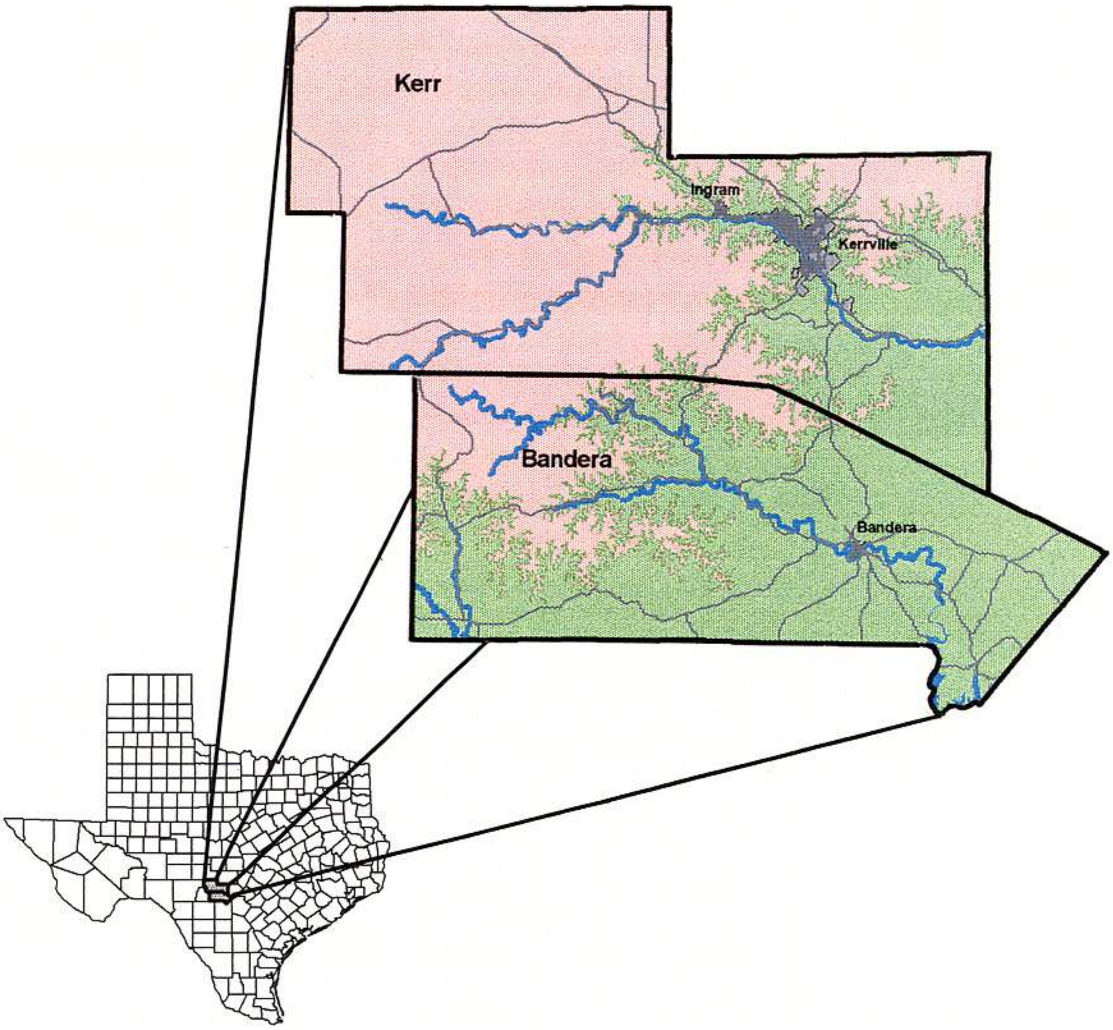
THE LOWER TRINITY AQUIFER OF BANDERA AND KERR COUNTIES, TEXAS

January 2001



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THE LOWER TRINITY AQUIFER OF BANDERA AND KERR COUNTIES, TEXAS

Prepared in Conjunction
with

Plateau Regional Water Plan

Prepared for

Plateau Regional Water Planning Group
and
Texas Water Development Board

January 2001

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EXECUTIVE SUMMARY

The lower Trinity aquifer is being used at an increasing rate in Bandera and Kerr Counties, mainly for public supply, domestic and livestock purposes. The lower Trinity is the oldest of the Cretaceous formations in the Hill Country area, and is comprised of the Hosston and Sligo Formations. Above the lower Trinity is the Hammett Shale, which serves as a confining unit for the lower Trinity where it is present. Where the Hammett is not present, the lower Trinity is difficult to differentiate from the overlying Cow Creek Limestone and Hensell Sand.

The results of this investigation were based on very limited data for the lower Trinity. Very few wells in the study area were completed in the lower Trinity alone, most wells identified during this investigation were either middle Trinity wells, or were dual completions in both the middle and lower Trinity aquifers. Many of the lower Trinity wells initially identified were found to be either abandoned or were domestic wells that were too shallow or had too little information to reliably conclude that they were lower Trinity wells. This lack of lower Trinity wells provided very few aquifer characteristic, water level, and water quality data upon which to base an evaluation of the aquifer.

The lower Trinity generally produces fresh water in small to very large quantities to wells. Yields of more than 1,000 gallons per minute (gpm) are possible in properly completed wells in certain areas. Water quality is generally good, with total dissolved solids generally between 300 and 500 milligrams per liter (mg/l). Water quality in downdip areas is slightly different than in updip areas, with downdip areas having lower concentrations of calcium and magnesium but higher concentrations of sodium, potassium, sulfate and chloride, as well as slightly higher total dissolved solids.

Hydraulic characteristics of the lower Trinity aquifer are difficult to estimate for most of the study area because of the lack of wells completed in the lower Trinity. In the Kerrville area, the aquifer tends to be more transmissive, with transmissivities of 15,000 to 46,000 gallons per day per foot (gpd/ft). Storativities for the lower Trinity were generally between 10^{-4} and 10^{-5}.

Outside the Kerrville area, the aquifer appears to be less transmissive. No estimates of storage for the lower Trinity have been made outside the Kerrville area.

Ground water in the lower Trinity moves to the south and southeast, generally in a downdip direction similar to the direction of ground-water movement in the middle Trinity. Some natural discharge from the lower Trinity probably occurs through leakage. Presently, most of the discharge from the lower Trinity is to wells completed and producing from this aquifer.

Recharge to the lower Trinity in the study area occurs vertically by leakage from the middle Trinity and horizontally by lateral inflow from the north and west. Water samples collected during this investigation show no chemical evidence of recent water in wells sampled. Leakage downward to the lower Trinity is probably restricted where the Hammett Shale is present.

