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GEOTHERMAL POTENTIAL ALONG THE BALCONES/OUACHITA TREND, CENTRAL TEXAS--ONGOING ASSESSMENT AND SELECTED CASE STUDIES

by

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INTRODUCTION

Numerous wells produce warm ground water from several Cretaceous aquifers located beneath the innermost part of the Texas Gulf Coastal Plain. The changes in landscape between the Coastal Plain and the uplands farther west result from a major geologic break. Texas is bisected along this trend by the Texas Craton, a hinge zone that separates the downwarping Gulf Coast Basin from the more stable continental interior. At depth this hinge is defined by the subsided Ouachita Mountains; at the surface the geologic break is expressed by the Balcones and Luling-Mexia-Talco Fault Zones.

The geologic hinge zone has clearly affected the physiography of the region. These effects include abrupt changes in terrain, climate, soils, vegetation, and availability of ground water across the hinge. These changes have, in turn, influenced human settlement patterns (Bybee, 1952). The Balcones/Ouachita hinge is a geocultural break similar in cause and comparable in effect to the Fall Line of the Eastern United States (Woodruff, 1980). Both trends are the loci of cities. The towns and cities along the Balcones/Ouachita trend might use the thermal resources; at some localities the warm water is already used although as drinking water and not generally for its energy content.

Studies at the Bureau of Economic Geology have documented geothermal waters in many places across Texas (Henry, 1979; Henry and Gluck, 1981; Woodruff and others, 1982). Locally, these waters may be hotter or more abundant than along the Balcones/Ouachita trend, but considering both geologic and socioeconomic aspects, Central Texas is probably the region with greatest potential for developing a cost-effective energy resource from low-temperature geothermal waters. The cities along the Balcones/Ouachita trend constitute a market for the geothermal energy resource.

PURPOSE AND SCOPE

This report focuses on three basic questions: What constitutes a "low-temperature" geothermal resource? What constitutes a geothermal anomaly? And why do these resources and anomalies occur in Central Texas? These questions will be addressed mainly in terms of local conditions along the Balcones/Ouachita trend near Bexar, Dallas, Falls, and Travis Counties (fig. 1). Warm ground water occurs in each of these areas, yet local geologic conditions are sufficiently different to allow the isolation of specific variables affecting geothermal resources. This affords different perspectives in addressing the three questions posited above.

A general geologic and hydrologic framework has already been established for the Balcones/Ouachita trend (Flawn and others, 1961; Woodruff and McBride, 1979; Woodruff and others, 1982). These studies include data on stratigraphy and structure of the various aquifers and on the chemistry and hydrodynamics of ground water. It is our aim to bring these diverse data to bear on our three questions.

First, we present a synopsis of the geologic conditions along the Balcones/Ouachita trend. Next, we address the problems in defining low-temperature resources and in recognizing anomalies. Finally, we assay local geologic and hydrologic conditions in terms of ambient thermal regimes, and in this way we present hypotheses for the origin of thermal waters.

GEOLOGIC CONTROLS--THE OUACHITA BASEMENT

The foundered Ouachita Belt is the fundamental control on the geology of the region. Its origins are obscure, but its effects are apparent. It has localized processes as diverse as sedimentation, faulting, emplacement of igneous plugs, and the actions of a variety of sediment/water processes such as diagenesis, secondary porosity development,

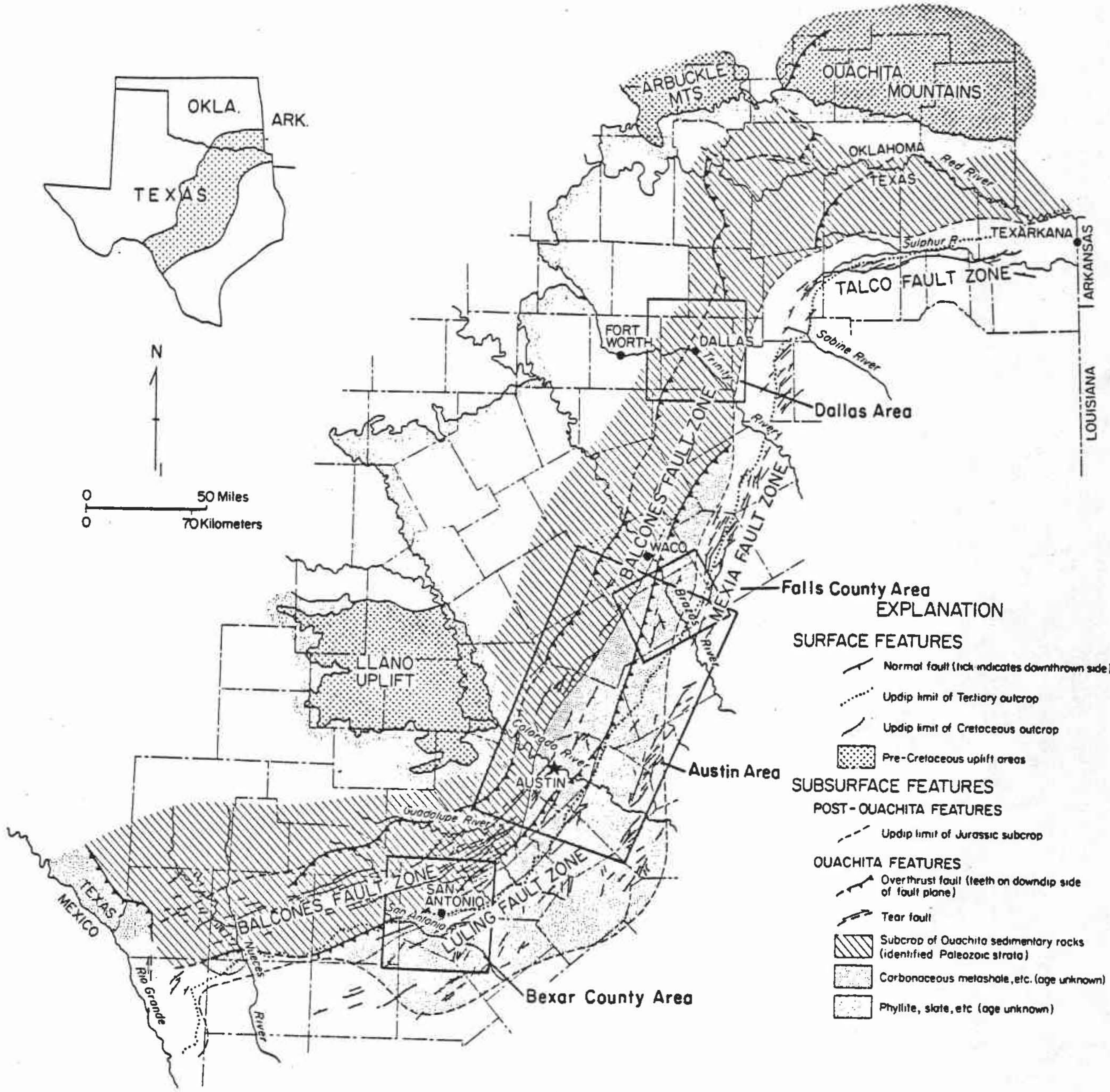

Figure 1. Regional tectonic features of Balcones/Ouachita trend and locations of case-study areas.

hydrothermal mineralization, and the maturation, migration, and entrapment of hydrocarbons. Tectonic development of the Ouachita Belt has ultimately been responsible for the landscapes and soils seen today within the region. The ongoing hydrodynamic evolution of the region also affords potential for yet-to-be-discovered economic resources at depth.

The Ouachita Belt consists of a steeply dipping, folded, overthrusted, and locally metamorphosed Paleozoic basement complex. It provided a subsiding substrate on which Mesozoic sediments were deposited along the western edge of the Gulf Coast Basin. It was also--along with pre-Ouachita uplift areas such as the Llano Uplift, the Muenster/Red River Uplift, and the Devils River Uplift--a source of sediment for initial clastic deposits in the western Gulf region. By controlling gross geometry of depositional systems as well as composition and texture of sediments, favorable avenues for ground-water flow were established early. Ongoing subsidence and tectonism resulted in faulting--both contemporaneous with sedimentation and subsequent to deposition. These faults afforded further avenues for ground-water flow, or in some instances they imposed hydrodynamic barriers.

The sum of these processes is seen in the persistent changes in hydrologic regimes across the Ouachita hinge. For Mesozoic strata, this structural trend marks the general basinward limit of downward-flowing, relatively fresh meteoric waters and the interface with upward-flowing, brackish to saline (commonly thermal) waters. These changes all occur within a relatively short traverse from craton to basin.

The Ouachita Belt consists of both frontal and interior zones of thrust faults (Flawn and others, 1961). The frontal zone involves unmetamorphosed or weakly metamorphosed Paleozoic strata. The interior zone is made up of metamorphic rocks, commonly phyllite and schist, whose age is not firmly established, although tentative findings during this survey indicate a Precambrian age at one locality (A. El Shazly, written communication, 1981). This metamorphic complex was long regarded by geologists as "basement." Conventional hypotheses held that once this metamorphic basement complex was reached further permeable strata at any greater depth would be unlikely. Hence, except for a few notable ventures (Nicholas and Rozendal, 1975), petroleum explorationists have generally avoided drilling into the Ouachita Belt.

Now this situation has changed. Plate tectonics affords a model whereby one might expect a metamorphic belt to overlie a stratigraphic section. Deep gas fields discovered in the Western Overthrust Belt of Utah and Wyoming provide economic incentives for testing these new paradigms elsewhere. Thus far, no hydrocarbons have been located beneath the interior thrust zone, but discoveries have been made in the frontal zone in the Ouachita Mountains of Oklahoma, the Marathon Uplift of West Texas, and within the buried Ouachita Belt in Grayson County, Texas (Petzet, 1982). The increased interest in this belt for deep gas (the generally accepted target horizons are the Ordovician and Cambrian limestones--Ellenburger and older) will stimulate drilling and thus disclose new data along this trend.

These data may also demonstrate new geothermal potential at depth. In that regard, one encouraging data point is a deep test (Mobil No. 1 Adams) near Marathon in Brewster County, Texas, where the well penetrated several imbricated thrust sheets and ultimately tested the Ellenburger limestone at 10,600 ft (3,231 m). At that depth, a drill-stem test indicated remarkably fresh water (a chloride content of only 350 mg/L) with a bottom-hole temperature of 308°F (153°C). The geothermal gradient at this point is 2.32°F/100 ft (42.3°C/km). If the Ellenburger produces this quality of water at similar depths along the buried Ouachita trend (either along the frontal or the interior zone), this would be an exceptional geothermal resource. If such temperatures persist, we are clearly not dealing merely with a "low-temperature" geothermal resource, but with one that has higher use potentials--including perhaps the generation of electricity.

As mentioned, data are sparse on quality and quantity of fluids produced within or beneath the Ouachita Belt. Hence, we resort to various indirect avenues of inquiry to delineate promising areas for enhanced geothermal potential along the buried part of this orogen. One method that will be discussed is the use of lineaments as an aid in detecting structural discontinuities at depth. These discontinuities--especially major lateral adjustments along an overthrust belt--may indicate promising areas to explore for hydrocarbons within the thrust zone. Such a discontinuity may also affect superjacent strata and enhance geothermal potential at these shallower depths as discussed in the case study of the Austin area.

As part of our ongoing assessment, we did obtain some new data that bear directly on the buried Ouachita orogen. One well in Bexar County, Pagenkopf No. 1 Blum, has been recognized as penetrating an anomalous section of nonmetamorphosed rock. Previous workers (for example, Flawn and others, 1961; Morgan, 1952) postulated that this material represents late Paleozoic sedimentation. Analysis (by El Shazly) of Rb/Sr ages of the clay fractions of these red beds showed an age as young as 136.7± 2.6 million years, indicating deposition during earliest Cretaceous time. Geometry, lithology, and age of these deposits strongly suggest the presence of grabens formed along the edges of the post-Ouachita rift zone. These grabens are similar to those containing the Triassic Newark Group of the eastern United States, but more work is needed in Texas to pursue these similarities further.

WHAT CONSTITUTES A GEOTHERMAL RESOURCE?

Definition

Low-temperature geothermal resources are defined rather arbitrarily. The U.S. Geological Survey (Sammel, 1979), in its evaluation of this resource base, stipulates that these water temperatures must be less than 90°C (194°F) but at least 10°C (18°F) above the local mean ambient air temperature. Furthermore, water produced from wells must show a geothermal gradient of at least 30°C/km (1.64°F/100 ft)--a value supposedly average for continental areas.

We have adhered to only part of this definition in our assessment of geothermal resources in Texas. We accept the variable lower limit keyed to ambient air temperature because shallow nonthermal ground water generally equals or is slightly above mean ambient air temperature at any location. This is true because recharging water represents a sampling of rainfall throughout the year, and thus recharging meteoric water provides an average across a range of temperatures. Moreover, shallow ground temperature approximates mean ambient air temperature, and in any area this stable ground temperature is a baseline for determining geothermal gradient. As we have found no hydrothermal waters in Texas as hot as 194°F (90°C), the upper limit is moot, although future deep exploration within the Ouachita Belt may change this. We do not, however, adhere to the gradient criterion because of uncertainties in determining the exact depths from which most water wells produce, and the total depth of such wells is an inaccurate variable by which to compute geothermal gradient based on water temperatures. Meanwhile, we are attempting to refine water temperature data in terms of precise producing zone, and considerable attention is given to this problem in some of the case studies presented herein. At any rate, many wells in Central Texas produce potable water in the "thermal" range (at least 18°F, or 10°C, above ambient) but apparently not with the requisite gradient. Adherence to this arbitrary criterion would result in a failure to recognize (and perhaps use) a potentially sizeable local resource.

Even beyond our more expansive definition of a low-temperature geothermal resource, other nonthermal ground waters also contain vast amounts of energy. This is because of the high specific heat of water, the insulation and thermal stability afforded by the aquifer, and the wide seasonal fluctuations in air temperature. The caloric value of ground water with its year-round mediated temperature is the basis for the design and use of ground-water heat pumps that provide both heat in winter and cooling in summer. In short, despite the fact that 77°F (25°C) ground water is a thermal resource on a day in which air temperature is 32°F (0°C), we have assayed only those waters having temperatures constantly hotter than the local average by the requisite 18°F (10°C). These we call low-temperature geothermal resources. Other, nonthermal ground water also warrants study for its caloric content, but it is beyond the scope of this survey.

Water and Heat

Geothermal resources are localized by the actions of two underground fluxes: water and heat. The two flows interact. Water, because of its high thermal inertia, is a major medium for the storage and transfer of heat. Heat, on the other hand, may influence water's physical and chemical properties, which in turn locally affect the flow of ground water through porous media. Ground-water flow is described by Darcy's Law; conductive heat flow is described by Fourier's Law (the heat-flow equation). The two equations are analogous and both assume the form

$$Q = -KAG$$

in which the flow in question (Q) equals the conductive properties of the rock medium (K), times the cross-sectional area studied (A), times a gradient (G). The minus sign indicates a negative linear function on a Cartesian graph. The individual variables of Darcy's Law, Fourier's Law, and Ohm's Law are presented in table 1.

Both water and heat within the earth represent energy reservoirs. Their flows are transfers of thermal and kinetic energy from areas of high potential to areas of low potential. The energy content of most relatively shallow ground water is exogenetic--that is, it is derived from the action of solar energy on earth materials (specifically, on water via the hydrologic cycle). In this way, the thermal content of shallow ground water

Table 1. Comparison of Darcy's Law, Fourier's Law, and Ohm's Law (after Guyod, 1946)

Heat Conduction	Hydrodynamics	Electrodynamics
$Q = \frac{df}{dt}$	$Q = \frac{df}{dt}$	$I = \frac{df}{dt}$
(heat flow per unit of time)	(fluid flow per unit of time)	(current flow per unit of time)
K	K	C
(thermal conductivity)	(hydraulic conductivity)	(electrical conductivity)
T	H	V
(temperature)	(pressure)	(potential)
$\frac{dT}{dz}$	$\frac{dH}{dl}$	$\frac{dV}{dx}$
(thermal gradient across path length, z)	(pressure gradient across path length, l)	(potential gradient across path length, x)
$Q = -KA \frac{dT}{dz}$	$Q = -KA \frac{dH}{dl}$	$I = CA \frac{dV}{dx}$
(Fourier's Law, the Heat-Flow Equation)	(Darcy's Law)	(Ohm's Law)

A = path cross section; minus sign indicates negative slope on Cartesian graph.

is a function of ambient climatic conditions. Heat flow is derived endogenetically. It is the result of radioactive decay deep within the earth. This thermal energy drives tectonic processes, and byproduct heat that does not perform work flows to areas of low thermal potential (that is, generally toward the earth's surface).

The underlying premises of the heat-flow equation are that radiogenic heat flows upward by means of solid-state conduction and that the main controls on this flow are the other two variables of the heat-flow equation: thermal conductivity within the rock column and geothermal gradient. Porosity is generally acknowledged as an influence on thermal conductivity, and there are empirical adjustments for this value if the pore spaces are filled with water. However, little work has been done with the transfer of heat by water as controlled by grain-to-grain Darcy flow (not by convective processes). Mathematical descriptions of the simultaneous transfer of water and heat have been published by Bredehoeft and Papadopulus (1965), but this knowledge has not been widely applied to the evaluation of geothermal resources.

Yet in most near-surface areas--that is, wherever open pore space within rock allows the two-phase (rock/water) system to exist--ground-water flow, not heat flow, is the dominant factor in determining local thermal regimes. Downward-flowing, recharging ground water depresses local thermal gradients; upwelling waters cause increases in these gradients. Both effects may occur without any change in conductive heat flow from below. There are, however, changes in apparent heat flow. Such misleading measurements are a result of a stratum's containing upward-flowing (hence warm) water at an anomalously shallow depth. In such instances, the heat-flow measurements "sense" the heat conducted from the water source instead of a (presumed) deeper crustal source. Although ground water may be either a heat source or a heat sink, shallow boreholes 50 to 500 m deep are commonly employed to measure presumed heat flow. In actuality, instead of measuring a variable in the heat-flow equation, they are often measuring the influence of Darcy's Law. That is, the variables of the Darcy equation may obscure the variables in the heat-flow equation, so that water flow (not conductive heat flow) often dictates local thermal regimes. In our statewide survey we have located areas: (1) where recharging waters have apparently depressed local thermal gradients; (2) where nonthermal ground water absorbs upward-flowing heat, thus decreasing a thermal anomaly; and (3) where upward-flowing ground water has created a false anomaly, that is, one not resulting from anomalously high conductive heat flow. Thus, although the heat-flow equation is generally applied to the assessment of geothermal resource potential, its application is only partly warranted. And it is sometimes highly misleading if one assumes that a high geothermal gradient results simply from low thermal conductivity in the rock column where the measurement is made or from high vertical heat flow.

In summary, conductive heat flow, being endogenetic, varies geographically according to tectonic conditions, crustal thickness, composition of crustal materials, and the like. Ground-water flow, on the other hand, is largely the result of exogenetic processes (the hydrologic cycle) acting on local rock properties (porosity and permeability). The thermal properties of shallow ground water may also result from the storage and transfer of solar energy by water, so that ground water often intercepts heat flow and thus lessens endogenetic thermal effects. Clearly, both Darcy's Law and the heat-flow equation must be considered in the evaluation of thermal resources in any area.

Geothermal Anomalies

The delineation of an anomaly assumes the recognition of a norm. For most geothermal data, however, a norm has not adequately been established. Thus, we have the arbitrary definition of thermal waters predicated on a so-called average geothermal gradient of 1.64°F/100 ft (30°C/km). But what do the actual well data show in Texas? They show different things, depending on which particular data are observed. The two fundamentally different data sets include: (1) wells that actually produce ground water having a reliable, measurable temperature; and (2) wells for which downhole (bottom-hole) temperatures (BHT) are measured.

Water wells clearly show the influence of Darcy's Law on underground thermal regimes; that is, there is only a general positive increase in temperature with depth. Temperature/depth plots show wide scatter, owing to (1) uncertainties about exact vertical locations where the ground water enters the well bore; (2) downward-flowing recharge waters that lessen the effects of conductive heat flow; and (3) local upward-circulating waters of higher temperatures. Just as plots of temperature with respect to depth show a wide scatter for ground-water data, the derivative plots--those of geothermal gradient with respect to depth--also commonly show an inchoate pattern. No average geothermal gradient may be discerned from most plots of this kind.

Wells that have BHT measurements generally show a more orderly temperature-to-depth relation. This is mainly due to the extensive vertical intervals through which these measurements are made. BHT values are recorded across a range of depths that may span up to tens of thousands of feet, whereas most ground water is produced across a range of only a few hundred to a few thousand feet. The general increase of bottom-hole temperature with depth persists although there are deviations, and these may result from actual thermal aberrances or from incorrect temperature or depth measurement owing to any number of reasons.

