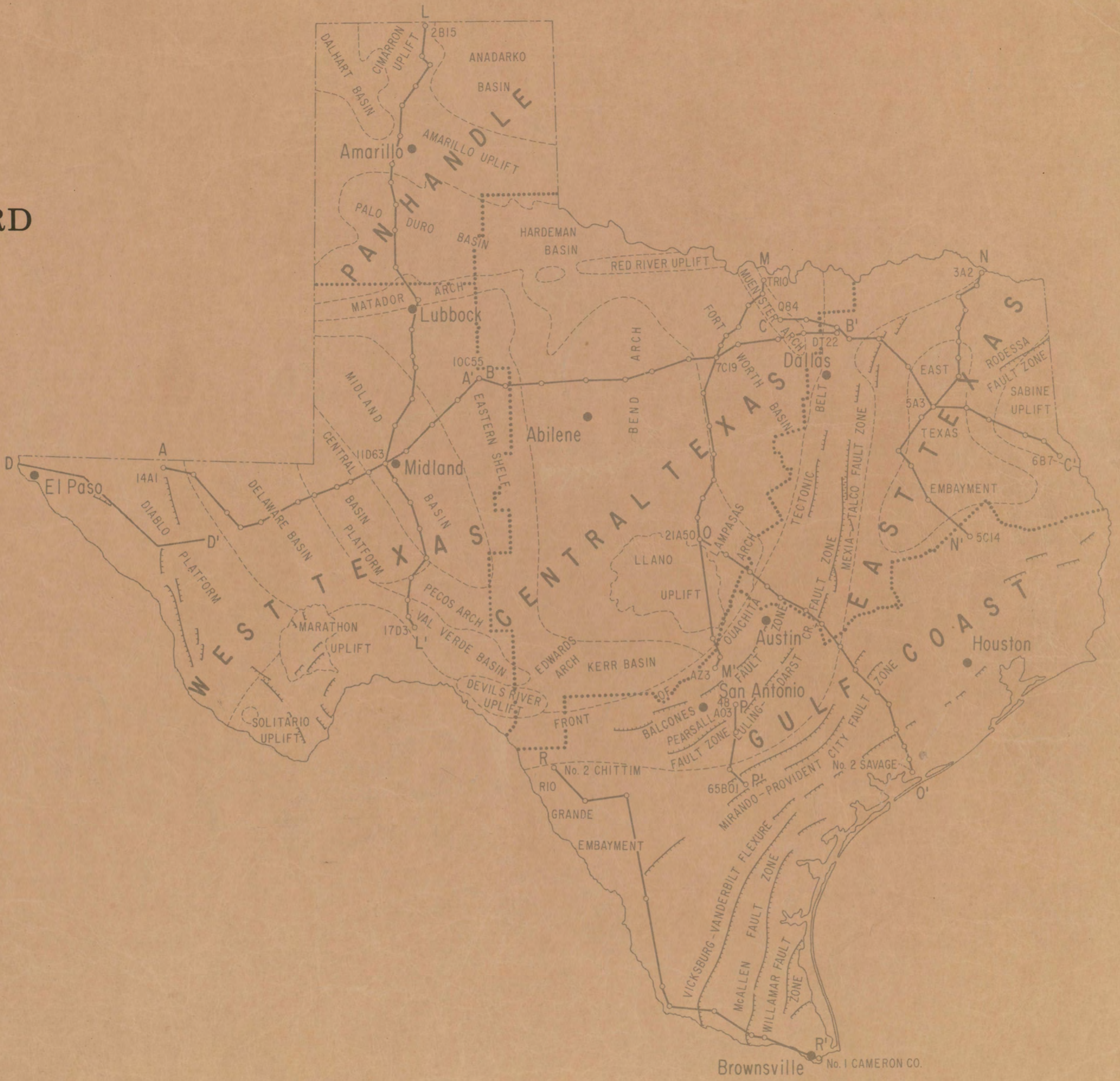
TEXAS WATER DEVELOPMENT BOARD

REPORT 157

# A SURVEY OF THE SUBSURFACE SALINE WATER OF TEXAS

VOLUME 1

*October 1972*



# TEXAS WATER DEVELOPMENT BOARD

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# A SURVEY OF THE SUBSURFACE SALINE WATER OF TEXAS

## VOLUME 1

*October 1972*

Prepared by CORE LABORATORIES, INC.
Consulting & Engineering Department, Dallas, Texas
under contract for the
Texas Water Development Board

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# FOREWORD

Texas has substantial saline and brackish ground-water resources which are amenable to desalting for the production of additional fresh water supplies. Although desalting is a relatively new technology, desalted water is presently being used, as of early 1972, by three Texas cities for all or part of their water supply, and industrial desalting plants are in operation in at least 25 locations. Additional plants are currently being considered or planned for construction. Also, some additional improvements that are expected in the desalting processes and techniques will allow higher efficiencies at lower operating costs. Desalting, then, has a very significant place in supplying part of Texas' future water needs.

This report provides a basic reference to the occurrence, availability, and quality of saline and brackish ground-water resources as part of the statewide inventory of ground-water resources. The information and data are expected to be particularly useful in future feasibility studies concerning cities and other water users having a potential for meeting their fresh-water requirements through desalting.

The complete report has been prepared in eight volumes. Volume 1 includes a descriptive inventory of the principal saline aquifers and their characteristics, and more than 100 geologic maps and sections which illustrate aquifer location, thickness, structure, and salinity.

Volumes 2 through 8 consist entirely of computer-listed tables of supporting basic data. These will not be needed by most readers, but will be useful to those making detailed studies of local areas. Accordingly, these tabulations have been published in smaller quantity for distribution to parties specifically requesting them after receipt of Volume 1. Contents of the basic-data volumes are as follows:

Volume 2—Chemical Analyses of Saline Water

Volume 3—Aquifer Rock Properties (porosities, permeabilities, ideal specific flow rates)

Volume 4—Geologic Well Data—West Texas (formation depths in wells, thicknesses, lithologies)

Volume 5—Geologic Well Data—Panhandle

Volume 6—Geologic Well Data—Central Texas

Volume 7—Geologic Well Data—East Texas

Volume 8—Geologic Well Data—Gulf Coast

The statewide reconnaissance investigation and preparation of the eight-volume report were accomplished under contract by Core Laboratories, Incorporated. The Water Development Board believes the report to be a major contribution to the body of information required for adequate water development and management in Texas, and expresses its appreciation to Core Laboratories, Incorporated for completion of the project within severe time constraints. Work commenced August 1, 1970, and the report was completed September 1, 1971.

TEXAS WATER DEVELOPMENT BOARD

Harry P. Burleigh

Harry P. Burleigh
Executive Director

# TABLE OF CONTENTS

## TABLES

## FIGURES

### CROSS SECTIONS

### MAPS

## TABLE OF CONTENTS (Cont'd.)

# A SURVEY OF THE SUBSURFACE SALINE WATER OF TEXAS

## INTRODUCTION

### Purpose and Scope

This report presents the results of an investigation of the major saline aquifers in the State of Texas. It was done by Core Laboratories, Inc. for the Texas Water Development Board in fulfillment of a contract dated August 1, 1970.

The purpose of the study was to make a reconnaissance and inventory of the principal saline aquifers of the State. The ultimate use of such an inventory is to serve as a basic reference to the occurrence and availability of large quantities of subsurface saline water that could be utilized in future desalting operations. The study was conducted and has been presented in three basic parts: the salinity of the aquifers, the productivity of the aquifers, and the geology of the aquifers.

The work is intended to provide the Texas Water Development Board with a means of determining which aquifers, if any, are present in all regions of the State that would satisfy the requirements of large-scale withdrawals of water. Through the application of the basic data and interpreted geology presented in the three parts of the study, the depth, thickness, and areal extent of aquifers along with their salinity and ideal producing capacities can be determined. From the use of all these data, potentially productive areas can be predicted and more detailed studies can be outlined.

The aquifer salinity inventory consists of a computer listing of total dissolved solids, sorted by formation and depth and listed by counties. This list was compiled from several sources of data and includes both complete chemical analyses and also those calculations of total dissolved solids which were derived from formation water resistivities (Rw). Many of these resistivities were calculated from spontaneous potential (S.P.) logs during the study. The resulting compilation was then used as basic salinity data to construct salinity maps of formations where data were sufficient.

The aquifer productivity portion of this report consists of an extensive computer listing of the basic rock properties of porosity and permeability, sorted by depth ranges and by geological formation and listed by counties. From these basic data, a calculation was made which gives the ideal specific flow rate of the aquifer on a county-wide average. A nomograph was constructed using the various parameters that go into this calculation and is included in this report. From the nomograph, rapid calculations for individual aquifers or wells can be made. The basic data for such calculations can be obtained from the listings and map interpretations provided in this report.

The geological portions of the study resulted in the mapping of saline aquifers through the development of structural and isopachous maps, as well as the salinity maps previously mentioned. The basic geological data were mostly obtained using well logs. Most of the stratigraphic correlations were based on work which was contracted, for use in this study, by Core Laboratories, Inc. to the Geo Mapping Company of Dallas, Texas (Central Texas Mapping Service, East Texas Mapping Service, Middle Texas Gulf Coast Mapping Service, Upper Texas Gulf Coast Mapping Service, West Texas-Southeast New Mexico Mapping Service, and Western Oklahoma-Texas Panhandle Mapping Service). Other correlations were taken from various literature sources, and all correlations were extended and extrapolated by Core Laboratories, Inc. geologists. More than 1,600 wells were correlated and encoded into a computer listing. The list is included as part of this report. Regional isopachous maps were constructed for each aquifer and consist of either a net or gross thickness map of the appropriate unit, depending on the complexity encountered in selecting the net aquifer thickness. In general, net thickness was mapped for sandstone aquifers and gross thickness for limestone aquifers. Where well control permitted, mapping of net and gross thicknesses extended to margins of zero thickness. In most maps subsurface geology has been integrated with surface geology.

Included in this report is a brief discussion of the regional geology of provinces of the State, and a description of the geographic limits of the aquifers, their structure, and stratigraphy. Each aquifer's potential productivity and salinity are also discussed.

### Definitions and Limitations

Saline water, as defined in this report, is water having more than 3,000 parts per million (ppm) of total dissolved solids. In some cases, aquifers were mapped beyond this limit due to lack of control that would allow the establishment of a 3,000-ppm boundary line. The Triassic Santa Rosa Formation of West Texas is known to have in places an average salinity below the 3,000-ppm range, but not enough data exist to delineate fresh water from saline water on a regional scale. Therefore, the aquifer was mapped throughout its entire extent in West Texas.

The productivity limit of aquifers used in the project was a minimum of 100 gallons of water per minute. Again, certain formations were doubtlessly mapped beyond this limit because of lack of data on a regional scale. The maps of the various aquifers presented in this report represent an interpretation of the producing capabilities of the formations based on known reservoir characteristics and extrapolated geology.

No recommendations on the use of water from any aquifer or in specific areas are given in this study. Certain formations that produce large quantities of oil, such as the Woodbine Formation of East Texas, can also produce large amounts of saline water. Obviously, formations containing large quantities of oil are not going to be suggested for use as saline-water sources. All formations in this investigation have been studied in the same manner, regardless of their present or future potential as an oil reservoir. Likewise, no attempt has been made to determine the economic feasibility of utilizing brine from one aquifer in preference to another. In other words, there has been no attempt to rate the aquifers. Tertiary formations adjacent to the Gulf Coast have been mapped to the shoreline, even though the sea would provide a more readily available source of brine.

Aquifers in this investigation have been grouped or mapped as larger, more widespread geological units. For example, in central Texas, various smaller aquifers consisting of thin but mappable sandstones or limestones in the various units of the Pennsylvanian System have been combined into one of the four Pennsylvanian series of that region. It was not feasible in this study to subdivide and map individual members. Therefore, many local aquifers have been grouped into larger units.

### Location

The area considered in this investigation was the entire State of Texas. Aquifers were systematically studied and mapped on a geological basis. No single aquifer covers the entire State, but some such as the Ellenburger have wide geographic extent. Most of the data available for use in this study comes from areas heavily drilled by oil wells and oil tests. Drilling is sparse or nonexistent in wide areas of Trans-Pecos Texas and over the Llano uplift and therefore only a minor amount of well control is available there. Figure 1 is a location map showing the major geographical and geological features of the State.

### Previous Investigations

The most comprehensive work concerning saline aquifers of Texas on a state-wide basis is "Saline-Water Resources of Texas" by A. G. Winslow and L. R. Kister. This paper, published as U.S. Geological Survey Water-Supply Paper 1365, gives a brief description of the saline-water resources of 28 formations, and includes small-scale maps on the geographic extent of each water-producing formation and tables of basic water data. Lithologies, well yields, and water-quality data are discussed.

Many publications of the Texas Water Development Board relate to aquifers in the State. These reports are generally on a

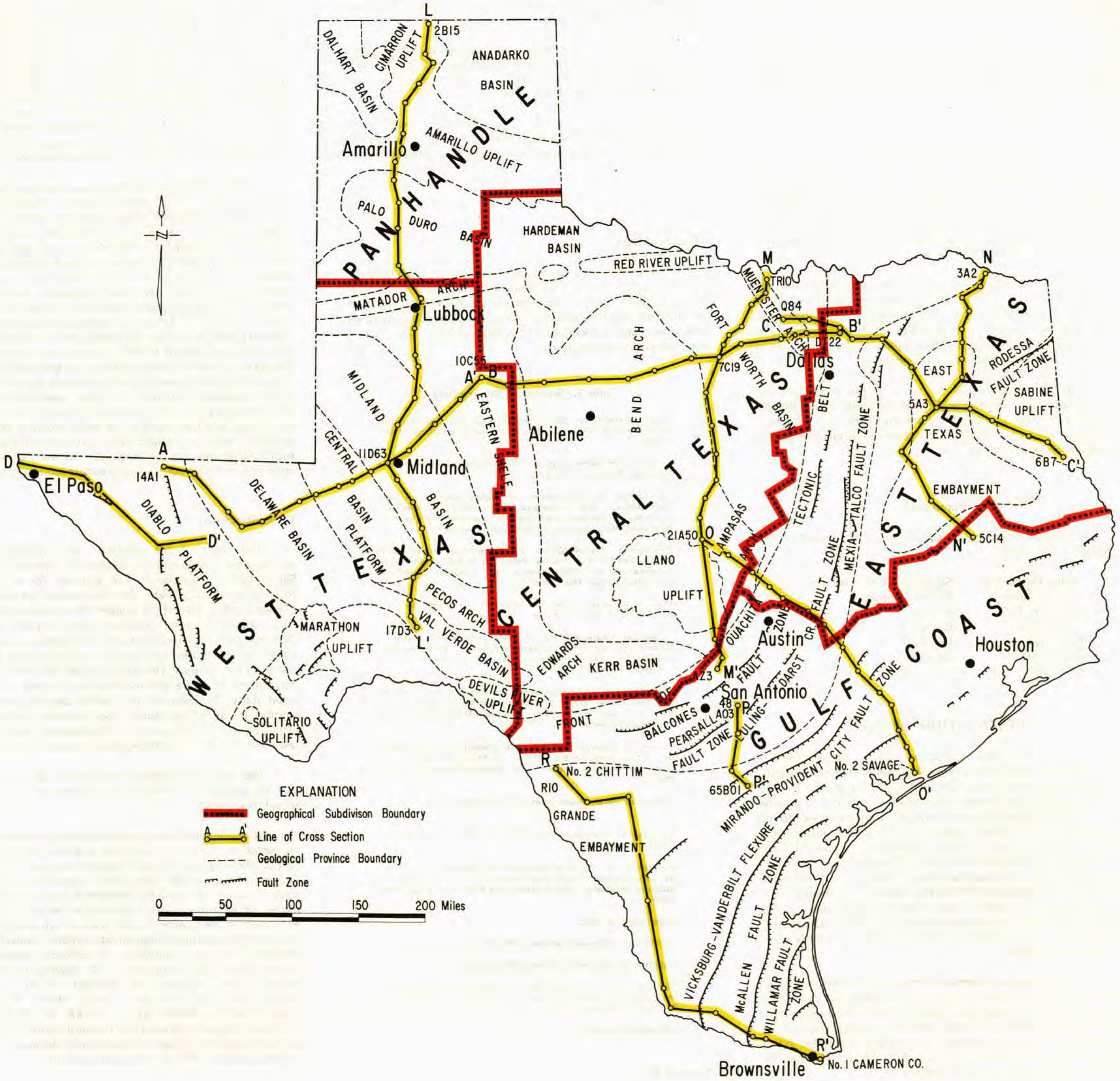


Figure 1

Tectonic Map of Texas Showing Location of Cross Sections and Geographical Subdivisions county-wide or river basin area, and many of them concern marginally fresh, hence marginally saline formations.

A great amount of literature concerning various aspects of the geology of Texas has been published, and many of these publications were referred to during this study. The more widely used of these references are listed either in the discussion or in the list of references.

### Well-Numbering System

The well-numbering system used on the maps and tabulations is, in general, unique to this report. Those wells in West Texas, central Texas, and the Panhandle region have well identification numbers (ID numbers) that are based on the key-well numbers of a commercial mapping service that was utilized for a portion of this study.

To refer to an individual well in the geological well data listings (Volumes 4-8), the well ID number should be looked up under the county in which it is located on the map. Within each county, a well number (such as 48B06) is filed first numerically by the first or left-hand digits, then alphabetically, and finally in numerical order of the last or right-hand digits.

The numbers assigned to wells in this report do not correspond in any way to the Texas Water Development Board's numbering system. It is possible that some of the wells listed here have been previously used in other reports, but no attempt was made to designate these wells.

### Personnel

Personnel of Core Laboratories, Inc. who worked on this report are as follows:

| | |
|---|---|
| Richard H. Snyder | Supervising Geologist |
| Leroy C. Buehrer | Project Manager |
| William H. Dorsey | Engineer |
| Frank O. Bell | Geologist |
| Paula Messinger | Geologist |
| Darrell Bush | Geologist |
| Peter Scott | Geologist |

## PRESENTATION OF DATA

This investigation of the saline aquifers of Texas has been organized into three general areas or phases of study: the salinity of the aquifers, the productivity of the aquifers, and the geology of the aquifers. The primary purpose of the study is to provide the Texas Water Development Board with a basic reference to the occurrence of the major saline-water sources throughout the entire State that can be used for future desalting operations. In that respect the salinity inventory will enable users to readily survey the different geographic areas of the State to determine the most desirable aquifers from the standpoint of salinity. That is, which formations are the least saline. The study accomplishes this by two means: an extensive listing of salinity data compiled by formation, depth, and county (Volume 2), and salinity maps of the major aquifers.

In the productivity phase of the study, a large amount of porosity and permeability data were compiled and these data were listed by formation and county (Volume 3). Average ideal flow rates have been calculated, and the resulting average flow rate is given on a county average. A nomograph is provided in this report from which rock property and salinity data may be converted into ideal flow rates (Figure 2).

The geological portion of the study provides an investigator with maps of the major saline water-bearing formations throughout the State. The depth, thickness, and areal extent of aquifers are readily determined by the use of these maps. The geological correlations used in the construction of the maps were taken from over 1,600 well logs. A computer listing of geological well data in the five areas of the State is included in this report (Volumes 4-8) and will be described later.

The salinity, productivity, and geological phases of this investigation have resulted in the development of 7 volumes of computer-listed data, 10 cross sections, and 91 geological maps. All of these are included in the report.

This report is therefore comparable to an inventory or catalog of the saline waters of the State. It provides the groundwork for future investigations and more detailed studies.

### Salinity Data

#### Sources of Data

Various sources of data have been drawn on to compile this salinity inventory of aquifers. Many of these data were found to be duplications of data from other sources. An attempt was made to eliminate duplicate samples in individual wells and in oil fields. However, some duplications of the data probably exist. Table 1 lists the sources of salinity data.

**Table 1.–Sources of Salinity Data**

"Saline-Water Resources of Texas," by A. G. Winslow and L. R. Kister. U.S. Geological Survey Water-Supply Paper 1365. 1956.

Resistivity of water samples in East Texas, compiled by the American Petroleum Institute.

"A Survey of Resistivities of Water from Subsurface Formations in West Texas and Southeastern New Mexico," compiled by Permian Basin Section, the American Institute of Mining, Metallurgical, and Petroleum Engineers.

"Increasing Concentrations of Subsurface Brines with Depth," by Parke A. Dickey. Presented at Kansas University Symposium on Geochemistry of Subsurface Brines, Lawrence, Kansas, Mar. 1968.

Interstitial water resistivity material, compiled by the American Petroleum Institute.

"Chemical Characteristics of Waters from the Canyon, Strawn, and Wolfcamp Formations in Scurry, Kent, Borden, and Howard Counties, Texas," by W. C. Elliott, Jr., in *Petroleum Engineer*, 1953.

"The Chemical Analyses of Brines from Some Fields in North and West Texas," by H. S. Beeler and others. Compilation of the American Institute of Mining, Metallurgical, and Petroleum Engineers.

"Chemical Analyses and Electrical Resistivities of Oilfield Brines from Fields in East Texas," by M. E. Hawkins, W. D. Dietzman, and C. A. Pearson. U.S. Bureau of Mines, RI 6422. 1964.

Formation waters resistivities catalog, compiled by Texaco, Inc.

Laboratory analyses from files of the Texas Water Development Board.

Resistivities and chemical analyses of formation waters from the west central Texas area, compiled by the American Institute of Mining, Metallurgical, and Petroleum Engineers. 1960.

Same as above, 1965.

Unpublished laboratory analysis data, Byron Jackson, Inc.

Unpublished laboratory analysis data, Dowell, Inc.

"Survey of Water Resistivities of Productive Formations of the Panhandle Region of Texas," compiled by the American Petroleum Institute. 1960.

Miscellaneous sources.

#### Types of Data

In collecting chemical analyses of formation waters from the various data sources listed in Table 1, several different formats were encountered. It was apparent that no standard system exists for listing the ionic radicals that comprise the dissolved solids in water. After reviewing many analyses, the resulting format of radicals was devised. It includes all of the important constituents normally listed along with pH, and specific gravity. Besides total dissolved solids, ionic radicals for which concentrations in parts per million are listed on the computer printout (Volume 2) are sodium (Na), calcium (Ca), magnesium (Mg), chloride (Cl), sulfate ($SO_4$), bicarbonate ($HCO_3$), and iron (Fe). The computer was programmed to show the presence of $H_2S$, where detected during analysis, by printing "yes" in the hydrogen sulfide column. Exact amounts are difficult to measure and reported concentrations are usually unreliable. However, the presence of the gas in any amount is meaningful due to its highly corrosive and toxic nature.

Much of the data available comes from published material that was gathered by oil companies and professional engineering and geological societies. These sources are primarily interested in obtaining only a figure for total dissolved solids, or just the resistivity of formation water (Rw) at a given temperature. Therefore, a considerable amount of available data, possibly 50 percent, is provided as water resistivity data. In addition to published water resistivity data, considerable data were added from direct water resistivity calculations using the spontaneous potential (S.P.) log. This is normally a reliable source of water resistivity data and allows the interpreter to select well logs in areas of sparse control to fill in with actual chemical analyses. Standard log interpretation techniques, as noted in Pirson (1963), were utilized for conversion of spontaneous potential deflection to an equivalent number for total dissolved solids. These calculations are limited to applicable areas of South Texas, the Gulf Coast, and East Texas where results compare favorably with laboratory analyses. In West Texas and most of central Texas, no such calculations can be made due to the nature of logging responses in the carbonate and evaporite sequence of rock strata.

#### Computer Listing

The result of the tabulation and calculation of water salinity data is the computer output of "Chemical Analyses of Saline Water," Volume 2. The printout format consists of fourteen columns of data. The first column on the left is the average depth in feet of the sample. The second column lists the concentration of total dissolved solids in parts per million. Depending on the type of data, the total dissolved solids figure is either an actual measured value or one obtained from water resistivity calculations. The third through the tenth columns give concentrations of the various chemical components which were listed above. The eleventh and twelfth columns are for pH and specific gravity of the water. The thirteenth column lists the geological formation (aquifer) of the sample. The fourteenth or last column is for the reference code number of the data source.

The samples are listed in descending depth sequence and also are grouped in 1,000-foot depth intervals. All samples are sorted by counties.

No calculations were involved on samples where complete or partial chemical analyses were available, with the printed output showing each analysis exactly as reported. Geological horizons of each sample were coded as reported with no attempt made to screen the data for correctness, use of local geological names, or improper depth relationships. In samples where the water-salinity data were in the form of an equivalent water resistivity, the computer program was written to convert the water resistivity to an equivalent of sodium chloride (NaCl) concentration by application of appropriate conversion factors. These numbers are reported in the total solids column of the computer listing with the notation "CALCULATED FROM RW = X.XXX AT 75 DEG. (F)." Most data that were obtained from original spontaneous potential log calculations are listed simply as total dissolved solids with only the notation "SP" in the reference column.

#### Data Quality, Averaging, and Use

In conjunction with tabulation of chemical compositions of these saline waters, salinity maps have also been prepared. The hydrological and geological significance of these maps will be discussed later. These maps illustrate the geographic or areal variation of formation waters within a given rock system. The maps generally depict regional salinity patterns, and where control is adequate, local anomalies are also apparent.

One of the problems encountered in selecting data for maps is that of averaging the data. In many oil fields of West Texas and the Gulf Coast, numerous samples exist in each field from the same producing formations. In this case, several values of total dissolved solids within the field area were arithmetically averaged and only one point was plotted on the map. Another problem occurs in the averaging of salinities in a vertical sequence. Since salinities can frequently vary with depth in a single well, the question arises as to what is a true, representative, and average salinity for the formation as a whole. Samples reported in tabulations are normally drawn from only a small portion of what is possibly a very thick formation. Thus, when these samples are plotted and used on a map, they represent an average value at best.

Another hazard in using reported data is the possibility of sample contamination. This is particularly true in the case of a sample obtained from a drill-stem test of a formation. There is no means available to determine the reliability of reported data. In the computer inventory in this report, data obtained from published and private sources have been accepted as reported and no attempt has been made to verify their accuracy. Generally, this compilation of subsurface water data is felt to be reliable and presents a representative sampling of the chemical composition of these waters. All data from various sources showed good agreement, and trends established by mapping appeared reasonable.

Approximately 8,000 individual saline-water samples are given in the computer listing. Although this is a large number, many aquifers are not adequately represented, and conversely, several of the oil-producing formations have abundant data.

The imbalance in the distribution of samples is due to the occurrence of oil in relatively small horizontal and vertical areas. Where one formation is a prolific producer of oil and gas, there will be an abundance of water samples taken. A formation such as the San Andres of West Texas will have a large concentration of samples in fields, and very few samples outside of producing fields. As a result of the practices of testing formation water in fields as compared to tests in wildcat wells, field salinity data are very abundant relative to the wildcat wells.

The same situation applies to nonproducing formations as a whole. Those formations which rarely yield hydrocarbons or which are less prolific are naturally not as well represented as the more productive zones. There is undoubtedly a great amount of additional salinity data in existence in oil company files that could be assembled and refined. To obtain these data, however, would necessitate spending much more time and money, and the expected results would probably not justify the effort.

The uses of a compilation of this type are several. The report provides a quick reference to the water quality of major saline aquifers, both through the use of data in printed format and by the use of salinity maps of individual aquifers. The convenience of having a large amount of salinity data covering the entire State in one report is obvious. The inventory also provides an extensive data source for the use of determining water resistivity in all the major oil-bearing formations statewide.

### Productivity Data

The permeability and porosity measurements of a reservoir rock are basic requirements in evaluating its storage and productivity capabilities. Therefore, determining these properties for the potential aquifers comprised an integral part of the study, with results tabulated in the computer-listed Volume 3, "Aquifer Rock Properties."

Permeability and porosity of rocks normally vary widely over relatively short vertical and horizontal distances. As a result, statistical methods are normally employed to reduce these numbers to one meaningful average number which can be used to describe the reservoir rock. Both the basic data used and the methods of averaging are significant and must be fully understood in order to judge the reliability of the data generated.

#### Data Scope

It is of statistical interest to define the scope or "universe" in which data are collected and averaged. For this study, an areal unit is defined as a county and a vertical unit is defined as a mappable geological unit of similar rock.

The number of data points used to obtain an average within these boundaries varied according to availability of data. Therefore, the output is designed to show the amount of data used to obtain an average as well as the variation among the data points.

#### Sources of Data

Investigation of rock properties of subsurface strata that contain saline water is normally limited to oil and gas exploration. Therefore, available data outside oil company files are somewhat limited. The data used in the productivity evaluation were obtained through the Texas Railroad Commission files, published oil reports, and the general literature. These data were then coded, sorted, and grouped into geological units for averaging.

#### Data-Grouping Technique

Before statistical averaging can be applied, the data must be grouped so that similar quantities are being compared. For this study, each county was defined as an areal unit. These units were the basis for the primary sorting of data.

Vertical grouping was then obtained by cataloging each sample by its geological time sequence. A nine-digit code was employed, with the first four digits used to signify the era, system, series, and group, respectively, which the sample represented. The remaining five positions designated the geological formation and member.

After examining all the available data, it was decided that grouping samples by formation resulted in a division of similar rock types which could be meaningfully averaged. This division became the vertical unit of grouping and the secondary sorting sequence in the program.

A final sort of data by depth of sample occurs within each areal and vertical unit. This is done only for convenience and logic of reporting.

#### Data Averaging

To average rock properties of similar type, four basic statistical methods are normally applied. Each method has its own merits, depending largely on the reliability and volume of data available for use.

Volume 3 shows permeability values for each formation or rock unit within each county computed as an arithmetic average, geometric average, and medium and mode values. The methods used in obtaining each average are discussed below. It will be a matter of personal judgment for the user as to which average permeability value is most representative. Arithmetic average, median, and modal values are available for the porosity data along with the arithmetically averaged depths.

##### Arithmetic Average

The arithmetic average is commonly called "the average number." It is defined as the sum of the individual values of the variable divided by the total number of such values. The mathematical equation as applied to permeability is

$$\overline{K}_{arith} = \frac{\sum_i^n K}{n}$$

where

$\overline{K}_{arith}$ = arithmetic average permeability;

$K$ = sample permeability; and

$n$ = number of samples.

When large numbers of samples are involved with small variations in each, the arithmetic average is adequate and should agree closely with other averaging techniques.

### Geometric Average

The geometric average of an array of i numbers is defined as the $i^{th}$ root of their product.

$$\overline{K}_{geo} = \text{antilog of} \frac{\sum_i^n (h_i \times l_n \times K_i)}{\Sigma (h_i)}$$

where

$\overline{K}_{geo}$ = geometric average permeability;

$K_i$ = sample permeability;

$h_i$ = length number of samples; and

$n$ = the logarithm base.

The use of the geometric mean for averaging permeability variations within a rock system has found favor among engineers as it tends to most often correctly describe flow behavior of the reservoir. However, data used within this study had already been reduced to an average number, which limits the value of this application.

This averaging technique was applied only to the permeability values. The method is not considered adequate to describe other rock properties.

### Median Value

The median is the value of the variable that divides the frequencies of occurrence into two equal portions. Its measurement is important in the branch of statistics dealing with the order of measurements. As applied in this study, it becomes a measure of data reliability, as it is by definition the value from which the sum of the absolute values of the deviations is a minimum.

### Mode

The mode as defined in this study is the mean value of the variable range which occurs most frequently. The variable range for this calculation is computed for each individual case by selection of ten equal groups which lie between the maximum and minimum value reported.

Normally, the mode value is of little quantitative significance in evaluation of engineering parameters. However, mode values as applied to this study do appear significant due to the necessity for random selection of data. Reported values of rock properties may or may not be valid depending on the individual capabilities of the reporting individual. Therefore, by computing mode values, unreasonable numbers are eliminated from consideration.

This value was used as the most representative value in calculating ideal specific flow rates, which are discussed in detail below.

### Data Reporting

Rock property data are reported completely on each individual sample to give maximum flexibility to the user. Each sample point is listed under the geological unit in which it was grouped. Additionally, all rock groups are tabulated under the appropriate county or areal unit which they represent.

The individual sample points give the local geological name, location and depth of the sampling point, and average rock properties reported. With these data, the user is free to scan and apply only that information most pertinent to the problems at hand.

### Ideal Specific Flow Rate

The ideal specific flow rate for each rock group has been included to give the user a reference for comparisons of flow potential of the water aquifer under study. To prevent misunderstanding of terms and subsequent misapplication of these values, a detailed explanation is required.

Ideal flow for a porous and permeable medium is described in this report as the application of Darcy's radial flow equation to the rock properties determined in the study. Mathematically, the equation applied to single-phase flow of an incompressible liquid is:

$$Q = \frac{0.2065 K_w h\,(P_e - P_w)}{\mu \ln (r_e/r_w)},$$

where

$Q$ = ideal flow rate in gallons per minute (gpm);

$K_w$ = permeability to water in darcies;

$h$ = bed thickness in feet;

$r_w$ = well-bore radius in feet;

$r_e$ = external drainage radius in feet;

$P_e$ = static aquifer pressure at $r_e$ in pounds per square inch gauge (psig);

$P_w$ = producing bottom hole pressure of aquifer in psig;

$\mu$ = viscosity of water in centipoises (cp); and

$\ln$ = natural logarithm.

The equation was modified from the above expression by arbitrarily setting the thickness value to unity, thereby making the flow rate expression gallons per minute per foot of thickness. The flow described then becomes *ideal specific flow rate*, which allows the user more flexibility in its application. Other terms in the equation are expressed in the following paragraphs.

### Permeability

The mode average value of air permeability was considered to be the permeability to water in the calculation of ideal specific flow rate. This assumption is valid when applied regionally to areas where large rock volumes are being described. However, in this application the users should be aware that there is an element of risk in applying such readily available data as air permeability alone in attempting to characterize reservoir flow. Variations in sorting, cementation, and other factors which affect pore geometry of a rock system also affect the accurate measurement of relative permeability. Therefore, for specific application where accurate flow calculations are required, the relative permeability must be a laboratory-measured value.

### External Drainage Radius

The external drainage radius is usually inferred from the well spacing, but is specifically the external flow boundary. Calculations presented in this report use an $r_e$ = 2,640 feet, or the equivalent of one mile spacing between wells.

### Well-Bore Radius

The well-bore radius is usually assigned from the drilling bit diameter, the casing diameter, or a caliper survey. In the general calculations presented, a standard radius of 0.5 foot was used throughout.

In practice, neither the external drainage radius nor the well-bore radius is generally known with precision. Fortunately, these values enter the equation as the logarithm of their ratio, so that errors in radii selection are severely reduced in the ultimate solution.

### Static Aquifer Pressure

The static aquifer pressure is generally taken as the static well pressure corrected to the middle of the producing depth interval. For the purpose of calculations presented in this report, the pressure was calculated as

$$P_e = \text{average depth} \times \text{specific gravity} \times 0.433,$$

which assumes a normal hydraulic gradient acting on each aquifer.

Specific gravity for each geological horizon was averaged from the chemical analyses and applied in this equation.

This method is adequate for a generalized assumption over a wide area. However, the user should attempt to measure or otherwise accurately determine the exact reservoir pressure for application to specific areas.

Ideal flow as defined in this study assumes that steady-state conditions exist, or the $P_e$ is not a function of time and is constant.

### Producing Bottom Hole Pressure of Aquifer

The flowing well pressure or producing bottom hole pressure is also corrected to the middle of the producing depth interval during a period of stabilized flow. In this report, this pressure is assumed to be 20 percent of the calculated static pressure, or

$$P_w = 0.2\,P_e.$$

Again, caution as expressed above applies to the use of this pressure.

### Viscosity

Saline-water viscosity is a function of water salinity and reservoir temperature. For this report, a simplifying assumption was made of a constant water salinity of 60,000 ppm, since deviation resulting from changes in salinity are slight and the use of one curve resulted in adequate accuracy.

In the handling of variations of viscosity due to reservoir temperature, data from Table 2 were used.

Reservoir temperature for each specific reservoir was calculated from the formula

$$\text{Temp } (^\circ\text{F}) = 74^\circ\text{F} + (\text{depth})\ (\text{gradient}),$$

after the work of Moses (1961) on temperature gradients in Texas. A gradient of each county was obtained from this work and is shown in Table 3.

**Table 2.—Viscosity of Water as a Function of Temperature**

| TEMPERATURE, °F | VISCOSITY, cp |
|---|---|
| 32 | 1.79 |
| 50 | 1.31 |
| 68 | 1.00 |
| 86 | 0.801 |
| 104 | 0.656 |
| 122 | 0.549 |
| 140 | 0.469 |
| 158 | 0.406 |
| 176 | 0.357 |
| 194 | 0.316 |
| 212 | 0.284 |
| 230 | 0.256 |
| 284 | 0.196 |
| 321 | 0.174 |

**Table 3.—Temperature Gradients by Counties**

**(Average Temperature Increase, °F per 100 Feet of Depth)**

| | | | |
|---|---|---|---|
| Anderson | 2.0 | Edwards | 1.8 |
| Andrews | 0.7 | Ellis | 2.0 |
| Angelina | 2.0 | El Paso | 0.8 |
| Aransas | 1.6 | Erath | 1.8 |
| Archer | 1.4 | Falls | 2.0 |
| Armstrong | 1.0 | Fannin | 0.9 |
| Atascosa | 2.0 | Fayette | 2.2 |
| Austin | 1.9 | Fisher | 1.2 |
| Bailey | 1.0 | Floyd | 1.0 |
| Bandera | 2.0 | Foard | 0.8 |
| Bastrop | 2.5 | Fort Bend | 1.7 |
| Baylor | 1.0 | Franklin | 2.0 |
| Bee | 2.0 | Freestone | 2.2 |
| Bell | 2.0 | Frio | 2.0 |
| Bexar | 2.0 | Gaines | 0.6 |
| Blanco | 2.0 | Galveston | 1.6 |
| Borden | 0.85 | Garza | 0.95 |
| Bosque | 2.0 | Gillespie | 2.0 |
| Bowie | 2.0 | Glasscock | 0.95 |
| Brazoria | 1.6 | Goliad | 1.9 |
| Brazos | 2.3 | Gonzales | 2.4 |
| Brewster | 0.8 | Gray | 1.0 |
| Briscoe | 1.0 | Grayson | 0.95 |
| Brooks | 1.9 | Gregg | 2.0 |
| Brown | 1.8 | Grimes | 2.3 |
| Burleson | 2.4 | Guadalupe | 2.0 |
| Burnet | 2.0 | Hale | 1.0 |
| Caldwell | 2.0 | Hall | 1.0 |
| Calhoun | 1.6 | Hamilton | 1.8 |
| Callahan | 1.6 | Hansford | 1.1 |
| Cameron | 1.6 | Hardeman | 1.0 |
| Camp | 1.9 | Hardin | 2.2 |
| Carson | 1.0 | Harris | 1.8 |
| Cass | 1.8 | Harrison | 2.1 |
| Castro | 1.0 | Hartley | 1.0 |
| Chambers | 1.7 | Haskell | 1.3 |
| Cherokee | 2.2 | Hays | 2.0 |
| Childress | 1.0 | Hemphill | 1.0 |
| Clay | 1.3 | Henderson | 2.0 |
| Cochran | 0.6 | Hidalgo | 1.95 |
| Coke | 1.15 | Hill | 2.0 |
| Coleman | 1.6 | Hockley | 0.7 |
| Collin | 2.0 | Hood | 1.8 |
| Collingsworth | 1.0 | Hopkins | 2.0 |
| Colorado | 2.0 | Houston | 2.0 |
| Comal | 2.0 | Howard | 0.95 |
| Comanche | 1.8 | Hudspeth | 1.0 |
| Concho | 1.4 | Hunt | 2.0 |
| Cooke | 1.0 | Hutchinson | 0.9 |
| Coryell | 1.8 | Irion | 1.05 |
| Cottle | 1.0 | Jack | 1.4 |
| Crane | 0.8 | Jackson | 1.9 |
| Crockett | 1.0 | Jasper | 2.2 |
| Crosby | 1.0 | Jeff Davis | 0.8 |
| Culberson | 0.8 | Jefferson | 2.0 |
| Dallam | 1.0 | Jim Hogg | 2.4 |
| Dallas | 2.0 | Jim Wells | 1.9 |
| Dawson | 0.6 | Johnson | 2.0 |
| Deaf Smith | 1.0 | Jones | 1.4 |
| Delta | 2.4 | Karnes | 2.3 |
| Denton | 1.2 | Kaufman | 2.4 |
| DeWitt | 2.2 | Kendall | 2.0 |
| Dickens | 0.9 | Kenedy | 1.6 |
| Dimmit | 2.0 | Kent | 0.8 |
| Donley | 1.0 | Kerr | 2.0 |
| Duval | 2.35 | Kimble | 1.8 |
| Eastland | 1.9 | King | 0.8 |
| Ector | 0.9 | Kinney | 2.0 |
| Kleberg | 1.8 | Roberts | 1.0 |
| Knox | 0.8 | Robertson | 2.0 |
| Lamar | 2.4 | Rockwall | 2.0 |
| Lamb | 1.0 | Runnels | 1.3 |
| Lampasas | 1.8 | Rusk | 2.1 |
| La Salle | 2.0 | Sabine | 2.0 |
| Lavaca | 2.1 | San Augustine | 2.0 |
| Lee | 2.4 | San Jacinto | 2.2 |
| Leon | 2.2 | San Patricio | 1.8 |
| Liberty | 2.0 | San Saba | 1.8 |
| Limestone | 2.5 | Schleicher | 1.6 |
| Lipscomb | 1.0 | Scurry | 0.8 |
| Live Oak | 2.3 | Shackelford | 1.6 |
| Llano | 2.0 | Shelby | 2.0 |
| Loving | 0.5 | Sherman | 1.0 |
| Lubbock | 1.0 | Smith | 1.9 |
| McCulloch | 1.8 | Somervell | 2.0 |
| McLennan | 2.0 | Starr | 2.4 |
| McMullen | 2.0 | Stephens | 1.9 |
| Madison | 2.4 | Sterling | 1.1 |
| Marion | 1.9 | Stonewall | 0.9 |
| Martin | 1.0 | Sutton | 1.8 |
| Mason | 1.8 | Swisher | 1.0 |
| Matagorda | 1.6 | Tarrant | 1.4 |
| Maverick | 2.0 | Taylor | 1.4 |
| Medina | 2.0 | Terrell | 1.5 |
| Menard | 1.8 | Terry | 0.8 |
| Midland | 0.9 | Throckmorton | 1.4 |
| Milam | 2.0 | Titus | 1.8 |
| Mills | 1.8 | Tom Green | 1.2 |
| Mitchell | 1.1 | Travis | 2.0 |
| Montague | 1.2 | Trinity | 2.0 |
| Montgomery | 2.1 | Tyler | 2.1 |
| Moore | 1.0 | Upshur | 1.8 |
| Morris | 1.8 | Upton | 1.0 |
| Motley | 0.9 | Uvalde | 2.0 |
| Nacogdoches | 2.0 | Val Verde | 1.8 |
| Navarro | 2.4 | Van Zandt | 2.2 |
| Newton | 1.6 | Victoria | 1.85 |
| Nolan | 1.15 | Walker | 2.0 |
| Nueces | 1.8 | Waller | 1.9 |
| Ochiltree | 1.1 | Ward | 0.5 |
| Oldham | 1.0 | Washington | 2.1 |
| Orange | 1.6 | Webb | 2.0 |
| Palo Pinto | 1.9 | Wharton | 1.8 |
| Panola | 2.2 | Wheeler | 1.0 |
| Parker | 1.6 | Wichita | 0.95 |
| Parmer | 1.0 | Wilbarger | 0.9 |
| Pecos | 0.6 | Willacy | 1.6 |
| Polk | 2.2 | Williamson | 2.0 |
| Potter | 1.0 | Wilson | 2.0 |
| Presidio | 0.8 | Winkler | 0.6 |
| Rains | 2.3 | Wise | 1.4 |
| Randall | 1.0 | Wood | 2.1 |
| Reagan | 1.0 | Yoakum | 0.7 |
| Real | 2.0 | Young | 1.55 |
| Red River | 2.2 | Zapata | 2.0 |
| Reeves | 0.6 | Zavala | 2.0 |
| Refugio | 1.7 | | |

In this manner, temperature changes due to areal and vertical variations were considered. Again it must be realized that these temperature calculations are regional in nature and a measured temperature is required for specific application.

### Nomograph

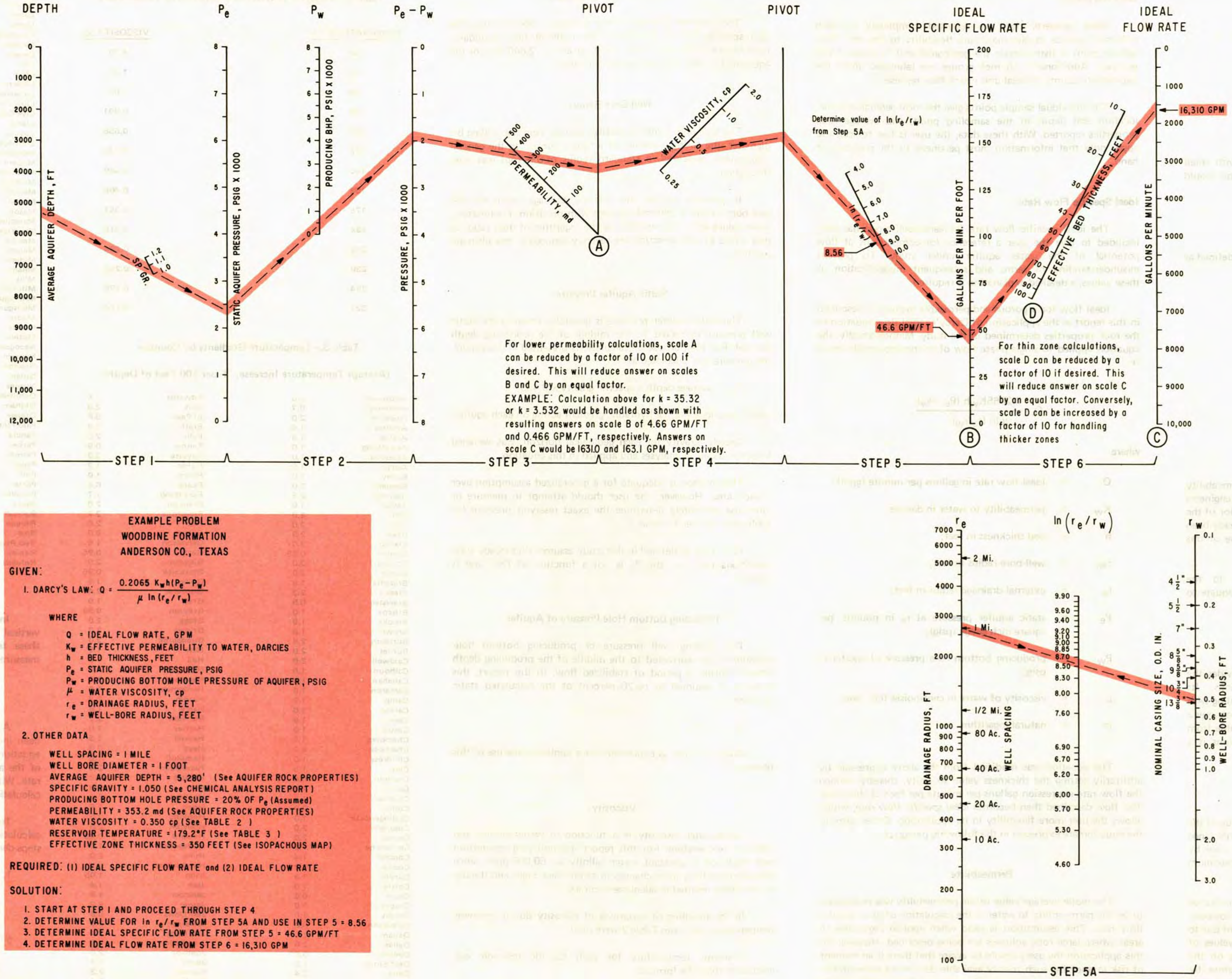
A nomograph of Darcy's Law as applied in this study has been included to assist the user in changing any variable in the equation (Figure 2). This is necessary due to the regional nature of the assumptions made for calculating the ideal specific flow rate. With more accurate data available in a specific area, accurate calculations can be readily made with this nomograph.

To assist the user, an example of an ideal specific flow rate calculation is given at the right of the nomograph. The following steps demonstrate this example.

1. Begin Step 1 with depth of the aquifer. These may be actual depths from well data or depths estimated from structural contour maps. For this example, assume an aquifer depth of 5,280 feet.

2. Proceed to $P_e$ (static aquifer pressure) through SP. GR. (specific gravity). Static aquifer pressure is in pounds per square inch gauge (psig) x 1,000. Specific gravity can be found in the chemical analyses, Volume 2, or can be obtained through outside sources. For this example, use 1.050.

3. In Step 2, proceed from $P_e$ through $P_w$ (producing bottom hole pressure) to $P_e$ - $P_w$; take 20 percent of the



For lower permeability calculations, scale A can be reduced by a factor of 10 or 100 if desired. This will reduce answer on scales B and C by an equal factor.
EXAMPLE: Calculation above for k = 35.32 or k = 3.532 would be handled as shown with resulting answers on scale B of 4.66 GPM/FT and 0.466 GPM/FT, respectively. Answers on scale C would be 1631.0 and 163.1 GPM, respectively.

For thin zone calculations, scale D can be reduced by a factor of 10 if desired. This will reduce answer on scale C by an equal factor. Conversely, scale D can be increased by a factor of 10 for handling thicker zones

**EXAMPLE PROBLEM**
**WOODBINE FORMATION**
**ANDERSON CO., TEXAS**

**GIVEN:**

1. DARCY'S LAW: $Q = \dfrac{0.2065\ K_w h (P_e - P_w)}{\mu \ln (r_e / r_w)}$

WHERE

$Q$ = IDEAL FLOW RATE, GPM
$K_w$ = EFFECTIVE PERMEABILITY TO WATER, DARCIES
$h$ = BED THICKNESS, FEET
$P_e$ = STATIC AQUIFER PRESSURE, PSIG
$P_w$ = PRODUCING BOTTOM HOLE PRESSURE OF AQUIFER, PSIG
$\mu$ = WATER VISCOSITY, cp
$r_e$ = DRAINAGE RADIUS, FEET
$r_w$ = WELL-BORE RADIUS, FEET

2. OTHER DATA

WELL SPACING = 1 MILE
WELL BORE DIAMETER = 1 FOOT
AVERAGE AQUIFER DEPTH = 5,280' (See AQUIFER ROCK PROPERTIES)
SPECIFIC GRAVITY = 1.050 (See CHEMICAL ANALYSIS REPORT)
PRODUCING BOTTOM HOLE PRESSURE = 20% OF $P_e$ (Assumed)
PERMEABILITY = 353.2 md (See AQUIFER ROCK PROPERTIES)
WATER VISCOSITY = 0.350 cp (See TABLE 2 )
RESERVOIR TEMPERATURE = 179.2°F (See TABLE 3 )
EFFECTIVE ZONE THICKNESS = 350 FEET (See ISOPACHOUS MAP)

**REQUIRED:** (1) IDEAL SPECIFIC FLOW RATE and (2) IDEAL FLOW RATE

**SOLUTION:**

1. START AT STEP 1 AND PROCEED THROUGH STEP 4
2. DETERMINE VALUE FOR ln $r_e/r_w$ FROM STEP 5A AND USE IN STEP 5 = 8.56
3. DETERMINE IDEAL SPECIFIC FLOW RATE FROM STEP 5 = 46.6 GPM/FT
4. DETERMINE IDEAL FLOW RATE FROM STEP 6 = 16,310 GPM

Figure 2
Nomograph for Calculating Ideal Specific Flow Rate

value of $P_e$ ($P_W = P_e \times .20$). Producing bottom hole pressure (BHP) is in psig x 1,000.

4. In Step 3, proceed from $P_e - P_W$ through the permeability scale to the pivot line. For this example, use a permeability of 0.3532 darcies.

5. Begin Step 4 at the pivot and proceed through water viscosity to the next pivot. To determine water viscosity use Table 2 in this report. For this example, use 0.350 centipoises.

6. Begin Step 5 at the pivot and proceed through the factor ln ($r_e/r_W$) to ideal specific flow rate. This factor, the ratio between the well drainage radius and well-bore radius can be estimated from the nomograph at the lower right-hand corner, Step 5A. For this example, use 8.56.

7. For the ideal flow rate proceed in Step 6 from ideal specific flow rate through bed thickness to the ideal flow rate. Bed thickness can be determined through the use of isopachous maps or by other sources. For this example, use 350 feet.

#### Results of Productivity Phase of the Study

The results of this phase of the study are given in the computer-calculated summary of aquifer rock properties (Volume 3). The rock properties are presented by the various averages which have been previously discussed, and are sorted by geological formation, using the county as the areal unit for averaging.

The advantages and disadvantages of these sorting and averaging techniques have been discussed in the previous section. However, there are geological advantages and disadvantages which also need some explanation. The most obvious advantage is to have such a large amount of rock property data from practically all the producing zones that occur in the State listed in one volume. These data provide a large selection of porosity and permeability measurements and are listed by the original local geological name as well as the field name and depth. Another advantage is to have the average of these rock properties on a formational or group basis within the area of one county. As to the drawbacks or disadvantages of using average data, one of the most apparent is that the samples taken from producing zones of a formation may not be representative of that formation as a whole, either in the well, field, or county. Facies changes, abrupt lithological changes, faulting, and folding can be drastic in certain regions, thus rendering county-averaged data inaccurate. Then too, averages from producing wells may be geologically biased by the fact that they are located on structural highs and in highly porous zones. Conversely, a nonproducer may be in a structural low and have low porosity and permeability. Thus, the use of average rock property data should be studied in its relationship to local and regional geology and results should be judged accordingly.

### Geologic Data

#### Well Data

The basic geological data used in this investigation have been obtained from electrical and other mechanical logs of oil wells and oil tests. A network of 1,620 wells was used in the synthesis of the geology. To conform with the geology as well as geography, five areas have been designated in the State, and a well data book has been assembled for each area. Within each well data book, data sheets are grouped alphabetically by county, and within each county the sheets are in sequence of the well identification (ID) number. A list of the counties in each area is provided at the beginning of each well data book. The well data books are separate volumes to this report, as follows:

| | |
|---|---|
| Volume 4 | West Texas |
| Volume 5 | Panhandle |
| Volume 6 | Central Texas |
| Volume 7 | East Texas |
| Volume 8 | Gulf Coast |

Stratigraphic correlations used in this study were taken from several sources, but were primarily based on those taken from a geological consultant who provided the map and log services for the project, and from regional cross sections of various geological societies. Correlations from these sources were usually accepted as received. Additional correlations were made using well logs, and these were tied into the cross-section network. Other correlations were provided by oil companies, sample logs from geological libraries, and the general literature.

Recognized stratigraphic boundaries and nomenclatures were used as a basis of all correlations. This eliminated the use of local member names and permitted mapping the aquifers on a regional scale. Even though certain local names were used and appear in the well data sheets, an attempt was made to make the tops or bases of units coincide with the more extensive stratigraphic boundaries. Local members were often recorded even if they were not mapped individually. Individual well information was recorded on sheets by keypunch format. The information was then punched on computer cards and a program was developed to print out the geological data using one page per well. The format was an open or free listing so that any stratigraphic name could be written into the well listing. All information pertinent to the well was recorded on the basic data sheet. Depths of formation tops and bases were entered, and the computer was programmed to calculate the elevation relative to sea level, as well as the gross thickness of the formation. The following is a brief description of the basic geological well data file, Volumes 4 through 8.

The first line lists county (with two-letter county code prefix), well ID number, derrick floor elevation, and total well depth. The second line lists the well operator (normally an oil company) and the well fee or ownership name and number. The third line gives survey information, including location in feet from section lines, section, township, range or block, and land survey.

The next lines give geological data on formations penetrated by the well, including stratigraphic name, depth of formation top and its altitude from sea level, depth of formation base and its altitude from sea level, net aquifer thickness, gross unit thickness, lithology, and type of formation top. The type of formation top designates the stratigraphic condition that exists at this point. Conditions such as estimated tops, faults, partial penetration, and equivalent names were abbreviated and placed in that column. A list of all abbreviations used on the geological well data sheets appears in front of each well data book. Any remarks pertaining to the well were printed at the bottom of the page. If a well exceeded 20 formations, the remaining formations and remarks were printed on the following page.

Each well in the study has a unique well ID number. The number on the left and the letter refer to statewide geological atlas codes of the commercial mapping service used during this project. The number on the right is the sequential well number.

An investigation of this type is largely dependent on the availability of well data. At the original mapping scale selected, the mapping results indicated that the number of wells used in the project is adequate on a regional scale. Several areas of the State have very few oil tests, and as a result the geology of these areas remains interpretive and conjectural. Trans-Pecos Texas, including the Big Bend and El Paso areas, is critically lacking well data. Portions of the southern Panhandle, Llano uplift, and Edwards plateau regions, while less critical, also lack adequate well control.

The geological data in this report are only a minute part of the vast quantity of data in existence. However, it is a fairly unique assemblage of subsurface correlations in that the coverage is geographically extensive and contains a high percentage of wells that are drilled to deep geological horizons, frequently to basement. The well data can provide a basis for future studies on either a local or regional scale.

#### Cross Sections

A series of regional cross sections have been constructed for this investigation (Figures 3-12). The positions of these sections are shown on the location map, Figure 1. They are diagrammatic, straight-line, structural sections constructed on a sea-level datum.

Cross sections have been positioned so as to give maximum coverage through the principal basins in the State and to include all the major aquifers. These sections show the stratigraphic units used in the study and illustrate which units have been mapped as potential saline aquifers. Generally, the aquifers are shown on the sections by heavy correlation lines. In East and West Texas, the cross sections are more detailed and should be consulted in conjunction with the text and the aquifer maps to understand the complex stratigraphic relationships. The dip sections in the Gulf Coast (Figures 10-12) show the relation of subsea zones that were mapped along with actual time-stratigraphic units.

The sections have been segmented by regions or geographic areas. Where this is a continuous line of section, the common end well has been duplicated on the adjacent cross section in order to retain geological continuity. Each segment has been designated by double letters, such as A-A'.

#### Mapping

The original base maps used in this study were obtained from the Texas Water Development Board. They were made by the U.S. Geological Survey at a scale of 1:500,000. These maps are in four quadrants for the State. Since geological provinces are not always confined to a single quadrant, it was necessary to splice portions of two or more quadrants together. Final drafting of the geological maps was done on transparent Mylar sheets which in turn were placed over the base maps and photographically reproduced simultaneously.

The geological phase of the study resulted in the development of three types of maps: structural, isopachous, and salinity maps.

##### Structural Maps

With few exceptions, structural contour maps were prepared for all the principal saline aquifers in the State. These maps depict regional structure on top of the aquifer. The contours represent mostly original interpretations of these structures although poorly controlled areas were occasionally mapped with the aid of references to published data. Only regional structures and faults have been depicted on the maps. Many of the major faults, as on the Central Basin platform, were based on interpretations obtained from published and other sources.

When a number of aquifers occurred in a vertical sequence and were relatively thin, structure maps of a few units were omitted. The structure of overlying or underlying units would be very similar and could serve as a reference to the particular aquifer.

Contour intervals are variable depending on the availability of control, complexity of the structure, and steepness of dip. Where possible, an attempt was made to retain a single contour interval on each geological unit, but this was not always feasible.

In the Gulf Coast region, a structure map was prepared only on the Carrizo-Wilcox aquifer.

##### Isopachous Maps

Isopachous (thickness) maps were prepared for nearly all major aquifers in the State. These maps are of three types: gross unit thickness maps; net aquifer thickness maps, net being defined as the non-shale intervals within the gross thickness; and net sand thickness maps in constant-layer intervals (Gulf Coast only).

Net thicknessess of aquifers were mapped for those formations having good quality electric log responses. Most of the central Texas Pennsylvanian units, East Texas Cretaceous sands, and Gulf Coast sands are accurately and easily mapped as net aquifer thickness. Most carbonates, particularly those with varying proportions of evaporites and chert, give poor log responses for attempting to determine a net porous interval. Most of the carbonate units in West Texas occur in this condition and were therefore mapped for gross thickness. In aquifers such as the Pennsylvanian of West and central Texas, net aquifer thicknesses were determined from logs but these net values include a variety of lithologies. Pennsylvanian aquifers consist of sandstones, biostromal and biohermal limestones, and occasional thick detritals, all of which alternate with shales. The net aquifer thickness which is used on the isopachous map is a total of the different lithological members and does not indicate the percent of one lithology relative to another. It only shows how much "clean" rock or potentially porous aquifer is present in the well.

##### Salinity Maps

The data for salinity maps were taken from the summaries of chemical analyses of saline water (Volume 2). Data points used to construct the maps are designated in different ways. Points for which salinities were obtained from reported data, either from complete chemical analyses or water resistivities, are shown by a triangle on the map, and these points for which salinities were originally calculated from spontaneous potential logs during the study are shown by a circle. In using reported field data, salinity was obtained by arithmetic average.

