EDWARDS UNDERGROUND
WATER DISTRICT

Report 92-03

Using Geophysical Logs in the Edwards Aquifer to Estimate Water Quality Along the Freshwater/Saline-Water Interface (Uvalde to San Antonio, Texas)

USING GEOPHYSICAL LOGS IN THE EDWARDS AQUIFER TO ESTIMATE WATER QUALITY ALONG THE FRESHWATER/SALINE-WATER INTERFACE

(Uvalde, Texas to San Antonio, Texas)

Prepared for the

EDWARDS UNDERGROUND WATER DISTRICT

SAN ANTONIO, TEXAS

By

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The freshwater/saline-water interface marks the downdip boundary of the Edwards aquifer in the San Antonio region. It divides the Edwards into the updip freshwater zone containing potable water and the saline-water downdip having a concentration of total dissolved solids greater than 1000 mg/L. These two zones are hydraulically interconnected but the capacity of the aquifer to transmit water in the freshwater zone in much greater than that in the saline zone. As a consequence, most of the meteoric water entering the aquifer moves through the freshwater zone before being discharged, either by pumping or springflow. However, some of the water in the freshwater zone moves into the saline zone and mixes with and dilutes the saline-water. The water enters the saline zone because the hydraulic gradient declines toward the saline zone. The higher heads in the freshwater zone are sustained by recharge from meteoric waters entering the Edwards aquifer in the recharge area which lies at significantly higher elevations.

To obtain information to better understand the exchange of waters across the freshwater/saline-water interface, geophysical logs of oil and gas test holes were collected and analyzed. Fluid conductivities were determined and total dissolved solids were estimated. This information was plotted on base maps and contoured. From these maps interpretations as to the location of the interface can be more accurately estimated where test wells are non-existent.

A diligent and concentrated effort has gone into the preparation of this report. However, all interpretations are opinions based on inferences from electrical or other measurements and other data. The author cannot, and does not guarantee the accuracy or correctness of any interpretations or the reliability of the data supplied from other sources, and shall not be liable or responsible for any loss, costs, damages or expenses incurred or sustained by anyone resulting from any reliance upon any interpretation made by the author.

An attempt has been made to present as much of this report as possible in layman's terms, as requested by Edwards Underground Water District personnel.

USING GEOPHYSICAL LOGS IN THE EDWARDS AQUIFER TO ESTIMATE WATER QUALITY ALONG THE FRESHWATER/SALINE-WATER INTERFACE (Uvalde, Texas to San Antonio, Texas)

by
ALVIN L. SCHULTZ

Abstract

Over one hundred geophysical logs from locations near the freshwater/saline-water interface of the Edwards aquifer between Uvalde and San Antonio, Texas, were acquired and analyzed. In conjunction with these logs, test data from several wells along the interface in San Antonio and to the northeast were used to verify a high correlation between estimated and measured water quality parameters. Geochemical conditions such as specific conductance and dissolved solids in the freshwater/saline-water transition zone in the Edwards aquifer can be interpreted from geophysical logs. Results of the estimated water quality data determined in this study indicate that the freshwater/saline-water interface is irregular, both vertically and horizontally, and extends downdip into Frio County in the area of the Frio-Zavala County line, contrary to the location previously estimated. Concurrently, a similar condition exists west of Devine, Texas, where the estimated position of the freshwater/saline-water interface is again downdip and farther south than has been shown in earlier studies.

Data such as rock color, information indicating lost circulation and/or caverns, and reports of "freshwater" on well tests supplements geophysical log-derived water quality parameter maps in supporting the concept of the occurrence of freshwater between the previous freshwater/saline-water interface and the position of the estimated freshwater/saline-water interface determined by this report.

INTRODUCTION

Qualitative interpretation of geophysical logs is a practical first step toward obtaining a close approximation of water quality and locating the freshwater/saline-water interface in the Edwards aquifer between San Antonio and Uvalde, Texas. A 1000 mg/L (milligrams per liter) dissolved solids contour is defined as the interface between the freshwater and the saline-water zone (Winslow and Kister, 1956) (Figure 1, Plate 1). The freshwater/saline-water interface is reasonably well defined between San Antonio and the Medina County line. Also, actual well sample data is available to help define the interface in Uvalde County, near the city of Uvalde. However, between the Sabinal River in Uvalde County and the eastern boundary of Medina County, documented well tests which have produced water in the 1000 mg/L to 9000 mg/L range (the interface is characterized by a generally rapid increase from 1000 mg/L to approximately 9000 mg/L [Maclay, et al, 1980]) are unavailable or non-existent. Since actual water sample measurements are not available in this area, and test wells necessary to locate and define the transition zone are very expensive, the use of geophysical logs from existing wells becomes a significant indirect method of studying water quality along the freshwater/saline-water interface.

The mapped location of the freshwater/saline-water interface has been changed as additional control has become available. Prior to the drilling of a test well two miles northwest of Devine, Texas in 1973, the interface line was believed to be several miles north of the test site (Holt, 1959). Results from the test well revealed the presence of water containing less than 1000 mg/L total dissolved solids (TDS) (Maclay, et al, 1980). As a result, the position of the freshwater/saline-water interface was relocated near its present position. The current interface (Nalley and Thomas, 1990) (Figure 1, Plate 1)

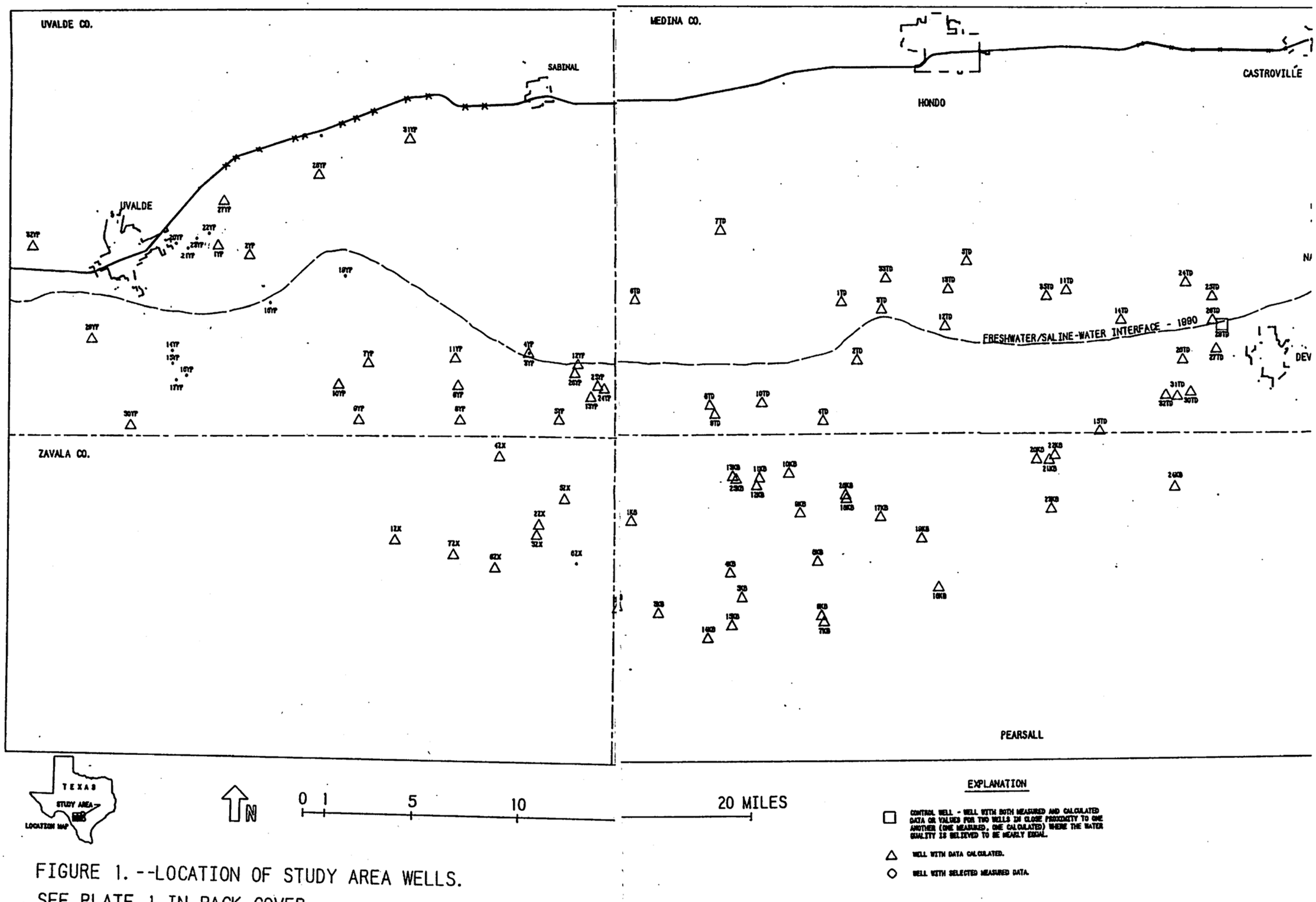


FIGURE 1.--LOCATION OF STUDY AREA WELLS.
SEE PLATE 1 IN BACK COVER.

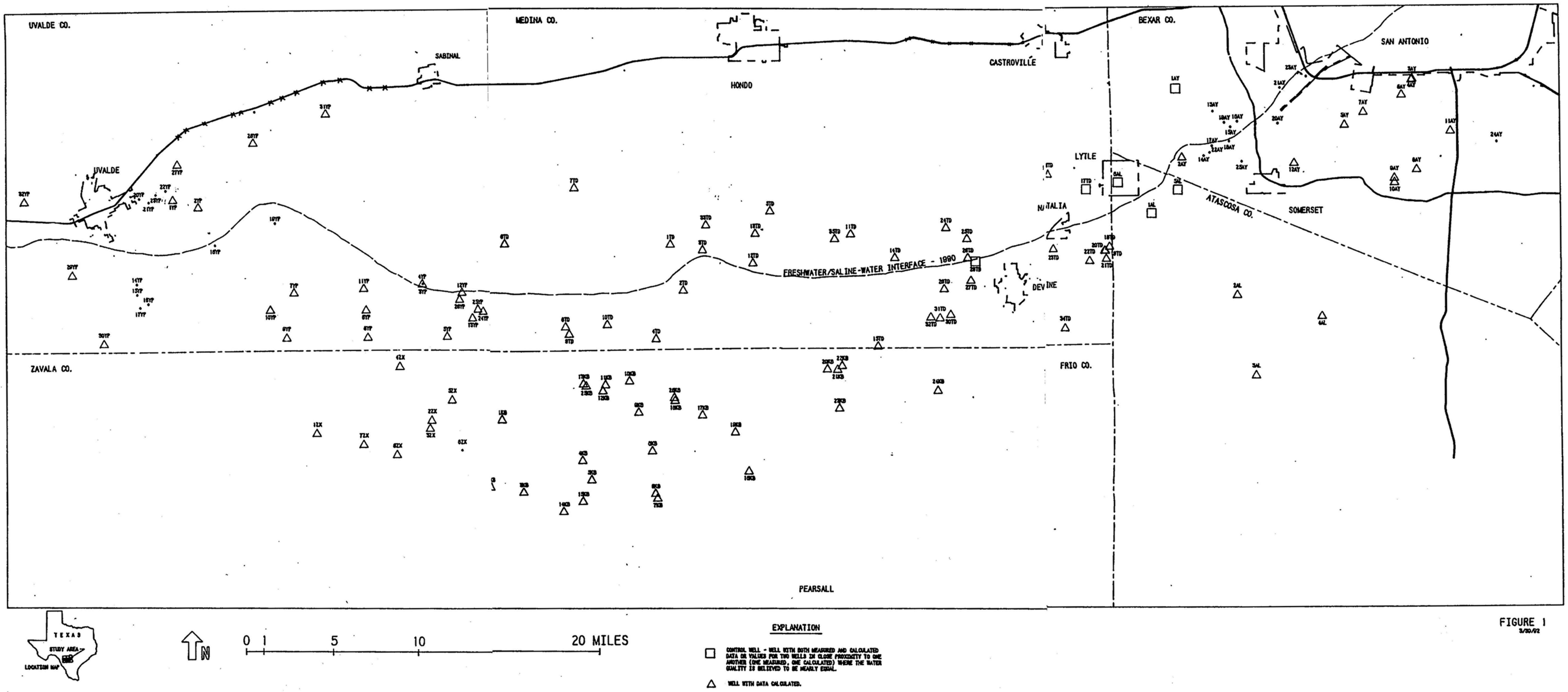


FIGURE 1

FIGURE 1.--LOCATION OF STUDY AREA WELLS.
SEE PLATE 1 IN BACK COVER.

reveals an anomaly approximately eighteen miles west of Devine, Texas (Brown, et al, 1991). The source of the data causing this feature is unknown. Research was conducted to locate the origin of the value responsible for the anomaly and it was determined that the value generating the "hump" in the freshwater/saline-water interface between Devine and the western boundary of Medina County is invalid. The freshwater/saline-water interface can be revised to the south (Figure 12) by using data from geophysical logs of previously drilled wells.

ACQUISITION OF DATA

The first step in evaluating the potential of employing geophysical logs in the determination of an accurate estimate of water quality was to identify wells which penetrated the Edwards aquifer along the trend of the present freshwater/saline-water interface. A reconnaissance of the area yielded over one hundred candidates for possible selection, providing the wells possessed the appropriate logs needed for calculating water quality parameters and that these logs were available. Various commercial geophysical log exchanges and log libraries have most resistivity logs available on a 1" = 100' vertical scale. However, for the method selected, porosity sensitive devices were required and very few can be obtained through such sources. Gathering porosity logs was by far the most difficult task in this project. Acquisition of this critical data took over ten months to complete. Most of the data was obtained from private sources. Some of the logs in key wells were obtained only after a confidential data document was signed. These logs are not available for examination. However, the values from the recordings were used in the water quality calculations.

Some type of quantitative analysis was performed on logs from over one hundred wells in the study area (Table 1). Locations for the wells were spotted using data from Tobin Surveys, Inc. as a guide (Figure 1, Plate 1). At least one other source was employed in verifying each location, such as a scout ticket (well history summary), Texas Railroad Commission form W-1, or information on the log heading. Where sources contained differing location data, but the locations were within 500 feet of the Tobin Survey, Inc. spotting, the Tobin map was used as the primary location. If the discrepancy exceeded five hundred feet, an attempt was made to locate other reliable sources and select the most likely correct site. Considering the purpose of this study, this accuracy is sufficient; however, if a test well or other research is dependent upon a very accurate location of a well or wells presented in this report, the location of the well in question should be found and the surface casing surveyed. Actual locations frequently differ from commercial county maps and other information believed to be accurate.

Upon acquisition of the necessary geophysical logs, various methods used to estimate water quality were evaluated.

SELECTION AND DEVELOPMENT OF A METHOD TO ESTIMATE WATER QUALITY

Several methods which use geophysical logs can be employed to estimate water quality (Turcan, 1962; Alger, 1966; MacCary, 1980; Alger & Harrison, 1989; Schultz and Stewart). Each method discussed in the literature has application provided the correct conditions exist. After examination of techniques presented by the above authors, a method combining the resistivity - porosity method (MacCary, 1980) with various empirical methods (Schultz and Stewart) was selected. The objective of this choice was to produce a "tailor-made" technique for estimating TDS along the freshwater/saline-water interface.

The heart of the method involves computing apparent water resistivity (Rwa) by the equations

$$Rwa = \frac{Rt}{F} \qquad \text{(Schlumberger, 1972)} \qquad (1)$$

where

F = the formation factor (computed from porosity sensitive logs or estimated from porosity values from nearby wells)

Rt = resistivity of the formation beyond the invaded zone (In this study, Rt is considered equal to Ro, the resistivity of a zone fully saturated with formation water. Whenever a zone is water bearing, Rwa reaches a minimum value equal to the formation water resistivity (Rw) (Schlumberger, 1972). Minor oil and gas shows are considered insignificant in equating Ro to Rt in this study.),

and

$$F = \frac{1}{\phi^m} \qquad (2)$$

where

ϕ = porosity (the fraction of the total volume occupied by pores or voids)

m = cementation factor (A cementation factor of 2 is a common value for carbonates. This has been used for the Edwards formation of South Texas (Coates and Dumanoir, 1974) and will be used in this study.).

