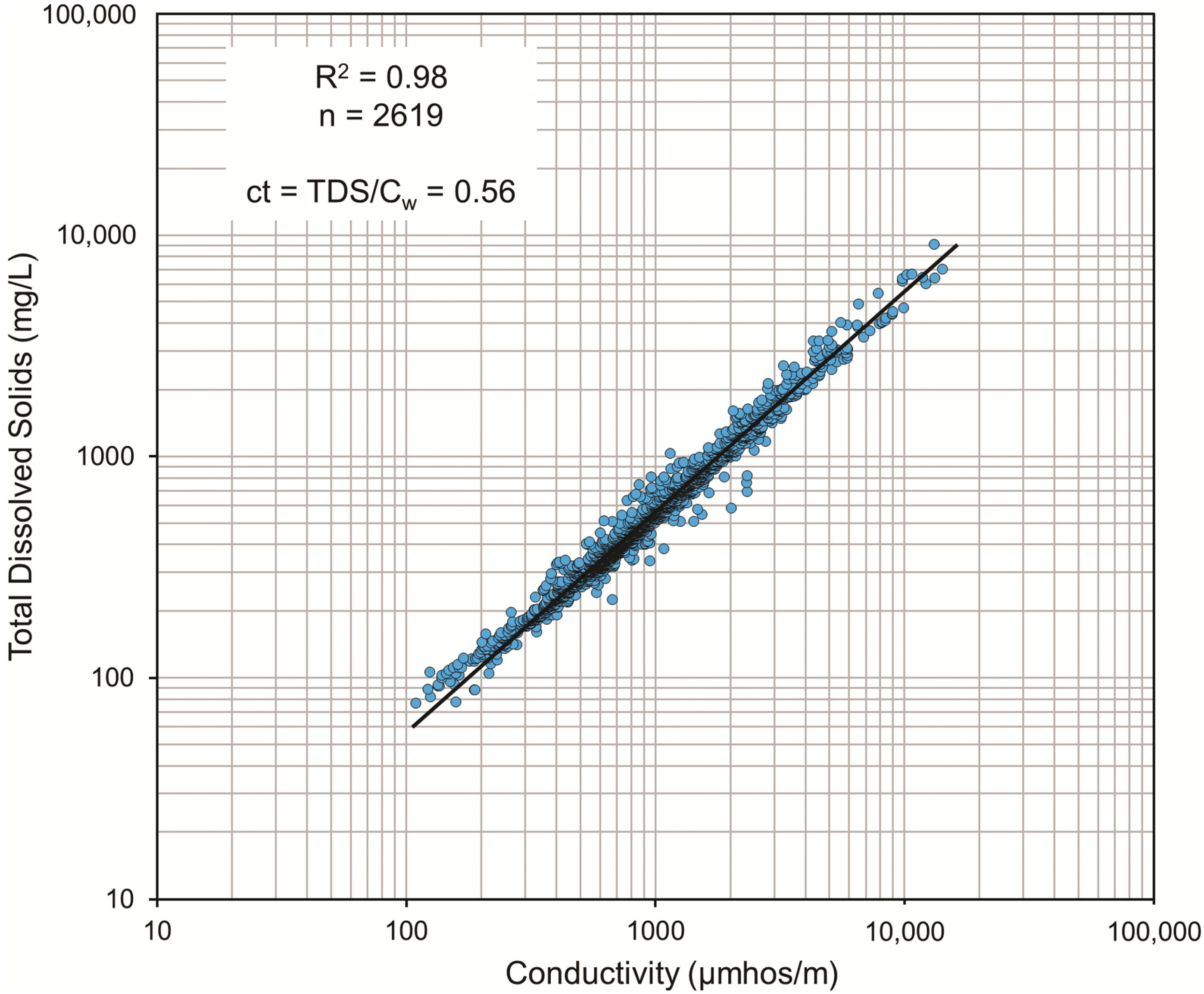


**Figure 6. Graph of conductivity (Cw) versus TDS for the study area. Both Cw and TDS were measured in water well samples. Cw and TDS are related by a proportionality constant (ct), which is specific to area and formation. In the South Texas region, however, a single value of ct is valid for the entire Carrizo-Wilcox Aquifer.**

**Table 2. $R_0$ cutoff values calculated using the $R_w$ method.**

| TDS (mg/L) | Depth range (ft) | Temperature (°F) | Porosity (%) | m | ct | $R_w$ | $R_0$ |
|---|---|---|---|---|---|---|---|
| 1000 | < 3000 | 110 | 30 | 1.8 | 0.56 | 3.78 | 33 |
| 3000 | 3000 – 6000 | 158 | 25 | 2.1 | 0.56 | 0.87 | 16 |
| 10000 | 4000 – 7000 | 177 | 20 | 2.4 | 0.56 | 0.23 | 11 |

In the lower Wilcox interval, depth to base of brackish water ranges from 5000 ft in the northeast to 1200 ft in the southwest (Fig. 18).

Hydraulic connectivity between subunits in a heterogeneous aquifer system is an important consideration for developing and managing groundwater resources. Hydraulically separated layers commonly have differing heads and hydrochemical compositions, and one layer might be produced without significantly affecting others (Nativ and Weisbrod, 1994). In the Carrizo-Wilcox Aquifer, shales and muds are aquitards that vertically separate aquifer sands. In this study, we assume (but do not prove) that the Carrizo–upper Wilcox interval is hydraulically isolated from the lower Wilcox interval by shales in the upper part of the lower Wilcox, although the degree of separation varies (Figs. 12–15). In contrast, within the Carrizo–upper Wilcox interval, fresh groundwater grades downdip into brackish groundwater without intervening flow barriers. Therefore, brackish groundwater volumes in place were calculated separately for the

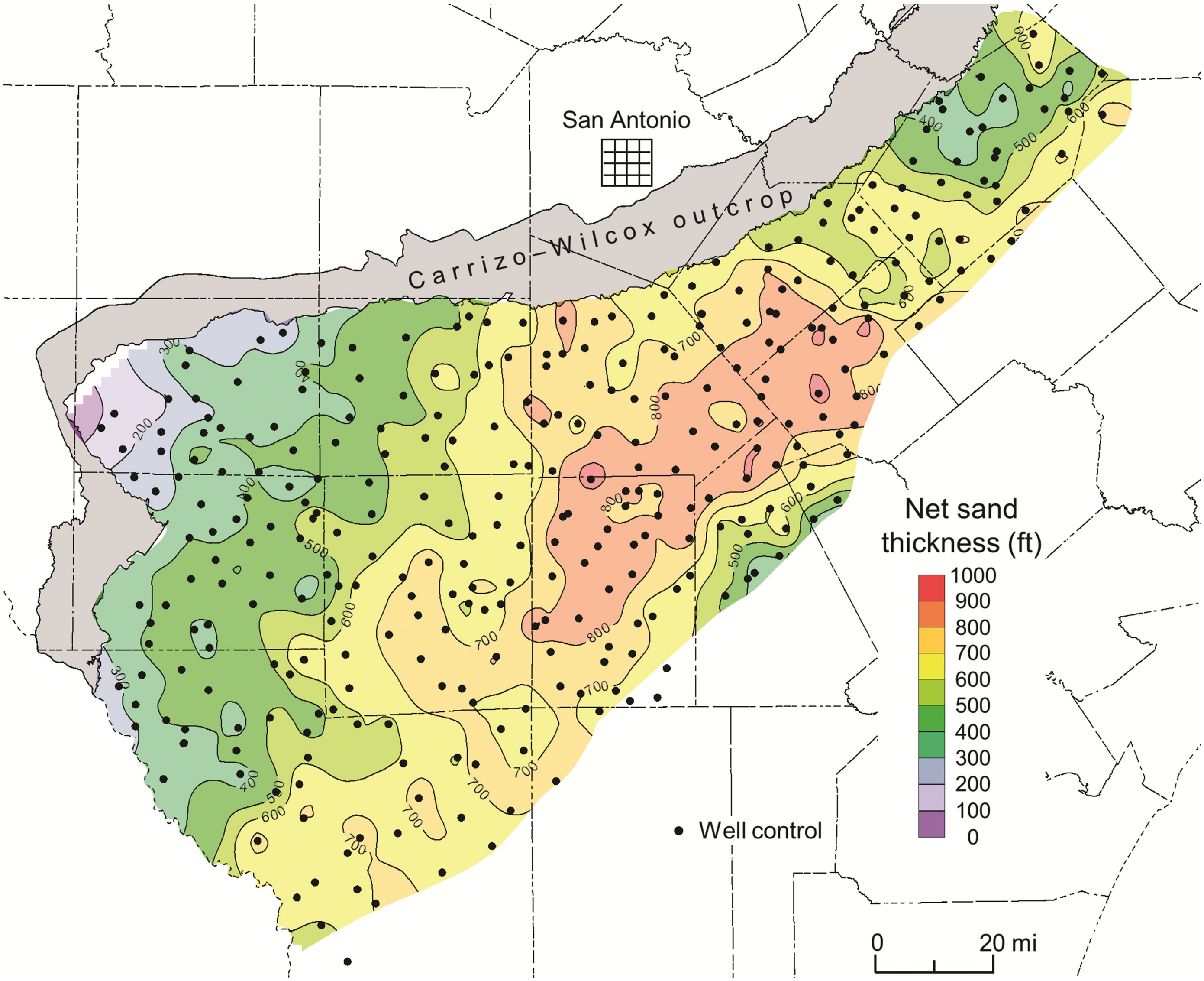


**Figure 7. Carrizo–upper Wilcox net sand thickness. Maximum sand thicknesses in the Carrizo–upper Wilcox form a depocenter south of San Antonio.**

Carrizo–upper Wilcox interval and the lower Wilcox interval. In South Texas, the lower Wilcox interval is the most favorable target for brackish groundwater production without impacting the fresh groundwater resource in the Carrizo–upper Wilcox interval.