Salinity maps on certain aquifers have been omitted. For these aquifers there was insufficient scatter of the data points, even though there may be a relative abundance of data in a few fields.

Contour intervals on the salinity maps are variable depending on the amount of control and the variation in total dissolved solids in the aquifer. The interval commonly used in East Texas and the Gulf Coast area is 20,000 ppm, while 50,000 ppm was possible in West Texas. Where possible, the 3,000-ppm line is shown on the maps.

## GENERAL GEOLOGY

The geology of Texas has been extensively studied and reported in many books, articles, and reports, a large part of which are available to the public. Probably as many geological studies exist in the files of oil companies operating in the State, which are not available to the public. This report on the geology and hydrology of the principal aquifers of Texas uses geological information from a wide range of sources and briefly covers the sedimentary geology of the entire State. It is a synthesis of the geology of Texas, but is, of necessity, limited to and concentrated on the geology and hydrology of saline aquifers. It is limited to a large degree by the availability of oil-well and oil-test data, primarily through the use of various types of well logs. The study is almost entirely restricted to the subsurface, both from the standpoint of data and of the natural occurrence of saline water.

Due to the size of the State and diversity of the geology, any endeavor such as this project must recognize the limitations imposed by the size of the problem. Within the State there are literally hundreds of individual sandstones, limestones, reefs, lenses, stringers, alluvial fills, and other types of strata capable of storing and transmitting water, either fresh or saline. The task of adequately sampling, inventorying, and mapping these aquifers is indeed enormous and largely unnecessary. The first step in the problem was to select mappable units which would include all the principal aquifers. This was accomplished by making a brief survey using the available literature. A cursory examination of the literature showed that a useful approach was to utilize recognized and established stratigraphic boundaries, and to extend the mapping of each aquifer to both its geological and hydrological limit. There is a certain degree of overlap among the various major aquifers, but there is also a similarity between geological and geographical regions of the State. For example, the Tertiary saline aquifers are largely confined to the Gulf coastal plain and the Permian aquifers occur in the western portion of Texas.

Within the terms of this project, saline aquifers are defined as those units having water with more than 3,000 ppm of total dissolved solids, and are capable of producing water at a minimum rate of 100 gpm. With the availability of a large quantity of reliable data, many aquifers could be readily mapped and their areal and vertical limits quickly established. Even though geological data on various formations are frequently abundant, productivity and salinity data can be quite scarce on the same formations. As a result, aquifer limits are often difficult to establish accurately.

After selecting the major aquifers on a stratigraphic basis, approximate mapping boundaries were established. For the convenience of handling geological well data, the State was divided into five areas designated as West Texas, Panhandle, central Texas, East Texas, and the Gulf Coast. Within an individual area, stratigraphy and structure are relatively constant. Boundaries of the five areas follow county lines. The areas are shown on the location map, Figure 1.

### West Texas Area

The West Texas area, as defined in this study, extends from El Paso on the far west side to the 101st meridian (Scurry, Mitchell, and Val Verde Counties) on the east; from the Big Bend counties on the south to Lubbock County on the north. For mapping purposes, the approximate edge of the so-called eastern shelf of the Permian basin was chosen on the east side as a boundary with the area mapped as central Texas. The northern mapping boundary with the Panhandle coincides with the Matador arch. Geographically, the region includes such features as the Llano Estacado, Stockton plateau, Davis Mountains, Big Bend mountain and canyon area, Diablo plateau, and bolsons of the far West Texas area. Numerous smaller but well-known mountains, plains, and canyons are present throughout this region.

The most prominent geological feature of the area is the Permian basin, a Paleozoic feature consisting of a deep western trough, the Delaware basin, a central uplifted area, the Central Basin platform, and a shallower eastern basinal area, the Midland basin. The basin is bounded on the north and west by shelf area generally called the northwest shelf, and on the east by the eastern shelf. The Diablo platform bounds the Permian basin on the far west side. The Delaware basin continues into the Val Verde trough or basin on the south. Another prominent structural feature is the Matador arch, a long east-west trending fault zone located on the northern margin of this area.

Formations ranging in age from Precambrian to Quaternary are exposed in the West Texas area, although most of the area is covered by Cretaceous, Tertiary, and Quaternary deposits. (See cross sections A-A', D-D', and L-L', Figures 3, 6, and 7, respectively.) The sedimentary history of West Texas began in upper Cambrian time, when sands and some calcareous deposits were laid down over the Precambrian igneous and metamorphic rocks. Continued subsidence caused extensive massive deposition of carbonates in late Cambrian time, continuing into early Ordovician time. This resulted in the widespread Ellenburger and its approximate equivalent, the Arbuckle of North Texas, the Panhandle, and Oklahoma. Since the underlying Cambrian sandstones and limestones are generally hydrologically continuous, these units have been combined with the Ellenburger in this study and are mapped as one unit. In deep basinal areas, relatively few wells penetrate the Cambrian, and it is more convenient to include Cambrian units with the Ellenburger.

Following the Ellenburger are the Simpson and Montoya, two upper Ordovician formations. The Simpson is a shale with widespread but thinner interbedded sandstones and shaly limestones, while the Montoya is a limestone with considerable chert. Silurian and Devonian time were marked by additional marine invasion and subsequent deposition of limestone and chert, similar in lithology to the Montoya. These units have been mapped as "Siluro-Devonian" in West Texas since the time boundary between them is uncertain. Another widespread marine transgression occurred during Mississippian time, when alternating thick limestones and black basinal shales were laid down. The limestones of the Mississippian have been mapped in this study. Following Mississippian deposition, much of western Texas was subjected to tectonic movements, and then another marine invasion during Pennsylvanian time resulted in the deposition of a variety of rock facies: basinal shales, thin biostromal limestone beds, limestone reefs, and thin sand members. Large reefs were formed in the waters of the emerging platform areas and shallow basins.

Another uplift occurred prior to Permian time, and the West Texas region was subjected to erosion. Yet another widespread marine transgression occurred at the beginning of Permian time. In the Wolfcampian age, thick deposits of black shale accumulated in the Delaware and Val Verde basins. In Leonard and Guadalupe times, reefs and bedded carbonates built up on the platform and shelf areas while sands and shales were deposited in the adjacent shallow basins. Permian time ended with the accumulation of salt and anhydrite deposits in the restricted late Permian seas. During the Triassic Period, continental deposition occurred over the high plains region resulting in deposition of sandstones interbedded with red shales. The last marine transgression took place in Cretaceous time when very shallow seas spread over the region. Additional continental deposition occurred during Pliocene and Quaternary times, producing sand and gravel deposits.

The following chart illustrates the geological units that have been mapped as aquifers in the West Texas area. Structure maps have been constructed for nearly all units listed.

| GEOLOGICAL AGE | AQUIFER (FORMATION OR UNIT) | TYPE OF ISOPACH* | LITHOLOGY |
|---|---|---|---|
| Triassic | Triassic undifferentiated | Net sand | Sandstone, shale |
| Triassic | Santa Rosa Sandstone | None | Sandstone, shale |
| Permian Ochoa | Rustler Formation | None | Dolomite, anhydrite |
| Permian Guadalupe | Upper Guadalupe; Whitehorse Group, Capitan Reef | Gross thickness | Limestone, sand, shale, dolomite |
| Permian Guadalupe | San Andres Formation | Gross thickness | Limestone, sandstone, shale, dolomite |
| Permian Leonard | Leonard undifferentiated; Clear Fork-Wichita, Leonard Reefs | Gross thickness | Limestone, dolomite, shale sandstone |
| Permian Wolfcamp | Wolfcamp undifferentiated | Net sand and limestone | Shale, limestone, sandstone, detritals |
| Pennsylvanian | Pennsylvanian undifferentiated | Net limestone, and minor detritals | Limestone, sand, shale detritals |
| Mississippian | Mississippian undifferentiated | Net limestone | Limestone, shale, chert |
| Siluro-Devonian | Siluro-Devonian undifferentiated "Devonian" and Fusselman | Gross limestone (Silurian shale formation excluded where present) | Limestone, chert, dolomite |
| Ordovician | Montoya Formation | Gross thickness | Limestone, chert, dolomite |
| Ordovician | Simpson Formation | Gross thickness | Shale, limestone, sandstone |
| Cambro-Ordovician | Ellenburger plus Cambrian sands | Gross thickness | Dolomite, limestone, sandstone |

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* Net thickness is defined as the non-shale intervals within the gross unit thickness.

### Panhandle Area

The area included in the Texas Panhandle consists of those counties north of the east-west trending Matador arch. Geographically, this is part of the high plains of the Llano Estacado, whose topography is broken by erosional features like the caprock scarp on the southeast side, Palo Duro Canyon, and the valley of the Canadian River.

Two structural elements dominate this region: the deep Anadarko basin and the buried Amarillo Mountains. The Palo Duro basin lies between the Matador arch and the Dalhart basin, which occupies the northwest corner of the Panhandle.

The sedimentary and geological history of the Panhandle area is somewhat similar to that of the West Texas area. (See north-south cross section L-L', Figure 7.) Late Cambrian and early Ordovician seas transgressed this region, followed by continuous subsidence and deposition through the Silurian and Devonian Periods, when the area was moderately unlifted. During Mississippian time, another major marine invasion began and thick alternating carbonates and shales were laid down. During Pennsylvanian time, the Amarillo uplift occurred which produced the Amarillo Mountains, a long northwest-southeast trending ridge. Older rocks were exposed down to the Precambrian basement complex and thick deposits of granite wash were shed into the Anadarko basin. The uplift continued into early Permian Wolfcamp time when a gradual subsidence returned the seas over the entire area once again. Widespread deposition of carbonates occurred at that time, followed by near-shore clastics and eventually continental deposits in late Permian time. During the Triassic, the area was covered with continental redbeds and some fluvial sands. Maps were constructed in the Panhandle area for the aquifers listed below. A structure map was prepared of the top of each unit except the Viola and Hunton; several of the West Texas maps previously listed extend partially into the Panhandle.

| GEOLOGICAL AGE | AQUIFER (FORMATION OR UNIT) | TYPE OF ISOPACH* | LITHOLOGY |
|---|---|---|---|
| Triassic | Triassic undifferentiated | Net sand | Sand, shale |
| Triassic | Santa Rosa Sandstone | Net sand | Sand, shale |
| Permian Wolfcamp | Wolfcamp undifferentiated sands and "brown dolomite" | Net sand and carbonates | Dolomite, limestone, sandstone, detritals |
| Pennsylvanian | Pennsylvanian undifferentiated | Net sand, detritals, and limestone | Detritals, shale, limestone, sand |
| Mississippian | Mississippian undifferentiated | Net limestone | Limestone, shale, chert |
| Siluro-Devonian | Hunton | Gross thickness | Limestone, dolomite, chert |
| Ordovician | Viola | Gross thickness | Limestone, chert |
| Cambro-Ordovician | Arbuckle | Gross thickness | Dolomite, limestone, sand |

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* Net thickness is defined as the non-shale intervals within the gross unit thickness.

### Central Texas Area

The area designated as central Texas extends from the Red River to the Llano uplift on the south, and from San Angelo on the west to Fort Worth on the northeast side. Geographically, this is a region of rolling plains, the gypsum plains, western cross timbers, and to the southwest, the extensive Edwards plateau.

Several large structural features dominate the geology and geography of the region. The most prominent are the Llano uplift and the Bend arch, which together form a northward-plunging arch away from which rocks dip westward into the Permian basin and eastward into the Fort Worth basin. The eastern and southern margin of the central Texas area is roughly bound by the arcuate front of the Ouachita tectonic belt, or commonly called Ouachita folded belt. This very large structural system trends through the entire length of Texas, from the Marathon uplift in far West Texas to the Red River northeast of Dallas. For this study, the Ouachita tectonic belt provides the eastern and southern limits for all Paleozoic rocks. Other prominent but smaller structural features of central Texas are the Red River uplift and Muenster arch.

Central Texas has a geologic history partly similar to West Texas and the Panhandle. Geological units are shown on cross sections B-B', M-M', and O-O', Figures 4, 8, and 10, respectively. Cambrian and Ordovician seas covered the region, depositing sands over the eroded Precambrian igneous and metamorphic rocks, followed by thick deposits of limestone. Most of the region was gently uplifted and exposed except for the north basinal areas. Throughout most of central Texas, there is a widespread unconformity between the upper Ordovician Ellenburger (Arbuckle in North Texas) and the Mississippian. The latter is represented by a thin shale and limestone. Another subsidence and marine transgression began in early Pennsylvanian time and resulted in thick deposits of Pennsylvanian rocks in basins on either side of the Bend arch, with thinner shelf deposits over the arch itself. These Pennsylvanian formations are mapped as four age units which are, from oldest to youngest, the Bend, Strawn, Canyon, and Cisco. In central Texas, the Pennsylvanian consists of numerous limestones and sands which alternate with marine shales. Many of the porous members are potential saline aquifers, but are far too numerous to subdivide in a regional study. These various members have been mapped as net porous rock and grouped in their respective age equivalents. A structure map of the top of the Pennsylvanian Series was also constructed in order to conform with and extend the mapping of the Pennsylvanian in West Texas. Following the Pennsylvanian, Permian rocks were deposited over most of central Texas. Subsequent uplift and erosion removed much of this section over the Bend arch. The last marine invasion was during Cretaceous time when shallow seas covered all of the region. Cretaceous rocks thicken eastward and southward away from the central Texas area.

The following units have been mapped as potential aquifers in central Texas.

| GEOLOGICAL AGE | AQUIFER (FORMATION OR UNIT) | TYPE OF ISOPACH* | LITHOLOGY |
|---|---|---|---|
| Permian | Upper Permian undifferentiated (Leonard-Ochoa) | Gross thickness | Shale, limestone, anhydrite, sand |
| Permian Wolfcamp | Wolfcamp | Net limestone and sand | Shale, limestone, sandstone |
| Pennsylvanian Cisco | Cisco | Net limestone and sand | Limestone, sand, shale |
| Pennsylvanian Canyon | Canyon | Net limestone and sand | Limestone, sand, shale |
| Pennsylvanian Strawn | Strawn | Net limestone and sand | Limestone, sand, shale |
| Pennsylvanian Bend | Bend | Net limestone and sand | Limestone, sand, shale |
| Cambro-Ordovician | Ellenburger, plus Cambrian sands | Gross thickness | Limestone, sand, shale |

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* Net thickness is defined as the non-shale intervals within the gross unit thickness.

### East Texas Area

The East Texas area was arbitrarily divided in this study in order to include as aquifers the Cretaceous formations which are present in the East Texas embayment. The area occupies the northeast portion of the State, and extends westward approximately to a line from Dallas to Waco to near Austin. The southern limit is quite arbitrary, but roughly coincides with the outcrop of the base of the Oligocene. Except for the deep Jurassic aquifers (and the shallow Tertiary aquifers that contain fresh water), the East Texas area is a Cretaceous province.

The chief structural features are the Sabine uplift and the East Texas embayment. Rocks on the southern margin dip southward into the Gulf basin. The Ouachita tectonic belt is common to the central and East Texas areas.

Little is known of the Paleozoic history in East Texas, especially east of the Ouachita folded belt, since those Paleozoic sediments adjacent to the Ouachita tectonic belt are metamorphosed, and no sediments older than Jurassic have been penetrated in the East Texas embayment. Early Jurassic seas appear to have been both open marine and restricted. The restricted marine conditions resulted in the deposition of salt and anhydrite. During the Cretaceous, gradual but continuous subsidence occurred throughout the East Texas area. The geological units of East Texas are illustrated on cross sections C-C' and N-N', Figures 5 and 9, respectively. Thick biostromal limestones, deltaic sand complexes, and basinal shales alternately were deposited. In Tertiary time, rapid subsidence of the Gulf Coast geosyncline had begun in the south and sediments were predominantly sand and shale. The following is a chart of the potential aquifers of this region that were mapped.

| GEOLOGICAL AGE | AQUIFER (FORMATION OR UNIT) | TYPE OF ISOPACH* | LITHOLOGY |
|---|---|---|---|
| Cretaceous | Nacatoch Sand | Net sand | Sand, shale |
| Cretaceous | Eagle Ford | Net sand | Sand, shale, limestone |
| Cretaceous | Woodbine | Net sand | Sand, shale |
| Cretaceous | Upper Glen Rose-Paluxy | Net sand | Sand, limestone, shale |
| Cretaceous | Lower Glen Rose | Net sand and limestone | Sand, limestone |
| Cretaceous and Jurassic | Pettet-Travis Peak-Cotton Valley | Net sand | Sand, limestone, shale |
| Jurassic | Cotton Valley-Smackover | Gross limestone | Limestone, shale |

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* Net thickness is defined as the non-shale intervals within the gross unit thickness.

### Gulf Coast Area

The Gulf Coast area was arbitrarily subdivided to include all the saline aquifers of the Tertiary of the Gulf Coast. It coincidentally includes two Cretaceous aquifers that extend the entire length of the Gulf coastal plain, the Edwards and lower Glen Rose Formations. Geographically, the area is relatively simple as it is comprised of flat or gentle rolling coastal plains, broken slightly by low cuestas which parallel the coast line. To the northwest, the low plains are terminated by the Edwards plateau and Balcones escarpment.

Several down-to-basin fault zones which also parallel the coast line occur in the subsurface. Subsidence on the Gulf side of these fault zones was much more rapid than on the landward side.

The Gulf geosyncline began subsiding in Jurassic time and continued throughout the Tertiary. Often contemporaneously with subsidence and sedimentation came the formation of salt domes in East Texas and along the coastal plain. The salt probably came from the Jurassic rocks below. As subsidence increased during the Oligocene and Miocene, the axis of the geosyncline moved farther gulfward. Enormous thicknesses of sand and shale were deposited in the geosyncline. Sedimentation in the Gulf basin is continuing into the present time. Geological units of the Gulf Coast area are shown on cross sections O-O', P-P', and R-R', Figures 10, 11, and 12, respectively.

Most of the Cretaceous and Tertiary formations contain fresh water near their surface exposure. Salinity increases downdip. Maps have been constructed on the Edwards and Glen Rose Formations, and the Carrizo-Wilcox aquifer of Eocene age, using a stratigraphic subdivision. However, Tertiary formations younger than the Carrizo-Wilcox have been mapped on the basis of zones, or layers 2,000 feet thick. This was done to eliminate the complex stratigraphic problems inherent in the Tertiary formations. The following aquifers, including the 2,000-foot zones, are included in the mapping.

| GEOLOGICAL AGE | AQUIFER (FORMATION OR ZONE) | TYPE OF ISOPACH* | LITHOLOGY |
|---|---|---|---|
| Tertiary | Zone 2<br>(  0 to - 2,000 ft.) | Net sand | Sand, shale |
| Tertiary | Zone 3<br>(-2,000 to - 4,000 ft.) | Net sand | Sand, shale |
| Tertiary | Zone 4<br>(-4,000 to - 6,000 ft.) | Net sand | Sand, shale |
| Tertiary | Zone 5<br>(-6,000 to - 8,000 ft.) | Net sand | Sand, shale |
| Tertiary | Zone 6<br>(-8,000 to -10,000 ft.) | Net sand | Limestone, shale, chert |
| Tertiary Eocene | Carrizo-Wilcox | Net sand | Limestone, shale, chert |
| Cretaceous | Olmos | Net sand | Sand, shale |
| Cretaceous | Edwards Formation | Net thickness | Limestone, shale, chert |
| Cretaceous | Glen Rose Formation | Gross thickness | Limestone, shale, chert |

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* Net thickness is defined as the non-shale intervals within the gross unit thickness.

## GEOLOGY OF THE INDIVIDUAL AQUIFERS

### Ellenburger Aquifer

The Ellenburger aquifer of Cambro-Ordovician age is located in parts of west, central, and the Panhandle areas of Texas and consists primarily of dolomite, limestone, and sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 13, 14, 15, 16, 17, and 18, respectively.

The Ellenburger Group is the most widespread of all the aquifers in the State of Texas. The aquifer or one of its age and facies equivalents occurs in wells as far south as Kinney and Edwards Counties to as far north as the Oklahoma boundary in the Texas Panhandle. It is also known from as far east as Grayson County in the subsurface, to its equivalent formations in outcrops at El Paso. Rocks of the Ellenburger Group outcrop on the flanks of the Precambrian rocks of the Llano uplift in central Texas, and dip away from the uplift in all directions. The Ellenburger or its equivalent also outcrops in the Van Horn uplift of far West Texas and in smaller uplifts of that region. It is not recognizable south and east of the Ouachita tectonic belt, and is absent due to uplift and erosion over a wide portion of the Panhandle. It is absent due to local uplift and erosion over portions of the Central Basin platform. As an aquifer containing water of over 3,000 ppm total dissolved solids, the Ellenburger is mappable throughout its entire extent except for the area of the Llano uplift, where the 3,000 ppm salinity boundary rims the uplift.

Several important regional structural trends affect the Ellenburger, as well as numerous minor and local structural elements. Areas of greatest subsidence and downwarp are the Delaware-Val Verde, Anadarko, Fort Worth, and Midland basins. Important uplifts and positive structural features include the Ouachita tectonic belt, the Amarillo and Matador uplifts, the Concho arch, the Central Basin platform, and the Muenster and

Red River arches of north central Texas. Most of these tectonic features affected the thickness of the Ellenburger either directly or indirectly. Elevations of the Ellenburger and its equivalents vary from 4,000 feet above sea level at its outcrops in far West Texas to more than 20,000 feet below sea level along the west flank of the Central Basin platform. In at least half of its areal extent the aquifer is more than 5,000 feet below sea level. (See structure maps, Figures 13 and 14).

The Ellenburger Group ranges in age from upper Cambrian to lower Ordovician. For this study, rocks of upper Cambrian, which are comprised mostly of porous sandstones, are not differentiated but rather are included in the isopachous map of the Ellenburger. These equivalents include the upper Cambrian Riley and Wilberns Formations of central Texas and the Bliss and Van Horn Sandstones of far West Texas. In the Panhandle and in north central Texas, the Arbuckle Formation is designated as Ellenburger even though it is considered younger than Ellenburger Limestone of central and West Texas. Most of the rocks of Cambrian age occur along the northwestern flank of the Llano uplift and in northwest Texas, particularly on the eastern shelf. For the most part, the Ellenburger is comprised of dolomite, limestone, or a combination of the two, frequently with a thin layer of clastics at the base. Ellenburger was deposited on Precambrian basement everywhere. Throughout most of its occurrence in Texas, there is an unconformity at the top of the Ellenburger. Thicknesses vary from zero at the erosional margins to as much as 4,000 feet in the extreme eastern portion of its occurrence in the Fort Worth basin. Thicknesses up to 1,700 feet are common throughout the Midland and Delaware basins, and the Arbuckle Formation attains a thickness of more than 2,500 feet in the Texas Panhandle; Lithologies are quite homogeneous in the Ellenburger, and the formation as a whole has a very high ratio of net porous rock to non-porous rock. In this study, the Ellenburger including the Cambrian sands is mapped in its gross thickness, even though not all of the rock is porous and permeable.

Salinities range from fresh water in the outcrop area of central Texas to highly saline waters in the subsurface of central and West Texas. Although data are scarce, there appears to be a trend toward fresher quality water west of the Delaware basin. This would suggest the influx of meteoric waters from outcrops of that region.

Due to its widespread extent, thickness, and relative homogeneity, the Ellenburger aquifer contains a large volume of saline water. However, productivities from both actual and ideal measurements can vary considerably. In general, porosities and permeabilities are rather low, with porosities ranging from 2 to 12 percent and averaging about 4 percent, and permeabilities ranging from 0.1 to 200 millidarcies.

## Simpson Aquifer

The Simpson aquifer of Ordovician age is located in parts of West Texas, central Texas, and the Panhandle and consists primarily of shale with thin but widespread beds of sandstone and limestone. Structure and isopachous maps have been prepared for this aquifer in the West Texas area only, Figures 19 and 20, respectively.

The Simpson rocks of middle Ordovician age in West Texas occupy the central portion of an ancient basin which was smaller and more restricted than the preceding Ellenburger depositional basin. The West Texas Simpson was separated from the Simpson of north central Texas and Oklahoma by a large ancient arch, generally called the Texas peninsular. Only the West Texas Simpson has been mapped for this report, since the Simpson of the Panhandle is very deep and other aquifers more abundant and widespread.

The Simpson of West Texas is largely confined to the subsurface. The formation has been mapped to zero thickness on its east flank, but control is lacking on the south and west portions of the area. The Simpson is absent over small areas of the Central Basin platform due to erosion. Structurally, the formation ranges from 3,000 feet subsea on the platform to more than 17,000 feet subsea in the Delaware basin. It is subject to thinning both by deposition and by erosion and varies in thickness from zero to 2,200 feet. The formation is comprised largely of gray or grayish green calcareous shale, interbedded with porous sandstones and limestones. The porous members of the formation comprise an estimated 15 to 25 percent of the total gross thickness. These porous members are oil productive in West Texas.

Very few salinity data were available for this study. Those data available show a range of salinities from 50,000 to more than 200,000 ppm.

Productivity data are also scarce for the Simpson, and due to differences in the characteristics of the porous members, the resulting averages of the formation as a whole are questionable. Any consideration for use of Simpson water would necessitate an evaluation of each individual porous unit in a given area. Thus, the aquifer must be rated low as a potential saline water source.

## Montoya Aquifer

The Montoya aquifer of upper Ordovician age is located in parts of West Texas and the Panhandle (as Viola Limestone) and consists of dolomite, limestone, and chert. Structure and isopachous maps of the Montoya and its equivalent in the Anadarko basin, the Viola Limestone, have been prepared for this aquifer, Figures 21 and 22, respectively.

The Montoya Formation occurs in West Texas in an area similar to the preceding Simpson Formation, and was also separated from its equivalent in the Panhandle and north central Texas by the so-called Texas peninsular. An isopachous map of the Montoya equivalent in the Panhandle, the Viola Limestone, is included in this study. The Montoya thins to zero on the north margin of the Central Basin platform and eastern flank of the Midland basin, although there are remnants in Crockett and Val Verde Counties. Montoya is also eroded off a portion of the platform in Pecos and Crane Counties. The Montoya outcrops in small areas of the Marathon, Van Horn, and El Paso areas around exposed Precambrian rocks.

The Montoya Formation conforms structurally to other Paleozoic formations of West Texas. It is found on surface exposures 4,000 feet above sea level and extends to depths of more than 16,000 feet subsea in the Delaware basin. The structure map, Figure 21, does not include the Panhandle, where the structure of the Montoya equivalent conforms very well to the Ellenburger.

The Montoya Formation is predominantly limestone and dolomite throughout its entire extent, although it becomes quite siliceous in places. The Montoya is normally separated from overlying Siluro-Devonian carbonates by a thin but extensive shale unit. In places, however, porous Montoya is in direct contact with porous rock above and therefore is a possible part of a larger aquifer system. The Montoya was mapped in its gross thickness on the isopachous map, Figure 22.

Salinity data in the aquifer are scarce, but available samples indicate a range of total dissolved solids in the magnitude of 40,000 to 150,000 ppm. There is not sufficient control to justify a salinity map on this formation.

The Montoya Formation is also a producer of hydrocarbons in the Permian basin, as is the equivalent Viola Limestone in the Anadarko basin. Rock property information is not abundant but indications are that porosities and permeabilities average 5 to 10 percent and 10 millidarcies, respectively. The Montoya would rank fairly low as a regional saline aquifer.

## Siluro-Devonian Aquifer

The Siluro-Devonian aquifer is located in parts of West Texas and the Panhandle areas of Texas and consists primarily of limestone and chert. Structure, isopach, and salinity maps have been prepared for this aquifer, Figures 23, 24, and 25, respectively.

The Siluro-Devonian aquifer of West Texas and the Panhandle has been designated and mapped as a single unit although in West Texas it is commonly two distinct stratigraphic units; the Silurian Fusselman Formation and the "Devonian limestone." The two units are usually separated by a thin shale commonly called the "Silurian shale," but over large areas the two formations are thought to be in direct contact.

The structure of the Siluro-Devonian aquifer closely resembles that of the underlying pre-Silurian formations, with a structural high area over the Central Basin platform adjacent to the deep Delaware basin depression on the west and a structural low axis in the Midland basin on the east. Elevations of the unit vary from 3,000 feet subsea on the Platform to 10,000 feet subsea in the Midland basin and 16,000 feet subsea in the Delaware basin. Siluro-Devonian rocks also occur in surface exposures in far West Texas at or higher than 4,000 feet above sea level. Figure 23 depicts the structure on top of the Siluro-Devonian aquifer.

The upper surface of the Siluro-Devonian is the top of the "Devonian limestone." This mapping horizon is often gradational with the overlying Woodford Shale, but it is always a sharp lithological boundary in West Texas. The upper Devonian rock is comprised of limestone or cherty limestone, and studies have shown that the chert content varies upward to 50 percent in the Delaware basin. The Fusselman is normally much less cherty. Both lithological units contain varying amounts of dolomite as well. To map the Siluro-Devonian, gross carbonate thickness was used, which includes the cherty portion but excludes any shale members. Refinement to include only porous limestone would require detailed study with the use of lithological logs. In Oklahoma as well as the Texas Panhandle, the Siluro-Devonian equivalent is known as the Hunton Formation. An isopachous map of the Hunton in the Anadarko basin is included, where a thickness of over 1,500 feet is interpreted, Figure 24. In West Texas, the Siluro-Devonian carbonates vary in thickness from zero at erosional margins to as much as 1,300 feet in the basins. Siluro-Devonian rocks are absent in several small areas over structures on the Central Basin platform, where they have been removed by later erosion.

Available salinity data in West Texas indicates a somewhat indistinct salinity pattern. The higher salinities are found over the Central Basin platform. A trend of lower salinities westward in the Delaware basin toward the outcrops is interpreted.

The Siluro-Devonian is an important producer of hydrocarbons in West Texas and the Panhandle area. Porosities are commonly in the 5 to 10 percent range, and permeabilities vary considerably, from less than 10 to more than 100 millidarcies.

## Mississippian Aquifer

The Mississippian aquifer is located in parts of West Texas and the Panhandle area and consists primarily of limestone and siliceous limestone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 26, 27, and 28, respectively.

The Mississippian System of western and northern Texas resulted from a gradual and broad subsidence forming a large shallow basin. Rocks of Mississippian age are mappable throughout West Texas, the Panhandle, central Texas and even outcrop as far southeast as the Llano uplift region. For this study, they have been mapped in West Texas and in the Panhandle. Mississippian rocks thin to a feather edge in the Van Horn area, are absent over much of the Central Basin platform, and are missing due to erosion over the buried Amarillo Mountains. They have not been mapped in central Texas because the Mississippian is considered a poor quality aquifer in that region.

Elevations on top of the Mississippian are quite variable throughout West Texas, ranging from 4,000 feet above sea level to more than 15,000 feet subsea in the basinal depressions. The structure map, Figure 26, is contoured on top of undifferentiated Mississippian regardless of age or lithology.

Mississippian rocks are divided into four ages which are, oldest to youngest, Kinderhook, Osage, Meramec, and Chester. In most of West Texas, the upper part of the section consists of the Barnett Shale and the lower part is a continuous limestone or cherty limestone usually called the "Mississippi lime." In the northern platform area, there is a thinner limestone unit above the Barnett Shale. In the Panhandle region, the entire section is present locally and consists predominantly of limestone or cherty limestone. The base of the section is the Woodford Shale which is gradational into the "Devonian limestone." Mississippian rocks were mapped on the isopachous map, Figure 27, as net limestone thickness, with no attempt to distinguish the more porous limestone. The thickest net potential aquifer occurs in the Anadarko basin where it attains a thickness of over 1,200 feet. Except for an isolated area in Yoakum County, the net thickness averages 600 feet or less in West Texas. Net thickness has been contoured to a minimum of 50 feet even though some wells were interpreted to have no measurable aquifer thickness. Rocks of Mississippian age cover most of central Texas except over the Bend arch northwest of the Llano uplift, and in an area northeast of the Muenster arch. Porosity development in limestone in central Texas is poor, and most of the section is comprised of shales and dense, cherty limestone and is not considered to be of any great consequence as a saline water source.

Salinity data are scarce regionally but indicate a salinity range between 50,000 and 150,000 ppm. The salinity map of the Mississippian System is highly conjectural (Figure 28).

Productivity data indicate that rock properties are similar in magnitude to the Siluro-Devonian and Montoya. Porosities average 8 to 12 percent and permeabilities from 10 to 50 millidarcies.

## Pennsylvanian Aquifer (Undifferentiated)

The Pennsylvanian aquifer is located in parts of West Texas and the Panhandle areas of Texas and consists primarily of limestone and shale with minor sandstone and detritals. For West Texas and the Panhandle, structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 29, 30, and 31, respectively.

Rocks of the Pennsylvanian System are present throughout most of West Texas and the Panhandle. This system thins to zero thickness in the Van Horn and Diablo plateau region, and is absent due to pre-Permian erosion over the platform, and over the Amarillo Mountains.

Pennsylvanian rocks are found at elevations greater than 4,000 feet above sea level in outcrops in the Van Horn and El Paso regions, and plunge to more than 15,000 feet below sea level in the Delaware basin. A large portion of the Midland basin is below 7,000 feet subsea and rises to 2,000 feet subsea along the edge of the Eastern shelf. The elevations vary in the Panhandle in the subsurface from 500 feet above sea level to more than 4,500 feet subsea in the Anadarko basin. Structure of the Pennsylvanian of West Texas and the Panhandle is shown on Figure 29.

In Texas, Pennsylvanian rocks are normally subdivided into four series which are, from oldest to youngest, Bend, Strawn, Canyon, and Cisco. Bend is commonly subdivided into Morrow (older) and Atoka. In central Texas, where the Pennsylvanian as a whole is a shelf facies, correlations are easily recognizable and can be accomplished with electrical logs over wide areas. In West Texas and the Panhandle, facies changes are often abrupt and paleontology is usually required in order to correlate and subdivide the Pennsylvanian into series. Facies vary considerably from basinal black shale, to reefal, to biostromal, to detrital. Therefore, it was decided to map the Pennsylvanian as an undifferentiated unit in West Texas and the Panhandle, and to subdivide it into series in central Texas. The structure map in the western area, Figure 29, is contoured on top of the uppermost Pennsylvanian series, regardless of age. Figure 30 is a net potential aquifer thickness map, regardless of lithology. In general, the map reflects regional facies. Surrounding the Central Basin platform is a rim of porous limestone with thicknesses up to 1,000 feet, which represents Pennsylvanian reefing of various ages. Pennsylvanian reefs are also discernable from the isopachous map in Scurry, Dawson, Terry, and Gaines Counties. Over the northwest shelf and into the Panhandle, the net aquifer thickness is comprised of variable amounts of clastic and carbonate porous rock. In the Anadarko basin, thicknesses which attain 1,400 feet are attributable to thick wedges of highly porous granite wash that was shed off the rapidly emerging mountains and dumped into the surrounding depressions.

Salinities are quite high in formation water in the Pennsylvanian rocks, varying from 50,000 to 200,000 ppm. The reef buildups seem to have the highest salinities of the region (Figure 31). In the Panhandle, brines vary between 20,000 and 130,000 ppm.

The Pennsylvanian System of West Texas and the Panhandle is an important producer of hydrocarbons from a variety of facies and traps. It also contains a large quantity of highly saline water. Due to the variability in rock types, reservoir rock properties are also highly variable. Porosities and permeabilities range from low in the bedded limestones, moderate to good in the reefal limestones, and good to excellent in sandstones and detritals. The porosity ranges from 5 percent to greater than 25 percent. Permeabilities and productivities can also be expected to have a wide range of variability.

## Pennsylvanian Aquifers of Central Texas

The area designated as central Texas in this study is bounded on the west approximately by the 101st meridian, on the north by the Red River, and on the east and south approximately by the Ouachita tectonic belt. The Llano uplift, Bend arch, Muenster arch, and Red River uplift are major structural features of the region. The Bend arch forms a dividing line between the Permian basin to the west and the Fort Worth basin on the east. The regional structure as mapped on top of Pennsylvanian (undifferentiated) rocks is shown on Figure 32.

As previously discussed, Pennsylvanian rocks which were mapped as an undifferentiated unit in West Texas can be readily subdivided into four series in central Texas: Bend, Strawn, Canyon, and Cisco. Well log correlations as used in this study were based on cross sections of the Abilene, North Texas, Fort Worth, and Dallas Geological Societies, and from other studies and reports pertaining to the region. In all Pennsylvanian series of central Texas, net aquifer thicknesses have been determined on the electric logs and isopachous maps have been constructed using these thickness values. Net aquifer thickness does not distinguish lithologies, but simply measures total "clean" or potentially porous rock. The stratigraphic units of the Pennsylvanian System of central Texas can be seen on cross sections B-B′ and M-M′, Figures 4 and 8.

### Bend Aquifer

The Bend aquifer of Pennsylvanian age located in the central Texas area consists of shales, limestone, conglomerates, and thin sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 33, 34, and 35, respectively.

Rocks of the Bend aquifer cover most of the study area except for small areas where these rocks are absent, possibly due to erosion. The Bend outcrops in the Llano uplift in parts of San Saba, Lampasas, and Burnet Counties. Bend rocks are conformably overlain by the Strawn, except where eroded and overlain by Cretaceous rocks.

The term "Bend" was chosen to include those rocks of basal Pennsylvanian age and can be further subdivided into Morrow and Atoka. "Bend" has become widely accepted in the literature and by the oil industry. For this study the top of the Bend was the base of the Caddo Limestone or top of Smithwick Shale, since these formations are easily correlated and recognized.

In central Texas, the base of the unit is selected as the top of Mississippian Barnett Formation, where present, or otherwise the top of the Chappel Limestone.

Salinities in the Bend vary from 50,000 to 200,000 ppm. Salinity contours suggest a slight decrease in salinity toward the south. Average porosity for Bend rocks ranges from 10 percent to as high as 20 percent, and permeability can vary from 5 to 600 millidarcies. Higher permeabilities are usually confined to well-sorted, coarse-grained sands and conglomerates. Limestones are also important in this section. However, net aquifer thickness is quite thin regionally, and the Bend is not considered to be a good source of saline water.

### Strawn Aquifer

The Strawn aquifer of Pennsylvanian age located in central Texas consists of limestone, shale, and sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 36, 37, and 38, respectively.

Rocks of the Strawn aquifer outcrop in two localized areas of central Texas. One area is in parts of San Saba, Brown, and southern Mills Counties, and the other area is in parts of Erath, Palo Pinto, and Parker Counties. From the Bend arch, Strawn rocks dip westward into the eastern shelf and Midland basin and eastward into the Fort Worth basin. As shown on the structure map, Figure 36, dip is gentle and uniform.

The correlation of the Strawn has been problematical for years and there is still a certain amount of confusion. For this study, the top of the Strawn is considered to be the base of the Palo Pinto Limestone of the Canyon Series. The base of the Strawn has been defined as either the base of the Caddo Limestone or as the top of the Smithwick Shale. Locally, the Pennsylvanian is deeply eroded and unconformably overlain by Cretaceous strata. The Strawn has a variable lithology throughout central Texas. Lithologies include biohermal and biostromal limestones, sandstones, and shales. Net aquifer thickness attains nearly 1,000 feet, and although lithologies are not distinguished in this study, the aquifer is believed to be divided equally between carbonate and clastic rock types. Carbonate rocks, chiefly limestone, take a great importance in the western margin of the area due to reefing. Figure 37 is a net isopachous map of the Strawn in central Texas.

Formation water in the Strawn is highly saline over a wide area seen in the salinity map, Figure 38. Total dissolved solids of over 200,000 ppm are common. There appears to be a trend to slightly lower salinities, less than 50,000 ppm, to the southeast.

The Strawn has a potentially high yield as a saline aquifer. Because of variations in the facies and rock types, it can also be expected that porosities and permeabilities will be highly variable. Porosity ranges from 5 to 20 percent, but the average is about 15 percent. Permeability can range from 5 millidarcies to greater than 500 millidarcies in clean sands. Reefal limestones can have very high porosity and permeability in a small local area. Due to all of these variables, any study of the Strawn as a potential saline water source would need to be more detailed than this regional investigation.

### Canyon Aquifer

The Canyon aquifer of Pennsylvanian age located in central Texas consists of limestone, sandstone, and shale. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 39, 40, and 41, respectively.

Rocks of the Canyon aquifer outcrop in a band about 10 miles wide in McCullough County and along a northeast trend through parts of Brown, Eastland, Palo Pinto, Jack, and Wise Counties. Width of the outcrop is as much as 20 miles in Palo Pinto County. Canyon rocks dip gently to the west and occur as deep as 3,900 feet below sea level in the western edge of central Texas. Structure on top of the Canyon is depicted on Figure 39.

The Canyon is conformably overlain by rocks of the Cisco. For this study the top of the Canyon was chosen as the top of the Home Creek Limestone, the base defined as the base of the Palo Pinto Limestone. These limits are generally accepted as boundaries of the unit and are easily recognized on electric logs. Lithologies are variable in Canyon rocks, but consist primarily of limestone, sandstone, and shale. The relatively thin shelf limestone and sands are common locally as in the underlying Strawn.

Salinities in the Canyon range from less than 50,000 to more than 200,000 ppm. The regional salinity trend is from very saline water in the west to less saline water in the direction of the outcrop on the eastern side of the area (Figure 41).

The Canyon can be considered as a potentially good saline water source in central Texas. Rock properties are variable with porosities ranging from 5 percent to as much as 25 percent, and reef porosity as high as 30 percent locally. This variability is reflected in permeabilities which can range from 1 to over 500 millidarcies. Most net porosity in Canyon rocks occurs in the sandstone on a regional scale, although the largest net values locally are due to limestone build-up in reefs. The Palo Pinto Limestone of the Canyon aquifer is both widespread geographically and consistently porous. Detailed local investigations would be necessary if Canyon rocks were to be considered for use as a saline aquifer.

### Cisco Aquifer

The Cisco aquifer of Pennsylvanian age located in central Texas consists of limestone, shale, and sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 42, 43, and 44, respectively.

Cisco rocks are the least extensive of the Pennsylvanian System, occurring in only the western portion of central Texas. These rocks outcrop in a band from 10 to 20 miles wide across Brown, Eastland, Stephens, Young, Jack, and Montague Counties with the eastern limit extending into the subsurface in Cooke County on the north and Edwards County on the south. The Cisco as seen on the structure map, Figure 42, dips gently to the west and attains a depth of 2,700 feet subsea on the western edge of central Texas.

Cisco rocks consist of a sequence of bedded sandstone, limestone, and shale, with some localized reefing. The bulk of porous Cisco rocks are sandstones. The top of the unit in this study was considered to be top of the Crystal Falls Formation and thus the contact line between Pennsylvanian and Permian. The base is defined as top of the Home Creek Limestone. The boundary between Cisco and Canyon is distinct along the eastern side of the study area but tends to be difficult in the west. The gross thickness of the Cisco varies from zero at the outcrop to 1,000 feet elsewhere, but net aquifer thickness only attains 10 to 15 percent of the gross (Figure 43).

Salinity ranges in the Cisco aquifer are similar to the other Pennsylvanian units, ranging upward to 200,000 ppm. Lower salinities are interpreted on the salinity map, Figure 44, near surface exposures.

Cisco rocks are not considered to be as important in central Texas as the Strawn or Canyon aquifers. However, locally developed porosities and permeabilities can be good. Porosities average 12 to 22 percent and permeabilities vary from 10 to 350 millidarcies.

## Wolfcamp Aquifer

The Wolfcamp aquifer of Permian age located in parts of West Texas, central Texas, and the Panhandle consists of shale, limestone, and sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 45-50.

Rocks of the Wolfcamp are very extensive throughout western Texas and are the thickest of any Paleozoic rocks in the State, attaining 14,000 feet in the Delaware basin and Val Verde trough. Wolfcamp rocks or their equivalents outcrop in Trans-Pecos Texas and in parts of central Texas. Due to its wide extent, the formation is carried on two sets of maps, West Texas-Panhandle and central Texas. Structurally, the Wolfcamp reflects the configuration of the underlying older units (Figures 45 and 46). Wolfcamp structure prominently reflects regional features like the Delaware, Midland, and Anadarko basins, the Central Basin platform, Amarillo Mountains, the eastern shelf, and Bend arch.

Due to its widespread nature, Wolfcamp rocks can be expected to have a wide variety of lithologies as well. Lithologies vary from thick basinal shales to porous shelf and reefal limestones, to interbedded limestones and sands. In the Panhandle, the Wolfcamp occurs as an extensive bedded carbonate unit known locally as the "brown dolomite." Around the margins of the Central Basin platform and northwest shelf, thick reefal-like limestones occur. The net aquifer thickness in West Texas depicts the regional facies. The 100-foot contour generally defines the Midland and Delaware basins. Isopachs of the combined limestone and sandstone in the Wolfcamp are shown on Figures 47 and 48.

The formational boundaries of the Wolfcamp are often difficult to determine. Both upper and lower limits are frequently gradational with Permian Leonard and Pennsylvanian units, respectively, particularly where reefing continued from one or the other ages across time lines. Locally, picking the top or base of the formation was arbitrary. In central Texas the most consistent correlation point for the Wolfcamp is the base of the Coleman Junction Formation. "Top of Wolfcamp" is normally the first major shale break below the evaporite-carbonate section of the Wichita-Albany and usually occurs 200 to 300 feet above the base of the Coleman Junction. Base of the Wolfcamp in central Texas is considered as top of the Crystal Falls of Pennsylvanian Cisco age.

Regional salinity patterns in the Wolfcamp, shown on the salinity map, depict a broad portion of the Midland basin, northwest shelf, and Anadarko basin as having salinities over 100,000 ppm. There appears to be a trend to salinities of less than 50,000 ppm on the east and southeast. Salinity maps are included as Figures 49 and 50.

Reservoir rock properties are as variable as facies within the Wolfcamp Series. Porosities can range from less than 5 to more than 25 percent, and permeabilities from 1 millidarcy to more than 1 darcy. Any productivity evaluation of this aquifer should be made on a local basis rather than on a regional scale.

## Leonard Aquifer

The Leonard aquifer of Permian age located in West Texas consists of limestone, shale, sandstone, and anhydrite. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 51, 52, and 53, respectively.

The Leonard aquifer as defined in this investigation occurs only in West Texas, since Leonard rocks in central Texas are included in an "upper Permian (undifferentiated)" aquifer in that region.

Leonard facies are variable but fairly well defined in the Permian basin. In the Delaware basin, the Leonard is represented by the Bone Spring Formation, a sequence of alternating thick basinal limestones, sands, and shales. In the Val Verde and Midland basins, there is a thick section of shale and shaly sandstones of low porosity and permeability. In this report, the sequence is simply called "Leonard undifferentiated," or in the Midland basin, the lower sands and siltstones are defined as Spraberry. On the platform and shelf areas, the Leonard facies changes abruptly to shelf and reefal limestones. Leonard shale carbonates are divided into an upper Clear Fork Formation and a lower Wichita Formation. The Wichita, or Wichita-Albany of central Texas, is the approximate equivalent of the Abo of New Mexico and the northwest shelf. Lower Abo is possibly Wolfcamp, but was included in the Leonard for mapping purposes. Both Clear Fork and Wichita Formations are dolomitized to varying degrees, and both produce hydrocarbons. Leonard carbonates are well developed along the eastern shelf, especially so along the Howard and Glasscock County lines. These units become increasingly evaporitic and shaly towards the east and north. The isopachous map of the Leonard depicts total thickness. Electric and radioactive log character in the Leonard does not permit picking net aquifer thickness with any degree of accuracy. This condition is due to low average permeabilities and highly varied lithologies. To map net aquifer thickness, it would be necessary to have good lithological log control available.

The structure of the Leonard is mapped on top of the Clear Fork and its equivalent where possible. It is therefore coincident with the base of the Glorieta Formation, or on the eastern shelf, the San Angelo Sandstone.

The Glorieta-San Angelo is considered in this study to be of Leonard age, although it is placed partially in the lower Guadalupe by some stratigraphers. The Glorieta-San Angelo consists of sandstone, conglomerate, and sandy dolomite. Where present, this unit is 100 to 300 feet thick in the Midland basin and surrounding shelf areas. The unit is considered to be a potential saline aquifer although no maps have been prepared. Configuration of a structure map on top of the Glorieta or San Angelo would be identical to that of the top of the Leonard.

Average water salinities in Leonard rocks are very high, with some samples over 250,000 ppm. Trends to slightly lower salinities to the south and southeast are interpreted on the salinity map (Figure 53).

Productivities and rock properties are predicted to vary with facies. The platform and shelf facies of the Leonard (Clear Fork and Wichita Formations) are the principal aquifers. Some producible saline water can be expected in the Delaware basin from the Bone Spring Formation. In the remainder of the area where Leonard undifferentiated and Spraberry occurs, very low water productivities can be expected.

## San Andres Aquifer

The San Andres aquifer of Permian Guadalupe age located in West Texas consists of limestone, dolomite, anhydrite, and sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 54, 55, and 56, respectively.

The San Andres Formation extends from New Mexico into central Texas, and from the Texas Panhandle into the southern Permian basin. However, only that portion shown on the structure and isopachous maps, Figures 54 and 55, is considered as a potential saline aquifer. That portion of the San Andres east of these maps on the eastern shelf in central Texas has been mapped as "upper Permian (undifferentiated)." The San Andres Formation outcrops in the San Andres Mountains of New Mexico and is broadly defined as the equivalent of the Cherry Canyon Formation above the Glorieta.

The lithologies of the San Andres vary according to facies. Along the western edge of the platform in Ward and Winkler Counties, it is a reefal limestone. On the platform proper are bedded limestones and dolomites. Reef-like limestone banks spread across the Midland basin during lower Guadalupe time in the area of Andrews, Martin, Howard, and Mitchell Counties. The lower San Andres is very porous and permeable throughout this bank facies. Northward, the formation becomes increasingly evaporitic. In the southern Midland basin, it becomes sandy. The isopachous map, Figure 55, is a total thickness map of the San Andres. Any net thickness evaluation would require detailed lithological log control. In the Delaware basin the San Andres is equivalent to the lower part of the Delaware Mountain Group, which has been mapped separately.

Salinities are very high in most of the San Andres. Over 200,000 ppm total dissolved solids are common on the northwest shelf where salt beds are present. Figure 56 is a salinity map of the San Andres.

Porosities average from 7 to 15 percent in the formation and permeabilities from 1 to 500 millidarcies. Potential aquifer quality is best in porous bank facies on the Central Basin platform and central Midland basin.

## Upper Guadalupe Aquifer

The upper Guadalupe aquifer of Permian age located in West Texas consists of limestone, dolomite, sandstone, and anhydrite. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 57, 58, and 59, respectively.

The type section of the Permian Guadalupe is exposed in the Guadalupe and Delaware Mountains of Culberson County. It includes the world famous outcrops of the Capitan Reef and its equivalent shelf and basin facies. For this study the entire Permian Guadalupe has been somewhat arbitrarily divided into two aquifers, the preceding San Andres and the "upper Guadalupe" aquifers. As defined here, the upper Guadalupe includes the Whitehorse Group on the Central Basin platform, Midland basin, and eastern shelf and the Capitan Reef surrounding the Delaware basin. The Delaware Mountain Group is also included, even though it is equivalent to both the San Andres and the upper Guadalupe units combined.

The Whitehorse Group, traced from central Texas, consists of five separate formations, which are from oldest to youngest the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations. The Tansill is mostly a thin dense anhydrite and the structure map was contoured on top of the Yates where the Whitehorse Group was mapped, and on top of the reef along the front of Capitan Reef. Over the platform, Whitehorse Group is comprised of interbedded limestone, sandstone, dolomite, and some anhydrite. To the north and east, the Whitehorse becomes increasingly evaporitic and shaly until salts occur interbedded with redbeds. Capitan Reef consists of massive limestones and dolomite.

The Delaware Mountain Group is mappable with electric logs and is divided into three formations, which are from oldest to youngest, Brushy Canyon, Cherry Canyon, and Bell Canyon. The group consists of sandstone, thin dense limestones, and shale.

The top of the upper Guadalupe varies in elevation from more than 5,000 feet above sea level to below 2,500 feet subsea in the Delaware basin. The isopachous map, Figure 58, depicts the gross thickness of the upper Guadalupe as defined here.

Salinities in the aquifer range from less than 10,000 ppm in the subsurface reef complex to more than 250,000 ppm in the Delaware basin. Salinities of less than 3,000 ppm are interpreted near the outcrop in Culberson County, as shown on the salinity map, Figure 59.

High productivities can be expected in the reef complex and in limited areas of the Whitehorse Group on the platform, with decreasing productivities in the basin and shelf areas. Moderate to limited productivity can be expected from sandstones of the Delaware Mountain Group. Porosities and permeabilities are highly variable depending on the facies.

## Upper Permian (Undifferentiated) Aquifer of Central Texas

The upper Permian (undifferentiated) aquifer located in west central Texas consists of limestone, dolomite, shale, anhydrite, and sandstone. An isopachous map, Figure 60, has been prepared for this aquifer.

All Permian strata above the Wolfcamp in central Texas have been grouped into one undifferentiated unit, arbitrarily termed the upper Permian (undifferentiated). Most of the unit is exposed on the surface and only the western margin is in the subsurface, therefore no structure map has been prepared. Figure 60 shows the gross thickness of the entire post-Wolfcamp, and includes equivalents of Wichita, Clear Fork, San Andres, Whitehorse Group, and Ochoan. No net aquifer thickness was picked above the Wolfcamp.

As most of the Permian in this section represents back-reef or lagoonal facies, there is a large percentage of shale, fine shaly sandstone, and anhydrite in this section. Individual aquifers consist of bedded carbonates, sandstones, and occasional conglomerates. No salinity map has been prepared for this aquifer, but salinities of individual strata can be expected to increase from the outcrop westward toward the Midland basin.

## Rustler Aquifer

The Rustler aquifer of Permian age located in West Texas consists of dolomite, anhydrite, shale, and sandstone. A structure map has been prepared for this aquifer, Figure 61.

The Rustler aquifer occurs mostly in the Delaware basin and Central Basin platform areas of West Texas. The Rustler Formation outcrops in the Rustler hills of eastern Culberson County. It is the uppermost section of a thick evaporite basin which filled the Delaware basin and covered the platform near the end of Permian time. It is overlain by the Dewey Lake Redbeds.

The Rustler aquifer consists of a uniformly thick deposit of dolomite and sandstone. The porous beds in the Rustler are from 50 to 100 feet below the actual top of the formation, and are from 100 to 300 feet thick through the Delaware basin and then to less than 50 feet over the platform. The porous beds thin to a feather edge to the south and east.

Structure on top of the Rustler anhydrite consists of several long ridge and trough features which are aligned north-south. The elongate troughs in the Delaware basin appear to be the result of salt removal from the underlying Salado Formation. These troughs also resulted in the accumulation of thick Cenozoic "fill" deposits which are excellent fresh water sources in this area.

Moderate to large flows of highly saline water have been recorded by drillers from the Rustler "dolomite," but salinity and productivity information are scarce.

## Triassic Aquifer

The Triassic aquifer located in West Texas consists of sandstone and shale. Structure and isopachous maps have been prepared for this aquifer, Figures 62 and 63, respectively.

Triassic rocks occur in a portion of the Permian basin and western Panhandle areas of Texas. They are exposed as far north as the Canadian River valley northwest of Amarillo and as far south as a narrow exposure in the Pecos River valley in Ward and Crane Counties. Triassic rocks are exposed in a continuous outcrop along its eastern margin from southeast of Amarillo to southeast of Big Spring.

The Triassic of West Texas is comprised entirely of the Dockum Group. This group consists primarily of red shales and sandstones up to nearly 2,000 feet thick in Cochran, Yoakum, and Terry Counties, and then gradually thins to zero thickness to the east and south. Approximately 20 percent of the redbeds are porous sandstones.

The most important sand body in the Dockum Group is the Santa Rosa Formation, a widespread, medium- to coarse-grained, well-sorted sandstone. The Santa Rosa Formation occurs at the base of the Dockum Group and averages about 150 feet in thickness. To facilitate mapping, a structure map (Figure 62) on top of the Santa Rosa Formation within the Triassic aquifer was prepared. This map indicates that the aquifer conforms to the regional structure of the Permian basin. Other sands occur in the Dockum Group which are potential aquifers, but none attain the thickness or extent of the Santa Rosa.

The waters of the Dockum Group range in salinity from fresh to brackish. No salinity maps have been prepared for the Triassic aquifer. Locally, the Santa Rosa and other sands in the Triassic have been well documented by the Texas Water Development Board, although data are scarce regionally. Rock property data are even less abundant than salinity data, since the Triassic is not an oil and gas producer. The Santa Rosa yields fresh or slightly brackish water to wells for both private and public sources in West Texas. In Ward County, where the formation is in direct contact with overlying Cenozoic alluvium, the gross aquifer produces fresh water and is used as a public-water source.

## Trans-Pecos Aquifers

Two groups of aquifers, ranging in age from Cambrian through Pennsylvanian and from Permian through Quaternary, are located in the region from El Paso to the Pecos River. Subcrop, structure, and isopachous maps have been prepared for these aquifers, Figures 64-68.

The Trans-Pecos saline aquifers have been studied in a region from west of the Pecos River to El Paso. The investigation primarily involves the counties of El Paso, Hudspeth, Culberson, Jeff Davis, and Presidio.

The main limitation of an investigation in this region is lack of well data. Only a few deep oil tests have been drilled in this area and even fewer were available for this study. Several reports by the Texas Water Development Board and U.S. Geological Survey were useful as references, but most of the information in these reports concerns fresh water. Of considerable help as a reference to this area was the U.S. Geological Survey open-file report "Saline Ground-Water Resources of the Rio Grande Drainage Basin—a Pilot Study," by T. E. Kelly and others.

Sedimentary rocks are present over most of the region, even though overlain in places by Tertiary volcanics. In several localities, Precambrian igneous and metamorphic rocks are exposed at the surface in structural highs. Some of the important geological features of the Trans-Pecos region west of the Delaware basin are the Diablo platform which trends northwest-southeast through the length of the area, Van Horn uplift, Davis Mountains, Franklin Mountains at El Paso, Salt basin and Salt flat, and the Hueco bolson which is a low synclinal trough between the Diablo platform and the Franklin Mountains. Although topography varies locally, much of the region is over 4,000 feet above sea level.

Because of limited subsurface control, a regional interpretation of the geology must be largely based on available surface geological information. An indispensible part of this study was the Geologic Atlas of Texas, Van Horn-El Paso Sheet, 1967, by the University of Texas Bureau of Economic Geology. Based on this map all major surface structures involving Precambrian basement or Cambro-Ordovician rocks were located. Lesser surface structures were also mapped by plotting their inferred structural axes on the 1:500,000 base map. The surface geological map was also used to extend stratigraphic information to poorly controlled areas. For the subsurface, every available well log west of the Delaware basin was correlated. Using a combination of subsurface and surface data, the subsurface geology of the entire region was interpreted.

It became apparent that due to the paucity of data, detailed maps of individual aquifers were not possible to obtain. Thus it was decided to map the region by designating two gross undifferentiated aquifers, Cambrian through Pennsylvanian and Permian through Quaternary. Using the combined data, a subcrop map of early Paleozoic rocks was compiled for five units: Cambro-Ordovician, Montoya, Siluro-Devonian, Mississippian, and Pennsylvanian, shown on Figure 64. Then a structure contour map was drawn on top of this pre-Permian undifferentiated unit, Figure 65. The next step was to estimate total formation thickness from all available sources of geological information. The average percent of net aquifer thickness used in West Texas and particularly the Delaware basin was applied to the estimated formation thickness. The result was an interpreted net aquifer thickness map, Figure 66.

From the preceding steps, it is interpreted that Paleozoic rocks are missing over local structures on the Diablo platform, such as the Van Horn uplift and Franklin Mountains. Considerable structural relief exists in the area, from more than 5,000 feet above sea level in the Van Horn Mountains to 8,000 feet below sea level in the Hueco bolson. Rocks dip away from the Diablo platform in all directions, particularly into the Hueco bolson, the Delaware basin, and the Marathon basin. Interpreted net aquifer thickness ranges from zero over local structures to 3,000 feet in the Hueco bolson.

Generalized lithologies for the pre-Permian aquifers are as follows:

| AGE | LITHOLOGY |
|---|---|
| Pennsylvanian | limestone, shale, sandstone |
| Mississippian | limestone, shale, chert |
| Siluro-Devonian | limestone, chert, dolomite |
| Montoya | dolomite, chert, limestone |
| Cambro-Ordovician | limestone, dolomite, sandstone |

The Cambro-Ordovician includes Ellenburger in the east and south, El Paso Formation in the west, and the Bliss and Van Horn Sandstones.

Salinities and productivities are not well known; however, the aquifer group would have to be rated from moderate to low in terms of estimated quality and aquifer yield.