Combining equations (1) and (2) gives

$$Rwa = Rt\ \phi^2 \qquad (3)$$

where Rt is obtained from the most appropriate deep investigating resistivity curve available on the log of the well being analyzed.

SELECTION OF INTERVALS TO EVALUATE

One of the main considerations in the selection of intervals for water quality determination was porosity development. It has been reported that porosity values need to exceed seven percent in carbonate aquifers for consistent apparent water resistivity results (MacCary, 1980). Also, very few points in Archie's original work, which is the basis for equation (2), involved porosities of ten percent or less (Archie, 1942). In addition, low porosity carbonates have been observed to require a special equation, such as the Shell Formula (Schlumberger, 1969). These factors, in conjunction with the assumption that the water we are interested in analyzing is most likely to be present in the higher porosity zones, led to the decision to examine only those intervals possessing porosities of ten percent and greater. For the most part, zones with over fifteen percent were evaluated. Selected intervals were of sufficient thickness that thin bed corrections were either not required or insignificant for this study.

POROSITY DETERMINATION

Establishing an accurate porosity (ϕ) value in the zone being evaluated was very important since porosity is an integral part of the Rwa equation. Sources used for porosity determination included various types of neutron logs, density logs, and sonic logs. Whenever porosity sensitive logs were not available, porosity was estimated from nearby well control.

To properly determine porosity from geophysical logs, where only a single recording is available, the general matrix lithology must be established. Assuming that the Edwards formation is predominately limestone and dolomite, a crossplot of density and neutron log values was used to determine the general matrix composition (Figure 2). Figure 2 was constructed from log data from wells 1-AL and 9-KB (Figure 1 and Table 1), which are found on each side of the study area. Crossplot results indicate a general lithology of dolomitic limestone. Whenever neutron and density logs were available and the borehole environment was satisfactory, they were used as the primary porosity source. Appropriate service company charts and/or equations were used for each type

POROSITY AND LITHOLOGY FROM FORMATION DENSITY LOG AND SNP NEUTRON POROSITY LOG

Fresh Water, Liquid-filled Holes, $\rho_f = 1$

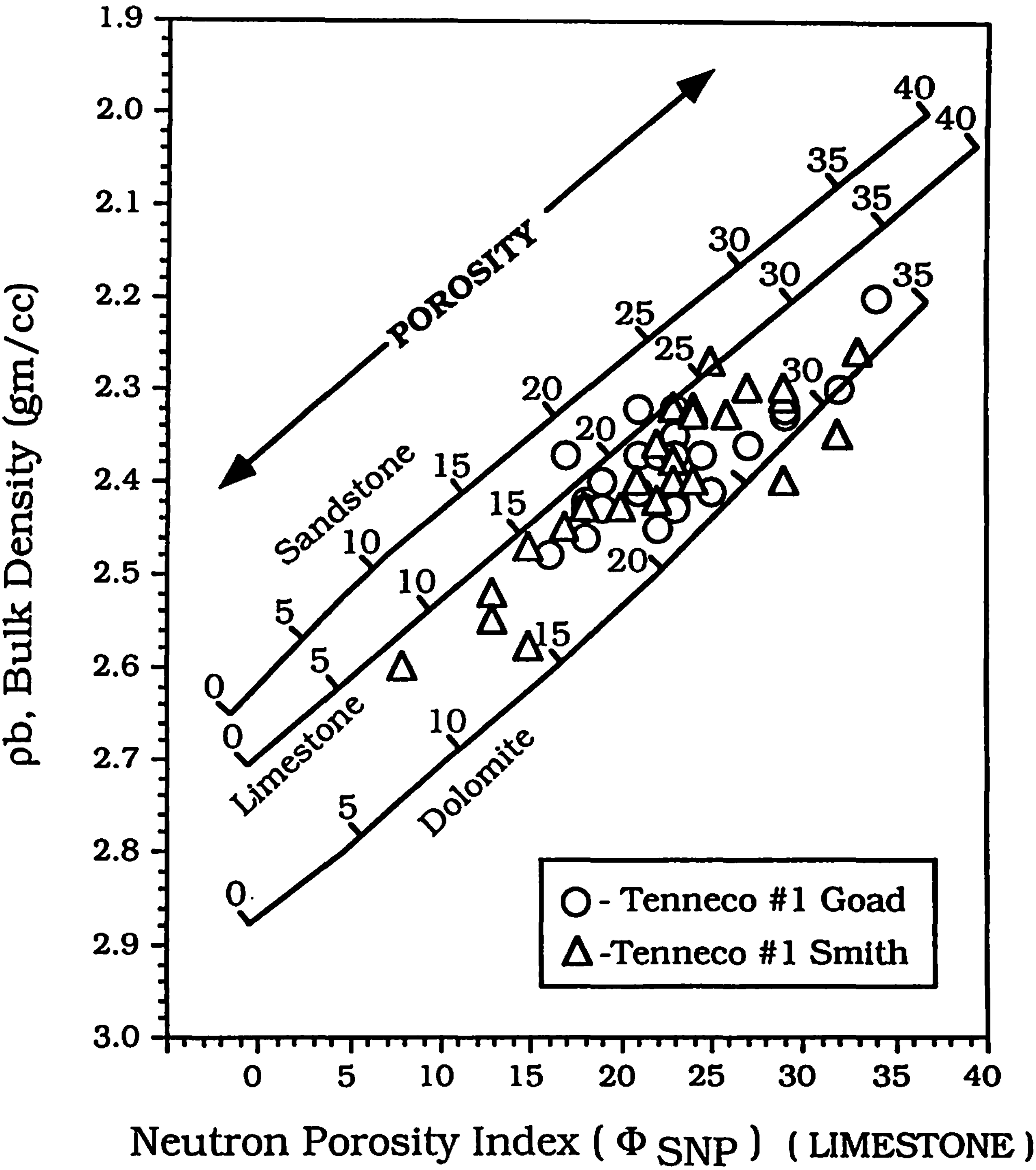


Figure 2. Porosity and lithology determination from density and sidewall neutron logs. Crossplot indicates lithology of zones is dolomitic limestone with porosity values of approximately 20%. Data is from wells 1-AL (Tenneco #1 Smith) and 9-KB (Tenneco #1 Goad). Neutron Porosity Index in percent. (Log interpretation chart after Schlumberger, 1972).

of tool involved to determine the best estimate of porosity.

Data shown in Figure 2 can be rearranged (Figure 3) in a manner to more easily determine grain density (ρma), which is required whenever the density log is selected as a single porosity source. The general equation for determining porosity (ϕ) from a density log is

$$\phi = \frac{\rho ma - \rho B}{\rho ma - \rho f} \tag{4}$$

where

ρma = matrix density in gm/cc
ρB = bulk density in gm/cc from density log recordings
ρf = fluid density = 1 (for freshwater).

From figure 3, a matrix density of 2.77 was selected. Thus, whenever the density log is chosen as a single porosity device, substitution in equation (4) yields

$$\phi = \frac{2.77 - \rho B}{2.77 - 1} \tag{5}$$

In a similar manner, the density-neutron porosity values from Figure 2 were plotted versus the formation interval transit time (ΔT) for the same zones (Figure 4). This plot facilitates the selection of matrix velocity (Vm) and is entered into the porosity equation for sonic log data:

$$\phi = \frac{\Delta T\ log - \Delta Tm}{\Delta Tf - \Delta Tm} \tag{6}$$

where

ΔT log = recorded sonic transit time in microseconds/ft
ΔTm = formation matrix velocity expressed as transit time in microseconds/ft
ΔTf = fluid velocity expressed as transit time = 189 microseconds/ft for fresh water.

From Figure 4, a matrix velocity of 23,000 ft/sec (corresponding to a matrix interval transit time of 43.5 microseconds/ft) was selected. The temptation to select a higher matrix velocity or to choose a field observation curve (Figure 4) existed. However, since the crossplot of density and neutron data reveals a dolomitic limestone matrix (Figure 2) and 23,000 ft/sec is in the mid-range of limestone to dolomite matrix velocities (Schlumberger, 1972),

FORMATION DENSITY LOG DETERMINATION OF POROSITY

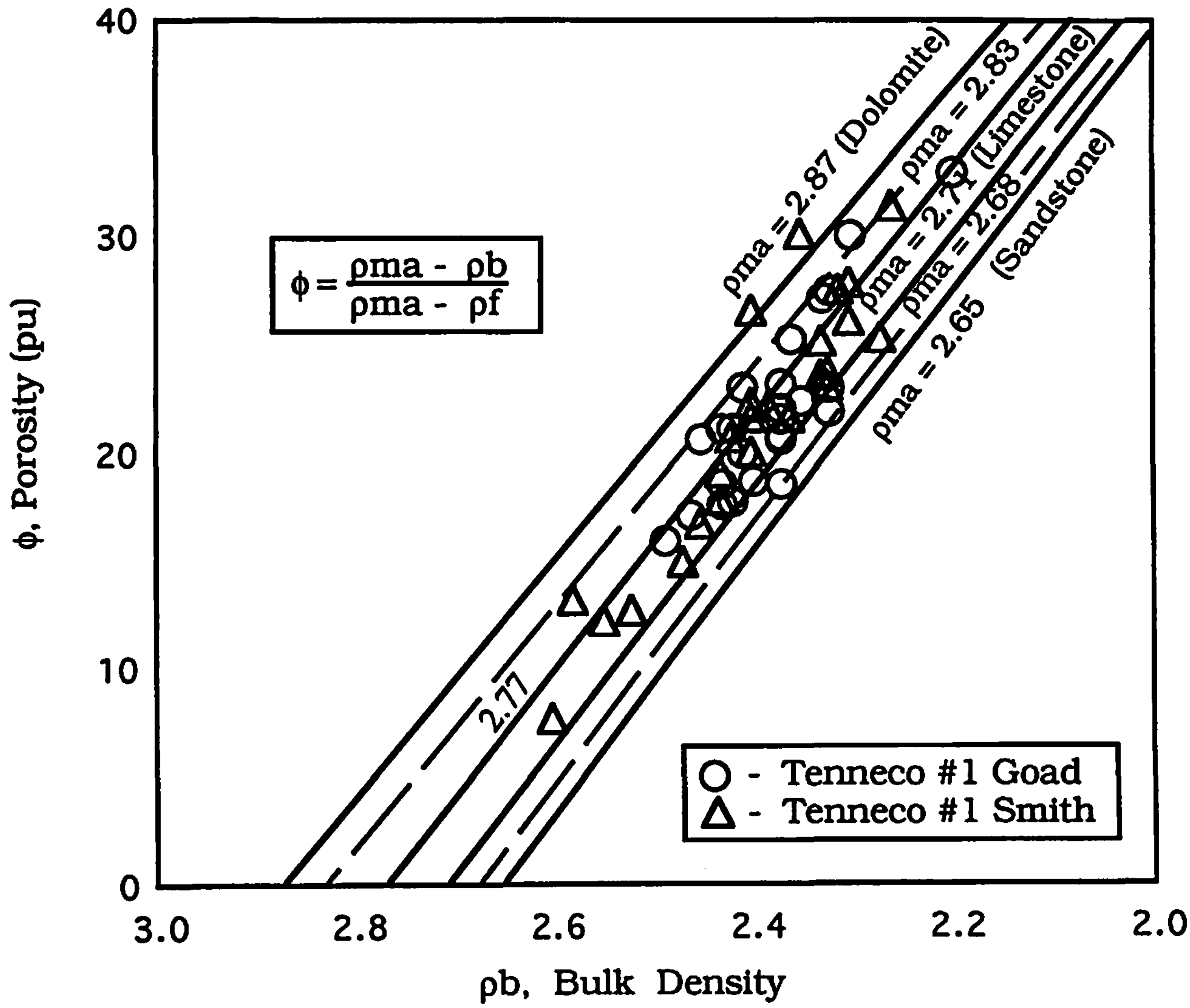


Figure 3. Crossplot of porosity from density and neutron data verses bulk density, used to facilitate estimation of matrix density (ρG). ρG = 2.77 was selected for use when the single source of porosity was a density log. Data is from wells 1-AL (Tenneco #1 Smith) and 9-KB (Tenneco #1 Goad). Porosity in percent. Bulk density in gm/cc. (Log interpretation chart after Schlumberger, 1986).

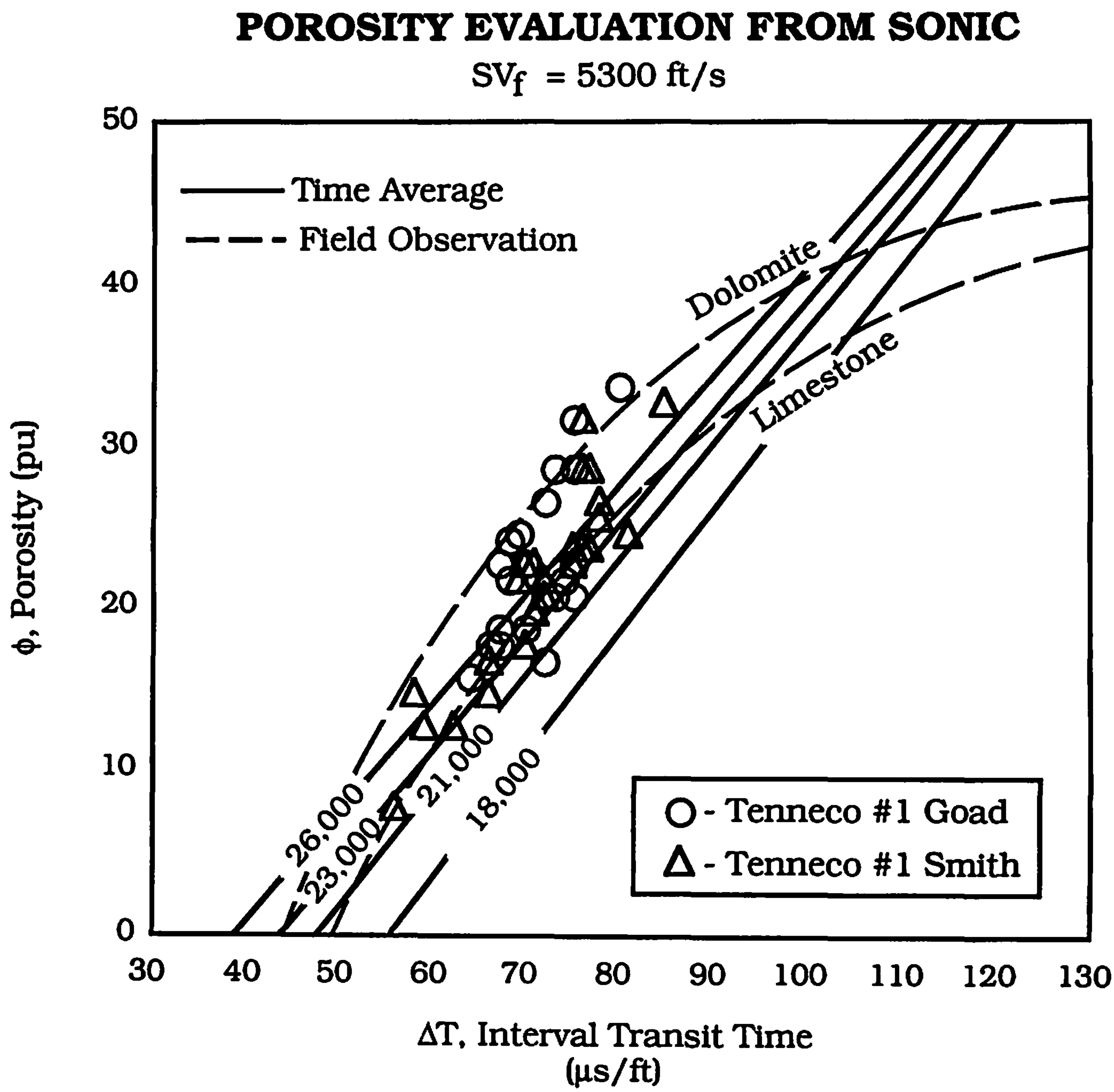


Figure 4. Density and neutron log-derived porosity plotted versus interval transit time, used to select a matrix velocity for porosity determination from sonic logs. A matrix velocity of 23,000 ft/sec (ΔT matrix = 43.5 microseconds/ft) was selected for the study area wells. Data is from wells 1-AL (Tenneco #1 Smith) and 9-KB (Tenneco #1 Goad). Porosity is percent. (Log interpretation chart after Schlumberger, 1986.)