The volume of groundwater in place, although not completely producible, provides a preliminary assessment of available resources. Volumes of groundwater in place were determined by calculating pore volumes in sands in the confined section of the Carrizo-Wilcox Aquifer. The outcrop was not included. Fresh groundwater and brackish groundwater volumes were calculated separately. A porosity of 25% was used in pore volume calculations, although this is probably a conservative value. Average porosity for Wilcox sands in the depth range from 4000 to 5000 ft is approximately 25%, but shallower sands are more porous (Loucks et al., 1986; McBride et al., 1991; Dutton and Loucks, 2014). In the study area, the Carrizo–upper Wilcox interval contains approximately 497 million acre-ft of fresh groundwater and 479 million acre-ft of brackish groundwater, and the lower Wilcox interval contains approximately 9 million acre-ft of fresh groundwater and 423 million acre-ft of brackish groundwater (Table 3). The amount of brackish groundwater that could be developed from aquifer storage depends on water-level drawdown and storativity in addition to aquifer pore volume. Assuming 300 ft of water-level drawdown and a storativity of $5 \times 10^{-4}$, estimated confined availability is approximately 0.1% of the volume in place (LBG-Guyton Associates, 2003). Using this relationship there is approximately 423,000 acre-ft of producible brackish groundwater in hydraulically separated sands in the lower Wilcox confined area (approximately 7800 mi$^2$) in South Texas.

## DISCUSSION

The empirical $R_0$/TDS method is a quick and effective way to map regional resources of fresh and brackish groundwater in some aquifers. Cutoff values of $R_0$ can be determined that distinguish broad categories of groundwater salinity: fresh, slightly saline, moderately saline, and very saline. Where TDS data are scarce, the computational $R_w$ method can be used to calculate $R_0$ cutoff values independently. Although the correlation between TDS and $R_0$ is commonly fair to good ($R^2 > 0.7$), other parameters significantly affecting $R_0$ are hydrochemistry, porosity, lithology, grain size, diagenesis, temperature, pressure, and borehole conditions. Variations in well logging instrumentation and

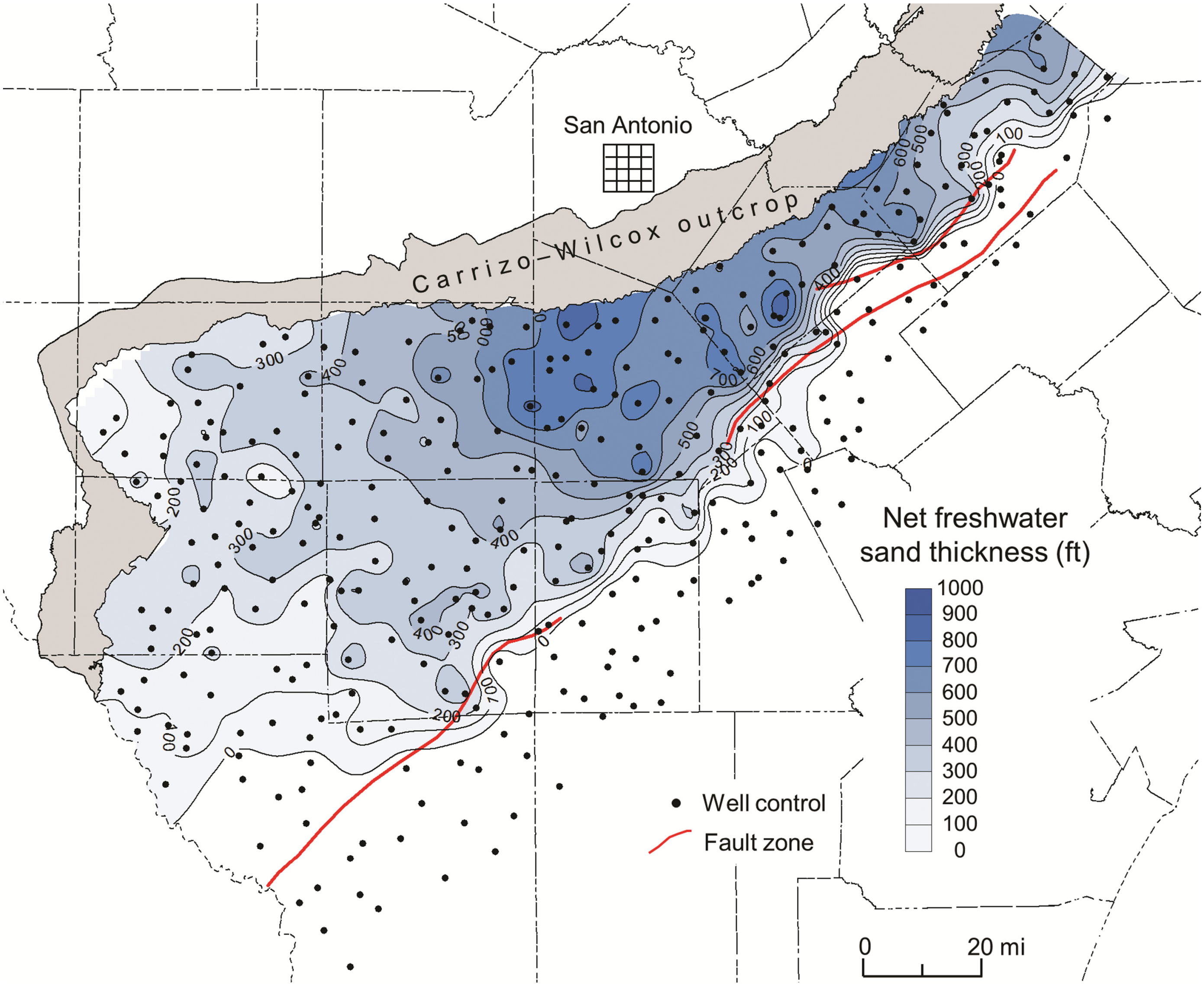


**Figure 8. Net thickness of sand containing fresh groundwater in the Carrizo–upper Wilcox interval. Fault zones modified from Ewing (1990). Groundwater salinities increase abruptly across these regional faults.**

practice, especially between old and new wells, also affect measured $R_0$. Therefore, the methods described in this paper do not precisely calculate TDS from $R_0$. More quantitative methods are available for calculating TDS from electric logs, but they are less amenable to regional reconnaissance. Instead, the $R_0$ and $R_w$ methods provide rough estimates of groundwater in place, which can be used in calculations of producible groundwater. In addition, these methods provide mappable parameters, such as net thickness of brackish groundwater sands, which can be used to locate and rank the resource.

## CONCLUSIONS

The Carrizo–upper Wilcox interval contains most of the fresh groundwater in the South Texas study area (497 million acre-ft in place). Fresh groundwater volumes are largest in the north and northeast and extend to depths greater than 5000 ft locally. The Carrizo–upper Wilcox contains an equally large volume of brackish groundwater (479 million acre-ft in place), which is located directly downdip from the fresh groundwater aquifer. In the southwest (Webb County), fresh groundwater is poorly developed, but large volumes of brackish groundwater are present in the Carrizo–upper Wilcox interval. The lower Wilcox interval contains minor fresh groundwater in South Texas, but its brackish groundwater resource is similar in size to that of the Carrizo–upper Wilcox (423 million acre-ft in place). Similar to the Carrizo–upper Wilcox, lower Wilcox brackish groundwater volumes are largest in the northern and northeastern parts of the study area.

Lower Wilcox brackish groundwater is separated from overlying fresh groundwater in the Carrizo–upper Wilcox by numerous shale beds. Sand/shale interbedding and general shale abundance near the top of the lower Wilcox probably result in hydraulic separation of the fresh and brackish groundwater flow systems. Lower Wilcox brackish groundwater could be produced without significantly affecting overlying fresh groundwater. In contrast, fresh groundwater grades downdip into brackish groundwater within the Carrizo–upper Wilcox, which implies hydraulic communication between fresh and brackish groundwater systems in this interval. Brackish groundwater production in the Carrizo–upper Wilcox could potentially affect the fresh groundwater resource by lowering fluid pressures and enhancing