Lower Trinity water levels in areas where pumpage has been heavy and localized have declined significantly in the past. The City of Kerrville relied on the lower Trinity as a source of water from the 1920s to the early 1980s, and water-level declines of as much as 250 feet were observed during that time. In 1981, a surface-water treatment plant was brought on-line, and ground-water production was reduced dramatically. This resulted in water levels in the Kerrville area rebounding as much as 200 feet between 1982 and 1990. Since 1990, however, many wells are again showing significant water-level declines as ground-water use has again increased. In the Bandera area, continuous declines in water levels have been observed for decades, with declines of as much as 400 feet in some wells. Water-level declines in areas outside of the Cities of Bandera and Kerrville are probably not as great due to the fact that very little ground-water production occurs in these areas.

A conservative estimate of availability during drought-of-record conditions was made. The estimate is based on the volume of confined storage, a low specific yield of 1 percent, and a 30-percent "recoverable yield." A total of about 582,000 acre-feet is estimated to be retrievable from the lower Trinity in Bandera (421,500 acre-feet) and Kerr (160,500 acre-feet) Counties. However, because all of this water cannot be withdrawn from any single area of the aquifer, the evaluation of availability on a square-mile or per-acre basis is recommended.

INTRODUCTION

The lower Trinity aquifer is an important water-supply source in the counties forming the "Hill Country" of south-central Texas. Ground water from the aquifer currently supplies various water-use categories including public supply, irrigation, domestic and livestock. Both the Cities of Bandera and Kerrville, along with other private water-supply systems, rely partially or totally on the lower Trinity for their public water supply. This report presents the results of a geohydrologic evaluation of this aquifer principally in Bandera and Kerr Counties and incorporates some data from surrounding counties.

Location and Geographic Setting

The study area is Bandera and Kerr Counties, which are located in the south-central part of the state locally referred to as the "Hill Country," and are shown in Figure 1. The Hill Country area, located near the southeastern edge of the Edwards Plateau, is characterized by rough, hilly terrain. Narrow valleys and steep canyons separated by large, flat-lying hills capped by resistive Edwards Limestone in the western part of the region give way to wide valleys and moderately sloping hills in the eastern part. Surface elevations in the study area range from approximately 2,200 feet in northwestern Kerr County to less than 1,200 feet in the Medina River Valley east of the City of Bandera.

Within Bandera and Kerr Counties, surface water flows to four separate river basins. The Guadalupe River Basin dominates most of Kerr County, although the northwestern part of the county drains by way of Threadgill Creek into the Colorado River Basin. While most of Bandera County lies within the San Antonio River Basin and is primarily drained by the Medina River, the southwest quadrant of the county drains to the Nueces River Basin through the Sabinal River.

Climate

The local climate is subhumid to semiarid, with annual precipitation ranging from approximately 33 inches in eastern Bandera County to 26 inches in northwestern Kerr County (Bomar, 1995). Average temperatures are 33º F in January for the minimum, and 96º F in July for the maximum (Larkin and Bomar, 1983). The average annual gross lake-surface evaporation ranged from 69 inches in the northwest to 63 inches in the east for the period 1950 to 1979. This evaporation rate is much higher than the mean annual precipitation rate in the study area.

Previous Investigations

Several ground-water resource investigations were previously conducted in the region. Stricklin and others (1971) authored one of the first major reports explaining how the Trinity was originally deposited. Ashworth (1983) and Bluntzer (1992) conducted regional investigations on Hill Country aquifers. In preparing the Regional Aquifer-System Analysis (RASA) for the Edwards-Trinity aquifer system, the U. S. Geological Survey produced several professional papers that included the lower Trinity aquifer. Local reports include investigations on ground-water resources of Kerr County (Reeves, 1969), Bandera County (Reeves and Lee, 1962), and in the Kerrville area (Guyton, 1973). CH2M Hill prepared several reports (1988, 1989 and 1992) on aquifer storage and recovery (ASR) investigations in the Kerrville area. Reports of the above investigations and others used in this evaluation of the lower Trinity aquifer in Bandera and Kerr Counties are listed in the section of this report on References.

GEOLOGIC SETTING

The onset of the Cretaceous Period marked a critical turning point in the geologic history of Texas. Prior to the influx of the Early Cretaceous sea, the central Texas landscape consisted of a folded and faulted erosional plain characterized by broad river valleys and low ridges (Hill, 1901) that sloped upward to the Llano Uplift, a dominant structural feature. This terrain represented the landward segment of the continental shelf abutting the ancestral Gulf of Mexico. Quartz-dominated sand and gravel carried by streams flowing off the ancient Llano Uplift were deposited as alluvial sediments along these drainages and became the initial deposits of the lower Trinity (Hosston Sand). The Early Cretaceous sea transgressed westward across the landward margin of the continental shelf burying these initial fluvial deposits with layers of marine limestone, marl and shale. Following submergence of the continental shelf, the Llano Uplift remained as a positive feature in the form of islands that continued to shed clastic debris onto the near-shore environment (Stricklin and others, 1971).

The deposition of the Trinity Group formations resulted in a wedge-shaped sequence of sediments thinning toward the Llano Uplift and thickening toward the south and southeast. The Edwards Limestone was subsequently laid down over the Trinity formations as the Cretaceous sea continued its landward migration and submergence of much of the central part of the existing continent.

About 10 million years ago in the latter part of the Cretaceous Period, continental uplift prevailed and the ancestral coastline began to regress seaward. As the submerged sea floor progressively became subareally exposed forming the Edwards Plateau, atmospheric elements slowly began the erosional process of removing the former marine deposits. Hard dense layers of Edwards Limestone eroded at a relatively slow rate, whereas, the underlying exposed Trinity units eroded much more quickly. The culmination of millions of years of erosion is visible in today’s hilly terrain where Edwards-capped hills attempt to maintain their elevation as rivers and streams continually dissect the landscape carrying less resistive Trinity sediment toward the Gulf of Mexico.

Structure

Major structural components that controlled deposition of the Trinity and that influence current hydrologic characteristics of the aquifer include the Llano Uplift, the Balcones Fault Zone, and the regional dip of the sedimentary units (Figure 2). Contour maps of the base of the Cretaceous and top of the lower Trinity are presented as Figure 3 and Figure 4. Several geologic cross sections through Bandera, Kerr and Kendall Counties (Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, Figure 14, Figure 15, and Figure 16) were constructed using geophysical logs, many of which are from oil-field exploration wells drilled into the deeper subsurface. These cross sections help define the structure and stratigraphy of the lower Trinity aquifer.