The second group of aquifers is the post-Pennsylvanian undifferentiated. This group consists of three units which include the Permian (Hueco and Leonard), Cretaceous (undifferentiated), and Quaternary. Generalized lithologies for the post-Pennsylvanian are as follows:

| AGE | LITHOLOGY |
|---|---|
| Quaternary (alluvium and bolson deposits) | sand, conglomerate, shale |
| Cretaceous undifferentiated | limestone, sandstone, shale |
| Permian Leonard | shale, sand, limestone |
| Permian Hueco (Wolfcamp) | limestone, shale, sandstone |

Three units have been mapped and are shown on the geological map of the post-Pennsylvanian, Figure 67. The units from the oldest are Permian, Cretaceous, and Quaternary. Using the U.S. Geological Survey map of the 3 gram per liter isosaline, the total thickness of the post-Pennsylvanian group of aquifers was mapped, Figure 68. The configuration of this unit is directly controlled by the structure of the underlying pre-Permian. Thickness of the post-Pennsylvanian ranges from zero over the structural highs of the Diablo platform to 12,000 feet in Hueco bolson.

Very little is known of the potential productivity of the post-Pennsylvanian aquifers, or even the percentage of porous and permeable rocks within the section. It seems reasonable, however, from general knowledge of the areal geology, to assume that 25 to 50 percent of the total stratigraphic column of the post-Pennsylvanian would be comprised of rocks having porosity and permeability within the section. To fully evaluate this area, it would be necessary to study as many lithological and electric logs as possible. These would have to be obtained directly from oil operators since most well data is not released to the public. Then an exhaustive search of the literature should be made, including the use of as many student's theses as are available. The study should also include the New Mexico area in order to obtain a regional evaluation.

## Smackover Aquifer

The Smackover aquifer of Jurassic age located in the East Texas area consists of limestone, sandstone, and shale. Structure and isopachous maps have been prepared for this aquifer, Figures 69 and 70, respectively.

The Smackover Formation and Cotton Valley Group of the East Texas embayment are of upper Jurassic age. The western limit of these units is essentially the structural limit of the East Texas basin itself, the Ouachita tectonic belt. These units were not mapped in South Texas due to sparce well control and lack of productivity information.

From the standpoint of geological age, the Smackover Formation and Cotton Valley Group should be mapped together as one unit. However, the boundary between the Jurassic Cotton Valley and the Cretaceous Pettet-Travis Peak is commonly difficult to map, even though there is an unconformity between them. Therefore, for mapping purposes in this study, it was arbitrarily decided to include the upper part of the Cotton Valley Group, which consists of sands and limestone, with the overlying Cretaceous Pettet-Travis Peak and to designate this as the Pettet-Travis Peak aquifer. The basal part of the Cotton Valley is locally gradational with the upper portion of the Smackover, and appears to form a hydrologically continuous unit. It seems more logical to include the basal unit, usually referred to as "Cotton Valley Limestone," with the underlying Smackover. This was done for the purpose of mapping in this report and will be hereafter referred to as the Smackover aquifer. Cross section N-N', Figure 9, illustrates these stratigraphic relationships, as well as the table below.

| AQUIFER | FORMATION OR GROUP | AGE |
|---|---|---|
| Pettet-Travis Peak Aquifer | Pettet and Travis Peak Formations,<br>Cotton Valley Group | Cretaceous<br>Jurassic |
| Smackover Aquifer | "Cotton Valley Limestone,"<br>Smackover Formation | Jurassic<br>Jurassic |

The upper member of the Smackover aquifer is a porous oolitic and dolomitic limestone which forms a belt that is confined to the margins of the East Texas embayment. This member grades into a dark shale down-dip into the basin. The basinward limit of the porous Smackover facies is approximately the line denoted on the structure and gross isopach of the Smackover-Cotton Valley as a datum change. Within the porous Smackover belt, the Buckner Formation is present and readily definable, separating the basinward developing lower Cotton Valley Limestone from the Smackover Formation. Basinward from this belt, the Buckner cannot be recognized and the Cotton Valley Limestone appears continuous with the Smackover Formation and is thus grouped together in a gross thickness map, Figure 70.

No salinity map was prepared for this aquifer due to lack of data. Rock property data are also scarce, but reported data indicate a porosity range of 7 to 24 percent, averaging 13 percent, and a permeability range of 1 to 350 millidarcies.

## Pettet-Travis Peak Aquifer (Includes upper part of Cotton Valley Group)

The Pettet-Travis Peak aquifer of Cretaceous and Jurassic age located in East Texas consists of sandstone, limestone, and shale. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 71, 72, and 73, respectively.

The Pettet and Travis Peak Formations, as used in this report, are time equivalents to the Sligo and Hosston Formations in South Texas and are Coahuilan in age as described by Barrow (1953) and Imlay (1945).

The Travis Peak is composed typically of thinly bedded, tightly cemented, medium-grained sands, occasionally ashy, with interbedded red shales and shaly red sandstones. Moving southward from the East Texas embayment, the sands become more silty and tightly cemented and eventually grade into a shale and shaly limestone sequence in Sabine County. Generally speaking, the Travis Peak is more sandy to the east (easily 50 percent sand or more), and thickens as a sand and shale unit averaging 35 percent sand into the East Texas embayment, where the greatest thickness of sands are found.

The Pettet or Sligo Formation consists of interbedded limestones and shales. The limestones are typically gray, generally fossiliferous, oolitic to pseudo-oolitic and in part crystalline. The unit extends throughout most of the East Texas embayment but is not recognized in the northwestern area (Hunt, Fannin, Delta, Lamar Counties) where the characteristic limestones and shales interfinger with the shales and sands of the Travis Peak Formation. The western limit of the Pettet, south of Hunt County, generally lies a few miles west of the Mexia-Talco fault zone. Southward through the center of the East Texas basin and across the Sabine uplift, the Pettet Formation gradually thickens at the expense of the underlying Travis Peak Formation.

As previously discussed, the upper part of the Cotton Valley Group is included in the Pettet-Travis Peak aquifer. The clastic portion of the Cotton Valley Group is predominantly nonmarine in the north and northeast parts of East Texas and generally described as lenticular light gray, pink, and red-brown fine-grained sandstones, and varicolored pastel to red-brown shales. The unit interfingers with light gray, fine-grained sandstones and increasingly dominant gray to black fossiliferous shales and thin dark limestone beds of marine origin to the south into the East Texas basin. Even though there is an unconformable contact between the Travis Peak of Cretaceous age and the top of the Cotton Valley Group, the contact is questionable over a large portion of East Texas. Therefore, the net sand thickness of the Cotton Valley Group is included on the isopachous map of net sands of the overlying Pettet and Travis Peak Formations.

Salinities vary from less than 3,000 to more than 250,000 ppm in the aquifer. There is a fairly progressive and constant increase of total dissolved solids from the margins of the East Texas basin into the center of the basin (Figure 73).

Porosities average approximately 15 percent and permeabilities have an average range of 15 to 65 millidarcies.

## Edwards and Glen Rose Aquifers

The Edwards and Glen Rose aquifers of Cretaceous age located in south and southwest Texas consist of limestones, dolomite, and chert. One structure and two isopachous maps have been prepared for these aquifers, Figures 74, 75, and 76, respectively.

Due to the rather complex stratigraphic relationships in the lower Cretaceous, the Edwards and Glen Rose Formations have been divided into two areas for this study. South and southwest of the East Texas basin, the formations have been mapped as the Edwards and Glen Rose aquifers, and in East Texas, the lower Glen Rose was mapped. In South Texas, the aquifers are the uppermost Edwards and the lowermost Glen Rose.

Since the Edwards and Glen Rose Formations are in direct contact, they form a single hydrological system, extending from the Louisiana line to the Rio Grande. One structure map contoured on top of the Edwards Formation, Figure 74, is sufficient for the Edwards and Glen Rose aquifer systems; however, two isopachous maps were needed to define the thickness. A net aquifer thickness map was prepared for the Edwards, Figure 75, but only a gross thickness map was feasible for the Glen Rose, Figure 76. In some areas on the Edwards isopachous map, the net thickness makes up the total or gross thickness.

The Edwards and Glen Rose aquifers dip gently south and southeast into the Gulf geosyncline from the Llano uplift. Both units are commonly fossiliferous, foraminiferal, pelletal, dolomitic micrites and sparites with algal and rudistid reefs.

Both units are related in that they are back-reef facies of the same barrier reef (Stuart City). Rudistids and associated organisms formed this extensive reef complex and a smaller complex over the San Marcos arch, near the time of early Glen Rose deposition.

During the time of Edwards deposition, the reef began to move north and northeast, where it interfingered with the basinal East Texas marly and nodular limestone of the Walnut and

Comanche Formations. As the reef moved north, it also interfingered with the lower part of the Georgetown Formation over the San Marcos arch and the northeastern "hinge line" (Trinity and Angelina Counties) between the East Texas embayment and the Gulf Coast geosyncline. At the reef core, the unit includes the Georgetown equivalent and, due to unconformity, the reef is partially overlain by the Eagle Ford Shale. In the Stuart City Reef facies, Edwards and Glen Rose are not recognizable as separate units and have been grouped together.

Salinities in the Edwards and Glen Rose aquifers range from less than 1,000 to more than 150,000 ppm. There are insufficient salinity data available to construct a salinity map, but indications are that salinities increase constantly from the outcrop southward into the Gulf Coast geosyncline.

The Edwards Formation is an important source of fresh water in south and south-central Texas, and is the primary ground-water resource for many municipalities, including San Antonio. Large volumes and rates of saline water can be expected from the Edwards and Glen Rose aquifers.

## Lower Glen Rose Aquifer (East Texas)

The lower Glen Rose aquifer of Cretaceous age located in East Texas consists of limestone and calcareous sandstones. Isopachous and salinity maps have been prepared for this aquifer, Figures 77 and 78, respectively.

The Glen Rose Formation may be defined as those rocks below the Fredericksburg Group and above the Pearsall Formation. Where the Pearsall or its equivalents (in descending order the Bexar Shale, James Limestone, and Pine Island Shale) are not definable in East Texas, the lower limit becomes the Pettet-Travis Peak aquifer. The James Limestone, where defined, is included with the lower Glen Rose on the net isopachous map due to the similar lithologies.

The Glen Rose of East Texas is commonly divided into the upper Glen Rose, which includes the Rusk Formation and Ferry Lake Anhydrite, and the lower Glen Rose which is synonymous with the Rodessa Formation.

The upper Glen Rose Limestone is characteristically tight in northeast Texas; therefore, an isopachous map of only the lower Glen Rose porous limestones and sands was constructed. (See the following Paluxy discussion for reference to upper Glen Rose sands.) The porous limestone is typically described as a gray, fossiliferous, crystalline to oolitic limestone, which varies in porosity and permeability as it grades into sandy limestones and calcareous sandstones. The area of increased net thickness in the northern area of northwest Texas from Collin and Hunt Counties through Lamar and Bowie Counties is due primarily to the porous sandy facies of the lower Glen Rose (see Figure 77). Porous limestone lenses increasingly become the more dominant lithology proceeding south and south-southeast into the East Texas basin.

The relatively abrupt development of porous limestone in Nacogdoches and Shelby Counties is due to reef development which thickens in the section and eventually takes over most of the Glen Rose Formation.

Salinity patterns in the lower Glen Rose aquifer of East Texas are similar to other Cretaceous aquifers. Salinities increase constantly and regularly from fresh water on the outcrop to highly saline in the deeper part of the East Texas basin. Total dissolved solids exceed 200,000 ppm in the center of the basin.

Porosity in the lower Glen Rose is estimated to average 10 percent, and the estimated permeability range is 1 to 100 millidarcies.

## Paluxy Aquifer

The Paluxy Aquifer of Cretaceous age located in East Texas consists of sandstone, limestone, and marl. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 79, 80, and 81, respectively.

For this investigation, the Paluxy aquifer includes a portion of the upper Glen Rose Formation. The Paluxy outcrops in a northerly trend from its southern facies limit in Coryell County to Montague and Cooke Counties. The unit dips from the west, north, and northeast into the East Texas basin. The sands are erratic and lenticular, fine to medium grained, interbedded with green lignitic shale and silty laminated sand.

The Paluxy Formation of central Texas and East Texas as defined by Forgotson (1957) is restricted to those sandstones and shales which are the time-stratigraphic equivalent of and laterally continuous with part of the Walnut Formation in the Fredericksburg Group. The sands of the Paluxy unit are progressively thinner to the south and eventually become the shale and marl facies of the Walnut Formation, the southern limit of this unit.

The upper Glen Rose Formation of East Texas includes the Rusk and Ferry Lake Anhydrite as defined by Forgotson (1957). The Rusk Formation, typically a non-porous, dense crystalline limestone, becomes increasingly sandy northward in the northern part of East Texas. These sands appear to be transitional with the overlying Paluxy Formation and have been included with the Paluxy sands in the net sand isopachous map. The effect of these "Paluxy-like" sands of the Rusk Formation can be seen in the extreme northeast corner of East Texas in Bowie and Cass Counties. The net thickness of more than 300 feet is due to an increase in sands in the Rusk Formation. The other main trend of thickness (Lamar, Delta, and Hopkins Counties) is a result primarily of massive sand development in the Paluxy, constituting about two-thirds of the total thickness of the unit.

The salinity map of the Paluxy aquifer, Figure 81, follows the similar pattern of East Texas basin Cretaceous aquifers. Total dissolved solids have been mapped from 3,000 to 120,000 ppm.

Paluxy sands have an extreme range of porosity and permeability, possibly due to having excellent original porosity partially plugged by anhydrite. Porosity can vary from 6 to 30 percent, and permeability from less than 1 millidarcy to several darcys.

## Woodbine Aquifer

The Woodbine aquifer of Cretaceous age located in East Texas consists of sandstone and shaly sandstone. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 82, 83, and 84, respectively.

The Woodbine Group of late Cretaceous (Gulf Series) is one of the chief aquifers in northeast Texas and a major source of oil in the East Texas basin.

The Woodbine crops out in a belt extending from northern McLennan County northward through Johnson, Tarrant, and Denton Counties to Cooke County, then swings eastward roughly parallel to the Red River near the Arkansas line. The Woodbine dips south and east from the outcrop area into the East Texas basin, where its subsurface areal extent in Texas is limited by erosion over the Sabine uplift and by facies changes to the south and southwest. The southern limit of the Woodbine Group, for the purposes of this report, is defined by the zero limit of net sand thickness. The Pepper Shale Member of McLennan County and the prodelta shale facies, both in the Woodbine Group, are of no importance to this study due to the absence of aquifer characteristics.

The Woodbine Group contains two divisions in East Texas; the uppermost unit is the Lewisville Formation, and the lowermost is the Dexter Formation. These formations are recognized in the northern portion of northeast Texas but become more or less arbitrary divisions south of an east-west trending line approximately in the same position as the north boundary of Henderson County. The Lewisville is typically a shale with fossiliferous and glauconitic sandstone lenses while the Dexter is comprised of non-marine beds of ferruginous and siliceous sandstone, interspersed with silty clay lenses. The Dexter Formation contains the majority of the sands in the northern East Texas basin. The pattern of the net sand isopachous map, especially in the northern portion of northeast Texas, suggests the deltaic depositional nature of the Dexter Formation.

South of this area the sands are more evenly distributed between both formations and are a result of a highly destructive delta system as evidenced by the progradational channel-mouth bar sands, coastal barrier sands, and prodelta shelf muds. The thickest accumulation of sands (over 400 feet) is in Smith County where the meander belt facies of the Dexter is well developed and the strand-plain facies of the Lewisville bar sands are present.

Near the end of Woodbine deposition, the Sabine area was uplifted resulting in removal of Woodbine sediments in that area. The massive accumulation of sands in southern Houston and Madison Counties and northern Walker County has been interpreted as redeposited Woodbine sediments, a deltaic deposition that took place during the time of late Woodbine and early Eagle Ford deposition. There has been no attempt to subdivide these sands in this area, hereby noted and contoured on the Woodbine net sand isopachous map as "undifferentiated Eagle Ford-Woodbine net sands."

The extreme northeast corner of Texas (eastern Bowie, eastern Cass, and northern Marion Counties) is also noted as "undifferentiated Eagle Ford-Woodbine net sands." The section in this area is visualized as truncated Woodbine with onlap of Eagle Ford sediments from the east. The total section here is thin, predominantly shaly with few clean sands interspersed throughout, making correlations difficult.

The salinity map of the Woodbine aquifer, Figure 84, is typical of other Cretaceous saline aquifers of East Texas. From the 3,000 ppm line, salinities increase toward the center of the basin, attaining 100,000 ppm. This map is relatively well controlled.

Woodbine sands have excellent reservoir properties, having been tested in thousands of producing oil wells from the East Texas and other fields. In producing areas, the Woodbine can attain average porosities of 25 percent and average permeabilities of over 1 darcy.

## Eagle Ford Aquifer

The Eagle Ford aquifer of Cretaceous age located in East Texas consists of sandstones and shale. Isopachous and salinity maps have been prepared for this aquifer, Figures 85 and 86, respectively.

The Eagle Ford Group of the Gulf Series was originally described as consisting of argillaceous shales of varying color. There are a number of surface subdivisions of this Group, but only one, the sub-Clarksville Sand, is recognized regionally in the subsurface of East Texas.

The sub-Clarksville, which occurs at the top of the Eagle Ford Group, consists of fine- to medium-grained sands, commonly ashy, argillaceous, and glauconitic. This sand unit crops out in an east-west direction, from eastern Grayson County to Red River County where it is covered by Red River Quaternary deposits. The sub-Clarksville extends over most of East Texas, grading into shales or sandy shales on the west, south, and east perimeters of the area. The thickest deposition of sands is in northern Titus County near the Mexia-Talco fault zone. This area appears to begin a channeling effect of thicker sands that occur through Franklin, Hopkins, Wood, and Smith Counties.

Sands that are possibly the same age as the Eagle Ford occur in the extreme northeast corner of Texas and in the extreme south portion of East Texas. Both areas are designated "undifferentiated Eagle Ford-Woodbine net sands" and contoured on the Woodbine net sand isopachous map, Figure 83. No structure contour map was made for the Eagle Ford aquifer since the unit is thin and structurally quite similar to the underlying Woodbine Group.

The sands of the Eagle Ford Group, consisting predominantly of the sub-Clarksville Sand, also include local sand developments in the lower Eagle Ford in an area including northeast Hunt, southern Hopkins, Franklin, Wood, Smith, Van Zandt, and Rains Counties.

The salinity map of the Eagle Ford aquifer is very similar to the Woodbine. From the 3,000 ppm salinity line, total dissolved solids increase toward the basin center where they attain 100,000 ppm. Salinity control is good for this aquifer (Figure 86).

Reservoir rock characteristics vary according to local facies. Sub-Clarksville sands have excellent properties, with average porosity of 24 percent and permeability of 600 millidarcies. Other Eagle Ford sands with higher shale content have about the same porosities but permeabilities average only 80 millidarcies.

## Navarro-Taylor Aquifers

The Navarro and Taylor Groups, the youngest in the Cretaceous series, outcrop in a narrow belt extending westward from Bowie County to Hunt County, where the belt turns south-southwesterly reaching the Mexican border and outcropping, for example, in areas such as Falls, Bexar, and Maverick Counties.

There are two sand units of regional importance in the upper Cretaceous Navarro and Taylor; the Nacatoch, limited to northern East Texas, and the Olmos, which is limited to Maverick, Zavala, Dimmit, northwest La Salle, northwest Webb, Frio, and west Atascosa Counties. Thus, these two widely separated units have been designated as two individual aquifers for this investigation.

### Nacatoch Aquifer

The Nacatoch aquifer of upper Cretaceous age located in East Texas consists of sandstones and shale. Structure and isopachous maps have been prepared for this aquifer, Figures 87 and 88, respectively.

The Nacatoch Sand consists of several lenses of shaly, silty sand and interbedded with sandy shales. The sand lenses are erratic, and thus unpredictable in the subsurface. The Nacatoch is one of the shallowest saline aquifers of East Texas, ranging from 500 feet above sea level at the outcrop to 4,000 feet subsea in the basin center, Figure 87. The sands attain a net thickness of 150 feet, Figure 88.

Due to lack of data, no salinity map was constructed although it can be assumed that salinity patterns approximate those of deeper Cretaceous aquifers.

Rock properties are estimated to vary considerably in the Nacatoch due to wide differences in facies.

### Olmos Aquifer

The Olmos aquifer of upper Cretaceous age located in South Texas consists of sands and shale. Structure and isopachous maps have been prepared for this aquifer, Figures 89 and 90, respectively.

The Olmos Formation occurs in a small area of south Texas, centering around Dimmit, Zavala, and Frio Counties. There is gentle southeast dip on top of the Olmos from zero feet sea level in the northwest to 7,000 feet subsea. The formation consists of nonmarine sands and clays with seams of coal at its outcrop in Maverick County. The unit thickens southeast into the Rio Grande embayment to a maximum of 1,000 to 2,000 feet and becomes a marine neritic facies where the sands are gray and friable, containing specks of lignite and glauconite. The Olmos sands are terminated at the northern limit by erosion and by facies changes to the east and south.

Sands of Escondido and San Miguel Formations, while not as extensive as the Olmos Formation, are important petroleum sources and have been included with the Olmos in the net sand isopachous map of south Texas, Figure 90. Total net thickness is over 250 feet in Zavala County.

Salinities in the Olmos aquifer increase from less than 3,000 ppm to about 40,000 ppm in Dimmit County. Productive characteristics are not generally known. The Olmos is considered to be a minor source of saline water.

## Carrizo-Wilcox Aquifer

The Carrizo-Wilcox aquifer of Tertiary (Eocene) age located throughout the Gulf Coast of Texas consists of sand and shale. Structure, isopachous, and salinity maps have been prepared for this aquifer, Figures 91, 92, and 93, respectively.

The Wilcox Group (early Eocene), according to Fisher (1969), "is a thick sequence of predominantly terrigenous clastic sedimentary rocks which is volumetrically a significant part of the large terrigenous fill of the Gulf Coast province. It is an economically important group of rocks, providing oil, gas and fresh water reservoirs, as well as deposits of lignite, ceramic clay and industrial sand." The Wilcox is a complex of seven principal depositional systems, primarily of deltaic environments. Most of the Wilcox in the upper Gulf Coast was deposited in fluvial, deltaic, or marginally continental environments while in approximately the lower third of the Gulf Coast region, the Wilcox was deposited in marine environments.

Overlying the Wilcox is the Claiborne Group, in which the Carrizo Sand is often placed at its base by stratigraphers. The Carrizo is commonly in direct contact with upper sands of the Wilcox Group, and it has been considered the top of an undifferentiated Carrizo-Wilcox aquifer for this study.

The structure map, Figure 91, is contoured on top of the Carrizo-Wilcox sands. The map is contoured on a 1,000-foot interval throughout its entire extent. It represents only the regional trend of the Carrizo-Wilcox and practically eliminates all faults and local structures.

The net sand isopachous map, Figure 92, represents the thickness of water sands having more than 3,000 ppm total dissolved solids. All thicknesses for this map were calculated from spontaneous potential (S. P.) logs. The thickest sands lie in the center of the upper Gulf Coast segment of the Carrizo-Wilcox trend. Net sands in the lower third of the Gulf Coast are thinner than those to the northeast, with abrupt thinning occurring near northern Live Oak County. The mapped zero limit of saline water sand thickness, which is on the up-dip side, coincides in some areas with the 3,000-ppm line taken from various existing ground-water reports and in other areas with the actual zero line of net saline water sand thickness as determined in this study.

The salinity map of the Carrizo-Wilcox aquifer typifies those of other Tertiary units of the Gulf Coast. Salinities vary from fresh on the up-dip side of the aquifer to highly saline toward the Gulf basin. The contortions in the contours are due to sampling density or lack of it in a vertical section, or by random sampling near salt domes where extraordinarily high salinities occur abruptly.

The productive characteristics of Carrizo-Wilcox rocks are variable but are generally excellent. Obviously, averages can be deceiving in such a large rock system. Porosity averages of 25 percent and permeabilities of 1 darcy are not uncommon. The Carrizo-Wilcox can be considered as one of the major potential sources of saline water in the State.

## Gulf Coast Tertiary Aquifers

The Tertiary of the Gulf Coast was mapped by a method unlike the remainder of the State. All of the previously discussed aquifers have been mapped as stratigraphic units, whether or not these units represented true time-stratigraphic boundaries or only rock boundaries. Isopachous maps of the respective stratigraphic units have been either gross thickness maps or a type of net aquifer thickness map. The Tertiary of the Gulf Coast geosyncline presents some difficult stratigraphic problems. Most stratigraphic units above the Wilcox Group are correlated by paleontological control. While certain units can be traced on electric logs for some distance, eventually faunal control is necessary to correlate and subdivide the Tertiary.

The Tertiary is unique in Texas compared with other rock systems as to the abundance of sand and shale and to the lack of carbonates in the section. The huge thickness of Tertiary formations contains only a minor percentage of limestone. The sands on the Tertiary are readily apparent on electric logs, and there is a high potential difference on the spontaneous potential curve, making it possible to obtain an accurate log analysis. Since correlations are difficult, but reservoir definitions are easily obtained, it was decided to use the maximum benefit of electric log data and map the Tertiary aquifers by layers or zones. "Zones", as used in this investigation, are horizontal layers 2,000 feet thick arbitrarily placed on sea-level datum. The zones have been designated by numbers beginning with Zone 1, from sea level to 2,000 feet above sea level. (Zone 1 was not mapped because there is practically no saline water above sea level in the Tertiary.) Zone 2 is from sea level to 2,000 feet below sea level, Zone 3 is from 2,000 to 4,000 feet subsea, and so on. Five zones have been mapped for this study, terminating with Zone 6, from 8,000 to 10,000 feet subsea.

Zone boundaries cut across formation and time lines. However, the resulting net sand isopachous maps permit a regional evaluation of sand content and distribution by convenient depth intervals irrespective of geological age. There are other advantages to this method. Salinity and rock property data are commonly listed by depth. These data have been sorted by depth in this investigation as well as by local geological name. This enables the application of the data directly to the sand thickness maps. Salinity maps of the zones were constructed by using field data supplemented by salinities obtained by spontaneous potential log calculations. In oil fields where several samples were listed, these samples were arithmetically averaged to obtain a value for the zone. In calculating total water resistivities from spontaneous potential logs, an average deflection through the 2,000-foot zones was used.

Only those sands containing saline water are included in the net thickness map for each zone. These maps are fairly similar in their configurations. Most have long thick sand "troughs" which trend parallel to the coast line. These seem to reflect the strike of various formations as they pass through the plane of the horizontal zones. A stratigraphic sequence comprised of a thick sand body overlain by a thick shale unit followed by another sand body would appear on the zone thickness map beginning on the inner or landward side, as a long sand "thick", a "thin", and then another "thick" as depicted by the contours. Although there is no age connotation to the regional sand distribution with any given zone, the sands become younger moving from the land toward the coast.

Since the methods used in constructing the zone net sand isopachous and salinity maps were somewhat mechanical, only a brief description of each of the zones is necessary. Rock properties are not discussed, since the reader can refer to the separate listings of these data which are sorted by depth ranges as well as by local formation name.

### Zone 1 (+2,000 Feet to Sea Level)

No maps have been included for Zone 1 since practically no saline water occurs above sea level.

### Zone 2 (Sea Level to 2,000 Feet Subsea)

Sands containing saline water in Zone 2 occur mainly in two areas. One area is located adjacent to the coast line, extending nearly the entire length of the coast. Another area of sand development occurs along a trend from Webb County to DeWitt County. Isopachous and salinity maps, Figures 94 and 95, have been constructed. Salinities vary from fresh water on the inland side to over 80,000 ppm. No particular pattern is discernable from the map.

### Zone 3 (2,000 Feet Subsea to 4,000 Feet Subsea)

Net sand thickness increases markedly in Zone 3 compared to the overlying Zone 2. Several areas contain more than 900 feet of net sand, while a few trends of less than 100 feet also occur, Figure 96. In the salinity map, Figure 97, several very high salinities are present in areas of otherwise lower salinities. These anomalies occur in the upper Gulf Coast and are thought to be near salt domes.

### Zone 4 (4,000 Feet Subsea to 6,000 Feet Subsea)

Several areas of thick net sands occur in Zone 4, Figure 98. The thickest accumulations occur along the coast line where thickness averages more than 500 feet and attains nearly 1,200 feet. Salinities of more than 100,000 ppm are common on the salinity map, Figure 99. Anomalous salinity values of over 250,000 ppm occur over salt domes.

### Zone 5 (6,000 Feet Subsea to 8,000 Feet Subsea)

The net sand isopachous map of Zone 5, Figure 100, shows a long, thick "trough" of sand which parallels the coast line. Sands totaling 500 feet extend the entire length of the Gulf Coast in this Zone, and attain 1,000 feet over part of that length. The salinity map, Figure 101, shows a considerable range of total dissolved solids.

### Zone 6 (8,000 Feet Subsea to 10,000 Feet Subsea)

The net sand thickness map of Zone 6, Figure 102, appears to result from the intersection of the horizontal zone with a single, thick sand body overlain and underlain by shale. The sand attains 800 feet in the lower Gulf Coast and thins to less than 100 feet in a long narrow strip from Corpus Christi to the Louisiana line. Portions of the map are interpreted due to lack of control with depth. The salinity map, Figure 103, is typical of those of other zones. There are several abrupt anomalies where total dissolved solids reach 200,000 ppm.

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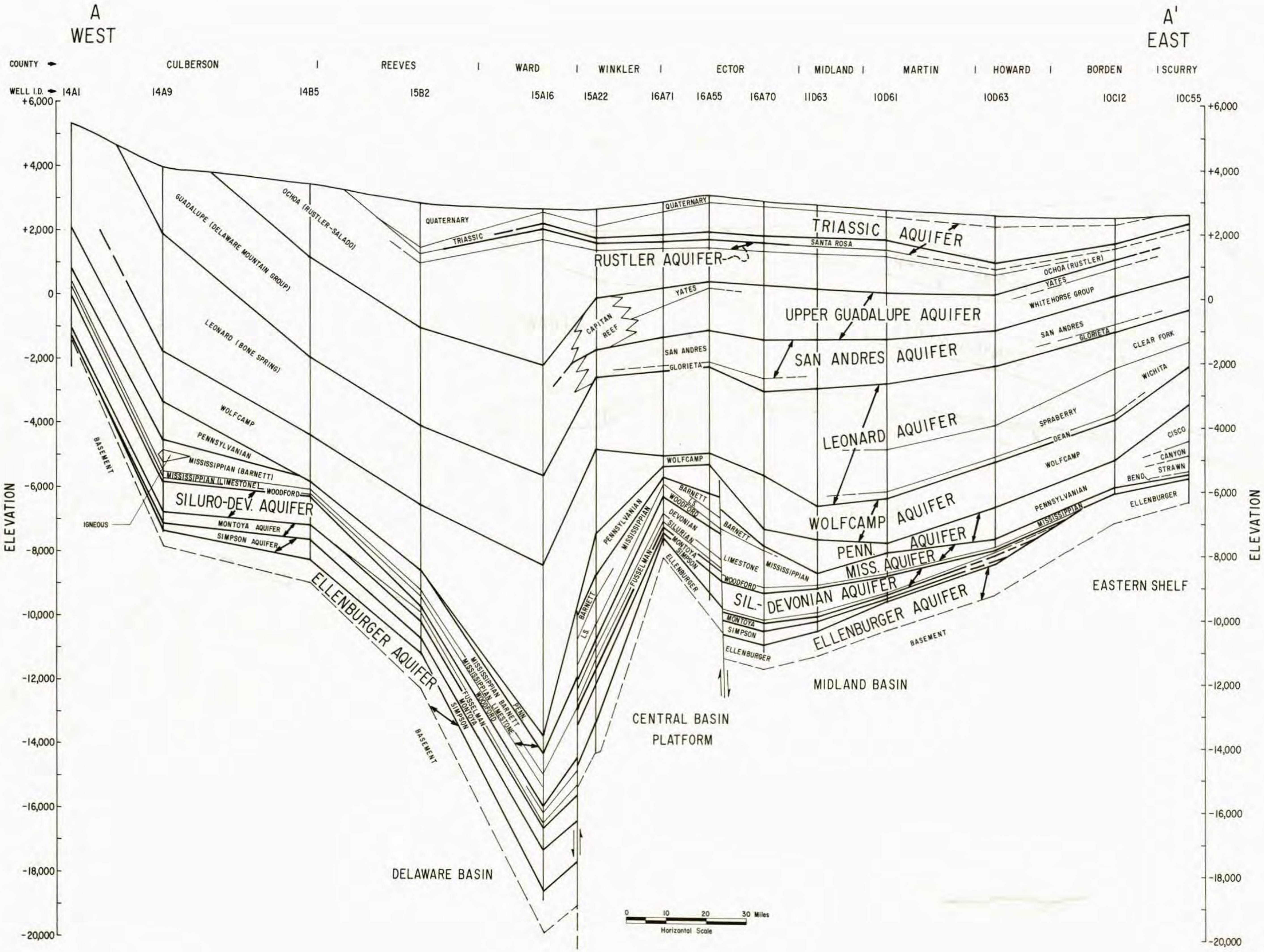


Figure 3

**A-A', West Texas, Culberson to Scurry Counties**

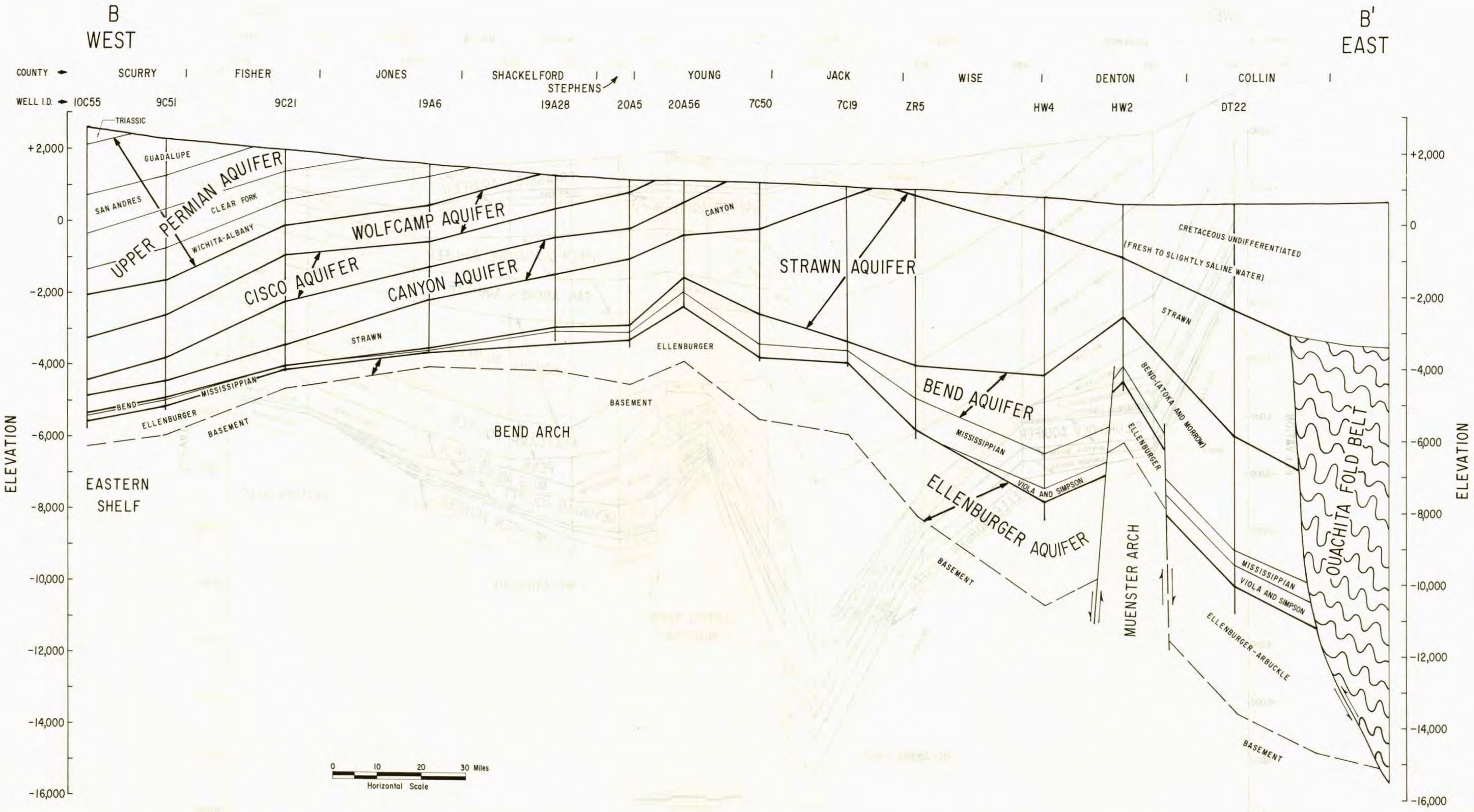


Figure 4
B-B', North Central Texas, Scurry to Collin Counties

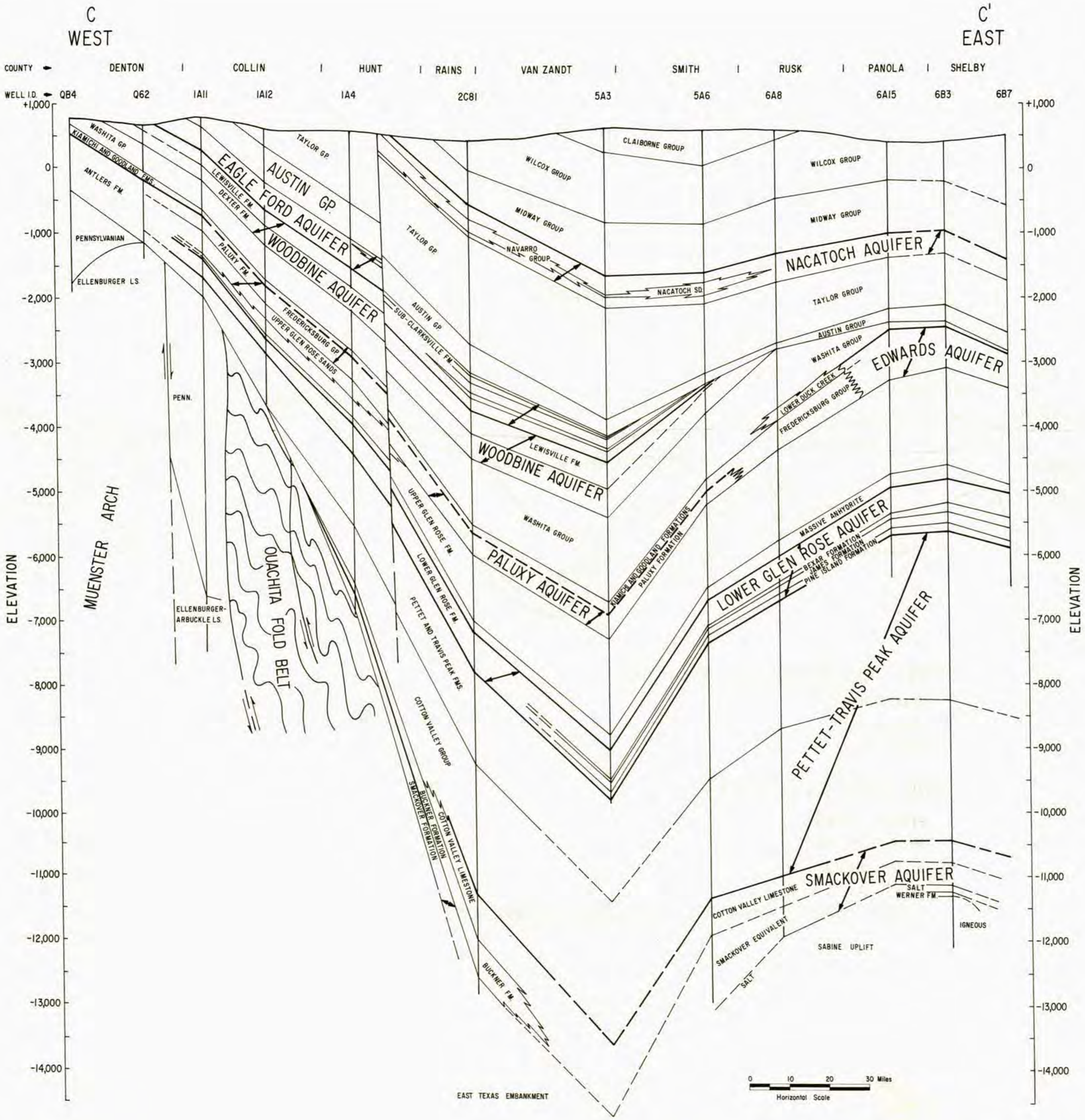


Figure 5

C-C', East Texas, Denton to Shelby Counties

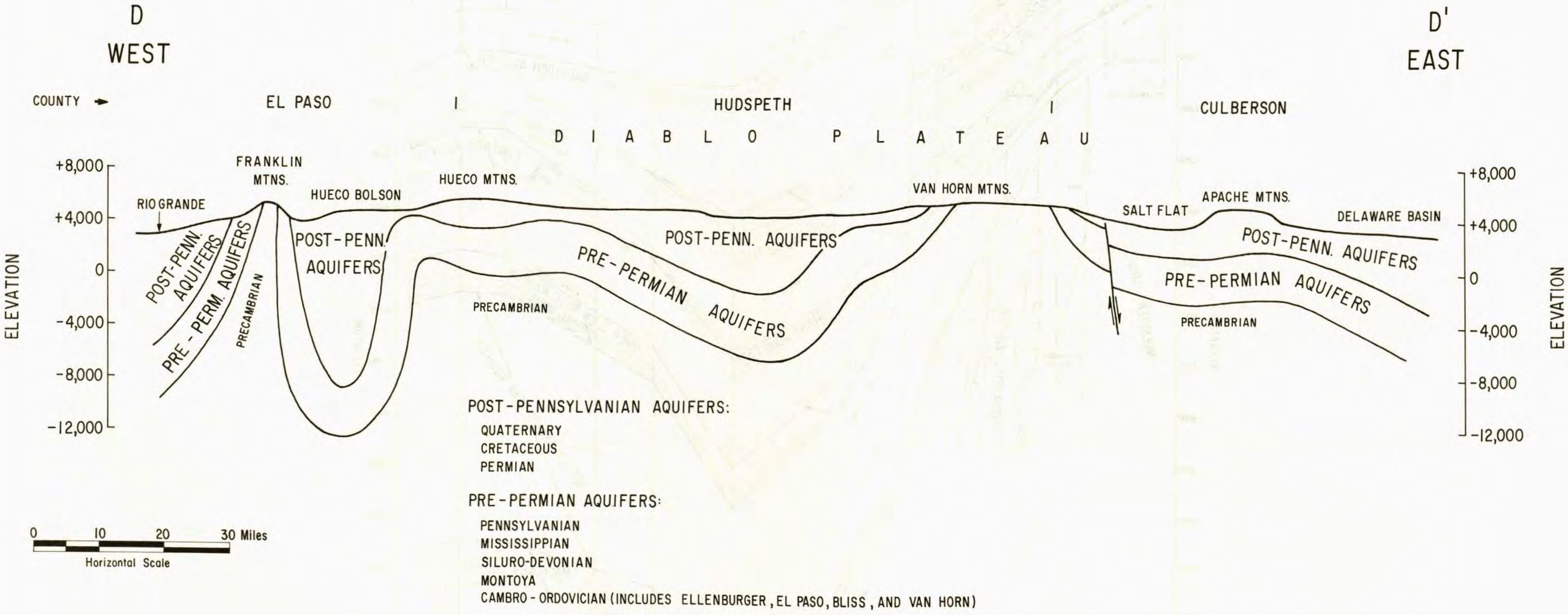


Figure 6

D-D', (Diagrammatic), Western Trans-Pecos, El Paso to Culberson Counties

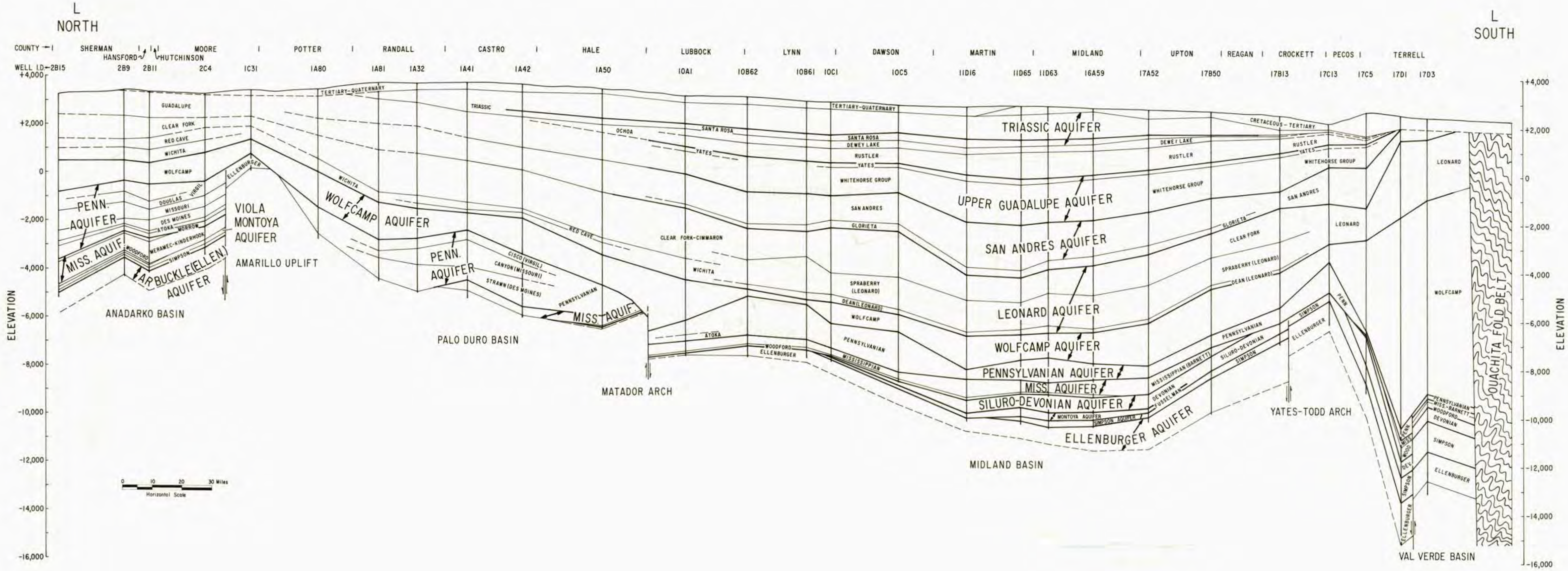


Figure 7
L-L', Panhandle and West Texas,
Sherman to Terrell Counties

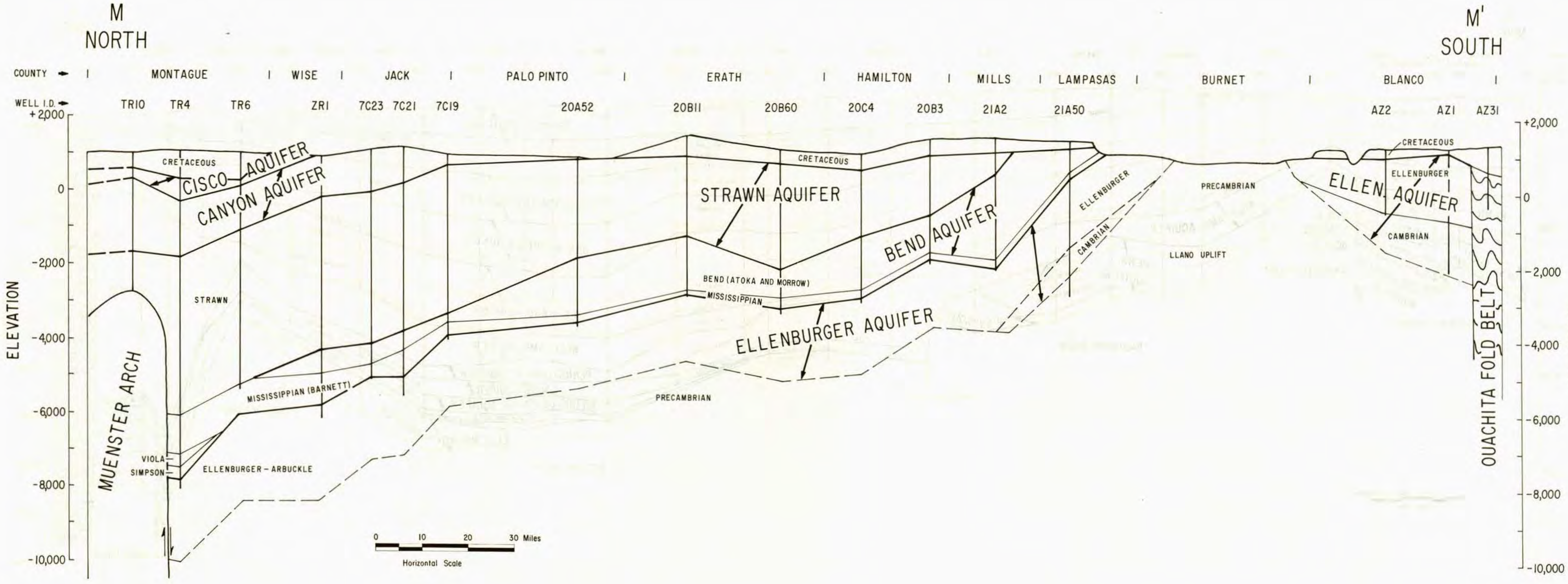


Figure 8

M-M', Central Texas, Montague to Blanco Counties

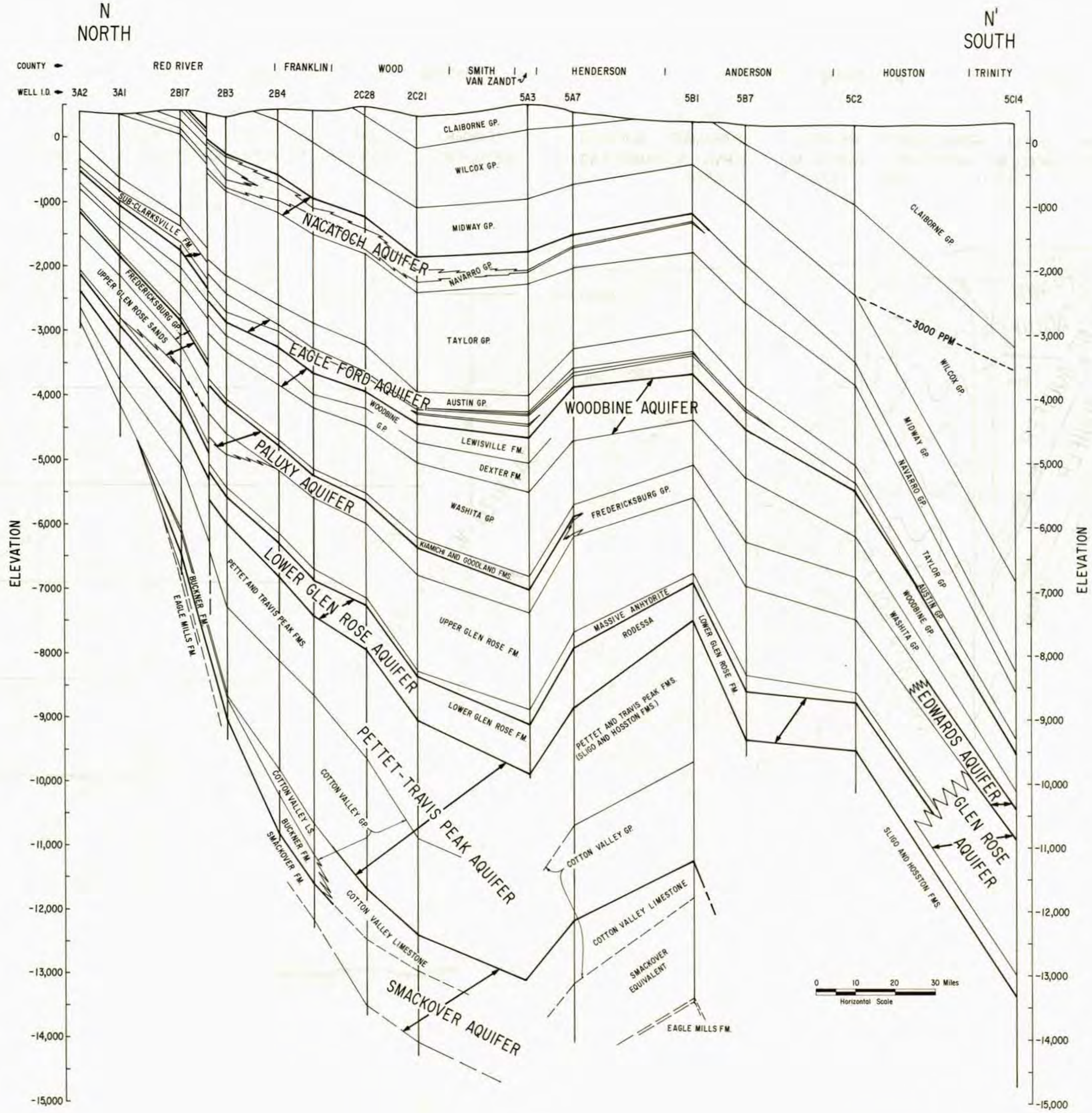


Figure 9
N-N', East Texas, Red River to Trinity Counties

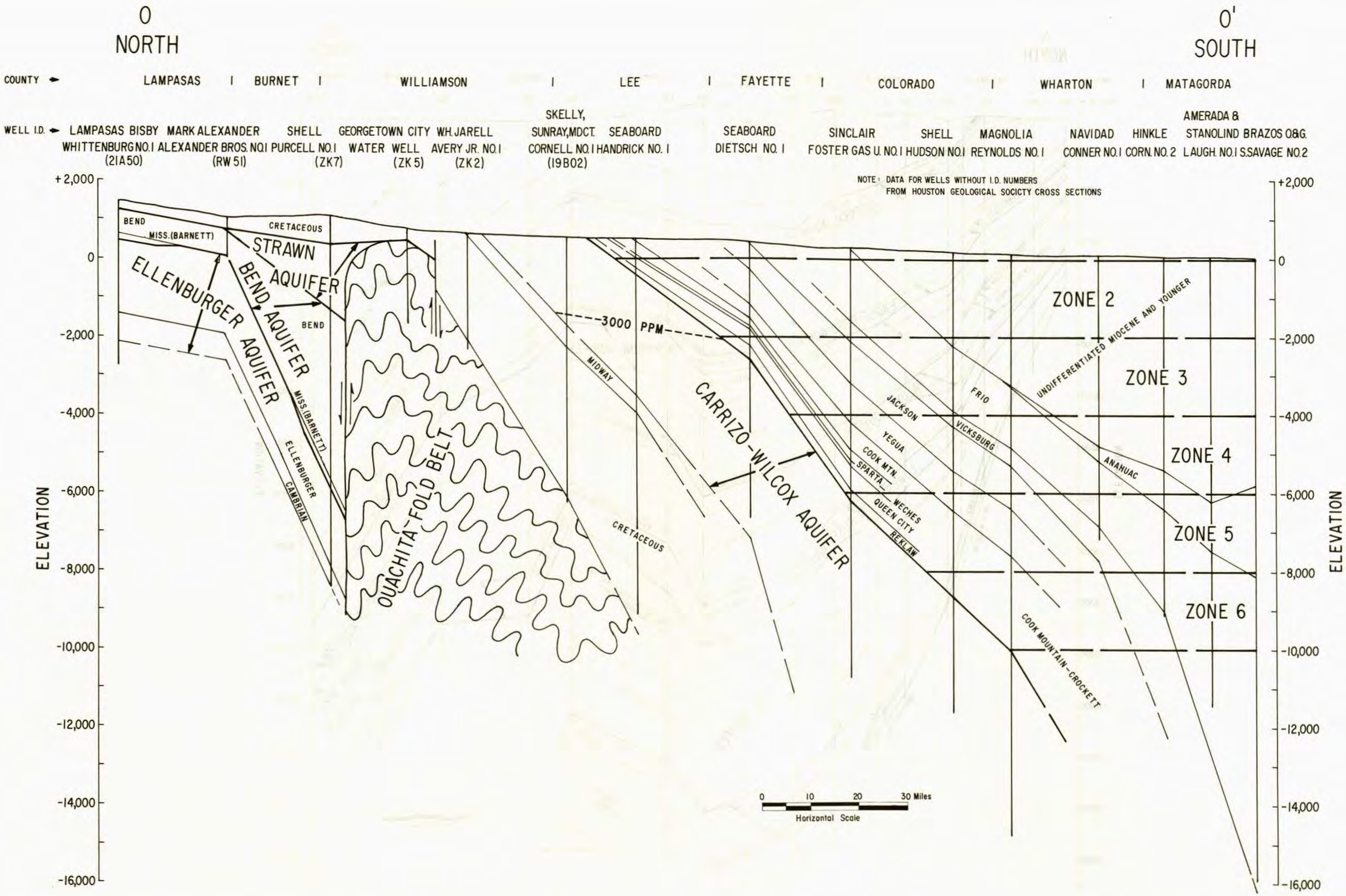


Figure 10

O-O', Central Texas and Gulf Coast, Lampasas to Matagorda Counties

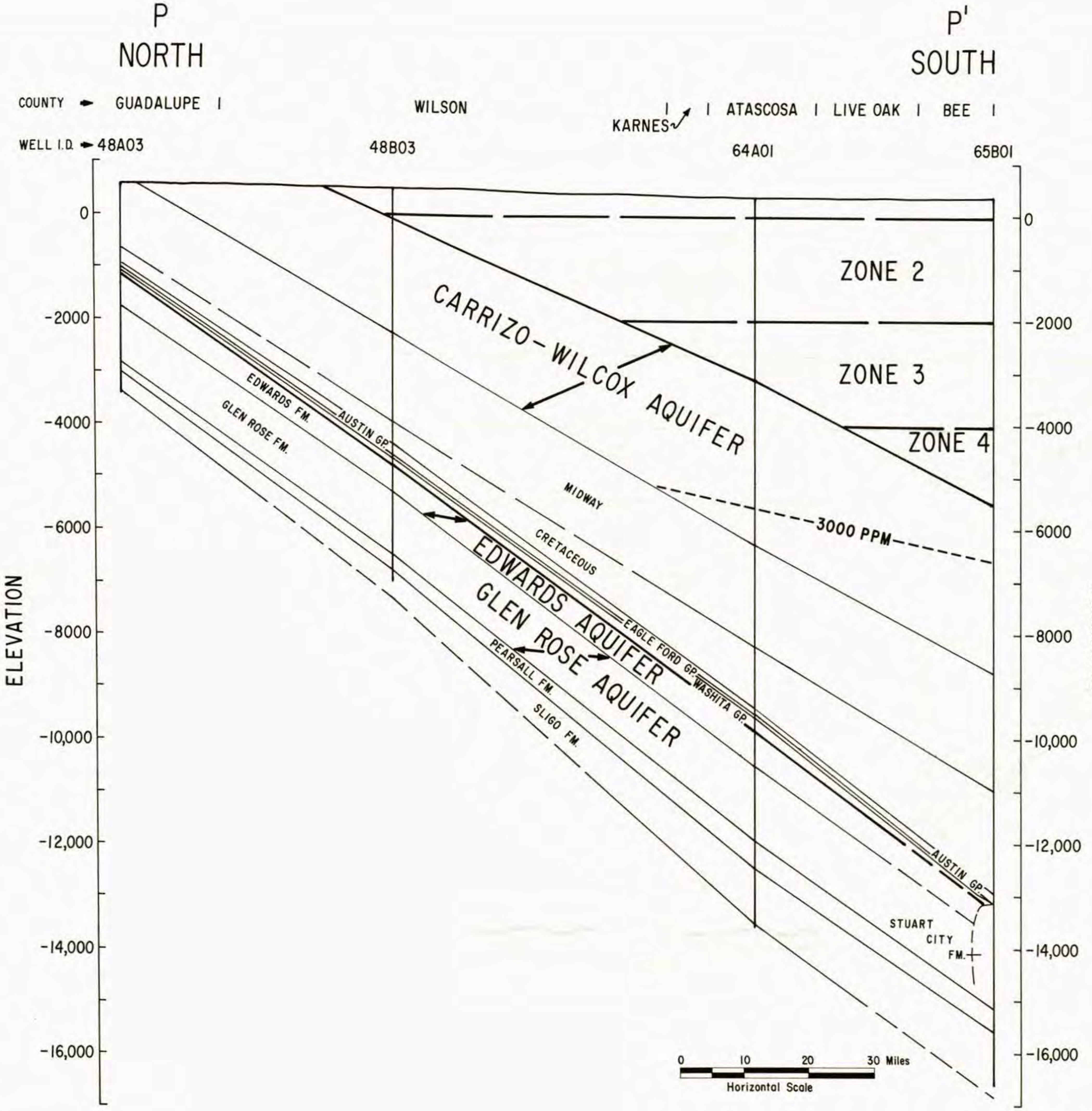
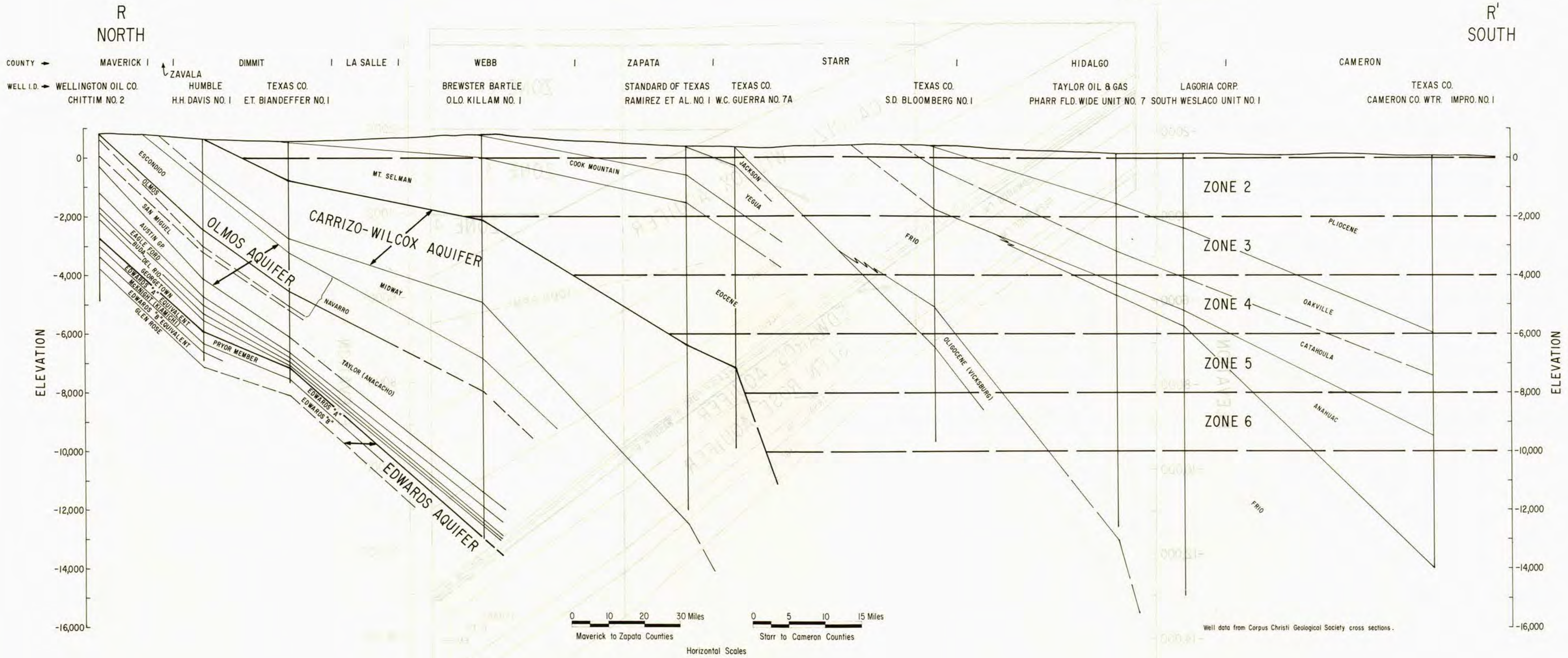


Figure 11

P-P', South Central Texas, Guadalupe to Bee Counties



Well data from Corpus Christi Geological Society cross sections.