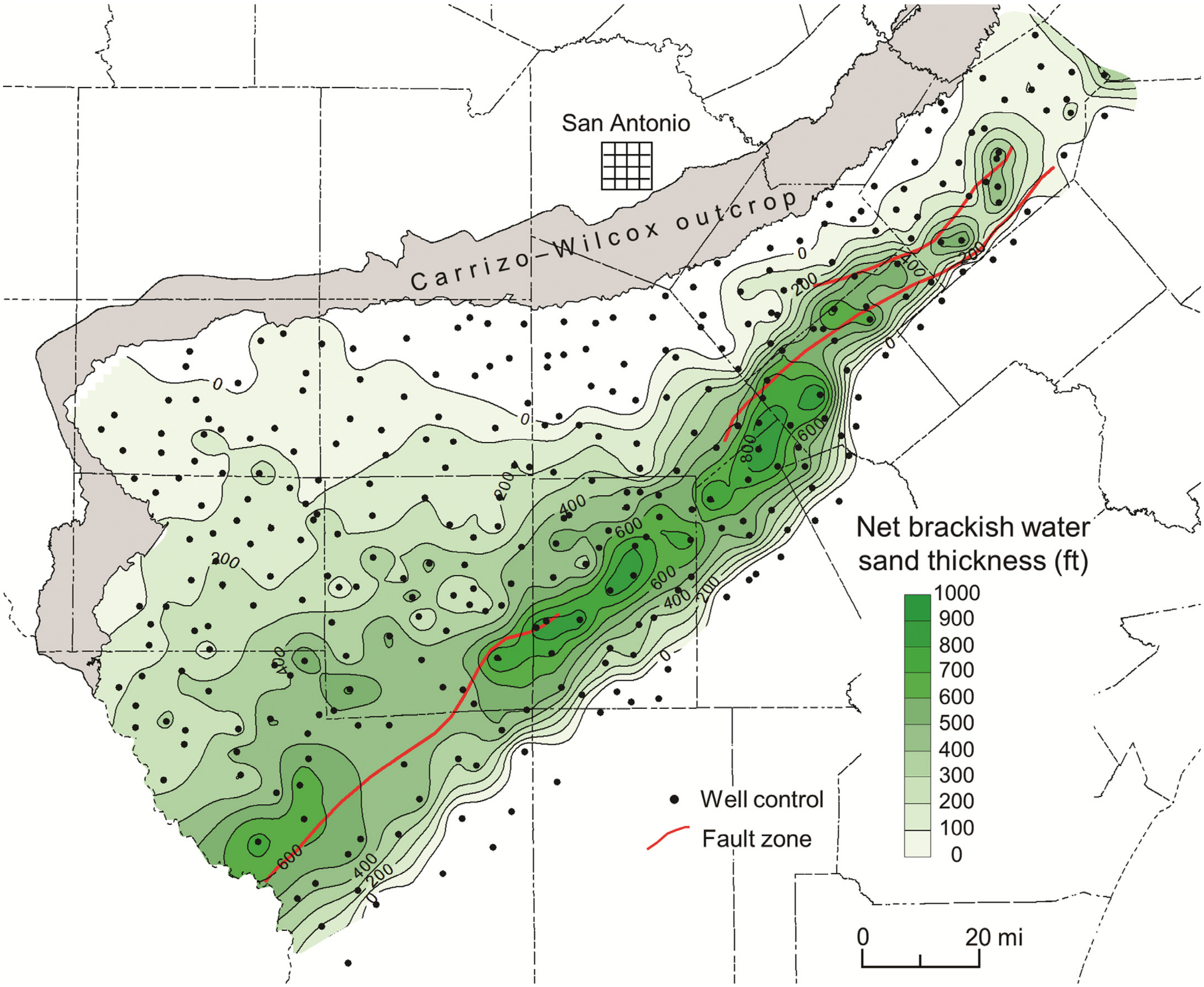


**Figure 9. Net thickness of sand containing brackish groundwater in the Carrizo–upper Wilcox interval. Fault zones modified from Ewing (1990). Thick sands and increasing groundwater salinities coincide to form strike-aligned trends of maximum brackish groundwater.**

mixing. In the South Texas Carrizo-Wilcox Aquifer, fresh groundwater is heavily produced primarily for agriculture, whereas brackish groundwater is relatively undeveloped. Therefore, the lower Wilcox interval is the most favorable target for brackish groundwater production without impacting the fresh groundwater resource. Lower Wilcox brackish groundwater is an important resource for oil field operations (hydraulic fracturing) and for desalination.

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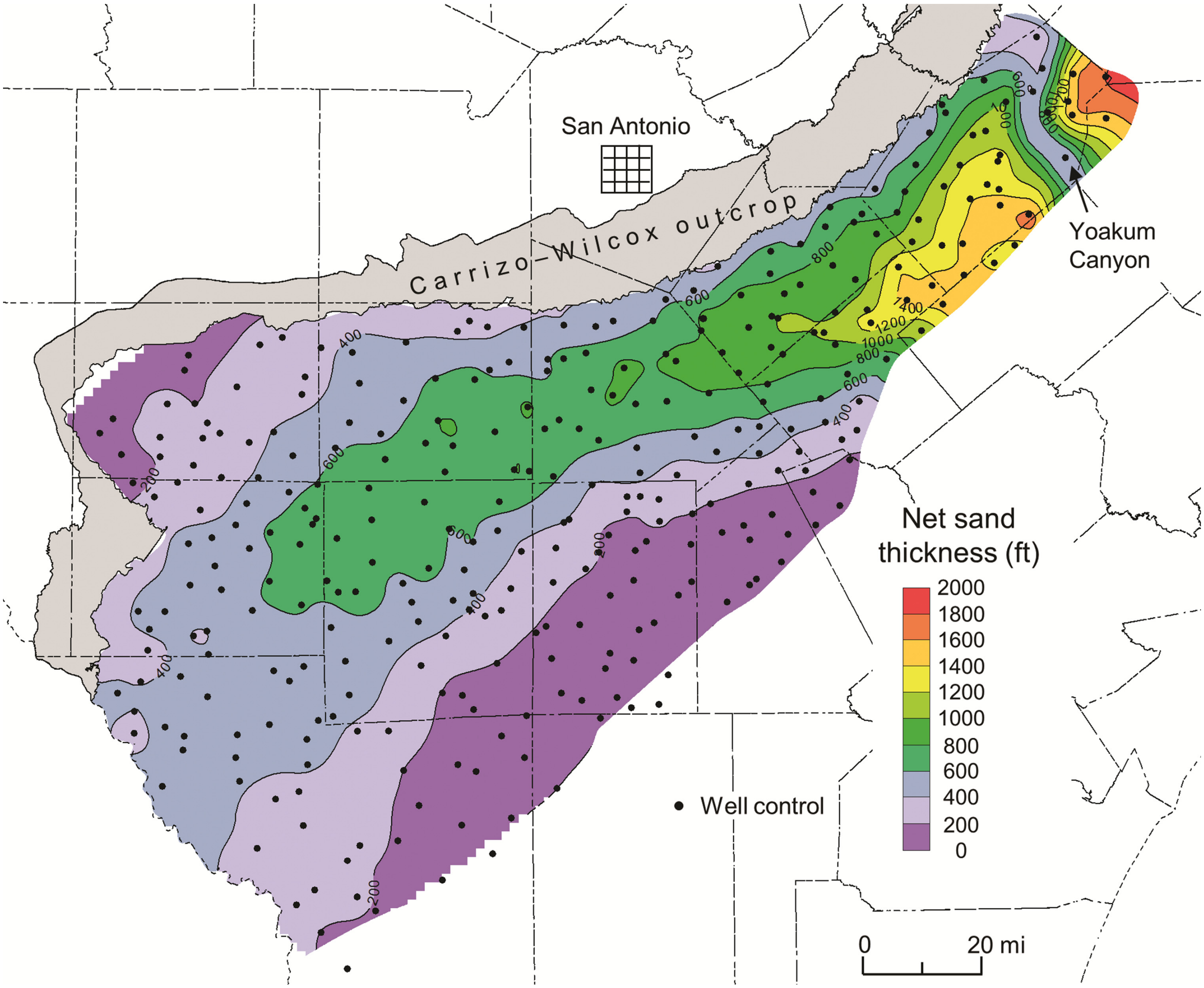


**Figure 10. Lower Wilcox net sand thickness. Maximum sand thicknesses in the lower Wilcox are located in the northeastern part of the study area. The shale-filled Yoakum Canyon erosionally truncates lower Wilcox sands.**

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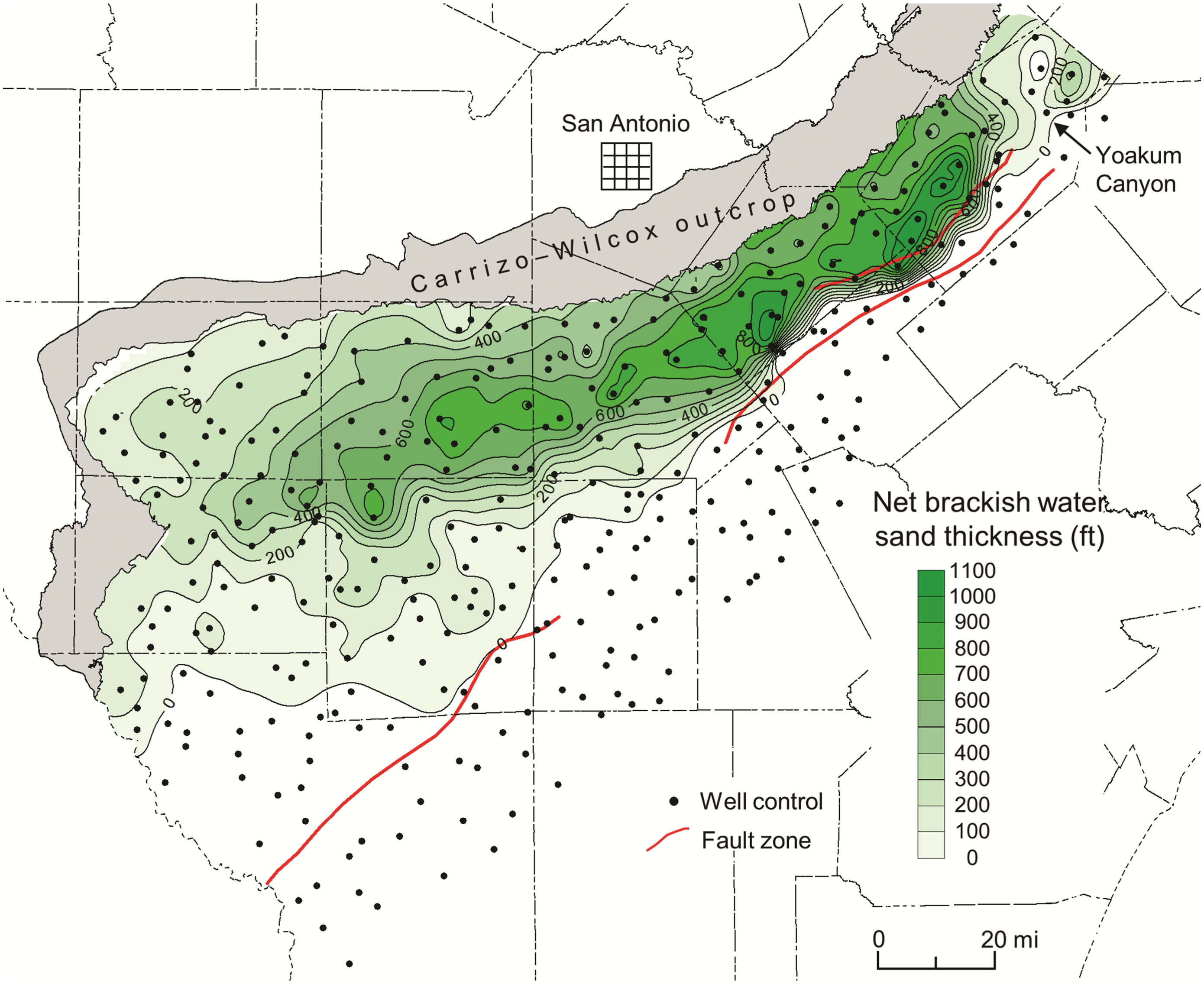