23,000 ft/sec was selected as a conservative choice. With substitution, equation (6) yields

$$\phi = \frac{\Delta T \text{ log} - 43.5}{189 - 43.5} = \frac{\Delta T \text{ log} - 43.5}{145.5} \qquad (7)$$

for porosity determination whenever the sonic log is selected as a single porosity tool.

CONVERSION OF Rwa TO APPARENT SPECIFIC CONDUCTANCE (Ca)

Specific conductance is the electrical conductivity of a water sample at 25° C (77°F) expressed in micromhos per centimeter (μm/cm), and is the accepted standard expression. To convert Rwa to Ca, the following equation is used:

$$Ca = \frac{10,000}{Rwa} \qquad (8)$$

where Rwa is in ohm-meters at 77°F.

However, since values of resistivity used in the Rwa equation (3) are at formation temperature (BHT), Rwa needs to be converted to 77°F. This is accomplished through the Arps formula (Schlumberger, 1969; Jorgensen, 1989):

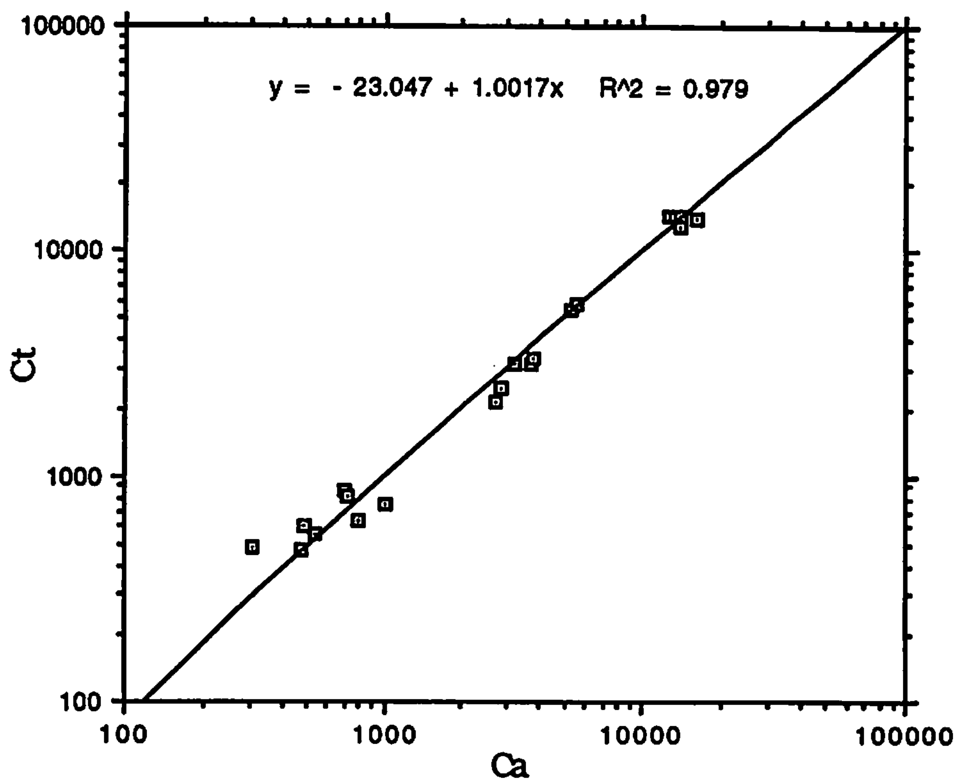
$$Rwa\ (77°F) = Rwa \times \frac{(BHT + 7)}{84} \qquad (9)$$

Formation temperatures (BHT) for wells in the study area have been estimated by combining the mean annual surface temperature and 1½°F per hundred feet (Woodruff, 1985) of maximum depth of the intervals shown on the geophysical logs. A 70°F mean annual temperature was used in the study area, since 69.6°F is the mean annual surface temperature for Hondo, Texas (Holt, 1959), and the mean annual surface temperature for Dilley, Texas, in southern Frio County, south of the study area, is approximately 71°F (Alexander and White, 1966). This combination for BHT appears reasonable based upon data from well 29-TD (Figure 1, and Table 1) near the freshwater/saline-water interface in Medina County, Texas. A temperature survey for this well recorded 115.9°F at a depth of 3200' (Small, personal communication). A temperature of 118°F is estimated with the method employed for the study area.

VERIFICATION OF METHOD

To verify that log-derived specific conductance values can be used to indicate water quality, data was gathered (Table 2) from several wells, where measured samples and estimates from geophysical logs could be compared. Some wells are recent test wells drilled by the Edwards Underground Water District (EUWD) and have multiple zone tests where comparisons can be made. Wells shown in Table 2, which do not appear in Table 1 or on Figure 1 can be identified by the standard well numbering system used by the Texas Water Commission and are on file at the EUWD. Specific conductance was calculated in the various wells over intervals from which actual samples were taken and measured. In a few cases, the comparison between estimated and measured specific conductance was made by observing data from a pair of wells in close proximity where water quality is believed to be nearly equivalent and one well has a measured value and the companion well's specific conductance is derived from geophysical log analysis. These wells are identified (Figures 11 and 12, Plates 2 and 3, and Table 2).

Since the main parameter being determined in this study is specific conductance, measured specific conductance (Ct) values have been graphically compared to log-derived specific conductance (Ca) values (Figure 5). Figure 5 displays a simple fit straight line through the data, revealing a well defined trend. The correlation coefficient squared (r^2) is equal to 0.979, showing a high degree of correlation and indicating that the method can be used to accurately estimate specific conductance. Apparent specific conductance (Ca) can be converted to an estimated true specific conductance (Ct) value using the equation shown in Figure 5. Comparison of the two sets of values



Figures 5. Correlation between measured specific conductance (Ct) and geophysical log-derived specific conductance (Ca) for control wells (Table 2). Specific conductance in micromhos/cm. R ^ 2 = r^2 (Correlation coefficient squared).

indicates they are nearly equal (e.g., when Ca = 1000, Ct = 979, which is within 3% of the measured value). Therefore, Ca was used directly on the specific conductance map without applying the formula in Figure 5 to convert to an estimated Ct.

Since specific conductance is a function of water quality and TDS (Alger, 1966), measured specific conductance points (Ct) were plotted versus measured TDS (Figure 6) from the control data (Table 2). Excellent correlation exists between Ct and TDS (Figure 6), with r^2 = .996. In addition, Ca was graphically compared to TDS (Figure 7) to establish an empirical relationship for construction of an estimated TDS map. Again, there is a high correlation coefficient (r^2 = .963) for the data (Figure 7). The results shown in Figures 5, 6, and 7 strongly imply that specific conductance data derived from geophysical logs can be used as a reliable source for estimating water quality along the freshwater/saline-water interface in the Edwards aquifer.

To insure that the changing hydrochemical facies across the study area does not have a significant effect on the determination of estimated TDS from Ca values, Ct was plotted versus TDS (Figure 8) for all wells in the study area (where Ct and TDS were measured) for comparison with the control wells (Figure 6). This was necessary since much of the control data is along the freshwater/saline-water interface where there are changes in the hydrochemical facies (Maclay, et al, 1980). Comparison of the two curves reveals that both have a very high correlation coefficient and both have a similar slope. A comparison of the TDS and Ca relationships between the two indicates that the hydrochemical facies is not a significant factor in our study (e.g. when TDS = 1000, Ct = 1453 for the control data (Figure 6), while a TDS of 1000 has a corresponding Ct of 1406 for the study area wells (Figure 8)). Inferring that

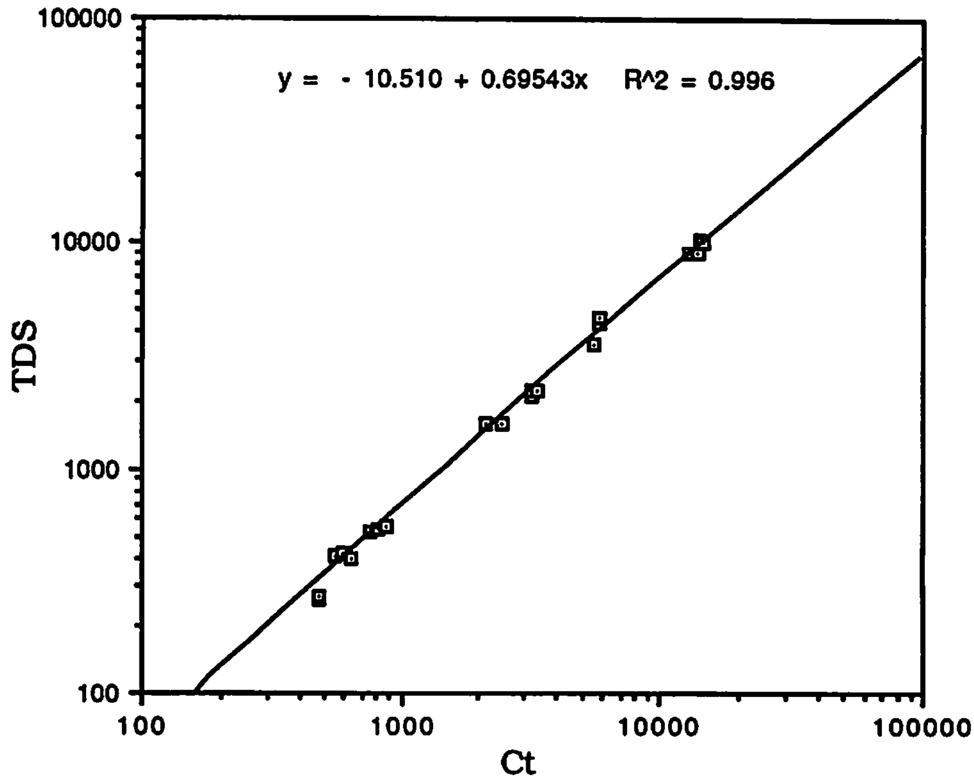


Figure 6. Relationship of measured total dissolved solids (TDS) to measured specific conductance (Ct) for control wells (Table 2). Total dissolved solids in mg/L. Specific conductance in micromhos/cm. R^2 = r^2.

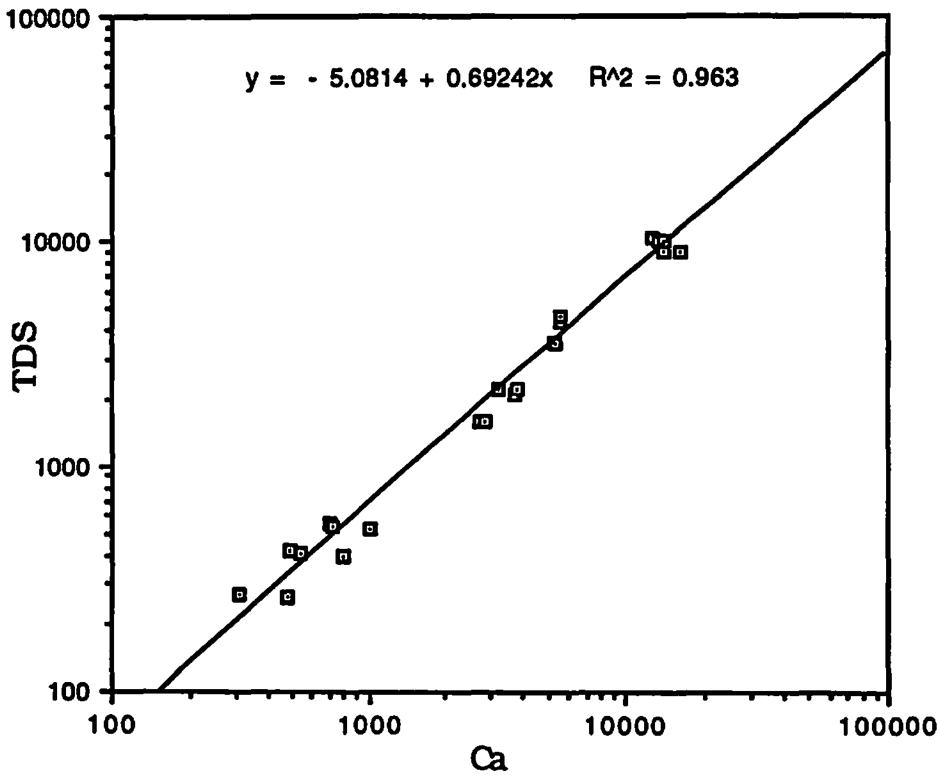


Figure 7. Correlation between measured total dissolved solids (TDS) and calculated specific conductance (Ca) from geophysical logs of control wells (Table 2). Crossplot reveals a well defined trend and a high correlation coefficient (r = .98). Total dissolved solids in mg/L. Specific conductance in micromhos/cm. R^2 = r^2.

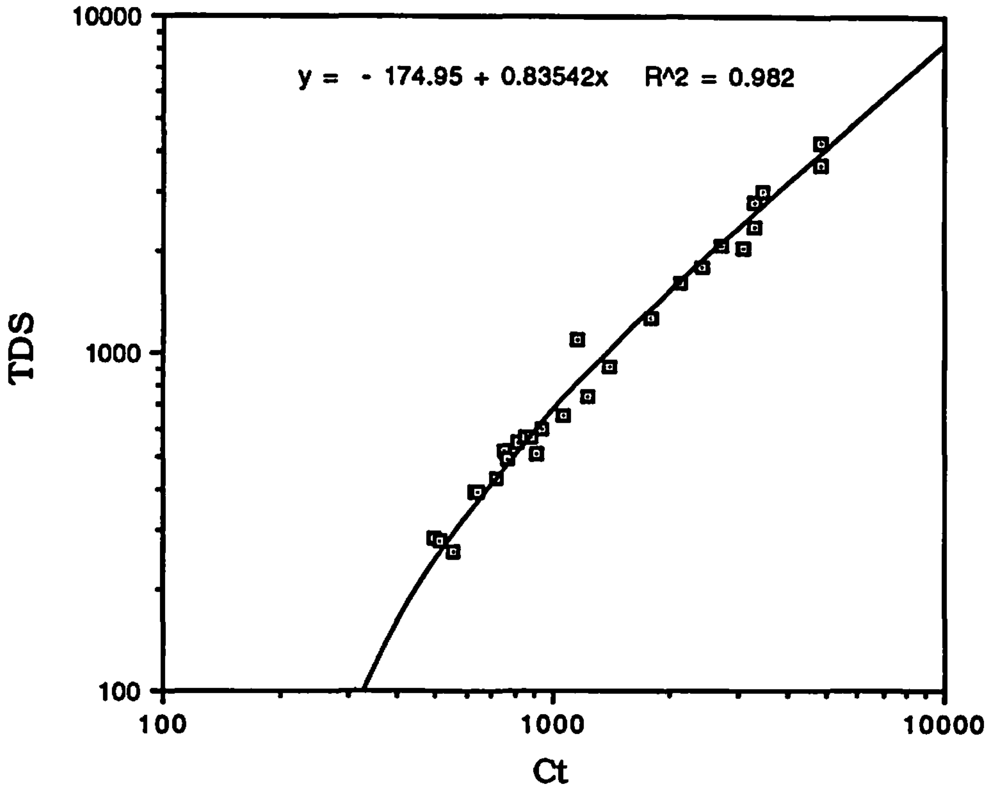


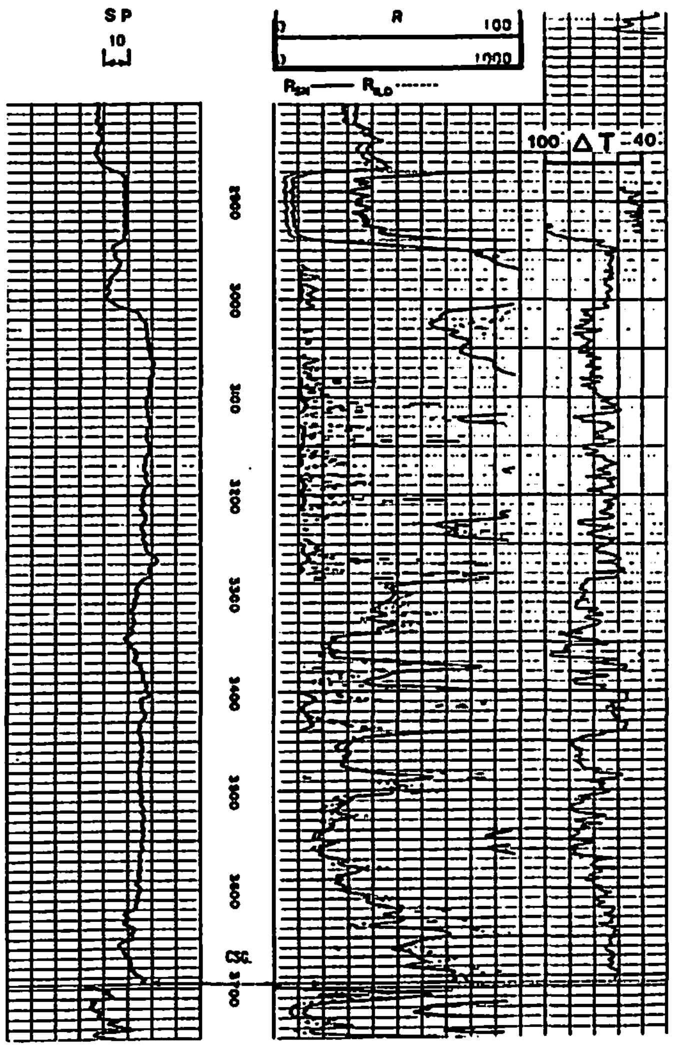
Figure 8. Relationship of measured total dissolved solids (TDS) to measured specific conductance (Ct) for wells within the study area (Table 1). Total dissolved solids in mg/L. Specific conductance in micromhos/cm. R^2 = r^2.

in this range there is less than 4% difference between the two estimates, a quick check indicates there is nearly an 18% difference in the 10,000 TDS range. However, since the freshwater/saline-water interface is defined as the 1000 mg/L TDS contour, discrepancies at values of 10,000 or greater are not significant for this study. If more accurate results are necessary, additional local comparisons involving crossplotting Ca, Ct and TDS may be required to tailor the interpretation to a more specific location.