As mentioned earlier, many researchers assume that--since geothermal gradient is a variable in the heat-flow equation--these gradient data reflect local heat-flow regimes. In the most general terms this may be true. On a statewide map of geothermal gradients of Texas (American Association of Petroleum Geologists and U.S. Geological Survey, 1976) West Texas is predominantly a region of relatively low gradients, whereas the Gulf Coast region has somewhat higher gradient values (Woodruff and others, 1981). These data generally conform to the heat-flow equation, in that most wells completed in the Permian Basin and surrounding areas are completed in limestones. Since limestone has a high thermal conductivity, a low geothermal gradient is expected; and some of the lowest gradient values in the state occur in the Permian Basin. The Gulf Coast region has a predominance of wells (at least those penetrating the Tertiary section) completed in sands and muds, the mud thicknesses being much greater on the average than those for sands. Since mudstones and shales have lower thermal conductivity values than limestones or sandstones, higher geothermal gradient values are expected there, and they do occur.

However, this simple statewide relationship breaks down when scrutinized. For example, the Balcones/Ouachita trend is the locus of highest geothermal gradient anomalies in the state, yet it is difficult to account for these anomalies on the basis of the heat-flow equation. Many wells along this trend are completed in rocks having high thermal conductivity: limestones, sandstones (high sand-to-mud ratios typically occur along this trend, as it lies close to source areas or along major deltaic distribution areas), and at depth, metamorphic rocks. High thermal conductivities along this trend suggest that geothermal gradient values should be depressed there, but clearly they are not.

High geothermal gradients may be accounted for by high conductive heat flow. However, such a flow must be very high indeed to cancel the effects of the strata having high thermal conductivity along the Balcones/Ouachita trend. High heat flow may result from (1) igneous bodies that are still warm--a condition that probably does not exist in the upper crust anywhere in Texas; (2) localized sources of radiogenic heat, such as felsic plutons buried by insulating sedimentary deposits, as described by Costain and others (1980); and (3) various other sources, such as exothermic chemical reactions, or a highly conductive rock (such as salt) that provides a mechanism for upward conveyance of heat but is capped and insulated at a relatively shallow depth. Moreover, since the variables in Darcy's Law may be substituted for values in the heat-flow equation, a high geothermal gradient may result from a high heat flow that is not a result of solid-state conduction nor from convection in the usual (thermal) sense of the term. Instead, a high value for "Q" on the left side of the heat-flow equation may be due mostly to the influence of relatively hot (upward-moving?) intergranular water--in other words, to the "Q" in Darcy's Law.

Geothermal Gradients in Central Texas

It is clear that a meaningful analysis of geothermal gradient data involves answering two questions: What constitutes an anomaly? What processes are responsible for a given anomaly? As part of our area-specific investigations in Central Texas, we addressed these questions first in a regional context and then in a local one.

Several constructs of contoured geothermal gradient values exist for the Central Texas region (American Association of Petroleum Geologists and U.S. Geological Survey, 1976; Woodruff and McBride, 1979; Woodruff and others, 1982). However, these maps are generally unsatisfactory because of the uncertainty about what factor(s) may be causing an anomaly in a given area. The raw data for these maps contain measurements for a range of depths and numerous rock units in various structural settings. Hence, even if the heat-flow equation were the sole governor of thermal anomalies, neither of the two other variables in that equation is isolated. A positive anomaly at any locale might be due either to high conductive heat flow or to low thermal conductivity. Furthermore, wide variations in temperature/depth conditions within a single well (for multiple runs) or for adjacent wells cast doubt on some of the so-called anomalies that have previously been mapped. Finally, there is the aforementioned influence of Darcy's Law, and the uncertainty that this casts on any uncritical depiction of geothermal gradient.

With these constraints in mind, we attempted to refine the geothermal gradient picture in Central Texas and, in so doing, to assay both the boundary conditions of geothermal anomalies in this area and the causes of these anomalies. Three tasks were involved in this reassessment. We first constructed a new average geothermal gradient map for Central Texas. We then constructed a series of contour maps of geothermal gradients for specific horizons. Finally, with geothermal gradients arrayed in both plan view and in cross section (for certain specific stratigraphic horizons), we were able to discriminate expected geothermal gradient norms with which local anomalies may be compared. These data also provide clues to the origin of certain apparent thermal perturbations.

Geothermal Gradient--A Moving Average

There is a great amount of uncertainty inherent in geothermal gradient data. These uncertainties have been discussed at length by Woodruff and others (1982); they exist because the measurements of downhole temperatures are conducted merely to calibrate electric log response and not to determine internal temperatures of the earth. So in using BHT values for geothermal evaluations, one is using not only second-hand data but also data that were intended for another purpose altogether. Moreover, there are often pragmatic standards for collecting and recording BHT values, and such standards may not favor high accuracy and precision. In short, the "acid test" for the technician who runs the logging device is a readable (electrically responsive) log. The actual downhole earth temperatures are incidental to this process.

We employed a moving average to dampen out lateral and vertical discontinuities in geothermal gradient values. In conducting this moving average, we disregarded any BHT readings from less than 2,000 ft of depth (we presumed this to be the locus of influence from surface effects--an assumption that is called into question by later data). In brief, the 2,000-ft data may still be too shallow to escape surface thermal perturbations. But note, nonetheless, that the depth commonly ascribed to interferences from surface phenomena is 1,000 ft. For each well with one or more measurements deeper than this

2,000-ft datum, we recorded a single value for geothermal gradient. Where more than one measurement (run) exists for a single well, we computed and averaged geothermal gradients for the various depths. Finally, we superimposed a grid on this map of gradient values and performed a moving average. This was done at a scale of 1:500,000 with a unit cell size covering 996 mi^2 (2,580 km^2) with 249-mi^2 (645-km^2) centers. Thus each well was averaged with the gradient values in four adjacent grid cells.

The resulting map of average gradients (fig. 2) is somewhat different from previous renditions of geothermal gradient. The so-called anomalies (areas of relatively high geothermal gradient) generally align with structural features such as fault zones (either at the surface or at depth) and areas of uplift. As noted by Woodruff and McBride (1979) and by Caran and others (1981), the overall trend of geothermal gradient anomalies generally aligns with known discontinuities along the Ouachita Structural Belt. But what is the content of these anomalies? Are they indicators of relatively shallow crustal heat sources such as the buried felsic plutons of the Atlantic Coastal Plain (Costain and others, 1980)? Or might they represent another sort of conductive heat source? Alternatively, what role might basinal hydrodynamics play in these areal differences?

Factoring Out Thermal Conductivity

To identify the origin of the variations in these geothermal gradients, we constructed separate maps for selected stratigraphic horizons. By assuming constant lithic properties and hence constant thermal conductivity within a stratigraphic horizon, we factored out thermal conductivities as a variable. However, some caution is still needed even with these refined data, because inhomogeneities do exist within any rock unit. In general, though, limestone units should be more consistent in this respect than

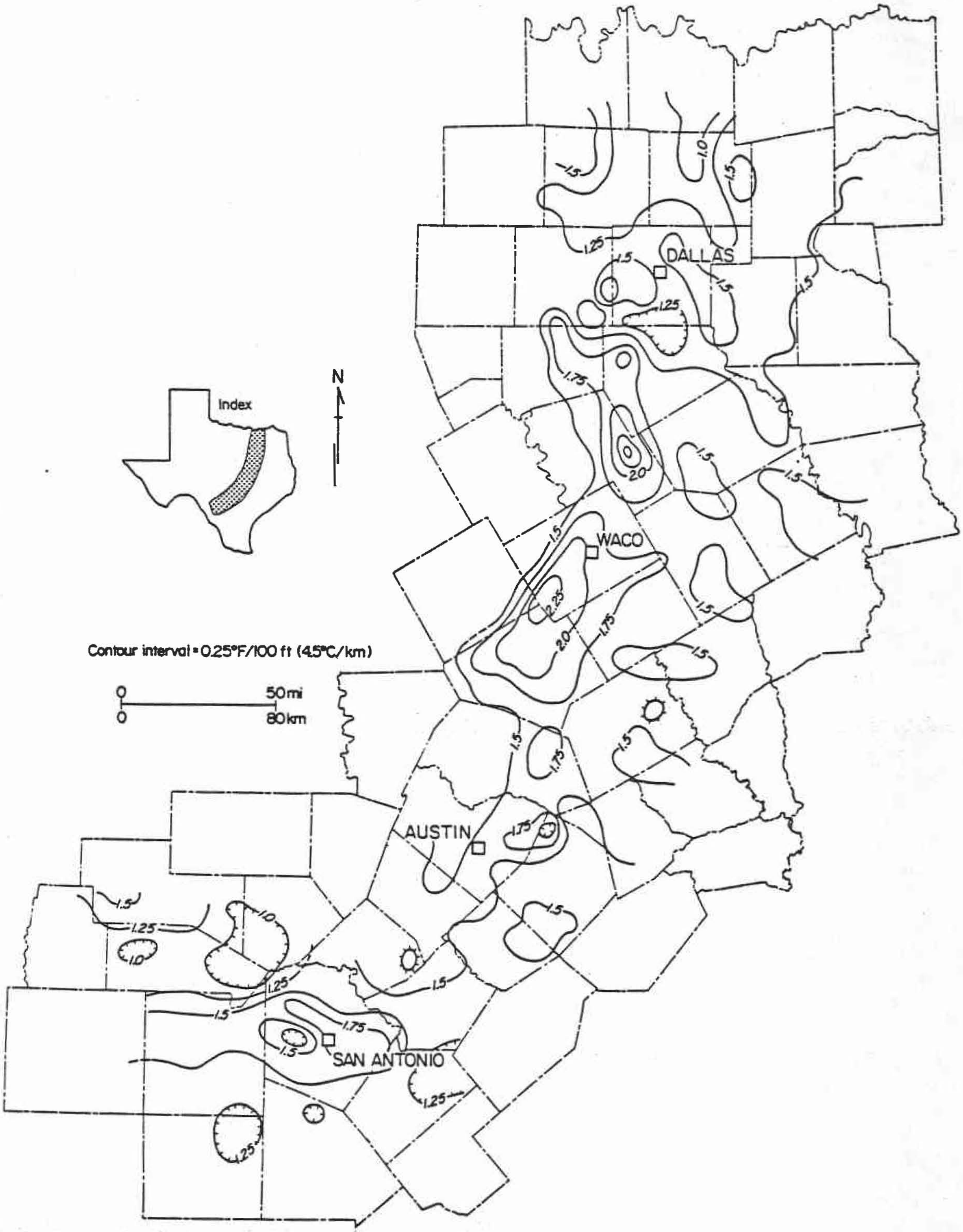

Figure 2. Moving average of geothermal gradients along part of the Balcones/Ouachita trend.

sands; therefore, we have focused especially on two limestone horizons: the Edwards and the Sligo Limestones (fig. 3). Geothermal gradients are also presented for the Hosston-Trinity Sands (fig. 4).

These constructs demonstrate two relations that are important in determining the source of differences among gradient values. First, the anomalies for various strata in the same area do not necessarily overlie one another. Yet physical continuity requires vertical correlation in the shape of gradient contours, even if the absolute values vary according to the thermal conductivities of specific strata. This is because heat flow should be constant in a vertical column. The gradient maps show deviations from one stratum to another, and this indicates that conductive heat flow is not the cause of these areal thermal variations. Second, a comparison of these gradient values to the general structural configuration of the horizons in question shows a marked correlation between areas of relatively high gradients and shallow depth. This indicates perturbations of the thermal regime owing to surface influences. If this is so, it poses questions regarding the validity of even the 2,000-ft datum (not to mention the conventional 1,000-ft datum) being sufficiently deep to avoid surface influences.

Geothermal Gradient Versus Depth

We plotted geothermal gradient versus depth for selected subsurface geologic units. Although there was considerable scatter, a clear inflection in these graphs occurs at depths ranging from 3,000 to 4,000 ft (approximately 1 km). At depths shallower than this, there is a general decrease in geothermal gradient with depth. Deeper than 4,000 ft, the gradient values do not vary systematically with depth. These general findings hold true for different rock units having markedly different thermal properties (compare figs. 5, 6, and 7).

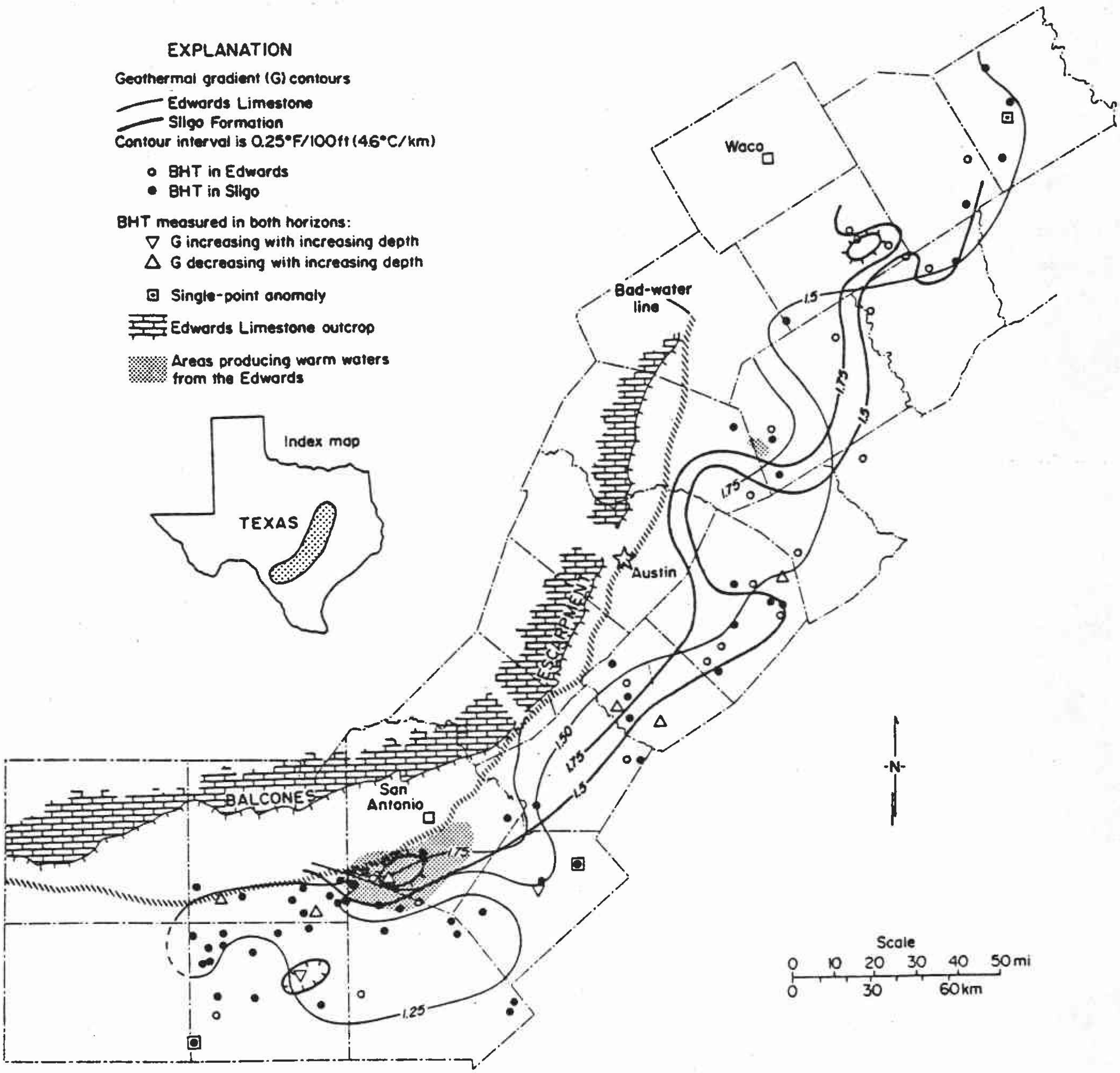

Figure 3. Geothermal gradients contoured for Edwards Limestone and Sligo Formation (from Woodruff, 1982).

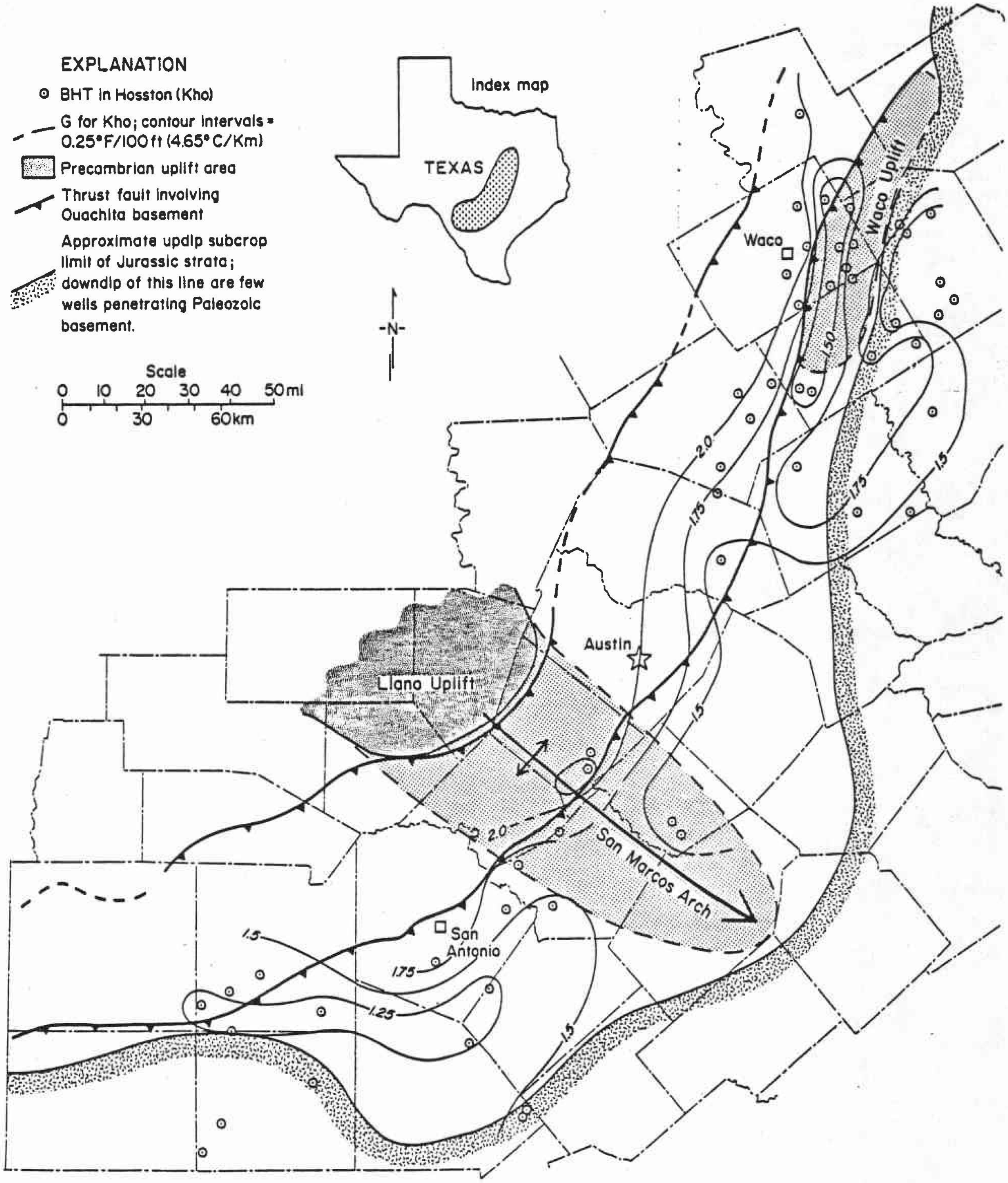

Figure 4. Geothermal gradient contours for Hosston/Trinity Sands.