Figure 12

R-R', South Texas and Gulf Coast, Maverick to Cameron Counties

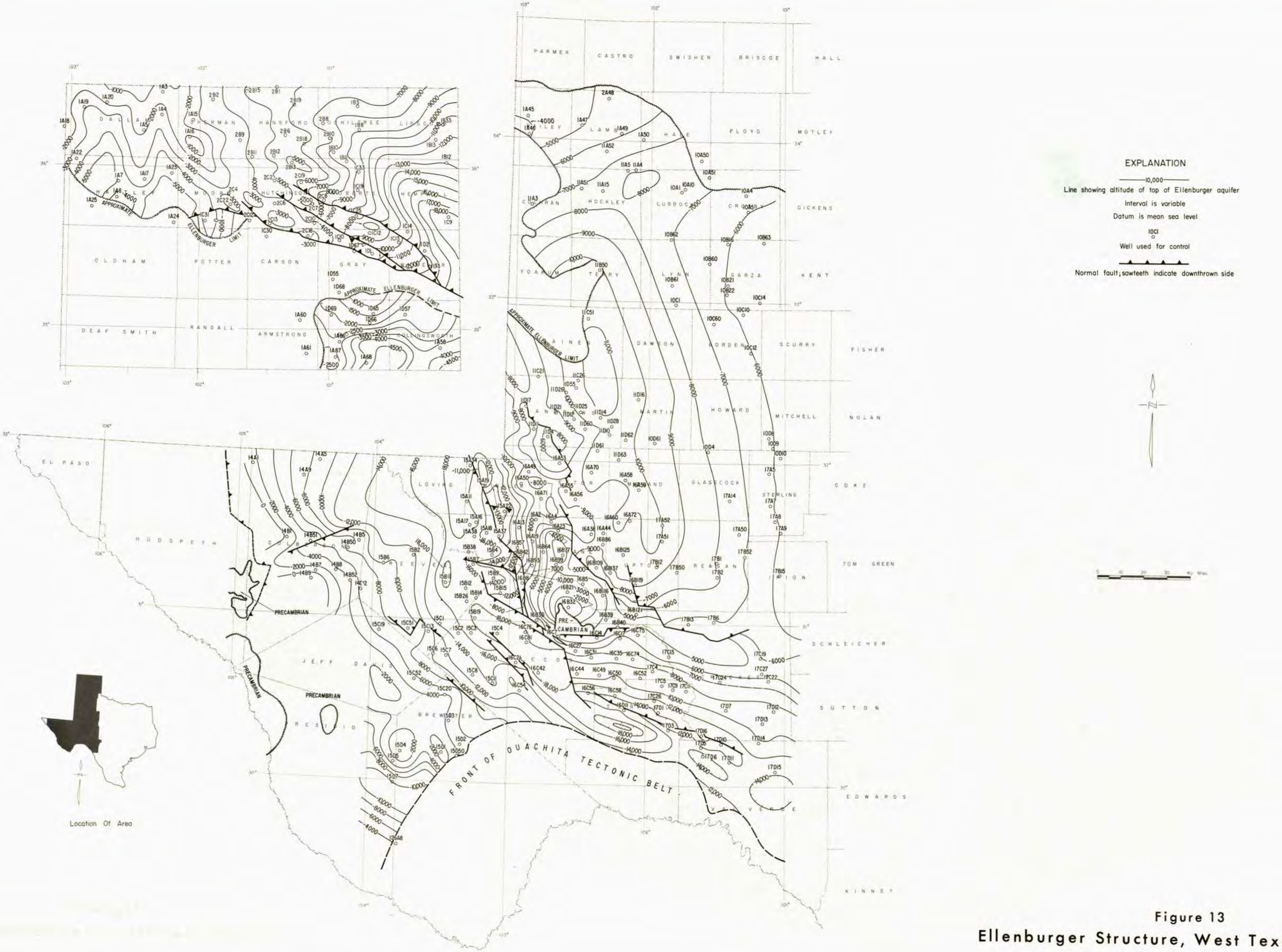


Figure 13

Ellenburger Structure, West Texas-Panhandle

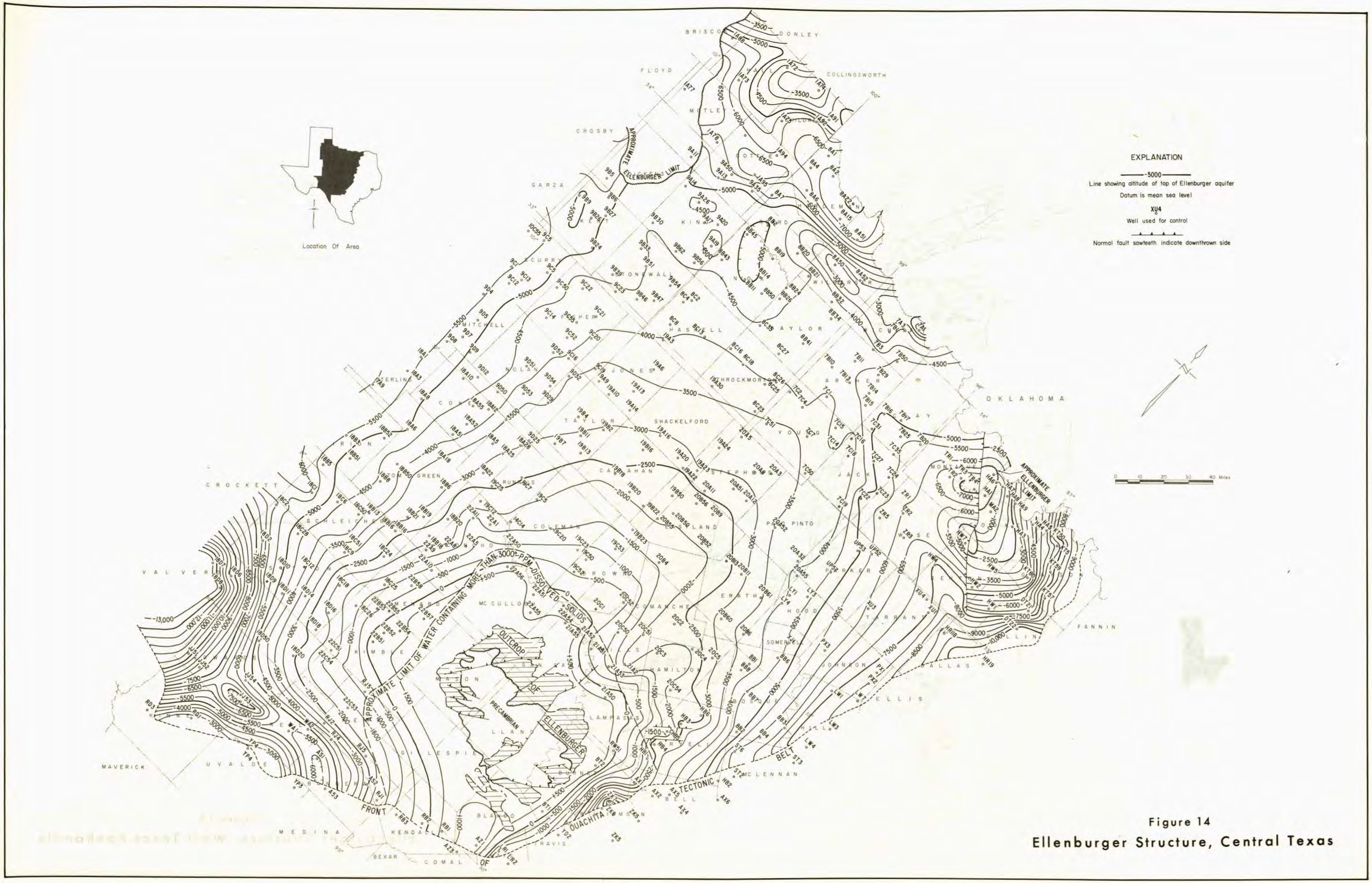
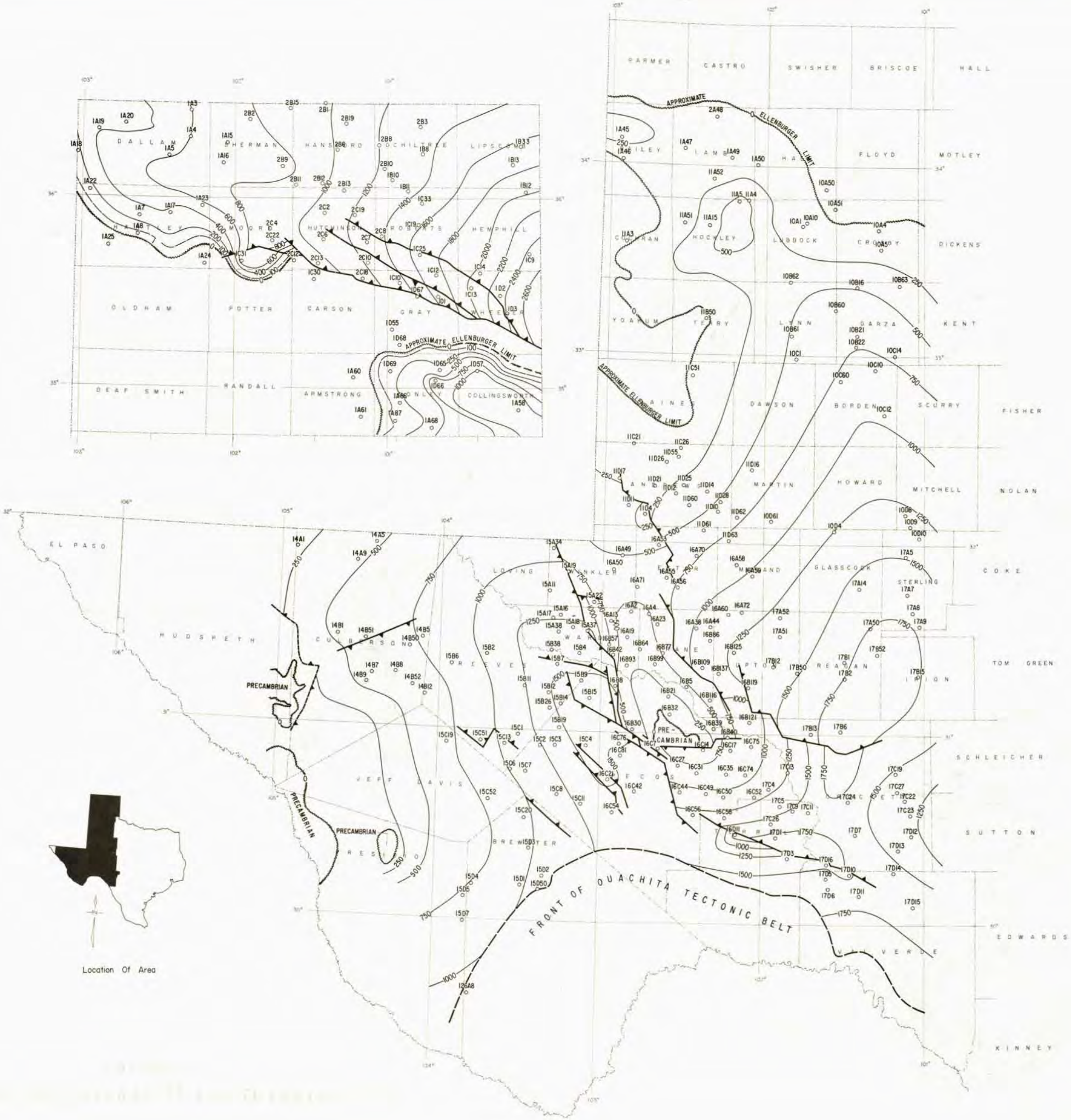


Figure 14

Ellenburger Structure, Central Texas



EXPLANATION

——1000—— Line showing gross thickness of Ellenburger aquifer. Includes Arbuckle and Cambrian sands. Interval is variable

1B12 ○ Well used for control

▲▲▲▲ Normal fault; sawteeth indicate downthrown side

**Figure 15**

**Ellenburger Gross Thickness, West Texas-Panhandle**

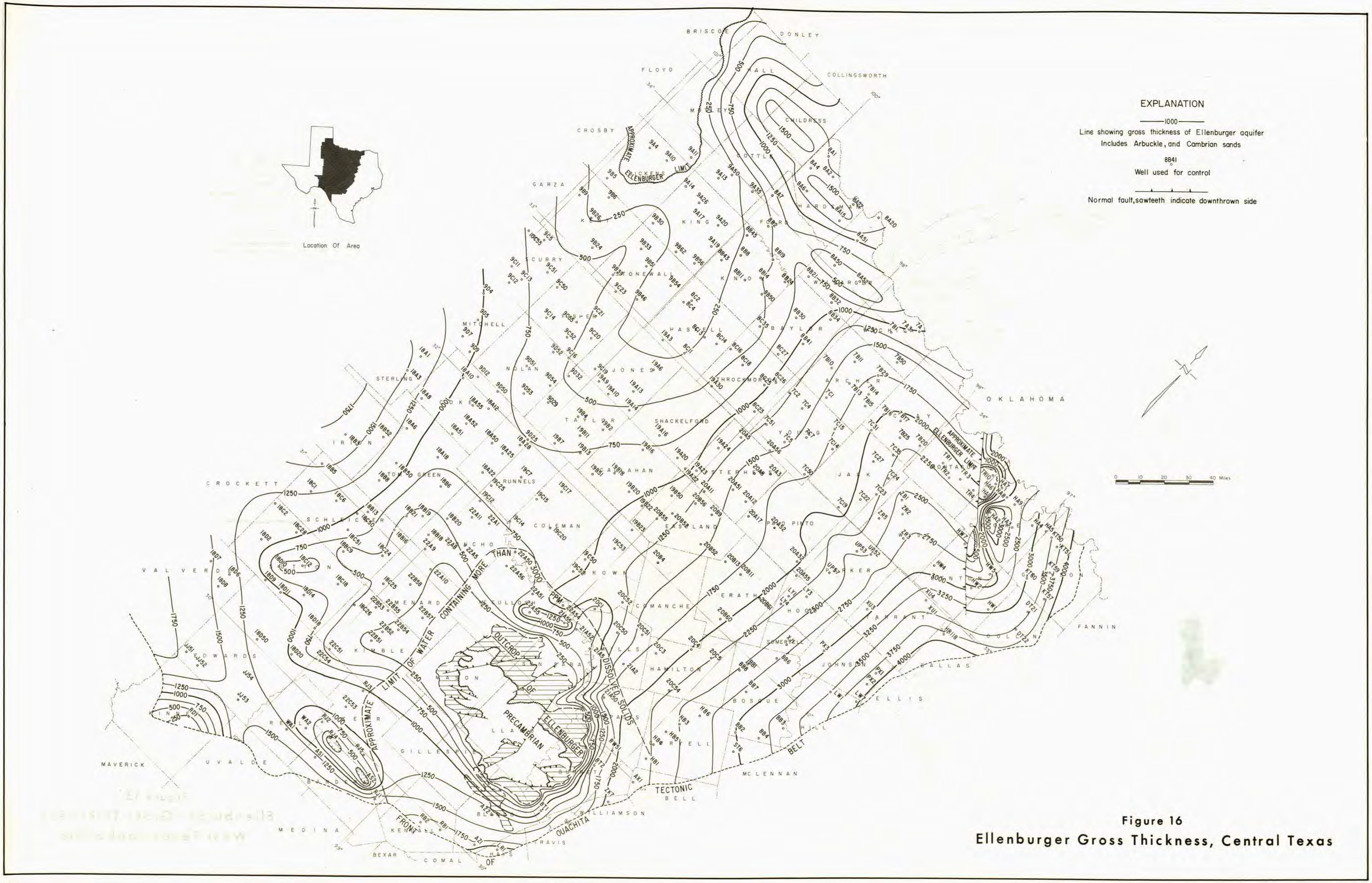


Figure 16
Ellenburger Gross Thickness, Central Texas

Figure 17
Ellenburger Water Salinity, West Texas

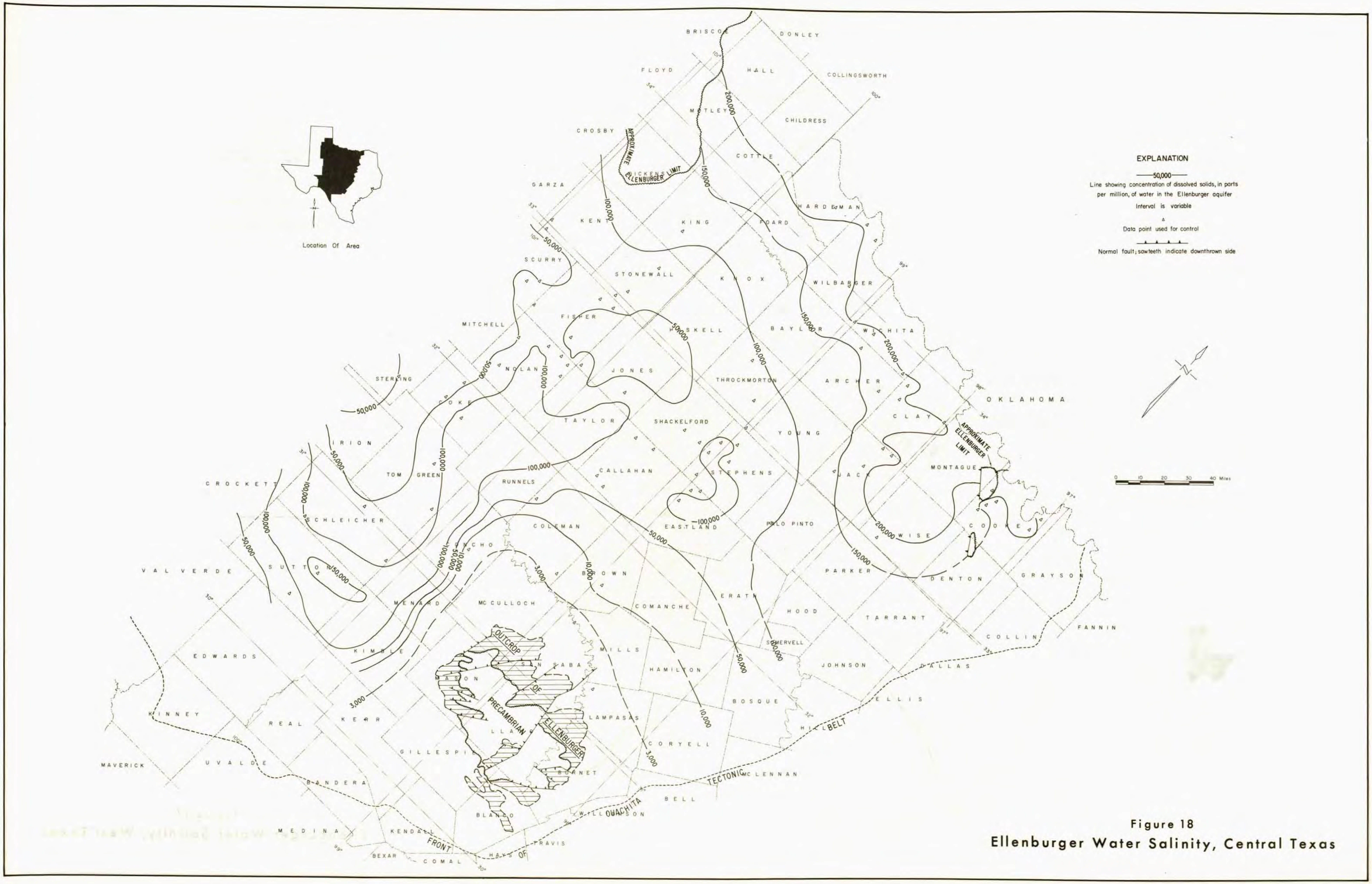
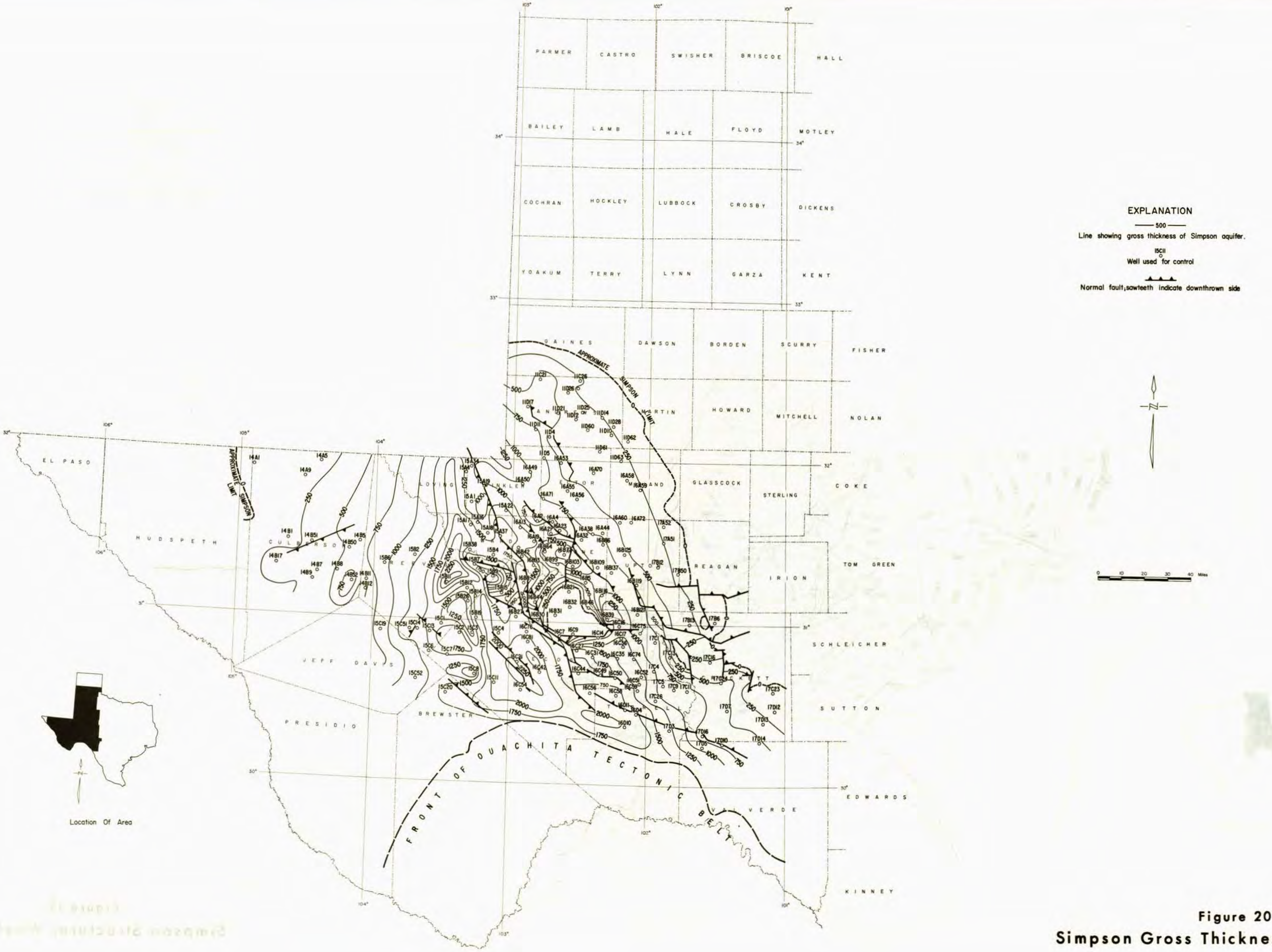


Figure 18
Ellenburger Water Salinity, Central Texas

Figure 19

Simpson Structure, West Texas



# Figure 20
# Simpson Gross Thickness, West Texas

Figure 21

Montoya Structure, West Texas

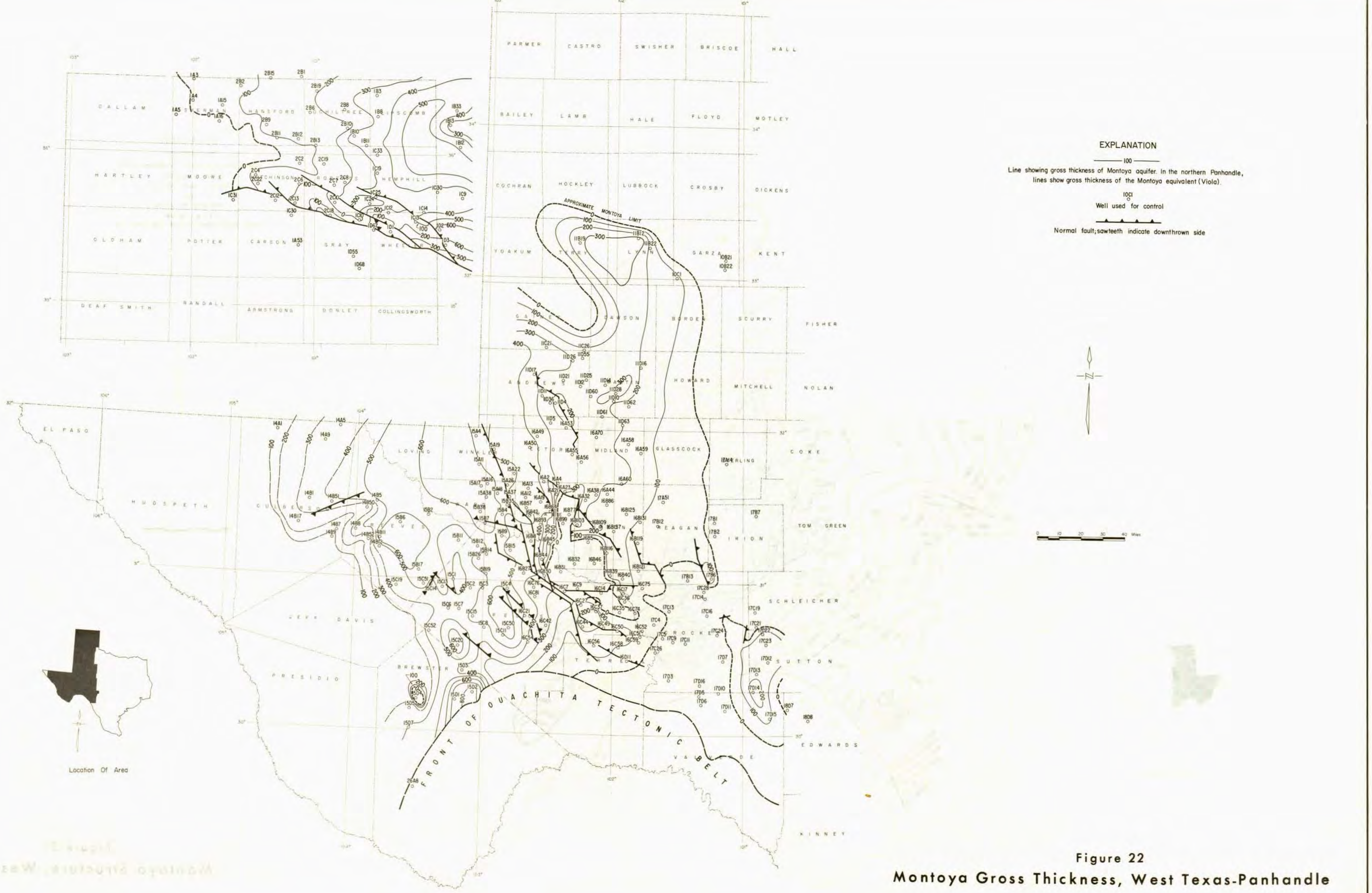
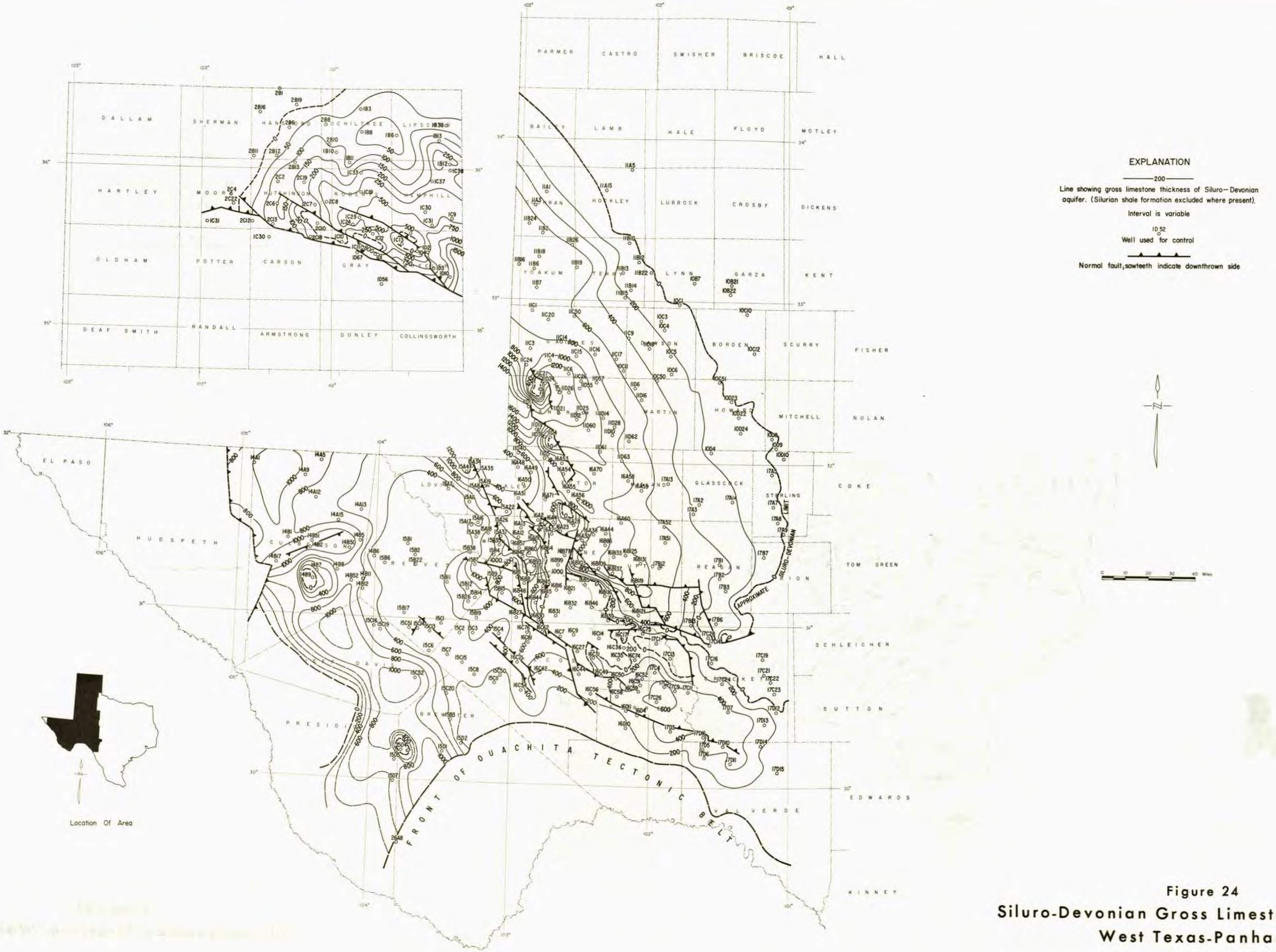


Figure 22

Montoya Gross Thickness, West Texas-Panhandle

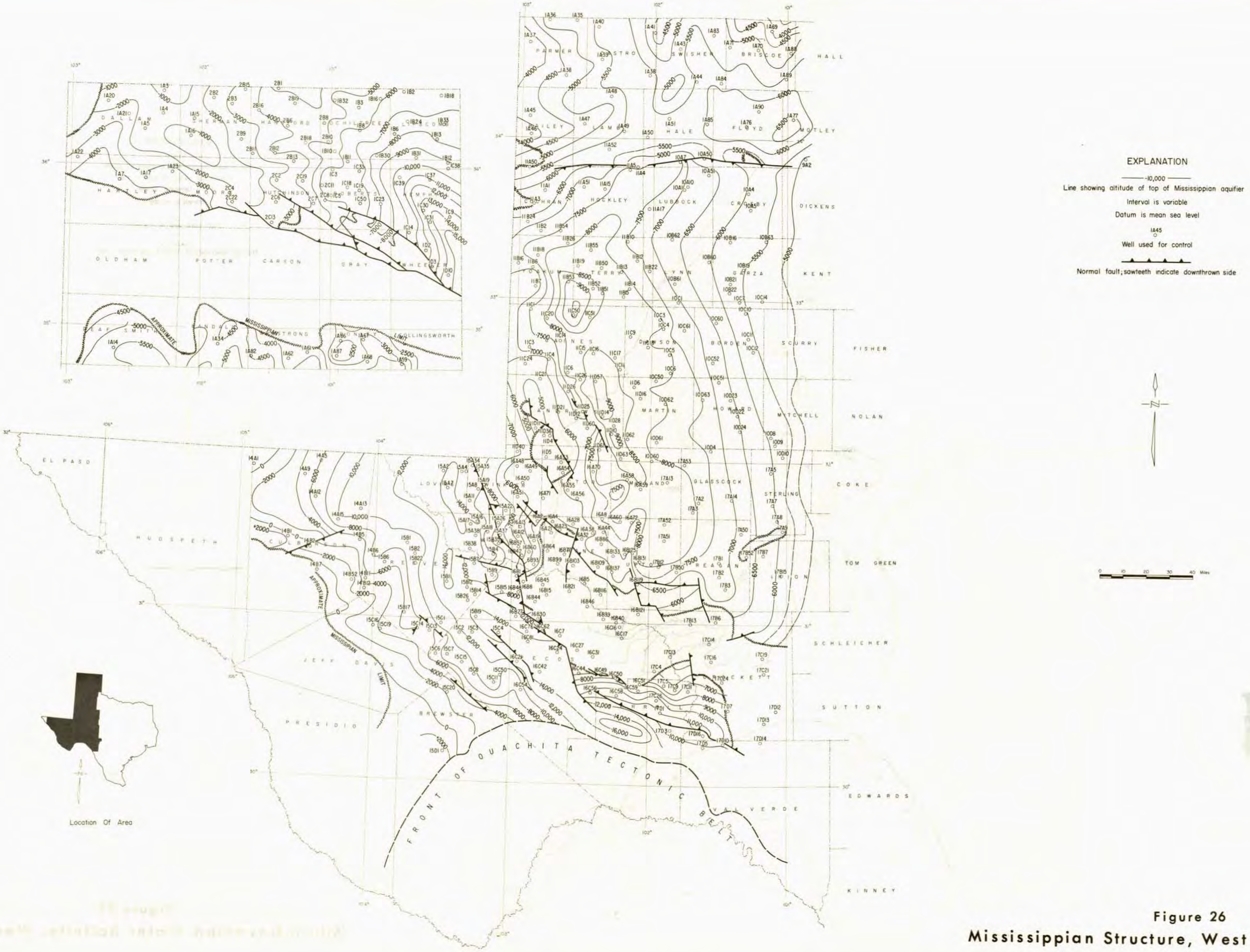
Figure 23

Siluro-Devonian Structure, West Texas

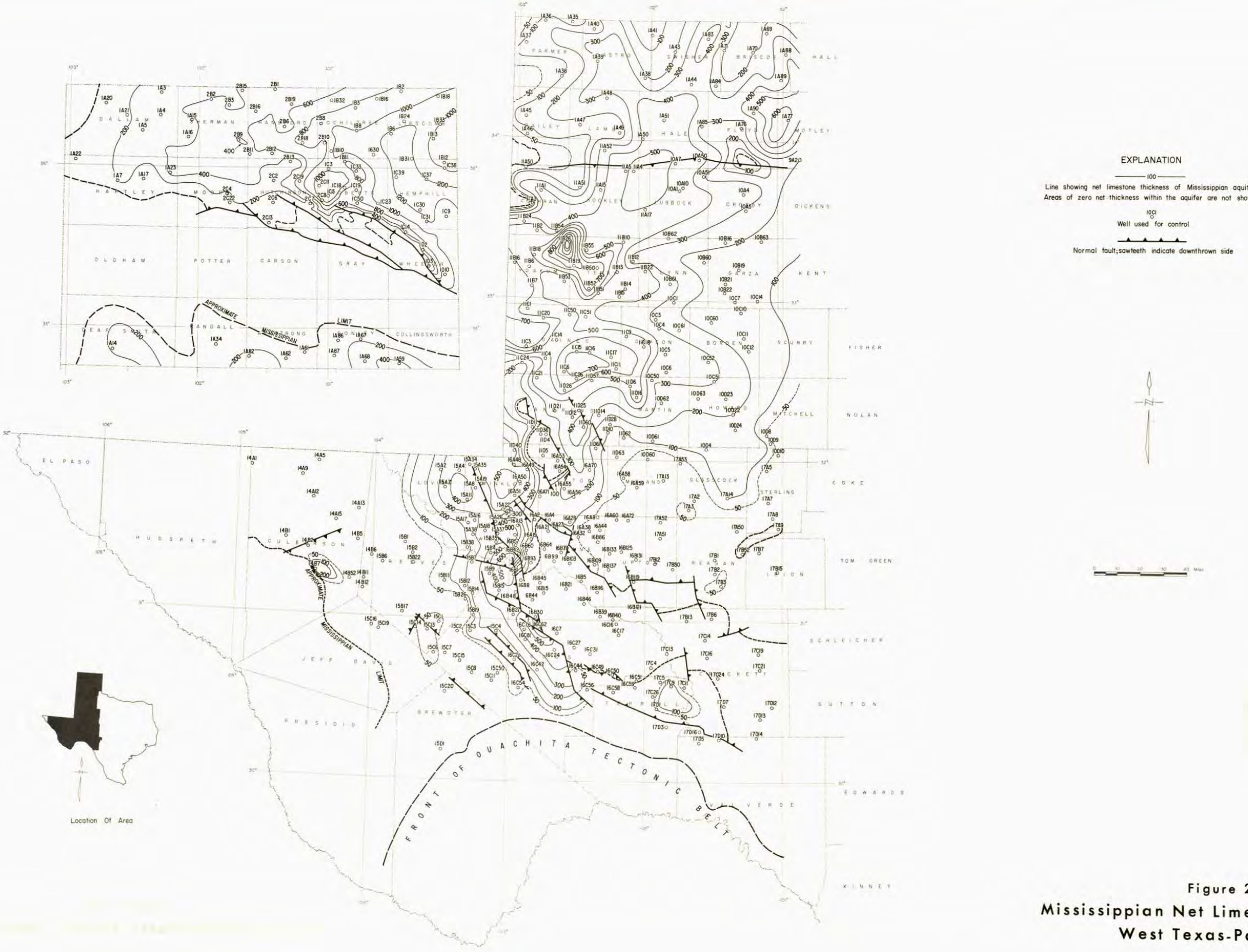


## Figure 24
## Siluro-Devonian Gross Limestone Thickness, West Texas-Panhandle

Figure 25
Siluro-Devonian Water Salinity, West Texas



## Figure 26
## Mississippian Structure, West Texas-Panhandle



EXPLANATION

100

Line showing net limestone thickness of Mississippian aquifer. Areas of zero net thickness within the aquifer are not shown.

10C1

Well used for control

Normal fault; sawteeth indicate downthrown side

Figure 27

Mississippian Net Limestone Thickness, West Texas-Panhandle

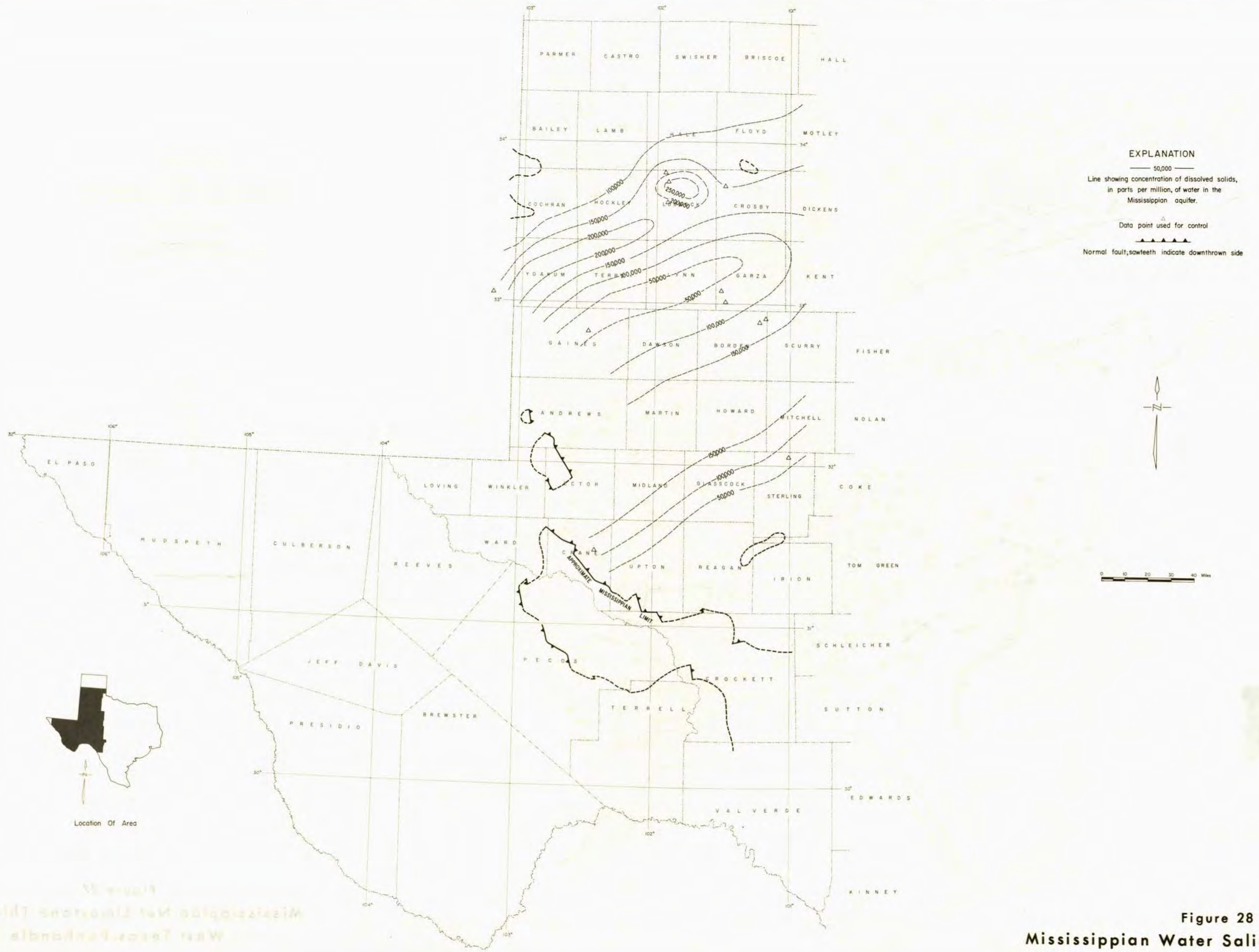


Figure 28
Mississippian Water Salinity, West Texas

Figure 29
**Pennsylvanian Structure, West Texas-Panhandle**

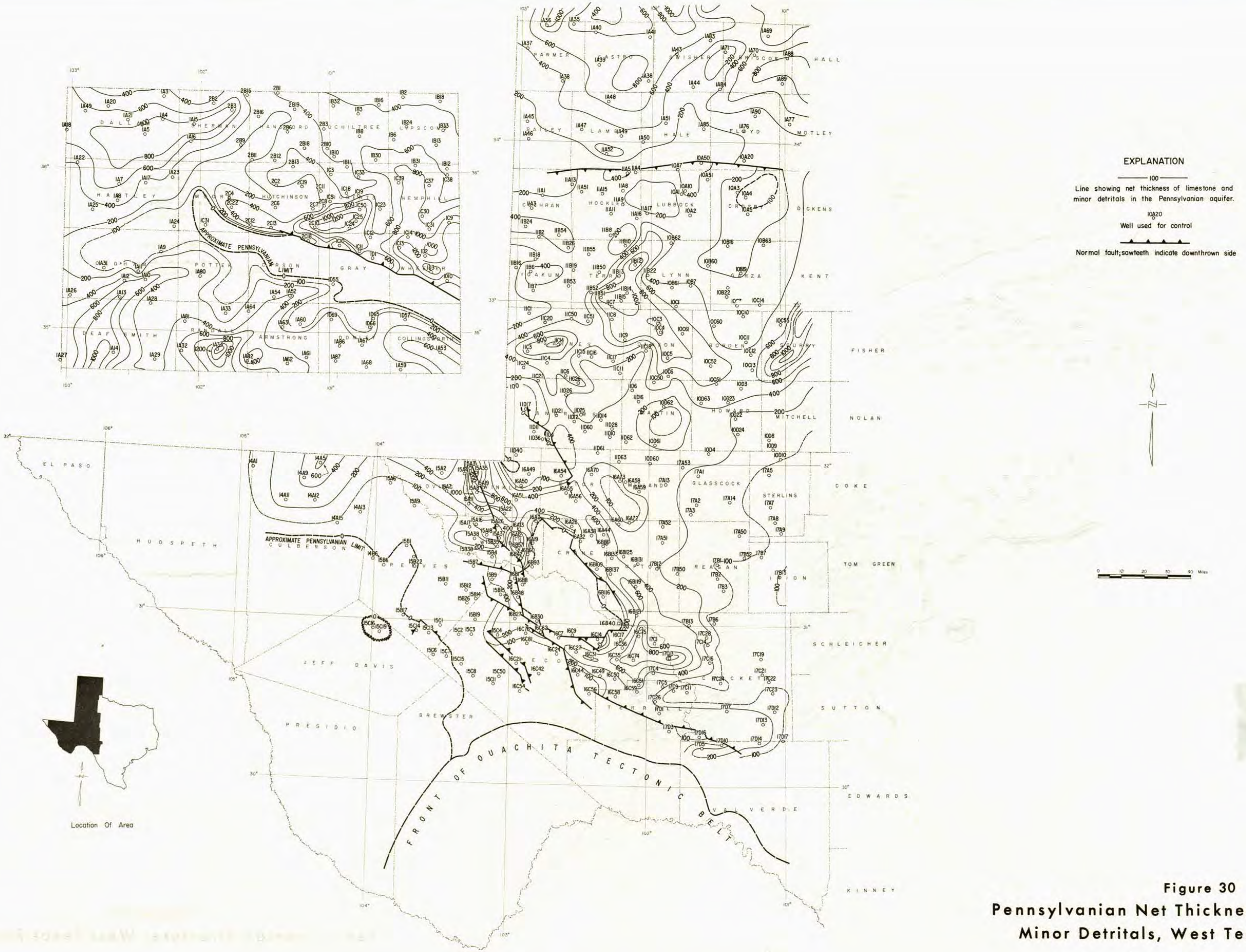


Figure 30
Pennsylvanian Net Thickness, Limestone and Minor Detritals, West Texas-Panhandle

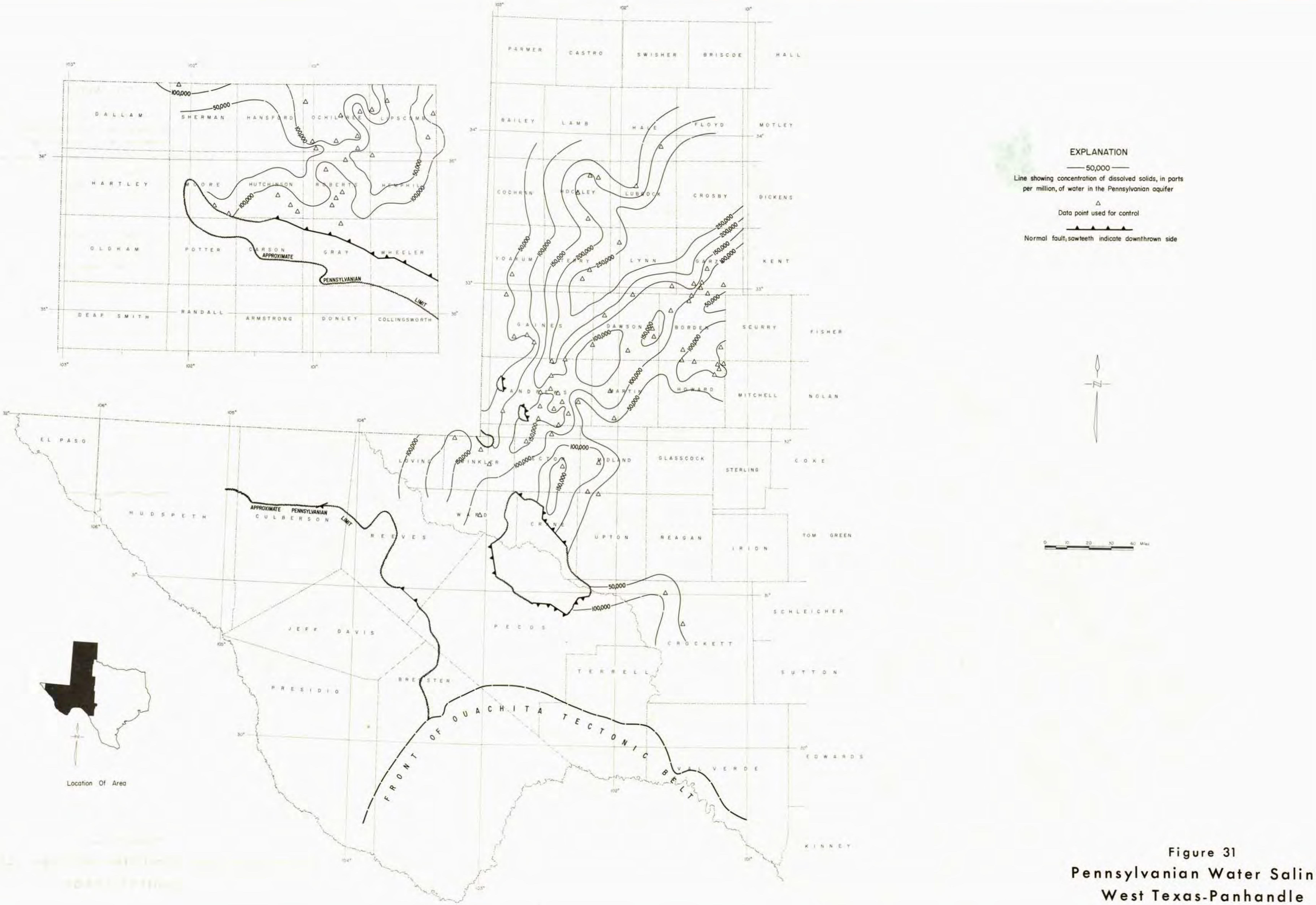
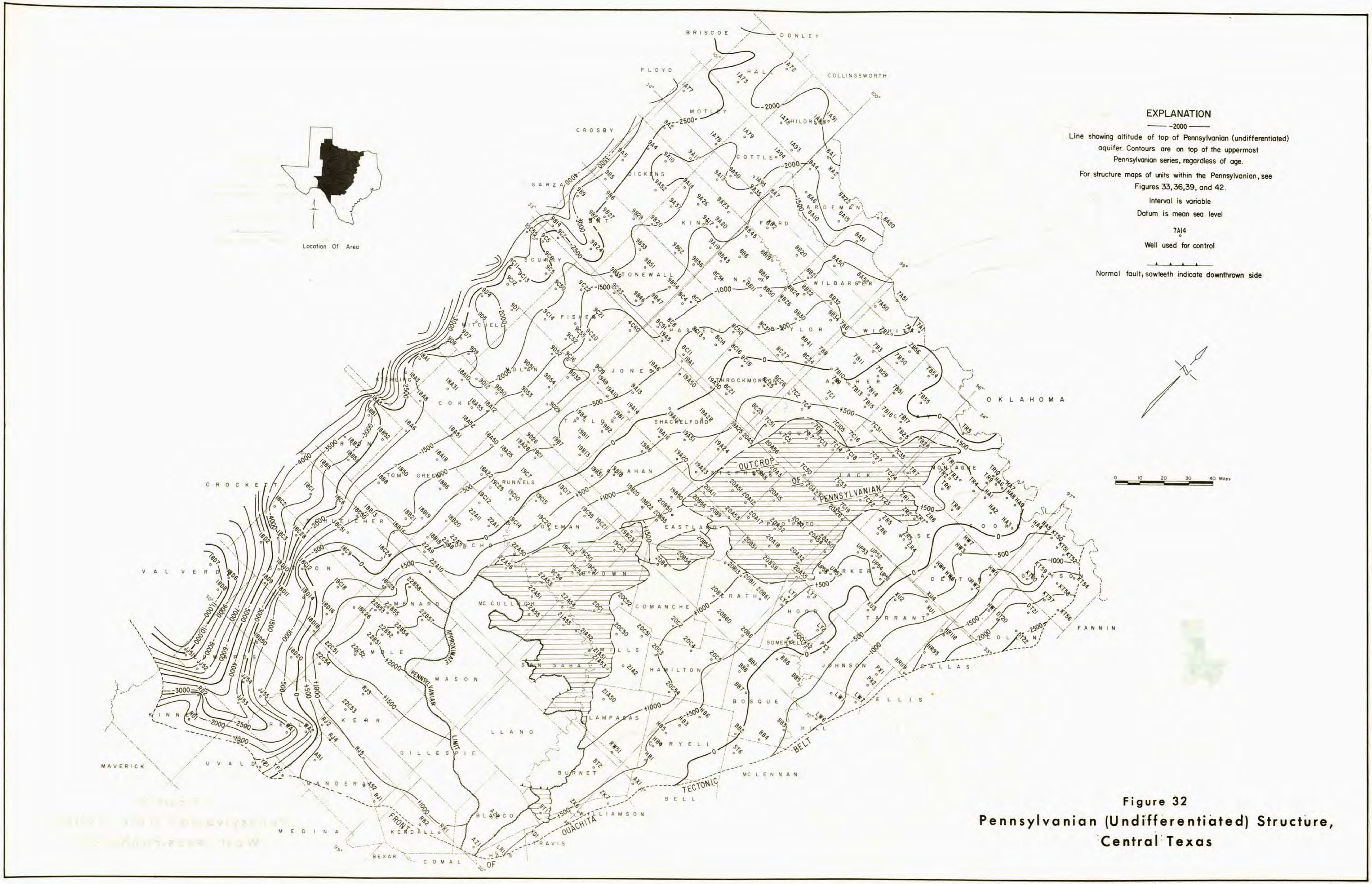


Figure 31
**Pennsylvanian Water Salinity, West Texas-Panhandle**



EXPLANATION

——— -2000 ———

Line showing altitude of top of Pennsylvanian (undifferentiated) aquifer. Contours are on top of the uppermost Pennsylvanian series, regardless of age.

For structure maps of units within the Pennsylvanian, see Figures 33, 36, 39, and 42.