DEMONSTRATION OF METHOD

The total technique for estimating water quality from geophysical logs can probably be more easily understood through the use of examples. Well 31-TD (Figure 1, Plate 1) has an induction-electric log and a sonic log recorded over the Edwards formation. Intervals selected for estimating water quality parameters, log values, and various components for the necessary equations needed for the computations are presented in Figure 9. In this well, conductivity-feet has been determined for three separate intervals and divided by the total footage of each interval to determine an average calculated specific conductance for that particular zone, since each displays a change in water quality. According to the classification by Winslow and Kister (1956), the zone from 3010' to 3154' is fresh water (less than 1000 mg/L TDS), the zone from 3226' to 3362' is slightly saline (1000 to 3000 mg/L), and the zone from 3367' to 3564' is moderately saline (3000 to 10,000 mg/L). Water quality information determined from in situ measurements by geophysical logs facilitates comparison of zones in the same well without production testing.

The second example, well 29-YP, involves determining Ca and estimated TDS using conventional electric log recordings without a porosity log run in the well (Figure 10). In this instance, the true resistivity was taken from the long normal curve and porosity was estimated from local knowledge. TDS was



DEPTH from	INTERVAL to	ΔT	ϕ_s	m	R_t	R_{wa}	BHT	R_{wa}@77°F	C_a	ft	Cond./ft.	Avg. C_a		TDS
PAN AM	LILLY#1													
3010	3030	74	0.210	2	95	4.174	115	6.085	1643	20	32866	from		
3033	3040	79	0.244	2	100	5.953	116	8.688	1151	7	8057			
3040	3058	74	0.210	2	120	5.273	116	7.713	1297	18	23337			
3060	3092	71	0.189	2	150	5.358	116	7.870	1271	32	40659			
3118	3124	79	0.244	2	62	3.891	117	5.442	1837	6	11025			
3148	3154	75.5	0.220	2	105	5.079	117	7.516	1330	6	7983	to	1392	959
3226	3231	79	0.244	2	56	3.334	118	4.979	2008	5	10042	from		
3288	3296	77	0.230	2	45	2.385	119	3.591	2785	8	22280			
3354	3362	87	0.299	2	22	1.968	120	2.983	3352	8	26818	to	2816	1945
3387	3393	81	0.258	2	15	0.998	121	1.517	6592	6	39550	from		
3450	3458	82	0.265	2	25	1.750	122	2.685	3724	8	29791			
3458	3478	78	0.237	2	28	1.574	122	2.421	4131	20	82619			
3514	3524	82	0.265	2	20	1.400	123	2.165	4619	10	46193			
3542	3550	82	0.265	2	17	1.190	123	1.846	5418	8	43346			
3554	3564	83.5	0.275	2	15	1.134	123	1.761	5680	10	56796	to	4811	3326

ΔT = Interval transit time from Sonic Log - in microseconds/ft

ϕ_s = Porosity calculated from ΔT - where $\phi_s = \dfrac{\Delta T_{log} - \Delta T_m}{\Delta T_f - \Delta T_m} = \dfrac{\Delta T_{log} - 43.5}{145.5}$

m = Cementation exponent

R_t = R_{ILD} - Resistivity measured from Deep Induction Log

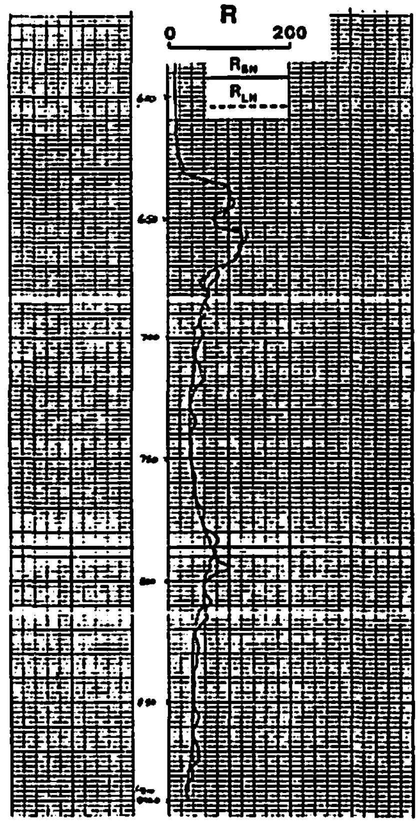
R_{wa} = Calculated apparent water resistivity at formation temperature

BHT = Maximum temperature of interval calculated

C_a = Calculated apparent specific conductance

TDS = Total dissolved solids (mg/L), estimated from empirical relationship from data shown in Figure 7

Figure 9. Example of calculations made using an induction-electric log and a sonic log. Example log is the Pan American #1 Lilly (31-TD) in Medina County. Resistivity in ohm-meters, interval transit time in microseconds/ft.



		Depth Interval		ϕ_{est}	m	R_t	R_{wa}	BHT	R_{wa} @ 77°F	C_a	TDS
		from	to								
YP-29	YP-69-50-803	696	770	0.3	2	40	3.6	81.6	3.795	2635	1819
	Willoughby										

ϕ_{est} = Porosity estimated from nearby well control
m = Cementation exponent
R_t = R_{LN} - Resistivity measured from Long Normal Resistivity curve
R_{wa} = Calculated apparent water resistivity at formation temperature
BHT = Maximum temperature of interval calculated
C_a = Calculated apparent specific conductance
TDS = Total dissolved solids (mg/L), estimated from empirical relationship from data shown in Figure 7

Figure 10. Example of calculations made using an electric log and estimated porosity. Example log is YP-69-50-803, Don Willoughby (29-YP) in Uvalde County. Resistivity in ohm-meters.

estimated using this data and the relationships expressed in equations (3), (8) and (9), and Figure 7.

The results of all estimates and calculations for all the wells in this study, along with other useful information, are shown in tabulated form in Table 1.

SPECIFIC CONDUCTANCE MAP

Calculated and measured specific conductance values from Table 1 were posted on a base map of the study area (Figure 11, Plate 2). Appropriate contours were constructed beginning with the 1000 micromhos/cm contour. The contour intervals vary with available control from area to area. For reference, the 1990 location of the freshwater/saline-water interface (Nalley and Thomas, 1990) is presented. Selected measured data is incorporated into the map to enhance control and facilitate comparison of estimated and measured points. Explanations of symbols and other identification is presented either on the specific conductance map or in Table 1. For those wells containing zones which display significant changes in specific conductance values within the formation, all values have been posted, and the zone with the minimum value has been selected for contouring. In situ water quality estimates from geophysical logs allows comparison of various zones, whereas pumped samples may represent a composite from several intervals.

Since the specific conductance equivalent to 1000 mg/L TDS is approximately 1450 micromhos/cm (Figure 7), the specific conductance map is in close agreement with the location of the 1990 freshwater/saline-water interface between San Antonio and the Medina County line. (The 1450 micromhos/cm contour is shown as a dashed line in Figure 11 and on Plate 2.) However, between the Uvalde-Medina County line and Devine, there is considerable disparity. In this area, where there is a lack of measured data registering

TDS in excess of 1000 mg/L, the location of the values representing an equivalent freshwater/saline-water interface (1450 micromhos/cm) extends into Frio County (Figure 11, Plate 2). In an area of extensive igneous activity and faulting in southeastern Uvalde County (northeast of Uvalde, Texas), the estimated freshwater/saline-water interface extends north of the 1990 interface.

From the spacing of the contours, the rate of increase of TDS can be observed. For example, in Frio County where the contour lines are very closely spaced, the rate of increase in salinity is rapid, whereas the rates in Uvalde County and Zavala County are less so. The most extreme case of dilution of the saline zone occurs in northwestern Atascosa County and southwestern Bexar County, Texas, between Somerset and San Antonio (Figure 11, Plate 2).

Application of apparent water resistivity and its reciprocal, apparent water conductivity (MacCary, 1980), can be used to determine areas of saturated brine, areas of freshwater recharge and probable direction of ground-water movement. One possible interpretation of the contour patterns on the specific conductance map (Figure 11, Plate 2) is that the direction of freshwater movement is from the Sabinal area toward Frio County and that freshwater has displaced brine as far south as well 5-KB. Indications are that from the most southern excursion of the freshwater movement into Frio County, the freshwater movement appears to be eastward along the perimeter of the saline area toward Devine, Texas. A more complex situation exists between Devine and Somerset, Texas. In this area, there is an indication that a considerable amount of freshwater has moved southeastward from the area near the farthest northwest corner of Atascosa County in a direction subparallel to the Atascosa-Bexar County line. Another excursion of this type is present between Somerset and San Antonio. For proper utilization of the specific conductance map, it should be used in conjunction with all other technical data for a better understanding of the Edwards aquifer hydrology.

A review of specific conductance values for several wells near Devine (25-TD, 26-TD, 30-TD, 31-TD, 32-TD), in southeast Uvalde County (5-YP, 13-YP, 24-YP, 12-YP, 3-YP) and in Frio County (5-KB) shows that variability in water quality occurs in a vertical sequence within the Edwards aquifer along the freshwater/saline-water interface. Nearby wells may have the highest water quality in different zones. This is evident in areas where several wells have multiple value listed (Figure 11, Plate 2), such as the area near Devine.

TDS MAP

Water quality comparisons are traditionally expressed in units of TDS. The groundwater classification used in Texas, based on dissolved solids, is as follows:

Water Quality	TDS (mg/L)
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

(from Winslow and Kister, 1956)

All measured and estimated TDS values were posted on the base map. Estimated TDS values were derived using the formula for converting Ca to TDS (Figure 7). Contours representing values described in the classification system above were constructed (Figure 12, Plate 3).

Water quality data presented in the form of TDS isocons is more convenient for the understanding of the overall picture along the freshwater/ saline-water interface since the units used are the same as those used to delineate the 1990 interface (Figure 12, Plate 3). This enables a direct comparison of the two interfaces. The discrepancy mentioned earlier concerning the area in southern Medina County and northern Frio County is well pronounced. However, the area formed by the southern extension of the estimated 1000 mg/L isocon into Frio County is partially offset by a northerly bulge in the estimated freshwater/saline-water interface in an area between Uvalde and Sabinal, Texas (Figure 12, Plate 3). In this case, the 1990 freshwater/saline- water interface is the more southerly of the two. The net area formed by the location of the estimated freshwater/saline-water interface south of the 1990 interface exceeds the area to the north by approximately 100 square miles between Uvalde and San Antonio, Texas.

Since the 1000 mg/L isocon of estimated TDS is nearly equal to and parallel to an approximate 1450 micromhos/cm contour on the specific conductance map in Figure 11 (also Plate 2), the same interpretations concerning freshwater movement and saline zone dilution can be made from the TDS map as from the specific conductance map. (Minor differences occurring between the two estimated equivalent 1000 mg/L contour lines are due to either the use of measured versus calculated values or minor differences in contouring style.) With the TDS map tied to the water quality classification presented, it is even more apparent that freshwater has considerably diluted the saline zone in the areas near the northeastern corner of Zavala County and the area near Somerset, Texas (Figure 12, Plate 3).

Of considerable value in estimating freshwater movement, and adding credibility to the interpretation suggesting freshwater flow south of the 1990 freshwater/saline-water interface, is other significant data acquired during this study (see Remarks, Table 1). Much of this information has been transferred to the appropriate wells on the TDS map (Figure 12, Plate 3). Of interest are sample descriptions reporting white, cream, tan or light colored rock (as compared to darker samples observed in wells penetrating the saline zone), since these can be an indication of circulation within the aquifer (Small and Maclay, 1982). Also, documentation of wells encountering lost circulation and caverns aids in identifying areas within the aquifer possessing high permeability necessary for fluid flow. Indications of freshwater from well tests are also shown.

A scan of Figure 12 (also Plate 3) shows much of the additional information is from wells within the area between the 1990 freshwater/saline-water interface and the 3000 mg/L contour, supporting the interpretation of freshwater movement in northern Frio County.

SUMMARY AND CONCLUSIONS

It has been shown that sufficient geophysical logs of acceptable quality are available and can be used to estimate water quality along an area updip and downdip from the freshwater/saline-water interface between Uvalde and San Antonio, Texas. Basic log interpretation equations and techniques are adequate when combined with simple empirical relationships to determine, with confidence, specific conductance from geophysical logs in the study area. A crossplot of calculated versus measured specific conductance data yields a well defined trend with a strong correlation coefficient.

The high degree of correlation between calculated and measured results is exceptional considering the variety of possible porosity types occurring in the Edwards aquifer (Small and Maclay, 1982) and the variety and vintage of logs employed in the study (Table 1).

Upon examination of the specific conductance map (Figure 11, Plate 2), TDS map (Figure 12, Plate 3), and data in Tables 1 and 2, the following observations and interpretations are justified:

(1) The freshwater/saline-water interface is irregular and extends farther south than has previously been estimated (Figures 12, Plate 3).

(2) All data gathered and results derived from geophysical logs can be used to support an interpretation indicating freshwater movement from the Sabinal, Texas, area into northwestern Frio County.

(3) Freshwater has been determined indirectly, through geophysical log analysis, to be present at a depth of at least 3900' (-3218') in Frio County (well 10-KB, Table 1).

(4) The wider areas between the 1000 mg/L and 3000 mg/L contour lines (Figure 12, Plate 3) indicate extended dilution of the downdip saline zone, while a narrow band represents a more rapid change from freshwater to varying degrees of salinity.

(5) The bulges in the 3000 mg/L contour south and northeast of Somerset, Texas (Figure 12, Plate 3) could be interpreted to have been generated by freshwater movement from the northwest.

(6) The separation between freshwater and saline-water is not a straight vertical plane defined by the 1000 mg/L contour line. In some areas only one zone in the Edwards formation possesses freshwater. The position of the higher quality water may vary from zone to zone within the formation (Table 1, Figure 11, Plate 2), which may suggest the need for further study of the control applied on the freshwater/saline-water interface by the stratigraphy of the Edwards Group across the various geologic provinces contained within the study area.

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Table 1. Calculated and/or measured data from geophysical logs and other sources for wells in study area.