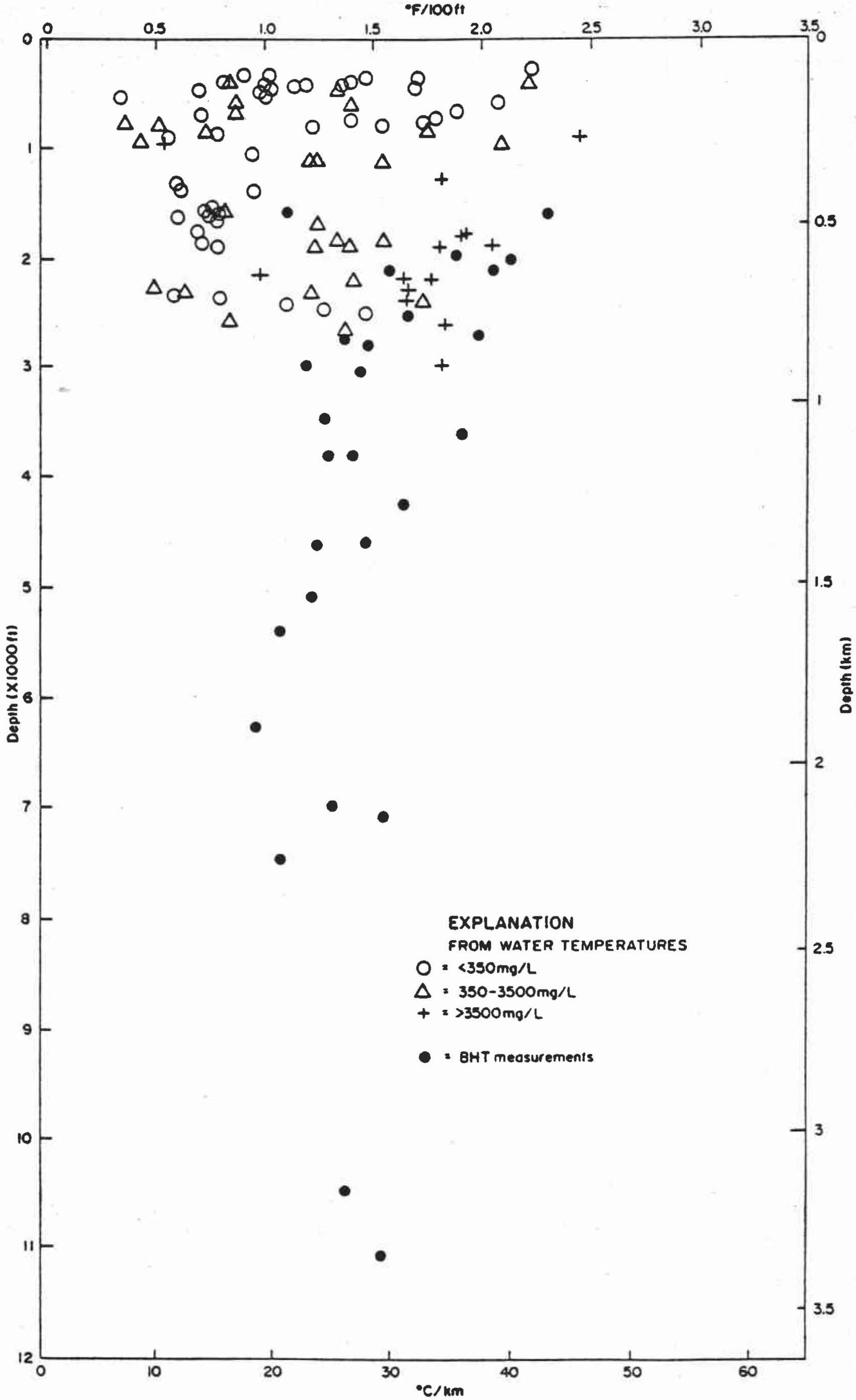

Figure 5. Geothermal gradient with respect to depth for Edwards Limestone; data derived from water temperatures and BHT measurements (from Woodruff, 1982).

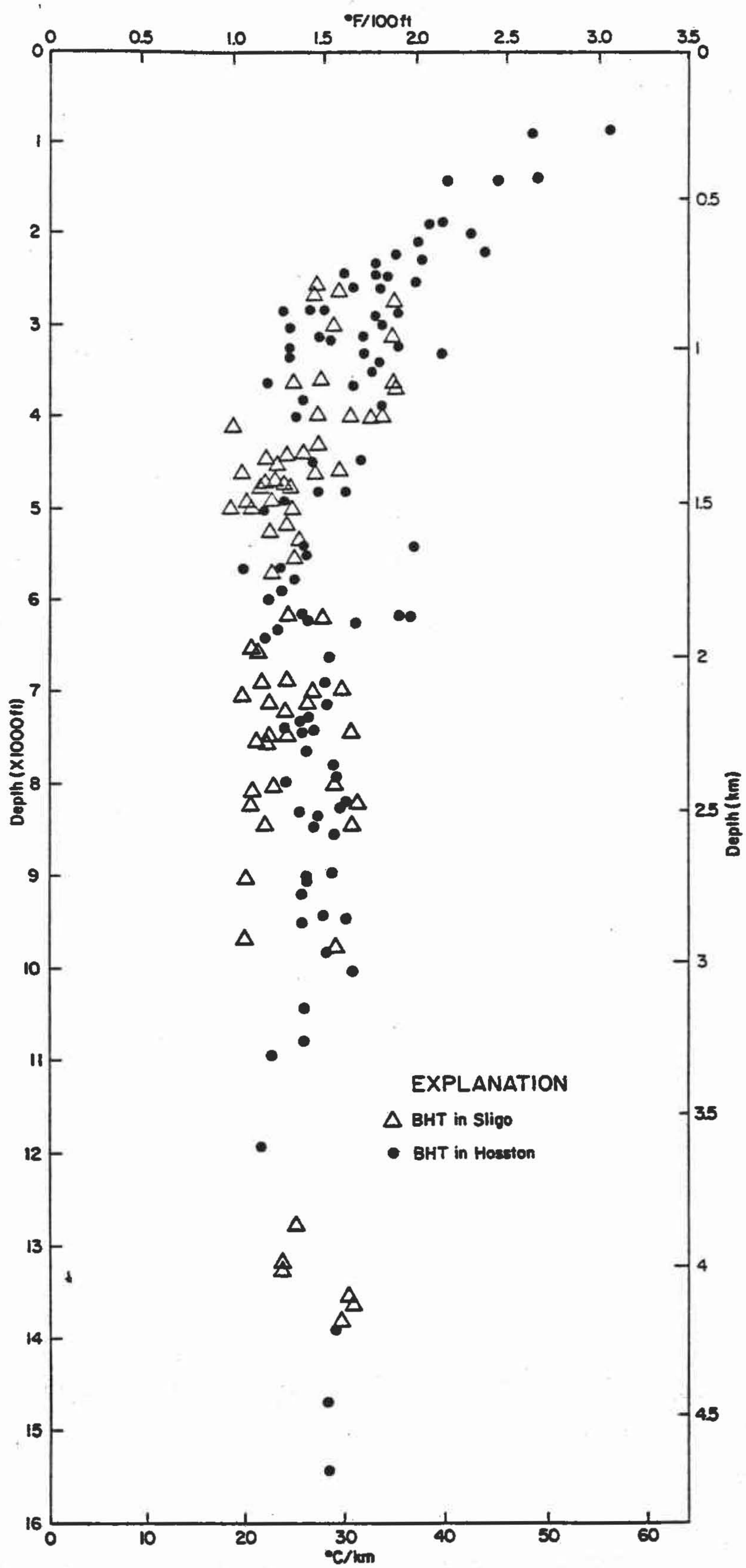

Figure 6. Geothermal gradient with respect to depth: Hosston and Sligo Formations.

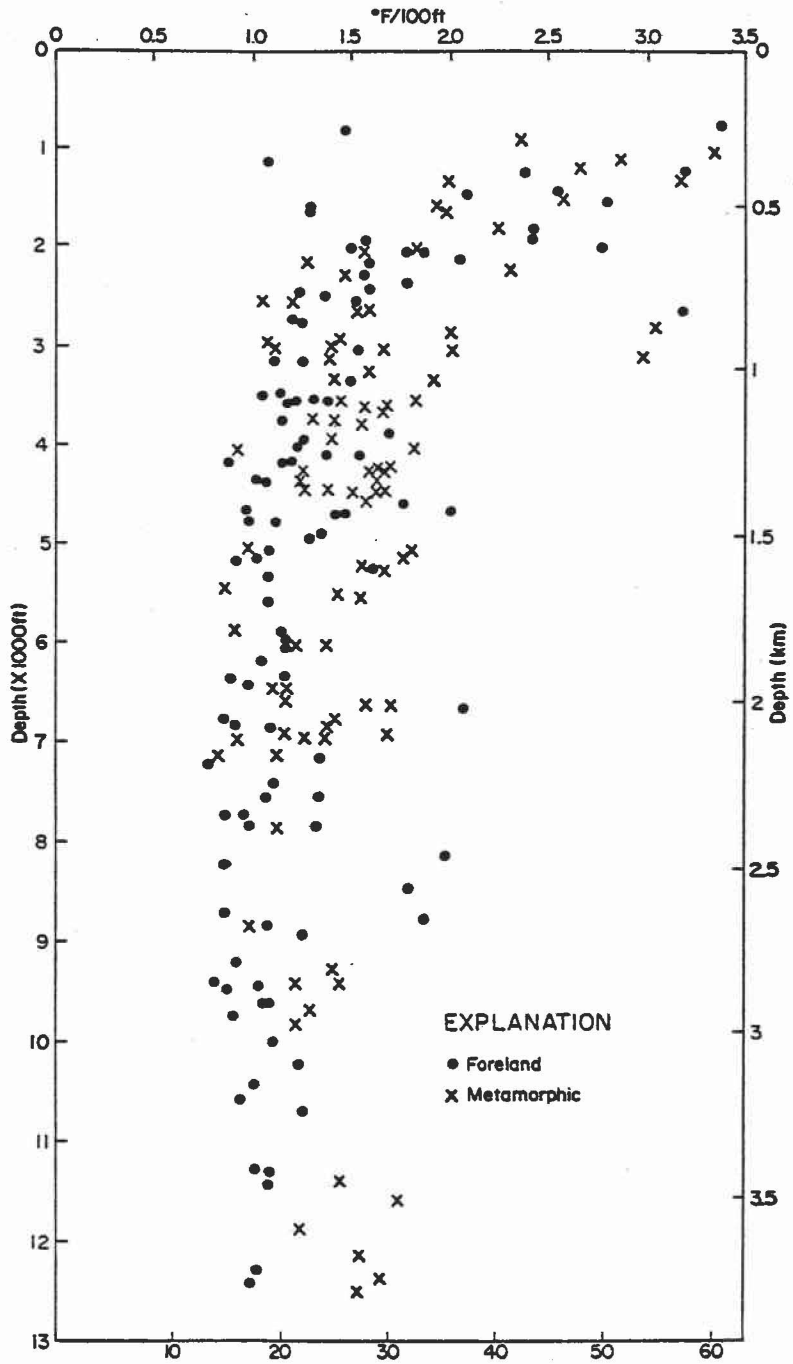

Figure 7. Geothermal gradient with respect to depth: Paleozoic Ouachita complex, Central Texas.

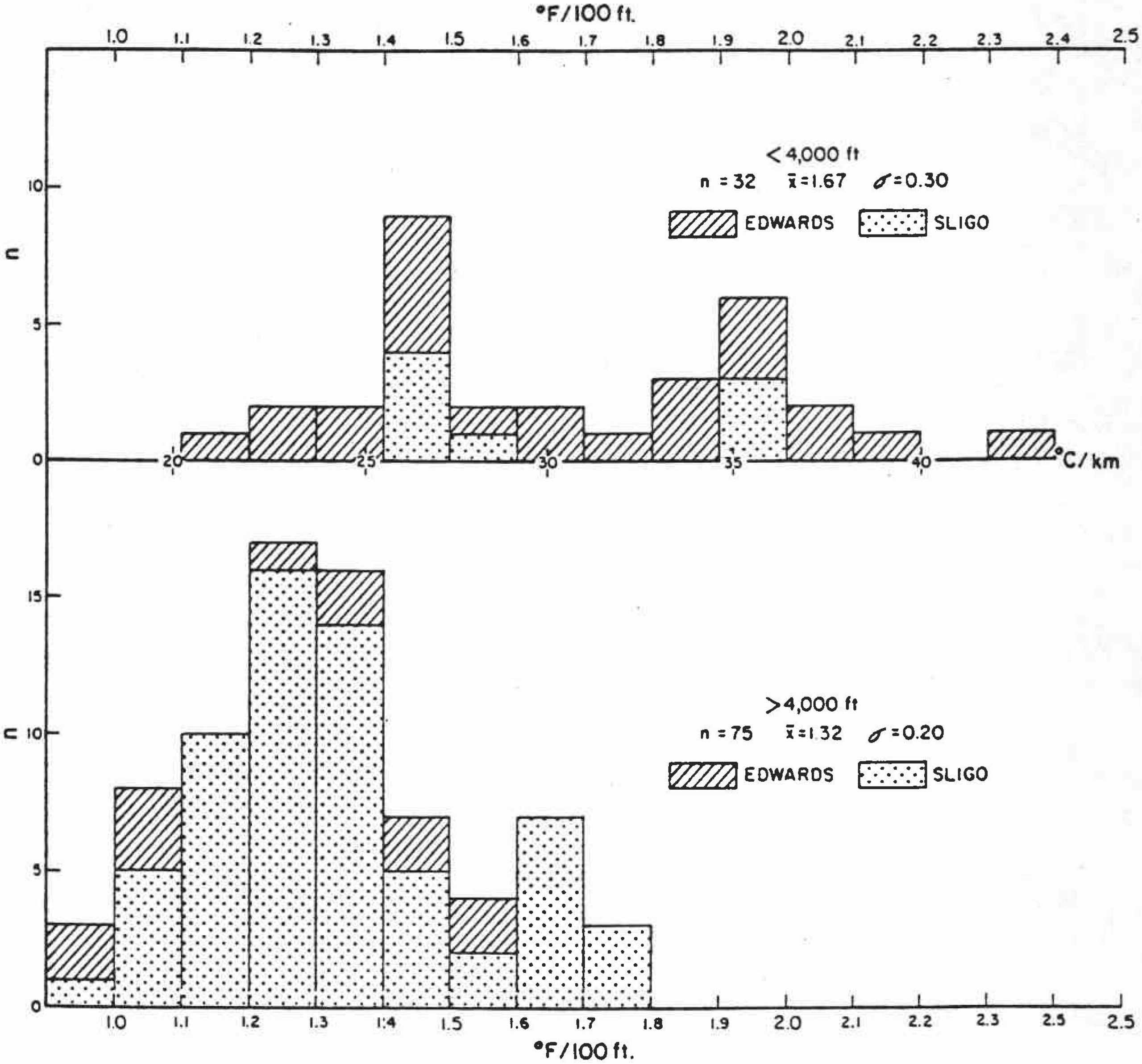

Figure 8. Histograms showing distributions of geothermal gradient values above and below the 4,000-ft (1.2-km) datum: Edwards Limestone and Sligo Formation (from Woodruff, 1982).

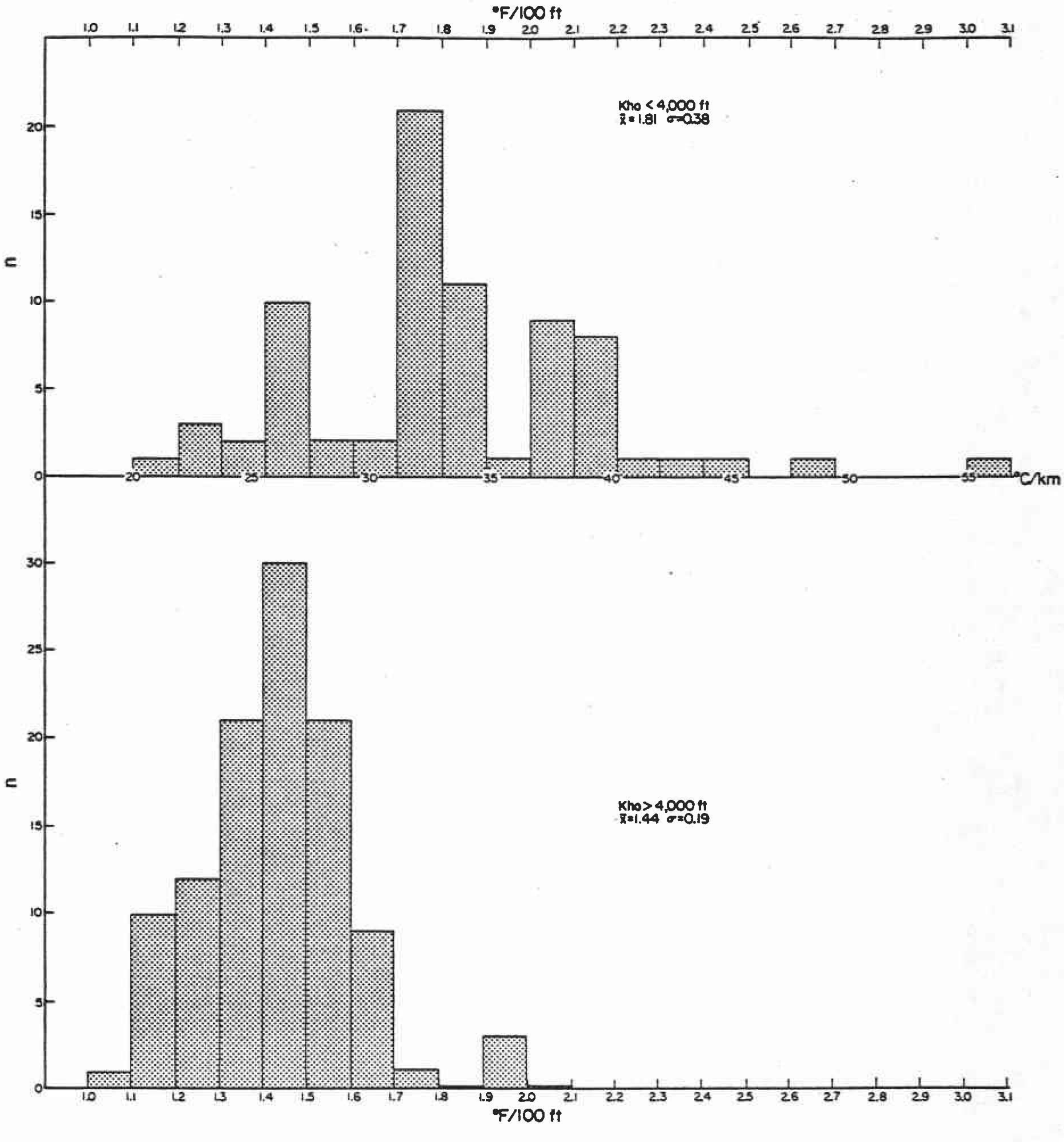

Figure 9. Histograms showing distributions of geothermal gradient values above and below the 4,000-ft (1.2-km) datum: Hosston Sand.

Histograms showing the distribution of gradient/depth data above and below the 4,000-ft level demonstrate the stabilization of geothermal gradient with depth (figs. 8 and 9). Also, the mean gradient value, where it has stabilized, is considerably less than the "average" value stipulated by the U.S. Geological Survey (Sammel, 1979). Further comparison of these data with geothermal gradients based on water temperature versus depth supports our rejecting the 1.64°F/100 ft (30° C/km) gradient criterion in defining thermal ground water. The data based on water temperatures, on the other hand, show so much scatter that no clear gradient-to-depth trend may be discerned.

The inflection in the graph of geothermal gradient versus depth has been noted by others (see, for example, Heasler, 1981), and several hypotheses have been invoked to account for the phenomenon. It may (as proposed by D. Blackwell to D. Foley, personal communication, 1981) simply reflect random error in measuring BHT or depth, and the fact that there is a tenuous connection between the measured downhole temperature and an equilibrated subsurface temperature at the point of measurement. Such a random error (or random uncertainty) should, however, show a greater scatter in the shallow reaches, similar to what is seen in the gradient data based on water temperatures. The consistent, direct, more or less linear, positive function between gradient and depth argues against this hypothesis. A second hypothesis (offered by H. Heasler to D. Foley, personal communication, 1981) is that mud temperature causes the systematic decrease in geothermal gradients with depth down to the inflection point. According to this hypothesis (developed in Wyoming), summer drilling activity will result in anomalously high mud temperatures owing to solar heating of the drilling mud pits. If most drilling is done in the summer (as in Wyoming), then the phenomenon can at least in part be explained. In Texas, however, drilling is a year-round activity, and solar heating of mud would account only for local, random aberrations and not for the systematic effects that we see. A third hypothesis (proposed by C. Swanberg and J. Costain to D. Foley, personal communication, 1981) is that compaction increases with depth. As compaction increases, so does the thermal conductivity, hence the geothermal gradient should decrease. This would account for our observations of the gradient/depth inflection for certain terrigenous sediments, but we also observe the same inflection in well-indurated limestones. Our own hypothesis is two-fold. We propose that the surface effects extend to greater depths than generally accepted, and this results in the maintenance of nearly constant water temperatures across a range of depths (owing to rapid recharge). Such a phenomenon will produce a positive gradient-to-depth line. The observed effects may also be achieved by the upwelling of basinal waters. This, we believe, can be demonstrated in several of our study areas.