The Llano Uplift is a structural dome comprised of Precambrian metamorphic and igneous rocks and Paleozoic sedimentary rocks that are among the oldest known geologic formations exposed in North America. The region was a resistive structural promontory when it was originally implaced in the Precambrian and then again when it was uplifted near the end of the Paleozoic Era (Spearing, 1991). This latter event formed the Ouachita structural belt; the northernmost boundary of this belt is delineated by a thrust fault that can be traced in the subsurface through Bandera, Kerr and Kendall Counties (Flawn and others, 1961).

Two additional structural features were formed at the same time – the San Marcos Arch and the Fredericksburg High. The San Marcos Arch is a wide anticline (a convex upward structural fold whose center contains the oldest rocks) that originates in central Blanco County and dips to the southeast through Comal and Hays Counties. The southwest limb of the anticline runs through eastern Kendall County. Although the arch is a rather large structural feature that defined a significant topographic high during Trinity deposition, significant thinning of the overlying basal Cretaceous sediments is not evident in the study area.

The Fredericksburg High is less than 10 miles wide and trends from the north-northeast to the south-southwest through central Gillespie and eastern Kerr Counties. This high is evident in Figure 3 and Figure 11. The Hosston Sand remains laterally continuous across the Fredericksburg High; however, it thins east of the Kerrville area.

The Balcones Fault system is the dominate structure related to the Balcones Escarpment along the edge of the Edwards Plateau, which is located in the southern portion of the study area. The last major episode of movement in the Balcones Fault Zone occurred during the late Early Miocene, approximately 15 million years ago (Young, 1972). Although most faults in the area trend northeast, a smaller contingent of cross-faults trend northwestward. Most faults within the Balcones Fault Zone are nearly vertical normal faults. Generally, the faults are *en echelon*, with the downdropped blocks toward the coast, but there are some occasional upthrown blocks. Based on the cross sections prepared for this report, offsets between fault blocks in Bandera and Kendall Counties are generally between 50 and 200 feet.

The regional dip of Cretaceous formations changes across the Balcones Fault Zone. Northwest of the fault zone regional dips average 10 to 15 feet per mile to the south, while south and east of the fault zone they are nearly 100 feet per mile (Bluntzer, 1992). Within Bandera, Kerr and Kendall Counties, the dip across the top of the lower Trinity ranges from 8 feet per mile in the western portion of the study area to16 feet per mile in the eastern part. The direction of dip is toward the south-southeast (Figure 3).

Stratigraphy

The geologic units underlying the study area are shown in Table 1 and are, in ascending order from oldest to youngest: pre-Cretaceous rocks; the Trinity Group (including the Travis Peak Formation and Glen Rose Limestone); the Edwards Group; and Quaternary deposits. Because much of the recharge to the lower Trinity passes through one or all of these units, each is briefly described below.

Pre-Cretaceous Rocks. In the study area, the lowest unit of interest is the formation directly beneath the Trinity Group, which is composed of Paleozoic rocks. The Texas Water Development Board (TWDB) has identified the downdip extensions of the Ellenburger-San Saba and the Hickory aquifers in northeast Kerr County. Because no known wells have penetrated these aquifers in Kerr County, very little is known about their water-bearing characteristics. The Ouachita thrust fault, which transects Bandera and Kerr Counties, separates two major Paleozoic sedimentary packages. The Upper Paleozoics, predominantly composed of tilted, weakly metamorphosed and interbedded shales and sandstones could have potentially weathered faster and produced a steeper slope than the more resistant Lower Paleozoics. The Upper Paleozoics exist in the subsurface on the south side of the thrust fault; therefore, the steeper gradient of the surface at the base of the Cretaceous can potentially be attributed to the greater erodibility of the shale-rich Upper Paleozoics. The thickest occurrences of the Sligo Limestone/Hosston Sand in the study area can be found south of the thrust fault.

Trinity Group. The Trinity Group is the most important water-bearing unit in the area and is collectively referred to as the Trinity Group aquifer. The Trinity Group consists of the Glen Rose and Travis Peak Formations. Based on their hydrologic relationships, the water-bearing rocks of the Trinity Group are organized into the following aquifer units (Ashworth, 1983):

Upper Trinity	Consists of the upper Glen Rose Limestone.
Middle Trinity	Consists of the lower member of the Glen Rose Limestone, and the Hensell Sand and Cow Creek Limestone members of the Travis Peak Formation.
Lower Trinity	Consists of the Sligo Limestone and Hosston Sand members of the Travis Peak Formation.

Because of fractures, faults and other hydrogeologic factors, the upper, middle and lower Trinity aquifer units often are in hydraulic communication with one another and collectively should be considered a leaky-aquifer system. Each of these is described below.

Upper Trinity Unit **–** The Glen Rose consists of an upper and lower member. The upper member is equivalent to the upper Trinity aquifer and is composed of relatively thin-bedded, alternating layers of resistant and nonresistant limestones, porous dolomites and nodular marl capable of yielding very small to small quantities of mostly slightly saline water to wells (Reeves, 1969; Ashworth, 1983; Bluntzer, 1992). The upper member of the Glen Rose Formation, when weathered, creates the distinctive "stair-step" topography found at the surface through much of the Hill Country. Water from wells completed in the upper Glen Rose Limestone generally contains elevated concentrations of sulfate and dissolved solids, which come from the dissolving of evaporite minerals found in two predominant beds in this unit. The total thickness of the upper Glen Rose in the study area ranges from 350 to 400 feet.

Middle Trinity Unit **–** The lower member of the Glen Rose Limestone is the upper portion of the middle Trinity aquifer, and is a massive fossiliferous limestone which grades upward into thinner limestone, dolomite, marl and shale beds. The lower member ranges in total thickness from 170 to 240 feet in Bandera, Kerr and Kendall Counties and is capable of yielding small to moderate quantities of good-quality water to wells.

In descending order, the Travis Peak Formation consists of the following members: the Hensell Sand, the Cow Creek Limestone, the Hammett Shale, the Sligo Limestone, and the Hosston Sand (see Table 1). The Hensell and Cow Creek and the lower Glen Rose member comprise the middle Trinity aquifer. The Hosston and Sligo members comprise the lower Trinity aquifer which is the focus of this investigation.

The Hensell Sand consists of red to gray clays, silts, sands, sandstone, conglomerate and thin limestone beds. The total thickness of the Hensell Sand is variable and in the study area is typically 40 to 180 feet, generally thickening to the south. The Hensell is capable of yielding small to moderate quantities of generally hard water to wells in the area. The Hensell transitions to the Bexar Shale to the south and southeast in the study area becoming more shaly and tighter the further away it is from the Llano Uplift.