Interval is variable

Datum is mean sea level

7A14
○

Well used for control

Normal fault; sawteeth indicate downthrown side

Figure 32

Pennsylvanian (Undifferentiated) Structure, Central Texas

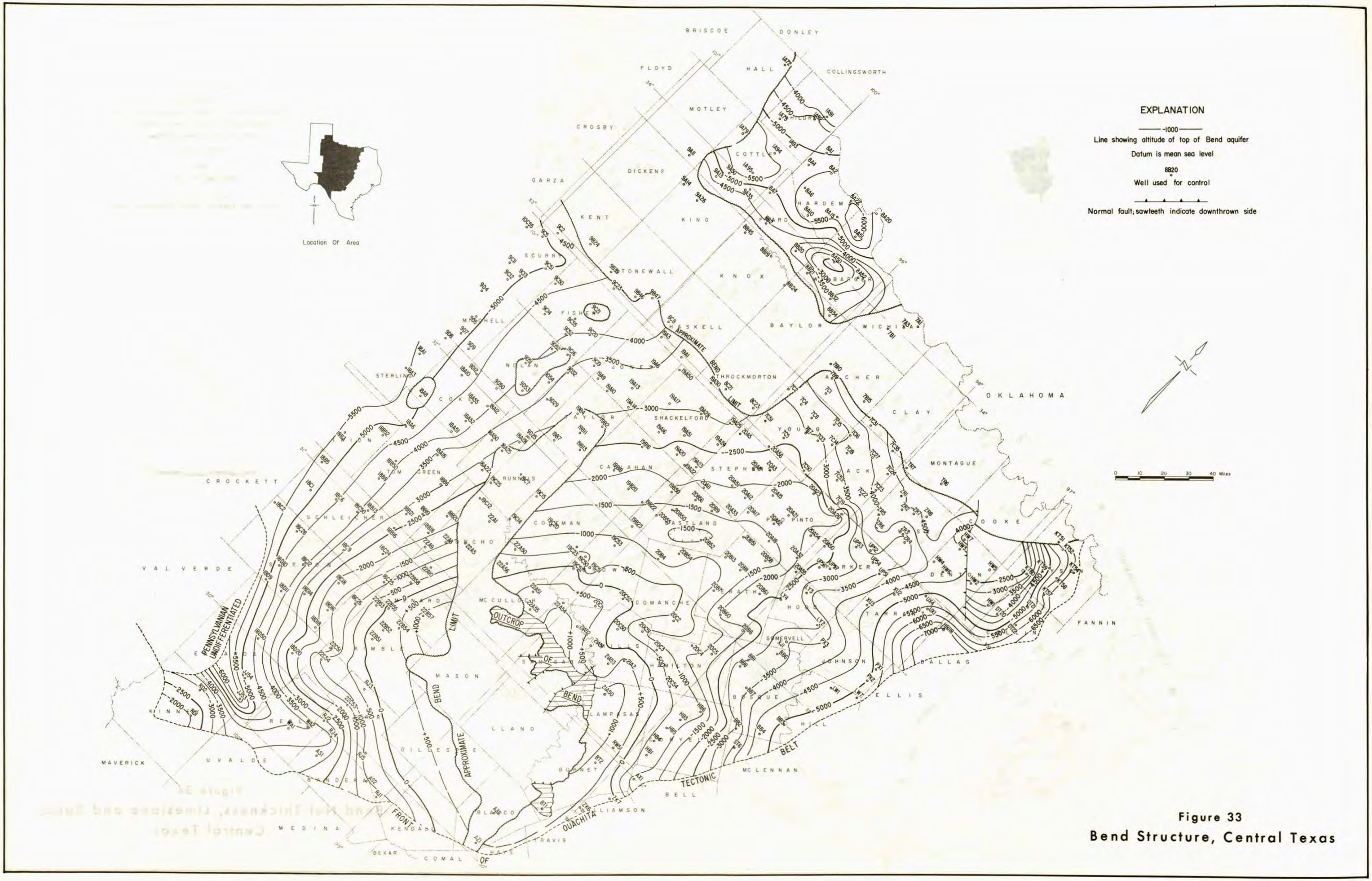
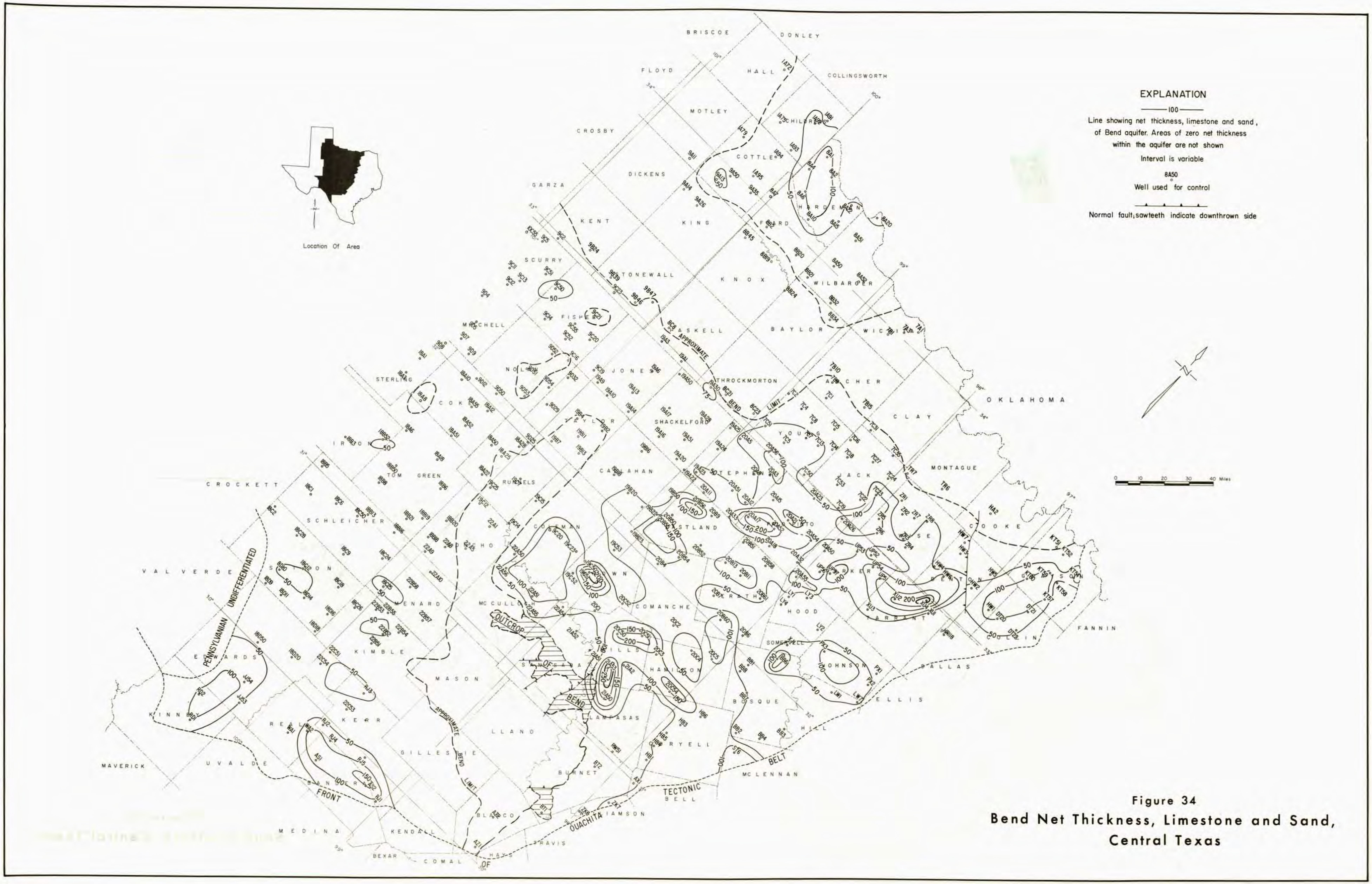


Figure 33
Bend Structure, Central Texas



## Figure 34

## Bend Net Thickness, Limestone and Sand, Central Texas

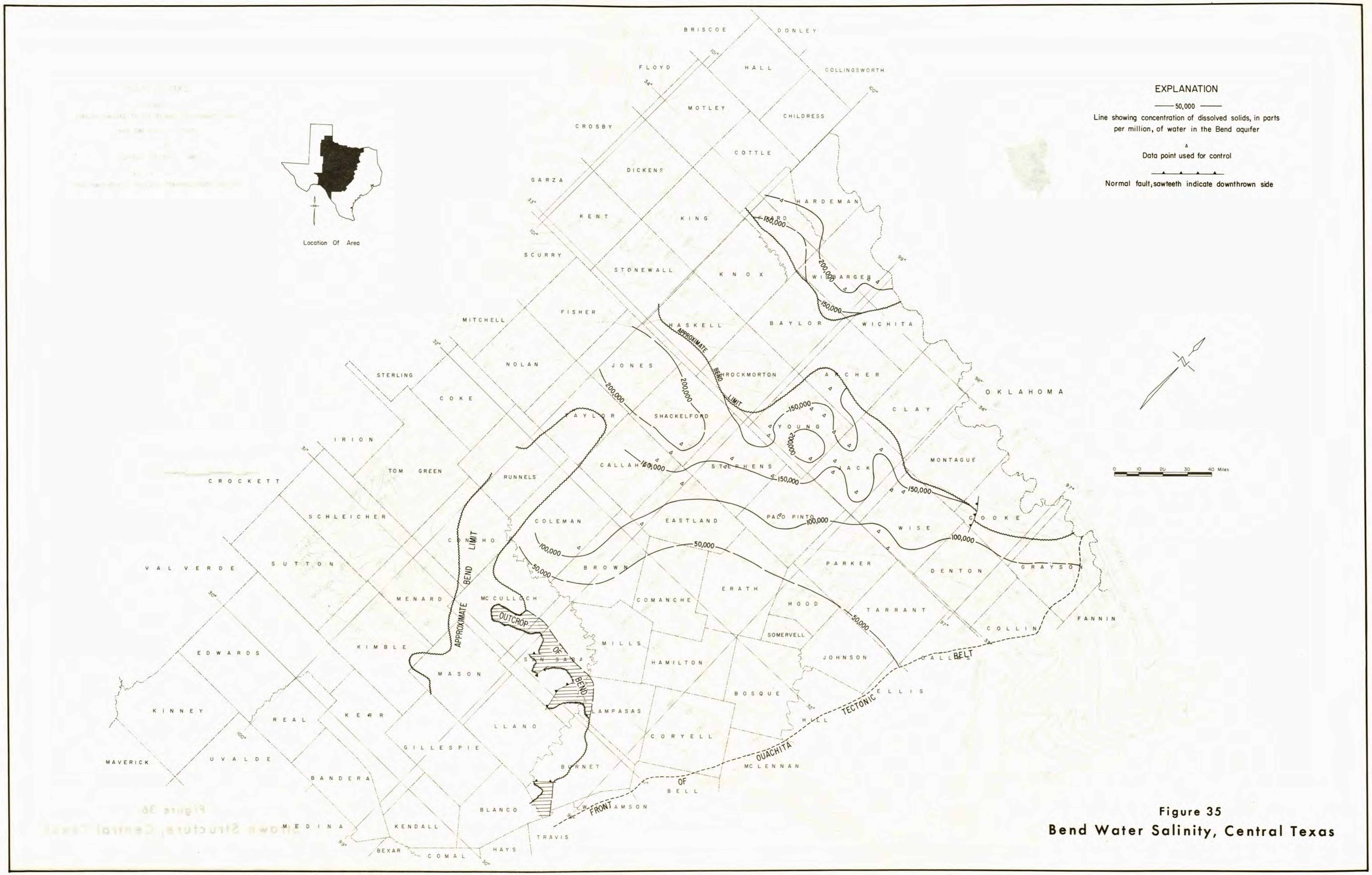
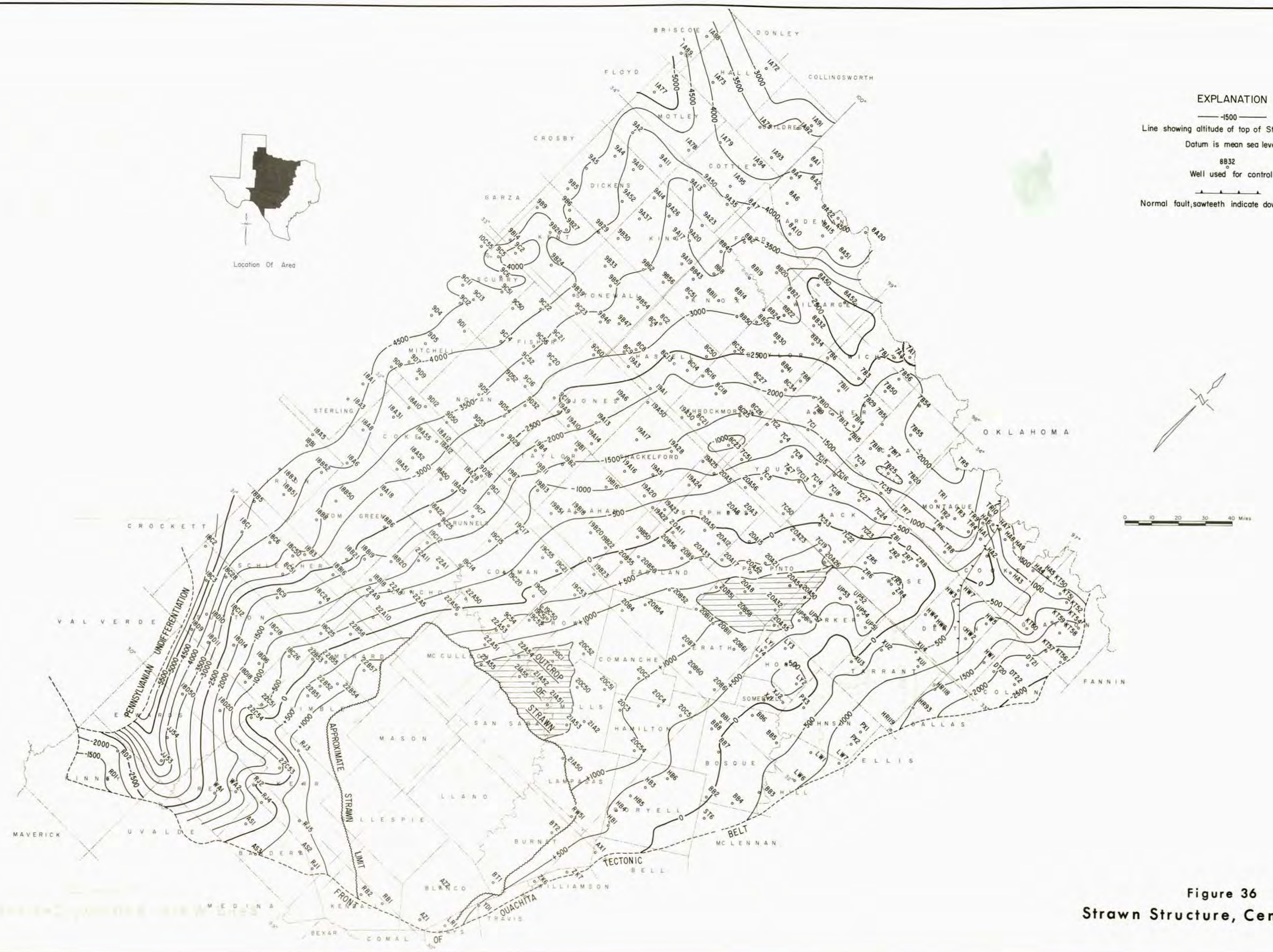


**Figure 35**
**Bend Water Salinity, Central Texas**



EXPLANATION

——— -1500 ———
Line showing altitude of top of Strawn aquifer

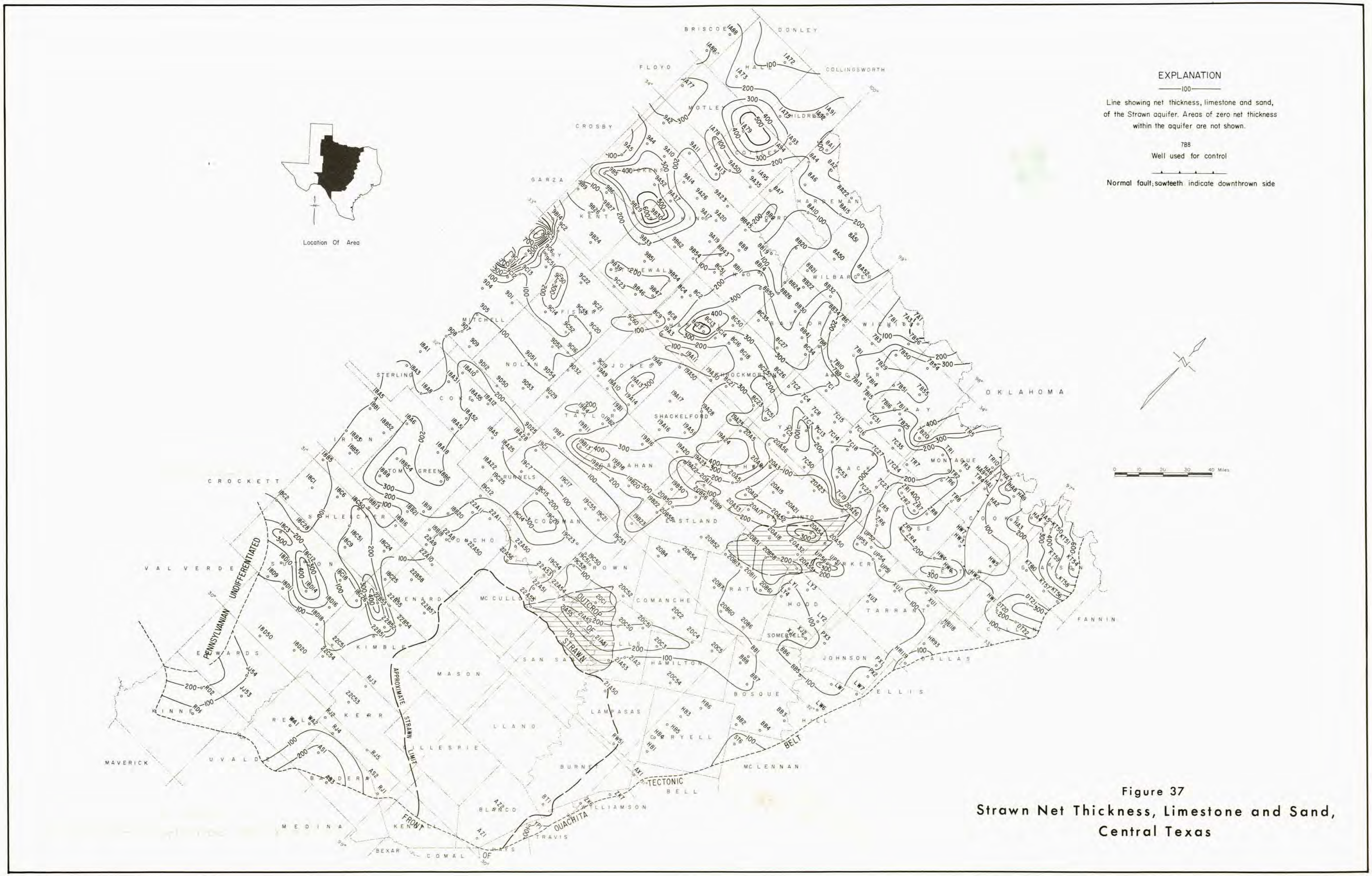
Datum is mean sea level

8B32
Well used for control

Normal fault,sawteeth indicate downthrown side

**Figure 36**

**Strawn Structure, Central Texas**



# Figure 37
## Strawn Net Thickness, Limestone and Sand, Central Texas

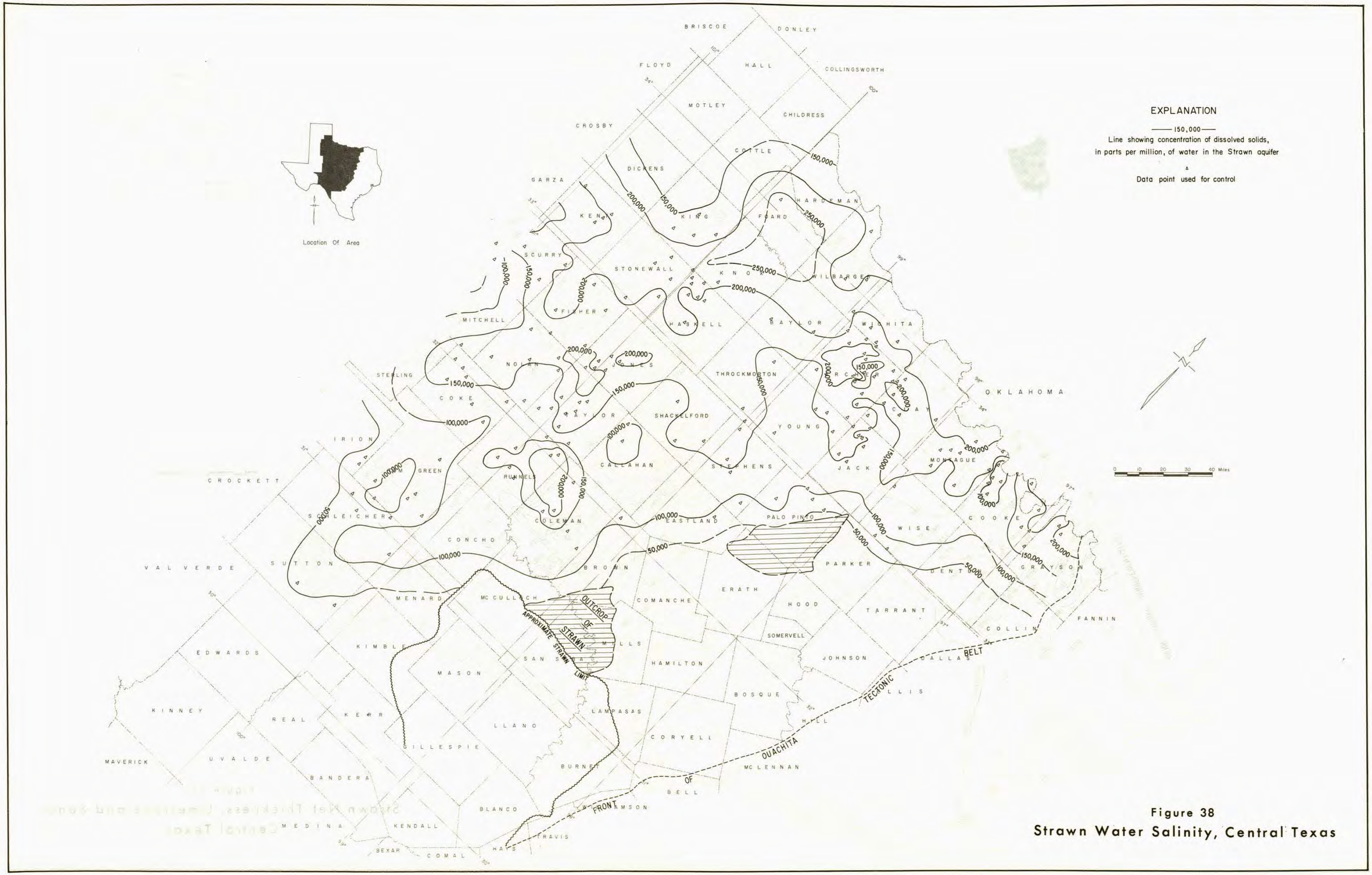
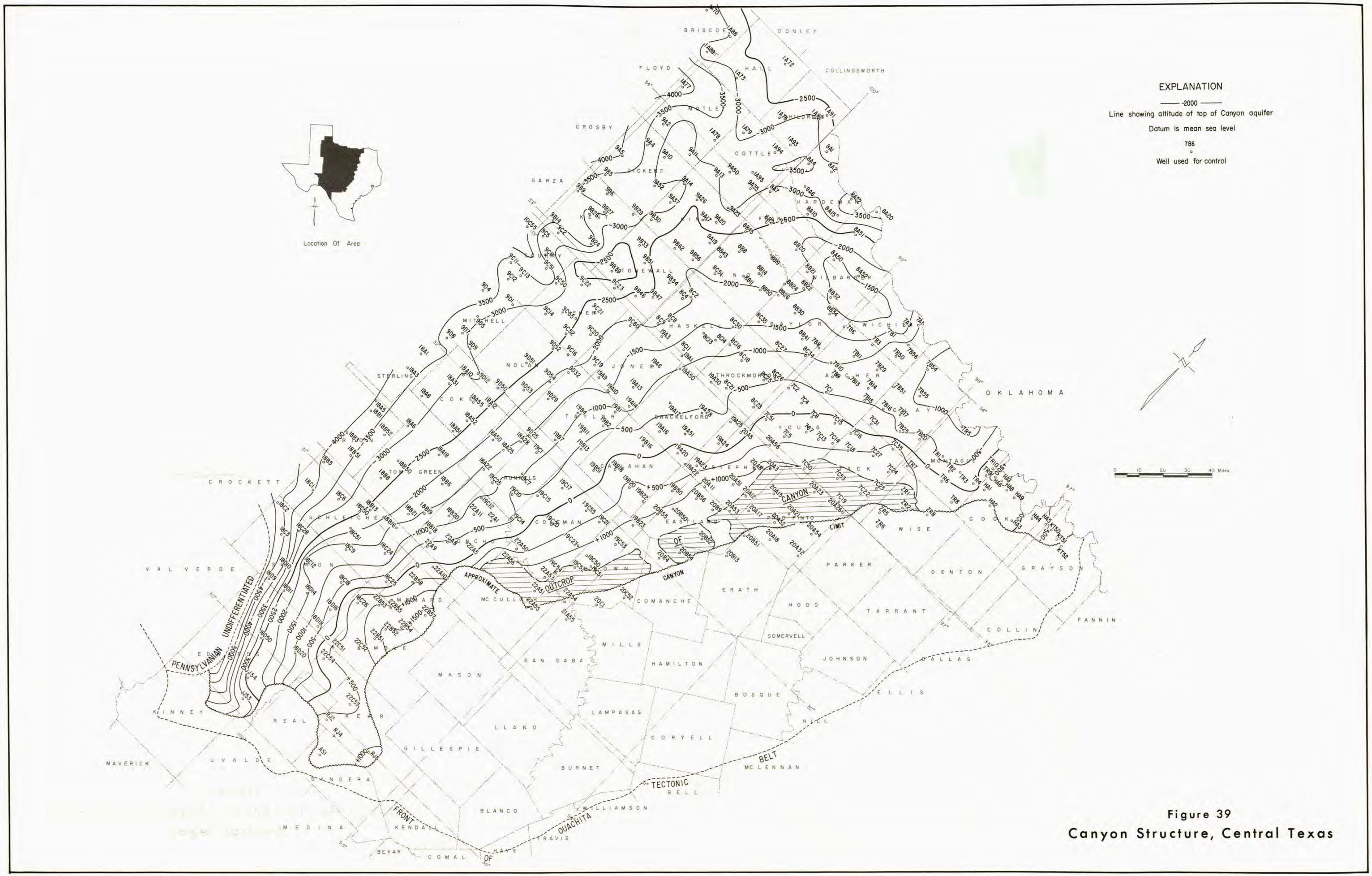
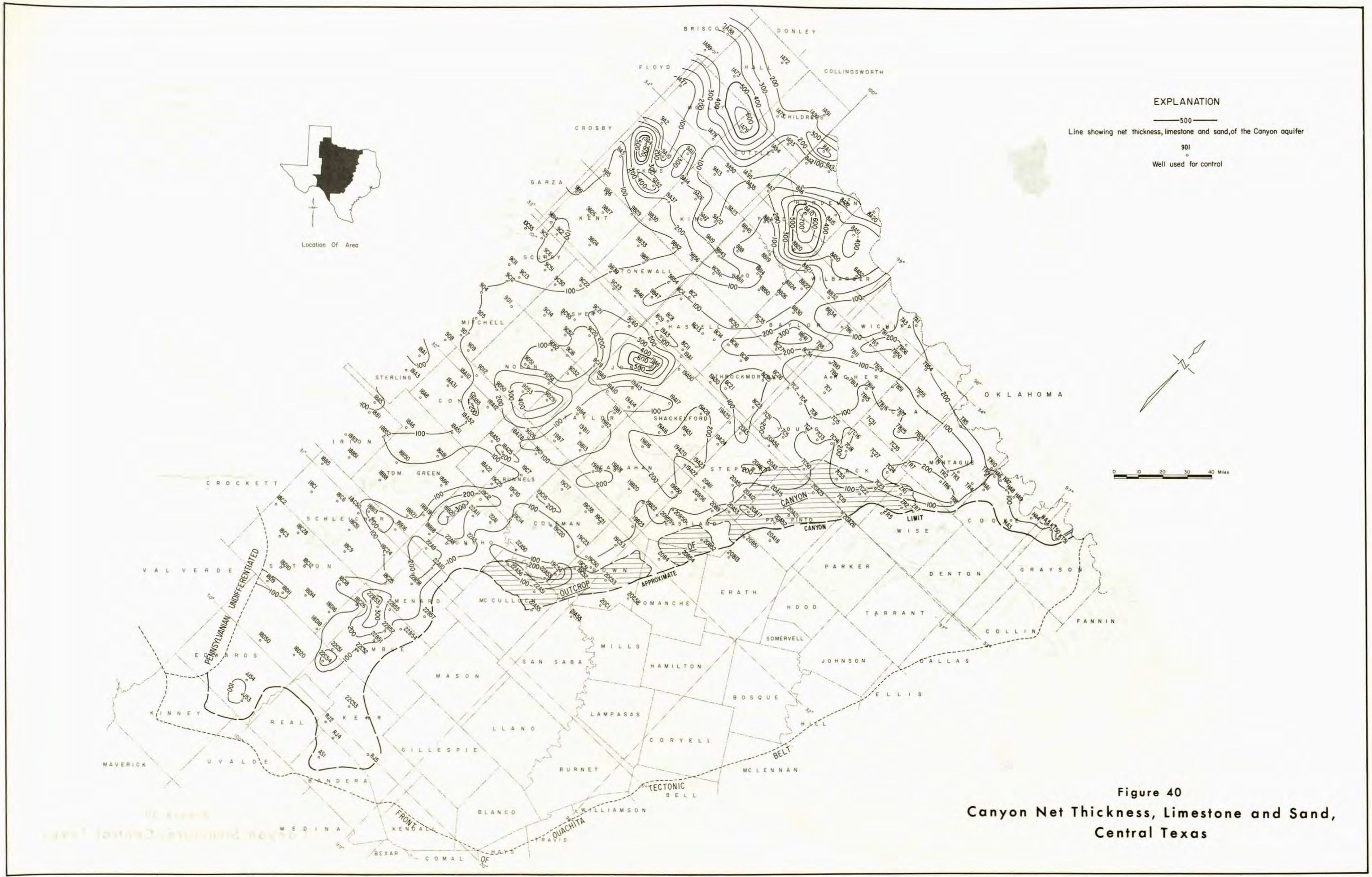


**Figure 38**
**Strawn Water Salinity, Central Texas**



## Figure 39

## Canyon Structure, Central Texas



# Figure 40
## Canyon Net Thickness, Limestone and Sand, Central Texas

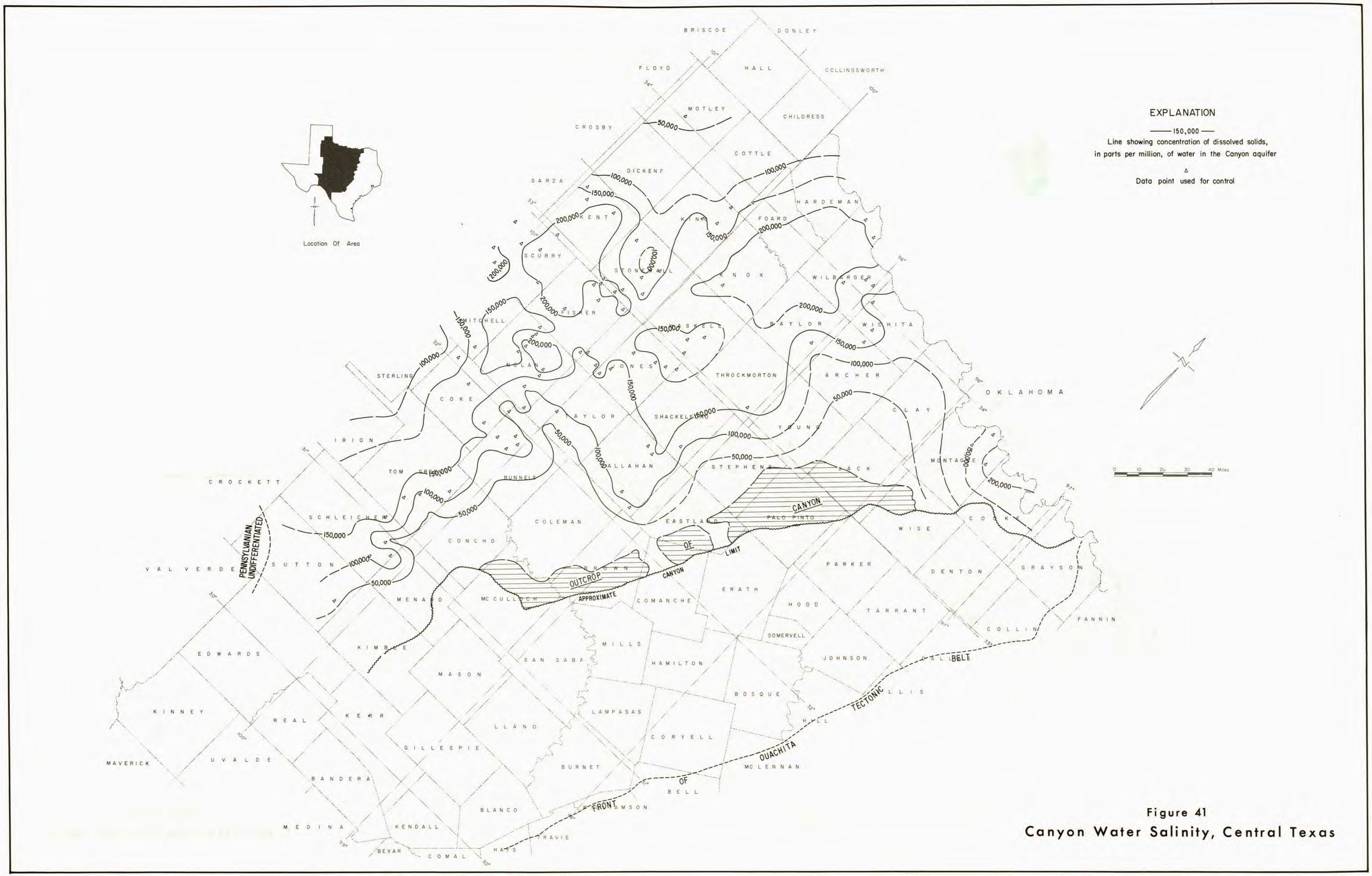


Figure 41

Canyon Water Salinity, Central Texas

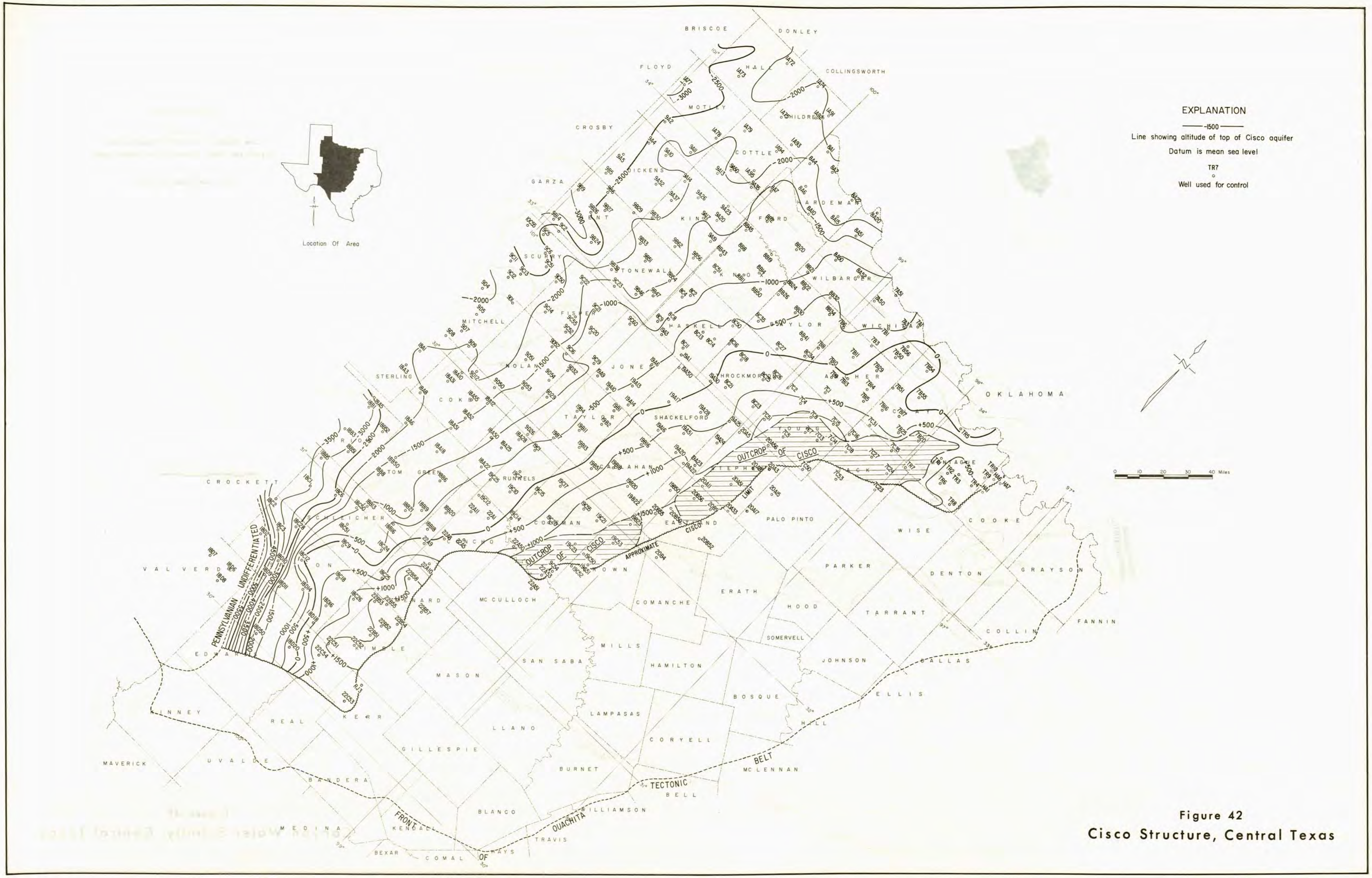


**Figure 42**

**Cisco Structure, Central Texas**

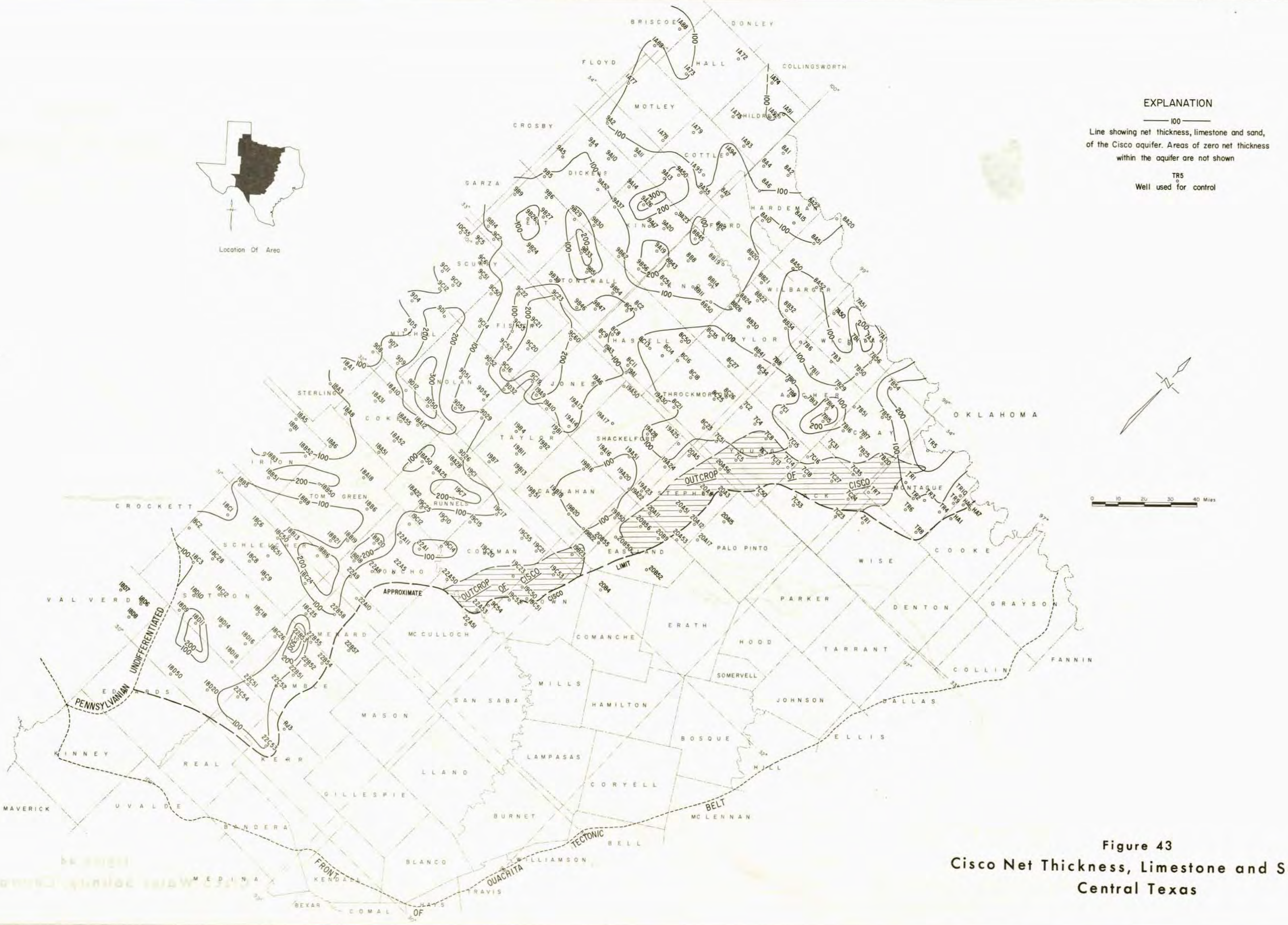


Figure 43

Cisco Net Thickness, Limestone and Sand, Central Texas

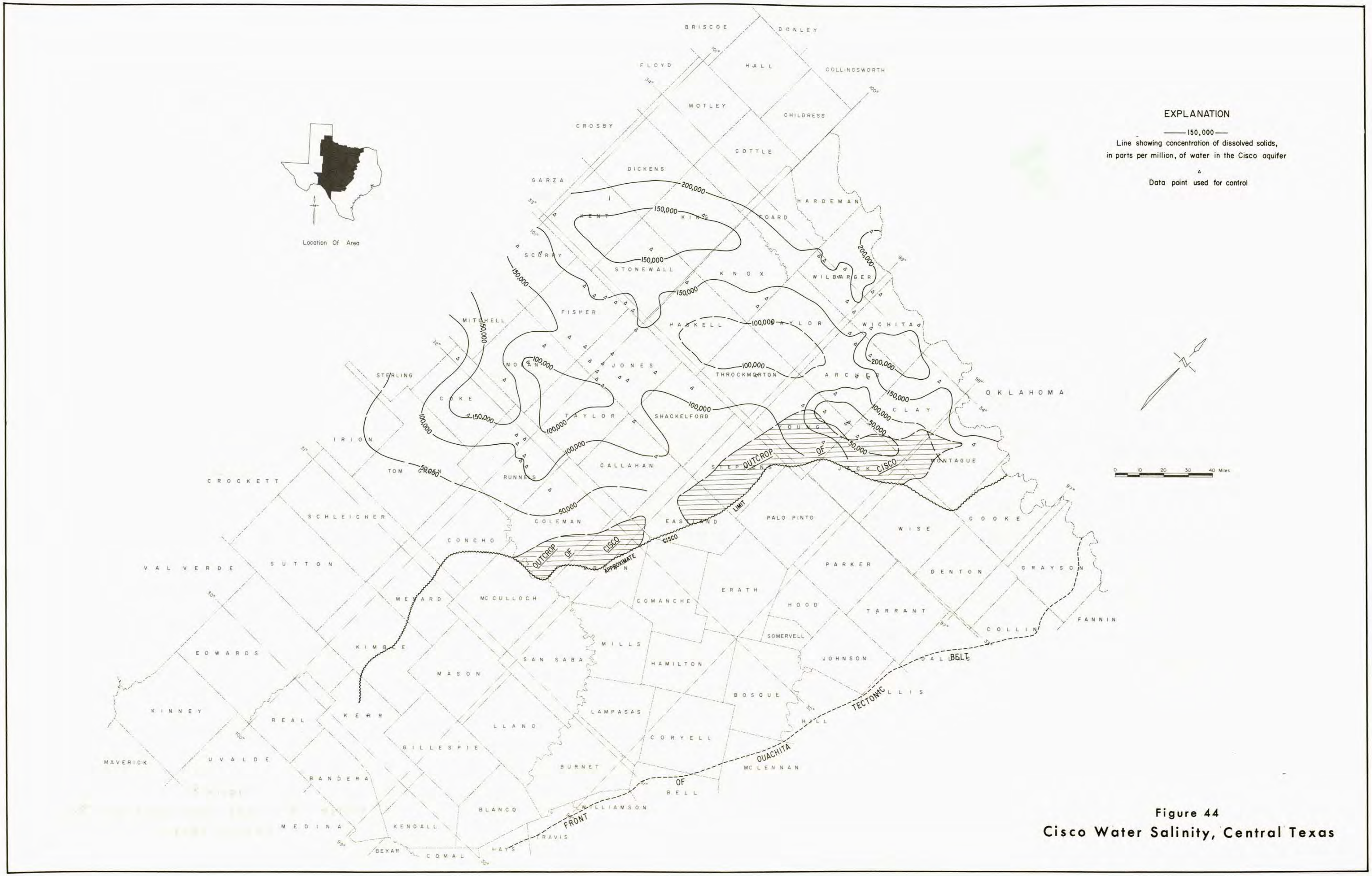


Figure 44
Cisco Water Salinity, Central Texas

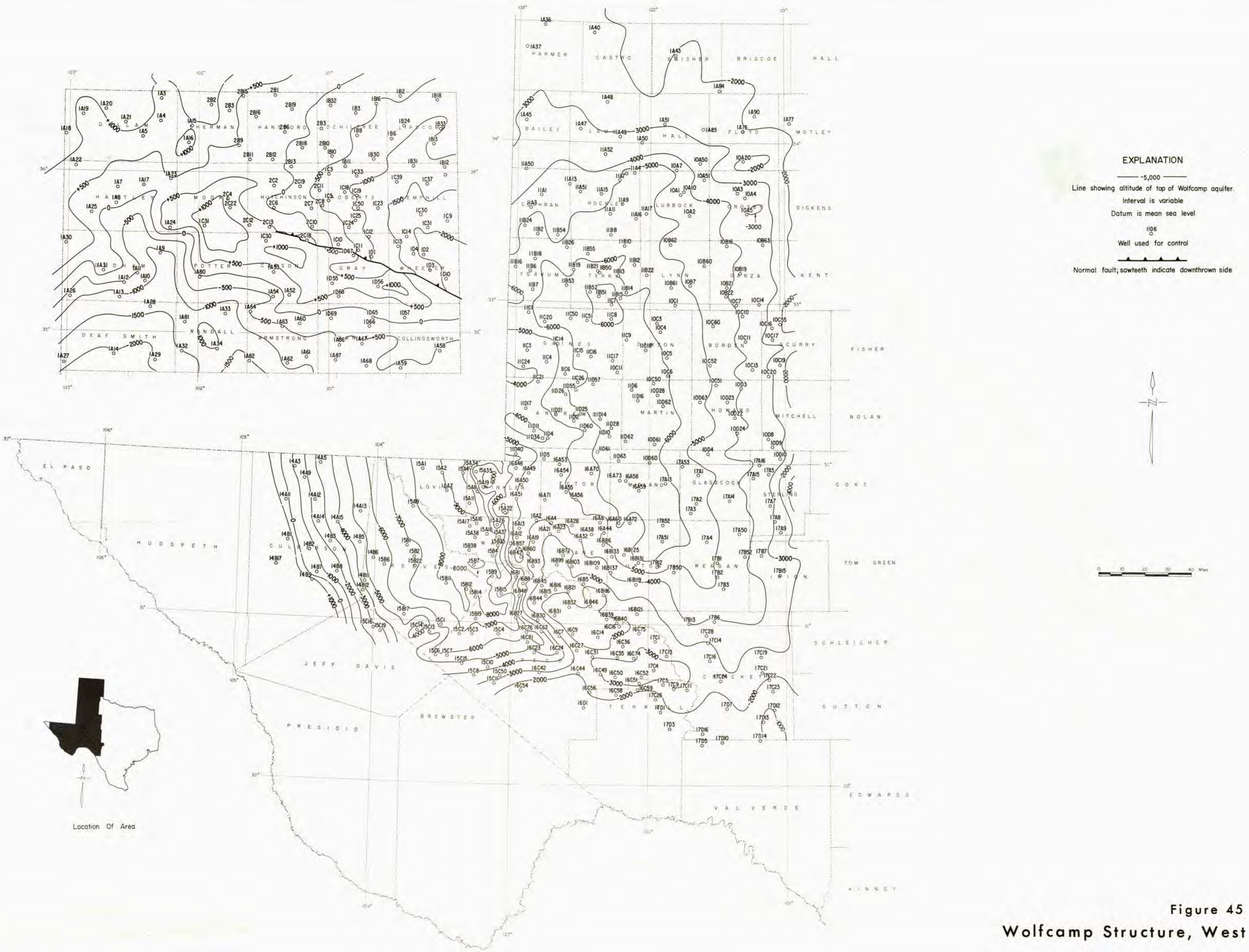


Figure 45
Wolfcamp Structure, West Texas-Panhandle

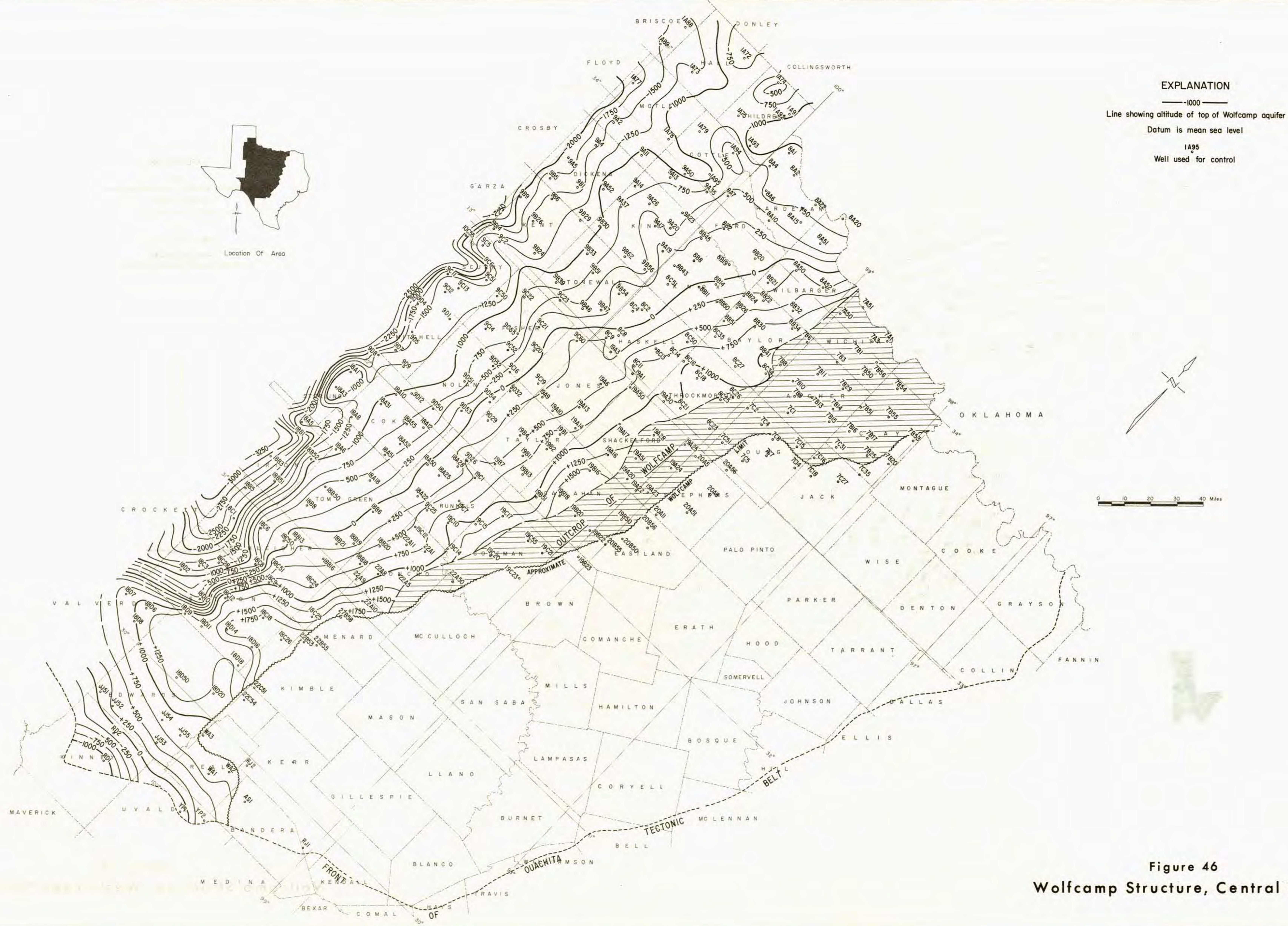
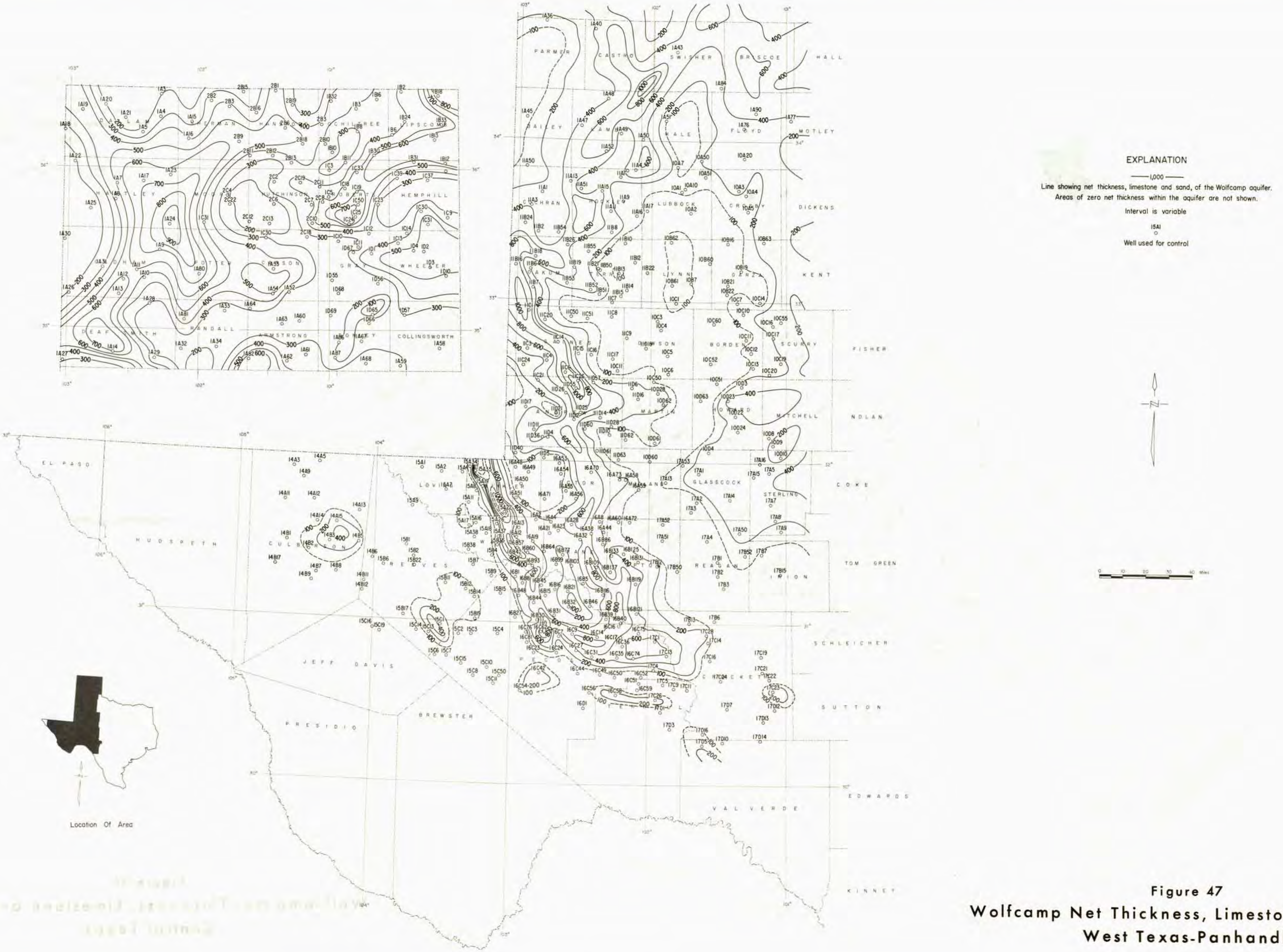


**Figure 46**
**Wolfcamp Structure, Central Texas**



EXPLANATION

——1,000——

Line showing net thickness, limestone and sand, of the Wolfcamp aquifer. Areas of zero net thickness within the aquifer are not shown.