CASE STUDY--EDWARDS LIMESTONE, BEXAR COUNTY AND VICINITY: Hydrologic Effects on Geothermal Gradients

The Edwards Limestone is one of the major fresh-water-producing rock units in Texas. It provides all drinking water for San Antonio, the largest city in the U.S. that is dependent exclusively on ground water. However, it has been long recognized (Pettit and George, 1956; Arnow, 1963; Klemt and others, 1979) that a major discontinuity in the Edwards aquifer occurs along the eastern part of the Balcones/Ouachita trend in South-Central Texas. This discontinuity is the "bad-water line." Across this line, water quality abruptly changes from fresh water to brackish or saline, and temperature changes from approximately that of the mean ambient air temperature of the recharge zone to thermal waters. The origin of the "bad-water line" has been variously attributed (1) to original lithic changes in the Edwards Limestone in response to downdip changes in depositional environment; (2) to structural influences--especially the influences of Balcones faulting; and (3) to the effects of regional hydrodynamics and hydrologic evolution of the aquifer.

We favor the hydrodynamic theory. Detailed investigations (Abbott, 1974) of lithic changes across the "bad-water line" indicate that original rock properties were similar over a broad area, and the changes seen today result not from original deposition but from diagenetic histories owing to the different interactions between host rock and ground water. The hypothesis favoring structural controls is also discredited because prior mapping (Woodruff and others, 1982) shows that the "bad-water line" trends oblique to faults and to the strike of the Edwards Limestone in the Bexar County vicinity. The hypothesis that the "bad-water line" is a hydrodynamic barrier suggests that there are two different genetic ground-water systems operating in the Edwards Limestone: a shallow fresh-water system denoted by rapid recharge, phreatic flow in a cavernous, well-integrated, high-porosity system, and discharge at major springs (Woodruff and Abbott, 1979); and a downdip system that is largely stagnant, is derived from deep-seated sources, receives little current recharge, and discharges brines upward along faults. This hypothesis, then, argues for upwelling of deep-seated ground waters in the "bad-water" part of the Edwards as a mechanism for producing the thermal anomalies. Data previously reported by Woodruff and others (1982)--especially the different water-chemistry suites--suggest this deep-seated origin for the brackish waters. Here we augment these data and propose further investigations.

Two sets of data converge along the "bad-water" line. These include ground-water data and data associated with petroleum exploration. Hence, in a single area and for a single geologic unit, we have considerable information on subsurface water properties--including chemistry, temperature, and various hydrologic characteristics, and we also have presumed rock temperatures for specific depths--that is, BHT/depth data (fig. 3). This convergence of the two data bases is rare, and it affords an opportunity to compare the geothermal conditions that bear on the hypotheses regarding the origin of the "bad-water line."

In considering only the information from the domain of petroleum exploration (that is, from electric logs), we note that the geothermal gradient/depth plot (fig. 5) shows a similar trend as noted for other horizons along the Balcones/Ouachita trend (compare to figs. 6 and 7). An inflection point occurs at about a depth of 1 km and a marked positive function (i.e., geothermal gradient increasing with decreasing depth) up to the shallowest measurement at approximately 1,000 ft (350 m).

The plotting of geothermal gradients with respect to depth from the ground-water data base shows inchoate scatter (fig. 5). There is, however, a pattern that is noted when the data points are discriminated according to the dissolved solids content of the respective ground-water samples. These data show that most of the high-salinity waters (TDS greater than 3,500 mg/L) lie along the same gradient trend as that derived from the BHT/depth data. Geothermal gradient/depth plots for the fresh water data set are of different slopes and encompass entirely different ranges of values. The transitional data points are more or less randomly scattered between the two end-member sets, suggesting a mixing of both meteoric and basinal waters and associated erratic thermal properties. A graph showing water temperatures with respect to depth shows a fairly orderly temperature-to-depth line for saline and transitional waters, but points in the fresh-water-producing zones are widely scattered (fig. 10). The Piper diagram (fig. 11) for all three types of waters further supports the different modes of origins of the two end members and the transitional set resulting from the mixing of the other two.

In summary, the graph showing geothermal gradient plotted with respect to depth indicates upwelling of fluids. This conclusion is based on the fact that thermal conductivity was held constant, since all measurements were made in the Edwards Limestone. Although conductive heat flow should also be constant in a vertical section, multiple measurements within the Edwards interval show different geothermal gradients in four wells in the Bexar County vicinity. Such a phenomenon is probably a result of

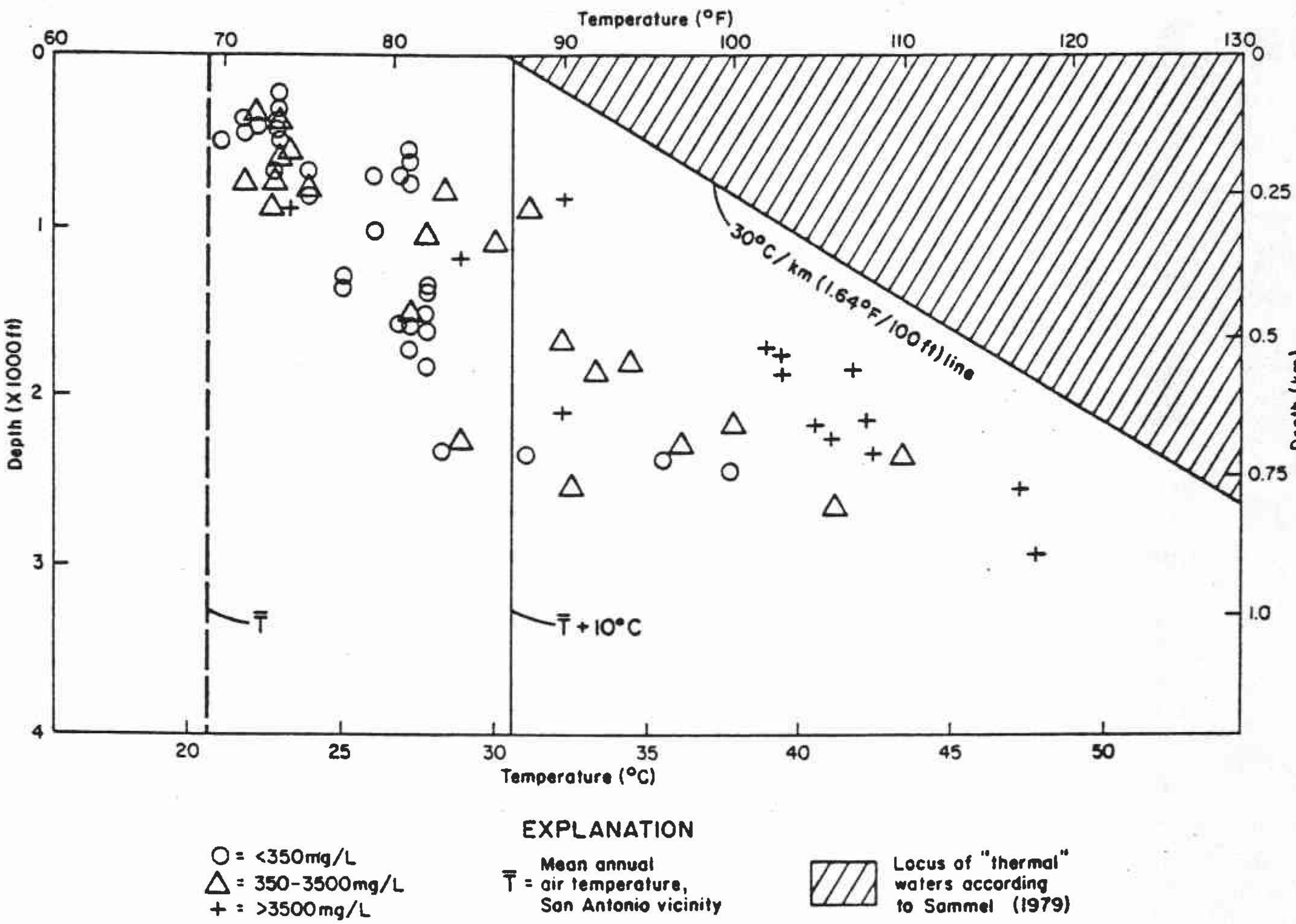

Figure 10. Water temperatures with respect to depth: Edwards Limestone, Bexar County and vicinity (from Woodruff, 1982).

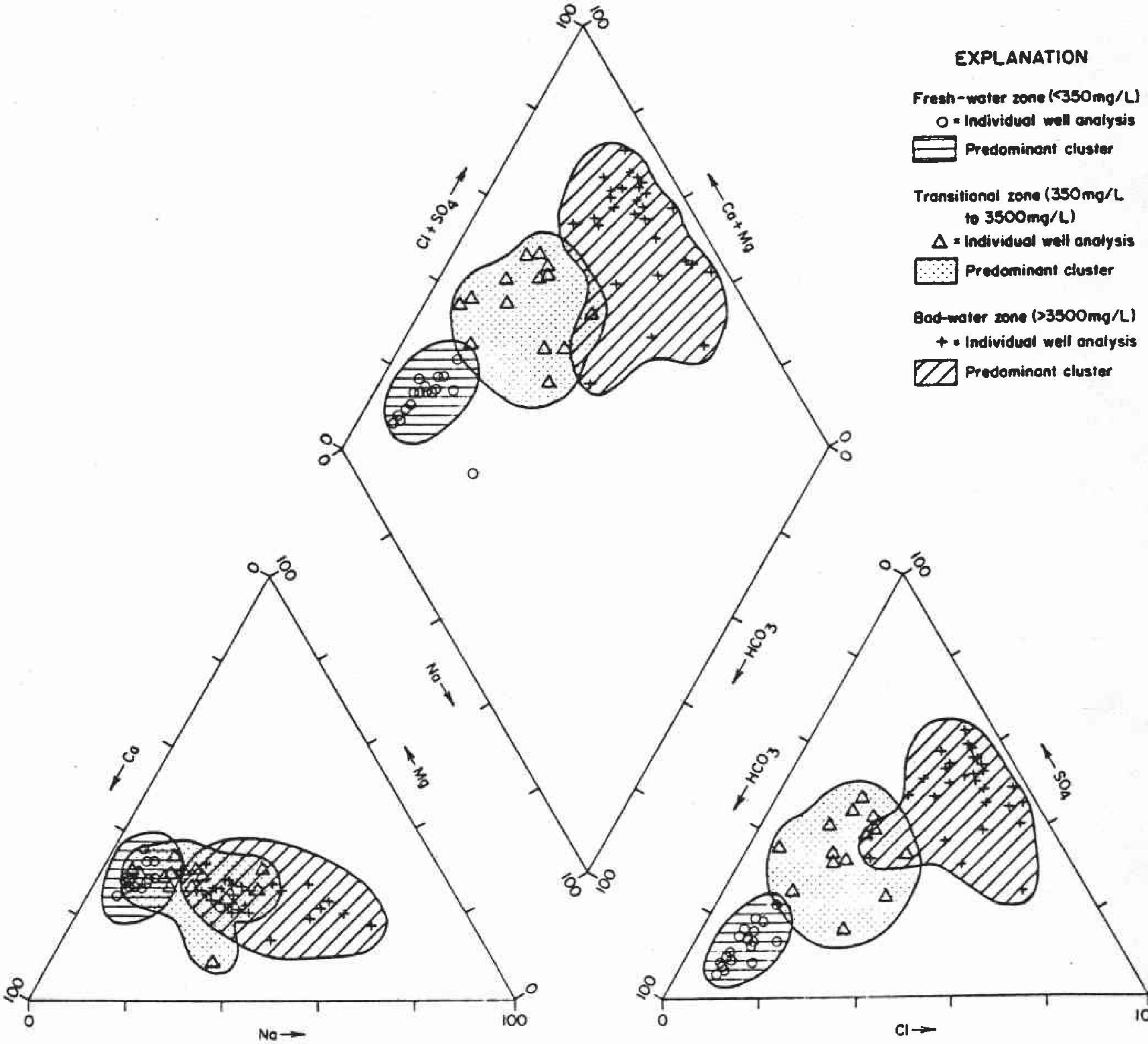

Figure 11. Piper diagram showing hydrochemical suites for ground water from the Edwards Limestone (from Woodruff, 1982).

hydrologic processes and not of conductive heat flow. These deviations may be explained in this way: in relatively high permeability rock units, such as the Edwards, ground-water circulation is sufficiently rapid to result in the same water temperature at the top and bottom of the rock unit (a vertical interval typically of 400 to 700 ft, or 122 to 214 m). This, in itself, might cause an anomalously low geothermal gradient in areas of rapid recharge and an anomalously high gradient in the deeper reaches of the aquifer.

CASE STUDY--AUSTIN AREA:
Lineaments and Geothermal Anomalies

As part of the statewide survey of lineaments in Texas, a test study was conducted in the Austin vicinity (Woodruff and others, 1982). In so doing, more time was spent perceiving lineaments in this area, and thus more lineaments were perceived. We also modified the method as described by Woodruff and Caran (1982), in that we jointly observed a mosaic of Landsat scenes in order to perceive long, throughgoing lineaments, which we term "juried lineaments." The lineaments thus perceived in this test area were compared to various other geologic and physiographic features to ascertain correlations between lineaments and documented phenomena of the solid earth. As pointed out by Woodruff and Caran (1981), in this area lineaments indicate areas of previously undocumented structural dislocations. A prominent alignment of lineaments was discovered extending from near Cameron in Milam County southeast to the Colorado River in Travis County (fig. 12). We call this alignment the Brushy Creek Lineament Zone. This zone lies along the boundary between the Blackland Prairie and the Post Oak Belt of the inner Gulf Coastal Plain and marks a major structural hinge at depth. The Ouachita interior thrust fault zone lies along this trend and--as control is lost on the Ouachita (Paleozoic) basement owing to increasing rates of dip and increases in depth--the Cretaceous section is intruded by numerous alkalic/ultramafic igneous plugs. This unusual rock type may

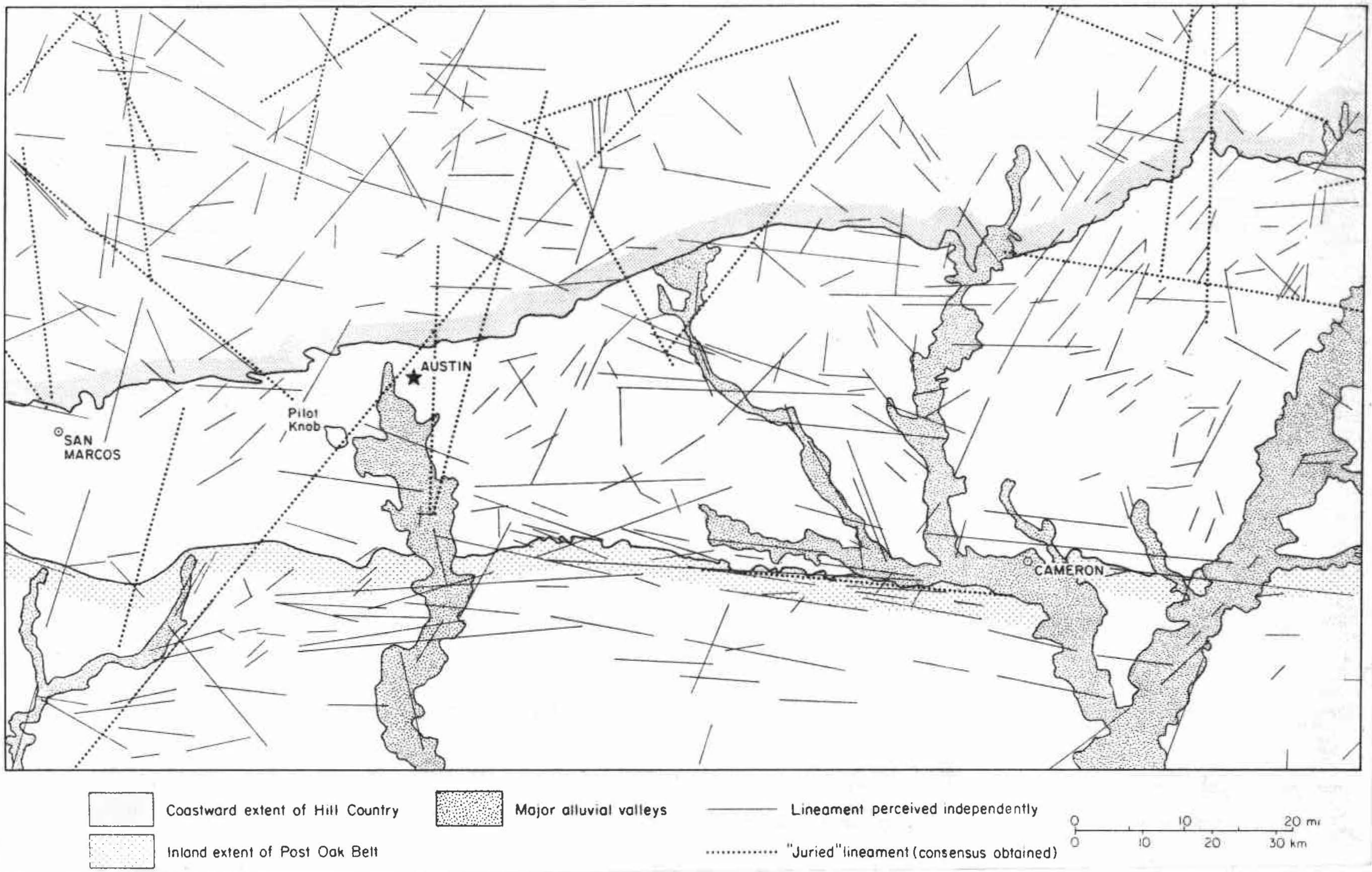

Figure 12. Lineaments perceived in the Austin area (from Woodruff, 1982).

mark the eastern edge of the foundered Paleozoic orogen and the beginning of the extensional regime characteristic of the Gulf Coast Basin. The igneous plugs also are commonly the sites of oil fields. They provide the structural trapping mechanism and the locus for upwelling, hydrocarbon-bearing waters in ways that are similar to those provided by salt domes. The upwelling associated with salt structures has been documented in both a geothermal and a geochemical context by Plummer and Sargent (1931) in their pioneering survey of subsurface temperatures in the East Texas Basin. In summary, the structural breaks noted by Woodruff and Caran (1981) document the coincidence of lineaments with numerous geologic phenomena in the Austin area. The Brushy Creek Lineament Zone, for example, apparently is a locus of upwelling similar to the "bad-water zone" of the Edwards Limestone of South Texas.

Refinements of subsurface well control allow a reconsideration of the structural setting along the Brushy Creek Lineament Zone (fig. 13). This mapping was done with additional control on the Buda/Del Rio contact (fig. 14); it shows an asymmetrical horst with moderate (300 to 700 ft or 91 to 213 m) displacement on its western side and more abrupt displacement (200 to 1,100 ft or 61 to 335 m) on the east. Farther west is a complementary graben system with displacement on its western side of up to 1,500 ft (457 m). Aligned along this zone of maximum displacement lie several of the buried Cretaceous volcanic plugs having a geochemical content that indicates that a possible mantle source and thus fracture systems extend all the way through the earth's crust. These plugs represent reactivation of an earlier fracture system because they are of Cretaceous age, and Gulf rifting is presumed to be a Triassic event. These igneous features thus provide not only a locus of upwelling but also a clue to the creation of the subsurface hinge zone. Foundering of the Ouachita Belt is probably tied directly to extensional forces that affect the entire crustal thickness along the eastern edge of the hinge.