Atascosa County

Map I.D. Number	Other well identification	Depth interval from:	to:	Ca	Ct	TDSm	TDSest	Mo/Yr log recorded	Mo/Yr measured	Remarks
1-AL	Tenneco #1 P.R. Smith	2306	2858	2680			1851	1-68		
2-AL	Tenneco #1 J.J. Smith	3130	3329	4116			2845	2-69		
		3375	3682	4671			3229			
3-AL	Tenneco #1 Finch	4018	4241	18149			12562	4-69		
		4292	4585	42031			29098			
4-AL	Tenneco #1 Rogers	3480	3720	4888			3379	3-68		
		3770	4076	9521			6587			
5-AL	AL-68-51-101		2656		2130	1600			7-85	(2)
6-AL	AL-68-50-201		N/A		759	518			7-70	(3)

Bexar County

Map I.D. Number	Other well identification	Depth interval from:	to:	Ca	Ct	TDSm	TDSest	Mo/Yr log recorded	Mo/Yr measured	Remarks
1-AY	Coastal States #1 Loessberg	1803	2222	802			550	4-73		
2-AY	Bur-Kan #1 Hubbard	1860	2430	1160			798	3-48		
3-AY	West #1 Timberlake	1604	2090	4764			3294	12-47		
4-AY	Coffee #1 Timberlake	1647	1684	5269			3643	11-56		
5-AY	Beer #2-A Prinz	1522	1533	4200			2903	7-56		
6-AY	Union #1 McKean	1627	2003	4311			2980	1-49		
7-AY	Sun #1 Forbes	1836	1968	3614			2497	2-64		(4)
8-AY	Long #1 Applewhite	2336	2343	4611			3188	7-39		
9-AY	U.S. Enhanced Oil Rec. #1 McClain	2182	2734	6362			4400	8-81		
10-AY	U.S. Enhanced Oil Rec. #2 McClain	2230	2767	7545			5219	9-81		

Table 1. Continued

				Ca	Ct	TDSm	TDSest			
11-AY	U.S. Enhanced Oil Rec. #1 Cooke-McClain	2204	2590	5478			3788	11-81		
12-AY	Jacobs #1 Gerhart	1920	1930	4405			3045	6-59		
13-AY	AY-68-43-811		2292		636	394			7-89	(1)
14-AY	AY-68-43-703		2030		1420	910			7-89	(1)
15-AY	AY-68-43-816		1993		1250	746			7-89	(1)
16-AY	AY-68-43-812		1800		561	260			5-76	(3)
17-AY	AY-68-43-810		1860		947	593			7-70	(3)
18-AY	AY-68-43-818		1950		1070	660			7-85	(2)
19-AY	AY-68-43-807		2292		720	429			7-89	(1)
20-AY	AY-68-43-901		2274		3110	-			3-76	(3)
21-AY	AY-68-43-601		1911		500	286			7-89	(1)
22-AY	AY-68-43-702		2054		1810	1280			7-70	(3)
23-AY	AY-68-44-401		1532		510	281			7-89	(1)
24-AY	AY-68-45-802		2444		4850	4180			7-70	(3)
25-AY	AY-68-51-201		2219		4850	3660			9-73	(3)
Frio County										
1-KB	Tenneco #1 Machen	3504	3878	3046			2104	6-69		(5)
2-KB	Kirkwood #1-A Brown	4440	4782	5481			3790	8-61		
3-KB	Gen. Crude #1 Browne	4490	4632	3978			2749	5-62		
4-KB	Tenneco #1 Roberts	-	-	-			-	9-69		(6)
5-KB	Moncrief #2 Rheiner	4596	4780	3046			2104	11-68		
		4850	4968	2051			1415			
		4982	4990	3361			2322			
		5120	5130	51722			35808			

Table 1. Continued

				Ca	Ct	TDSm	TDSest		
6-KB	Arrow #1 Thompson	4910	4930	245360			169887	12-89	
7-KB	Energy Expl. #1 Boysville Foundation	4980	4990	116145			80416	8-76	
8-KB	Tenneco #2 Goad	-	-	-			-	8-69	Used for correlation & porosity control
9-KB	Tenneco #1 Goad	3736	4400	1792			1236	6-69	
10-KB	Amerada #1 Hiler	3300	3900	1098			755	4-55	(7)
11-KB	Tobin #1 McMahan	3240	3305	685			469	10-68	
12-KB	Tobin #2 McMahan	3300	3340	785			538	1-69	
13-KB	Graham #1 Ireland	3130	3160	463			316	7-59	
14-KB	Tenneco #1 Mack	5045	5580	34404			23817	3-68	
15-KB	Moncrief #1 Rheiner	4888	5620	47575			32937	8-68	
16-KB	Tenneco #1 Stoker	4685	5410	49821			34492	10-67	
17-KB	Jergins #1 Goad	3900	3930	2471			1706	1-53	Sulphur wtr on DST 3898-3930' BHSIP: 1515#
18-KB	Strake #2 Henry	3610	3670	1063			731	8-46	
19-KB	Tenneco #1 Wilbeck	4160	4552	5303			3667	1-69	
		4740	4800	10976			7595		
20-KB	Allied #1 Williams	3374	3766	2473			1707	2-83	
		3782	3983	3952			2731		
21-KB	Border #1 Mann	3382	3790	2721			1879	11-80	
		3836	3998	4388			3033		
22-KB	Michelson #2 Jones	-	-	-			-	2-64	NDE
23-KB	Tenneco #1 Sirianni	3976	4552	4628			3199	2-68	
24-KB	Tenneco #1 Edgar	3710	3862	4152			2870	1-69	
		3938	4180	5812			4019		
		4250	4283	11922			8250		

Table 1. Continued

				Ca	Ct	TDSm	TDSest		
25-KB	Pagenkopf #1 Blackaller	3200	3240	926			636	6-37	
26-KB	Strake #1 Henry	3590	3605	1602			1104	6-46	DST 3601-28' rec 260' mud & 210' fresh wtr
Medina County									
1-TD	TD-69-55-4 (Scott Petty, Jr.)	2244	2330	1000			687	7-86	
2-TD	Pan Am #1 Muennink	2400	2982	726			498	12-63	
3-TD	Pan Am #1 Ward	2120	2590	480			327	6-65	
4-TD	Humble #1 Wilson	2815	3240	942			647	11-48	
5-TD	Tenneco #1 Ney	1450	1827	661			453	10-66	
6-TD	Ford & Hamilton #1 Nunley	1750	2126	560			383	12-59	
7-TD	Ford & Hamilton #1 Raybourn	1365	1780	358			243	11-59	DST: Fresh wtr; hit cavity 1431-39'
8-TD	Galaxy #1 Leoncita	2540	3218	1042			716	10-77	
9-TD	Tenneco #1 Hardie	2644	3300	682			467	5-69	(8)
10-TD	Tenroc #1 Hardie	2570	2650	312			211	4-81	
11-TD	San Antonio Oil Prod. #1 Adams	1990	2025	402			273	10-56	
12-TD	Tenneco #1 Wilson	2275	2700	900			618	6-67	
13-TD	Mowinkle #1 Mofield	1920	1950	610			417	7-49	
14-TD	Johnson #1-A Howard	2430	2750	557			381	2-65	
15-TD	Thomas & Rife #1 Zadich	-	-	-			-	8-36	(9)
16-TD	Parker & McCune #1 Walker	2180	2240	246			165	9-51	

Table 1. Continued

				Ca	Ct	TDSm	TDSest			
17-TD	Tenneco #1 Carroll	2314	2698	1001			688	10-69		
18-TD	Wood #2 Collins	2557	2685	3153			2178	12-69		
		2720	3050	3987			2756			
19-TD	Wood #1 Collins	2708	2856	2612			1804	5-69		
		2885	3056	4043			2794			
20-TD	Venus #1 Collins	2715	2890	2570			1774	10-79		
		2890	3136	3401			2350			
21-TD	Moncrief #1 Collins	2828	2978	4446			3073	7-68		
		3043	3290	5004			3460			
22-TD	Tenneco #1 Powell	2730	3112	2076			1432	7-67		
23-TD	Hughes & Hughes #1 Plachy	2604	2832	1856			1280	11-68		
		2877	3102	4133			2857			
24-TD	Cities Service #1 Briscoe	2518	2866	440			300	1-72		possible cavern(2492-94'); lost circ. for 2 weeks
25-TD	Hughes & Hughes #1 Keller	2404	2618	2011			1387	6-69		DST 3674-3824' rec. 3500'
		2662	2898	882			606			fresh wtr(700'below Edwds)
26-TD	Hughes & Hughes #1 Cadenhead	2498	2740	1241			854	11-68		
		2766	2912	1005			691			
27-TD	Progress #1 Haass	2685	2910	881			605	1-56		
		3000	3160	723			496			
28-TD	Progress #1 Bendele	2715	2935	520			355	11-54		
		2990	3210	470			320			
29-TD	TD-68-49-813	2605	3098	701	865	562	480	3-73	3-73	(3); lost circ.
		2838	3098	714	821	544	489			
30-TD	Pan Am #1 Knipp	2995	3258	2118			1461	11-65		(10)
		3289	3398	3274			2262			
		3452	3558	3959			2736			

Table 1. Continued

				Ca	Ct	TDSm	TDSest			
31-TD	Pan Am #1 Lilly	3010	3154	1392			959	1-67		
		3226	3362	2816			1945			
		3387	3564	4811			3326			
32-TD	Douglas #1 Watson	2988	3216	2932			2025	2-72		Lost circ. (C.Atkinson); in nearby well (Atkinson #1 K. Seale) bit fell 6', pumped 5 tons LCM, no returns
		3257	3408	2125			1466			
		3450	3500	4895			3384			
33-TD	TD-69-55-5 (Hart-Bar Deer Farm)	1990	2227	226			151	12-89		
34-TD	Lewis #1 Blatz	-	-	-			-	1-41		NDE: used for correlation
35-TD	Fair #1 McAnelly	2080	2580	398			271	11-45		
Uvalde County										
1-YP	Branham #1 Downie	720	850	2857			1973	7-64		
2-YP	Pan Am #1 Houston	100	670	-			-	7-63		(11)
3-YP	Gorman #1 Woodley Ranch	2075	2200	619	620	393	424	6-60	7-74	Same as 33-YP, TD 2575'
		2470	2480	1532			1056			
4-YP	Gorman #2 Woodley Ranch	2150	2380	884	763	484	607	7-60	4-72	Same as 34-YP, TD 1990'
5-YP	Howeth (Michelson) #1 Kincaid	2735	3116	585			400	7-63		DST 2616-2848' rec. 1350' fresh wtr.
		3144	3151	2885			1993			
		3222	3233	4760			3291			
6-YP	International Nuclear #1 Kincaid Ranch	2230	2280	5284			3654	11-68		(12)
7-YP	International Nuclear #2 Kincaid Ranch	1790	1884	6087			4210	12-68		
8-YP	Phillips #2 Kincaid	2520	2620	1909			1317	5-50		
9-YP	Steeger #1 Kincaid	2420	2480	25329			17533	7-61		

Table 1. Continued

				Ca	Ct	TDSm	TDSest			
10-YP	Steeger #2 Kincaid	1885	2040	21983			15216	12-61		
11-YP	Tenneco #1 Kincaid	1940	1975	3504			2421	8-69		
12-YP	Gorman #B-11 Woodley	2350	2500	799			548	3-64		
		2590	2610	3287			2271			
13-YP	Gorman #B-1 Woodley	2470	2500	2445			1688	8-60		
		2660	2700	811			557			
		2915	2970	1045			719			
14-YP	YP-69-51-702		1000		2430	1800			7-85	(2)
15-YP	YP-69-51-703		1580		2740	2100			7-85	(2)
16-YP	YP-69-51-704		1640		3330	2800			7-85	(2)
17-YP	YP-69-51-705		1660		3450	3000			8-85	(2)
18-YP	YP-69-51-501		1050		3320	2380			10-72	(3)
19-YP	YP-69-52-403		1400		3090	2050			7-89	(1)
20-YP	YP-69-51-104		430		920	503			5-89	(1)
21-YP	YP-69-51-112		250		1170	1100			3-85	(2)
22-YP	YP-69-51-115		570		885	560			3-85	(2)
23-YP	YP-69-51-102		391		639	390			3-85	(2)
24-YP	Gorman #B-5 Woodley	2410	2420	1225			843	10-60		
25-YP	Gorman #B-9 Woodley	2400	2415	1226			844	2-61		
26-YP	Gorman #B-10 Woodley	2260	2280	705			483	3-61		
27-YP	Pan Am #1 Jernigan	100	800	-			-	6-63		(11)
28-YP	YP-69-43-9 (Friesenhahn)	1010	1050	915			629	4-90		
29-YP	YP-69-50-803 (Willoughby)	696	770	2635			1819	11-90		

Table 1. Continued

				Ca	Ct	TDSm	TDSest			
30-YP	YP-69-58-3 (General Tire Co.)	1830	1890	9152			6332	7-88		
31-YP	YP-69-44-8 (Mosing/4-M Ranch)	932	1394	1043			717	8-89		
32-YP	YP-69-50-100 (Duval)	680	750	529			361	3-88		
33-YP	YP-69-53-701		2575		620	393			7-74	(3);Ct est.from TDS; same as 3-YP
34-YP	YP-69-53-703		1990		763	484			4-72	(3); same as 4-YP
Zavala County										
1-ZX	Andreen #1 Batesville Farming	3654	3708	36654			25375	3-75		
2-ZX	Bluebonnet #1 Kincaid	3570	4268	3326			2298	5-54		
3-ZX	Rowe #1 Kincaid	3643	4248	3193			2206	12-68		
4-ZX	Humble (Exxon) #1 Kincaid	2900	2990	2154			1486	5-61		
5-ZX	Humble (Exxon) #3 Kincaid	3320	3460	3619			2501	6-63		
6-ZX	Venus #1 Capps Ranch	3878	3933	-			-	8-77		NDE
7-ZX	Magnolia #1 Capps	3654	3670	11044			7642	10-48		
8-ZX	ZX-69-61-526		N/A		3920	3300	-		3-75	(3)

Ca = Calculated specific conductance in micromhos/cm @77°F
Ct = Measured specific conductance in micromhos/cm @77°F
TDSm = Measured total dissolved solids in mg/L
TDSest = Estimated total dissolved solids in mg/L

Remarks:
(1) EUWD, Bulletin #49, 1990
(2) EUWD, Bulletin #45, 1987

(3) TX Dept. Water Res., LP-131, 1980
(4) 380'+ fault @2000'±; values calc. are for upper part of Edwds only - on downthrown side of fault
(5) Samples - lt. tan lm, white porous lm, lost circ @4,000'; no log 3890-4360'
(6) No drill returns 4456-5056' - lost circ; used for porosity control, correlation & information
(7) Samples in porous intervals described as wht, tan, cream-wht in color, porosity is obvious in samples
(8) $R_{(m)} \cong R_{(w)}$ - since $R_{(LL8)} \cong R_{(ILM)} = R_{(ILD)}$, $C_t \cong 429$; lost circ. @3110-20' (log depth) - possible cavern
(9) DST 3210-37½' rec. 650' fluid: sli brackish & sulphur wtr, w/lt flecks of free oil; DST 3210-3243' rec. 590' fluid: not very brackish, sli sulph. taste; insufficient porous Edwds logged
(10) DST on perfs. 3160-3210', rec 25 bbls. fresh wtr, 500 ppm cl & sulph. odor; IFP 899#, FFP 1339#, FSIP 1339#, IHP 1665#, FHP 1665#
(11) No calculation; correlation problem due to volcanic activity and/or faulting
(12) Bit fell 10' @ 2324' (cavern); lost circ. - no circ. 2324-2781'

Table 2. Calculated and measured specific conductance and measured total dissolved solids from selected area wells (used as control data for construction of figures 5, 6, and 7).