Interval is variable

15A1
○
Well used for control

## Figure 47

## Wolfcamp Net Thickness, Limestone and Sand, West Texas-Panhandle

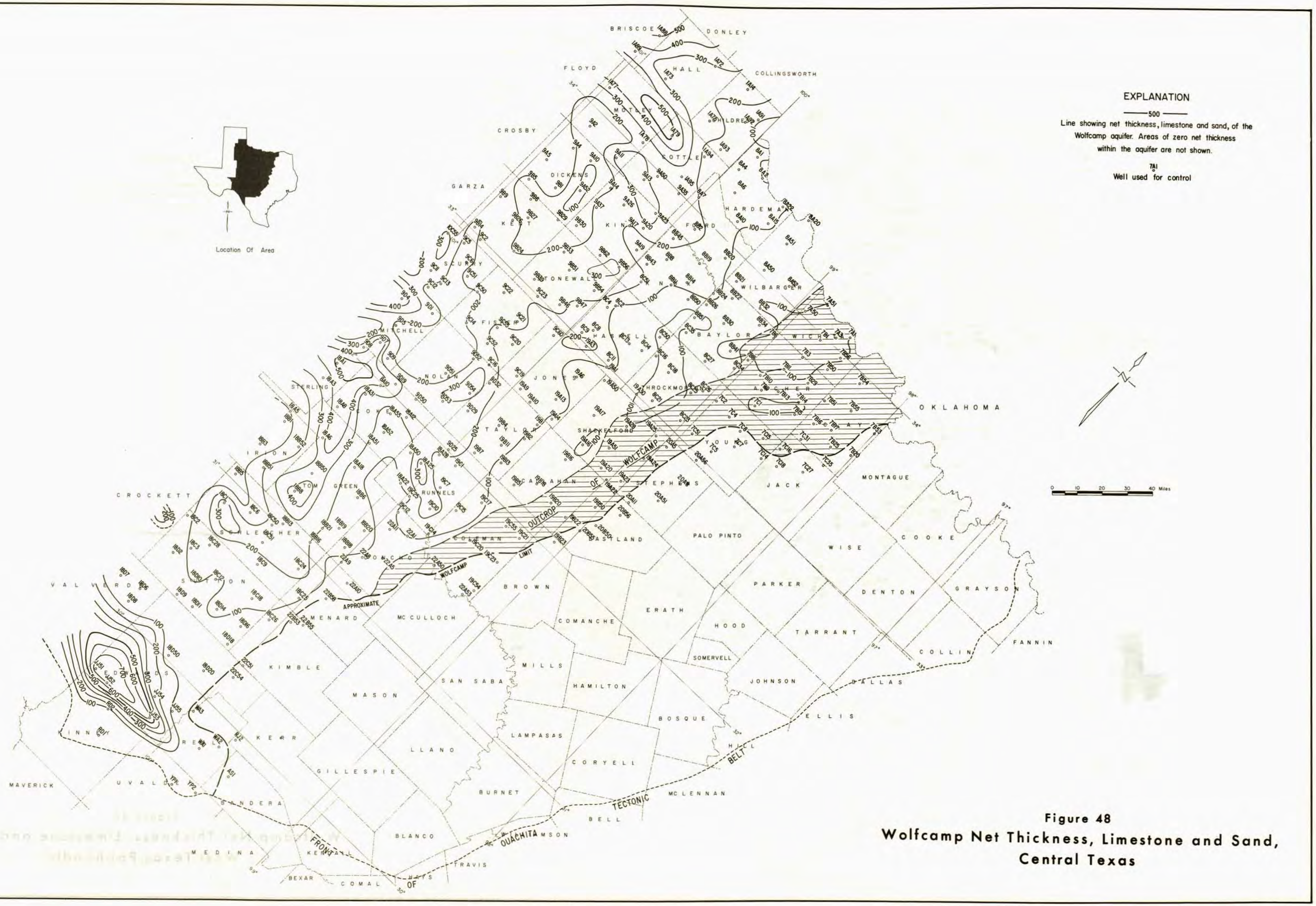
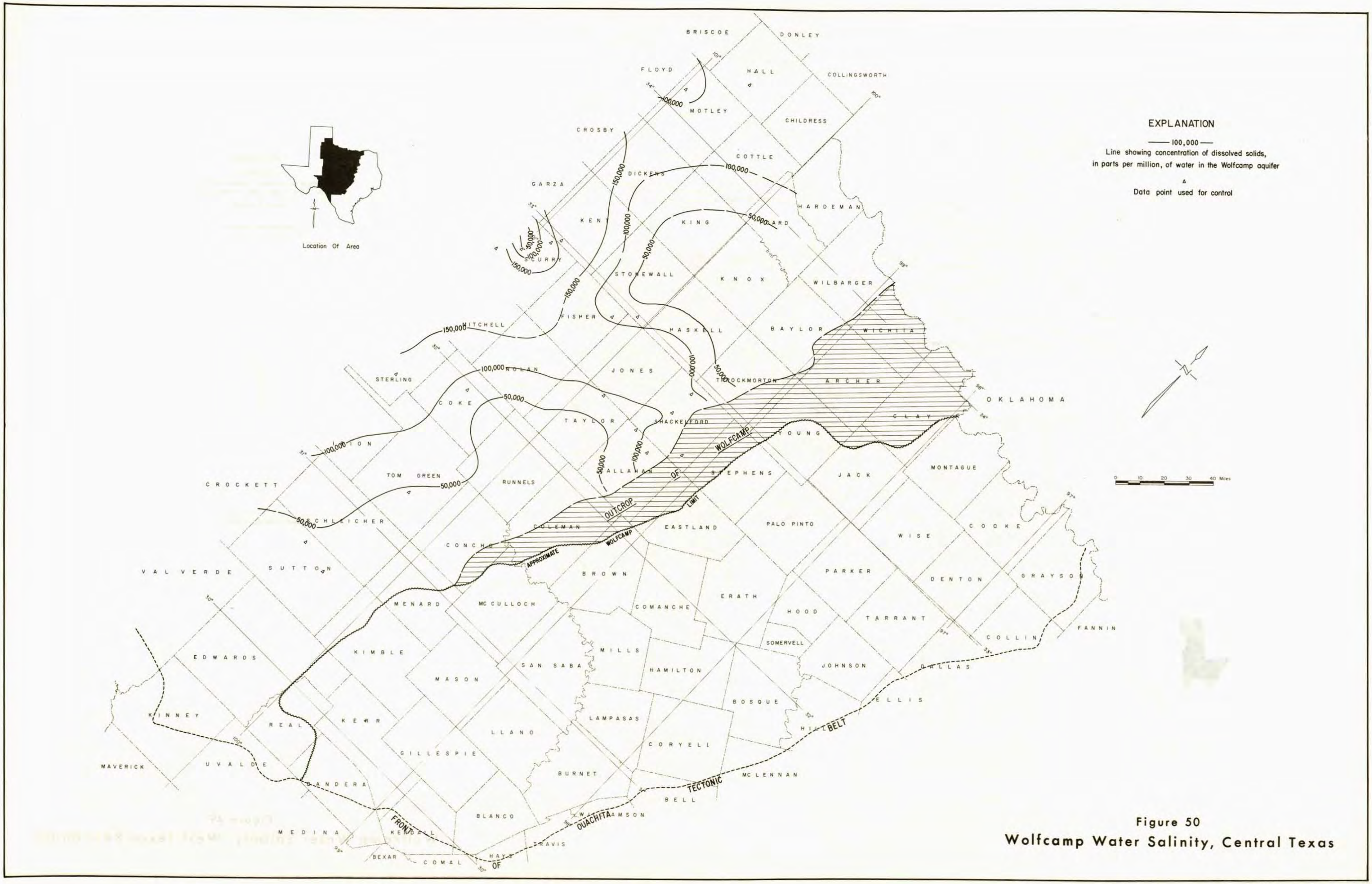
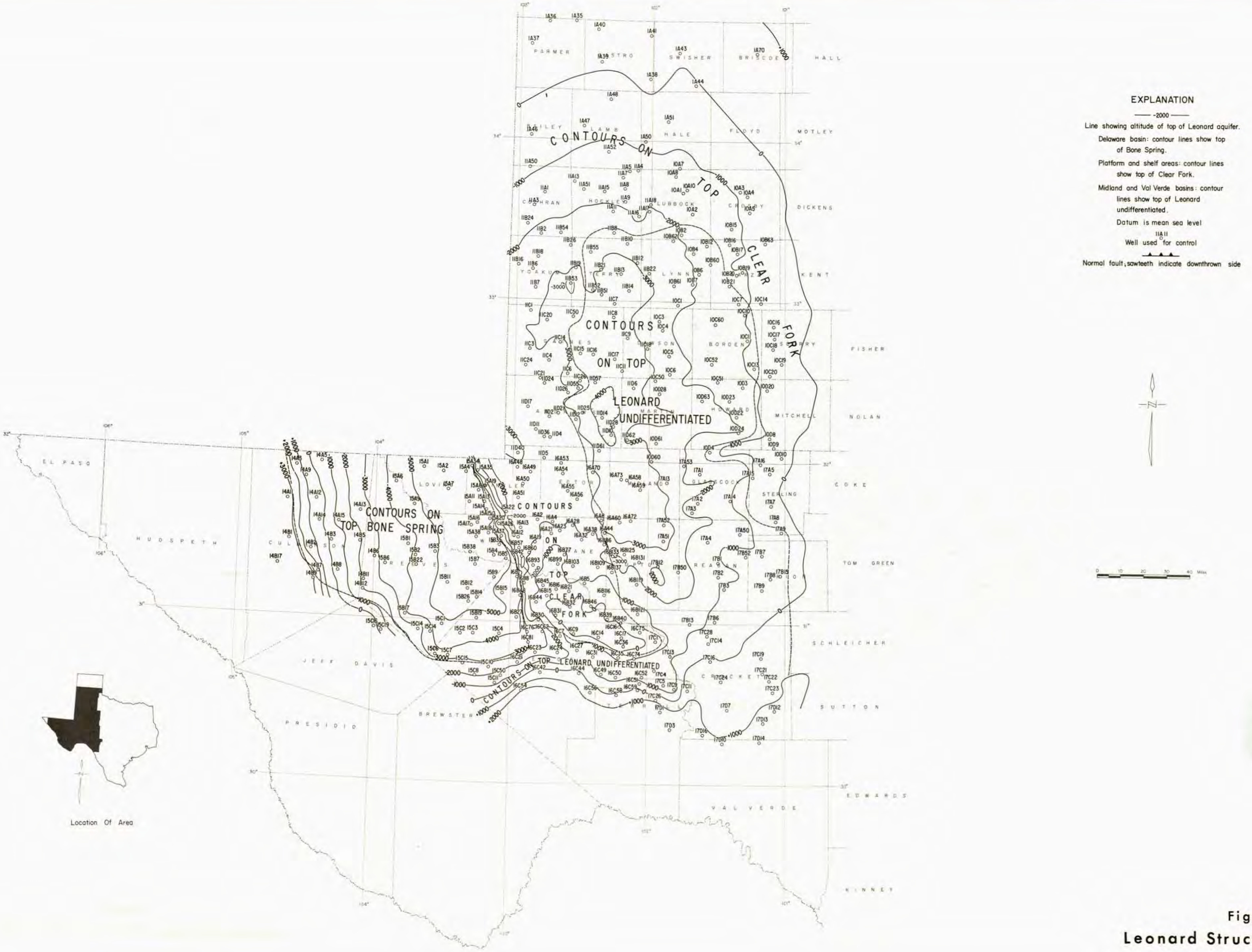


**Figure 48**
**Wolfcamp Net Thickness, Limestone and Sand, Central Texas**

Figure 49
Wolfcamp Water Salinity, West Texas-Panhandle



## Figure 50
## Wolfcamp Water Salinity, Central Texas



EXPLANATION

—— -2000 ——
Line showing altitude of top of Leonard aquifer.
Delaware basin: contour lines show top of Bone Spring.
Platform and shelf areas: contour lines show top of Clear Fork.
Midland and Val Verde basins: contour lines show top of Leonard undifferentiated.
Datum is mean sea level

11A11
Well used for control

Normal fault, sawteeth indicate downthrown side

**Figure 51**

**Leonard Structure, West Texas**

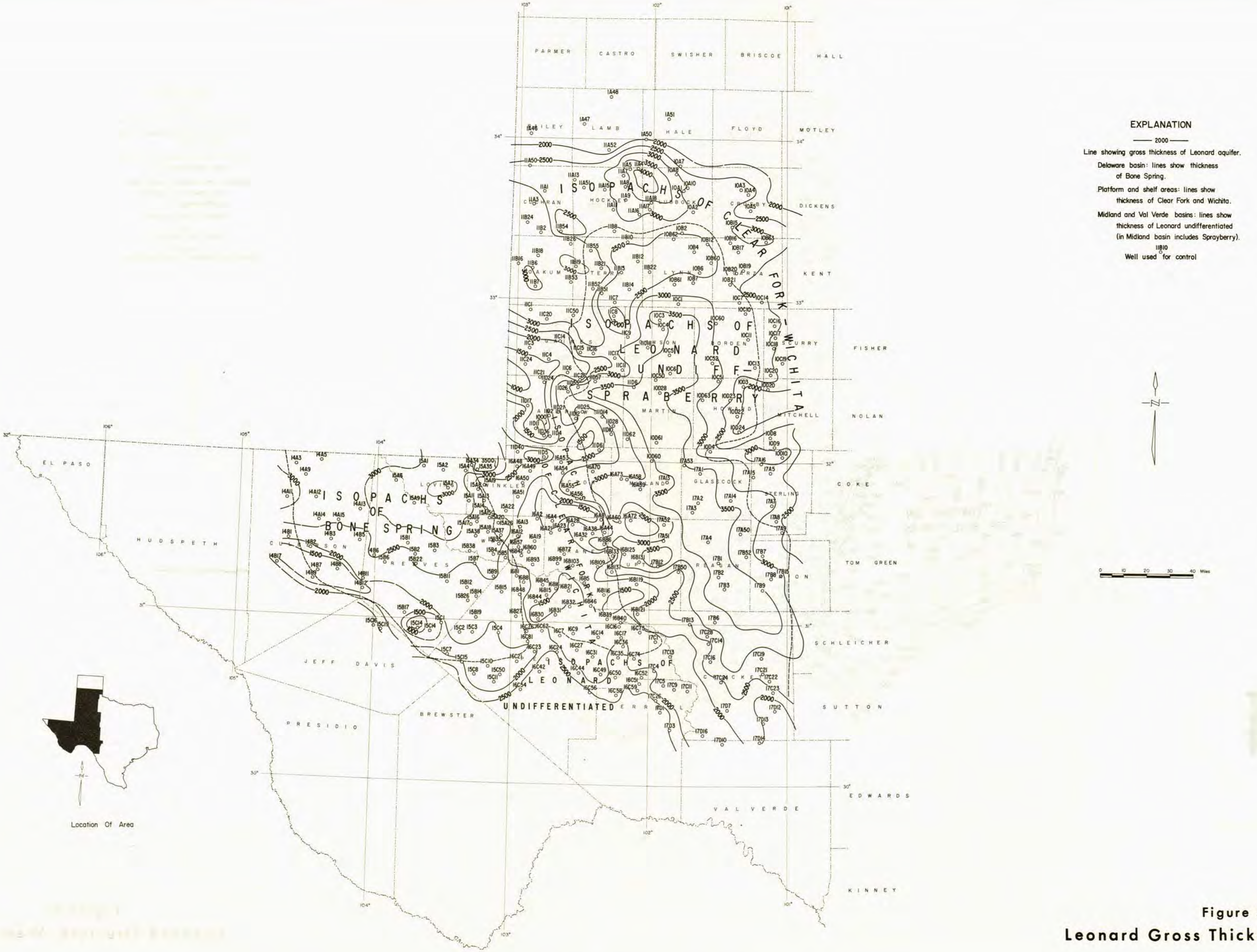


Figure 52
Leonard Gross Thickness, West Texas

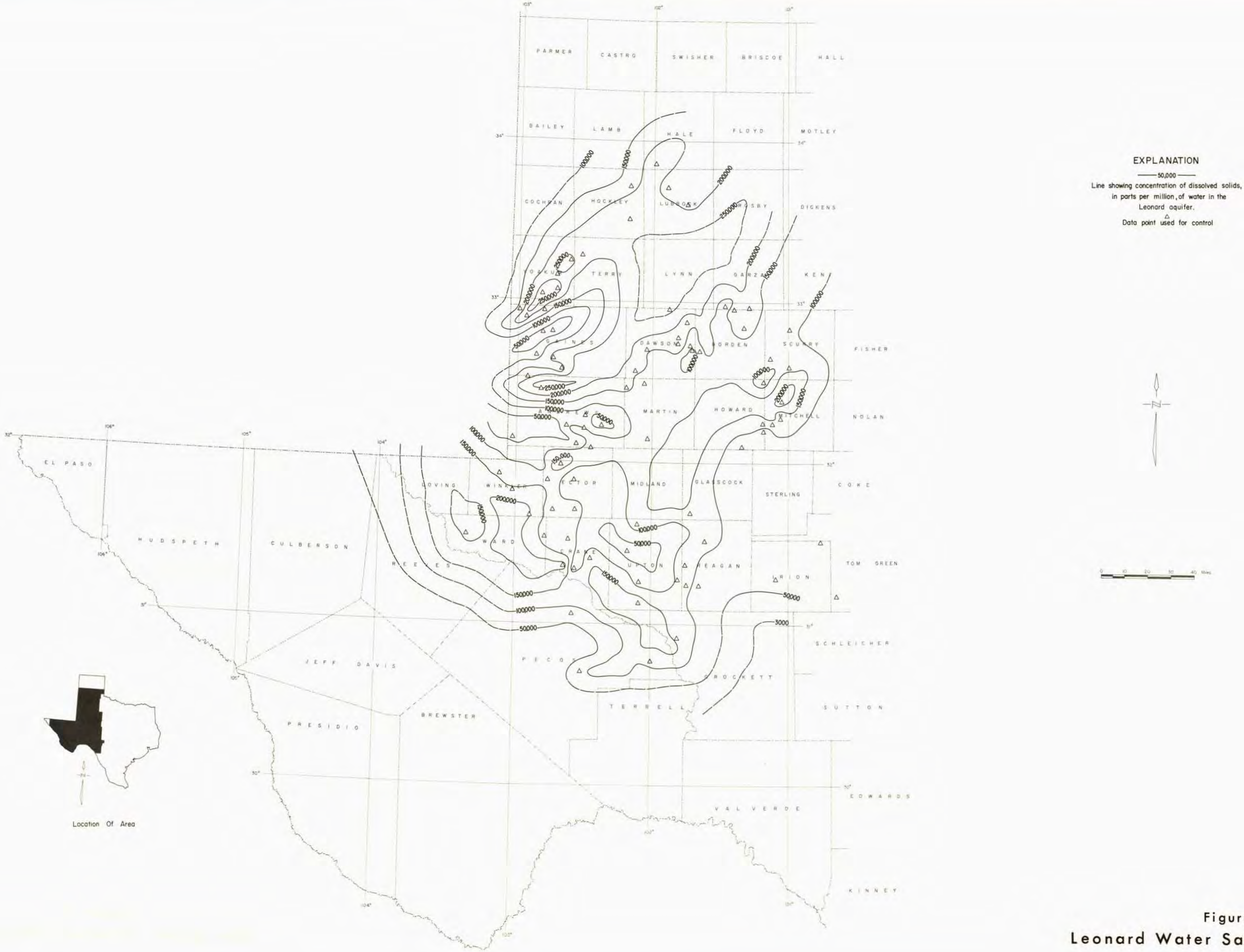


Figure 53
**Leonard Water Salinity, West Texas**

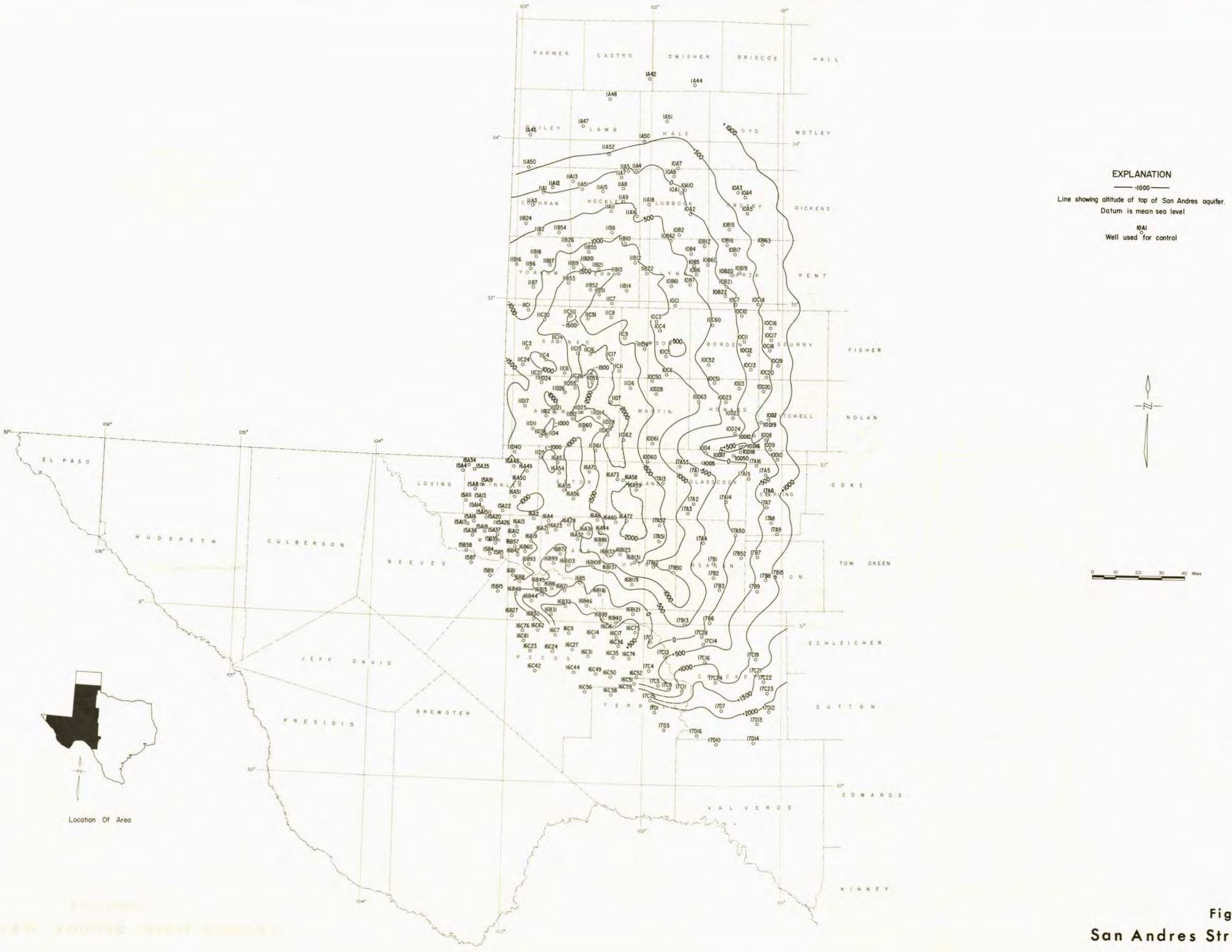
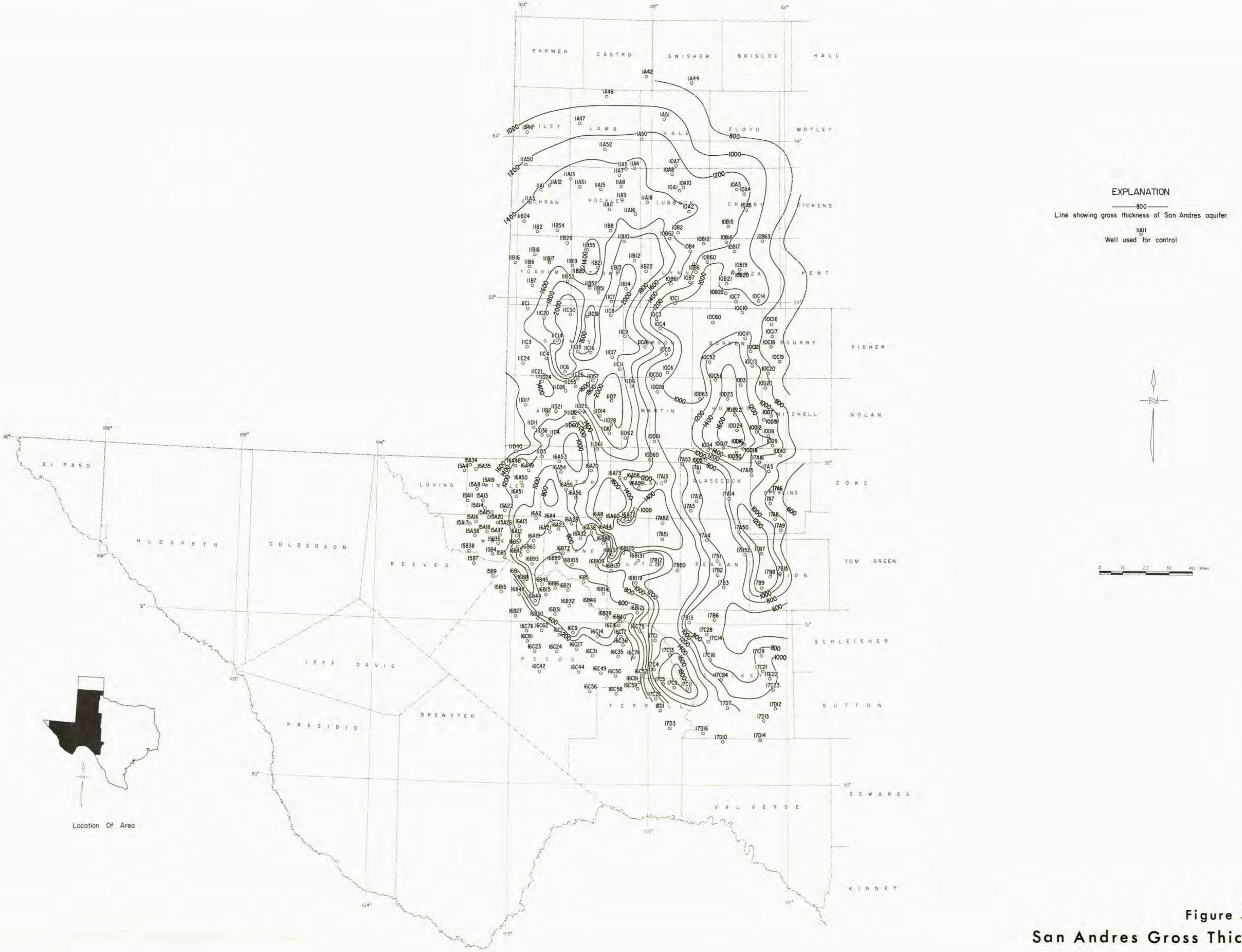


Figure 54

San Andres Structure, West Texas



## Figure 55
## San Andres Gross Thickness, West Texas

Figure 56

San Andres Water Salinity, West Texas

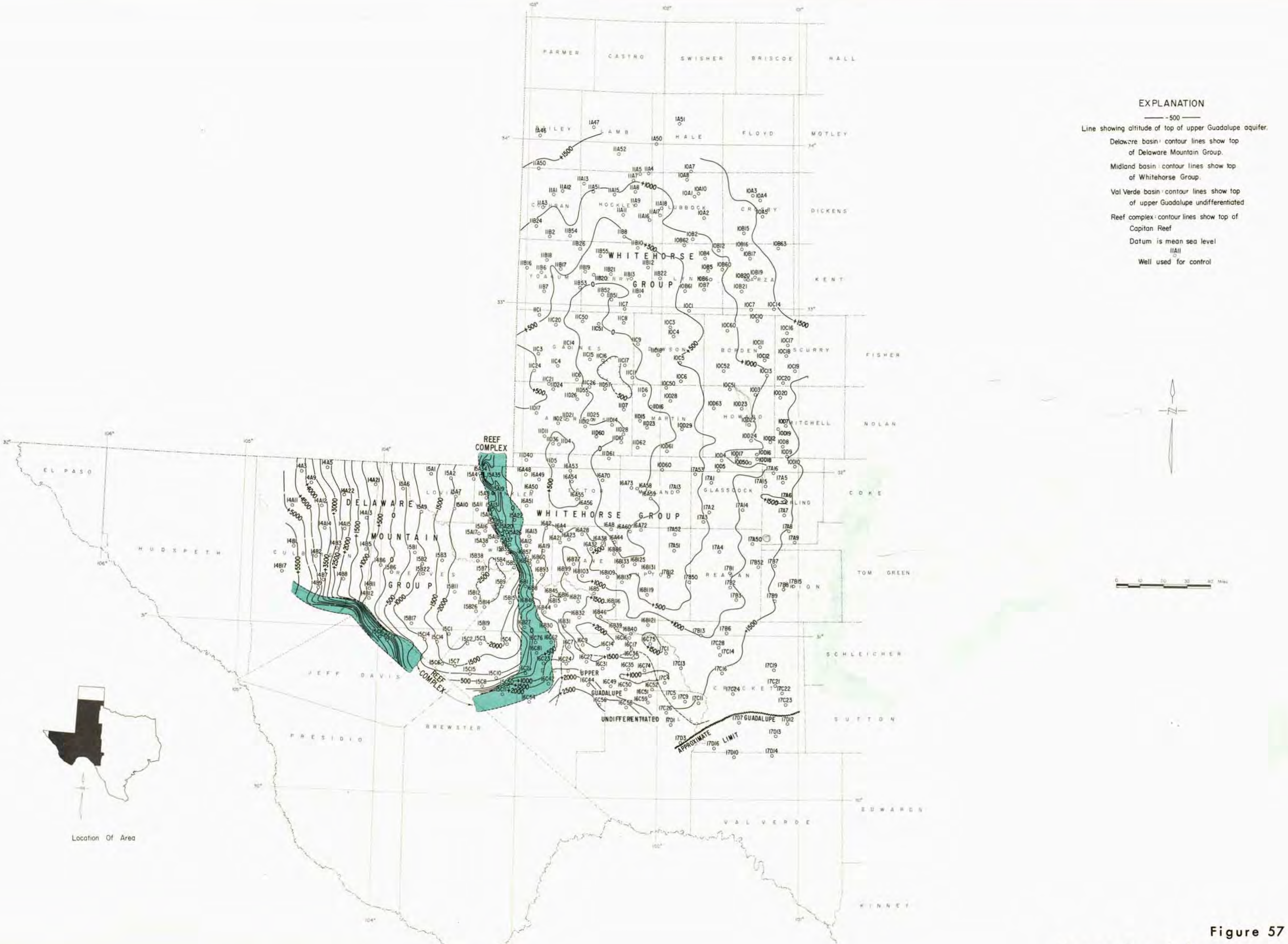
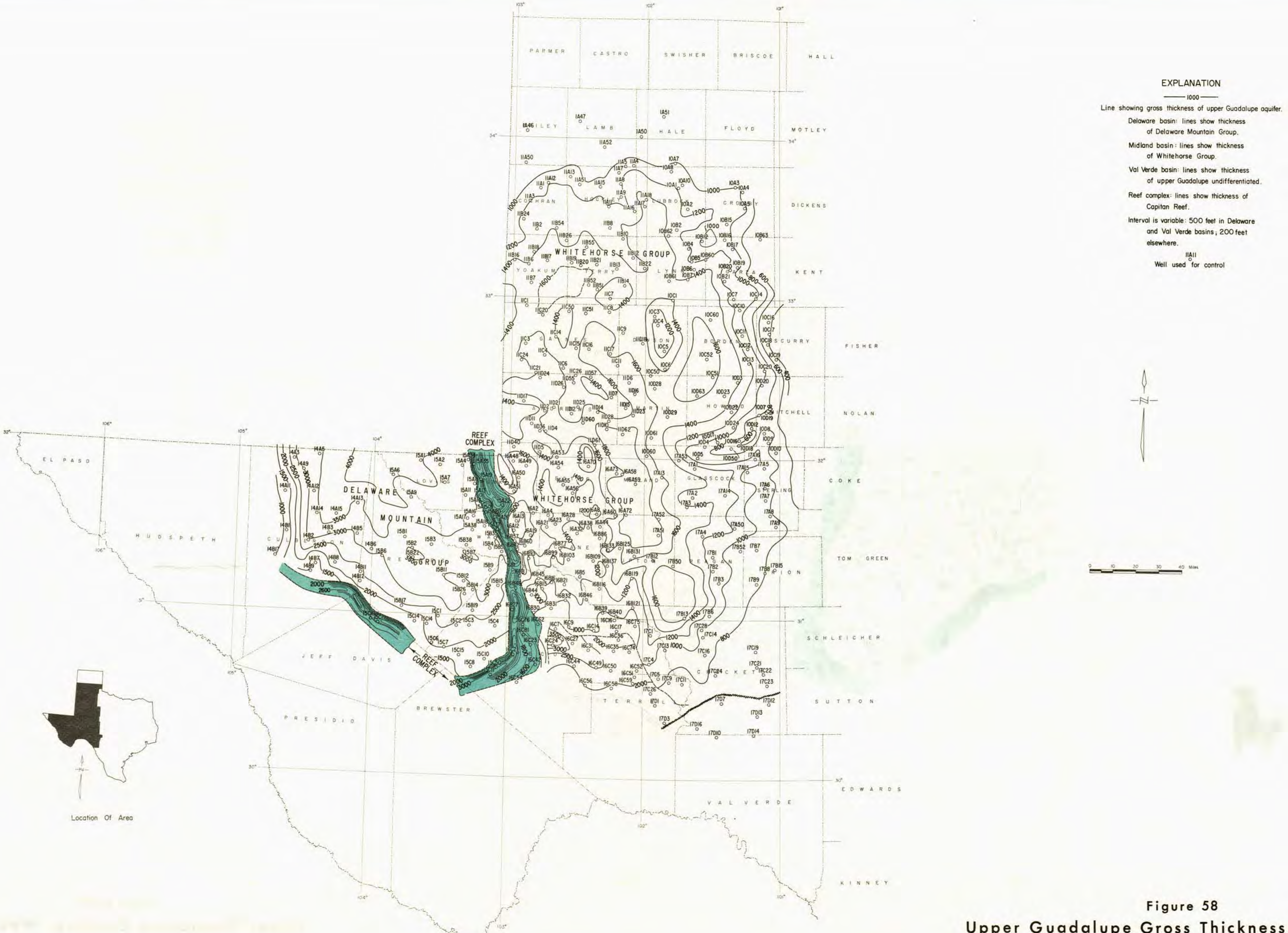


Figure 57
Upper Guadalupe Stucture, West Texas



EXPLANATION

——1000——

Line showing gross thickness of upper Guadalupe aquifer.

Delaware basin: lines show thickness of Delaware Mountain Group.

Midland basin: lines show thickness of Whitehorse Group.

Val Verde basin: lines show thickness of upper Guadalupe undifferentiated.

Reef complex: lines show thickness of Capitan Reef.

Interval is variable: 500 feet in Delaware and Val Verde basins; 200 feet elsewhere.

11A11 ○ Well used for control

Figure 58
Upper Guadalupe Gross Thickness, West Texas

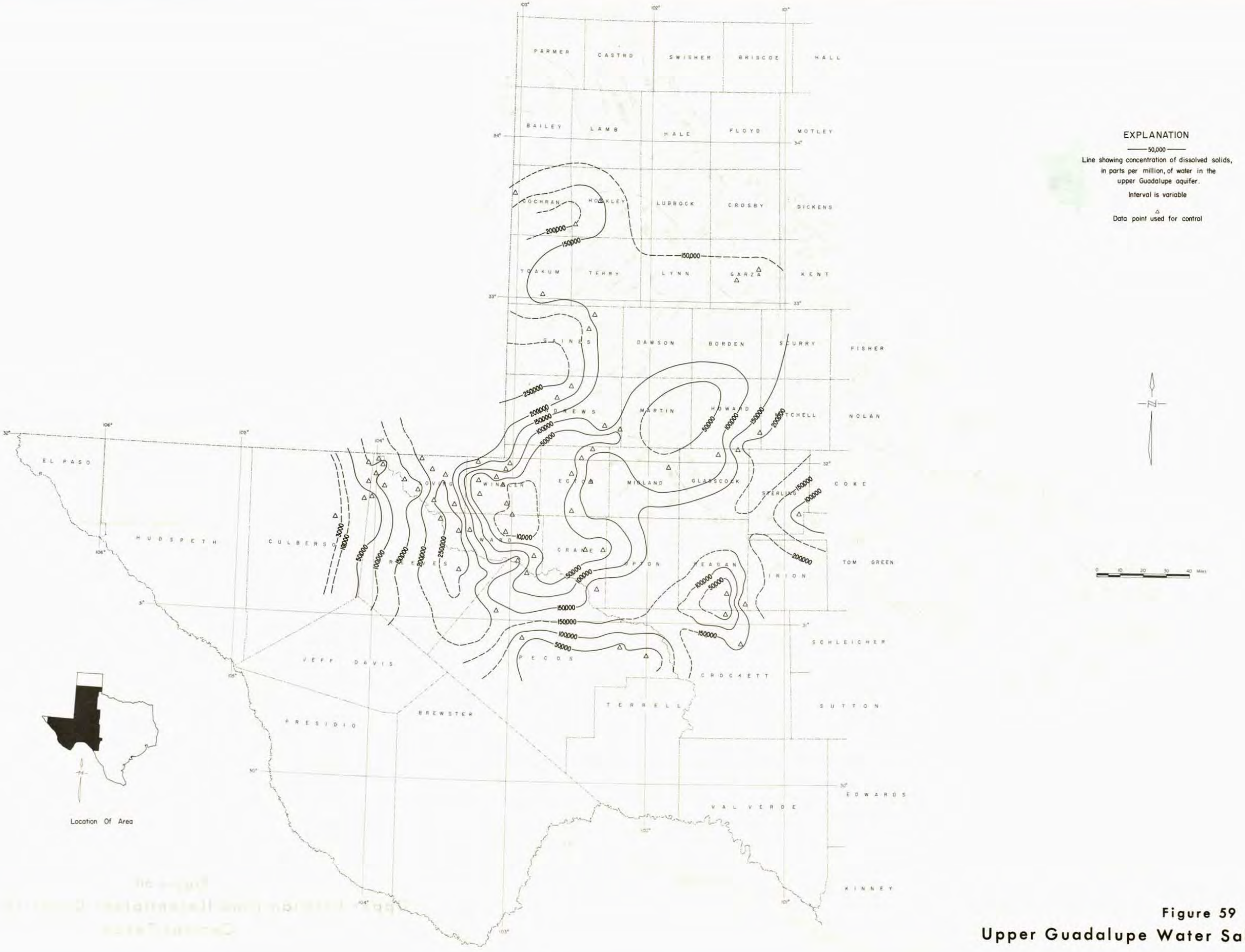


Figure 59

Upper Guadalupe Water Salinity, West Texas

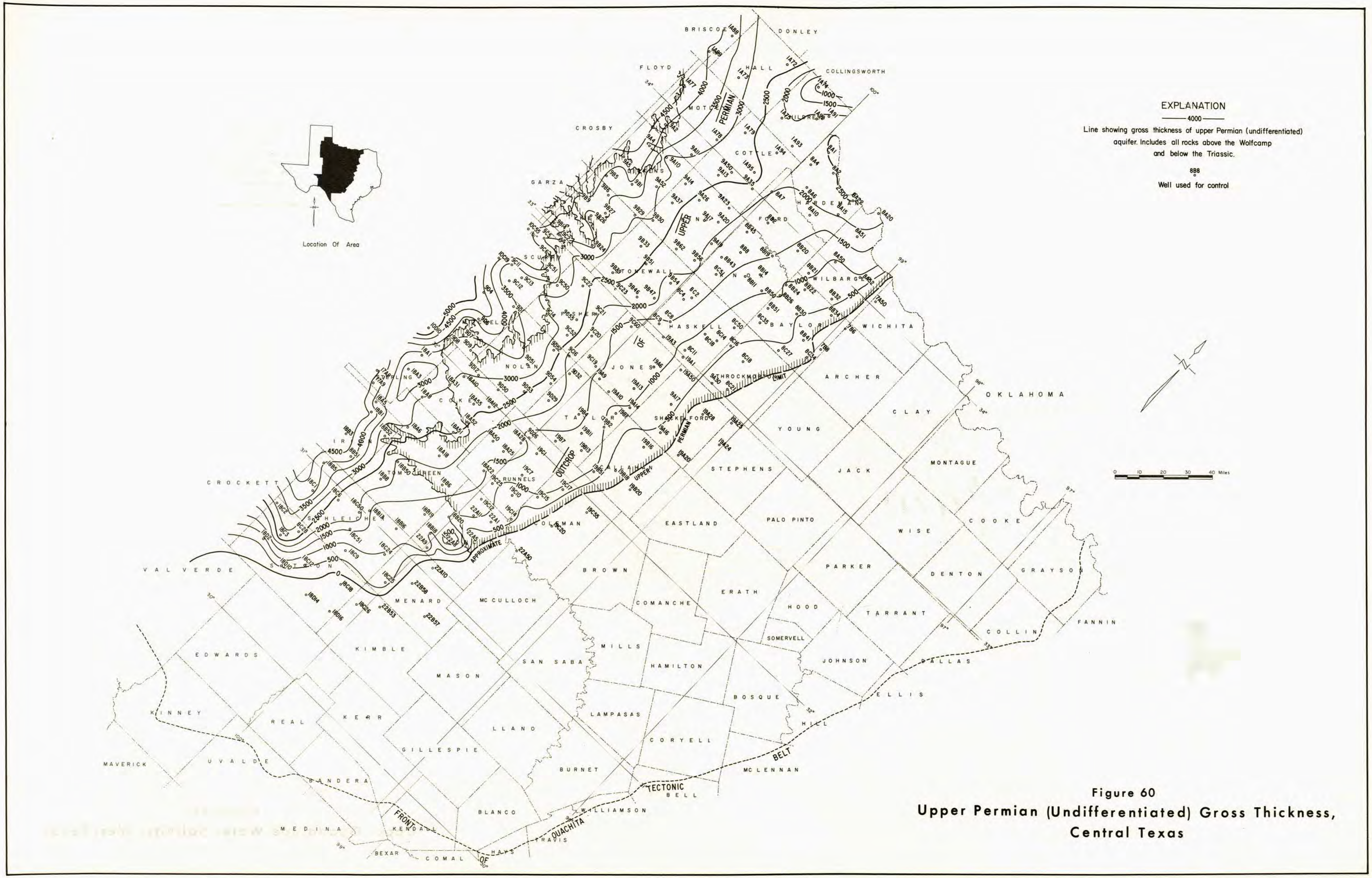


Figure 60
Upper Permian (Undifferentiated) Gross Thickness, Central Texas

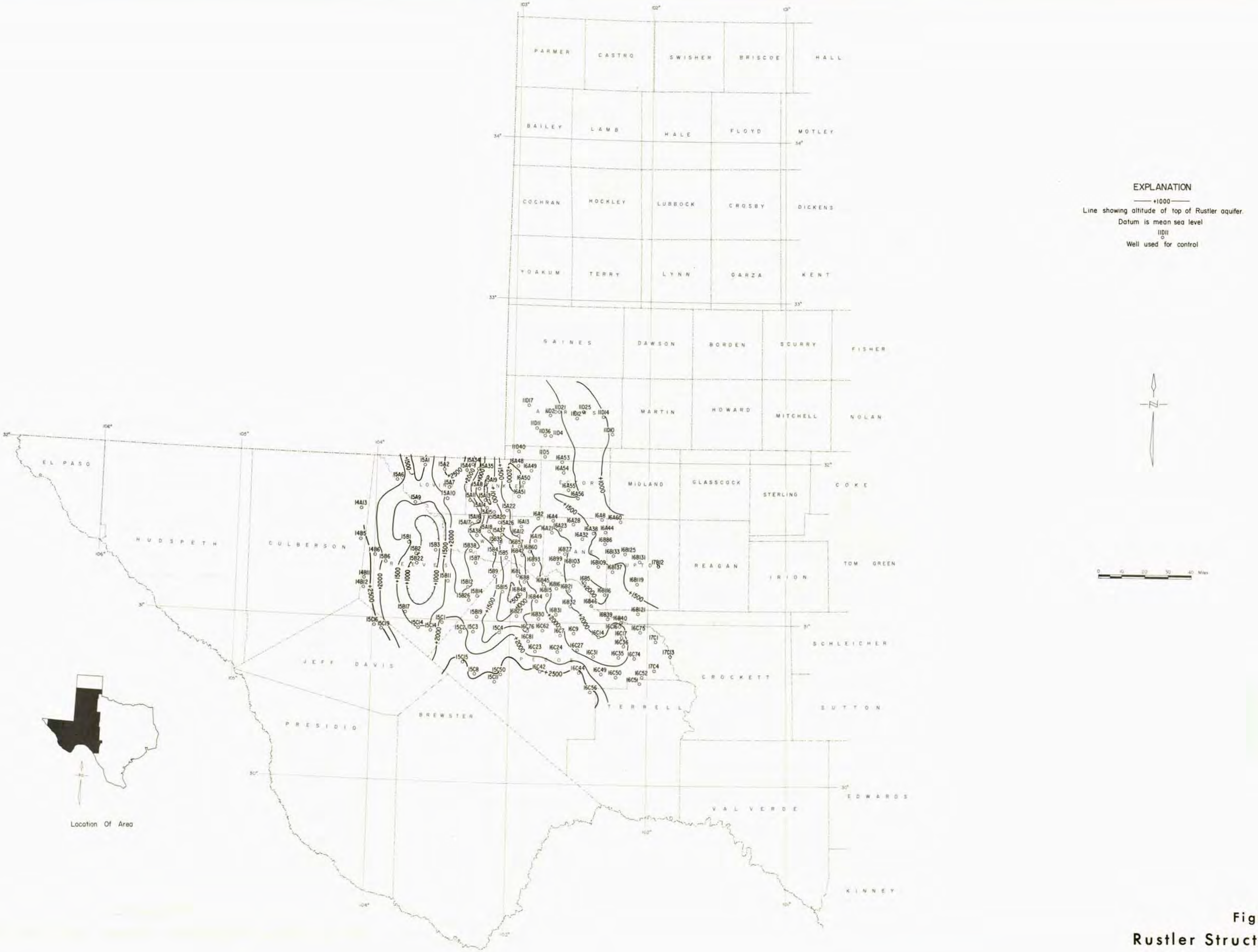
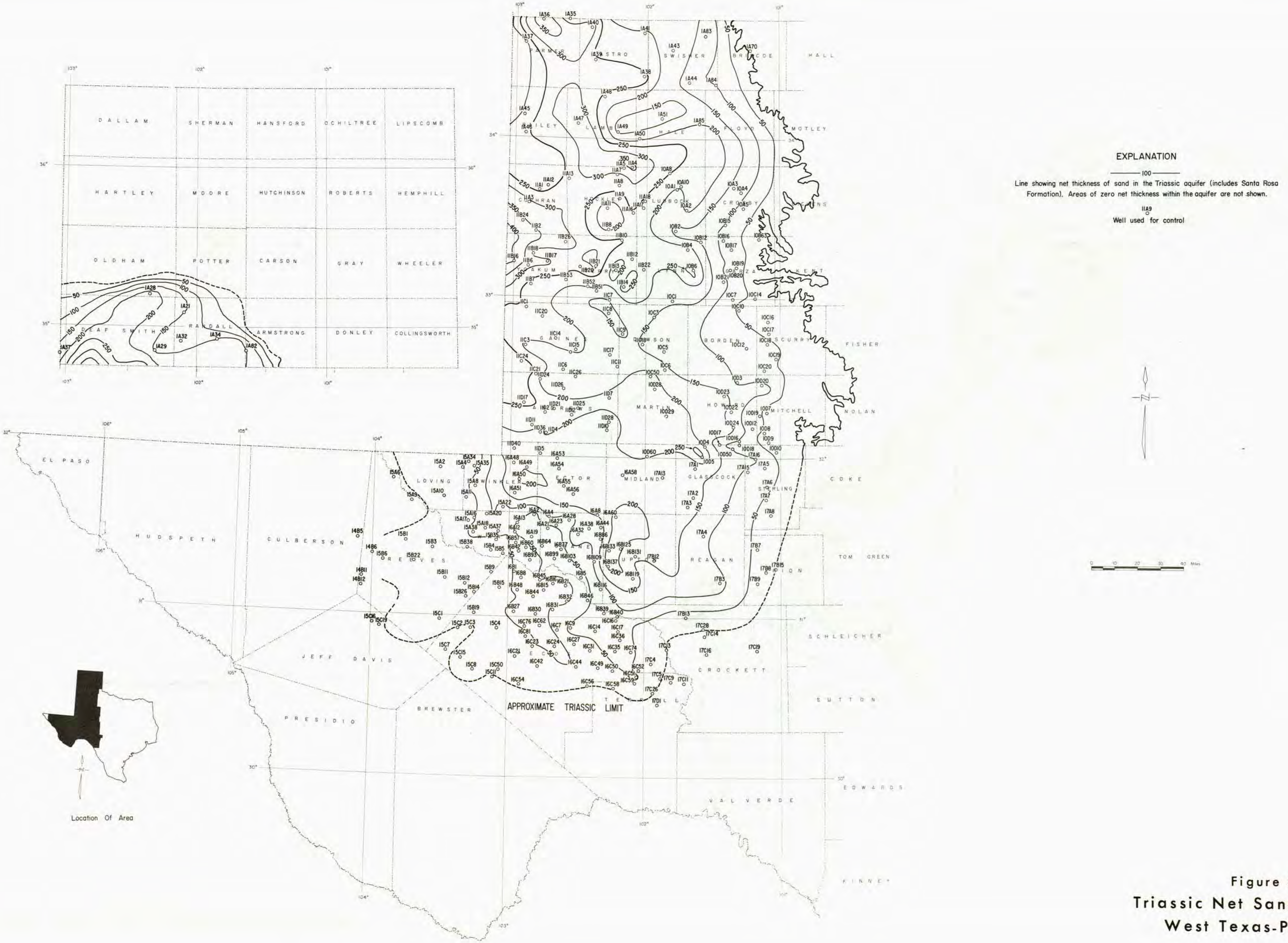


Figure 61
**Rustler Structure, West Texas**

Figure 62

Santa Rosa Structure, West Texas-Panhandle



EXPLANATION

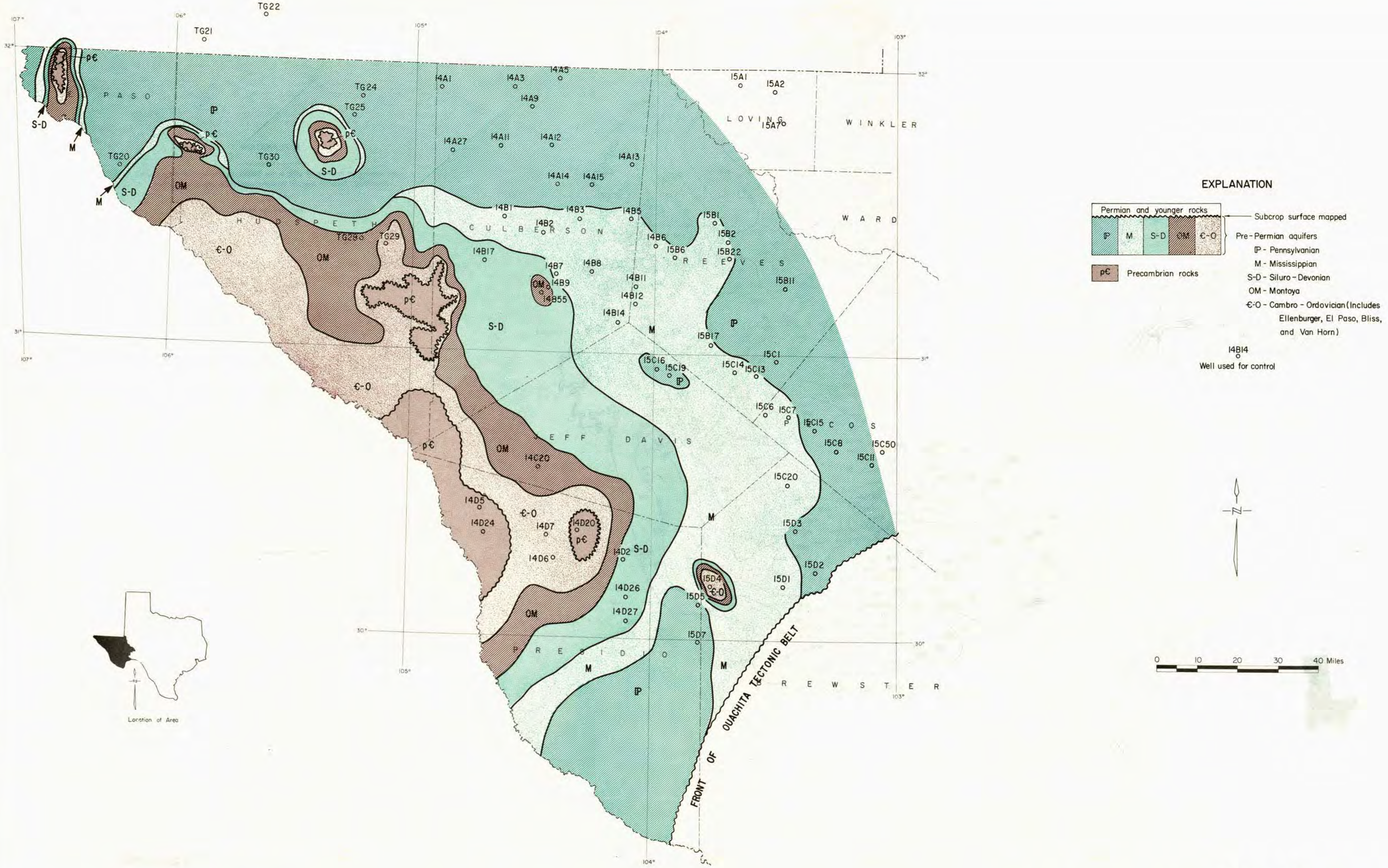
——— 100 ———

Line showing net thickness of sand in the Triassic aquifer (includes Santa Rosa Formation). Areas of zero net thickness within the aquifer are not shown.

IIA9
○
Well used for control

Figure 63

Triassic Net Sand Thickness, West Texas-Panhandle



## Figure 64
## Subcrops of Pre-Permian Aquifers, Trans-Pecos

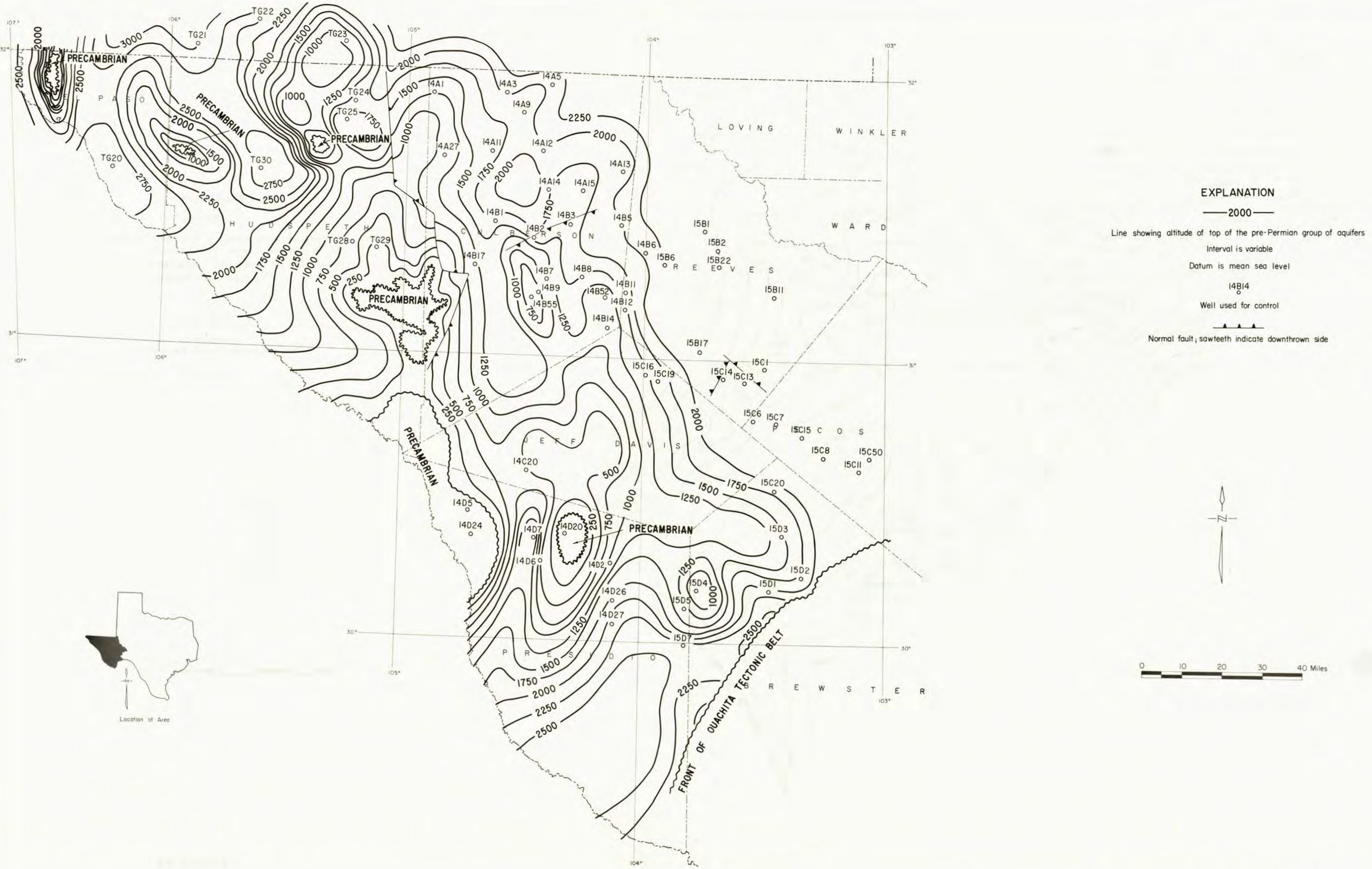
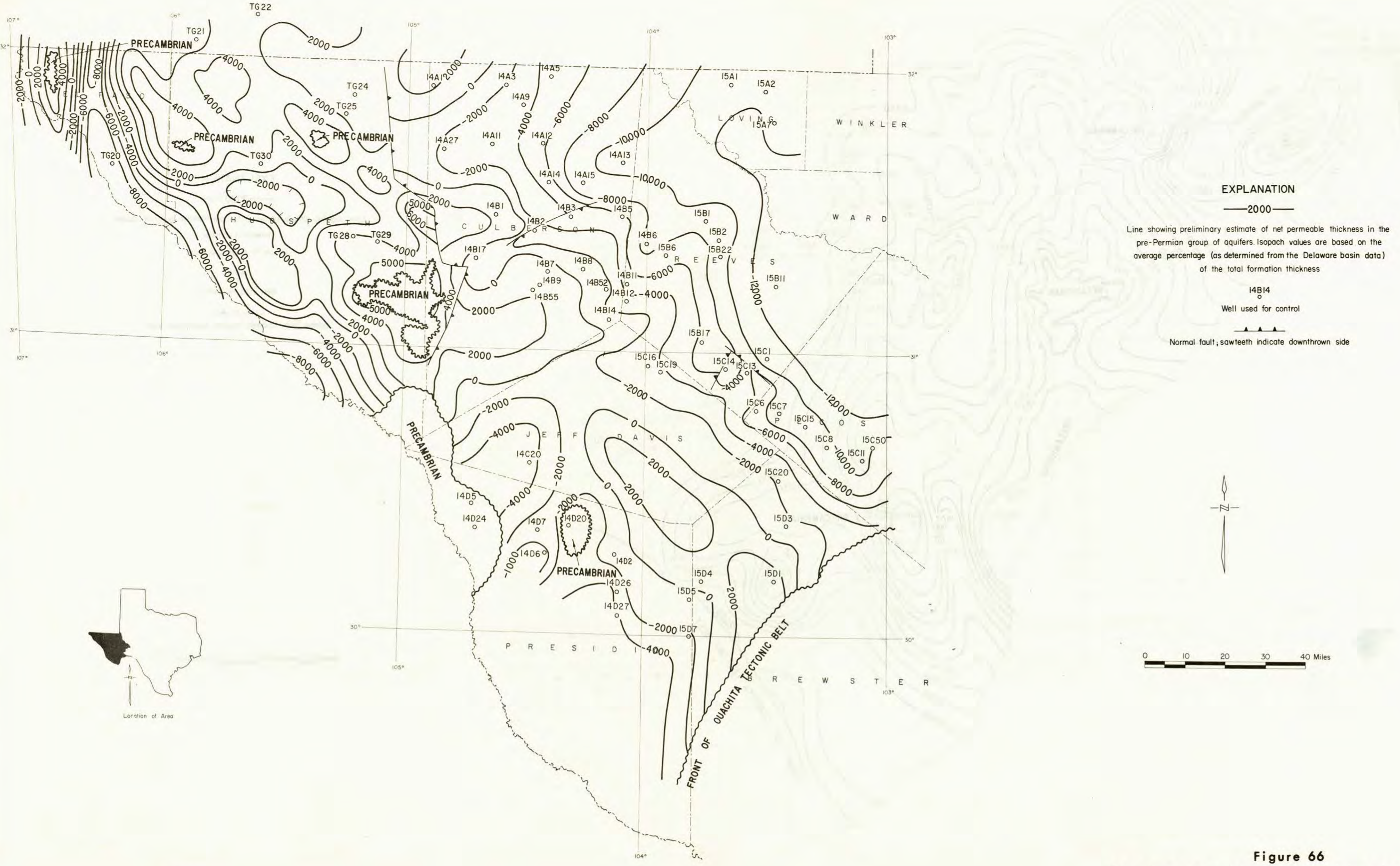


Figure 65

Pre-Permian Structure, Trans-Pecos



EXPLANATION

—2000—

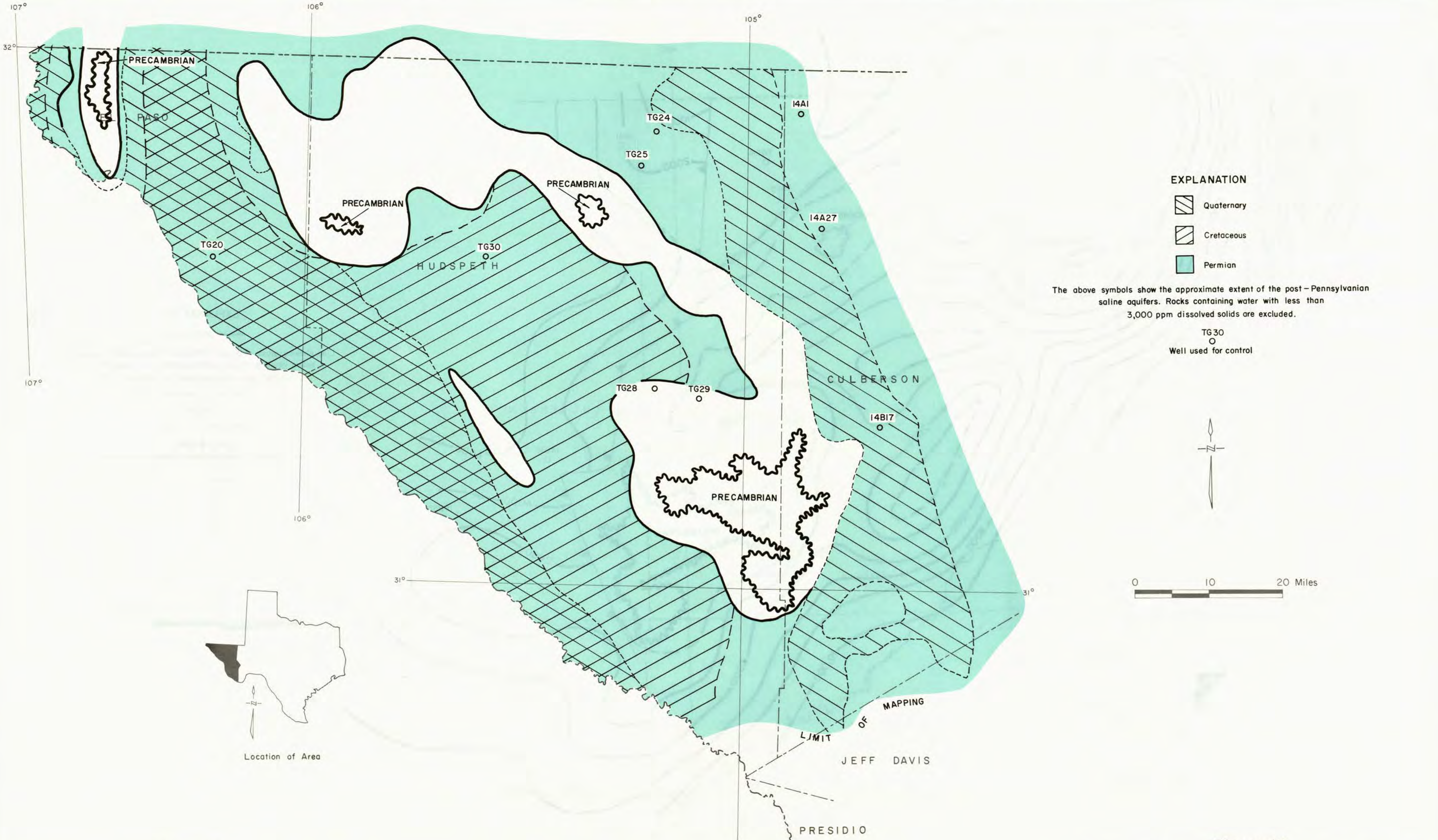
Line showing preliminary estimate of net permeable thickness in the pre-Permian group of aquifers. Isopach values are based on the average percentage (as determined from the Delaware basin data) of the total formation thickness

14B14
○
Well used for control

Normal fault; sawteeth indicate downthrown side

Figure 66

Pre-Permian Net Permeable Thickness, Trans-Pecos



The above symbols show the approximate extent of the post-Pennsylvanian saline aquifers. Rocks containing water with less than 3,000 ppm dissolved solids are excluded.