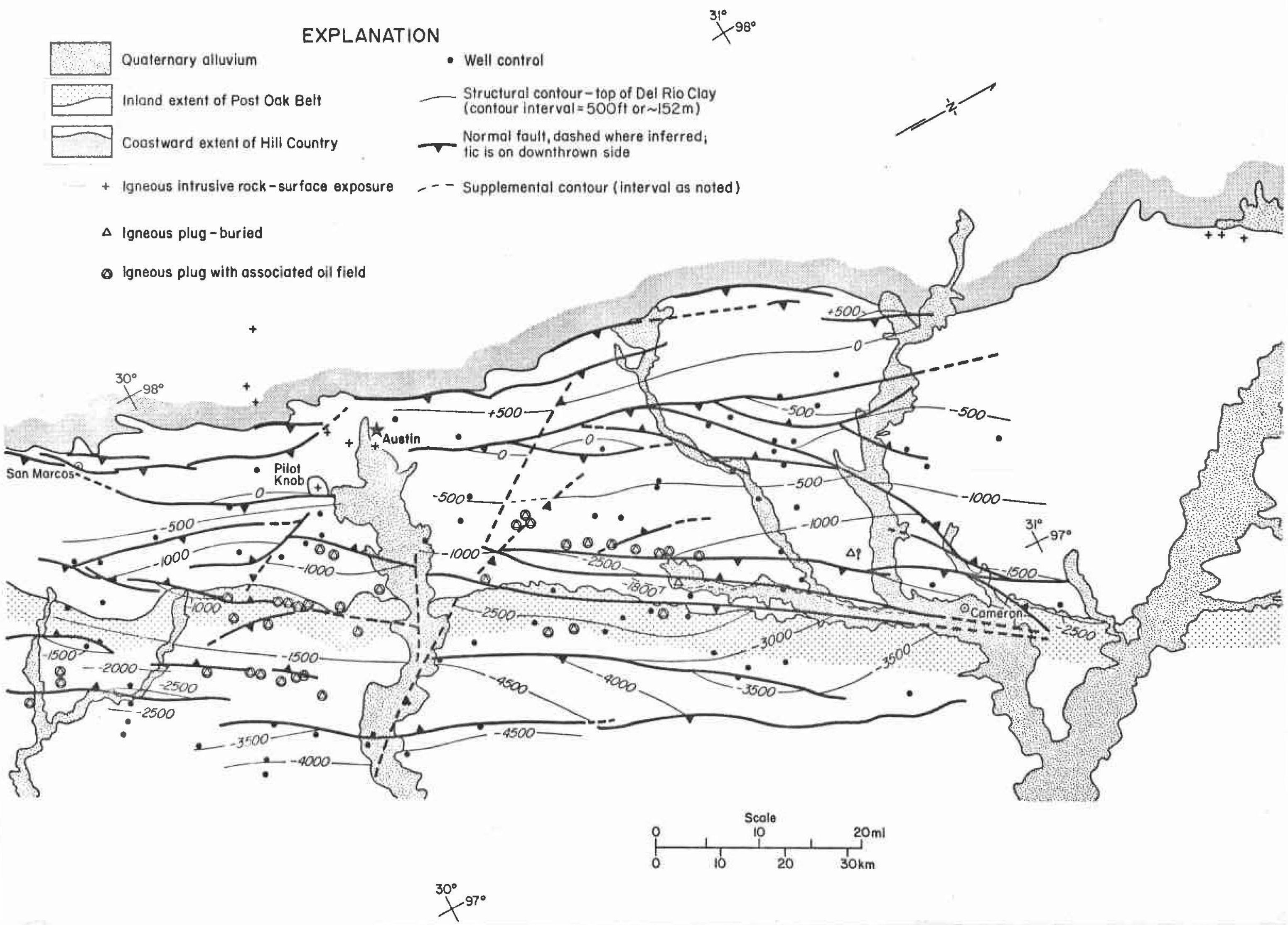

Figure 13. Subsurface structure, top of Del Rio Clay, Austin area.

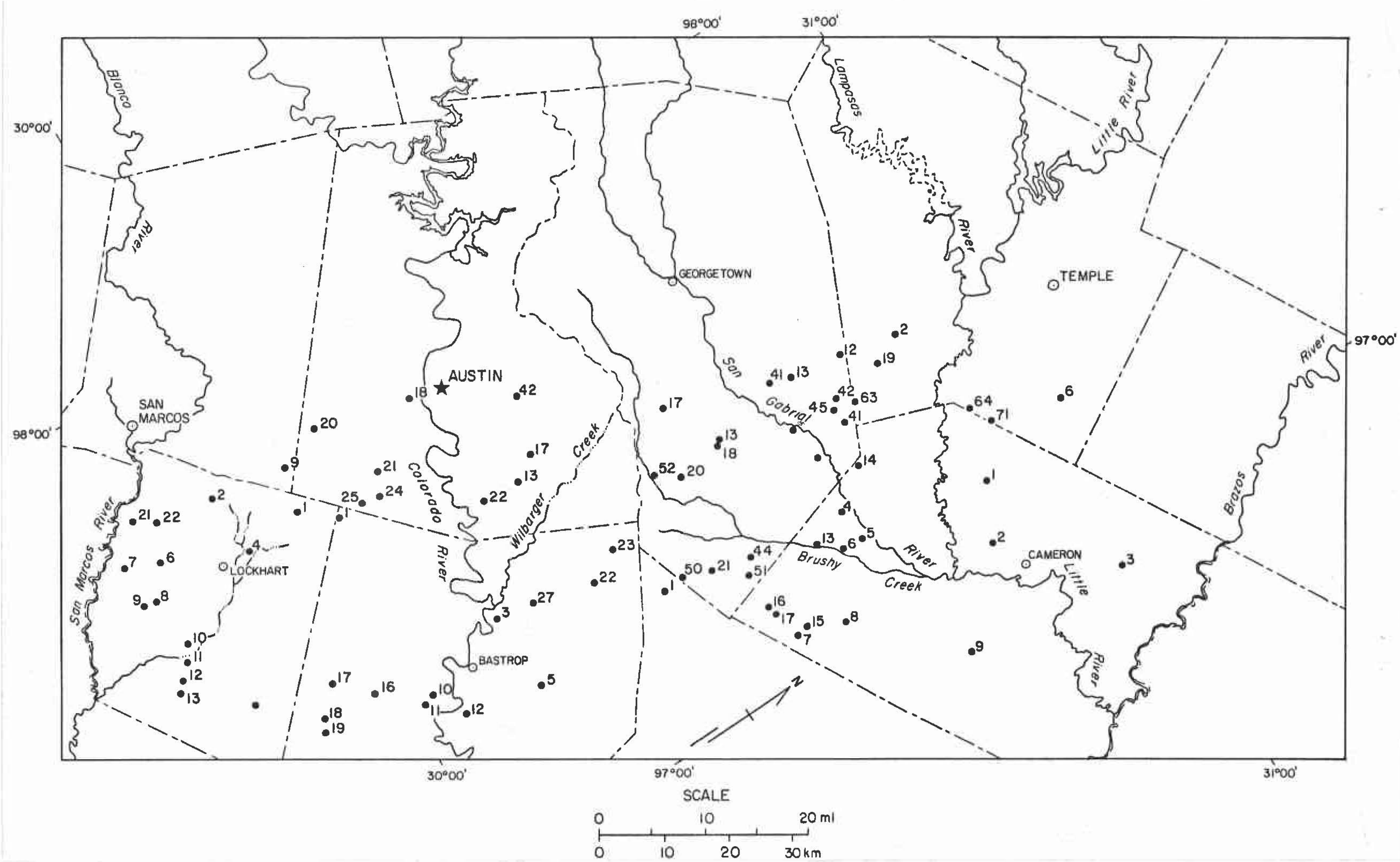

Figure 14. Selected drainage features and county boundaries with well control, Austin area (for identification of individual wells see Appendix A).

Average geothermal gradient contours show a closure over part of the Brushy Creek Lineament Zone with a nonequilibrated maximum value somewhat more than 2.0°F/100 ft or 36.5°C/km (fig. 15). Also one well at Thorndale (well no. 13 in Milam County; see fig. 14) produces mineralized, thermal (126°F or 52.2°C) water from the Edwards Limestone at a depth of 2,213 ft (674.5 m)--a gradient of more than 2.5°F/100 ft (45.5° C/km). However, unlike the situation in Bexar and Atascosa Counties, there are no drill-stem tests or other completion data in wells penetrating this horizon, nor is there other, more extensive information on water chemistry. Hence, the possibility of upwelling of deep basinal brines cannot be investigated or documented further.

The subsurface structural map of the Buda/Del Rio contact also shows areas of abrupt discontinuities normal to or at high angles to the prevailing structural and stratigraphic strike along the Balcones and Luling/Mexia Fault Zones and that align with certain major cross-cutting lineaments. Such cross-strike discontinuities have been recognized in other overthrust areas and correlate to enhanced fracture permeability and hence to deep-seated gas fields beneath thrust belts (Wheeler, 1980). Presumably the cross-strike features indicate loci of lateral adjustment (strike-slip movement) within the overthrust. A prime example of a surface exposure of such a feature is the major tear fault that marks the edges of the Pine Mountain Overthrust in the Cumberland Plateau region of Tennessee and Kentucky. We have no direct evidence of such major tear faults involving basement along the Balcones/Ouachita trend, and the same kind of surface phenomenon may also result from vertical adjustments. One of the cross-strike features in the Austin area trends northwest from the Colorado River Valley in Bastrop County along the lower reaches of Wilbarger Creek into Travis County and from there across the Balcones Escarpment at an oblique angle in Williamson County. No surface faults have previously been mapped along this trend, possibly because large parts of its reaches lie beneath Quaternary alluvium. Abrupt vertical displacements are, however, evident on a

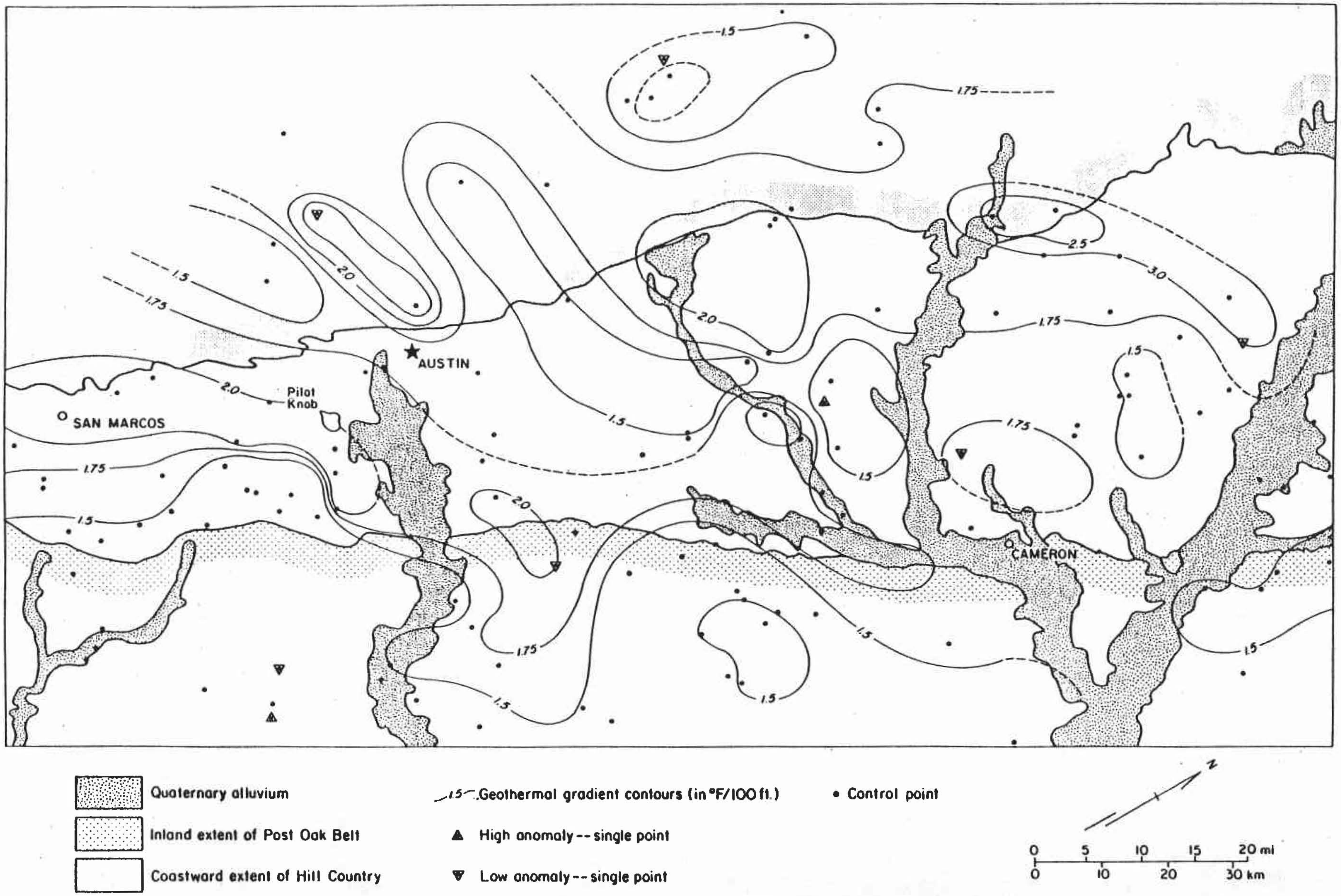

Figure 15. Composite geothermal gradient contours (that is, not discriminated according to specific horizon) Austin area (from Woodruff and Caran, 1981).

map of the Buda/Del Rio contact, and in places, such as near Utley in Bastrop County, this displacement is more than 1,500 ft (457 m). This lineament zone may be a subtle expression of the northern flank of the San Marcos Arch, a positive uplift affecting Cretaceous depositional patterns. These new observations--based on lineaments--may point to an earlier (pre-Cretaceous) structural discontinuity involving Ouachita basement as an ultimate cause of this platform. In other words, lateral adjustments within the Ouachita Belt--perhaps adjustments into discrete thrust blocks around the Llano massif--may be expressed as normal faults in the overlying strata. Data at hand, however, do not allow more than speculation on these causal relations.

The link between lineaments and geothermics needs some elaboration. In areas of ongoing structural activity, geothermal phenomena include (1) anomalous heat flow; (2) emplacement of molten plutons and associated volcanism; and (3) fracture porosity transmitting hot water via convective (?) systems. These active tectonic belts, however, generally have evident surface expression, and lineaments are part of this expression. Even where the tectonic activity is dormant or buried, lineaments provide straightforward clues to high porosity fracture zones, though these are often overlooked by conventional mapping techniques (Bedinger and others, 1979; Geiser, 1979). In much of Texas we have used lineaments to perceive "blind" structures in much the same way as described by Doeringsfeld and Ivey (1964). In many areas, correlations between lineaments and buried features are supported by substructural mapping, but the detailed data required for this correlation are not always available.

The causes of subtle surface expressions of structures are problematical. We have been perceiving inactive, long dormant buried structures, except for the areas affected by the subtle epeirogeny of the Gulf Coast Basin with attendant (active?) salt tectonics and growth faulting. Certainly, any structures in the Austin area may be classed as effectively dormant, even though it is likely that small-scale seismic adjustments involving the Ouachita orogen still continue (Don Steeples, personal communication, 1981). How are these buried features expressed? And what are we perceiving? These two questions warrant more attention, and we address them here.

As Woodruff and others (1982) pointed out, we are perceiving tonal contrasts--both across a linear boundary and between a feature and its background--and apparent relief, which is also a function of tone in the distribution of light and dark (presumably shadow) areas. These tonal contrasts registered on the Landsat image may be a direct response to one or a combination of phenomena: vegetation, soils, bedrock, relief, drainage, and various human artifacts or uses of the land. Some of these features are fortuitous and thus constitute "noise"; others represent features of the solid earth and thus are part of the geologic "signal" that often is of interest in a subsurface context.

In the Austin area, lineaments commonly align with drainage features. Conventional wisdom suggests that this would be so, but one would also think that there would be a strong correlation between lineament density and areas of high relief. In fact, lineaments coincide with topographic breaks less commonly than would be expected. Note that in the Austin area there is no discernible expression of lineament density along the Balcones Escarpment, whereas Brushy Creek is extremely well registered (fig. 16). Note also that the Brushy Creek Lineament trend extends along strike and crosses several other drainage courses. High lineament density, then, does not simply coincide with the river courses or alluvial valleys alone.

For the cross-strike features, it is difficult to judge any one phenomenon that is being perceived, but contoured relief registered for each 7.5-minute topographic sheet (fig. 17) shows cross-strike lineaments that align with major breaks in relief. Also, this same figure illustrates that high relief alone does not ensure a high lineament count. The Brushy Creek Lineament Zone lies mainly along an alluvial valley and beyond that is contained within a low-relief area between two relatively high topographic areas.

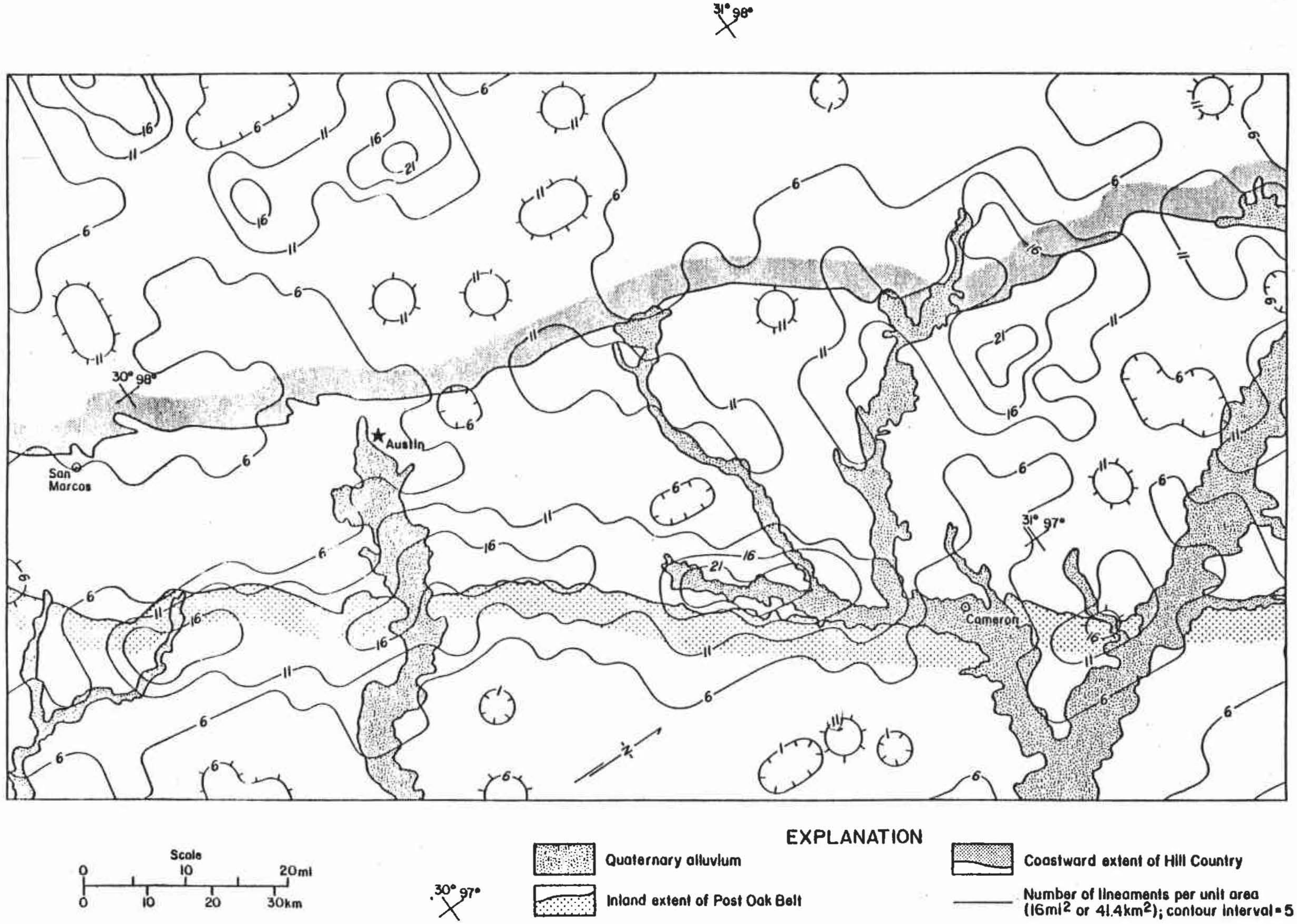

Figure 16. Lineament density, Austin area.