The Cow Creek is a massive, fossiliferous, white to gray limestone with thin layers of sand, shale and lignite. The most porous and permeable portion of the Cow Creek is usually near the top of the formation. The Cow Creek is typically 30 to 90 feet thick in the study area and is capable of yielding small to moderate quantities of water to wells in the area, although wells in the study area rarely screen just the Cow Creek (Reeves, 1969; Ashworth, 1983; Bluntzer, 1992).

The Hammett Shale (sometimes referred to as the Pine Island Shale) consists of a relatively impermeable dark blue to gray fossiliferous, calcareous, and dolomitic shale with some thin beds of sand and limestone. It is often identified as a "“soft, sticky blue shale" in drillers’ reports. The Hammett Shale is sandier near the pinch-out line in the northern portion of the study area. It is 10 to 35 feet thick in the Kerrville area and thickens downdip to as much as 60 feet in southern Bandera County. North of Kerrville, where the Hammett pinches out, the middle Trinity aquifer (Hensell/Cow Creek) is difficult to differentiate from the underlying lower Trinity aquifer (Sligo/Hosston). The Hammett Shale can heave, expand and collapse into the well bore, and as a result, generally must be cased off prior to drilling into the underlying lower Trinity aquifer. Because of its impermeable nature, the Hammett Shale forms a hydrologic barrier between the lower and middle Trinity aquifers and is the confining unit over the lower Trinity. However, some leakage may occur through the Hammett Shale between these two aquifers, especially through well bores (CH2M Hill, 1992). The Hammett Shale is probably not present north of Kerrville.

Lower Trinity Unit **–** The lower Trinity aquifer is comprised of the Sligo and Hosston units. The Sligo Limestone is the upper portion of the lower Trinity aquifer. This unit is a sandy, dolomitic limestone, dolomite and shale. The Sligo exists in the study area where the Hosston grades into a sandy dolomitic limestone and pinches out in the middle of the study area as shown in Figure 4. It reaches a maximum thickness of 80 feet in southern Bandera and eastern Kendall Counties. Water-yielding capabilities of the Sligo are not fully documented (Reeves, 1969; Ashworth, 1983; Bluntzer, 1992).

The Hosston Sand is the lower portion of the lower Trinity aquifer. Local water well drillers often refer to the Hosston as the "Lower Trinity Sand." The thickness of the Hosston is variable because of the uneven surface in the underlying Paleozoic rocks on which it was deposited. The Hosston Sand consists of a basal conglomerate and grades upward to sandstones, claystones, shales, dolomites, and limestones. The Hosston grades upward into the Sligo and the contact between the two is often hard to determine. From well cuttings obtained during the drilling of a well, sometimes the distinction can be made by a color change from dark gray to pink or red. The total thickness of the Hosston in the study area ranges from a maximum of 280 feet in southeastern Bandera County to the area where the Hosston pinches out in northwestern Kerr County. The Hosston Sand does not outcrop anywhere in the study area, but an equivalent-age outcrop can be found to the north and east and is referred to as the Sycamore Sand. The total net thickness of the Sligo/Hosston (lower Trinity) is shown in Figure 17. The Sligo/Hosston is between 50 and 130 feet thick in the Kerrville area. Generally, the most productive section of the Hosston Sand is the basal conglomerate found at the bottom of the formation. In both Kerr and Bandera Counties, wells completed in the lower Trinity aquifer are capable of yielding small to large quantities of water.

Most wells, especially domestic wells, located in the two-county area are completed in the middle Trinity aquifer, as the middle Trinity aquifer usually supplies sufficient water to meet the users' needs. Wells previously drilled into the lower Trinity are often screened in both the middle and lower Trinity aquifers in order to get the maximum production possible out of the well. However, new regulations in Bandera and Kerr Counties do not allow this type of dual completion. In the vicinity of the Cities of Kerrville and Bandera, many of the public-supply wells have been completed only in the lower Trinity aquifer.

Edwards Group. The Edwards Group overlies the Trinity Group and consists of the Edwards Limestone and other minor formations. The Edwards is found at the surface over the western half of Kerr County and the northwestern quadrant of Bandera County. Elsewhere in these counties, many of the hilltops are capped with the resistant Edwards limestone. In the study area this group does not serve as a major source of ground water, yielding only small quantities of water to domestic and stock wells.

Quaternary Alluvium. The Quaternary deposits in the area consist of gravel, sand, silt, clay and caliche. The beds are generally thin, localized, and follow surface topography, ranging in thickness from less than a foot to as much as 50 feet. These deposits are located mainly in the alluvial floodplain deposits of the Guadalupe and Medina Rivers and their principal tributaries. They are highly permeable and able to transmit small quantities of fresh water to domestic and stock wells in the area.

AQUIFER CHARACTERISTICS

The hydraulic characteristics of the lower Trinity are difficult to determine because very few wells are screened in the lower Trinity alone. Wells in the study area are usually completed only in the middle Trinity aquifer, as this aquifer usually supplies sufficient water to meet users' needs. Several lower Trinity wells exist in certain parts of the study area (mainly in the vicinity of Kerrville), and therefore a more detailed description of the lower Trinity aquifer can be made in these areas. Four lower Trinity wells outside the City of Kerrville (three in Bandera County and one in Kerr County) were tested during this investigation, and the results from these tests provide additional understanding of the characteristics of the lower Trinity outside of the Kerrville area.

Table 2 provides a summary of the wells identified in the study area that are producing from the lower Trinity, including dual-completion wells. The locations of these wells are shown in Figure 18 and Figure 19 for Bandera and Kerr Counties, respectively. As shown in this table, about half of these wells are middle/lower Trinity combination wells. Of the wells that are completed in the lower Trinity only, most in Bandera County are domestic wells, and most in Kerr County are public water-supply wells in the vicinity of Kerrville. Many of the wells listed in Table 2 are inactive or have been abandoned. No lower Trinity wells were identified in the western half of either Bandera or Kerr County where the middle Trinity aquifer is sufficiently productive so that deeper wells are unnecessary.

Hydraulic Characteristics

Hydraulic characteristics of the lower Trinity aquifer vary throughout the region. Table 3 shows the hydraulic characteristics for the lower Trinity determined from pumping tests performed for this investigation as well as from previous testing. The transmissivity of the lower Trinity aquifer ranges from as high as 46,000 gpd/ft in the Kerrville area to less than 100 gpd/ft in other areas. An overall average transmissivity in the study area is approximately 10,000 gpd/ft. Coefficients of storage values for the lower Trinity in the Kerrville area range from about 1×10^{-5} to 3×10^{-3}. Storage values have not been estimated outside of the Kerrville area.

Specific capacities are also variable, ranging from 2.5 to 31.9 gpm/ft in the Kerrville area, but averaging between 10 and 20 gpm/ft.