**Figure 11. Net thickness of sand containing brackish groundwater in the lower Wilcox interval. Fault zones modified from Ewing (1990). In the lower Wilcox, groundwater salinity increases in the northeastern region are fault related, whereas in the southwestern region, high groundwater salinities are related to poor sand development and low recharge.**

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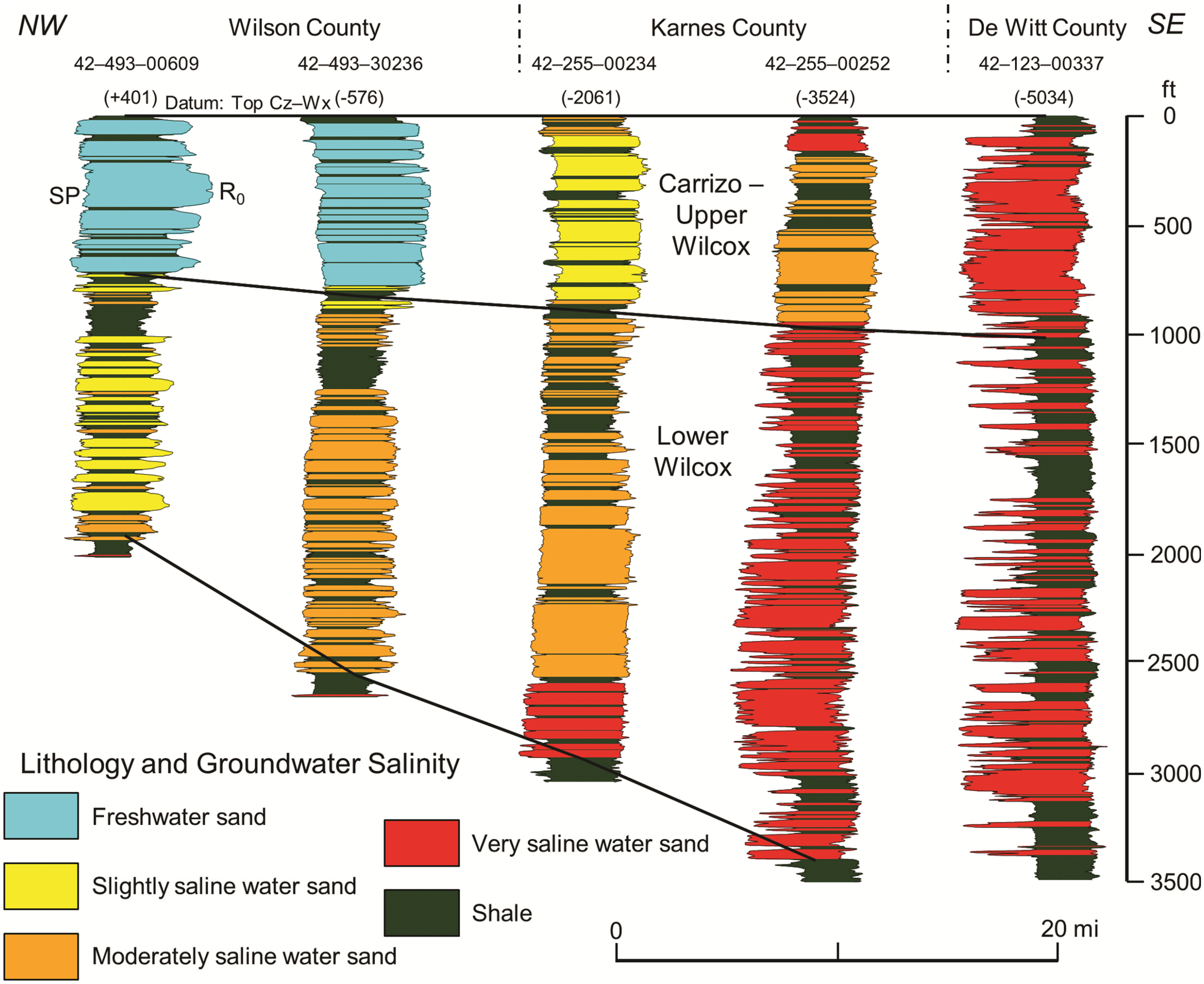


**Figure 12. Stratigraphic cross-section 1 showing lithologies and groundwater salinities. See Figure 1 for location. Well API numbers are shown at top. SP increases and resistivity decreases with increasing groundwater salinity.**

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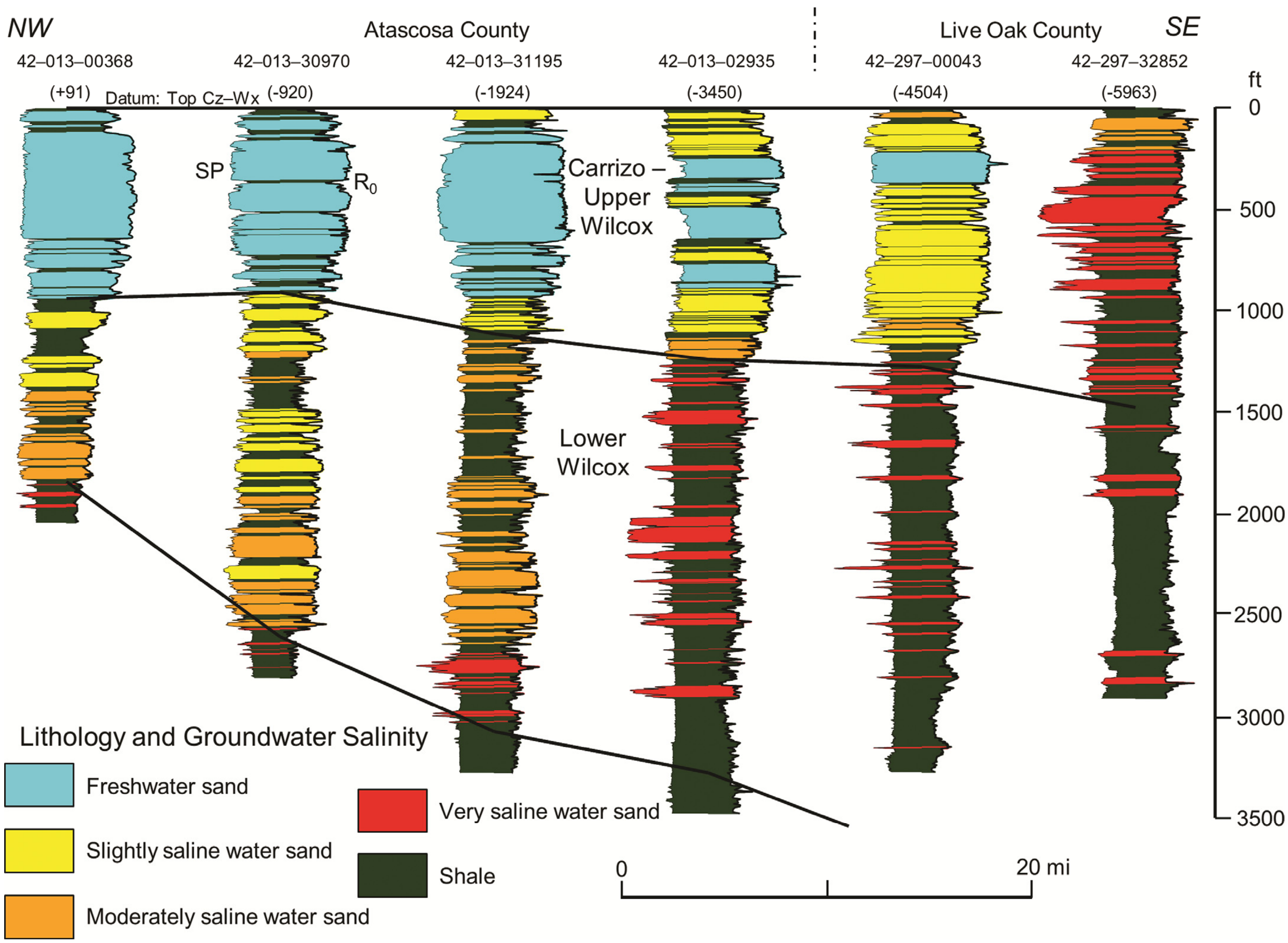


**Figure 13. Stratigraphic cross-section 2 showing lithologies and groundwater salinities. See Figure 1 for location. Well API numbers are shown at top. In northern Live Oak County, low groundwater salinities extend as deep as 5000 ft before increasing abruptly.**