Well Number	Other well identification	Zone calculated		Test interval or well depth		Ct	Ca	TDS	Remarks
		from:	to:	from:	to:				
AY-68-29-913		479	730		799	483	313	274	
AY-1	Coastal States #1 Loessberg	1898	2222		2292	636	802	394	(1);control well: AY-68-43-811
AY-68-37-526	(1-D)	848	1010	854	1052	475	476	260	(5)
TD-17	Tenneco #1 Carroll	2314	2698			759	1001	518	(3);control well: AL-68-50-201
TD-68-49-813	TD-29	2605	3098	2600	3200	865	701	562	(3)
		2838	3098	2800	3200	821	714	544	(3)
DX-68-23-617		515	528	470	528	595	494	420	(4)
		515	554	470	560	557	534	410	(4)
DX-68-23-616		488	500	445	505	2460	2811	1567	(4)
		554	625	535	635	3170	3718	2083	(4)
		848	901	800	935	5540	5304	3560	(4)
LR-67-01-812		478	490	403	508	13000	13989	8943	(4)
		528	770	509	707	14400	12526	10348	(4)
LR-67-01-813		490	497	416	520	14000	16044	9039	(4)
		544	550	520	584	14300	13835	10222	(4)
		762	770	746	920	14500	13097	10007	(4)
AY-68-37-524		1270	1311	1240	1396	5870	5629	4600	(5)
		1071	1236	1056	1396	5860	5581	4400	(5)
AY-68-37-521		1014	1026	965	1019	3198	3185	2200	(5)
		1040	1064	965	1071	3324	3810	2200	(5)
AL-1	Tenneco #1 P.R. Smith	2306	2858		2650	2130	2680	1600	(2);control well: AL-68-51-101

Table 2. Continued

Ca = Calculated specific conductance in micromhos/cm @77°F
Ct = Measured specific conductance in micromhos/cm @77°F

TDS = Total dissolved solids in mg/L

Remarks:
(1) EUWD, Bulletin #49, 1990
(2) EUWD, Bulletin #45, 1987
(3) TX Dept. Water Res., LP-131, 1980
(4) Measured data supplied by EUWD, 1991
(5) USGS, OF-87-389, 1987

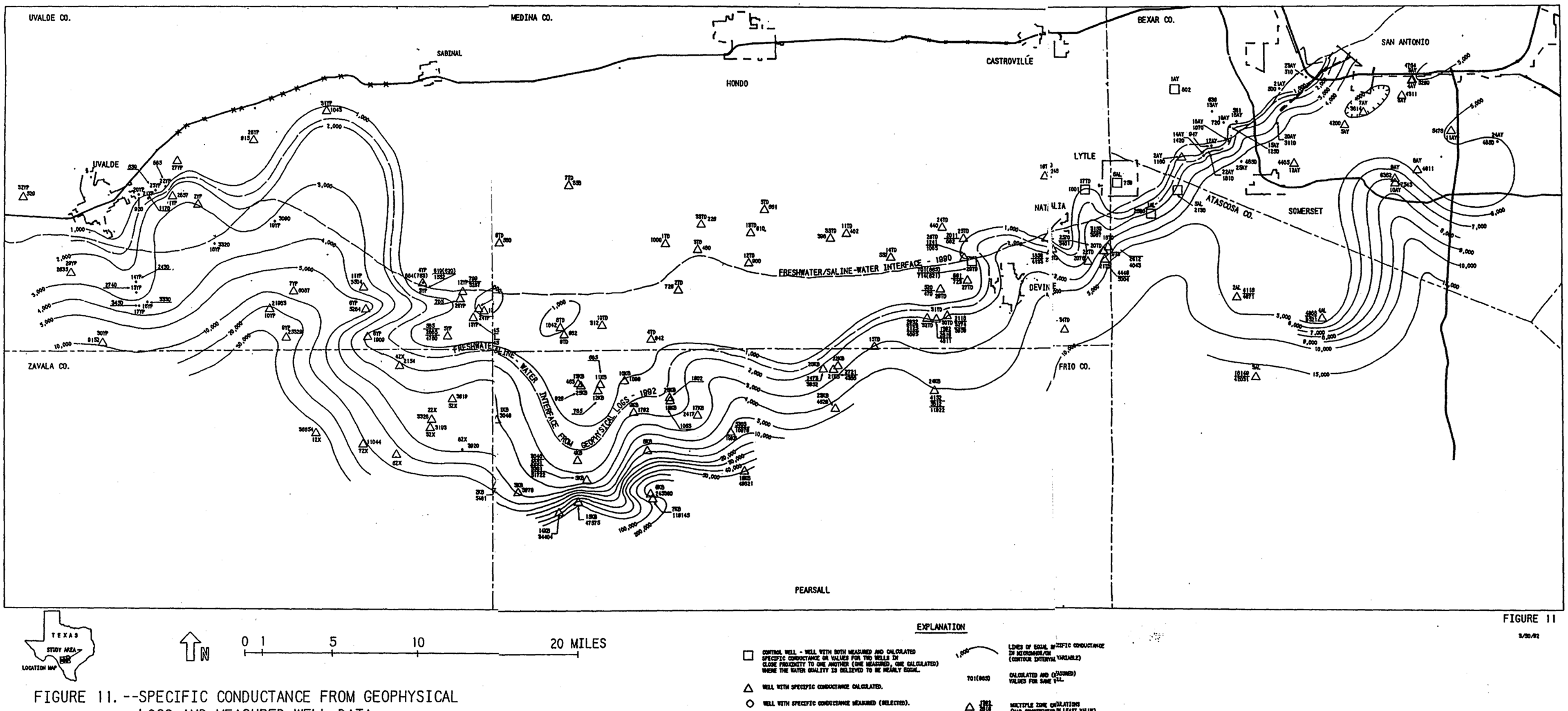
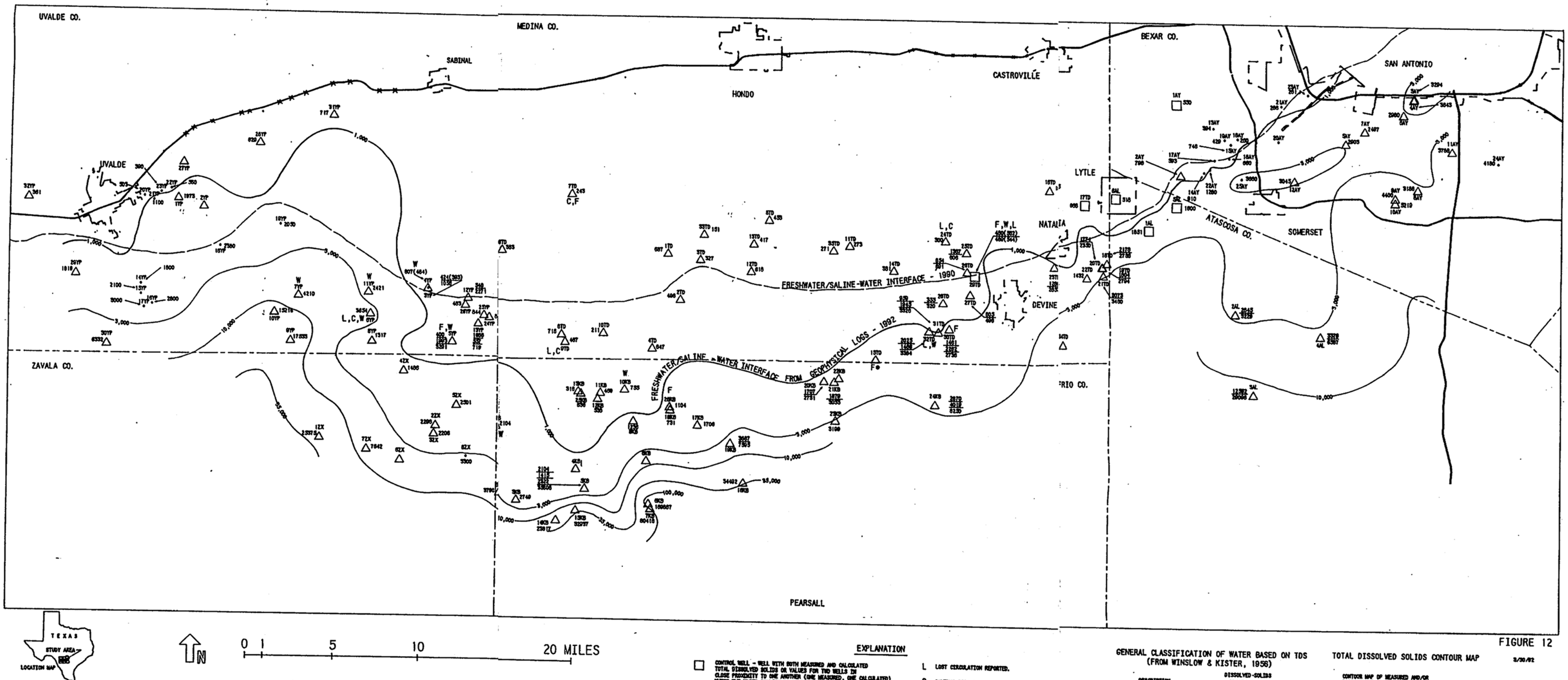


FIGURE 11.--SPECIFIC CONDUCTANCE FROM GEOPHYSICAL LOGS AND MEASURED WELL DATA.

SEE PLATE 2 IN BACK COVER



EXPLANATION

- □ CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED TOTAL DISSOLVED SOLIDS OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.
- △ WELL WITH TOTAL DISSOLVED SOLIDS CALCULATED.
- ○ WELL WITH TOTAL DISSOLVED SOLIDS MEASURED (SELECTED).
- 1,000 LINES OF EQUAL ESTIMATED TDS IN MG/L (CONTOUR INTERVAL VARIABLE).
- L LOST CIRCULATION REPORTED.
- C CAVERNS REPORTED OR OBSERVED ON LOGS.
- F FRESH WATER REPORTED ON DST - (MAY NOT BE LESS THAN 1000 MG L TDS)
- F● BRACKISH IN TOP, FRESHER 5' DEEPER.
- W WHITE, CREAM OR TAN SAMPLE DESCRIPTIONS REPORTED IN EDWARDS.

GENERAL CLASSIFICATION OF WATER BASED ON TDS (FROM WINSLOW & KISTER, 1956)

DESCRIPTION	DISSOLVED-SOLIDS CONCENTRATION MG/L
FRESH	LESS THAN 1,000
SLIGHTLY SALINE	1,000 TO 3,000
MODERATELY SALINE	3,000 TO 10,000
VERY SALINE	10,000 TO 35,000
BRINE	GREATER THAN 35,000

FIGURE 12

TOTAL DISSOLVED SOLIDS CONTOUR MAP

3/30/92

CONTOUR MAP OF MEASURED AND/OR ESTIMATED (●) TOTAL DISSOLVED SOLIDS (IN MG/L).

● - ESTIMATED FROM GEOPHYSICAL LOGS USING EMPIRICAL DATA (FIGURE 7)

480(352) - ESTIMATED (MEASURED) VALUES FOR SAME WELL.

1979/3035 - MULTIPLE ZONE VALUES FOR ONE WELL.

FIGURE 12. --TOTAL DISSOLVED SOLIDS CONTOUR MAP
SEE PLATE 3 IN BACK COVER.

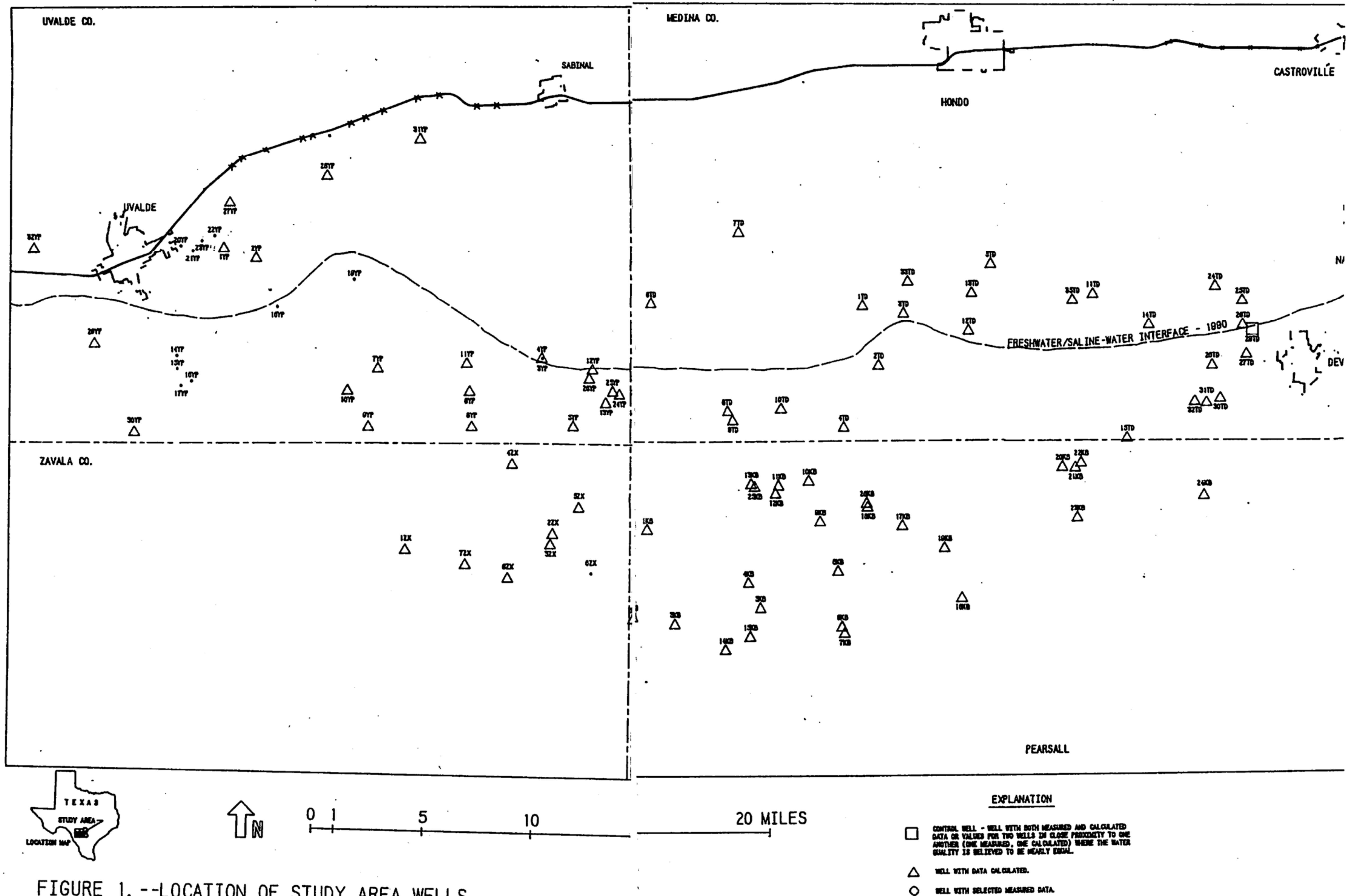


FIGURE 1.--LOCATION OF STUDY AREA WELLS.
SEE PLATE 1 IN BACK COVER.

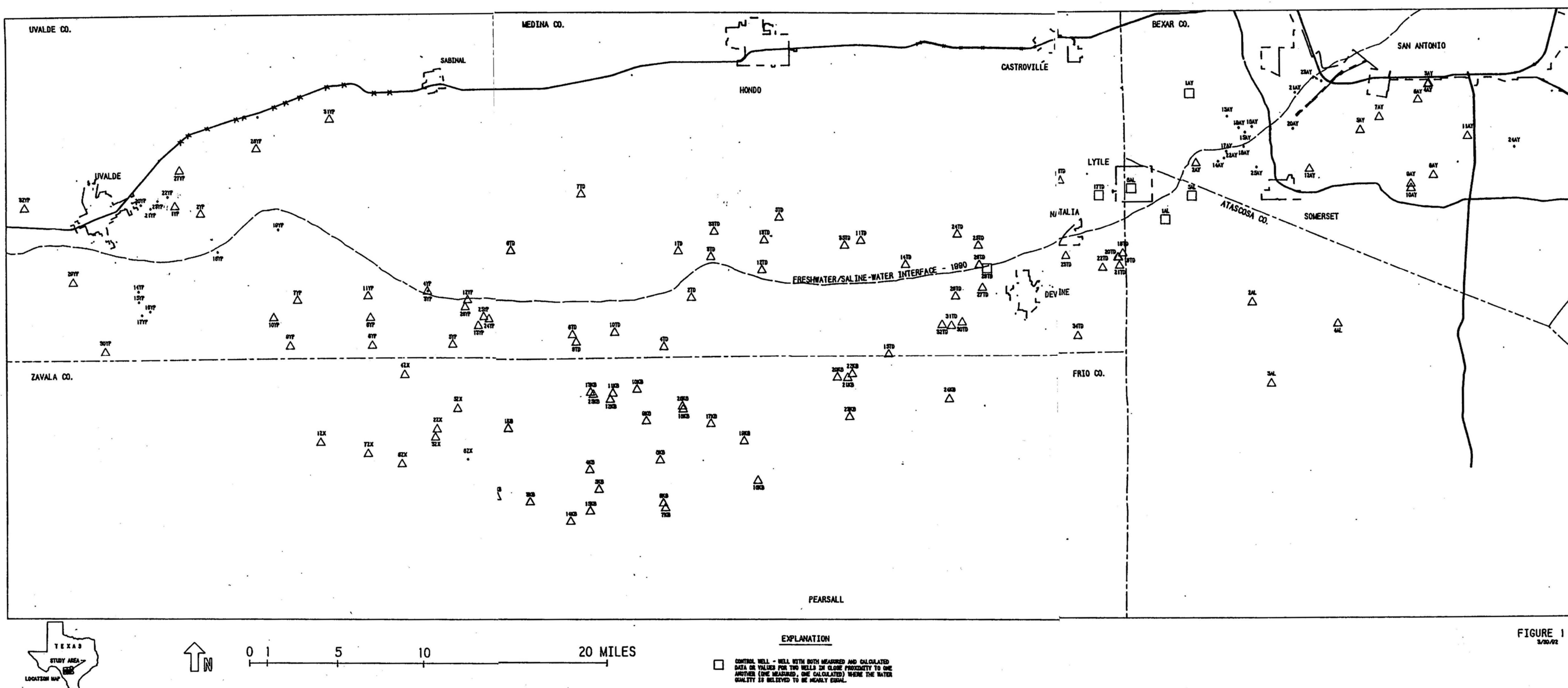


FIGURE 1.--LOCATION OF STUDY AREA WELLS.
SEE PLATE 1 IN BACK COVER.