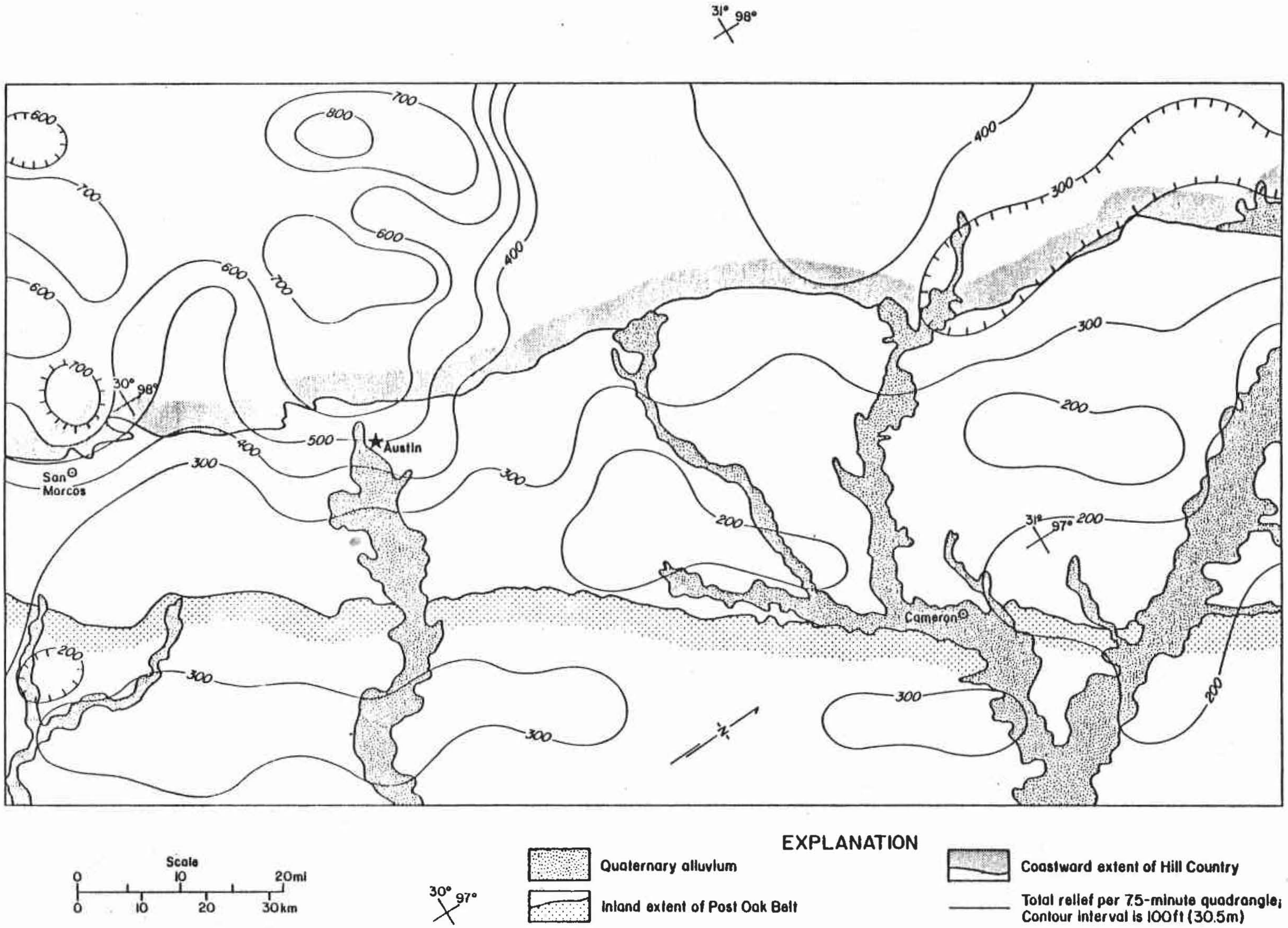

Figure 17. Total topographic relief, per 7.5-minute quadrangle, Austin area.

The coincidence of geologic features at depth--buried igneous plugs, buried normal faults, the eastern edge of control on the buried Ouachita Belt--indicates a major structural break at depth along the Brushy Creek Lineament Zone. An upward propagation of fractures appears to be associated with these deep-seated geologic features. The propagation may be a result of continued or periodic (microseismic?) activation, where the buried feature includes a fault zone and a fault-bound basement hinge, as in this instance. In other areas, similar lineament zones define the surface projections of carbonate banks that occur on the tops of positive structures involving basement and that may have fault-bound margins. Examples include the San Marcos Arch and the Belton High/Moffat Mound. Elsewhere in Texas, the Central Basin Platform provides another example of this phenomenon, and that platform has associated lineaments along parts of its margin (Woodruff and Caran, 1982). What apparently occurs is selective deposition of carbonate sediment with differential compaction in adjacent areas that have less carbonate material deposited.

The strong correlation between lineaments and rivers suggests subtle ways for ongoing propagation of certain buried structures. The river may establish a valley along a zone of weakness (say a fracture zone), then the linear feature is reinforced by fluvial processes of erosion and sedimentation. Even though such linear features have been noted along the lower part of the Mississippi River alluvial valley (Fisk, 1944), cause and effect may easily become confused. A linear reach of a river may either (a) be without deep-seated or antecedent causes; or (b) reflect an expression of some linear (structural?) feature at depth. In other words, do we perceive lineaments along stream courses because they provide local straight patterns that, in aggregate, point downstream (and thus indicate little more than present-day topography and hypsometry)? Or do rivers represent a structural-related self-ramifying <u>process</u> that continually adjusts to local stress regimes--either ongoing or dormant? Probably both situations exist. But wherever the latter case occurs, rivers become key locales for perceiving lineaments and possibly for discerning surface expressions of structures at depth. In Central Texas--and especially in the Austin area--the coincidence of lineaments with various structurally related features suggests that the lineaments are indicative of subsurface phenomena and are not merely random expressions of surficial processes.

The link between lineaments and geothermal anomalies in the Austin area is probably due mostly to the upwelling of deep basinal waters, as occurs elsewhere in Texas (for example, in the Edwards Limestone of South Texas or in the East Texas Basin). The correlation with igneous plugs in the Austin area, however, indicates that in some areas radiogenic (felsic) plutons may occur along some of these buried, structurally disturbed areas, although these features would be limited to the Paleozoic basement and would not be the ultramafic piercement structures already identified in the region. These felsic plutons, if they do occur, may be a source of anomalous local heat flow in the inner Gulf Coast Basin in the same way as along the Atlantic Coastal Plain (Costain and others, 1980).

CASE STUDY--FALLS COUNTY AREA:
Hydrodynamics of Geothermal Resources

The Falls County area is of special interest in a geothermal context because of recent development of geothermal ground water from the Hosston aquifer (fig. 18). This geothermal resource is applied to direct-heat use at the Torbett-Hutchins-Smith (THS) Memorial Hospital in Marlin. In western Falls County (from Marlin west), depositional history, structure, ground-water hydrology and heat flow combine to create an economically attractive low-temperature geothermal resource. This case study focuses on the hydrologic effects on geothermal resources and on the geothermal gradient anomalies that occur in the Falls County area. In this area considerably more ground-water data exist

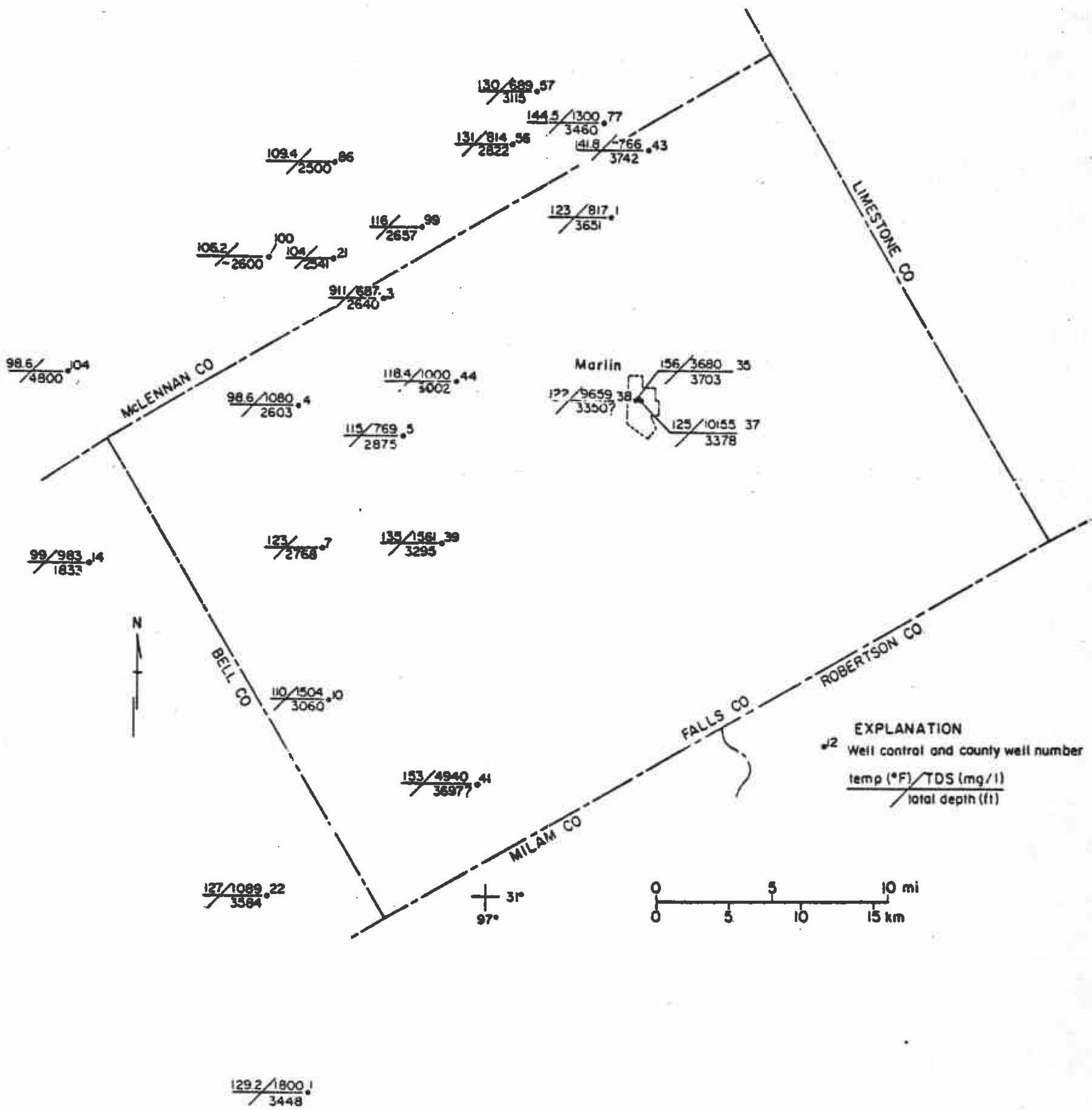

Figure 18. Geothermal resources in the Falls County area.

from updip areas and from petroleum fields producing from downdip areas within equivalent strata. The Falls County area complements the perspectives on geothermal anomalies provided by hydrogeochemical data (in the Bexar County vicinity) and by buried structures and lineaments (in the Austin area). The three types of data augment one another, and all point to upwelling of deep basinal fluids as a probable cause of local geothermal anomalies.

The part of the lithologic column that has been studied in the Falls County area is the "Hosston/Cotton Valley" sequence (Macpherson, 1982). This term is an informal designation that isolates a single lithic unit that is in hydrologic continuity. In traditional stratigraphic usage, the Hosston is designated as basal Cretaceous, and the "Cotton Valley clastic member" of the Schuler Formation is presumed to be uppermost Jurassic. An unconformity is thought to exist between the two formations, but the evidence of this unconformity and even of the presumed Jurassic/Cretaceous boundary is not well established. Instead, examination of electric logs and well cuttings along this part of the margin of the Gulf Coast Basin indicates that the two formations--both terrigenous sandstones--represent several facies (and probably more than one depositional system) in common; that is, genetic sedimentary packages cut across presumed formational boundaries. Log patterns and sediment characteristics as seen from cuttings strongly suggest that the two units may be treated as a single hydrologic unit (Tóth, 1978, p. 807), and that is what we have done.

Stratigraphic Setting: Synopsis

The Hosston/Cotton Valley hydrogeologic unit thickens to the southeast into the Gulf Coast Basin. An abrupt thickening is seen across the Ouachita hinge (fig. 19); as control on the Ouachita basement is lost, the Mesozoic section thickens markedly, and there are several pre-Hosston/Cotton Valley stratigraphic units that are present in this

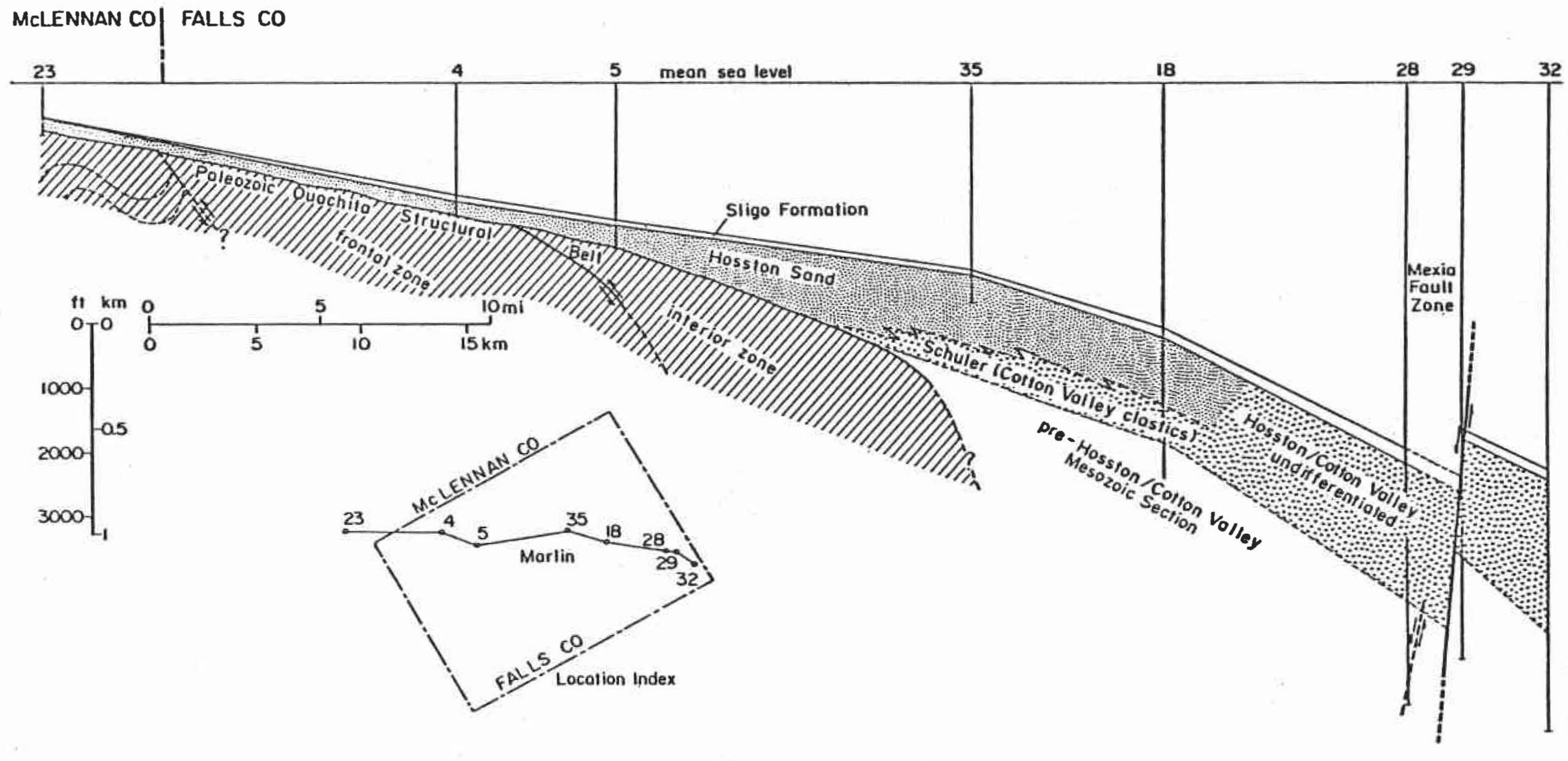

Figure 19. Cross section showing Lower Cretaceous and Jurassic strata across Balcones/Ouachita trend in Falls County area.

expanded section. Schematic depictions by Macpherson (1982) of total thickness, net-sand thickness, and percentage sand of the Hosston/Cotton Valley show this thickening as well as salients (low-sand areas) and embayments (high-sand areas). The salients and embayments are important to aquifer properties because sand thickness influences aquifer properties, especially transmissivity.

The contours of both the isopach and net-sand maps of the hydrogeologic unit show sand axes that trend southeastward in McLennan County and southward in Bell County (Hall, 1976; Macpherson, 1982). These axes disappear, and uniform basinward thickening dominates through eastern McLennan and northwestern Limestone Counties, central Falls County, and through southeastern Bell County and all of Milam County. In Robertson and Limestone Counties, the basinward sediments again show dip-oriented axes of thick sands, which appear to be radially filling another, deeper embayment. The changes in strike suggest major changes in depositional systems from fluvial and deltaic in the updip reaches to barrier/marine in the middle parts. Beyond the eastern edge of the Ouachita hinge, the recurrence of recognizable dip-oriented trends suggests an earlier (deeper) dip-fed system (fluvial or submarine fans are two possibilities, according to Macpherson [1982]) before the marine transgression represented by the strike-fed sands in the middle part of the region.

Structural Setting: Synopsis

Marlin lies between the Balcones and Mexia Fault Zones; the study area considered here encompasses parts of both structurally disturbed zones (fig. 20). One zone of thrust faulting crosses northwestern Falls County. This displaces frontal strata with the metamorphic rocks of the interior zone (Flawn and others, 1961). Unlike the Austin area, no igneous features (buried or exposed) are known in Falls County, although highly weathered igneous exposures occur locally southwest of Waco in McLennan County. No

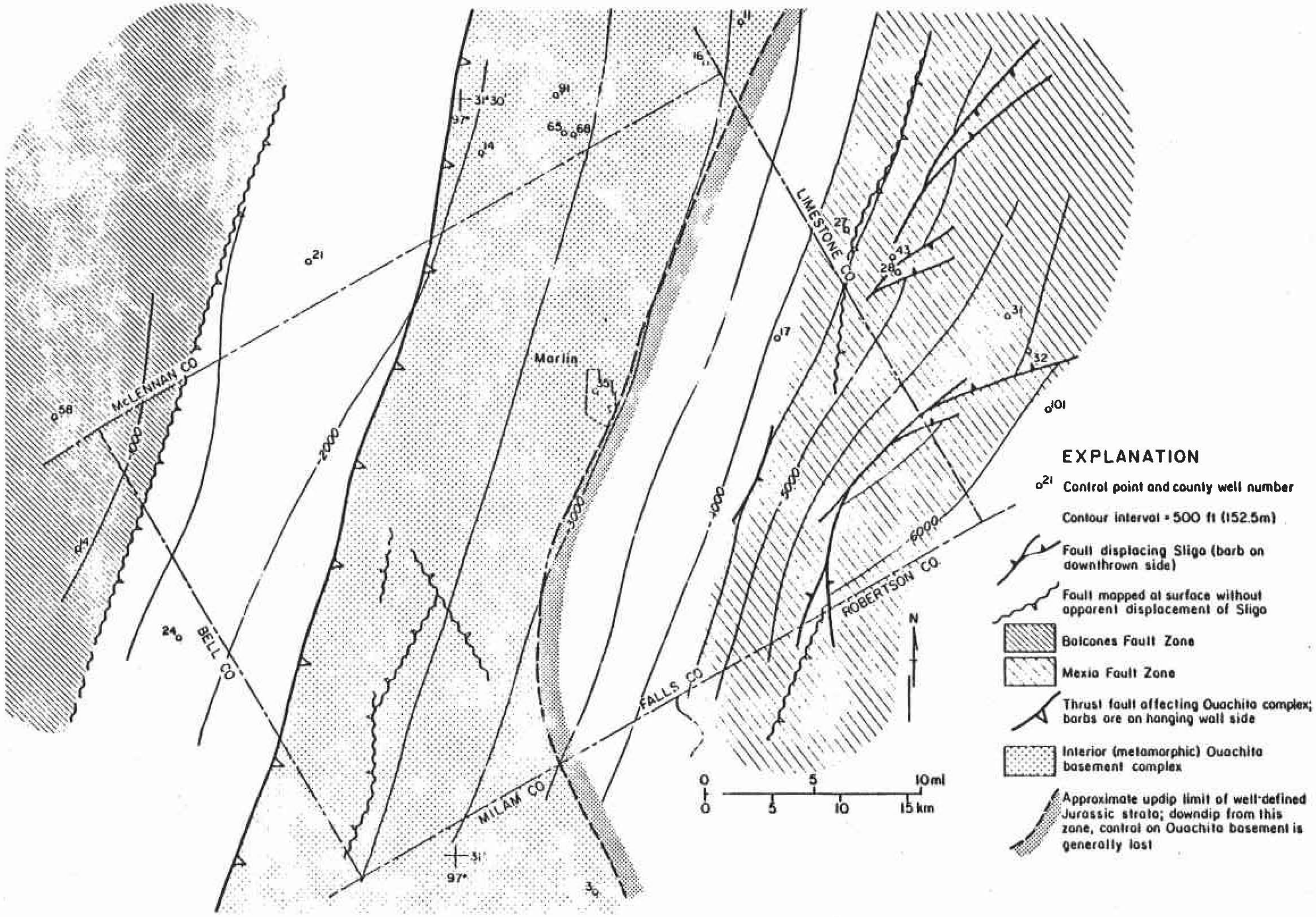

Figure 20. Subsurface structure, top of Sligo compared to selected structures involving basement and surface strata, Falls County area.

major lineament zones are mapped in our survey (Woodruff and others, 1981) or in the pilot study (Austin area) that includes part of Falls County. However, the Brushy Creek Lineament Zone may extend northeast beyond Cameron and into eastern Falls County (fig. 12), perhaps coinciding with the Mexia Fault Zone near Mexia and Grosbeck in Limestone County. Also, as pointed out by Woodruff and Caran (1981) the Brazos River alluvial valley from northern Burleson County to Waco constitutes a mega-lineament of unusual proportions. It is too large to be perceived on the Landsat images at a scale of 1:250,000, hence it is not included on our map. But the feature is discernible on imagery at smaller scales and on conventional regional geologic maps. Unlike the cross-strike features in the Austin area, however, no major subsurface structural breaks appear to lie along the Brazos River Valley.