Four pumping tests were performed for this investigation, one in Kerr County and three in Bandera County.

The results of these pumping tests are included in Table 3, and are some of the only pumping tests available in the study area that are outside of the Kerrville area. These results show that aquifer characteristics outside of the Kerrville area are much different than in the Kerrville area, with lower Trinity transmissivities decreasing in the downgradient direction (south). The lower Trinity has been reported to be a very poor producer south of Kerrville (personal communication with Charles Wiedenfeld, 2000). Some aquifer tests have been conducted in the lower Trinity in Bexar and Kendall Counties, and the transmissivity of the lower Trinity in these areas is about 1,000 gpd/ft (Ashworth, 1983).

Vertical permeability of the Sligo-Hosston was measured in a single rock core analysis and showed a value of 5.5×10^{-6} feet per day (CH2M Hill, 1989). Porosity in the formation varies but generally ranges from about 15 percent to 35 percent, with some zones as high as 50 percent (CH2M Hill, 1989).

Well yields from properly constructed lower Trinity wells can be as high as 500 to 1,000 gpm (Reeves, 1969). Bluntzer (1992) reported that 35 percent of the well yields surveyed during his study were more than 500 gpm, and another 25 percent were between 100 and 500 gpm in Kerr, Bandera and Kendall Counties.

Recharge

Recharge is the process by which water is added to an aquifer and is often equated with a percentage of average annual rainfall that percolates downward from the surface to the saturated zone. While this analogy is appropriate for many aquifers, for some aquifers, including the lower Trinity, recharge from precipitation to a surface outcrop does not occur. In the case of the lower Trinity, this is because very little of this aquifer crops out anywhere. For these aquifers, recharge to the aquifer occurs by leakage from overlying or underlying aquifers.

Based on limited aquifer information, water currently in the lower Trinity in Bandera and Kerr Counties likely entered the aquifer system as recharge in areas to the immediate north and west and moved laterally into the study area. A lesser amount may have originated locally by vertical movement of water (leakage) through overlying formations within the study area. However, this movement is significantly restricted by the Hammett Shale that separates the lower Trinity from the overlying middle Trinity within the study area.

Available aquifer data is presently insufficient to quantify recharge with any degree of accuracy. Data needed for this purpose involve the establishment of continuous water-level measurements in several wells throughout the study area, as well as detailed data on the amount of water being pumped from the aquifer. The water-level measurements can be compared to precipitation and pumpage data to help determine recharge estimates.

Average annual rainfall in the study area range from 26 inches per year in northwest Kerr County to 33 inches per year in eastern Bandera County (Bomar, 1995). General estimates for the Hill Country by Ashworth (1983) and Bluntzer (1992) indicate that approximately 4 to 5 percent of precipitation percolates downward and enters the Trinity units as recharge. However, because the lower Trinity aquifer units do not crop out in the study area, correlating rainfall to recharge directly to the lower Trinity is difficult.

Recharge can also be evaluated by determining the age of the ground water present in the aquifer. For this investigation, several ground-water samples were analyzed for tritium, which is used to help determine if ground water has a component of younger water (less than 50 years). Details of these results are given in the section on Ground-Water Chemistry later in this report, and they show that none of the samples from the lower Trinity aquifer contains recently precipitated water.

Movement

Before wells began producing water from the lower Trinity, the movement of ground water in the aquifer was probably downdip to the south and southeast, eventually leaking upwards into the overlying middle Trinity aquifer (Guyton, 1973). In areas where large pumping centers are now located (i.e. the Cities of Kerrville and Bandera), the production from wells influences the flow of ground water. However, overall regional flow in the lower Trinity continues to be in a south to southeasterly direction.

Ground-water movement is typically depicted with directional arrows perpendicular to water-level contours on a potentiometric-surface (water-level) map. However, due to the lack of lower Trinity water-level data, a regional potentiometric-surface map cannot be constructed for that aquifer. Figure 20 shows water levels and ground-water flow direction for the middle Trinity aquifer, which is likely to be similar to that in the lower Trinity. Figure 21 shows a potentiometric-surface map of water levels in the lower Trinity in the Kerrville area and indicates general ground-water flow direction to the southeast. However, this figure also shows the impact of Kerrville’s pumpage on water levels in the area, as indicated by the deviation of the water-level contour lines.

Leakage

Vertical ground-water movement, or leakage, may occur from the overlying middle Trinity aquifer downward into the lower Trinity aquifer, especially where the Hammett Shale pinches out and no longer provides a hydrologic barrier between these two aquifers in the northern part of Kerr County. However, it is difficult to quantify the leakage between the middle and lower Trinity aquifers. Guyton (1973) noted that wells in the Kerrville area completed in the Hensell reflected the general cone of depression caused by the City of Kerrville production from the lower Trinity aquifer. However, it is not known how much of this water-level decline is due to leakage between the aquifers across the Hammett Shale as opposed to leakage within well bores.

Leakage between the lower and middle Trinity was evaluated during the testing of the Kerrville ASR system. During the pump-testing portion of the test, it was determined that minimal leakage was occurring. However, during the ASR injection testing, which was over a much longer period of time (nearly a month), the study determined that some leakage between the aquifers might be occurring, because a Cow Creek monitoring well rose 7.5 feet during the injection cycle. A Glen Rose monitoring well also rose 4 feet during the injection cycle. However, the conclusion reached in this study was that the leakage was occurring through boreholes that penetrated into the lower Trinity, rather than through the Hammett Shale. It was estimated that as much as 75 gpm could have been moving up a nearby City of Kerrville well (Well No. 8) into the overlying middle Trinity during the ASR injection test.

Water Levels

Long-term water-level changes indicate whether or not ground-water production is causing declines in the water level and whether or not these declines appear to be permanent (i.e. "mining" of ground water). Reeves (1969) noted that lower Trinity wells in the Kerrville area had declined between 32 and 70 feet between the early 1950's and 1966-67. Guyton (1973) noted that water levels in the Kerrville area were between 200 and 250 feet below where they probably had been prior to any pumping occurring in the area. Figure 22 and Figure 23 show hydrographs for two of the City of Kerrville's wells, No. 4 and No. 11. Both of these show declines of as much as 200 feet through the early to mid-1980s. Between the early to mid-1980s and the early 1990s, water levels increased by as much as 200 feet in response to the decreased pumpage by the City. However, since the early 1990s, water levels have again begun to decline, as much as 100 feet or more in many Kerrville wells (Jones, 2000). As with the increase in water levels in the 1980s, these declines are due to a change in the City of Kerrville's pumpage. Other wells in the Kerrville area show a similar pattern to the City production wells, including - the City of Kerrville Airport Well (69-08-101), shown in Figure 24.