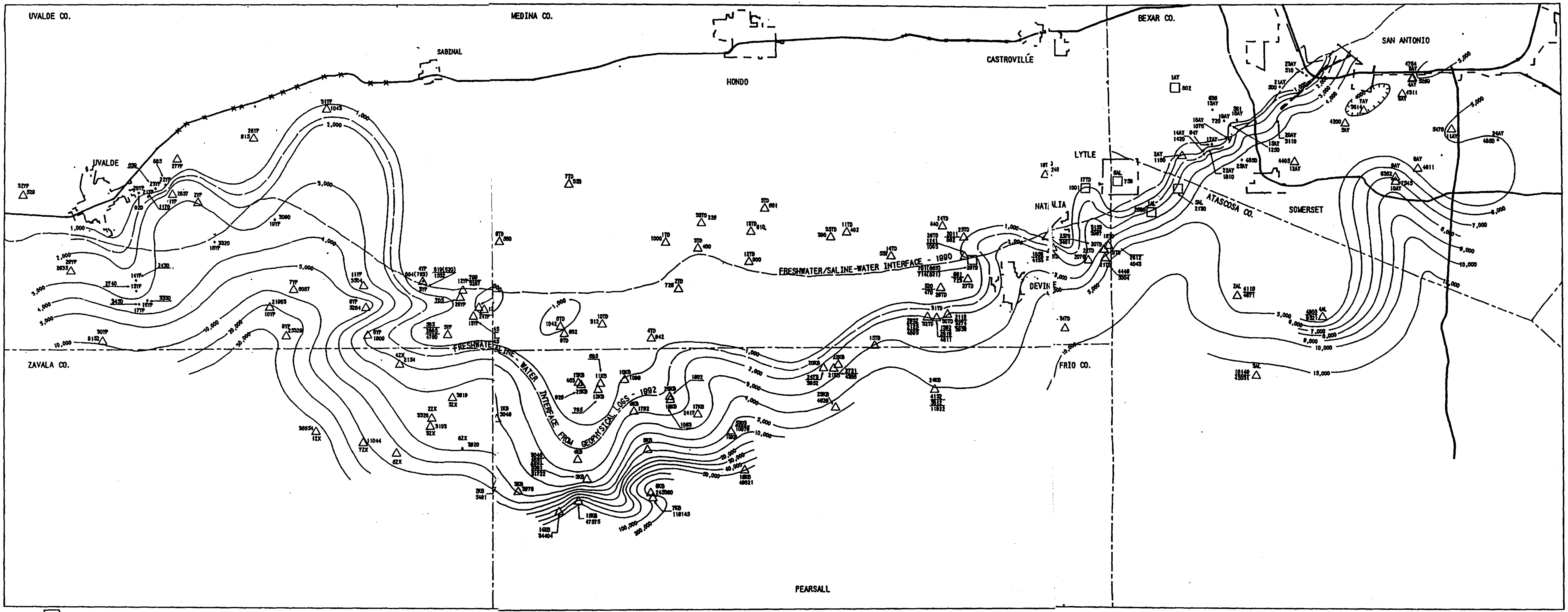
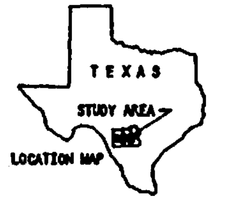


FIGURE 11



N

0 1 5 10 20 MILES

EXPLANATION

CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED SPECIFIC CONDUCTANCE OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.

WELL WITH SPECIFIC CONDUCTANCE CALCULATED.

WELL WITH SPECIFIC CONDUCTANCE MEASURED (SELECTED).

1,000 LINES OF EQUAL SPECIFIC CONDUCTANCE IN MICROMHOS/CM (CONTOUR INTERVAL VARIABLE)

701(863) CALCULATED AND (MEASURED) VALUES FOR SAME WELL.

MULTIPLE ZONE CALCULATIONS (MAP CONSTRUCTED ON LEAST VALUE).

FIGURE 11.--SPECIFIC CONDUCTANCE FROM GEOPHYSICAL LOGS AND MEASURED WELL DATA.

SEE PLATE 2 IN BACK COVER

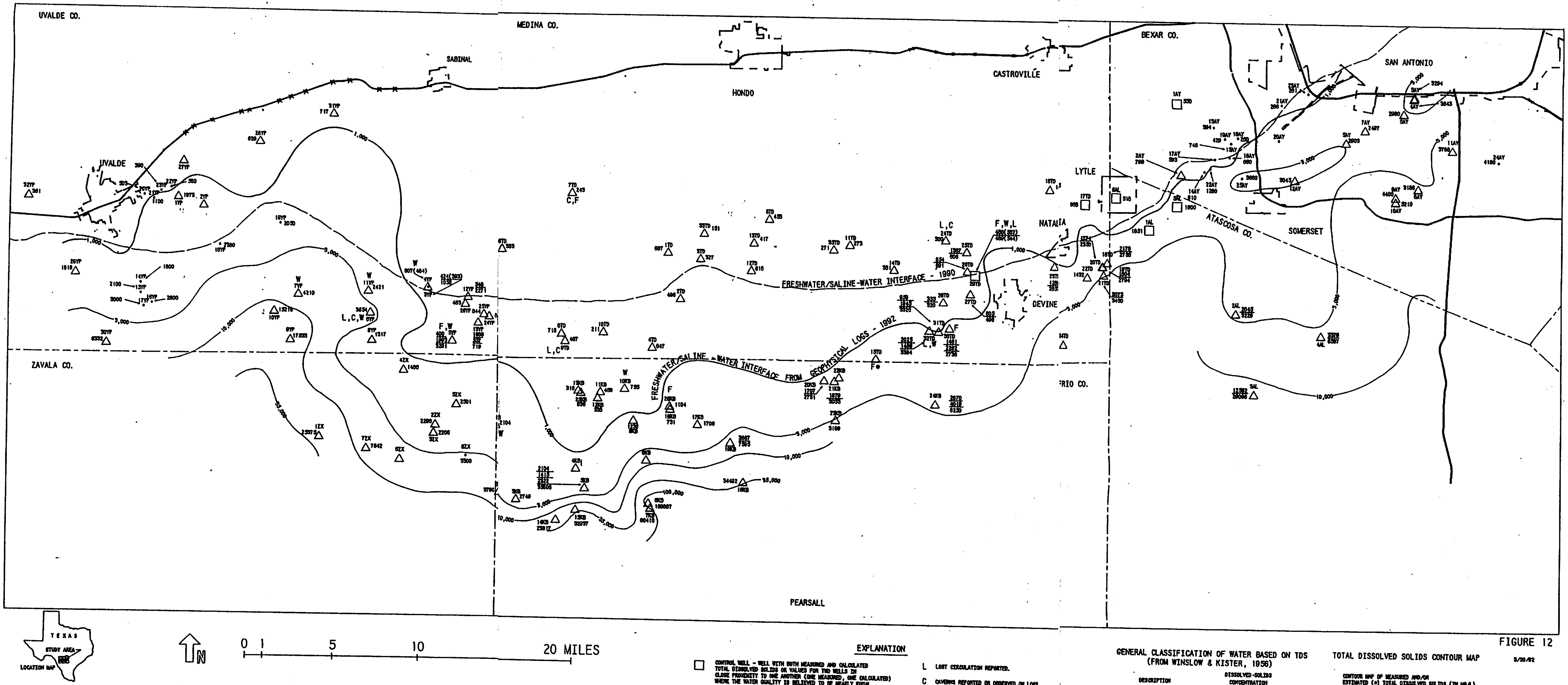


FIGURE 12.--TOTAL DISSOLVED SOLIDS CONTOUR MAP
SEE PLATE 3 IN BACK COVER.

EXPLANATION

- □ CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED TOTAL DISSOLVED SOLIDS OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.
- △ WELL WITH TOTAL DISSOLVED SOLIDS CALCULATED.
- ○ WELL WITH TOTAL DISSOLVED SOLIDS MEASURED (SELECTED).
- 1,000 LINES OF EQUAL ESTIMATED TDS IN MG/L (CONTOUR INTERVAL VARIABLE).
- L LOST CIRCULATION REPORTED.
- C CAVERNS REPORTED OR OBSERVED ON LOGS.
- F FRESH WATER REPORTED ON DST - (MAY NOT BE LESS THAN 1000 MG L TDS)
- F• BRACKISH IN TOP, FRESHER 5' DEEPER.
- W WHITE, CREAM OR TAN SAMPLE DESCRIPTIONS REPORTED IN EDWARDS.

GENERAL CLASSIFICATION OF WATER BASED ON TDS (FROM WINSLOW & KISTER, 1956)

DESCRIPTION	DISSOLVED-SOLIDS CONCENTRATION MG/L
FRESH	LESS THAN 1,000
SLIGHTLY SALINE	1,000 TO 3,000
MODERATELY SALINE	3,000 TO 10,000
VERY SALINE	10,000 TO 35,000
BRINE	GREATER THAN 35,000

FIGURE 12

TOTAL DISSOLVED SOLIDS CONTOUR MAP

3/30/92

CONTOUR MAP OF MEASURED AND/OR ESTIMATED (•) TOTAL DISSOLVED SOLIDS (IN MG/L).

- • - ESTIMATED FROM GEOPHYSICAL LOGS USING EMPIRICAL DATA (FIGURE 7)
- 480(552) - ESTIMATED (MEASURED) VALUES FOR SAME WELL.
- 1979/3033 - MULTIPLE ZONE VALUES FOR ONE WELL.

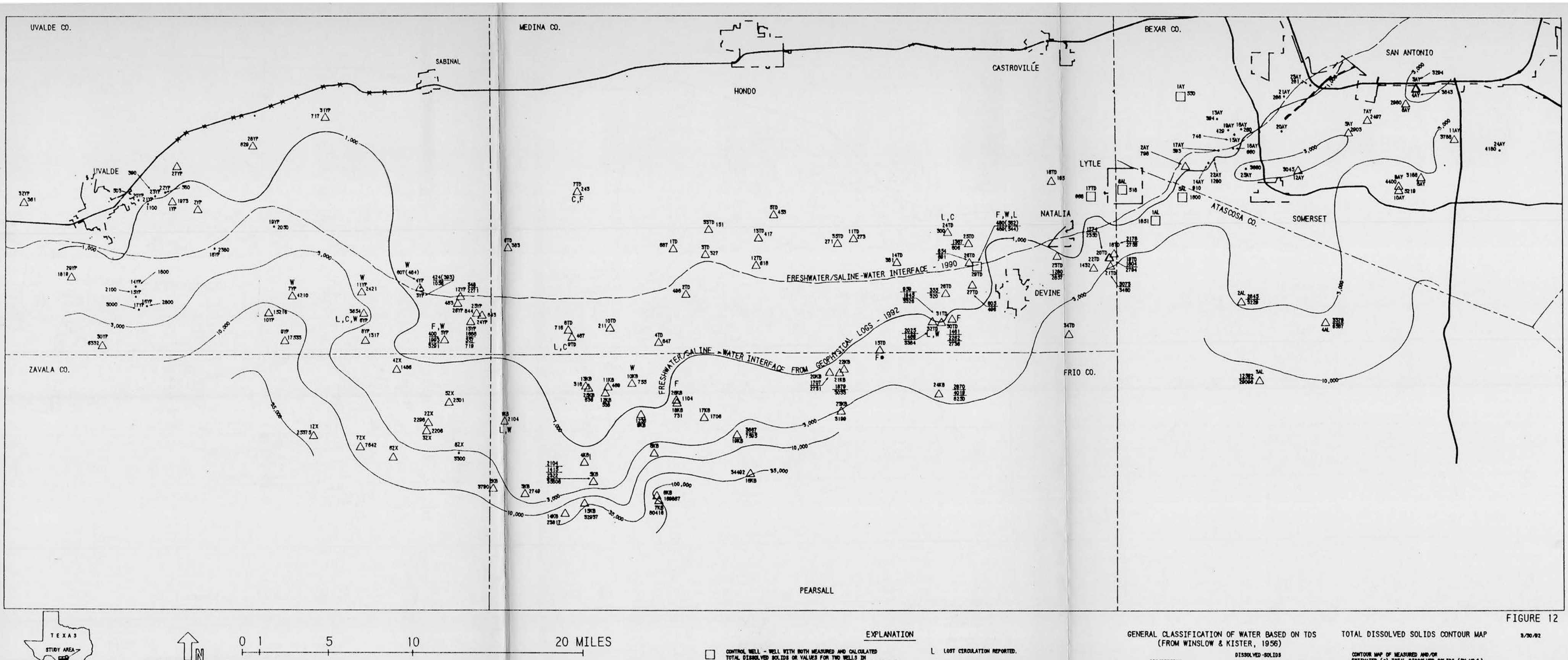


FIGURE 12

EXPLANATION

□ CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED TOTAL DISSOLVED SOLIDS OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.

△ WELL WITH TOTAL DISSOLVED SOLIDS CALCULATED.

○ WELL WITH TOTAL DISSOLVED SOLIDS MEASURED (SELECTED).

1,000 LINES OF EQUAL ESTIAMTED TDS IN MG/L (CONTOUR INTERVAL VARIABLE).

L LOST CIRCULATION REPORTED.

C CAVERNS REPORTED OR OBSERVED ON LOGS.

F FRESH WATER REPORTED ON DST - (MAY NOT BE LESS THAN 1000 MG L TDS)

F• BRACKISH IN TOP, FRESHER 5' DEEPER.

W WHITE, CREAM OR TAN SAMPLE DESCRIPTIONS REPORTED IN EDWARDS.

GENERAL CLASSIFICATION OF WATER BASED ON TDS (FROM WINSLOW & KISTER, 1956)

DESCRIPTION	DISSOLVED-SOLIDS CONCENTRATION MG/L
FRESH	LESS THAN 1,000
SLIGHTLY SALINE	1,000 TO 3,000
MODERATELY SALINE	3,000 TO 10,000
VERY SALINE	10,000 TO 35,000
BRINE	GREATER THAN 35,000

TOTAL DISSOLVED SOLIDS CONTOUR MAP

3/30/92

CONTOUR MAP OF MEASURED AND/OR ESTIMATED (•) TOTAL DISSOLVED SOLIDS (IN MG/L).

• - ESTIMATED FROM GEOPHYSICAL LOGS USING EMPIRICAL DATA (FIGURE 7)

480(582) - ESTIMATED (MEASURED) VALUES FOR SAME WELL.

$\frac{1879}{3033}$ - MULTIPLE ZONE VALUES FOR ONE WELL.

FIGURE 12. --TOTAL DISSOLVED SOLIDS CONTOUR MAP
SEE PLATE 3 IN BACK COVER.