Figure 67
Extent of Post-Pennsylvanian Aquifers, Western Trans-Pecos

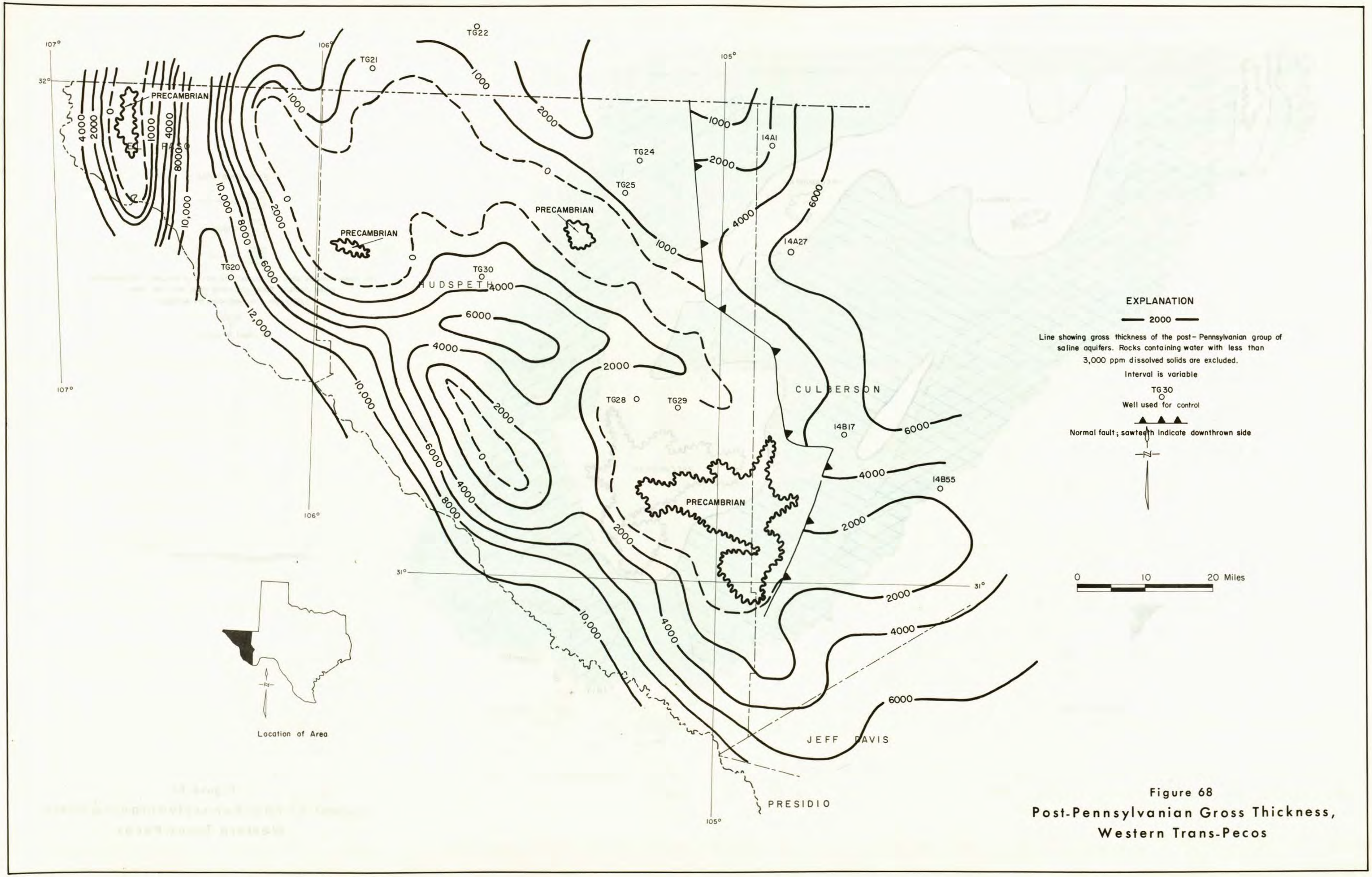
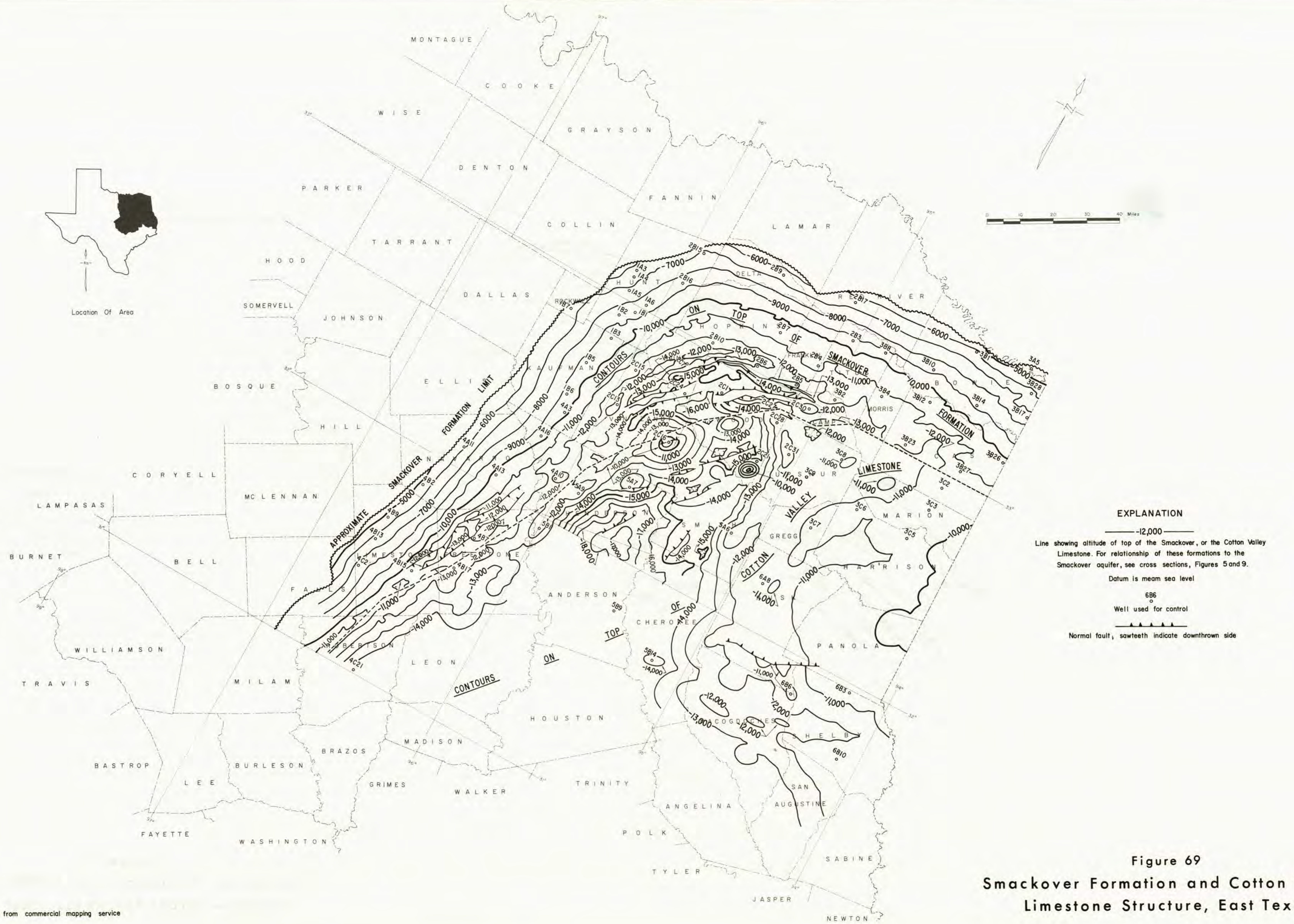


Figure 68

Post-Pennsylvanian Gross Thickness, Western Trans-Pecos



EXPLANATION

-12,000 Line showing altitude of top of the Smackover, or the Cotton Valley Limestone. For relationship of these formations to the Smackover aquifer, see cross sections, Figures 5 and 9.

Datum is meam sea level

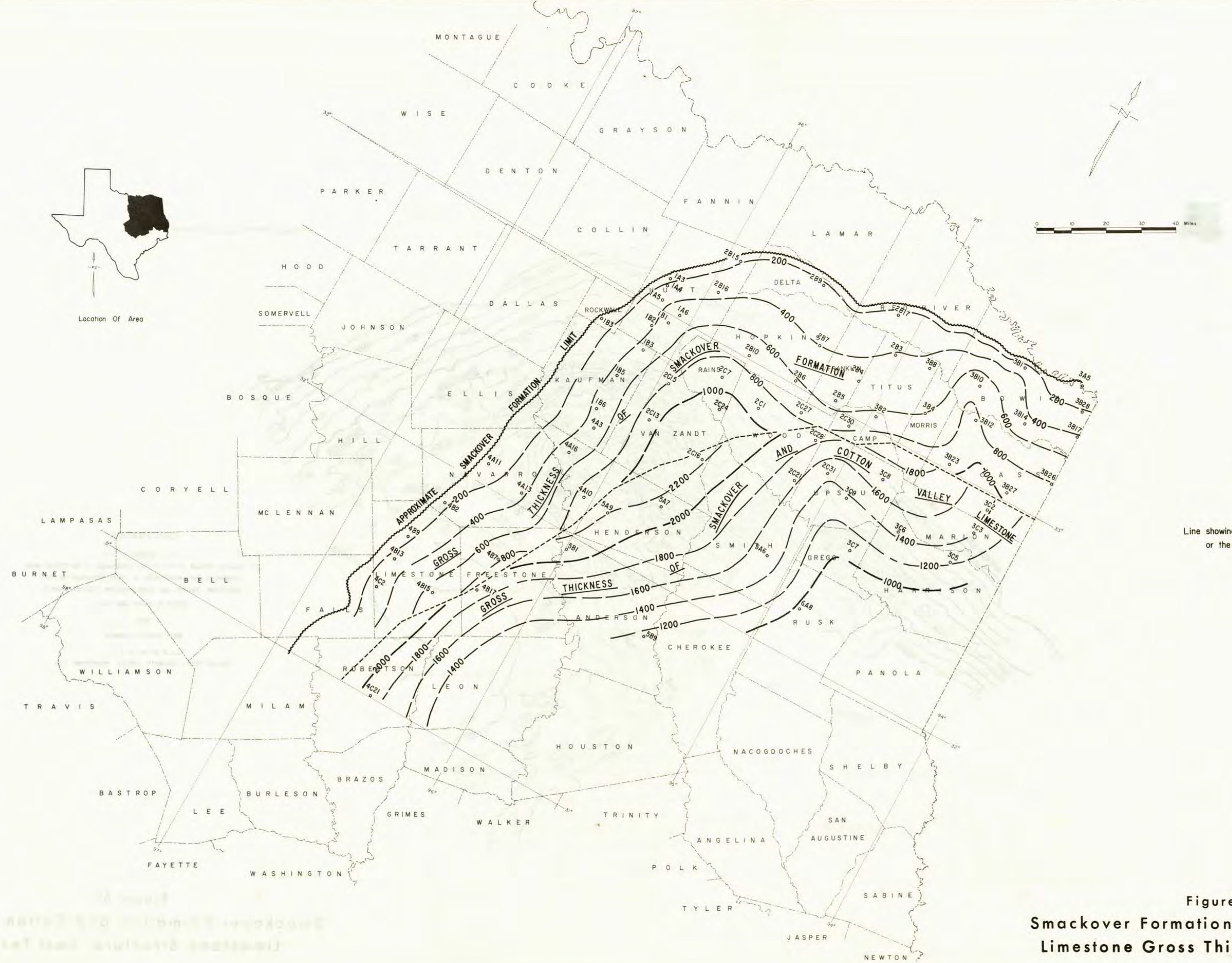
6B6 ○ Well used for control

Normal fault; sawteeth indicate downthrown side

Structure contours from commercial mapping service

Figure 69

Smackover Formation and Cotton Valley Limestone Structure, East Texas



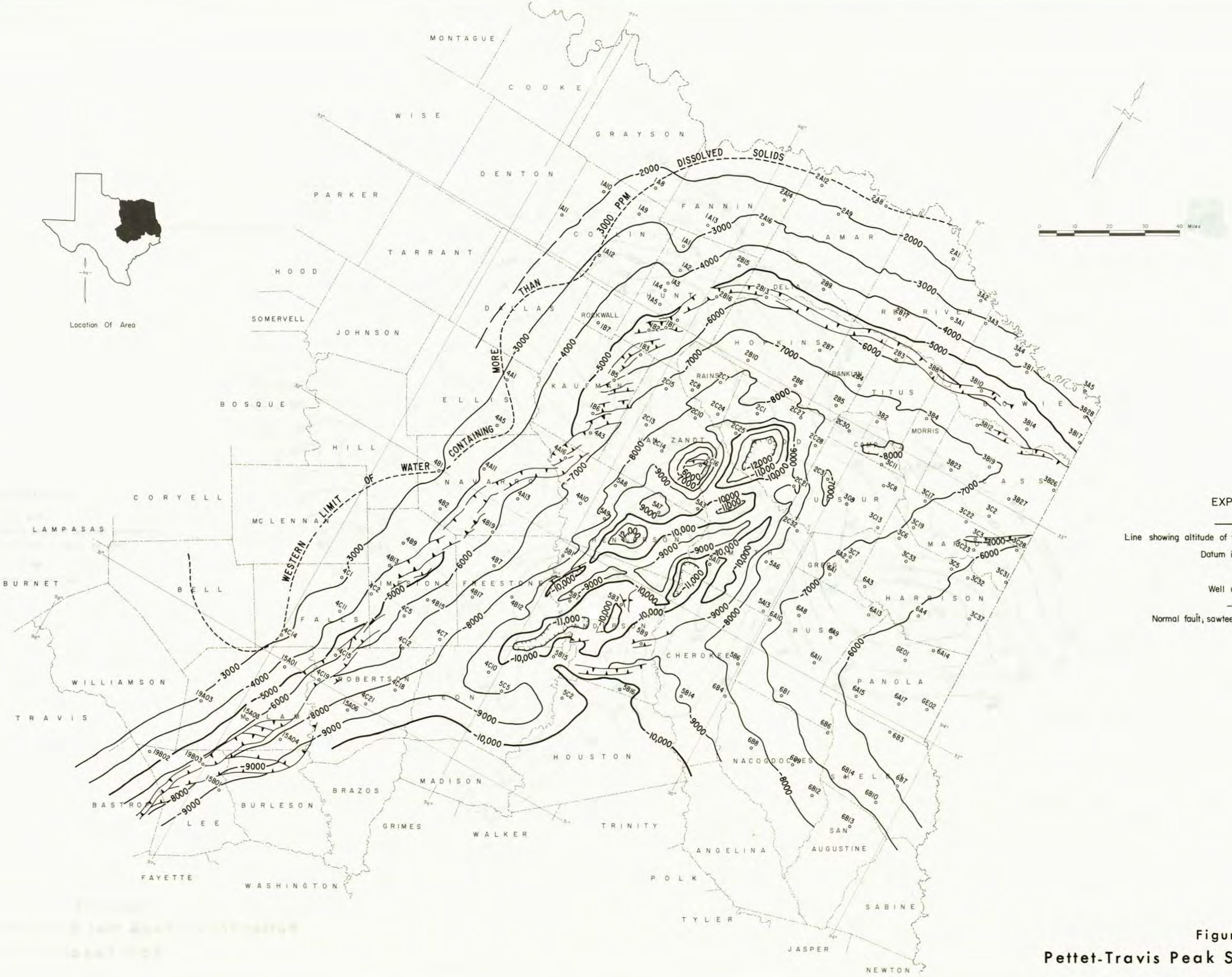
EXPLANATION

——1000—— Line showing gross thickness of the Smackover Formation, or the Smackover and Cotton Valley Limestone

3C6 ○ Well used for control

## Figure 70

## Smackover Formation and Cotton Valley Limestone Gross Thickness, East Texas



EXPLANATION

——-4000——

Line showing altitude of top of Pettet - Travis Peak aquifer. Datum is mean sea level

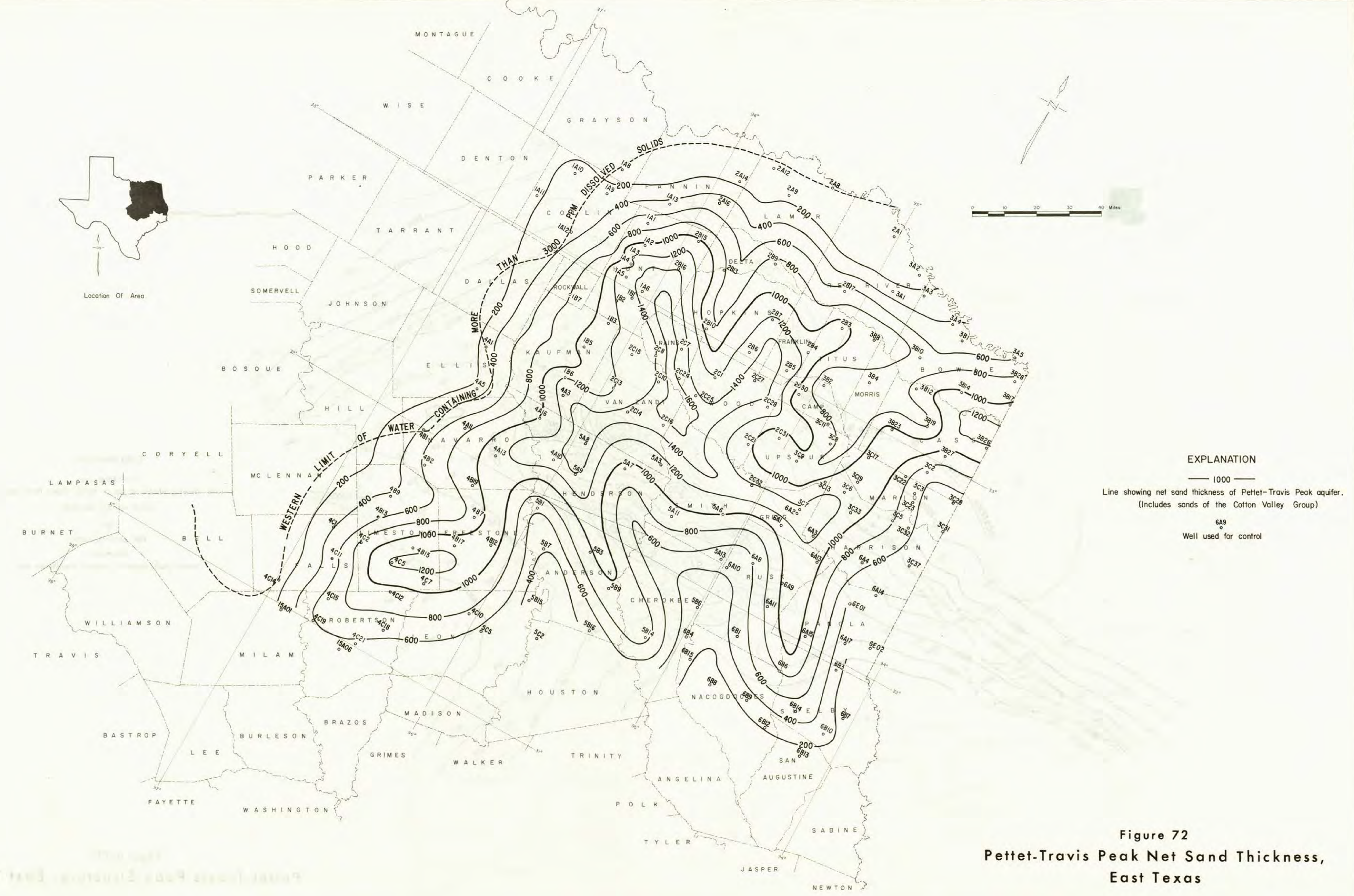
384
○
Well used for control

▲▲▲▲▲

Normal fault, sawteeth indicate downthrown side

Figure 71

Pettet-Travis Peak Structure, East Texas



EXPLANATION

—— 1000 ——
Line showing net sand thickness of Pettet-Travis Peak aquifer. (Includes sands of the Cotton Valley Group)

6A9
Well used for control

Figure 72
Pettet-Travis Peak Net Sand Thickness, East Texas

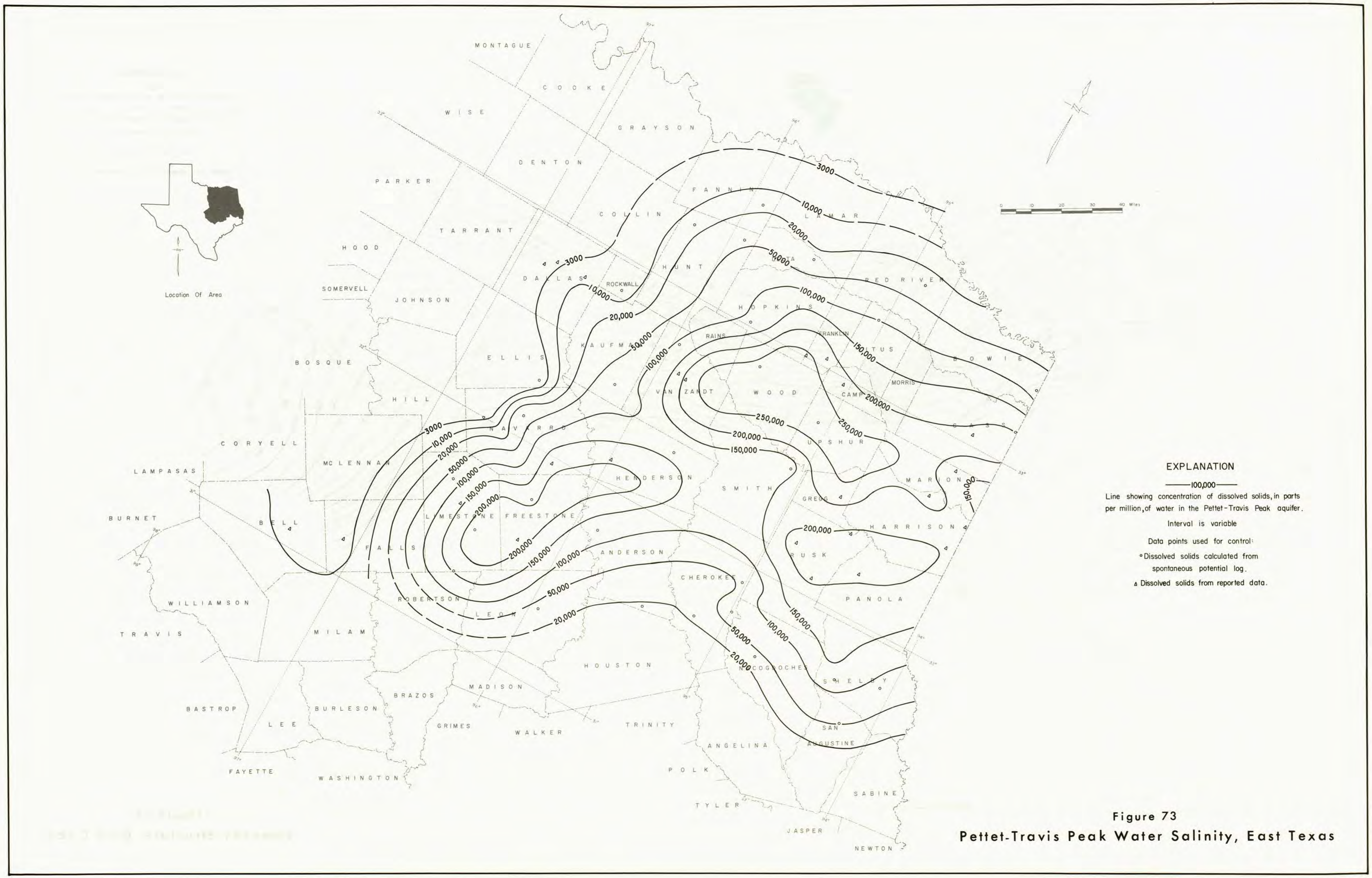


Figure 73

Pettet-Travis Peak Water Salinity, East Texas

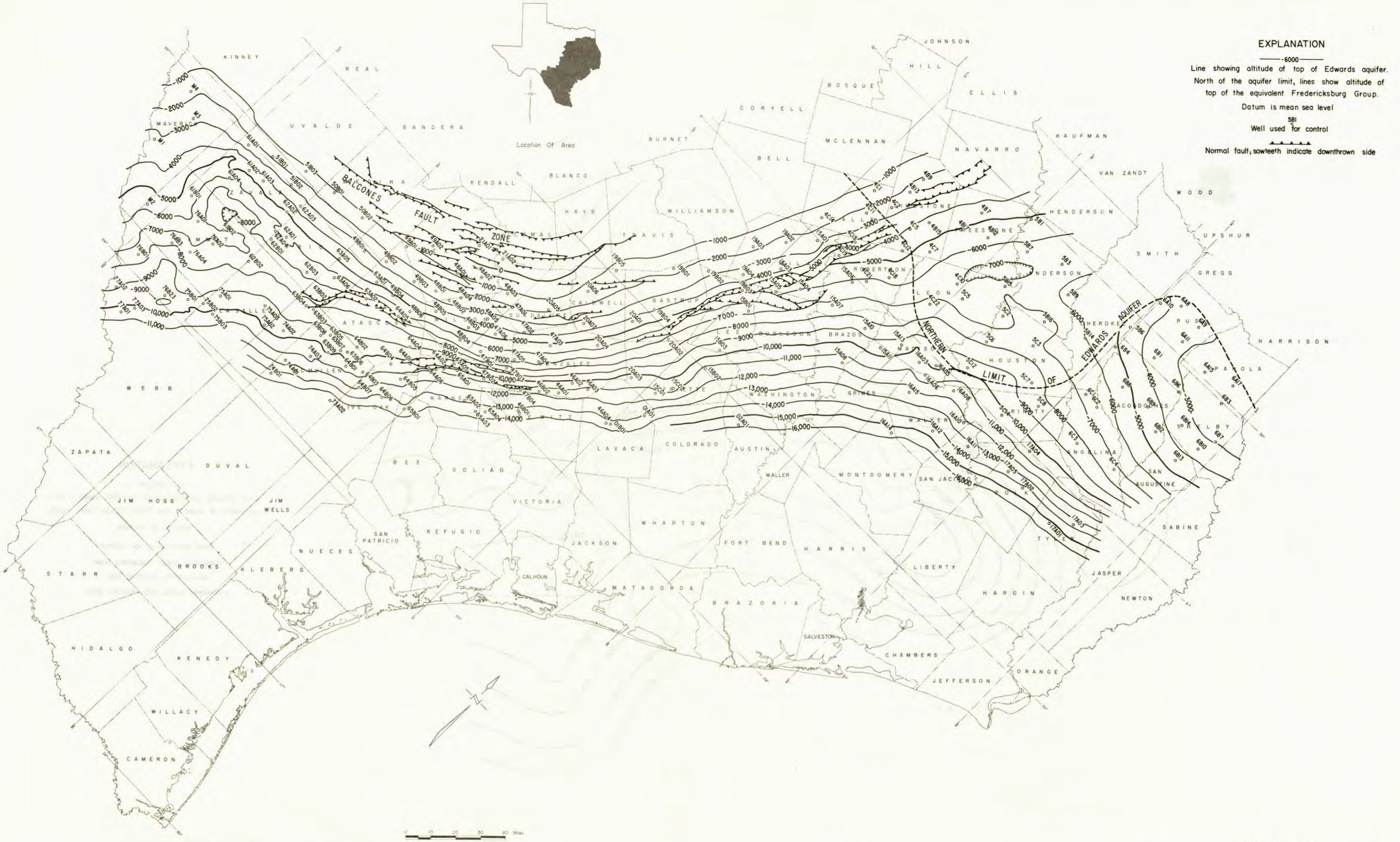
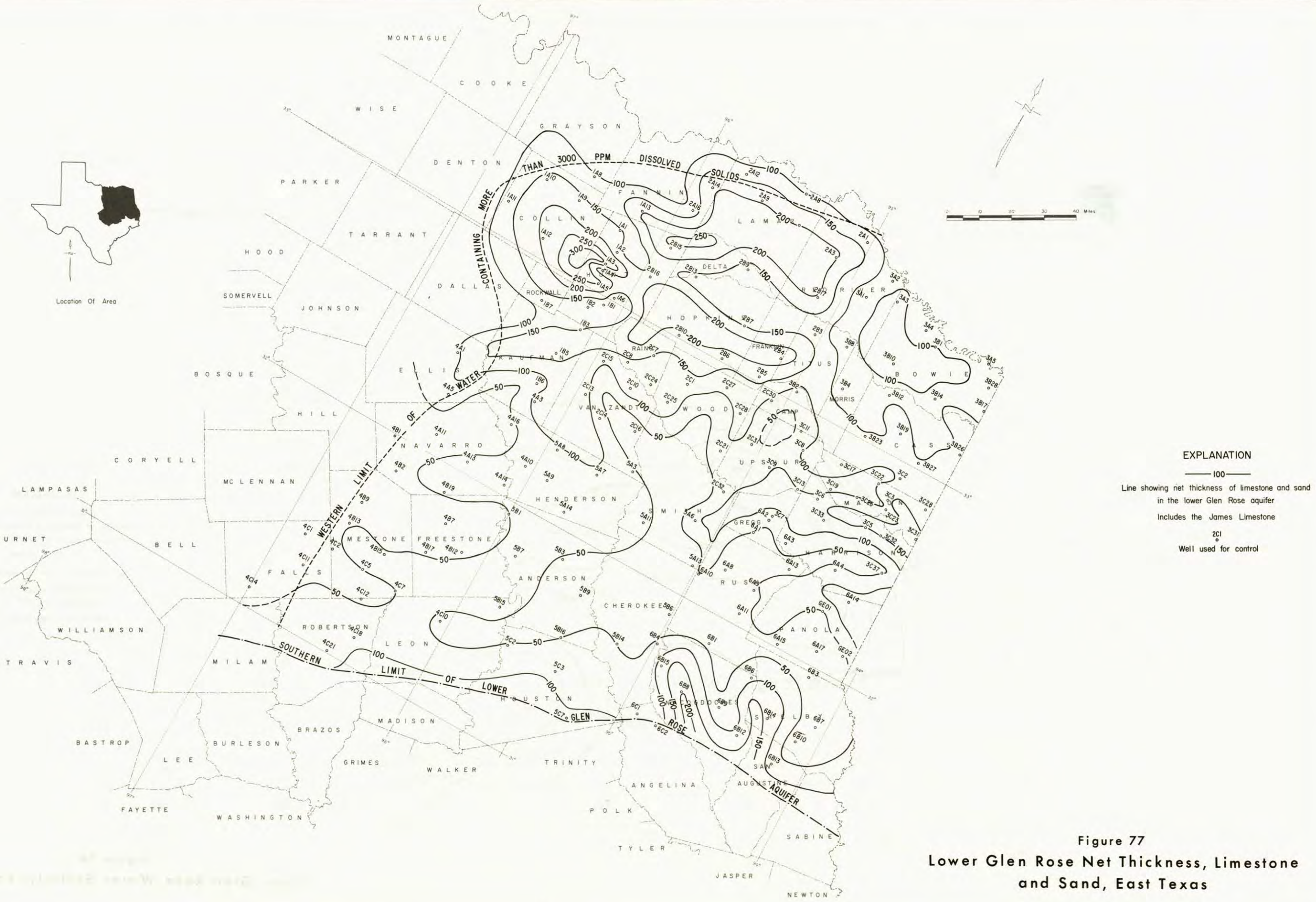


**Figure 74**
**Edwards Structure, Gulf Coast**

Figure 75
**Edwards Net Thickness, Gulf Coast**

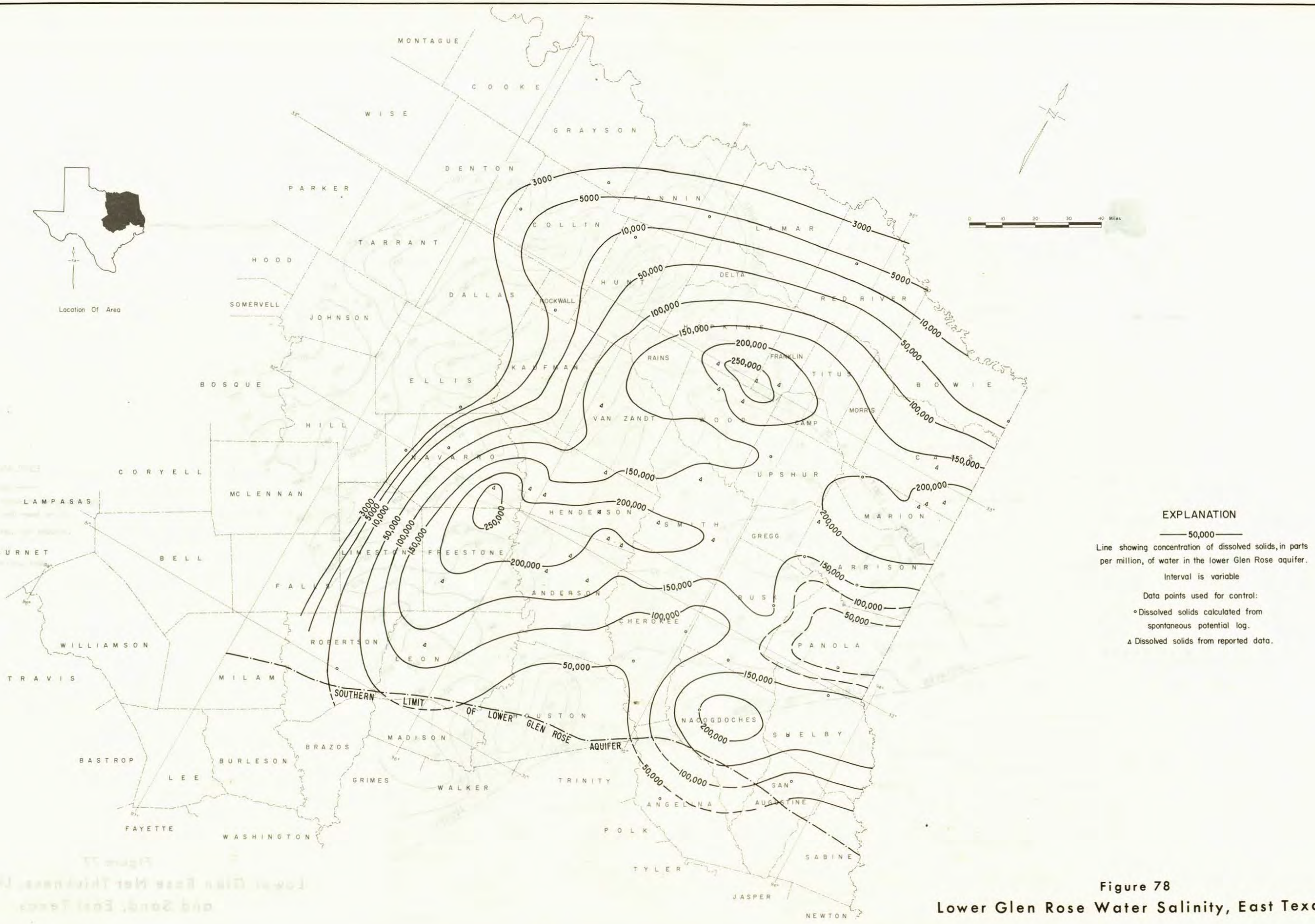
Figure 76

Glen Rose Gross Thickness, Gulf Coast



## Figure 77

## Lower Glen Rose Net Thickness, Limestone and Sand, East Texas



EXPLANATION

——50,000——
Line showing concentration of dissolved solids, in parts per million, of water in the lower Glen Rose aquifer.

Interval is variable

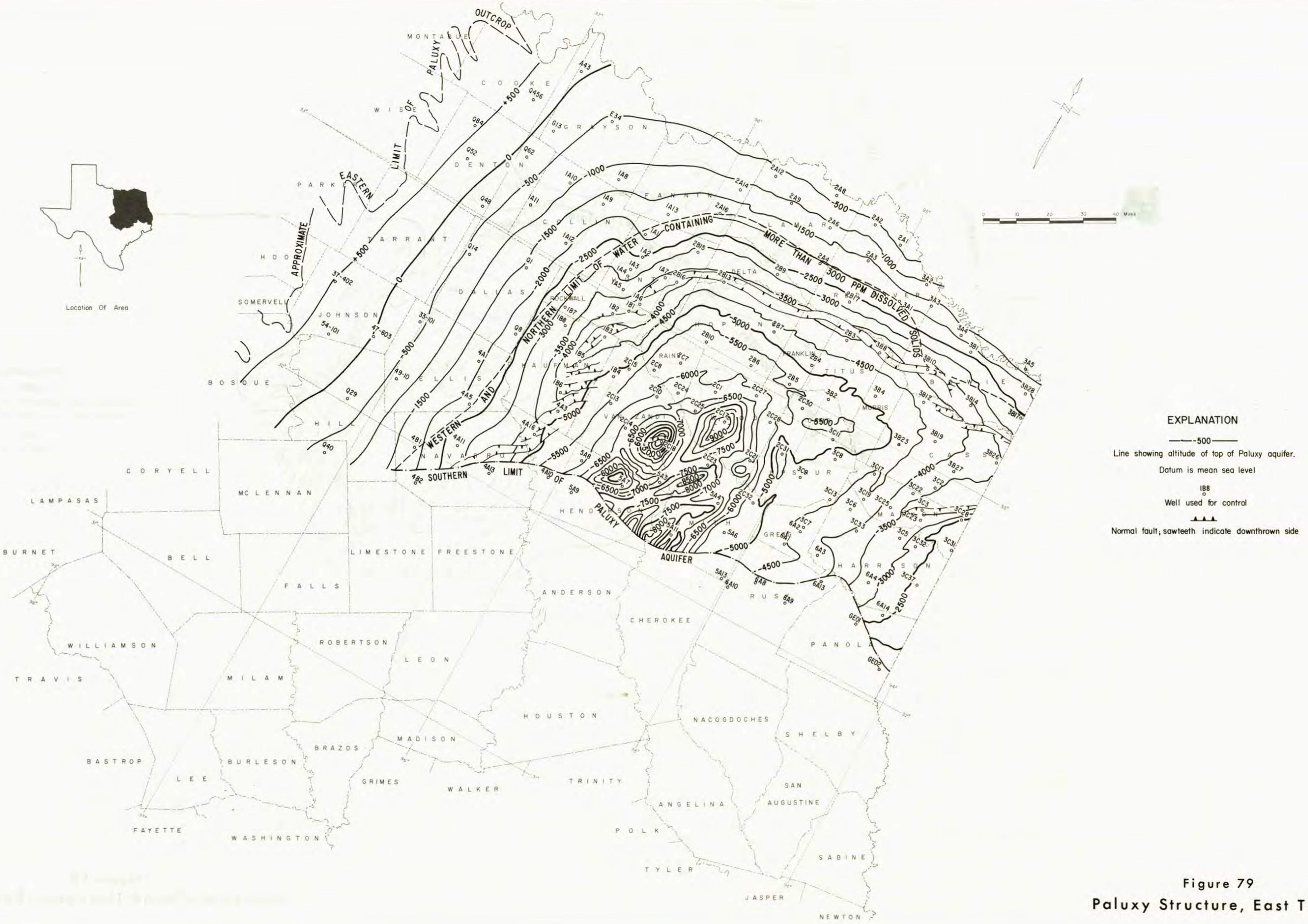
Data points used for control:

○ Dissolved solids calculated from spontaneous potential log.

△ Dissolved solids from reported data.

Figure 78

Lower Glen Rose Water Salinity, East Texas



## Figure 79
## Paluxy Structure, East Texas

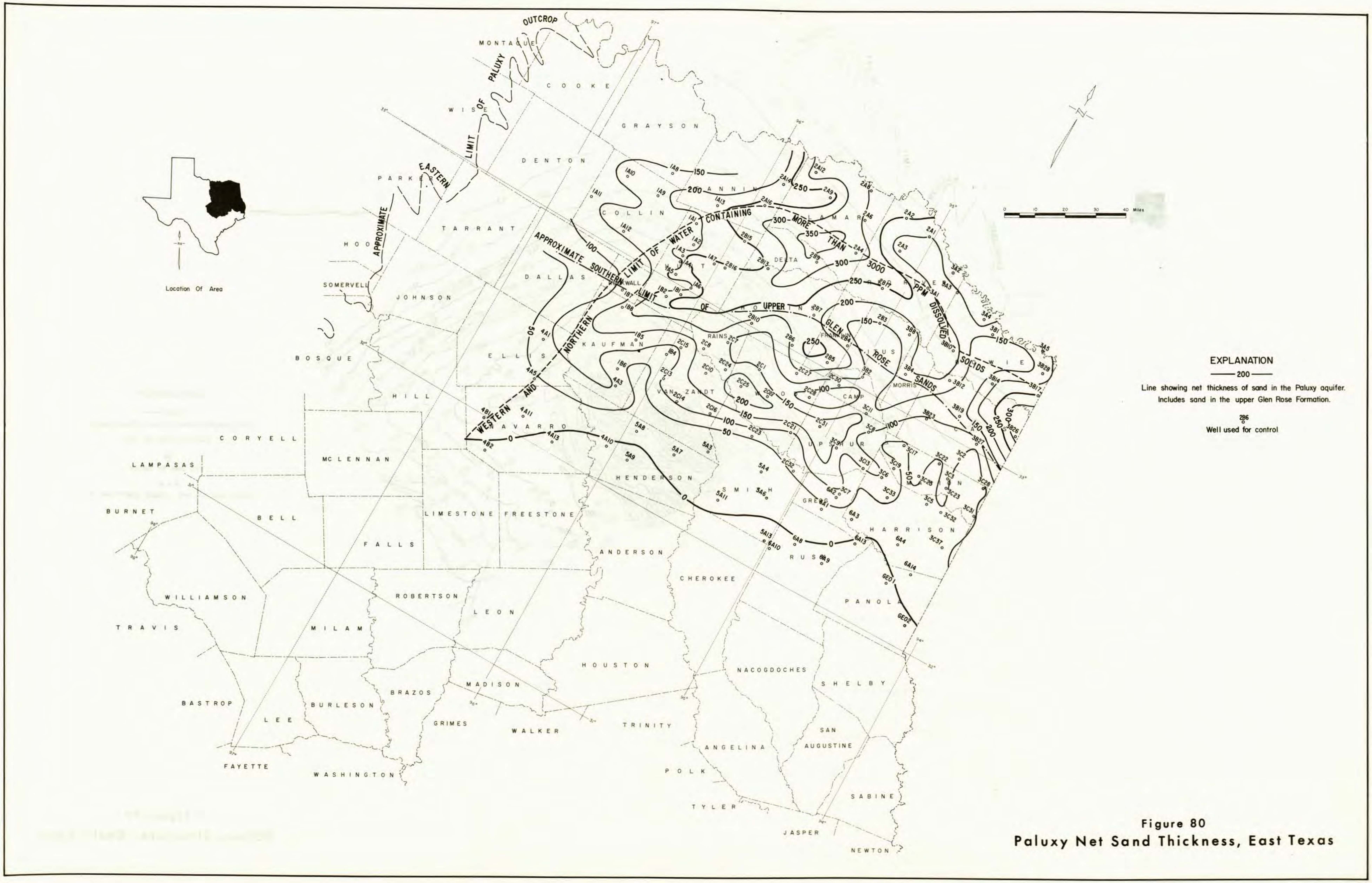


Figure 80
**Paluxy Net Sand Thickness, East Texas**

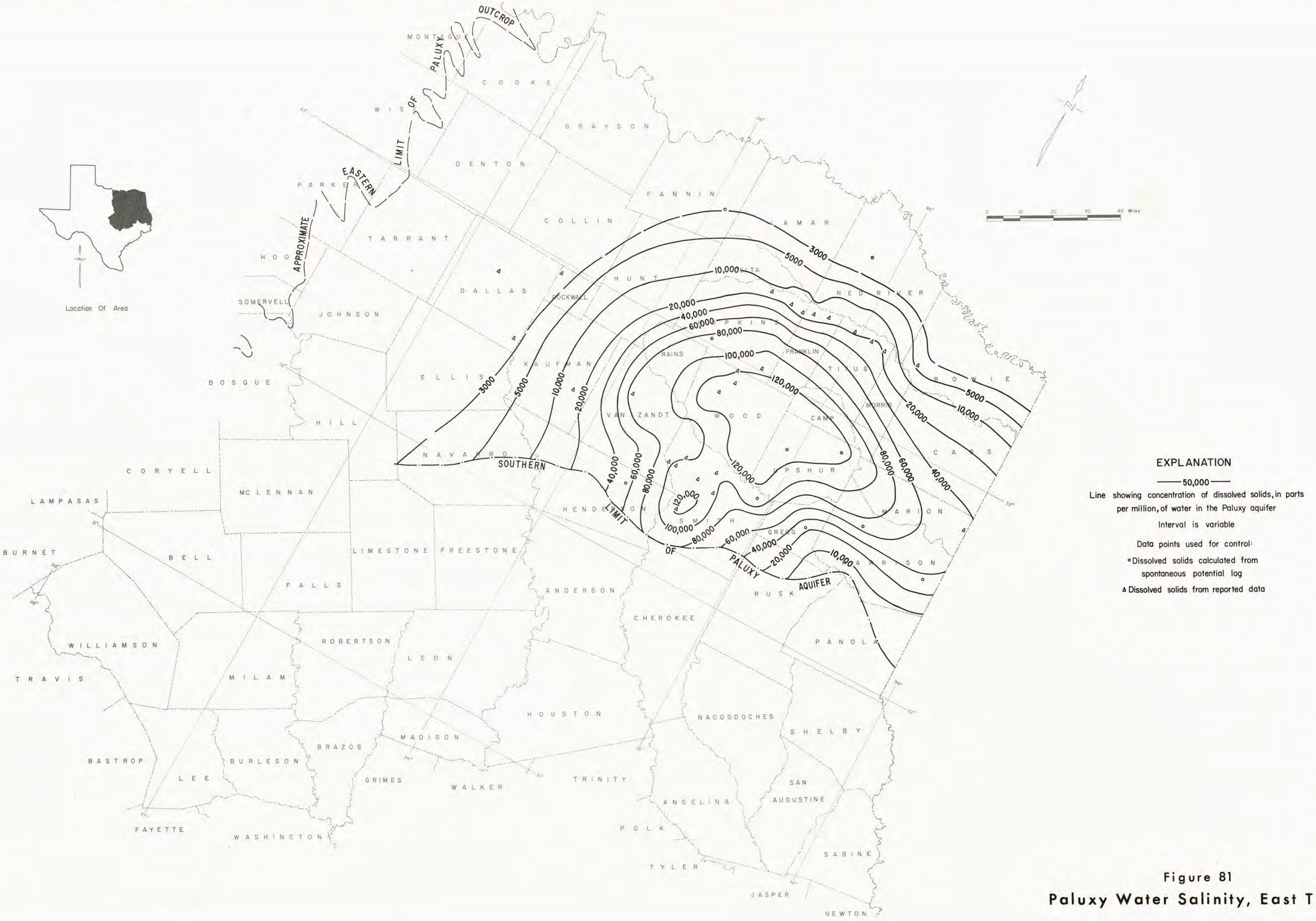
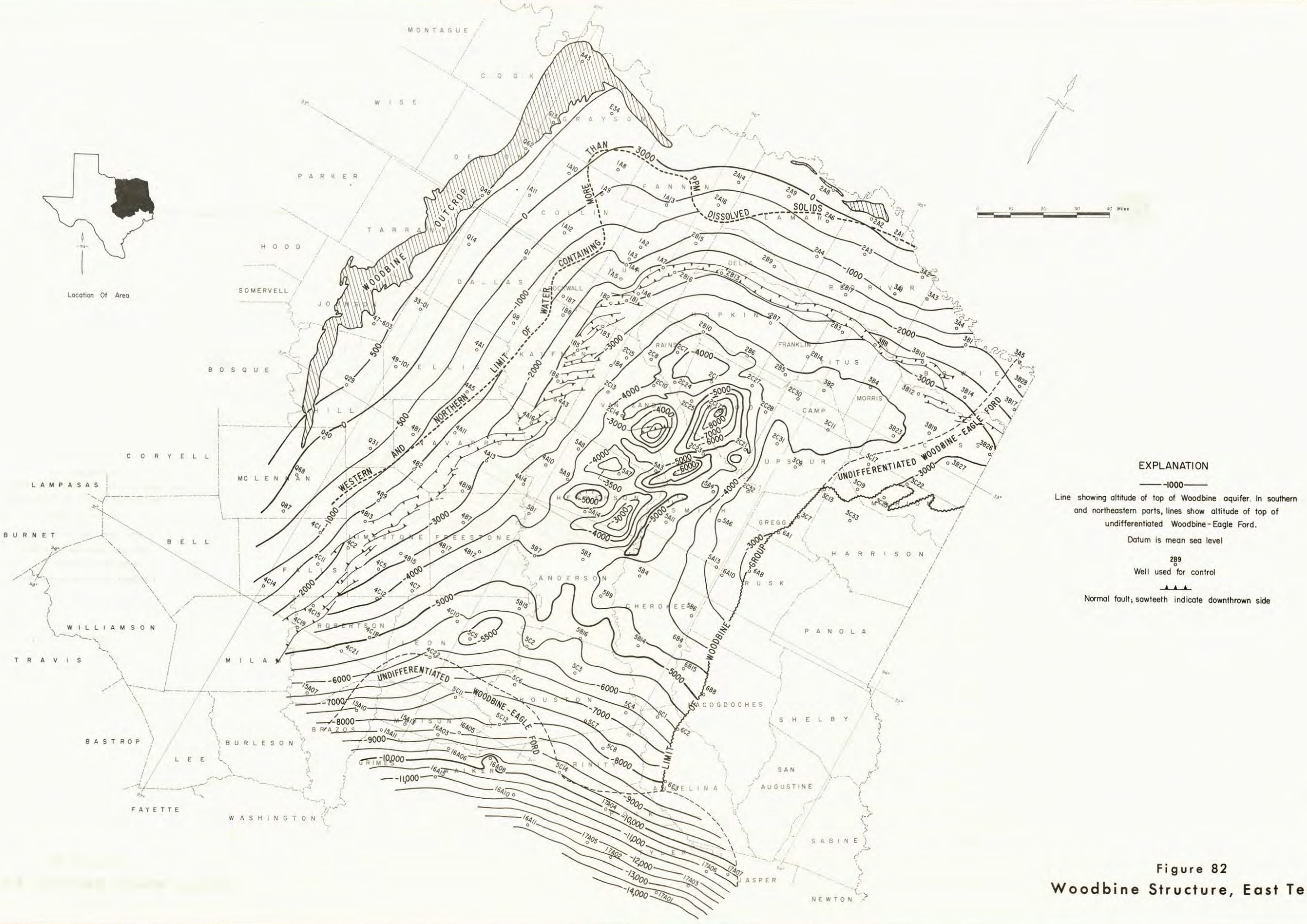


Figure 81

Paluxy Water Salinity, East Texas



EXPLANATION

——-1000——

Line showing altitude of top of Woodbine aquifer. In southern and northeastern parts, lines show altitude of top of undifferentiated Woodbine-Eagle Ford.

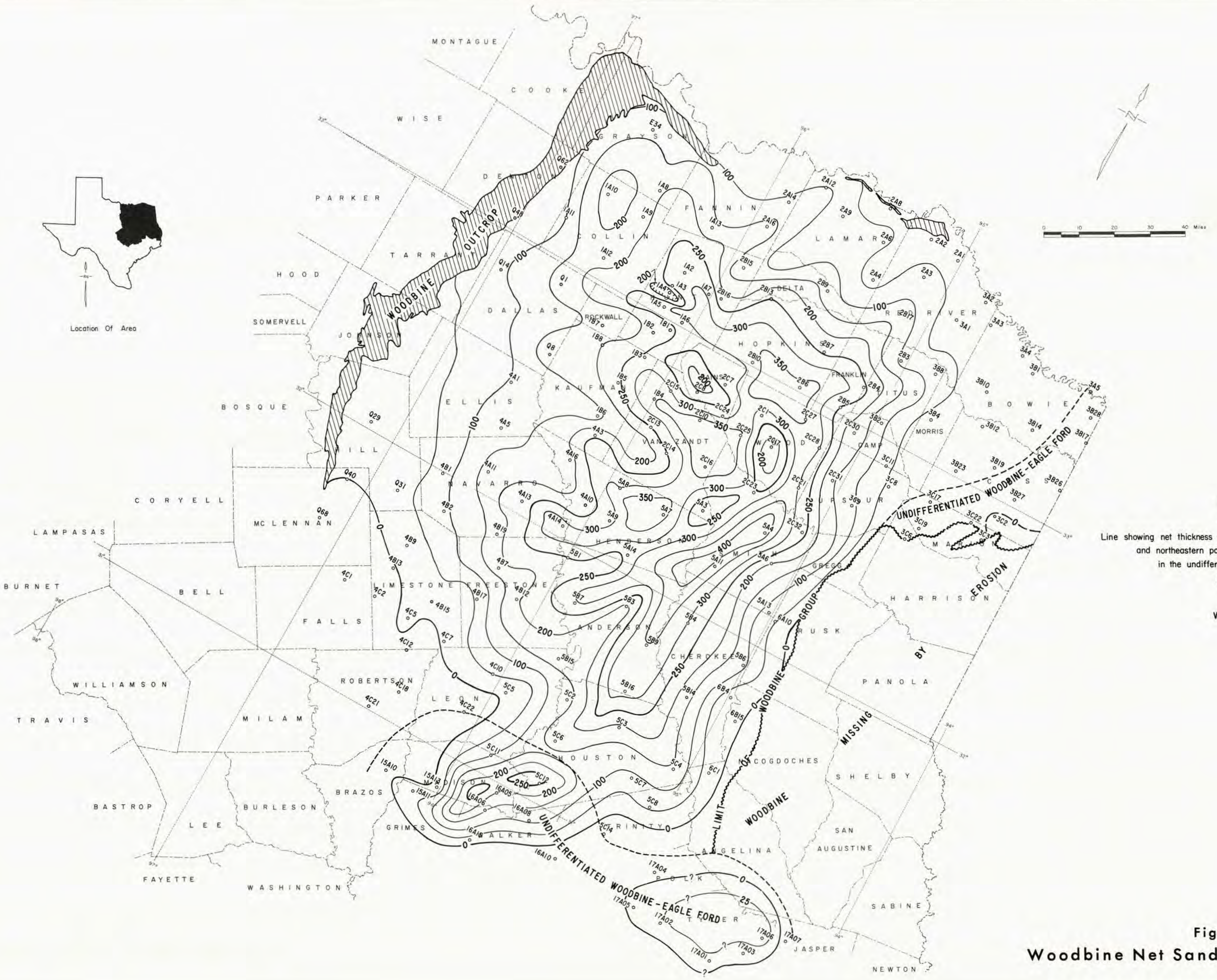
Datum is mean sea level

289 ○ Well used for control

▲▲▲ Normal fault; sawteeth indicate downthrown side

**Figure 82**

**Woodbine Structure, East Texas**



EXPLANATION

——100——

Line showing net thickness of sand in the Woodbine aquifer. In southern and northeastern parts, lines show net thickness of sand in the undifferentiated Woodbine - Eagle Ford.