The Ground-Water System

Since, as seen in other areas of Central Texas, geothermal gradient may be influenced by ground-water flow, the aquifer properties that influence or reflect ground-water flow are of interest when describing the geothermal regime of an area. Darcy's Law states that ground-water flow per unit area is the product of hydraulic conductivity and hydraulic gradient. The latter is manifest in a potentiometric-surface contour map of the aquifer; the former is so-called field permeability and is directly measured during a pumping test of a well. Maps depicting both transmissivity and hydraulic conductivity have been presented during an earlier assessment of geothermal potential of this area (Woodruff and others, 1982). In this presentation, we refined and reevaluated certain of the hydrologic data. Specifically, we employed a moving average to recontour hydraulic conductivity (fig. 21). This moving-average contour map factors out certain confusing effects of thickening of the Hosston/Cotton Valley into the Gulf Coast Basin and the apparent high transmissivity values that occur because of this thickening.

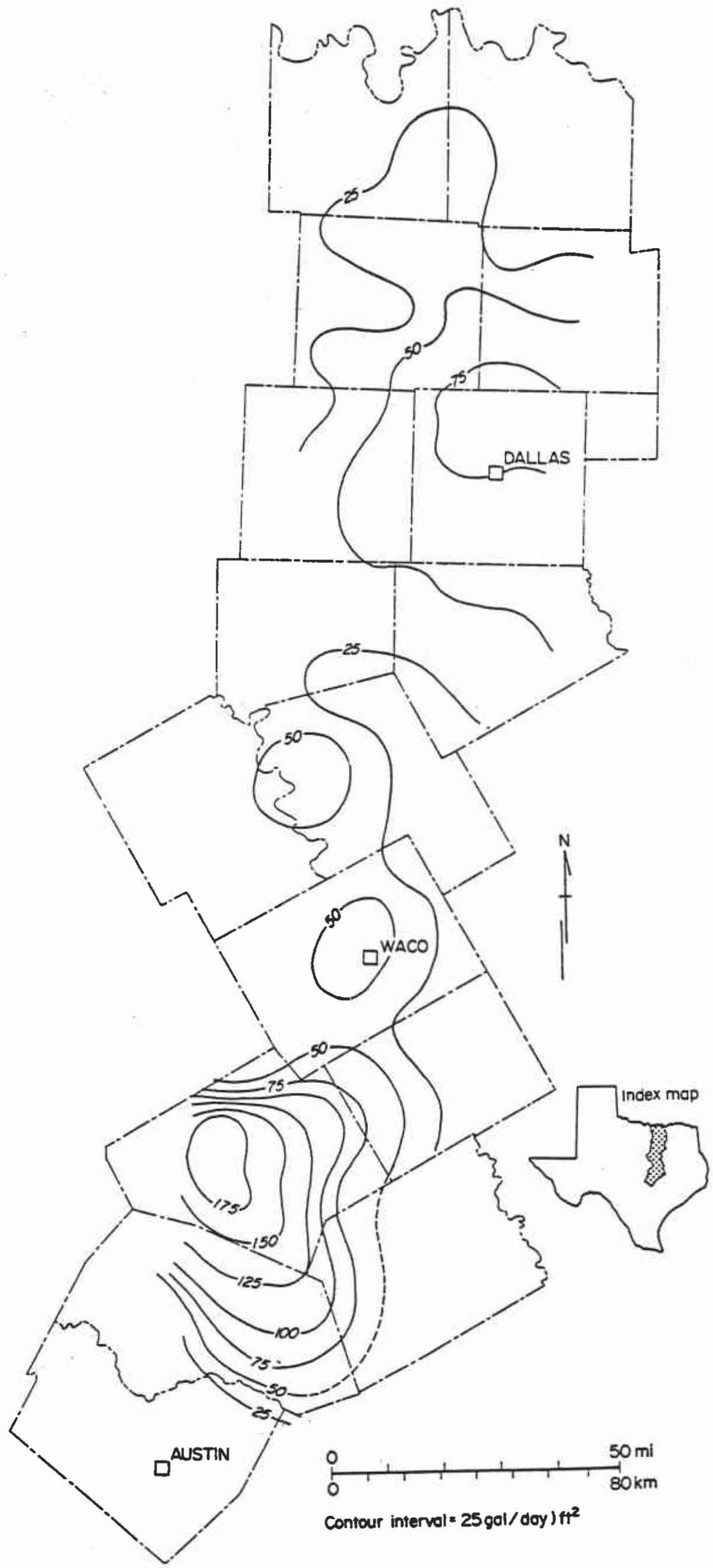

Figure 21. Moving average of hydraulic conductivity along part of the Balcones/Ouachita trend.

The higher hydraulic conductivity values coincident with the Balcones Fault Zone suggest two possibilities. (1) Faulting contemporaneous with deposition of the Hosston controlled sedimentation rates and type, resulting in relatively coarse and thick sediments of higher hydraulic conductivity in the immediate vicinity of the faults. (2) Faulting has restricted ground-water movement to corridors along the strike of the faults, which localized enhancement of hydraulic conductivity by diagenetic or post-diagenetic processes (such as dissolution of cement). The former is not supported by aquifer and net-sand thickness (Macpherson, 1982), but the latter is supported by the configuration of the potentiometric surface, as will be shown.

In the eastern part of the study area, from Marlin east to the areas producing petroleum along the Mexia Fault Zone, wells of any type are scarce, and hydrologic data are practically nonexistent. For this reason, we ran a pumping test on the THS Memorial Hospital geothermal well in September 1980. The transmissivity calculated from this test, 7,600 gallons per day per foot (gal/d/ft), is considerably higher than that from an earlier test run by the driller of 2,500 gal/d/ft. This may be the result of well development having occurred during the earlier test, or of a more accurate static-water-level measurement during the latter test. The initial recovery of the well to a point higher than the static water level suggests that storage decreased during the test (Jacob, 1963), which may affect long-term withdrawal of water from the aquifer. In general, though, the projected pumping rates of the THS Hospital well seem to be in line with aquifer capabilities.

We had hoped to construct a unified hydrologic properties map across the Mexia Fault Zone using new data from Marlin and pressure-test data from oil fields in Limestone and Robertson Counties. However, for the saline part of the system no formation-test charts were available for calculating hydraulic conductivity. According to the limited pressure data, hydraulic conductivity is relatively low and transmissivity increases to the east. Both findings are supported by the sand-body geometry of the aquifer; thickening toward the east produces the observed effects. Our data also indicate slightly higher transmissivity and hydraulic conductivity near the Balcones Fault Zone in McLennan County and dip-oriented or isolated areas of higher transmissivity and hydraulic conductivity in Bell County, where aquifer and net-sand thicknesses are relatively high and dip-oriented.

The potentiometric surface of an aquifer is the level to which water in that aquifer will rise under atmospheric pressure. From contours on this surface (that is, contours of equal potential), the hydraulic gradient is calculated. Lines drawn in the direction of maximum potential gradient (perpendicular to the potentiometric contours), represent flowlines within the aquifer. In the Hosston/Cotton Valley in March 1966 (fig. 22), the potentiometric surface in the potable-water part of the aquifer shows a cone of depression elongate along the Balcones Fault Zone with a relatively steep hydraulic gradient in the western, eastern, and northern sides of the cone, and a relatively gentle hydraulic gradient in the southern side. The cone, itself, is a result of extensive ground-water pumpage in the Waco area, but the coincidence of steep gradient areas with the Balcones Fault Zone suggests that faults are acting as flow barriers. In the saline part of the Hosston/Cotton Valley sequence along the eastern edge of the study area, data are scarce and of poor quality. The potentiometric surface is based on bottom-hole-pressure data collected during a 30-year period; thus, the use of these data assumes a steady-state hydrologic system. The contoured data suggest that basinal fluids have the potential to move updip into the fresh-water system. The Mexia Fault Zone may be a zone of discharge, since the few measurements in that area indicate a potentiometric-surface low. Between the fresh-water system updip and the saline system downdip, there are no data. However, the regional flow system generally works in this way: In the fresh-water system, the aquifer is relatively thin and ground-water movement is toward the cone of

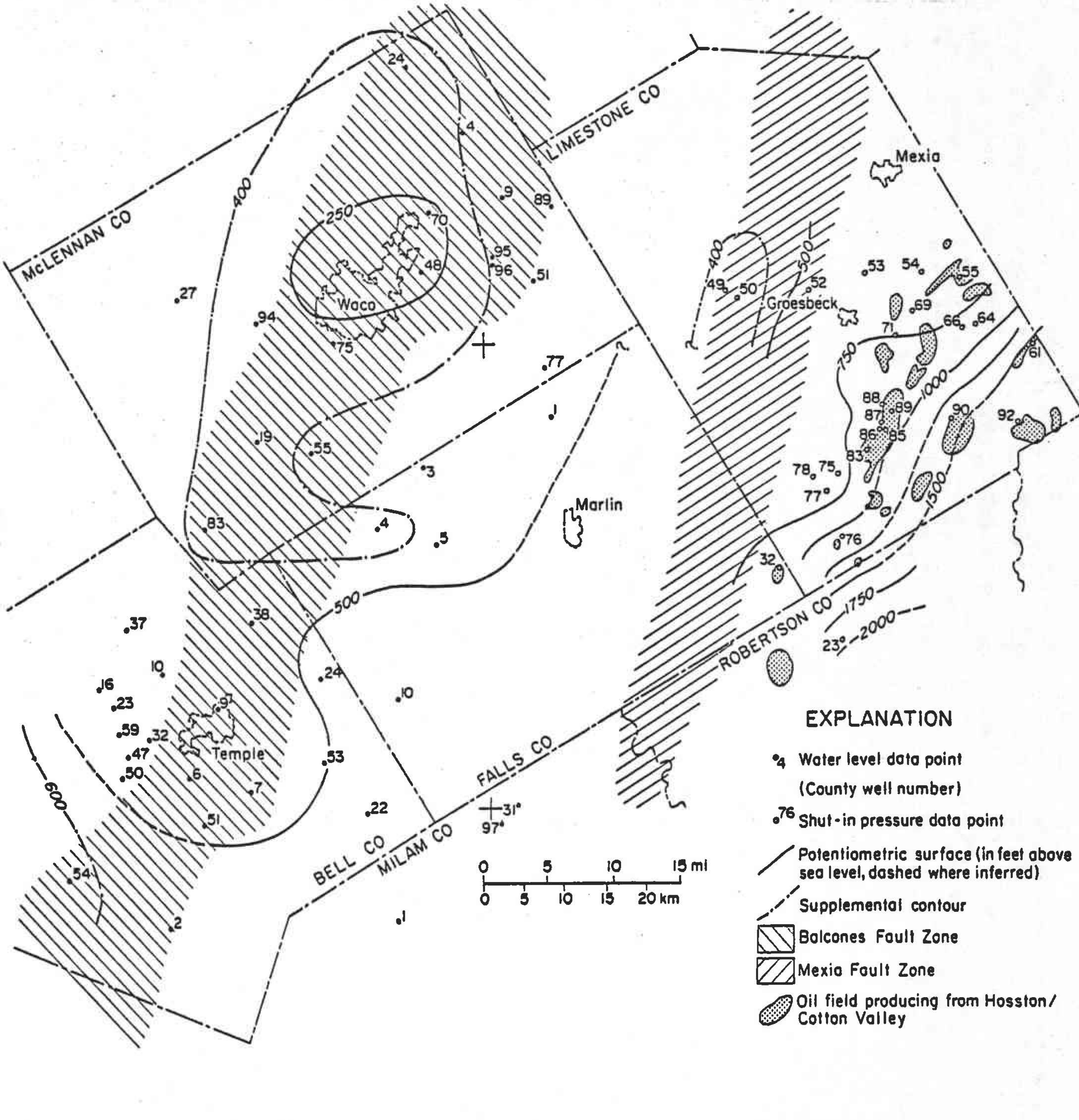

Figure 22. Potentiometric surface, Hosston/Cotton Valley hydrologic unit, Falls County and vicinity.

depression in the Waco area, owing to high rates of discharge from wells. In the saline water system, the aquifer is much thicker and water movement appears to be updip. The water level in the Waco area dropped about 40 m between 1966 and 1980; presumably, downdip saline water has migrated toward this depression because of the lowering of head, although there are no chemical data spanning this time period to support this contention. In Bell and Milam Counties, on the other hand, encroachment of the deep saline water is evident in the changing water chemistry of some of the water wells (Macpherson, 1982); considering the large decrease in head in the fresh-water system and the relatively high heads in the downdip saline system, however, there should be more encroachment of saline water than appears from the meager geochemical data.

There are three possible barriers to updip movement of basinal water in the Hosston/Cotton Valley. The first barrier effect may be caused by the abrupt thinning of the unit updip near the Balcones Fault Zone. The second barrier may be the Mexia Fault Zone, but the faults also probably provide some means of slow vertical discharge. The third possibility is that there is a permeability barrier that restricts ground-water movement. This barrier may occur near the fairly abrupt fresh-water/brackish-water contact that runs along strike through Falls County near Marlin. Downdip from this contact, there is silicified and calcite-cemented strata in the Hosston/Cotton Valley as seen in the cuttings from the THS Memorial Hospital geothermal well. The THS well, however, does not penetrate the entire section, and it is difficult to judge the total extent of cementation, but the pump test on that well also resulted in a fairly low hydraulic conductivity, implying a decrease in permeability. This hypothesis for a hydrodynamic barrier is similar to that presented for the formation of the bad-water line in Bexar County. Unfortunately, there are few data of any kind on the fresh-water/brackish-water contact, so that the cause of the water-quality break cannot be resolved in the Falls County area.

In summary, the ground-water flow system in the Hosston/Cotton Valley hydrogeologic unit probably consists of discrete sections compartmentalized by structural features. The downdip, saline part of the aquifer in the eastern segment of the study area is probably partially confined by the Mexia Fault Zone, which may act as a pressure-relief valve by allowing upward leakage of fluids. In the updip fresh-water part (west of Falls County), ground-water flow appears to be controlled by the Balcones Fault Zone and by present-day withdrawal of ground water through wells in the Waco area. The central part of the area encompasses the zone between the traces of the two fault zones; there, fresh, saline, and intermediate-concentration water coexist. The area is affected by ground-water withdrawal to the west, which probably results in saline water locally moving updip through Falls County and through other adjacent areas between the fault zones. This updip movement is not as extensive or as rapid as might be expected--especially considering the marked drop in the fresh-water head during recent years and the relatively high elevation of the saline-water head in the eastern part of the study area. Thus, it appears that this middle region (including Falls County) may be the location of a ground-water system in which saline water from deeper in the basin partly moves up faults by leakage and partly flows along strati-bound permeable zones from downdip areas. Some of this water mixes with potable water in the western segment of the aquifer, thus mediating water quality. Probably the saline-water-fresh-water boundary responds to changes in the fresh-water head, migrating updip when that head is lowered (by decreased recharge or withdrawal of water from storage by pumping) and migrating downdip when that head is raised (by abundant recharge). The main influence of all this in a geothermal context is that the Falls County area has warmer water than would be expected, given prevailing geothermal gradients while generally maintaining potability.

Water Chemistry

As expected, the total dissolved solids (TDS) concentration of Hosston ground water in the Falls County area increases basinward. The TDS concentration increases abruptly in the central part of the study area, where TDS changes from 1,000 mg/L to more than 100,000 mg/L in about 15 mi (25 km). But this change is not due exclusively to increases in sodium and chloride ions as normally occurs deep in sedimentary basins. Instead, where TDS begins to increase rapidly, the dominant anion added is sulfate. The zone of sodium-sulfate-type water is fairly small, probably less than about 9 mi (15 km) wide and is located near Marlin and in other nearby areas along strike. In the eastern part of the study area (in Limestone County, for example) the brines are mainly of the sodium-chloride type, with relatively little sulfate. In some aquifers, evidence shows brines to be leaking out of the basin through faults (Prezbindowski, 1981). In the Falls County area, there is some evidence of this leakage, such as seen where a water well near a fault in the Balcones Fault Zone produces water with a slightly different water chemistry than that of nearby wells. This evidence suggests upwelling. How might this proposed upwelling occur? The Marlin area provides a locality for investigating this phenomenon.

Hydrodynamic Controls on the Geothermal Regime in the Marlin Area

As seen in figure 3, southern Falls County is one of the areas in which geothermal gradients vary markedly between two formations of similar lithology. The presumption is that--given similar rock type--thermal conductivity should be roughly equal. And, as already pointed out, in any vertical column the heat flow must be the same. The fact that the geothermal gradients diverge, plus the other data presented throughout this report (inflection points at a consistent depth of about 1 km, geochemical evidence, and the like), all combine to indicate upwelling basinal waters as a means for explaining the apparent breakdown of the heat-flow equation. In short, because of upward-moving ground-water flow--either confined within a single permeable stratum, or leaking up fault zones--the apparent heat flow changes from one stratum to another. This apparent heat flow is what is commonly being measured both by shallow heat flow observation holes, such as those described by Smith and others (1981), and by the geothermal gradients refined from raw BHT measurements taken during logging of petroleum exploration wells. These perturbations of the vertical flow of heat by the actions of ground water are commonly assumed to be part of convective flow systems. However, some discussion of convection is in order, because the upwelling that we have documented may not be thermally induced. Instead, it may be due to a number of factors acting singly or in concert. Two examples include increased pressures at depth owing to sediment compaction, or diagenetic changes at depth that evolve water or other fluids that, in turn, provide another source of pressure drive.

There are two end-member types of convective heat transfer: free convection and forced convection. In free convection, the motion of the fluid is due to density variations caused by temperature gradients, and no fluid enters or leaves the system. In forced convection, fluid motion is due to hydraulic gradients and fluid does enter and leave the system. Most meteoric ground-water systems are of the latter type; some high-temperature geothermal systems are of the former type, and many are influenced by both mechanisms and thus are of a mixed type. Donaldson (1962) modeled the effects of ground-water circulation on a free-convective system. His models illustrate the relatively low geothermal gradient in areas of ground-water recharge, and areas of high geothermal gradient in areas of ground-water discharge. Domenico and Palciauskas (1973) also looked at forced convection in a ground-water basin and found that the depth-to-length ratio of the basin is important in determining whether conduction or convection dominates the geothermal regime. In fact, the heat transfer mechanism depends on a factor "F" calculated by:

$$F = \frac{B K_w b}{\alpha L}$$

where B = mean water-table elevation above top of aquifer
K_w = hydraulic conductivity of the medium (for water)
b = thickness of aquifer
L = length of aquifer (in downdip direction)
α = thermal diffusivity

When "F" is less than one, these workers presume that conduction is the heat transfer mechanism. For "F" greater than 1, convection is presumed to be the heat transfer mechanism. In the meteoric Hosston/Cotton Valley aquifer, this factor is $6.806 \cdot 10^{-5}$ (table 2 for calculations); so conduction is the apparent heat transfer mechanism. This, however, is a questionable conclusion until a source for high heat flow is determined in this area. As mentioned previously, this is an area of rocks having high thermal conductivity and a heat flow anomaly would have to be very high to counteract these influences if the heat-flow equation were the sole controlling factor. In the deep, saline Hosston/Cotton Valley, "F" is difficult to determine since the lateral extent of the aquifer is not known. Convection is probably an important process in the deep basin, as the much greater aquifer thickness would allow the density-driven convective cells to operate. The second set of calculations in table 2 is presented for the region in which the aquifer begins to thicken across the Ouachita hinge. There geothermal gradients calculated from ground-water temperature values are high. In this part of the meteoric water system, forced convection may be important.