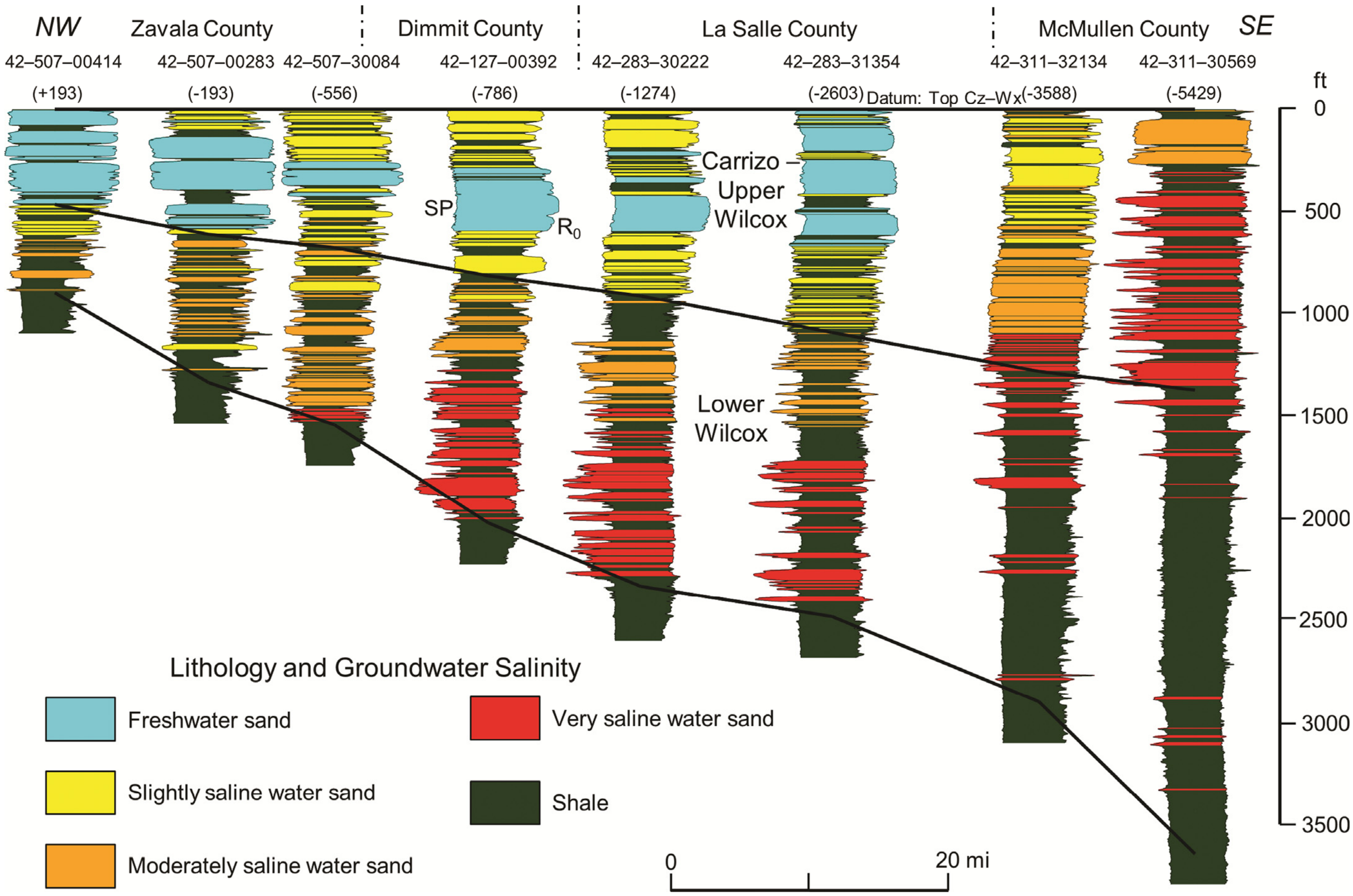


**Figure 14. Stratigraphic cross-section 3 showing lithologies and groundwater salinities. See Figure 1 for location. Well API numbers are shown at top. Massive sands in the Carrizo–upper Wilcox form the most important freshwater aquifer in the study area.**

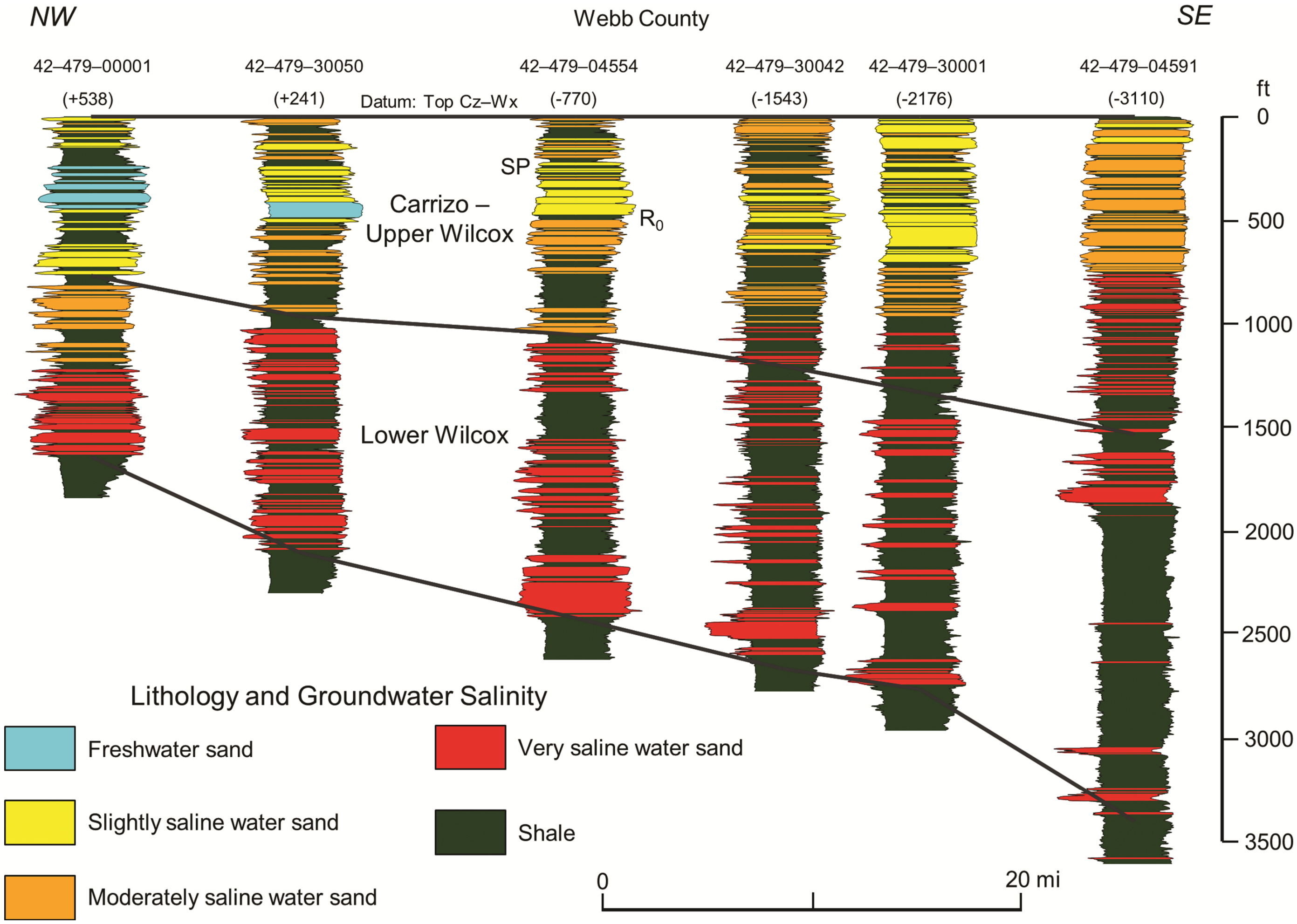


**Figure 15. Stratigraphic cross-section 4 showing lithologies and groundwater salinities. See Figure 1 for location. Well API numbers are shown at top. Sands are thinner and shales are thicker here in the southwest relative to the rest of the study area. Freshwater groundwater is limited to updip areas.**

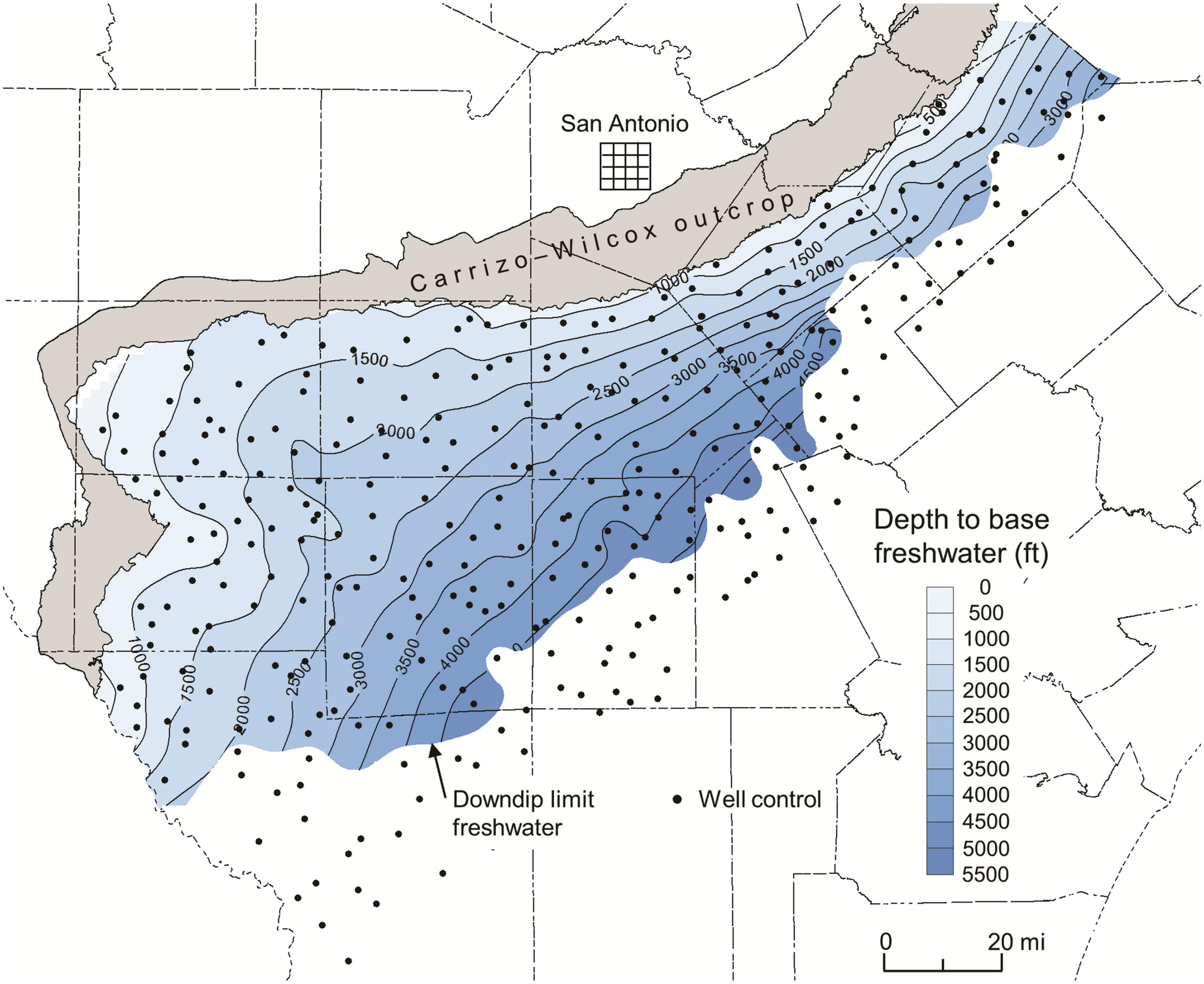


**Figure 16. Depth from surface to base of fresh groundwater in the Carrizo-Wilcox Aquifer. Almost all fresh groundwater is in the Carrizo–upper Wilcox interval.**