Figure 25 shows a hydrograph for a City of Bandera well (69-24-202), which indicates consistent declines from the 1950s through the 1990s, with a total of approximately 400 feet of water-level decline. Because there are little data available outside of the Kerrville and Bandera areas, regional declines in ground-water levels cannot be determined.

Water levels in the aquifer also tend to fluctuate seasonally, in particular in areas of heavy ground-water pumpage such as Kerrville. Data collected for this investigation show that seasonal fluctuations are as high as 125 feet in the Kerrville area, where ground-water pumpage is relatively high. In addition, over 100 feet of seasonal fluctuation can be observed between increased pumping in the summer and much lower pumping in the winter.

Aquifer Storage and Recovery

The City of Kerrville began a study of the potential for a lower Trinity aquifer storage and recovery (ASR) operation in the late 1980s. Construction of a full-scale ASR system began in 1990, and the system was tested in 1991. Testing included one recharge/storage/recovery cycle of about a week, and a second test of about three months. This latter test provided good data on the effect of injection operations on the aquifer and other wells in the area because of the length of the test and the amount of water that was injected during the test.

During the injection portion of the second test, 24 million gallons of water was injected over a period of nearly 1 month. Water levels in all of the City of Kerrville wells being monitored increased, forming a large cone of impression around the injection well. After 28 days of injection, water levels had risen as much as 57.7 feet in City wells. Even wells on the other side of Kerrville, 2-1/2 miles from the injection well, rose between 15 and 20 feet.

GROUND-WATER CHEMISTRY

All ground water contains minerals that are dissolved and transported in solution. The types and concentrations of the minerals depend upon the solubility of the minerals present in the rocks through which the water moves, the length of time the water is in contact with the rocks, and the chemical activity of the water. In general, the concentration of dissolved minerals in ground water increases with depth, especially where circulation in the deeper sediments is restricted by low permeability. Restricted circulation retards the flushing action of water moving through the aquifer and causes the water to become more stagnant and highly mineralized.

The lower Trinity aquifer in Bandera and Kerr Counties generally yields water that ranges from fresh (defined as less than 1,000 mg/l dissolved solids) to slightly saline (defined as 1,000 to 3,000 mg/l dissolved solids). The salinity of the water is higher in the downdip areas of the lower Trinity aquifer. In general, for water to be considered acceptable for public consumption, the concentrations of certain constituents should not exceed the Primary and Secondary Safe Drinking Water Standards mandated by the U. S. Environmental Protection Agency and the Texas Natural Resource Conservation Commission (TNRCC). The recommendations for maximum concentrations of the common inorganic constituents for which samples were analyzed in this study are as follows:

Primary Standards

Constituent	Maximum Concentration (mg/l)
Fluoride	4
Nitrate (as N)	10

Secondary Standards

Constituent	Maximum Concentration (mg/l)
Chloride	300
Fluoride	2
Iron	0.3
Manganese	0.05
Sulfate	300
Dissolved Solids	1,000

Primary Standards are concerned with dissolved constituents that are known to have adverse effects on human health. Secondary Standards are concerned with aesthetic qualities of drinking water (e.g., taste and odor). Often, water with concentrations higher than the Secondary Standards is consumed, especially where that is the only water available. Generally, water that contains more than 2,000 mg/l dissolved solids is not used for human consumption. However, livestock and many irrigated crops can tolerate levels much higher, possibly up to 3,000 to 5,000 mg/l (Hem, 1989).

Table 4 summarizes the water analyses for the lower Trinity available from the TWDB database and for the 11 samples collected and analyzed during this study. The average, median, minimum and maximum concentrations from all available results are provided in Table 5. It should be noted that for wells for which multiple analyses were made, one representative sample from all of the analyses was selected to be included in the table. This eliminated the possibility that a few wells with large numbers of analyses would skew the statistics below.

Total Dissolved Solids

The total dissolved solids (TDS) of waters produced from the lower Trinity in the study area range from 309 to nearly 1,000 mg/l, averaging 475 to 500 mg/l. Lower Trinity water from Bandera County, which is farther downdip than Kerr County, tends to be slightly higher in TDS, averaging over 500 mg/l compared to approximately 420 to 450 mg/l in Kerr County. Water from the lower Trinity in Kendall County to the east is much higher in TDS (averaging more than 1,100 mg/l) than in the study area.

Major Cations

Major cations in ground waters include calcium, sodium, potassium and magnesium. As shown in Table 5, calcium ranges from about 20 to 100 mg/l (averaging about 57 mg/l), sodium ranges from 9 to nearly 200 mg/l (averaging about 65 mg/l), potassium ranges from 3 to 20 mg/l (averaging about 11 mg/l) and magnesium ranges from 20 to 80 mg/l (averaging about 40 mg/l). Lower Trinity water from Bandera County tends to be significantly higher in sodium, averaging over 75 mg/l compared to approximately 25 mg/l in Kerr County. Potassium averages around 14 mg/l compared to 8 mg/l in Kerr County. Lower Trinity water from Kerr County tends to have slightly higher concentrations of calcium and magnesium (averaging over 70 and 44 mg/l, respectively) than water in Bandera County (55 and 36 mg/l, respectively). In Kendall County, sodium concentrations are significantly higher than in either Bandera or Kerr County, averaging about 250 mg/l, and calcium concentrations are slightly higher, averaging about 80 mg/l, than in the study area.

Major Anions

Major anions in ground waters include bicarbonate, chloride, sulfate and nitrate. Bicarbonate is the primary form of alkalinity in ground water from the lower Trinity. Bicarbonate forms carbonate hardness in combination with calcium and magnesium and results from the dissolution of carbonate rocks such as limestone and dolomite by the ground water and the equilibrium of these dissolved constituents with carbon dioxide. The bicarbonate concentrations in ground water produced from the lower Trinity ranges from about 250 to 450 mg/l. There does not appear to be an increasing trend in bicarbonate alkalinity concentrations farther downdip.

Lower Trinity water from Bandera County, which is farther downdip than Kerr County, tends to be slightly higher in sulfate, averaging over 100 mg/l compared to approximately 70 mg/l in Kerr County. Sulfate concentrations in Kendall County to the east are much higher, averaging about 200 mg/l. Sulfate results from the dissolution of gypsum and other sulfur-containing materials in soils and rocks.

Lower Trinity waters from Bandera County were also slightly higher in chloride than in Kerr County. As with sulfate, chloride in lower Trinity water from Kendall County was much higher, with concentrations between five and eight times higher than in either Bandera or Kerr County. Chloride is often present in high concentrations in brines produced from oil fields. These brines can also migrate from great depths into shallower aquifers naturally.