To summarize the influences of hydrodynamics on geothermal resources: the study area overlies the structural hinge of the Ouachita Structural Belt and is cut by the Balcones and the Mexia Fault Zones. All three of these structural features seem to control the Hosston/Cotton Valley hydrologic system and the local geothermal regime. The faults are associated with high geothermal anomalies, and the shallower part of the aquifer has a higher geothermal gradient than the deeper reaches. This is consistent with our findings elsewhere in Central Texas. The Mexia Fault Zone marks the western

Table 2: Calculations to determine heat-transfer mechanism.

$$F = \frac{B \cdot K_w \cdot b/L}{\alpha} \quad \text{where} \quad \alpha = \frac{K_h}{\rho \cdot c_p}$$

	Western Aquifer	Central Aquifer
B	50 m	50 m
K_w	1.0 m/d	1.0 m/d
b	30 m	225 m
L	282×10^3 m	25×10^3 m
α	0.0868 m^2/d	0.0868 m^2/d
k_n	0.01 cal/sec/cm/deg	0.01 cal/sec/cm/deg
ρ	0.995 kg/L	0.995 kg/L
cp	1 cal/g/deg	1 cal/g/deg
Factor	6.806×10^{-5}	5.1823
Heat transfer	conduction	convection

B = mean water-table elevation above b
b = top of producing horizon
K_w = hydrologic conductivity
L = length of aquifer, from recharge area to point of discharge
∂ = thermal diffusivity
K_h = thermal conductivity
ρ = density
c_p = heat capacity

boundary of the saline-water part of the Hosston/Cotton Valley. The Balcones Fault Zone on the west is probably only partially effective as a flow barrier in relatively shallow reaches of the aquifer. These major structures apparently compartmentalize the hydrologic system. A saline reach lies downdip of the Mexia Fault Zone; a meteoric zone occurs updip of the Balcones Fault Zone; and a transitional area lies between the two fault zones. The transitional and meteoric parts are hydrologically connected to a higher degree than are the saline and transitional. This suggests that meteoric water generally flows only as far as the Mexia Fault Zone and is there heated in accordance with the prevailing geothermal gradient. These downward-flowing waters also receive some augmentation of heat (and solutes) from leaked waters from the deeper basinal part of the aquifer. Some of this heated water then apparently moves by upwelling (by forced convection) to the vicinity of the Balcones Fault Zone where it is retarded from further upward flow. This upwelling results in some of the highest geothermal gradients in the region--or for that matter in the entire state.

In the Dallas County and Travis County areas, similar mechanisms may be operating. In the Dallas County area it appears that forced convective heat flow may dominate: geothermal gradients are relatively low and may be depressed by the proximity of the outcrop of the Hosston, and thus of cold, recharging ground water. In the Travis County area, data are sparse, but it appears that the Ouachita "basement" may be influencing geothermal gradient, either by acting as a locus of upwelling basinal water or by providing local zones of anomalously high conductive heat flow.

CASE STUDY: DALLAS AREA

The Dallas area has considerable geothermal potential. Numerous wells there produce thermal ground water from three Cretaceous sandstone aquifers: the Hosston/Trinity, the Paluxy, and the Woodbine (fig. 23). Temperatures of waters produced from

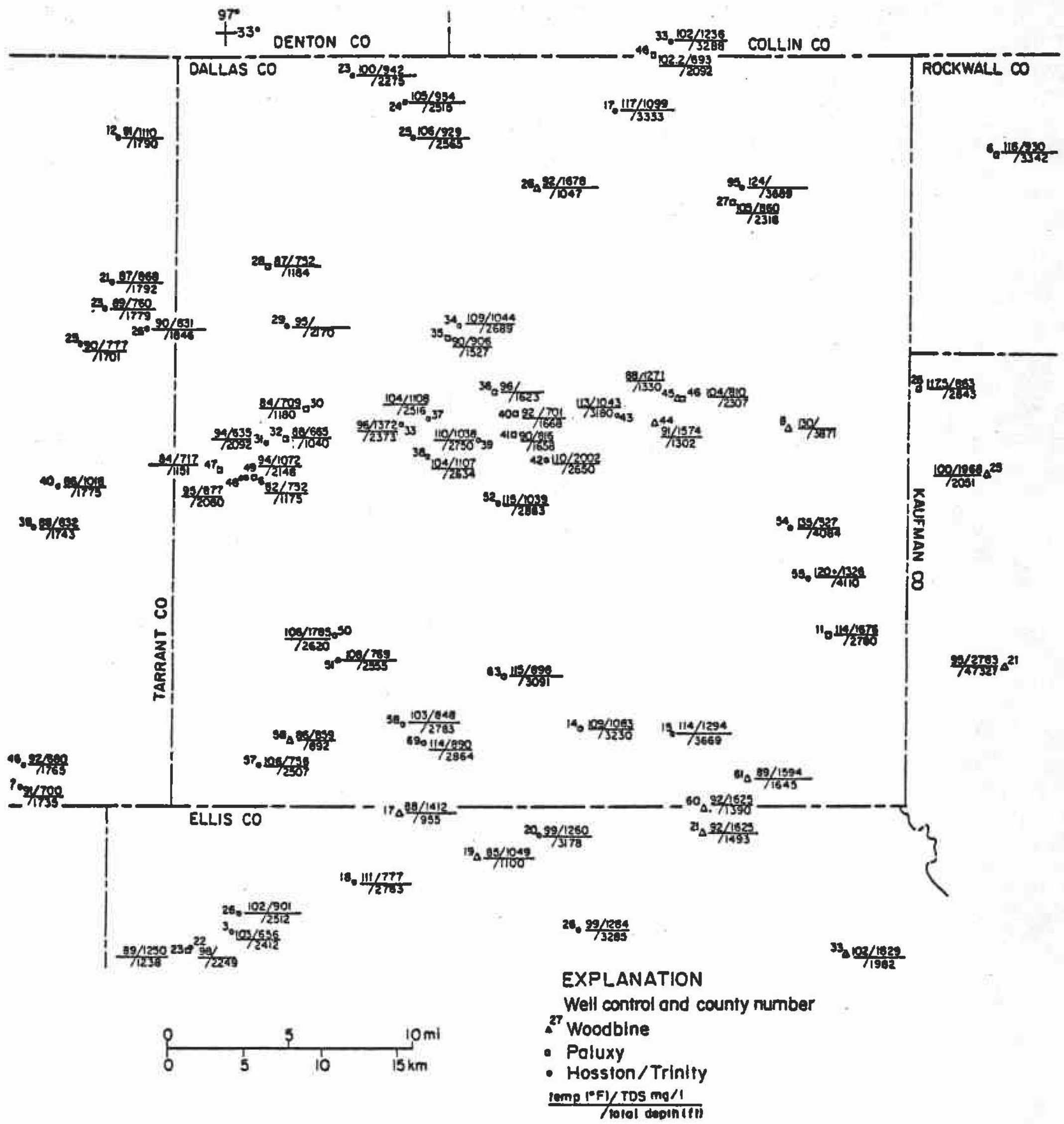

Figure 23. Geothermal resources in the Dallas area.

these aquifers range from subthermal in the shallow reaches of the Woodbine (which crops out immediately west of Dallas County) to more than 130°F (54°C) for wells producing from the Trinity in eastern Dallas County. Salinity values vary markedly according to aquifer and also locally within each aquifer. In general, the Woodbine ground water, though shallower than the other two, has typically higher salinity values.

Dallas County seems to be an ideal location for the use of low-temperature geothermal resources. There are three aquifers to tap (including a potentially acceptable shallow horizon--the Woodbine--for reinjecting the spent waters); numerous wells already tap the thermal horizons; and there are various facilities that are potential users of such a direct-heat source. Also, the Dallas area--being the most populous urban area along the Balcones/Ouachita trend--demands that we present the best available information on the geothermal resources there. This is done in graphical form in figure 23, which is a refinement of data presented earlier (Woodruff and McBride, 1979). However, initial on-site engineering and economic evaluations (such as at the City of Wilmer) still show the economic feasibility to be wanting.

In the Dallas area, as in the Bexar County area, we have obtained temperature/depth data both from water wells and from BHT measurements from electric logs for all three horizons. All three formations considered here are terrigenous deposits, thus they locally contain both sand and mud--two sediment types having markedly different thermally conductive properties. Certain gradient values obtained from BHT readings may be affected by the local penetration of these diverse lithologies and hence by variations in thermal conductivities. However, in the aggregate, the gradient values appear to be internally consistent, and probably are comparable from unit to unit.

Only one of the three stratigraphic units shows a marked deviation in gradient-to-depth in the shallow reaches of the well bore (fig. 24). The Woodbine Sand shows a marked deflection (positive slope); just as seen in the Edwards Limestone in southern

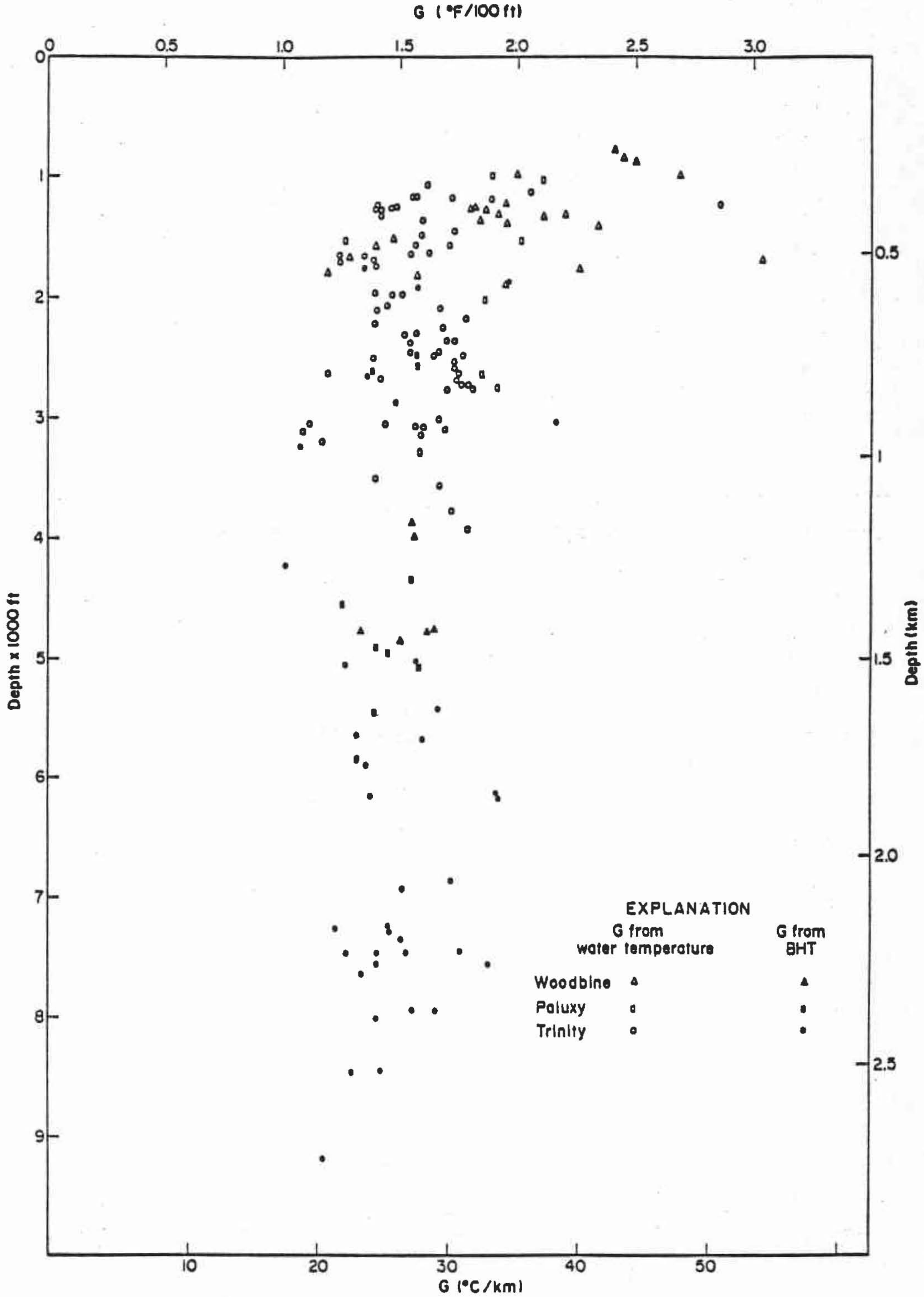

Figure 24. Geothermal gradient with respect to depth: Woodbine, Paluxy, and Hosston/Trinity aquifers, Dallas area.

Bexar County, shallower temperature data show generally higher gradients than do measurements deeper in the well bore. The inflection point in this instance is only 2,000 ft (610 m)--a depth of inflection considerably shallower than that observed in other areas. However, there is a hiatus in Woodbine well data for almost 2,000 ft (from approximately 1,900 ft, or 700 m, to about 2,850 ft, or 869 m). This lack of data is due to the absence of any wells (producing either water or petroleum) completed in that depth range--probably owing to poor ground-water quality of the Woodbine aquifer. For the other two formations, the inflection point is barely suggested with a slight gradient increase for a few Paluxy wells, and--except for one major deflection (possibly an artifact in the data)--even less of a deflection occurs for the Trinity.

The situation with the Woodbine temperature data provides a fitting conclusion to the matter of gradient/depth anomalies. The Woodbine has been studied extensively by Plummer and Sargent (1931), who noted that the sand provides a preferred hydrologic pathway for circulating waters from the edges to the deepest reaches of the East Texas Basin. One result of this basin-wide hydrodynamic system is the giant East Texas oil field. Other results are the smaller Woodbine fields along the Mexia Fault Zone (in Navarro County), and those associated with certain salt domes. Another effect of this deep circulation is the conveyance--under hydrodynamic pressure--of thermal, mineralized waters into the shallow reaches of the Woodbine. This, of course, locally renders the Woodbine an undesirable water resource, and such is the case in parts of the Dallas area. However, the positive deflection of geothermal gradient with respect to depth is an indicator of this documented upwelling. And so is the high content of total dissolved solids. In short, the analysis of water temperature/depth data may be used as an exploration tool not only for thermal waters but perhaps also for hydrocarbons. An abrupt increase in geothermal gradients with increasingly shallow depths indicates upwelling of basinal waters. Such an increase is a valid indicator of hydrothermal potential at depth even when the parts of the aquifer being measured themselves have water temperatures too low to be economically attractive as a heat resource. This is the case with the Woodbine in the Dallas area. Moreover, in certain instances, anomalously high TDS content of waters may indicate upwelling in a way similar to anomalous gradient-to-depth curves. The high TDS areas were also noted by Plummer and Sargent (1931) for parts of the Woodbine; salinity anomalies are seen even at depths where high temperatures no longer persist. However, caution is needed in uncritical use of water salinity as a prospective tool. High TDS may be due to a number of causes, such as surface contamination, local host rock conditions, and the like. When used with water temperature data and BHT readings from electric logs, salinity is one more guide to areas that may have hydrodynamic conditions that favor upwelling. Such is the apparent case in both the Dallas and the Bexar County areas. It also may be true near Austin and Marlin, but the interactions with shallower, cooler, lower salinity meteoric waters obscure this relationship.

One final point about the Dallas area in particular--and this applies to the rest of the thermal water data throughout Texas--is that the depth presented in the conventional "slash-bar" depiction (as in fig. 23) is <u>total depth drilled</u>. We do not usually show depth of water production because these values are usually either unavailable or are ambiguous because of open-hole completion (so that water may enter the borehole from any part of the stratigraphic column that is penetrated by a well) or because of the use of multiple completion zones. However, we obtained somewhat better control on ground-water-producing zones for the Dallas area. This better control is due to the existence there of well-recognized, discrete sand horizons, and these horizons are screened and recorded by water-well drillers. Open-hole completion is rare in this area owing to the possibility of collapse of loose sand or mud into the well bore from the terrigenous aquifers. Figure 24 thus depicts gradients based on what is the actual or average depth of water production and not on the total depth of the well. The variation in gradients derived from these two depths has caused problems in assaying the total energy content of thermal waters in Texas; the U.S. Geological Survey (Reed, in press) in updating their national assessment of geothermal resources used the more conservative total depth value because it constituted the only data generally available. On the basis of these computations, most of the putatively thermal waters (18°F or 10°C above mean ambient air temperature) were not deemed truly thermal because they did not meet the gradient criterion. This criterion--coupled with defects in data records (specifically with actual depth of production)--arbitrarily reduces the apparent quantity and geographic extent of thermal waters in Texas and elsewhere. As seen in figure 24, most of the data points meet the gradient criterion to be thermal in all respects, whereas the thermal waters in Bexar County do not meet both criteria (fig. 10). But even those wells producing ground water below the requisite gradient still constitute a potentially usable resource, especially at shallow depths and in salinity ranges that allow multiple uses of the water. These findings from more reliable depth data in the Dallas area indicate that the total thermal-water resources in Texas are greater than those computed by the USGS. Perhaps in the future other criteria could be applied to define such a resource base so that the resource is not tied to an arbitrary climatic (or other such) criterion.

SUMMARY AND CONCLUSIONS

The investigation of selected case-study areas along the Balcones/Ouachita trend in Central Texas demonstrates the effects of hydrologic processes on geothermal resources in this region. Darcy's Law dictates hydrologic limits to any geothermal resource, except perhaps for the human-engineered hydraulic systems used to tap heat energy from hot, dry rock. Our survey shows, however, that Darcy's Law is more fundamentally involved in the actual occurrence of geothermal anomalies and of hot water. At least this is so in an environment such as studied here, where a tectonic hinge provides the structural framework for permeable sedimentary strata at shallow depths to have hydrologic communication with the deepest part of an adjacent basin. These stratabound aquifers, the abrupt basement discontinuities, and extensive systems of normal faults, all combine to promote basin-wide circulation of waters. This circulation is not convection in the usual sense, in that the processes operate across the entire basin, and thus, the scale is too great to discern discrete thermally driven density cells. And, although the so-called forced convection operates across stratigraphic boundaries and without being particularly constrained by aquitards, there are local highly permeable zones--either discrete aquifers or zones of fractures and faulting--where this upwelling is especially enhanced. These areas are denoted as loci of geothermal gradient anomalies or as localities producing warm waters.

Our surveys thus discriminate geothermal resources from two perspectives: the location of actual warm water; and the location and magnitude of geothermal gradient anomalies. Conventional approaches to geothermal assessment indicate that the geothermal gradient anomaly is the more fundamental of the two, representing anomalous heat flow, which in turn heats local ground water and thus provides a usable resource. This is the way geothermal systems operate in zones of thin crust, ongoing tectonic activity, and all the associated thermal manifestations of these processes and conditions. In such instances, the heat-flow equation defines the situation adequately, and the hot water is, in fact, a derivative of high heat flow (and consequently, of locally high geothermal gradients). However, in this part of the Gulf Coast Basin the cause and effect relations are reversed. The geothermal gradient anomalies are, for the most part, caused by upwelling waters--a lateral (or updip) hydrodynamic effect--instead of from vertical heat flow. In short, high geothermal gradient closures occur associated with strata such as limestones or sandstones that have high thermal conductivity values, and thus--according to the heat-flow equation--should display low geothermal gradients. This apparent contradiction is a result of the strata in question having a high hydraulic conductivity (field permeability--the "K" in Darcy's Law). This high conductivity--given a proper potentiometric gradient--will result in upwelling, the conveyance of hot water from deep in the basin. This, in turn, results in a geothermal gradient anomaly without any anomalous source of conductive heat flow from below. These interactions among key parameters of the heat-flow equation and Darcy's Law have not been very well elucidated by assessors of geothermal resources in sedimentary basinal environments. That is, it has not been adequately demonstrated how hydraulic conductivity tends to cancel the effects of thermal conductivity, and thus Darcy's Law and the heat-flow equation often operate counter to one another even though the two equations are of identical form. These inadequacies probably result from the fact that the most spectacular (and hence, most intensively used) geothermal resources occur where the systems operate according to the heat-flow equation: in areas of thin crust, for example, <u>not</u> in sedimentary basins. Only when this approach has been applied elsewhere, for example, in the eastern United States and in the sedimentary basins of the mid-continent, have problems arisen. And, even though many of the data have posed contradictions, proper explanations have been slow in coming.

Given the findings in this survey, we propose several operations to expedite the assessment of geothermal resources in a sedimentary basinal environment:

1. Focus on any aquifer that has hydrologic communication with the deep reaches of a basin.

2. In assessing geothermal gradients, factor out thermal conductivity. This should be done by including in computations only those temperature measurements made in the same general rock type. In other words, avoid measurements across facies changes, which would result in abrupt changes in thermal or hydrologic conductivity.

3. Compare geothermal gradients based on bottom-hole temperatures with gradients based on producing water temperatures. Valid data on well completion, specifically on precise ground-water-producing intervals are necessary. This comparison can be best done by graphically arraying geothermal gradients with respect to depth. This also should allow the discrimination of a normal prevailing geothermal gradient--a baseline with which to compare deviations.

4. Conduct whatever hydrologic assessments the local data will allow. Construct contour maps of hydraulic conductivity and potentiometric surface because they provide information on two of the variables in Darcy's Law.

5. In assaying areas of high geothermal gradient, consider the effects of fractures and fault zones either as conveyance systems or as barriers. In this regard, lineament surveys may provide clues to certain buried structures.

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