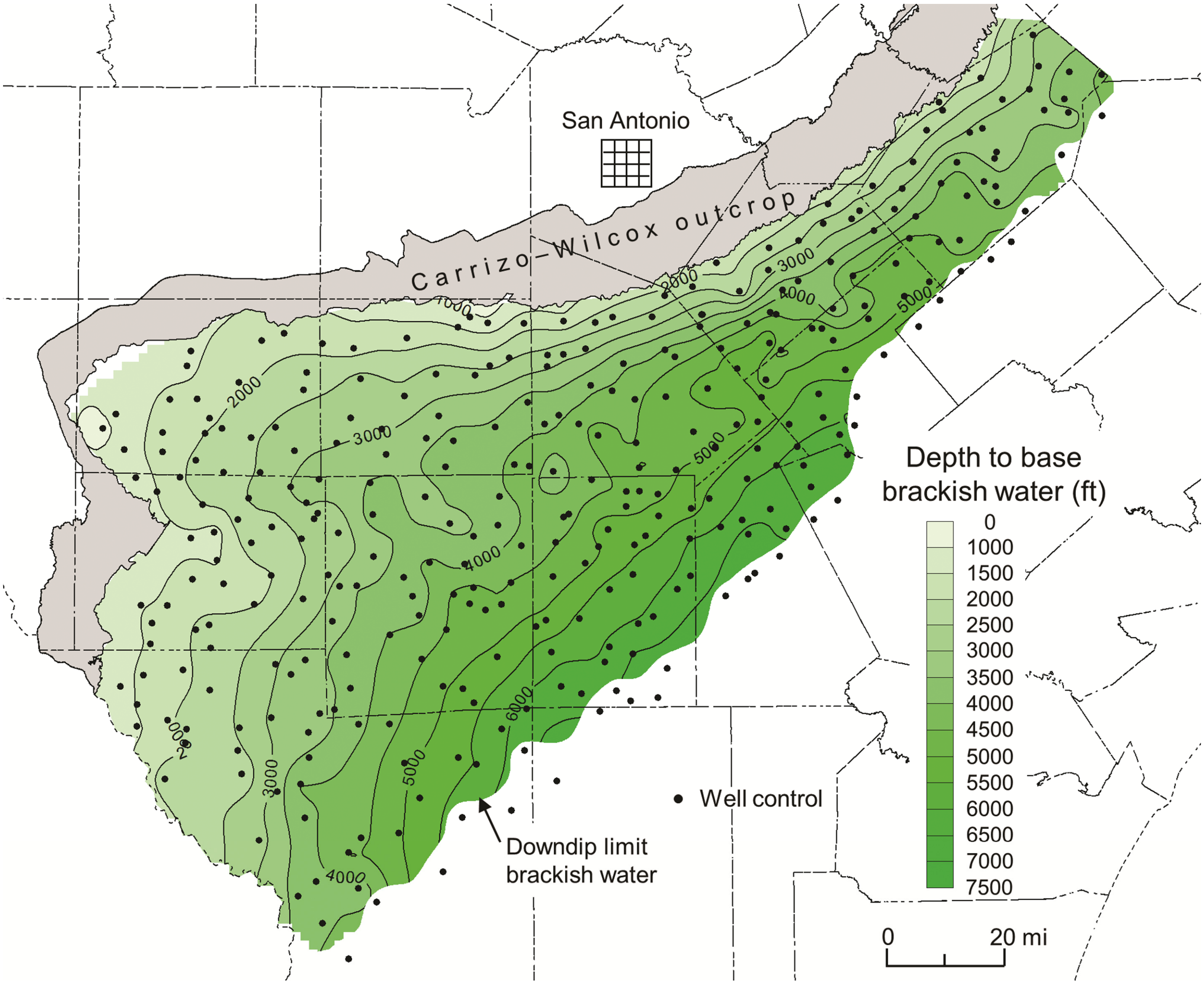


**Figure 17. Depth from surface to base of brackish groundwater in the Carrizo-Wilcox Aquifer. Base of brackish groundwater is in the lower Wilcox interval in updip areas but is in the Carrizo–upper Wilcox interval in downdip areas (Figs. 12–15).**

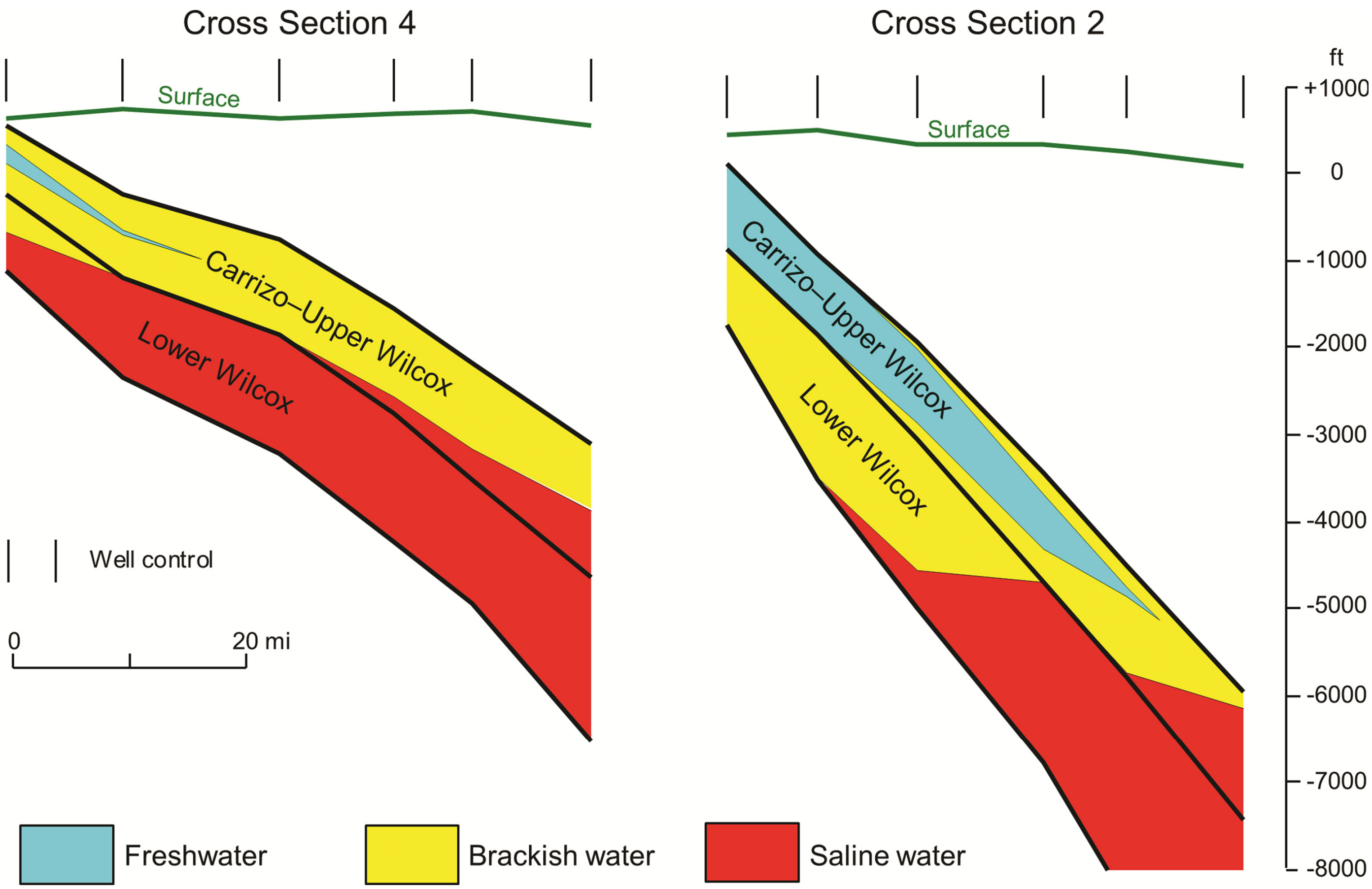


**Figure 18. Schematic structural cross-sections 2 and 4 showing relationship of groundwater salinity to depth in the Carrizo-Wilcox Aquifer. These are the same section lines as shown in Figures 13 and 15.**

**Table 3. Volumes of fresh and brackish groundwater in place* in the confined section of the Carrizo-Wilcox Aquifer in South Texas.**

| County | Fresh Groundwater ($10^6$ acre-ft) | | Brackish Groundwater ($10^6$ acre-ft) | |
|---|---|---|---|---|
| | Carrizo–upper Wilcox | Lower Wilcox | Carrizo–upper Wilcox | Lower Wilcox |
| Atascosa | 109 | 0.1 | 25 | 81 |
| Bee | 0 | 0 | 4 | 0 |
| Dimmit | 42 | 0 | 30 | 32 |
| Duval | 0 | 0 | 1 | 0 |
| Frio | 86 | 4 | 7 | 90 |
| Gonzales | 47 | 1 | 21 | 59 |
| Karnes | 3 | 0 | 38 | 5 |
| La Salle | 69 | 0 | 84 | 37 |
| Live Oak | 1 | 0 | 31 | 0 |
| McMullen | 25 | 0 | 83 | 2 |
| Webb | 14 | 0 | 136 | 3 |
| Wilson | 59 | 0.1 | 12 | 75 |
| Zavala | 41 | 4 | 7 | 38 |
| Total | 497 | 9 | 479 | 423 |