Nitrate was not detected in any of the samples collected for this investigation. Nitrate results from organic matter, including sewage, animal waste and fertilizers. Elevated concentrations of nitrate usually indicate the presence of surface waters in the ground water, especially in areas where fertilizers are used or farms or feedlots or other waste-producing business is present. Nitrate also indicates the influence of surface water on the aquifer. The fact that no nitrate was detected in ground-water samples is expected in an aquifer like the lower Trinity which is not recharged by surface waters in the study area.

Summary of Water Chemistry

Figure 26 is a Piper diagram of water chemistries for the lower Trinity in Bandera, Kerr and Kendall Counties. A Piper diagram is a trilinear plot of the major dissolved ions. The composition of waters can be approximated in terms of three sets of cations (Ca, Mg, Na plus K) and three sets of anions (bicarbonate and carbonate, SO_4, and Cl). The proportions of these constituents are plotted as points in separate triangles of cation and anion constituents, which are then projected into a central diamond-shaped field to identify general compositions in terms of water-chemistry types.

Figure 26 shows the evolution/mixing of sodium-bicarbonate water as the water moves downgradient from Kerr to Bandera County. The ground water in Kendall County is also included in this figure and shows much higher TDS, sodium, chloride and sulfate concentrations. Concentrations of some major constituents (sodium, potassium, sulfate, chloride and TDS) tend to be slightly to significantly higher in downdip areas (i.e. Bandera County). In general, this diagram shows the evolution of the geochemistry of the ground water as it flows downgradient to the south and southeast. As the ground water moves downgradient, it evolves into a more sodium-chloride and sulfate-rich water with calcium and magnesium carbonate becoming less dominant.

A trend that was noted was the increase in sodium, chloride and TDS in one of the City of Kerrville wells during the late 1960s to mid-1970s. The Travis Well (Well No. 14, SWN 56-63-606) showed a steady increase in sodium (18 to 72 mg/l), chloride (55 to 200 mg/l), and TDS (417 to 624 mg/l) between 1968 and 1976, as shown in Figure 27. This corresponded with the time period when large drawdowns in water levels were being seen in the Kerrville area. Although water levels in this particular well were not available, nearby wells showed declines of about 150 feet during this time period. This indicates that large withdrawals of lower Trinity ground water in the Kerrville area may cause a degradation in water quality.

Tritium

Tritium is a radioactive isotope of hydrogen found in many waters at very low concentrations. A tritium unit (TU) is a measure of tritium concentration and is defined as a ratio of tritium to hydrogen in a sample of water of 10^{-18}. Tritium has a half-life of 12.4 years; for example, if rainwater has an initial concentration of 6 TU, the concentration of tritium in this same water 12.4 years later will be 3 TU. After 25 years, the concentration will be about 1.5 TU.

There are two main sources of tritium in natural waters. It is naturally produced at low levels in the atmosphere by reactions with incoming sunlight. Tritium generated in the atmosphere has always been present at low levels in rainfall, generally between 5 and 8 TU. The second main source of tritium is from the atmospheric testing of hydrogen bombs that began in 1952. This testing released large amounts of tritium into the atmosphere, peaking in the early 1960s when atmospheric testing was banned. At the peak, tritium concentrations in precipitation in certain areas of the United States were as high as 10,000 TU. This resulted in an artificial spike of tritium that, when detected in ground water, signifies recharge of water precipitated from the atmosphere since the beginning of the bomb-testing period. Waters with no measurable tritium are likely older than 50 years. Waters with tritium concentrations above 10 TU were precipitated after 1952. Waters with measurable concentrations less than 10 TU probably have a mixture of pre- and post-1952 aged water.

Tritium concentrations can rarely quantify the exact age of waters, due to the variable concentrations in precipitation over the last 50 years. Ground water is most often a mixture of recently recharged water and water that previously existed in the aquifer (Mazor, 1991). However, tritium concentrations can often give a relative evaluation of the age of ground water, or an idea of whether or not recently recharged waters are mixing with the ground water.

For this investigation, a total of nine water samples were collected and analyzed for tritium from wells completed in the lower Trinity aquifer (Hosston-Sligo) in Bandera and Kerr Counties. The samples were analyzed by the Tritium Laboratory of the University of Miami/RSMAS. These samples were enriched in order to measure low levels of tritium above

0.2 TU. For the purpose of this evaluation, a TU concentration of less than the laboratory detection limit (0.2 TU) is considered to be an indication of no tritium content.

Six ground-water samples collected for this study were from wells completed only in the lower Trinity aquifer, two samples were from wells completed in both the middle and lower Trinity aquifers, and one sample was of the water being injected into the lower Trinity by the City of Kerrville at its ASR operation. The locations of the wells sampled for tritium are shown in Figure 28. In addition to the samples collected for this investigation, three samples were collected by the Upper Guadalupe River Authority (UGRA) from the Kerrville ASR operation. One was a sample of the raw water put into the system, one was of the water recovered from the ASR well, and a third sample came from a middle Trinity (Cow Creek) monitor well at the ASR site. The tritium sample analysis results are summarized in Table 6 below and indicate that none of the ground-water samples contained recent-precipitation recharge water.

The tritium concentration in the City of Kerrville injection water was 2.59 TU, which is lower than would be expected for surface water. However, the raw water sample collected by the UGRA also indicated tritium at approximately the same concentration. This low value may be due to the fact that when this sampling occurred, flow in the Guadalupe River (the source for the injected water) was very low and was probably predominantly comprised of base-flow discharge from the Edwards. This would tend to dilute tritium concentrations contributed by precipitation that would occur when the river is discharging at a higher rate. The recovered water sample collected by the UGRA also showed a relatively low value of 1.4 TU.

TABLE 6
Results of Tritium Analyses

State Well Number or Well Owner	Location Description	Tritium (TU)
69-24-221	Bandera Blvd. Well	<0.20
69-24-211	Bandera High School Well	<0.20
69-23-803	Hill Country Preserve Well	<0.20
56-63-611	Kerrville Lois Park Well	<0.20
56-63-614	Kerrville Harper Road Well	<0.20
56-64-605	DOT Rest Stop Well	<0.20
56-64-702	VA Hospital Well	<0.20
69-08-103*	Guadalupe Heights Well	<0.20
City of Kerrville	ASR Injection Water	2.59
City of Kerrville**	ASR Raw Water	2.2
City of Kerrville**	ASR Recovered Water	1.4
Unknown**	ASR Cow Creek Monitor Well	0.0

Note: Samples with tritium concentrations of <0.20 TU are considered to be tritium-free.