Interval is variable

5C4 ○

Well used for control

Figure 83

Woodbine Net Sand Thickness, East Texas

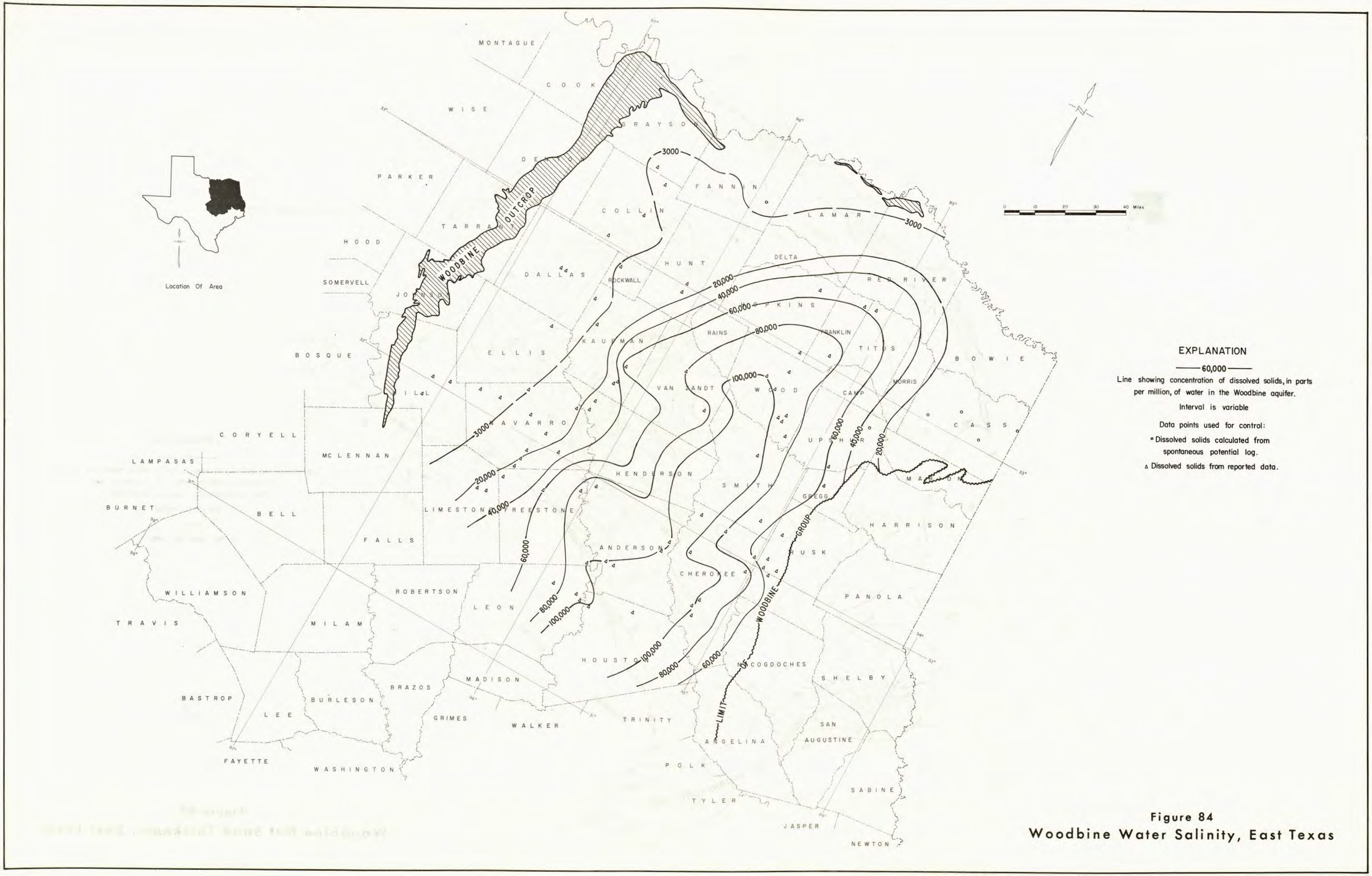


**Figure 84**
**Woodbine Water Salinity, East Texas**

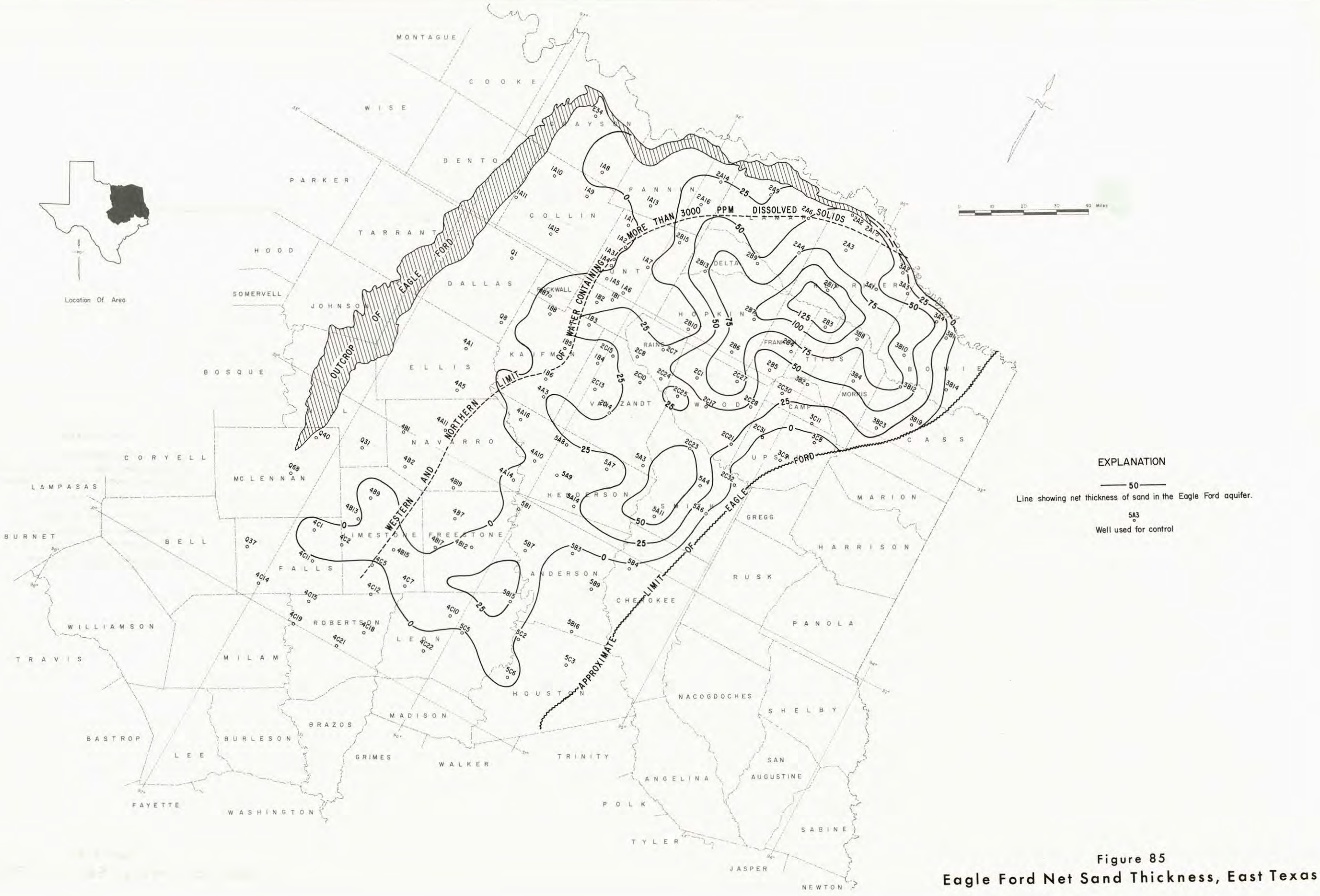
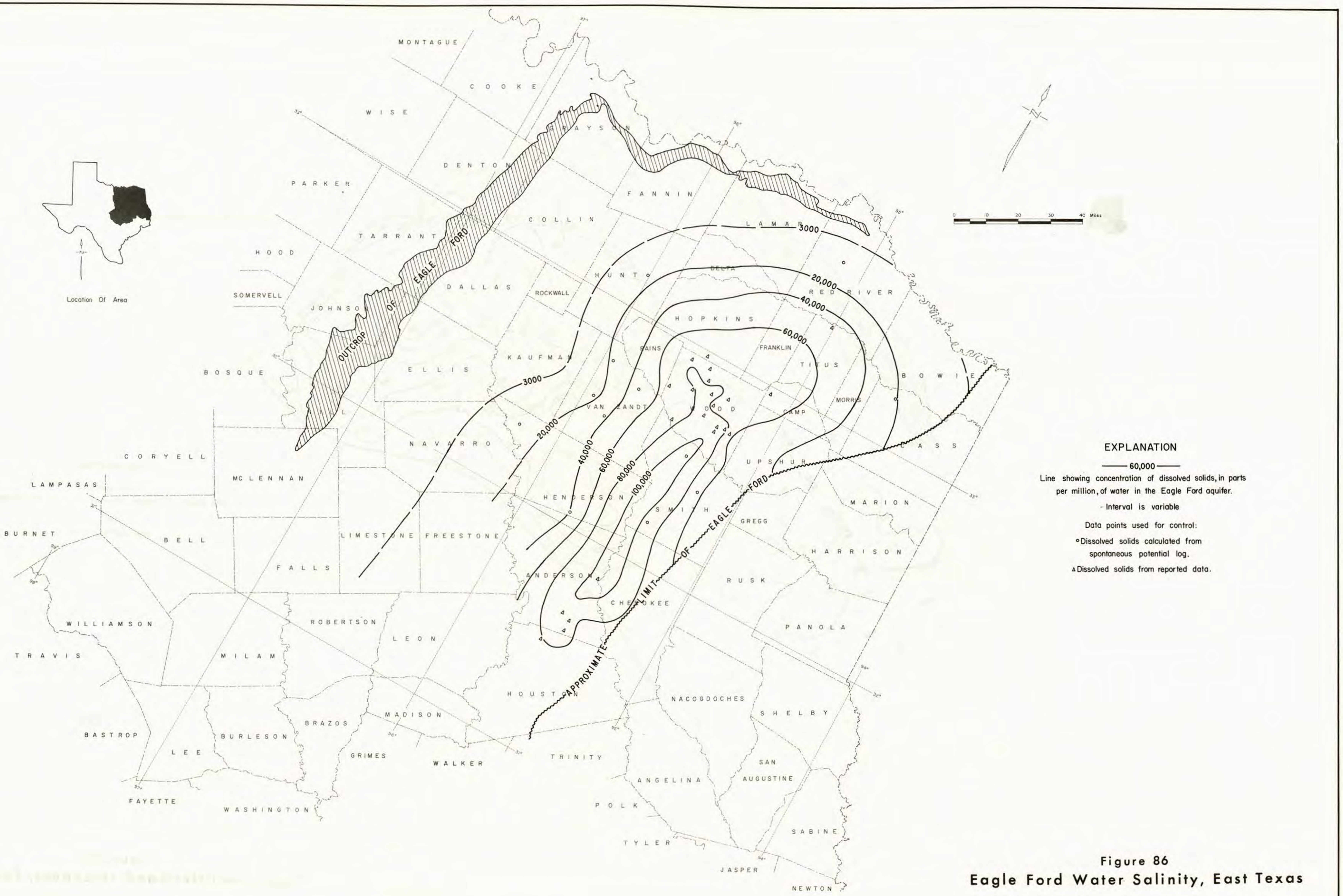


**Figure 85**

**Eagle Ford Net Sand Thickness, East Texas**



## Figure 86

## Eagle Ford Water Salinity, East Texas

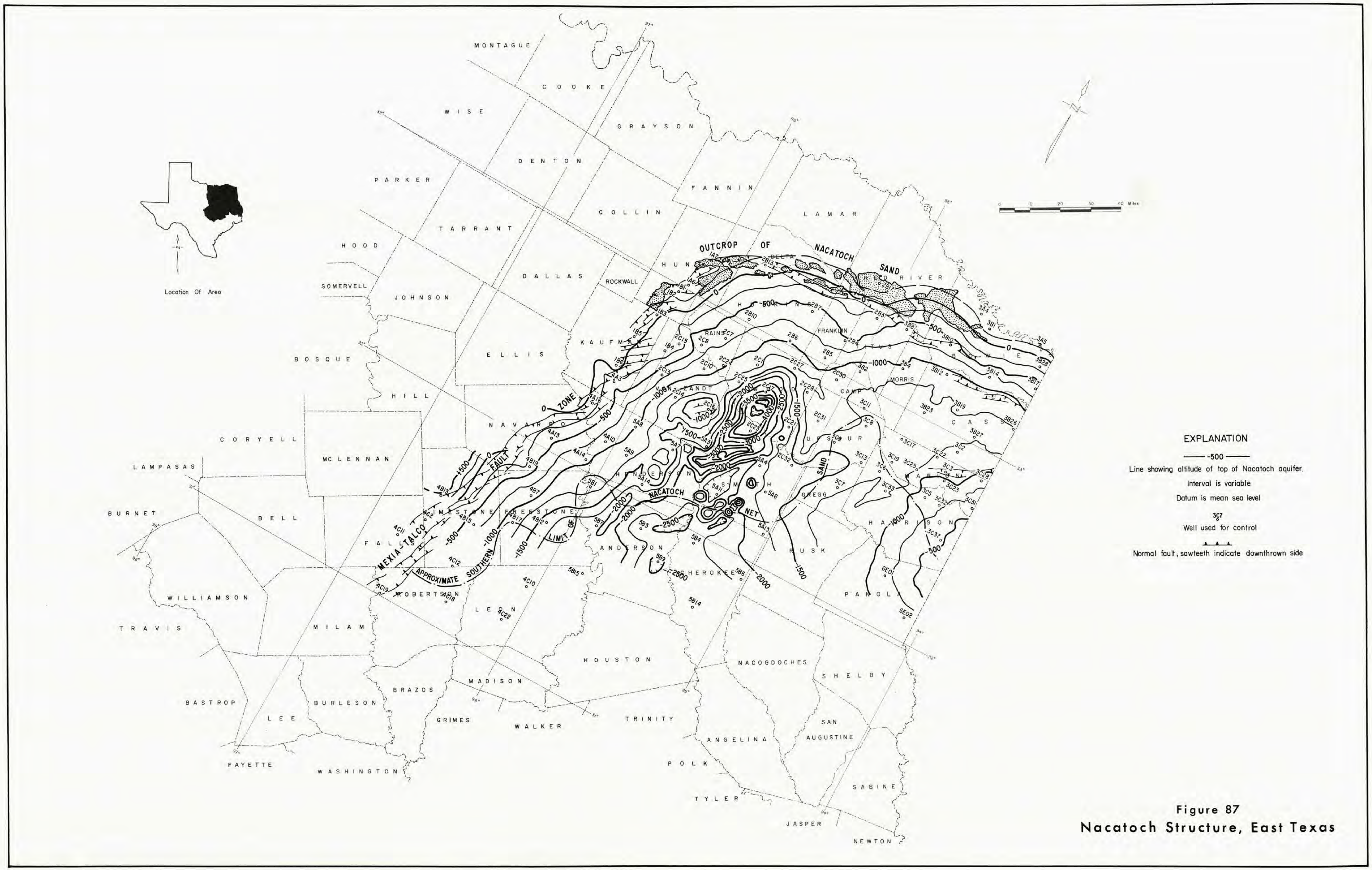


Figure 87

Nacatoch Structure, East Texas

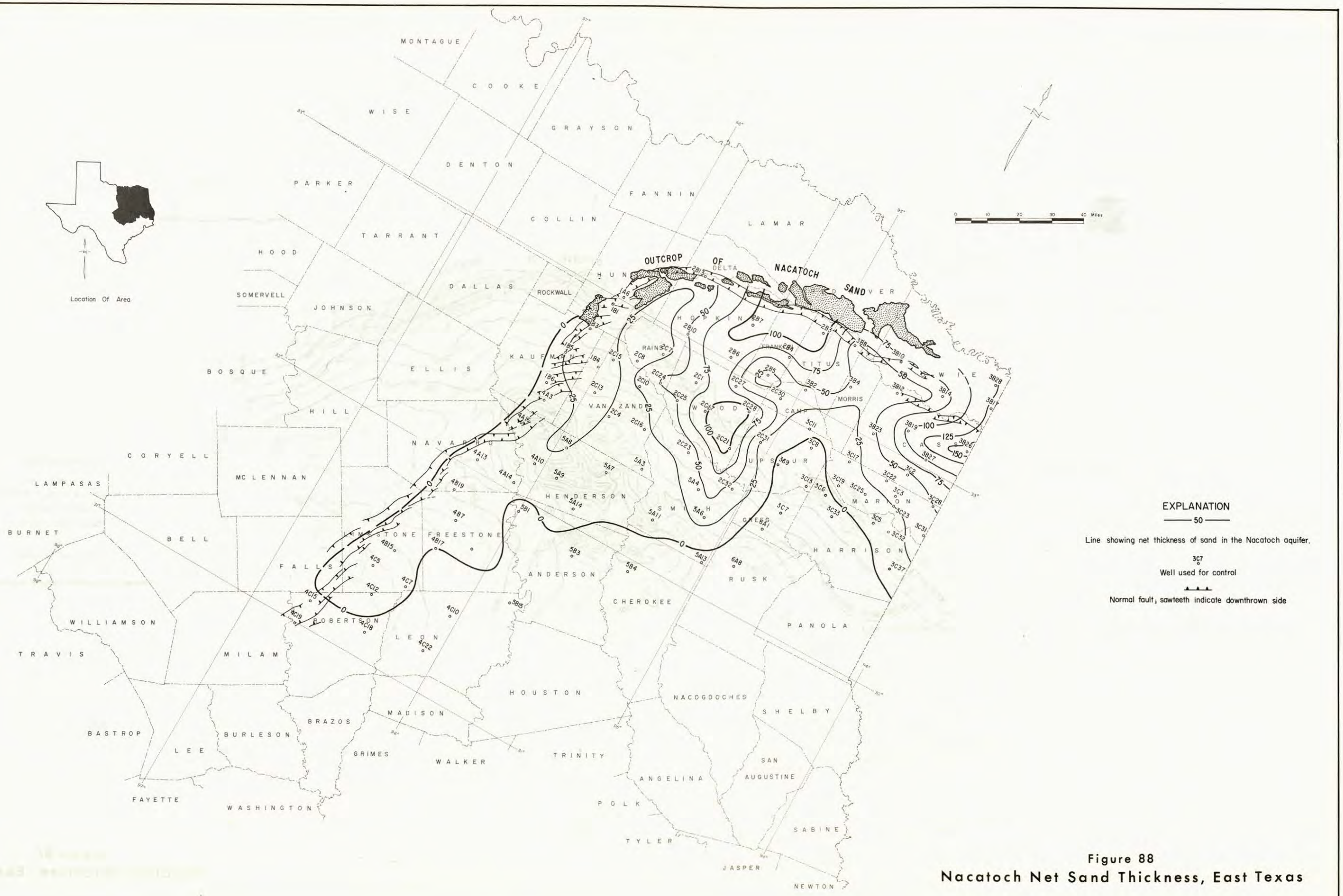


Figure 88
Nacatoch Net Sand Thickness, East Texas

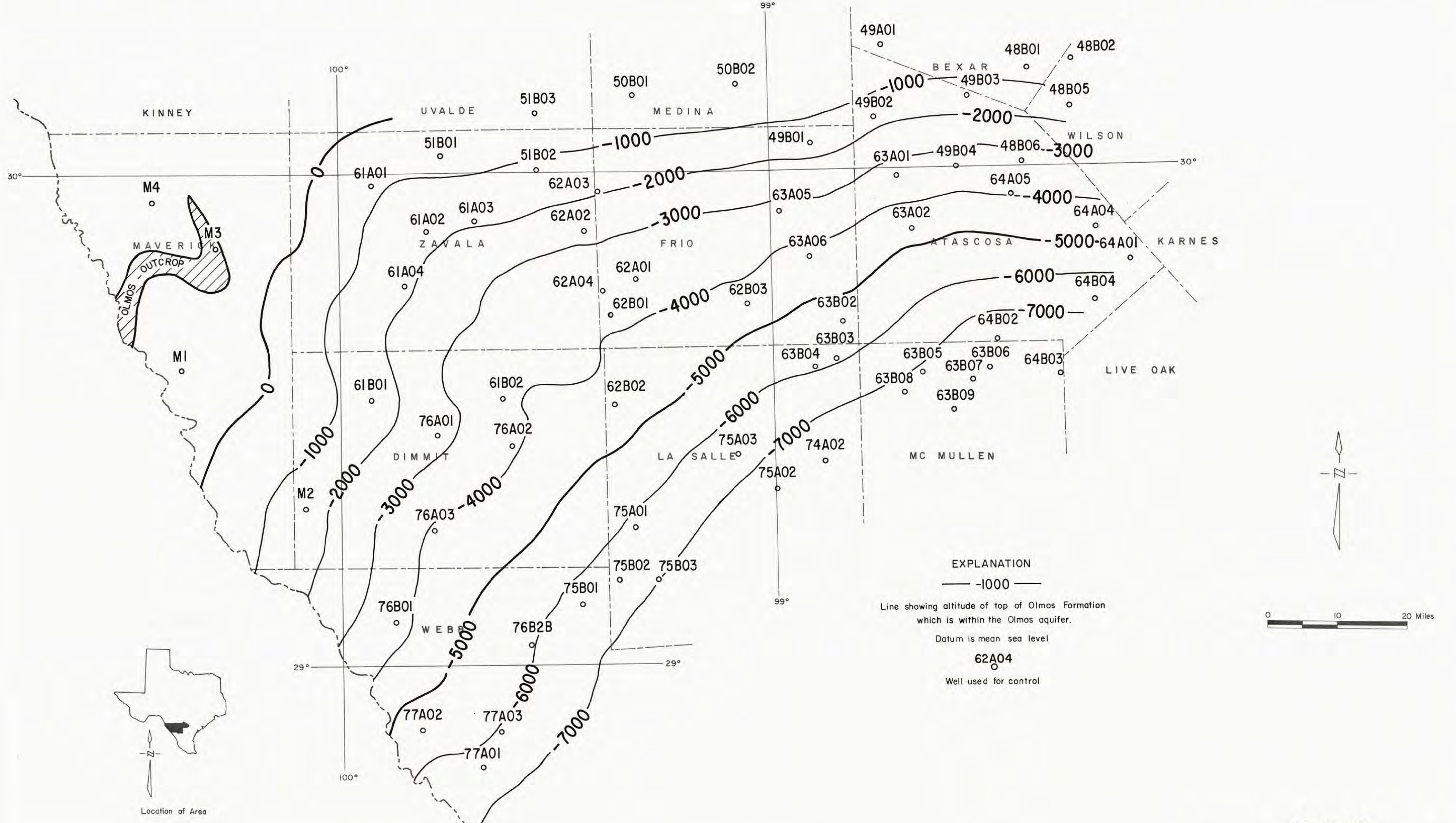
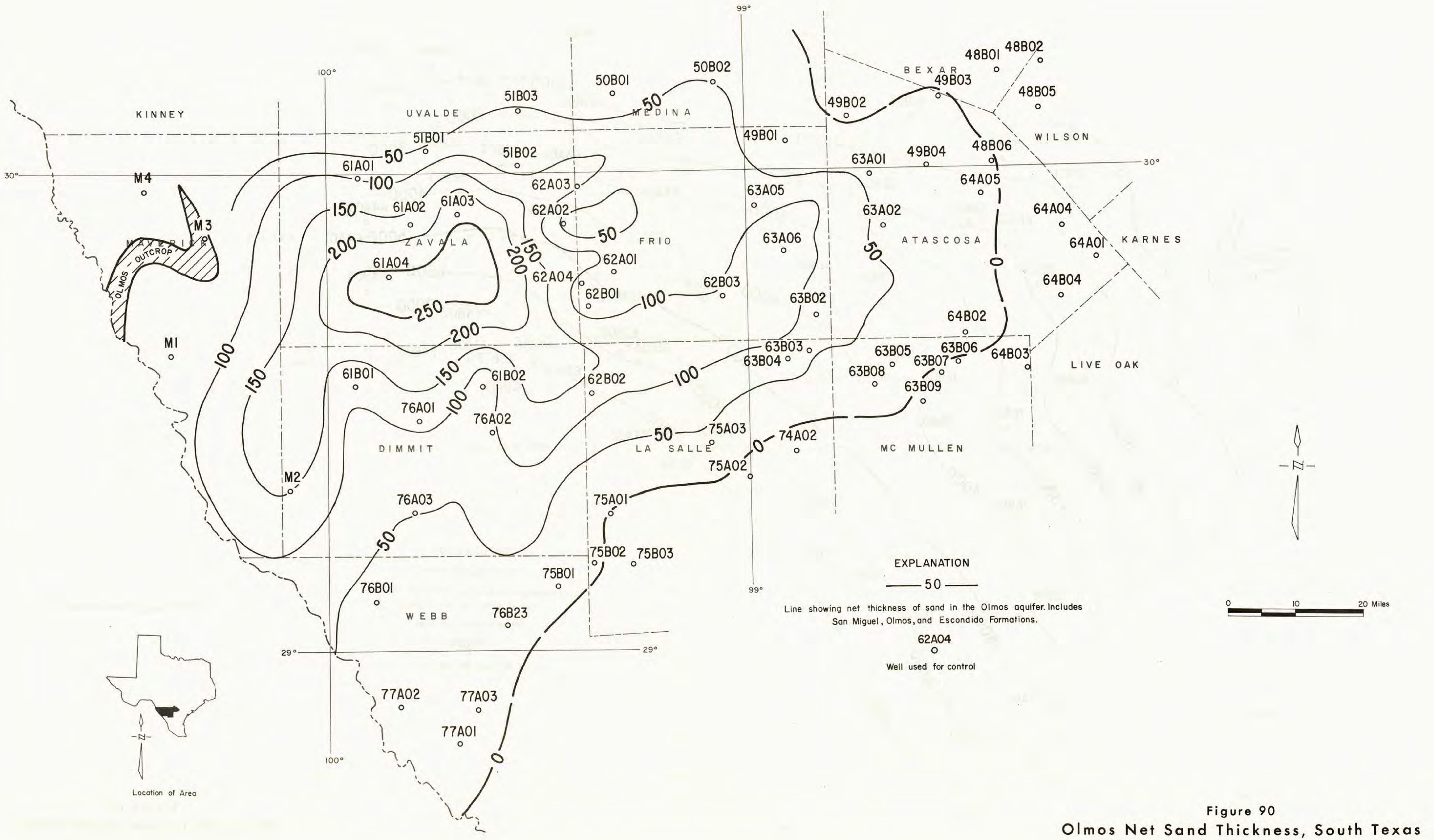


Figure 89
Olmos Structure, South Texas



EXPLANATION

—— 50 ——

Line showing net thickness of sand in the Olmos aquifer. Includes San Miguel, Olmos, and Escondido Formations.

62A04
○
Well used for control

Figure 90

Olmos Net Sand Thickness, South Texas

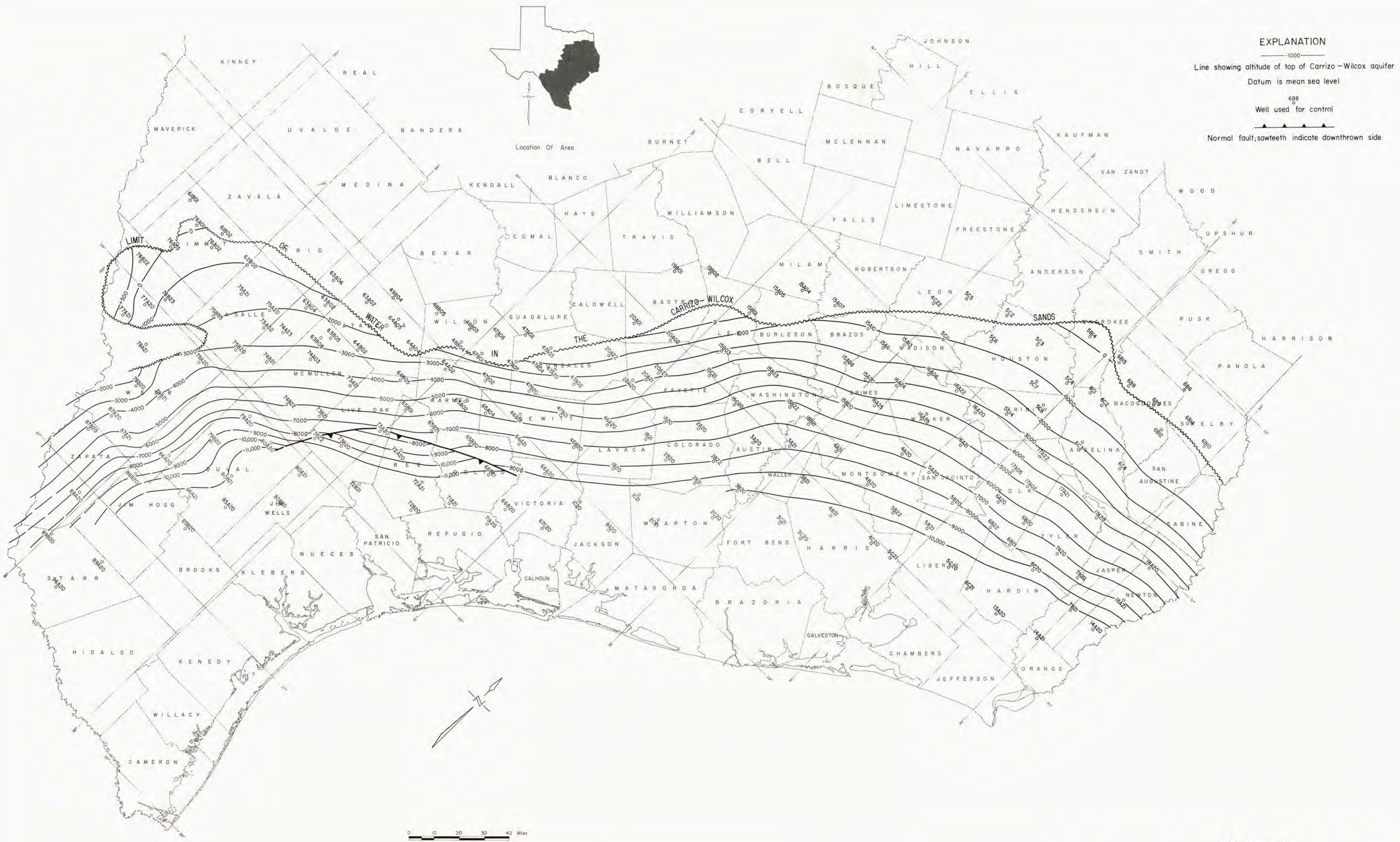
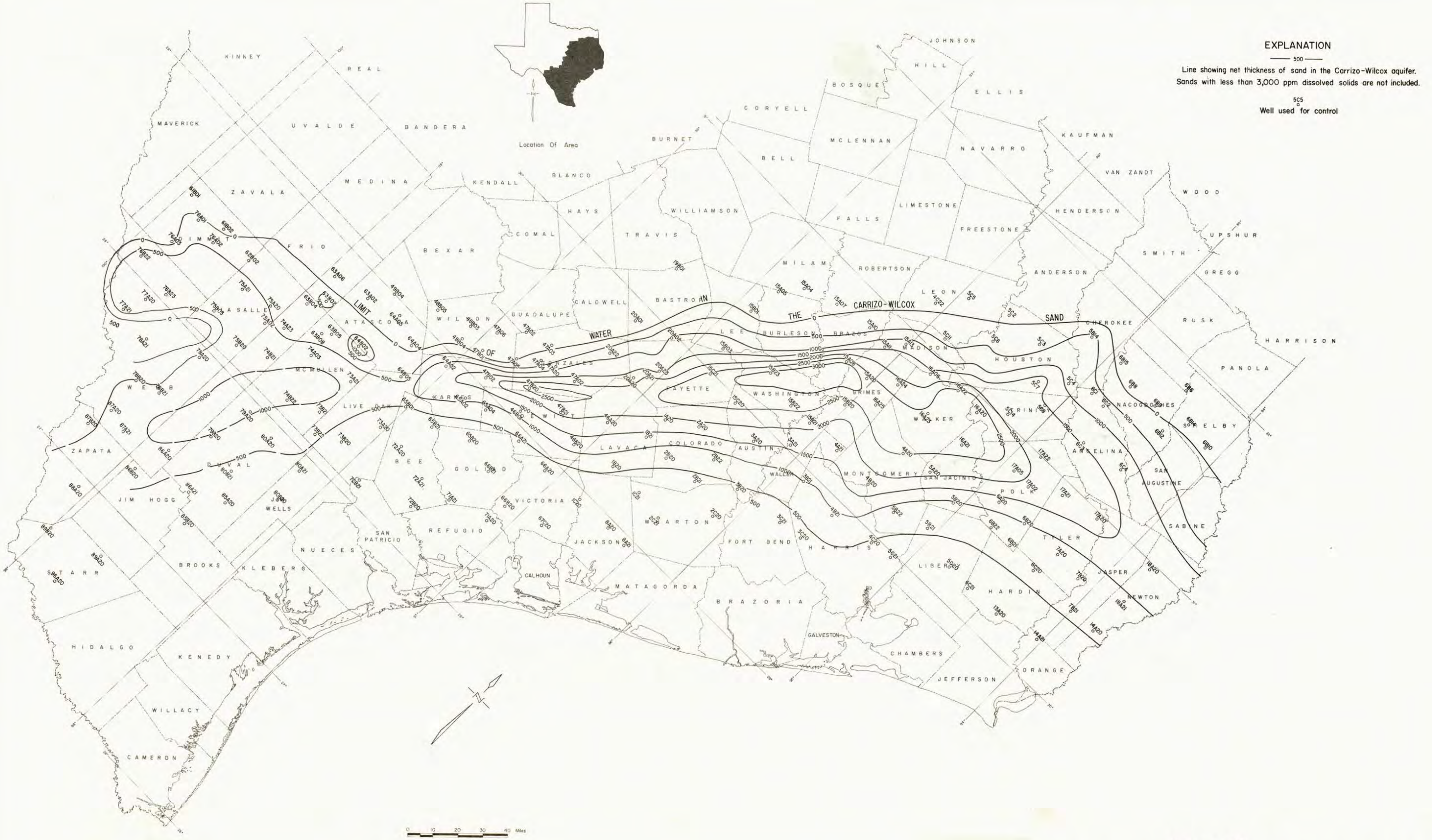


Figure 91

Carrizo-Wilcox Structure, Gulf Coast



EXPLANATION

—— 500 ——
Line showing net thickness of sand in the Carrizo-Wilcox aquifer. Sands with less than 3,000 ppm dissolved solids are not included.

5C5
○
Well used for control

**Figure 92**
**Carrizo-Wilcox Net Sand Thickness, Gulf Coast**

EXPLANATION

——40,000——

Line showing concentration of dissolved solids, in parts per million, of water in the Carrizo—Wilcox aquifer. Interval is variable

Data points used for control :

○ Dissolved solids calculated from spontaneous potential log

△ Dissolved solids from reported data

Figure 93

Carrizo-Wilcox Water Salinity, Gulf Coast

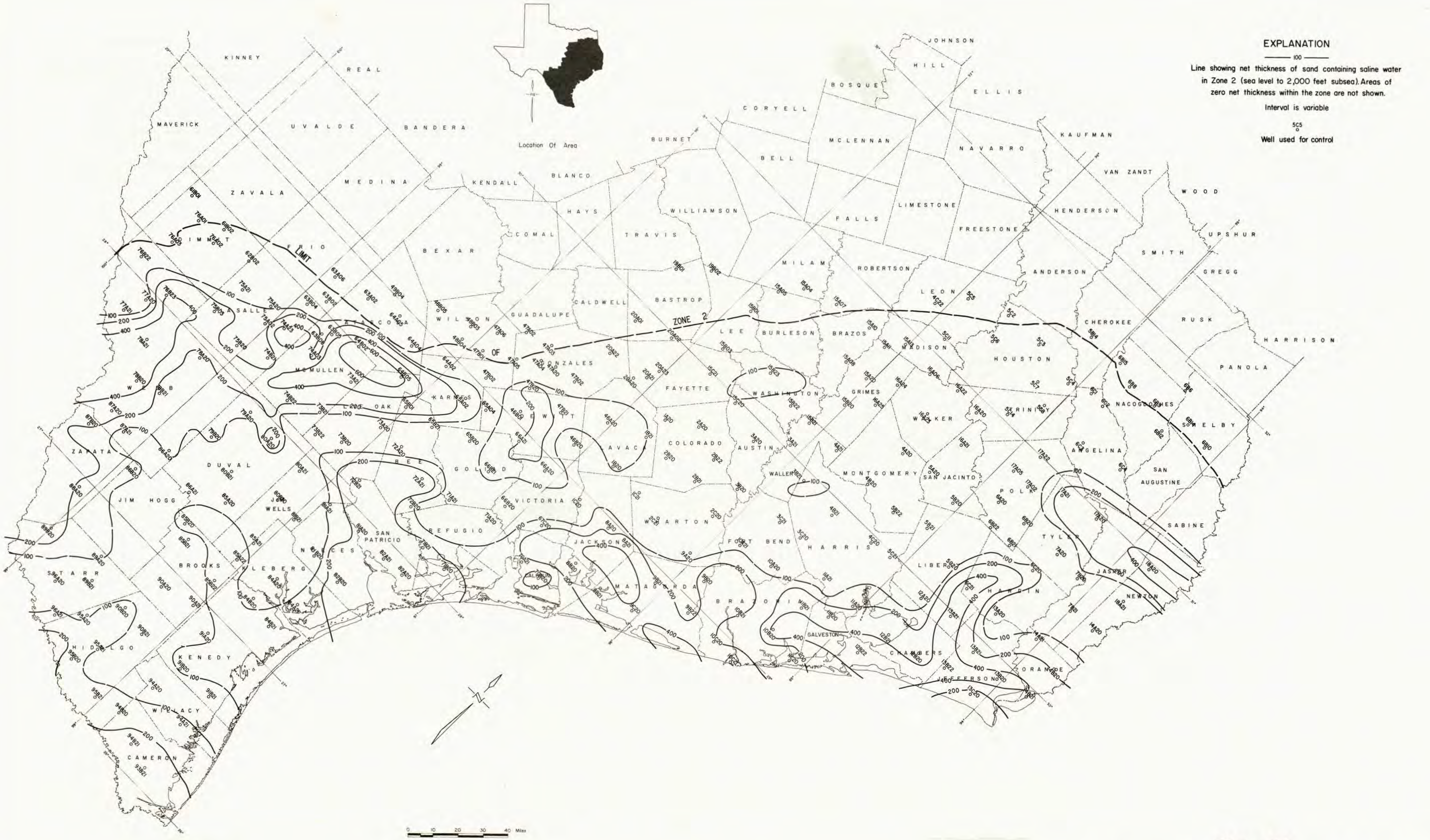
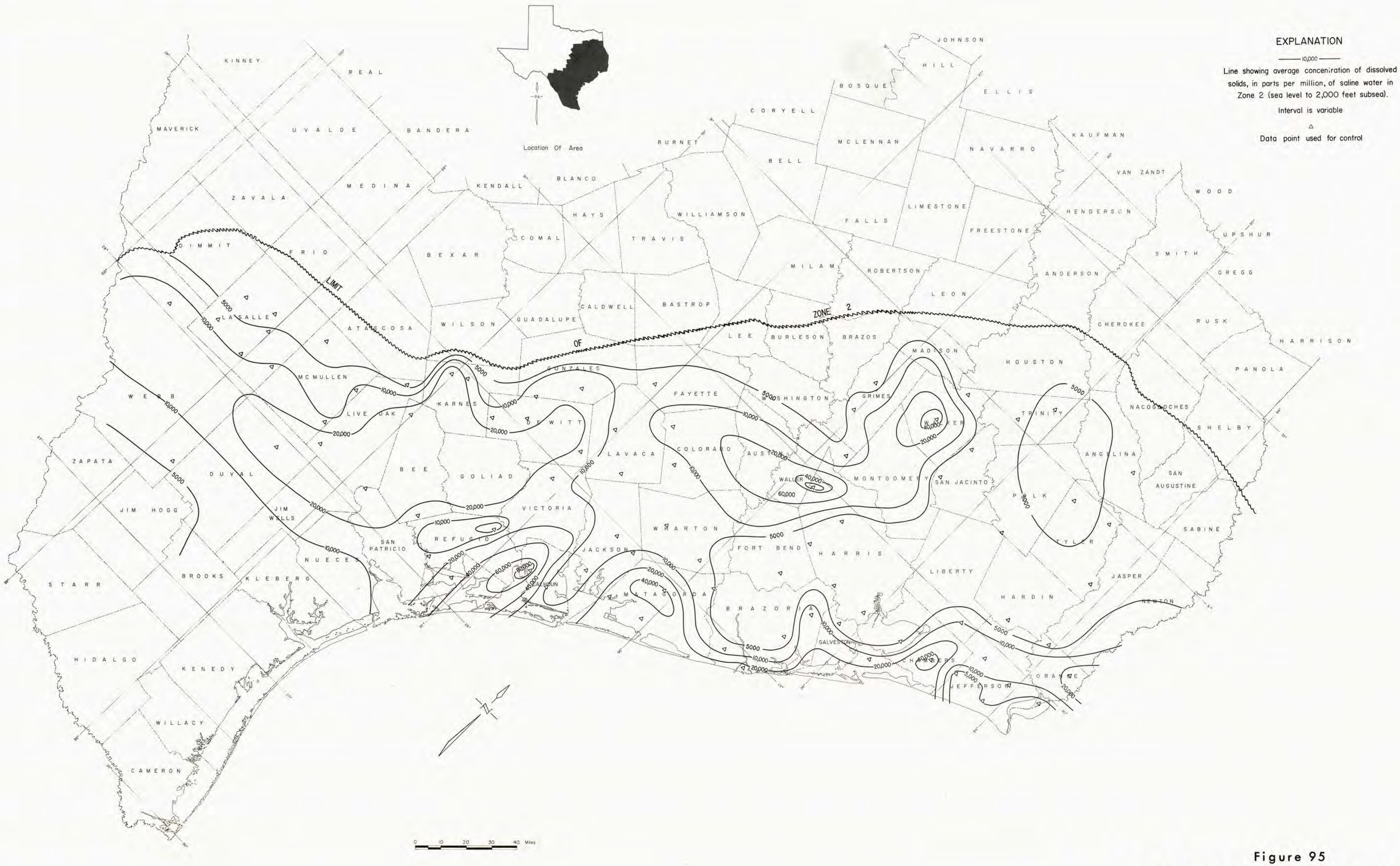


Figure 94
Zone 2 Net Sand Thickness, Gulf Coast



EXPLANATION

——10,000——

Line showing average concentration of dissolved solids, in parts per million, of saline water in Zone 2 (sea level to 2,000 feet subsea).

Interval is variable

△

Data point used for control

Figure 95

Zone 2 Water Salinity, Gulf Coast

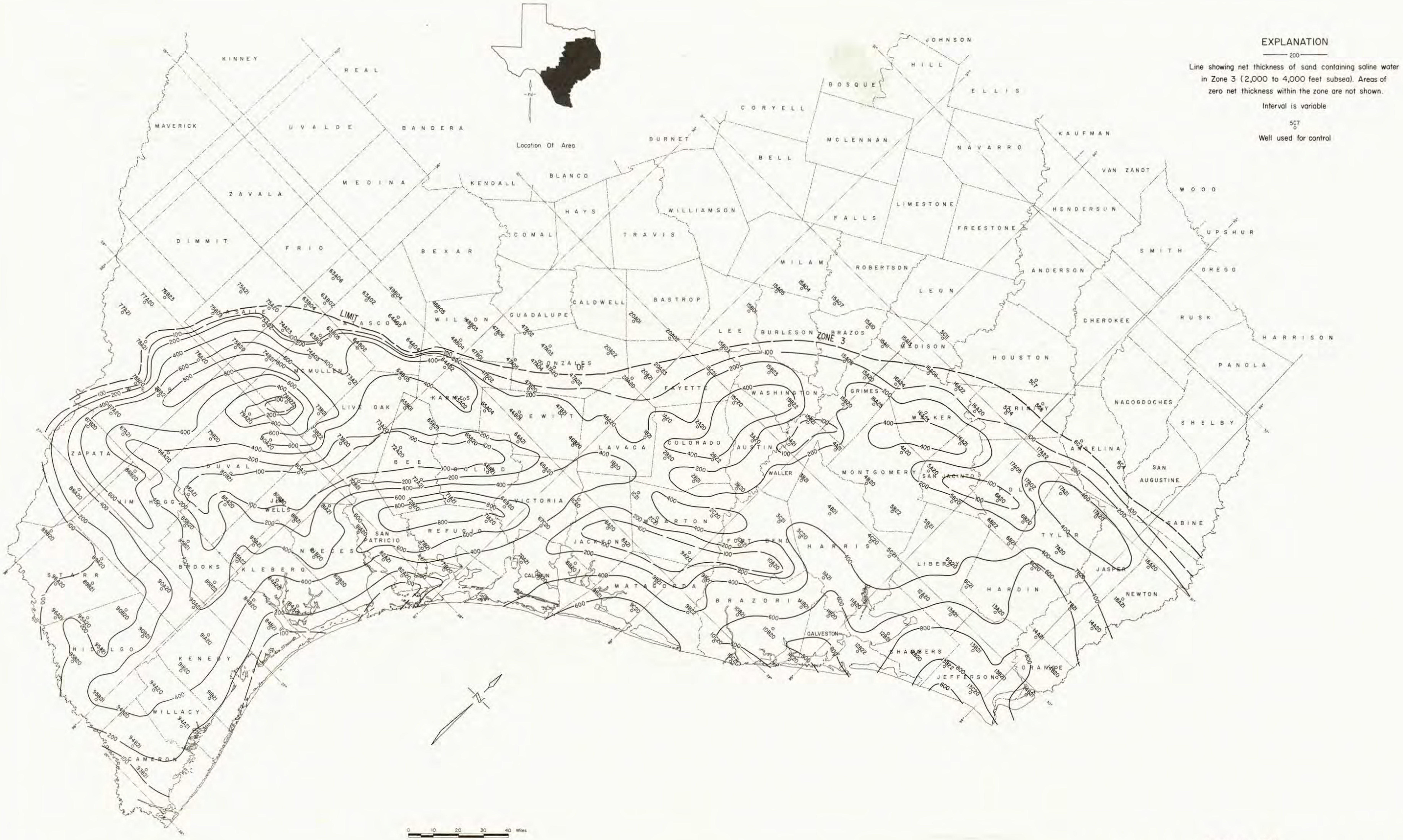
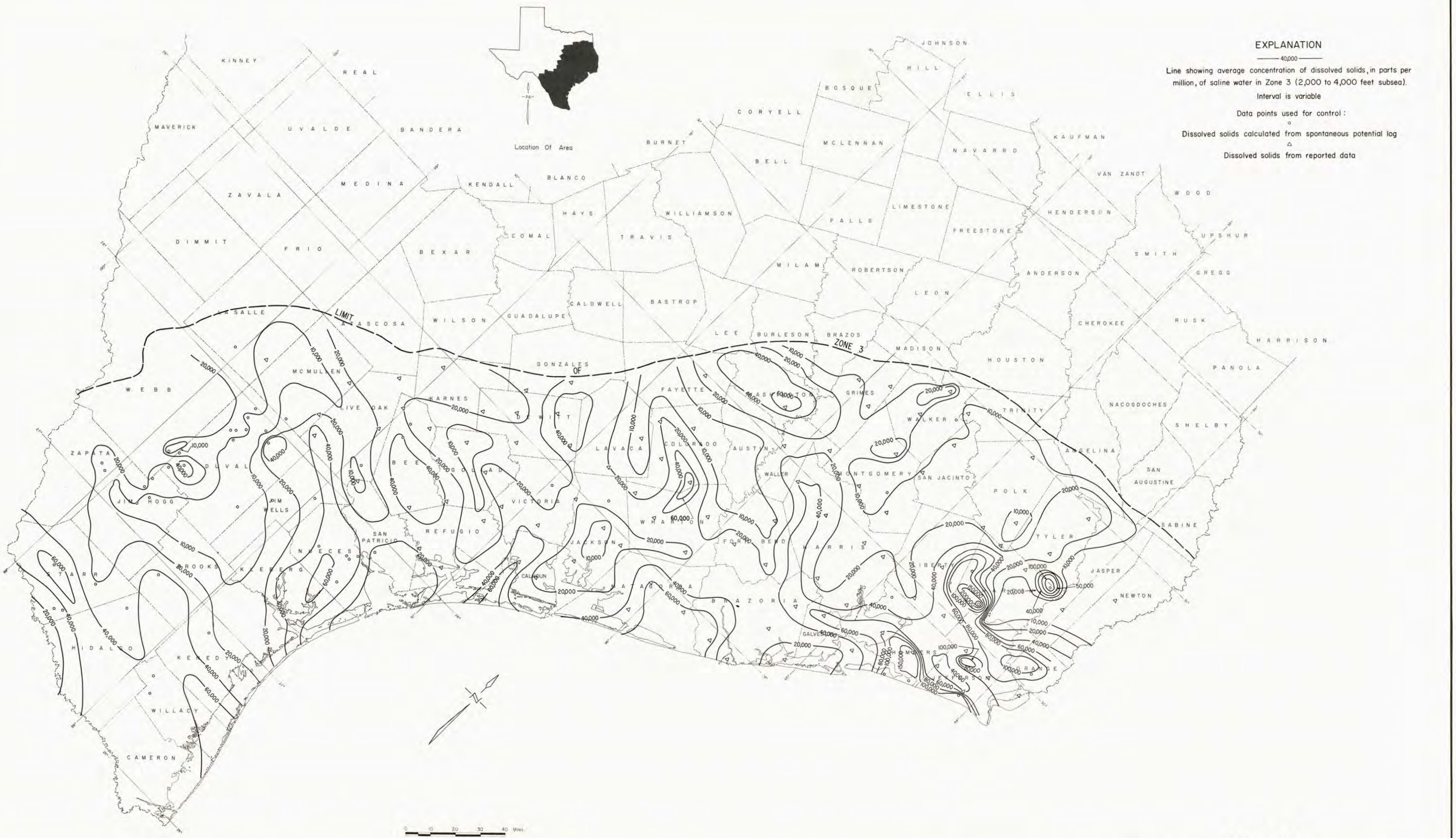


Figure 96

**Zone 3 Net Sand Thickness, Gulf Coast**



EXPLANATION

——40,000——

Line showing average concentration of dissolved solids, in parts per million, of saline water in Zone 3 (2,000 to 4,000 feet subsea). Interval is variable

Data points used for control:

○ Dissolved solids calculated from spontaneous potential log

△ Dissolved solids from reported data

Figure 97

Zone 3 Water Salinity, Gulf Coast

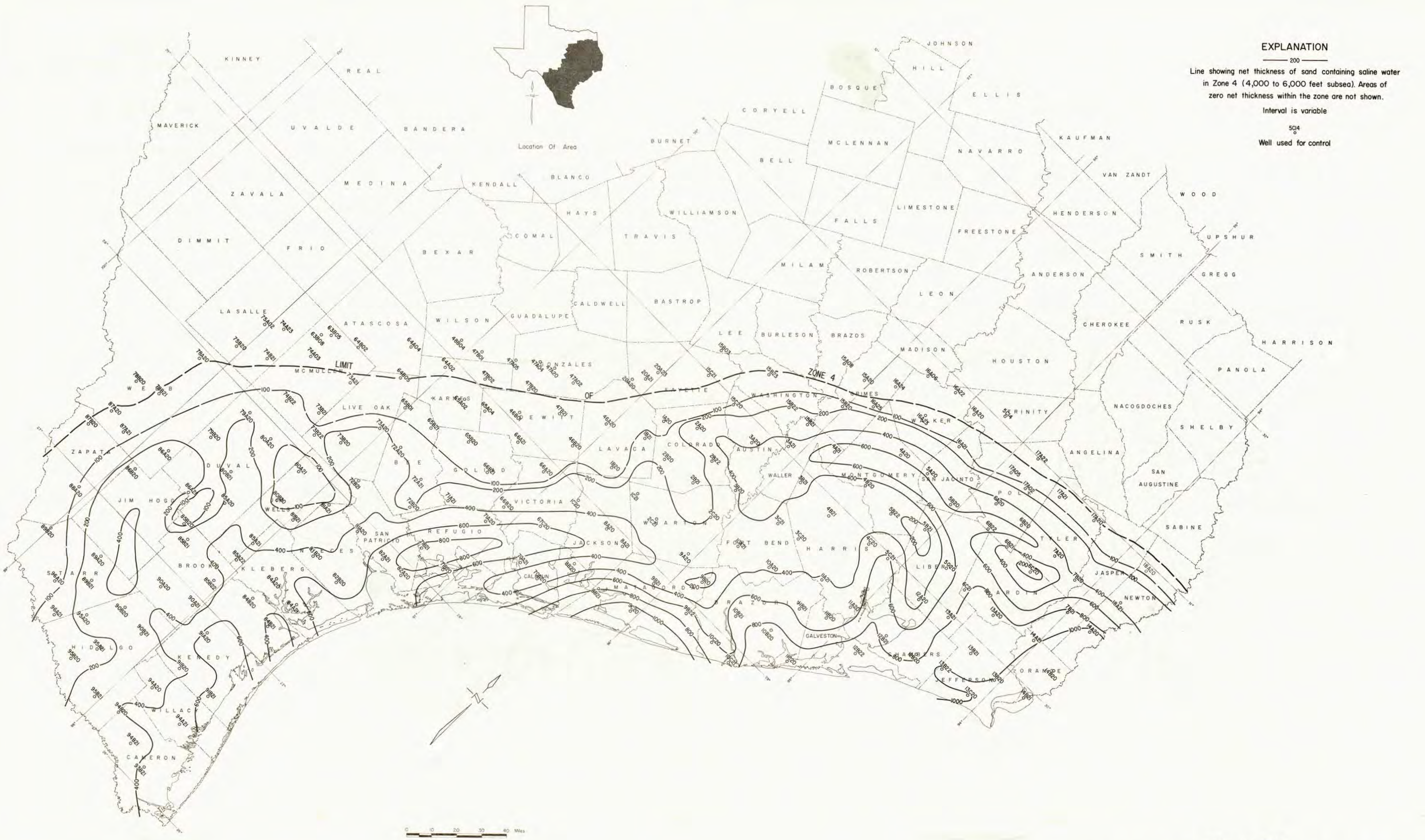


Figure 98

Zone 4 Net Sand Thickness, Gulf Coast

EXPLANATION

—— 40,000 ——

Line showing average concentration of dissolved solids, in parts per million, of saline water in Zone 4 (4,000 to 6,000 feet subsea). Interval is variable

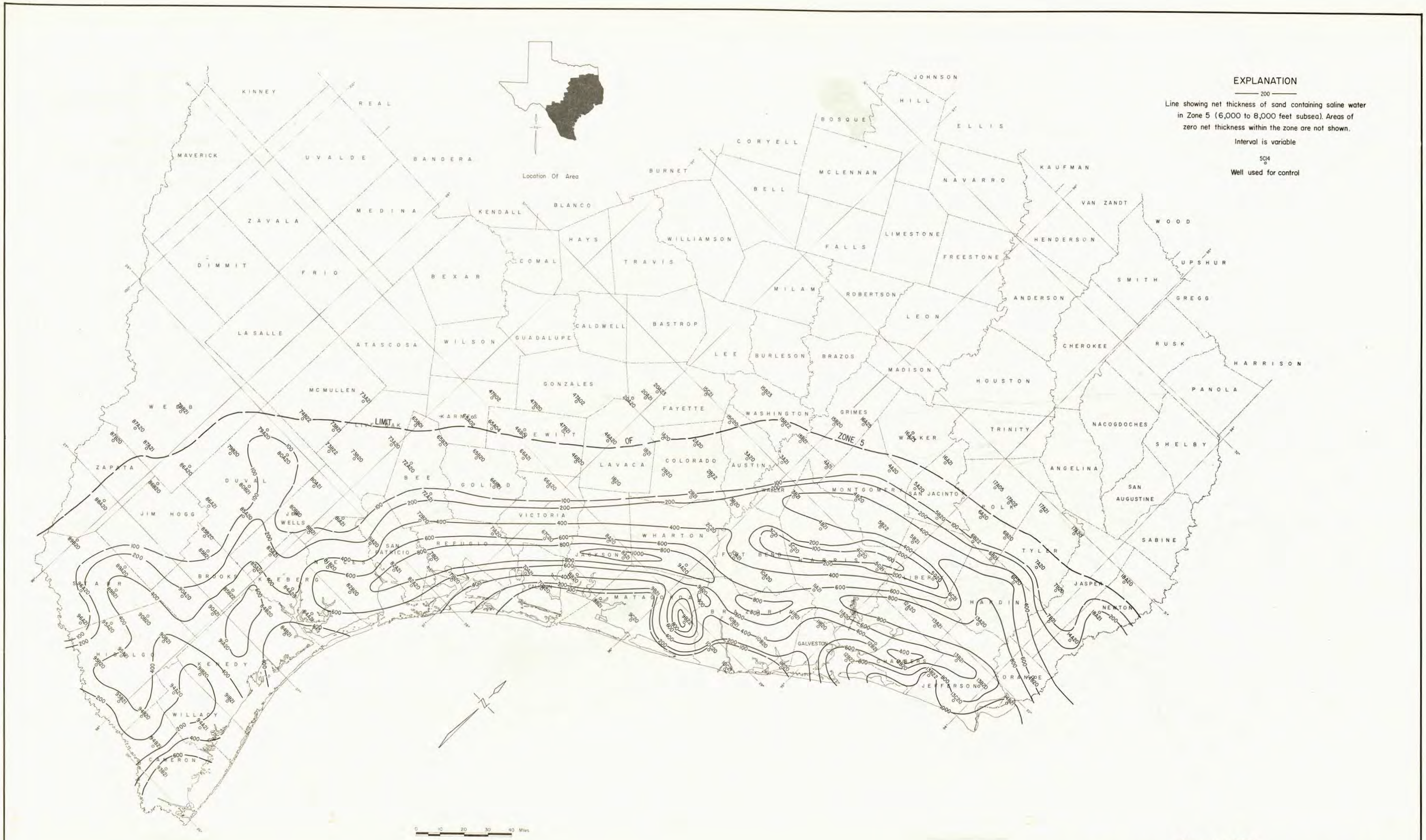
Data points used for control:

○ Dissolved solids calculated from spontaneous potential log

△ Dissolved solids from reported data

Figure 99

Zone 4 Water Salinity, Gulf Coast



EXPLANATION

——— 200 ———

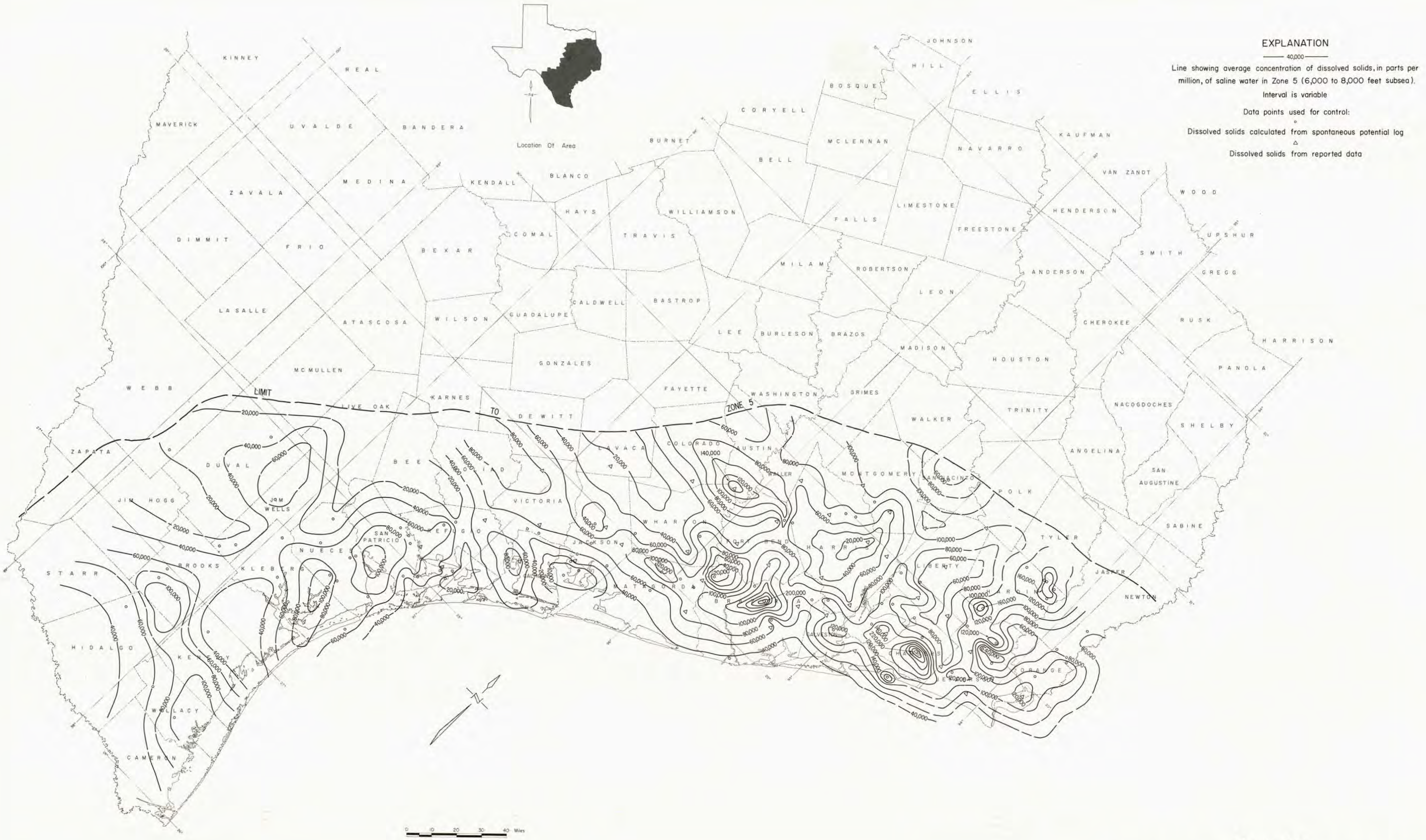
Line showing net thickness of sand containing saline water in Zone 5 (6,000 to 8,000 feet subsea). Areas of zero net thickness within the zone are not shown.

Interval is variable

5014
o
Well used for control

Figure 100

Zone 5 Net Sand Thickness, Gulf Coast



EXPLANATION

——— 40,000 ———

Line showing average concentration of dissolved solids, in parts per million, of saline water in Zone 5 (6,000 to 8,000 feet subsea). Interval is variable

Data points used for control:

○

Dissolved solids calculated from spontaneous potential log

△

Dissolved solids from reported data

Figure 101

Zone 5 Water Salinity, Gulf Coast

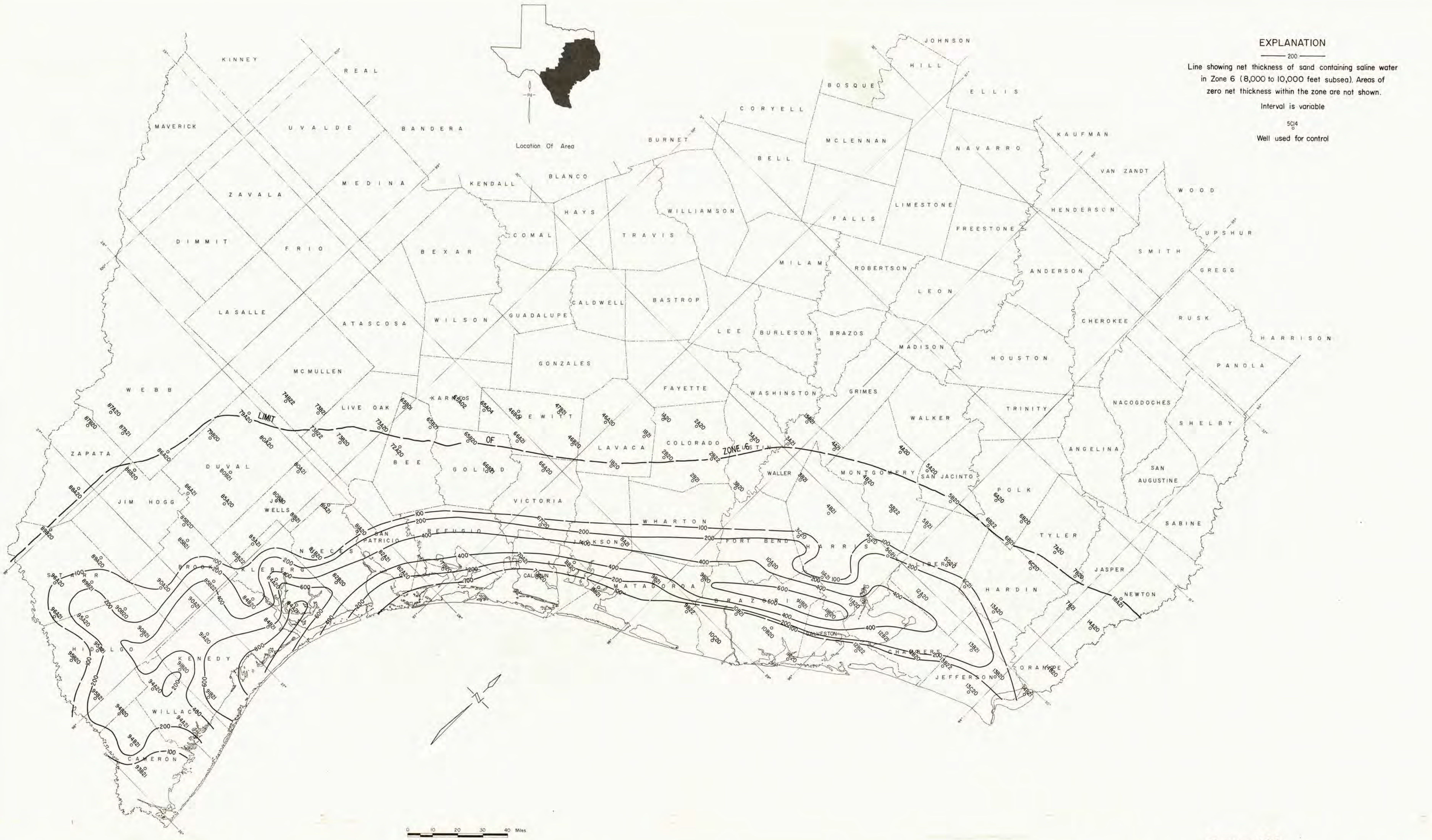


Figure 102

**Zone 6 Net Sand Thickness, Gulf Coast**

EXPLANATION

—— 40,000 ——

Line showing average concentration of dissolved solids, in parts per million, of saline water in Zone 6 (8,000 to 10,000 feet subsea)

Interval is variable

Data points used for control:

○

Dissolved solids calculated from spontaneous potential log

△

Dissolved solids from reported data

Figure 103

Zone 6 Water Salinity, Gulf Coast