***based on 25% porosity (sand volume × 0.25 = pore volume)**

## APPENDIX

## Well Data Used to Develop $R_0$/TDS Regressions

| County | Petroleum Well API No. | Water Well State Well No. | Elevation Screened Interval[1] (ft) | Total Dissolved Solids (mg/L) | Resistivity ($R_0$) (ohm-m) | Distance between Wells (ft) | Interval[2] | Source[3] |
|---|---|---|---|---|---|---|---|---|
| Atascosa | 4201300363 | 6859801 | -148 | 195 | 100 | 2831 | CZUWX | TWDB |
| Atascosa | 4201300368 | 6860724 | -70 | 239 | 120 | 1561 | CZUWX | TWDB |
| Atascosa | 4201300617 | 6861207 | -295 | 164 | 180 | 2742 | CZUWX | TWDB |
| Atascosa | 4201300767 | 7815805 | -3890 | 587 | 25 | 7237 | CZUWX | TWDB |
| Atascosa | 4201300806 | 7814701 | -3270 | 2010 | 16 | 8142 | CZUWX | TWDB |
| Atascosa | 4201300831 | 7814201 | -2965 | 494 | 55 | 6561 | CZUWX | TWDB |
| Atascosa | 4201301001 | 7805605 | -1810 | 321 | 45 | 6766 | CZUWX | TWDB |
| Atascosa | 4201301319 | 7803202 | -946 | 293 | 75 | 9280 | CZUWX | TWDB |
| Atascosa | 4201301929 | 7812201 | -1685 | 381 | 70 | 4275 | CZUWX | TWDB |
| Atascosa | 4201302348 | 7811402 | -1872 | 341 | 75 | 532 | CZUWX | TWDB |
| Atascosa | 4201302496 | 7802301 | -622 | 369 | 75 | 4866 | CZUWX | TWDB |
| Atascosa | 4201302606 | 7802903 | -925 | 363 | 75 | 3194 | CZUWX | TWDB |
| Atascosa | 4201302871 | 7818204 | -1363 | 296 | 60 | 17927 | CZUWX | TWDB |
| Atascosa | 4201302882 | 7820101 | -2330 | 345 | 70 | 6822 | CZUWX | TWDB |
| Atascosa | 4201302887 | 7821106 | -2670 | 341 | 60 | 7183 | CZUWX | TWDB |
| Atascosa | 4201302908 | 7821801 | -3222 | 702 | 40 | 17358 | CZUWX | TWDB |
| Atascosa | 4201302935 | 7822201 | -3787 | 595 | 35 | 10960 | CZUWX | TWDB |
| Atascosa | 4201303114 | 7803405 | -836 | 334 | 80 | 6840 | CZUWX | TWDB |
| Atascosa | 4201330868 | 7805211 | -1557 | 333 | 40 | 3846 | CZUWX | TWDB |
| Atascosa | 4201330970 | 7804502 | -1160 | 337 | 65 | 3027 | CZUWX | TWDB |
| Atascosa | 4201331768 | 6860821 | -380 | 172 | 200 | 3085 | CZUWX | TWDB |
| Atascosa | 4201332196 | 7821903 | -3501 | 546 | 25 | 4642 | CZUWX | TWDB |
| Atascosa | 4201332467 | 6861702 | -440 | 196 | 170 | 11578 | CZUWX | TWDB |
| Atascosa | 4201333956 | 7812302 | -1785 | 367 | 100 | 8975 | CZUWX | TWDB |
| Atascosa | 4201334190 | 7823204 | -3837 | 777 | 25 | 8305 | CZUWX | TWDB |
| Atascosa | 4201334208 | 7803901 | -1311 | 340 | 50 | 5727 | CZUWX | TWDB |
| Dimmit | 4212700076 | 7717803 | 190 | 520 | 76 | 6118 | CZUWX | TWDB |
| Dimmit | 4212700346 | 7726615 | -218 | 382 | 74 | 4924 | CZUWX | TWDB |
| Dimmit | 4212700377 | 7728502 | -820 | 617 | 52 | 16721 | CZUWX | TWDB |
| Dimmit | 4212700385 | 7729201 | -1200 | 1013 | 40 | 8699 | CZUWX | TWDB |
| Dimmit | 4212700386 | 7729602 | -1489 | 495 | 53 | 11447 | CZUWX | TWDB |
| Dimmit | 4212700392 | 7729901 | -1550 | 546 | 67 | 13919 | CZUWX | TWDB |
| Dimmit | 4212700399 | 7737201 | -1226 | 467 | 71 | 3515 | CZUWX | TWDB |
| Dimmit | 4212700542 | 7734302 | -89 | 404 | 39 | 1980 | CZUWX | TWDB |
| Dimmit | 4212700657 | 7749601 | -128 | 850 | 34 | 12593 | CZUWX | TWDB |
| Dimmit | 4212730220 | 7728601 | -1185 | 473 | 33 | 16609 | CZUWX | TWDB |
| Dimmit | 4212730527 | 7718802 | -621 | 350 | 71 | 1512 | CZUWX | TWDB |
| Dimmit | 4212730642 | 7735801 | -499 | 410 | 46 | 7771 | CZUWX | TWDB |
| Dimmit | 4212730782 | 7736801 | -874 | 551 | 42 | 6951 | CZUWX | TWDB |
| Dimmit | 4212730949 | 7742801 | -761 | 683 | 45 | 17650 | CZUWX | TWDB |
| Dimmit | 4212731729 | 7728702 | -813 | 434 | 63 | 10558 | CZUWX | TWDB |
| Dimmit | 4212732067 | 7735701 | -411 | 745 | 38 | 10526 | CZUWX | TWDB |
| Frio | 4216300025 | 7708201 | -206 | 494 | 57 | 18467 | CZUWX | TWDB |
| Frio | 4216300039 | 6964611 | 212 | 551 | 61 | 12836 | CZUWX | TWDB |
| Frio | 4216300092 | 6857806 | 120 | 584 | 49 | 5850 | CZUWX | TWDB |
| Frio | 4216300161 | 6858506 | -25 | 375 | 76 | 5489 | CZUWX | TWDB |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Frio | 4216300529 | 7802402 | -863 | 394 | 78 | 7661 | CZUWX | TWDB |
| Frio | 4216300706 | 7801801 | -912 | 329 | 62 | 9101 | CZUWX | TWDB |
| Frio | 4216300729 | 7801501 | -674 | 436 | 63 | 8979 | CZUWX | TWDB |
| Frio | 4216300816 | 7809801 | -1219 | 315 | 69 | 9102 | CZUWX | TWDB |
| Frio | 4216300849 | 7810102 | -1179 | 348 | 51 | 12185 | CZUWX | TWDB |
| Frio | 4216301158 | 7708809 | -850 | 394 | 79 | 523 | CZUWX | TWDB |
| Frio | 4216301360 | 7716502 | -1178 | 408 | 71 | 5192 | CZUWX | TWDB |
| Frio | 4216301407 | 7715301 | -797 | 413 | 63 | 8336 | CZUWX | TWDB |
| Frio | 4216301455 | 7714805 | -1133 | 381 | 67 | 14136 | CZUWX | TWDB |
| Frio | 4216301662 | 7706205 | -455 | 761 | 39 | 5390 | CZUWX | TWDB |
| Frio | 4216330005 | 6963902 | -130 | 536 | 41 | 12154 | CZUWX | TWDB |
| Frio | 4216331938 | 7724101 | -1496 | 302 | 74 | 6884 | CZUWX | TWDB |
| Gonzales | 4217700152 | 6721705 | -509 | 317 | 69 | 5202 | CZUWX | TWDB |
| Gonzales | 4217700219 | 6728403 | 128 | 155 | 300 | 4400 | CZUWX | TWDB |
| Gonzales | 4217700246 | 6737203 | -1895 | 2027 | 19 | 17544 | CZUWX | TWDB |
| Gonzales | 4217700324 | 6734904 | -200 | 115 | 164 | 13161 | CZUWX | TWDB |
| Gonzales | 4217700371 | 6736803 | -1490 | 822 | 60 | 12902 | CZUWX | TWDB |
| Gonzales | 4217700413 | 6743806 | -1615 | 239 | 160 | 7984 | CZUWX | TWDB |
| Gonzales | 4217700429 | 6751102 | -1905 | 731 | 61 | 10002 | CZUWX | TWDB |
| Gonzales | 4217700481 | 6727903 | -255 | 240 | 110 | 3135 | CZUWX | TWDB |
| Gonzales | 4217700602 | 6728902 | -502 | 552 | 47 | 4775 | CZUWX | TWDB |
| Gonzales | 4217700615 | 6728406 | 33 | 284 | 112 | 4120 | CZUWX | TWDB |
| Gonzales | 4217730230 | 6737203 | -1895 | 2027 | 13 | 11449 | CZUWX | TWDB |
| Gonzales | 4217731385 | 6745203 | -2570 | 2844 | 12 | 11599 | CZUWX | TWDB |
| Gonzales | 4217731801 | 6744802 | -2230 | 1356 | 15 | 10029 | CZUWX | TWDB |
| Gonzales | 4217732114 | 6730507 | -2590 | 554 | 50 | 3998 | CZUWX | TWDB |
| Karnes | 4225500060 | same well | -4547 | 9756 | 3 | 0 | LWX | USGS |
| Karnes | 4225500061 | same well | -5698 | 31579 | 2 | 0 | LWX | USGS |
| Karnes | 4225500064 | same well | -4599 | 6924 | 4 | 0 | CZUWX | USGS |
| Karnes | 4225500234 | 6750803 | -2275 | 1500 | 13 | 20780 | CZUWX | TWDB |
| Karnes | 4225500622 | 7816601 | -4853 | 1146 | 15 | 16661 | CZUWX | TWDB |
| Karnes | 4225500668 | 7901202 | -4160 | 2255 | 9 | 7456 | CZUWX | TWDB |
| Karnes | 4225500674 | 7808304 | -4386 | 1488 | 14 | 18750 | CZUWX | TWDB |
| Karnes | 4225500795 | 7807901 | -3336 | 629 | 15 | 7459 | CZUWX | TWDB |
| Karnes | 4225500824 | 7815301 | -4325 | 600 | 16 | 3141 | CZUWX | TWDB |
| Karnes | 4225530272 | 7816601 | -4853 | 1146 | 9 | 15498 | CZUWX | TWDB |
| La Salle | 4228300015 | 7722903 | -1482 | 404 | 64 | 5916 | CZUWX | TWDB |