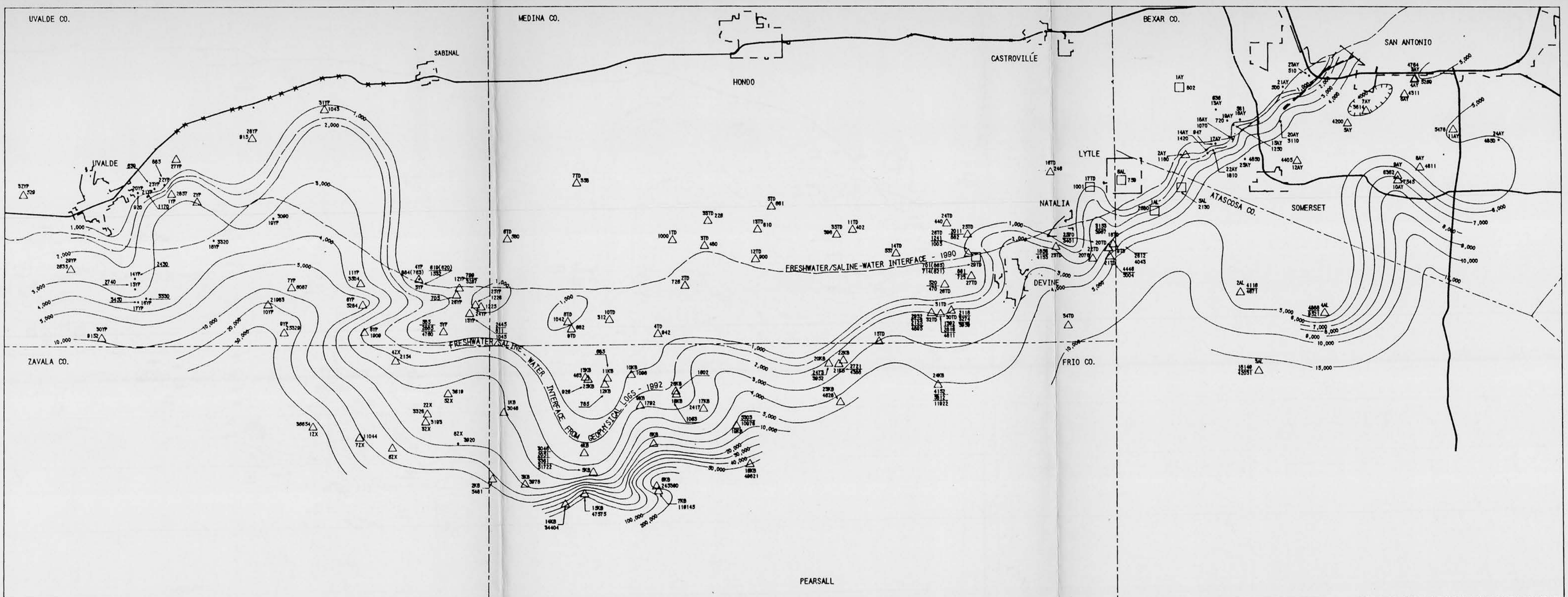
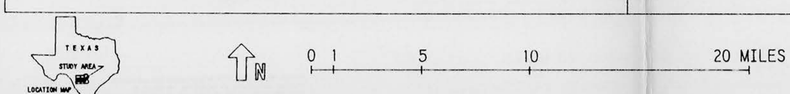


FIGURE 11

3/30/92



EXPLANATION

□ CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED SPECIFIC CONDUCTANCE OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.

△ WELL WITH SPECIFIC CONDUCTANCE CALCULATED.

○ WELL WITH SPECIFIC CONDUCTANCE MEASURED (SELECTED).

1,000 LINES OF EQUAL SPECIFIC CONDUCTANCE IN MICROMHOS/CM (CONTOUR INTERVAL VARIABLE)

701(865) CALCULATED AND (MEASURED) VALUES FOR SAME WELL.

△ 1302 2816 4811 MULTIPLE ZONE CALCULATIONS (MAP CONSTRUCTED ON LEAST VALUE).

FIGURE 11.--SPECIFIC CONDUCTANCE FROM GEOPHYSICAL LOGS AND MEASURED WELL DATA.
SEE PLATE 2 IN BACK COVER

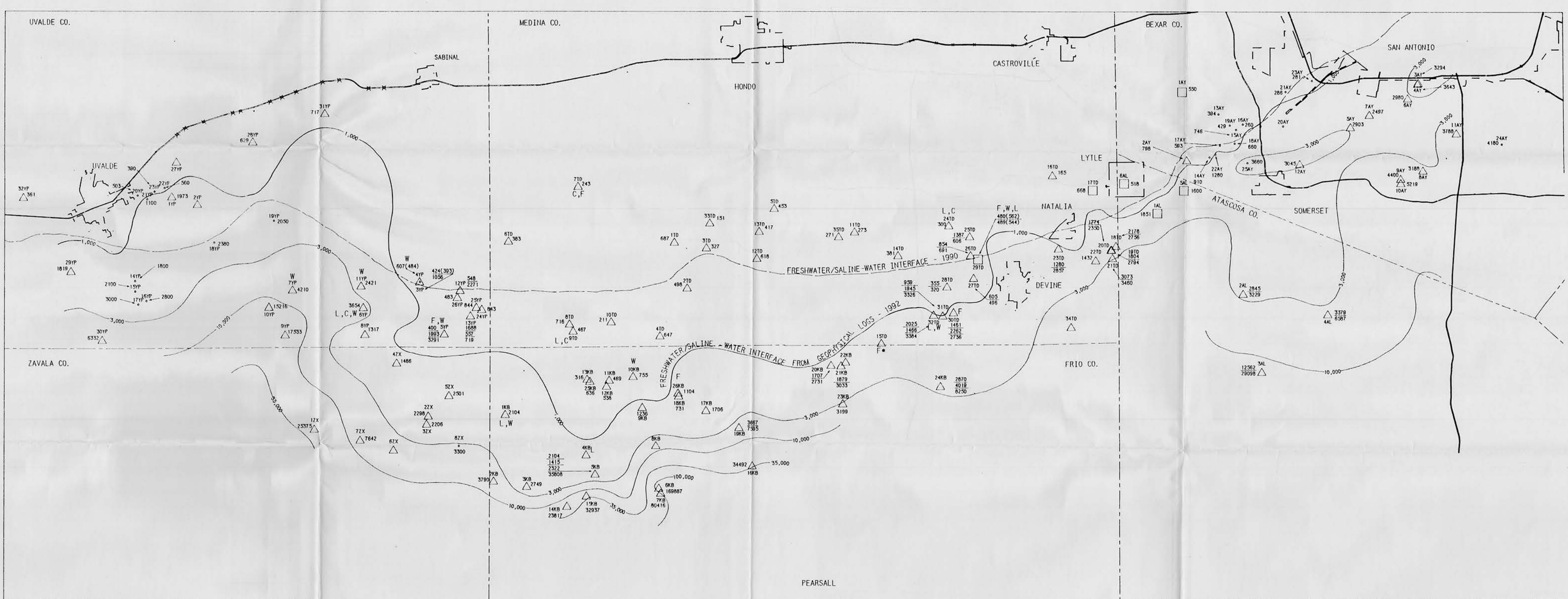


FIGURE 12

N

0 1 5 10 20 MILES

PLATE 3. --TOTAL DISSOLVED SOLIDS CONTOUR MAP

EXPLANATION

□ CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED TOTAL DISSOLVED SOLIDS OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.

△ WELL WITH TOTAL DISSOLVED SOLIDS CALCULATED.

◇ WELL WITH TOTAL DISSOLVED SOLIDS MEASURED (SELECTED).

1,000 LINES OF EQUAL ESTIAMTED TDS IN MG/L (CONTOUR INTERVAL VARIABLE).

L LOST CIRCULATION REPORTED.

C CAVERNS REPORTED OR OBSERVED ON LOGS.

F FRESH WATER REPORTED ON DST - (MAY NOT BE LESS THAN 1000 MG/L TDS)

F* BRACKISH IN TOP, FRESHER 5' DEEPER.

W WHITE, CREAM OR TAN SAMPLE DESCRIPTIONS REPORTED IN EDWARDS.

GENERAL CLASSIFICATION OF WATER BASED ON TDS (FROM WINSLOW & KISTER, 1956)

DESCRIPTION	DISSOLVED-SOLIDS CONCENTRATION MG/L
FRESH	LESS THAN 1,000
SLIGHTLY SALINE	1,000 TO 3,000
MODERATELY SALINE	3,000 TO 10,000
VERY SALINE	10,000 TO 35,000
BRINE	GREATER THAN 35,000

TOTAL DISSOLVED SOLIDS CONTOUR MAP

3/30/92

CONTOUR MAP OF MEASURED AND/OR ESTIMATED (•) TOTAL DISSOLVED SOLIDS (IN MG/L).

• - ESTIMATED FROM GEOPHYSICAL LOGS USING EMPIRICAL DATA (FIGURE 7)

480(562) , ESTIMATED (MEASURED) VALUES FOR SAME WELL.

$\frac{1879}{3033}$, MULTIPLE ZONE VALUES FOR ONE WELL.

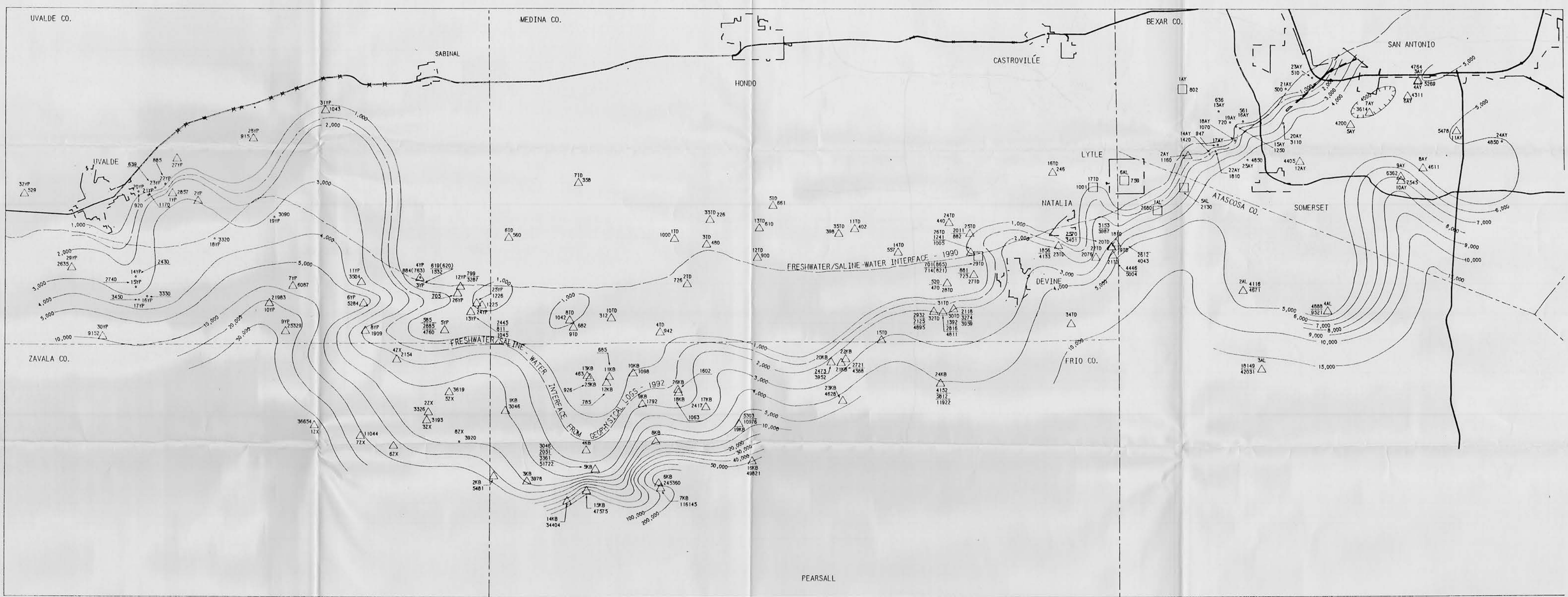


FIGURE 11

3/30/92

TEXAS

STUDY AREA

LOCATION MAP

N

0 1 5 10 20 MILES

EXPLANATION

CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED SPECIFIC CONDUCTANCE OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.

WELL WITH SPECIFIC CONDUCTANCE CALCULATED.

WELL WITH SPECIFIC CONDUCTANCE MEASURED (SELECTED).

1,000 LINES OF EQUAL SPECIFIC CONDUCTANCE IN MICROMHOS/CM (CONTOUR INTERVAL VARIABLE)

701(865) CALCULATED AND (MEASURED) VALUES FOR SAME WELL.

1392 / 2816 / 4811 MULTIPLE ZONE CALCULATIONS (MAP CONSTRUCTED ON LEAST VALUE).

PLATE 2.--SPECIFIC CONDUCTANCE FROM GEOPHYSICAL LOGS AND MEASURED WELL DATA.

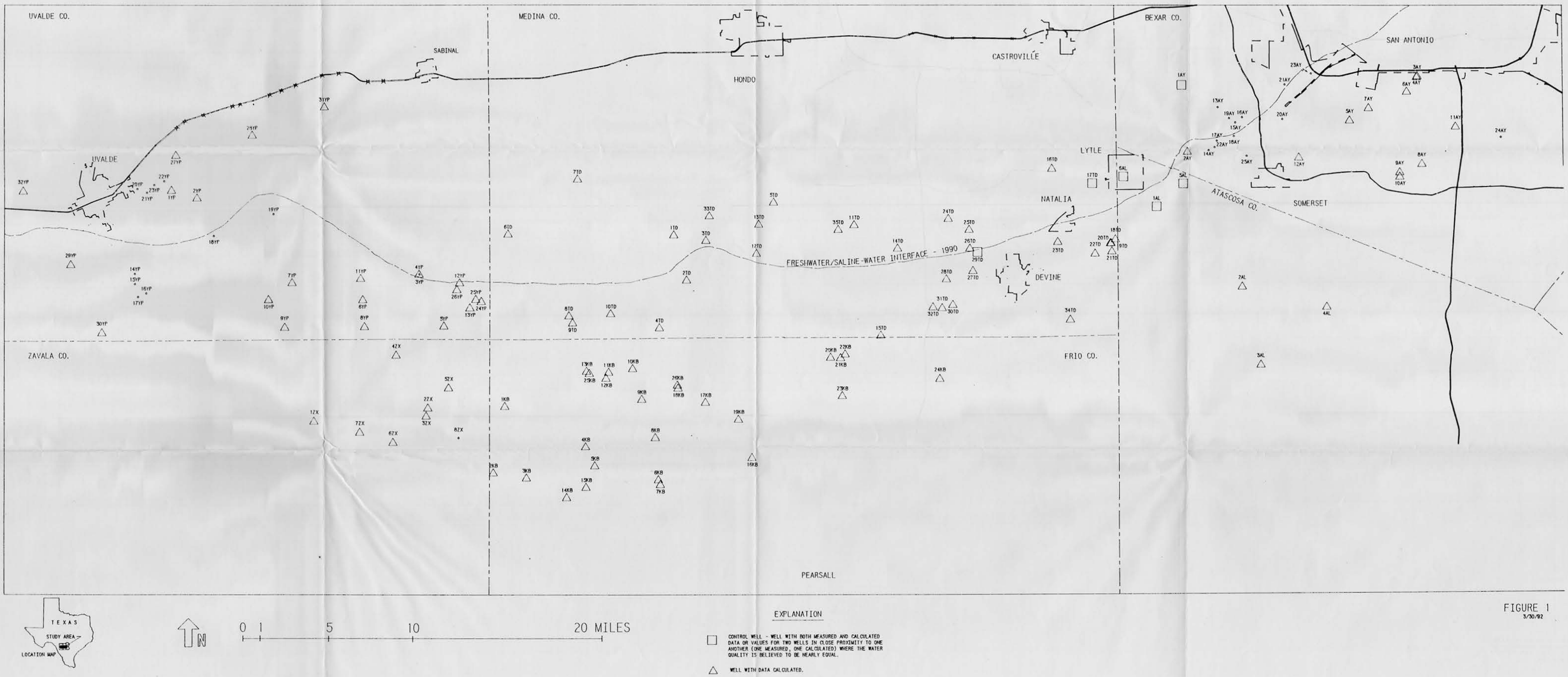


FIGURE 1
3/30/92

EXPLANATION

□ CONTROL WELL - WELL WITH BOTH MEASURED AND CALCULATED DATA OR VALUES FOR TWO WELLS IN CLOSE PROXIMITY TO ONE ANOTHER (ONE MEASURED, ONE CALCULATED) WHERE THE WATER QUALITY IS BELIEVED TO BE NEARLY EQUAL.

△ WELL WITH DATA CALCULATED.

○ WELL WITH SELECTED MEASURED DATA.

PLATE 1.--LOCATION OF STUDY AREA WELLS.

Note: Large-format versions of the plates for this report are available in a companion document.