| La Salle | 4228300016 | 7730602 | -1688 | 439 | 53 | 12748 | CZUWX | TWDB |
| La Salle | 4228300038 | 7825601 | -2622 | 524 | 54 | 14400 | CZUWX | TWDB |
| La Salle | 4228300060 | 7740305 | -2338 | 617 | 34 | 13438 | CZUWX | TWDB |
| La Salle | 4228300094 | 7834205 | -3258 | 603 | 28 | 8822 | CZUWX | TWDB |
| La Salle | 4228300124 | 7841302 | -3182 | 805 | 33 | 19765 | CZUWX | TWDB |
| La Salle | 4228300196 | same well | -5120 | 25691 | 4 | 0 | LWX | USGS |
| La Salle | 4228300222 | 7841101 | -2853 | 612 | 37 | 4844 | CZUWX | TWDB |
| La Salle | 4228300309 | 7747901 | -2719 | 833 | 38 | 11911 | CZUWX | TWDB |
| La Salle | 4228300688 | 7745602 | -1688 | 557 | 42 | 17862 | CZUWX | TWDB |
| La Salle | 4228330178 | 7825901 | -2719 | 535 | 44 | 5823 | CZUWX | TWDB |
| La Salle | 4228330222 | 7739402 | -2035 | 687 | 43 | 3112 | CZUWX | TWDB |
| La Salle | 4228330229 | same well | -4392 | 17400 | 3 | 0 | LWX | CCGS |
| La Salle | 4228330304 | 7738102 | -1621 | 471 | 40 | 4938 | CZUWX | TWDB |
| La Salle | 4228331029 | same well | -5542 | 26100 | 3 | 0 | LWX | CCGS |
| La Salle | 4228331049 | 7740305 | -2338 | 1652 | 18 | 17861 | CZUWX | TWDB |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| La Salle | 4228331147 | 7849802 | -3870 | 1336 | 12 | 18025 | CZUWX | TWDB |
| La Salle | 4228331354 | 7748301 | -3063 | 591 | 35 | 7824 | CZUWX | TWDB |
| La Salle | 4228332209 | 7748801 | -2955 | 940 | 24 | 15949 | CZUWX | TWDB |
| Live Oak | 4229700043 | 7823502 | -4484 | 1012 | 23 | 12751 | CZUWX | TWDB |
| Live Oak | 4229730935 | same well | -6545 | 22675 | 2 | 0 | CZUWX | CCGS |
| McMullen | 4231100007 | 7828101 | -3685 | 558 | 36 | 18299 | CZUWX | TWDB |
| McMullen | 4231100022 | 7828602 | -4272 | 633 | 26 | 8675 | CZUWX | TWDB |
| McMullen | 4231100035 | same well | -4414 | 10312 | 5 | 0 | LWX | USGS |
| McMullen | 4231100035 | same well | -4854 | 24743 | 2.5 | 0 | LWX | USGS |
| McMullen | 4231100076 | 7828603 | -3371 | 659 | 25 | 4184 | CZUWX | TWDB |
| McMullen | 4231100156 | 7827503 | -3160 | 613 | 30 | 10752 | CZUWX | TWDB |
| McMullen | 4231100167 | 7821801 | -3222 | 702 | 22 | 17460 | CZUWX | TWDB |
| McMullen | 4231100677 | 7838101 | -5172 | 1034 | 18 | 86 | CZUWX | TWDB |
| McMullen | 4231101245 | same well | -5567 | 12228 | 3 | 0 | LWX | USGS |
| McMullen | 4231101428 | 7842902 | -3818 | 1430 | 17 | 8462 | CZUWX | TWDB |
| McMullen | 4231101532 | 7851201 | -4800 | 2007 | 15 | 19012 | CZUWX | TWDB |
| McMullen | 4231101805 | same well | -6795 | 22721 | 5 | 0 | CZUWX | CCGS |
| McMullen | 4231132690 | 7837103 | -4855 | 1561 | 16 | 11804 | CZUWX | TWDB |
| McMullen | 4231134159 | 7827503 | -3160 | 613 | 25 | 5128 | CZUWX | TWDB |
| Webb | 4247900630 | same well | -5573 | 12943 | 7 | 0 | CZUWX | USGS |
| Webb | 4247900630 | same well | -5112 | 15254 | 6 | 0 | CZUWX | USGS |
| Webb | 4247904554 | 8504401 | -1380 | 1047 | 22 | 7839 | CZUWX | TWDB |
| Webb | 4247930001 | 8521501 | -2659 | 2274 | 18 | 32470 | CZUWX | TWDB |
| Webb | 4247930050 | 8501301 | -820 | 1157 | 37 | 25636 | CZUWX | TWDB |
| Webb | 4247930166 | 7752801 | -1670 | 724 | 43 | 8847 | CZUWX | TWDB |
| Webb | 4247930248 | 7759401 | -1080 | 792 | 47 | 21353 | CZUWX | TWDB |
| Webb | 4247930373 | same well | -3489 | 10656 | 7 | 0 | LWX | CCGS |
| Webb | 4247930464 | 8519903 | -1486 | 1916 | 14 | 29230 | CZUWX | TWDB |
| Webb | 4247930680 | 8503905 | -1305 | 1416 | 15 | 4852 | CZUWX | TWDB |
| Webb | 4247931169 | same well | -2661 | 3050 | 20 | 0 | CZUWX | Estepp (1998) |
| Webb | 4247932519 | 7757501 | -130 | 949 | 47 | 5992 | CZUWX | TWDB |
| Webb | 4247932859 | 7749601 | -128 | 850 | 68 | 16719 | CZUWX | TWDB |
| Webb | 4247932947 | 7759401 | -1080 | 792 | 45 | 15336 | CZUWX | TWDB |
| Webb | 4247934159 | 7763201 | -2742 | 1875 | 22 | 29420 | CZUWX | TWDB |
| Webb | 4247934601 | 8529202 | -2705 | 3055 | 14 | 9749 | CZUWX | TWDB |
| Wilson | 4249300609 | 6741102 | 318 | 82 | 227 | 9089 | CZUWX | TWDB |
| Wilson | 4249300768 | 6741501 | -54 | 325 | 118 | 15790 | CZUWX | TWDB |
| Wilson | 4249301054 | 6749401 | -542 | 834 | 27 | 16854 | CZUWX | TWDB |
| Wilson | 4249301239 | 6856409 | -531 | 475 | 65 | 11369 | CZUWX | TWDB |
| Wilson | 4249301419 | 6856307 | -424 | 778 | 43 | 1880 | CZUWX | TWDB |
| Wilson | 4249301501 | 6863208 | -1190 | 338 | 61 | 8332 | CZUWX | TWDB |
| Wilson | 4249301541 | 6864103 | -756 | 464 | 32 | 6044 | CZUWX | TWDB |
| Wilson | 4249301551 | 6864401 | -1612 | 526 | 39 | 12130 | CZUWX | TWDB |
| Wilson | 4249301641 | 6862802 | -1158 | 333 | 30 | 8930 | CZUWX | TWDB |
| Wilson | 4249301709 | 6862802 | -1158 | 333 | 59 | 9134 | CZUWX | TWDB |
| Wilson | 4249301740 | 6854703 | -332 | 191 | 120 | 3795 | CZUWX | TWDB |
| Wilson | 4249301742 | 7806302 | -1607 | 440 | 52 | 514 | CZUWX | TWDB |
| Wilson | 4249301747 | 7807501 | -3010 | 449 | 49 | 15266 | CZUWX | TWDB |
| Wilson | 4249330060 | 6856801 | -678 | 638 | 28 | 16547 | CZUWX | TWDB |
| Wilson | 4249330236 | 6742801 | -702 | 286 | 42 | 7320 | CZUWX | TWDB |
| Wilson | 4249330683 | 6862802 | -1158 | 333 | 60 | 4907 | CZUWX | TWDB |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Wilson | 4249330907 | 6750701 | -1883 | 3026 | 13 | 12992 | CZUWX | TWDB |
| Wilson | 4249331431 | 6742801 | -702 | 286 | 84 | 17573 | CZUWX | TWDB |
| Wilson | 4249331652 | 6741702 | -240 | 147 | 78 | 4330 | CZUWX | TWDB |
| Wilson | 4249332275 | 6863801 | -1789 | 399 | 67 | 2912 | CZUWX | TWDB |
| Zavala | 4250700122 | 7713202 | -761 | 355 | 77 | 13333 | CZUWX | TWDB |
| Zavala | 4250700193 | 7704202 | 201 | 408 | 80 | 2244 | CZUWX | TWDB |
| Zavala | 4250700283 | 7711707 | -516 | 426 | 50 | 14826 | CZUWX | TWDB |
| Zavala | 4250700379 | 7711703 | -503 | 424 | 79 | 688 | CZUWX | TWDB |
| Zavala | 4250700414 | 7702606 | -132 | 423 | 50 | 10062 | CZUWX | TWDB |
| Zavala | 4250700463 | 7702202 | 430 | 379 | 60 | 12400 | CZUWX | TWDB |
| Zavala | 4250700588 | 7717107 | -19 | 340 | 93 | 3993 | CZUWX | TWDB |
| Zavala | 4250700612 | 7718105 | -394 | 313 | 112 | 9457 | CZUWX | TWDB |
| Zavala | 4250700615 | 7718406 | -354 | 308 | 92 | 3170 | CZUWX | TWDB |
| Zavala | 4250700634 | 7718602 | -457 | 521 | 60 | 6032 | CZUWX | TWDB |
| Zavala | 4250730084 | 7720801 | -1442 | 2010 | 12 | 8331 | CZUWX | TWDB |
| Zavala | 4250730114 | 7719803 | -731 | 412 | 60 | 4965 | CZUWX | TWDB |
| Zavala | 4250731618 | 7710604 | -276 | 467 | 62 | 6005 | CZUWX | TWDB |

**[1]Relative to mean sea level**

**[2]Stratigraphic interval:  CZUWX, Carrizo–upper Wilcox; and (LWX) Lower Wilcox**

**[3]Source of TDS data:  TWDB, Texas Water Development Board; USGS, U.S. Geological Survey (Taylor, 1975); and CCGS, Corpus Christi Geological Society (Gaither, 1986)**