* - Exact well number is unknown

** - Collected by UGRA.

Three of the samples were collected to evaluate the impact of the City of Kerrville ASR project. Potentiometric-head maps indicate that the ASR operation causes a significant cone of impression, or water-table mounding, around the injection facility. To determine if injected water is moving upward and outward beyond the retrievable range of the ASR wells, samples were collected from the upgradient Harper Road well and the downgradient Park well. A sample of the injection water was collected to show the characteristics of the water actually being injected. The tritium results indicate that while the potentiometric head in the wells surrounding the injection well may be rising due to the pressure induced by the injection operation, the actual water being injected is not physically moving to these other wells. The Cow Creek monitor well sample indicated that none of the injected water appears to be migrating upward into the middle Trinity.

The general conclusion reached from these results is that water present in the lower Trinity aquifer in the areas sampled (near Bandera and Kerrville) is older than 50-60 years. Therefore, rapid recharge from surface sources is not likely occurring. However, this should not be interpreted to suggest that there is no recharge to the lower Trinity. This evaluation does not preclude the potential for lateral inflow of older water from outside the sampled area, or the vertical leakage of older water from overlying water-bearing zones.

The U. S. Geological Survey (USGS) published the results of an Edwards-Trinity Aquifer System water-quality evaluation in 1997. Isotopic analyses were conducted on ground-water samples from 26 wells, seven of which were samples specifically from the lower Trinity aquifer. Conclusions drawn from the USGS study were similar to these conclusions in that no tritium was detected in lower Trinity ground water (USGS, 1997).

GROUND-WATER AVAILABILITY

One of the most important questions with regard to the lower Trinity is the availability, or sustainability, of ground water for future use. As described above, the availability of lower Trinity ground water in a large portion of the study area is speculative due to the lack of lower Trinity wells and the period of record available for those data. However, some estimates can be made based on the available data and the extrapolation of aquifer characteristics from those areas where a significant amount of data does exist.

Current Utilization

Currently the lower Trinity aquifer is mainly used for public supply and rural domestic and livestock purposes. Very little irrigation occurs in the study area because of limited ground-water availability and poor soils. The lower Trinity aquifer is the primary source of ground water for the Cities of Bandera and Kerrville, as well as the only source of water for many small water-supply entities such as those supplying small communities and mobile home parks in the region. The summary of current utilization for this investigation focuses only on these major water users, and not on the smaller domestic and livestock users.

Figures 29 and 30 show the total ground-water use from the Trinity aquifer in Bandera and Kerr Counties. These totals include the upper, middle and lower Trinity aquifers. Although the lower Trinity use cannot be separated out from these totals, these figures do give a good idea of ground-water use patterns. The Upper Guadalupe River Authority brought a new surface-water treatment plant on-line in 1981, significantly reducing the ground-water use by the City of Kerrville and the entire county, as shown in Figure 30. (The treatment plant is now operated by the City of Kerrville.) Water levels in the lower Trinity rebounded several hundred feet between 1981 and 1990 (see hydrographs in Figures 22 to 24). Since 1987, however, ground-water use in Kerr County has steadily increased again. In Bandera County, ground-water use has steadily increased since 1980, increasing 66 percent between 1980 and 1996.

Table 7 provides a summary of the total ground-water use in Bandera and Kerr Counties from 1980 to 1996. As shown in Table 7, public supply accounted for 80 percent to 90 percent of the total ground-water use during the 1980s and 1990s. This is higher than was reported for Kerr County in the late 1960s, when public supply accounted for 69 percent of total use (Reeves, 1969). Of water used for public supply in Kerr County, 90 percent was for the City of Kerrville. Only 19 percent of the ground-water use in Kerr County was for domestic and stock, and very little was used for irrigation, manufacturing or industry.

Areas of Current Concern

Areas where historic ground-water production has caused significant declines can be expected to again see declines in water levels with increased ground-water production. Ashworth (1983) noted that a primary area of concern for the lower Trinity aquifer was in the vicinity of the City of Kerrville. In the mid-1980s, the City began using surface water for a significant portion of their water supply, and ground-water levels rose. However, since 1990, many of the declines in ground-water levels have again been observed. Declines in winter static water levels of 25 to 50 feet have been observed in some Kerrville wells, and declines in summer static water levels of more than 100 feet have been observed between 1992 and 1999 (Jones, 2000). These data indicate that pumping during the summer has been increasing, which not only increases drawdowns during these months but also causes declines in water levels in the Kerrville area throughout the year. Water-chemistry data indicate that there may also be a decline in water quality when water levels are drawn down too far, although this is based on only one limited data set and should be evaluated further.

Availability

The amount of ground water capable of being retrieved from the lower Trinity aquifer includes the quantity of water that can be recovered from storage and the amount of water added to the aquifer (recharged) over time. The ability to accurately estimate these two factors requires a significant amount of knowledge concerning the aquifer’s hydrogeologic characteristics such as thickness, porosity, permeability, and the rate at which the aquifer recharges.

For regional water planning purposes, lower Trinity aquifer availability estimates represent retrievable quantities available during drought-of record conditions and should not be confused with the amount available during average or above average rainfall conditions. For this reason only the unconfined portion of the aquifer was considered in the availability estimate as the artesian head above the top of the aquifer was assumed to be depleted during drought-of-record conditions. Also, the confined/artesian storage coefficient is two to four orders of magnitude less than the unconfined storage coefficient, which means 100 to 1,000 times less the amount of water per each foot of water-level decline.

The unconfined storage of the lower Trinity was determined based on thickness and storage coefficient of the aquifer. The top and the bottom of the aquifer were estimated from structure maps of contacts between geologic units. These maps were derived from interpretations of geophysical logs of oil test wells drilled to depths below the aquifer, many of which are shown in the geologic cross sections in this report.

A very conservative unconfined storage coefficient of 1 percent (0.01) was first applied to the total calculated volume of the lower Trinity aquifer. Because it is not economical or physically realistic to spread wells evenly throughout the extent of an aquifer and because wells are not able to produce water when water levels drop below a certain point, all the water in an aquifer cannot be drained by wells. Therefore, a conservative 30-percent "recoverable yield" was then applied to the calculated aquifer total storage volume.

The estimated recoverable ground water from the lower Trinity in Bandera and Kerr Counties is 421,479 and 160,472 acre-feet, respectively, as summarized in Table 8. Each county estimate is divided into parts of river basins that occupy the western, higher-elevation plateau areas and the eastern, lower elevation areas. Again, these volumes represent the total quantity of water estimated to be retrievable from the lower Trinity during drought-of-record conditions and is not indicative of a quantity available for withdrawal on an annual basis.

TABLE 8

Estimates of Total Recoverable Water from the Lower Trinity Aquifer in Bandera and Kerr Counties

River Basin *	Area (acres)	Total Recoverable Water (acre-feet)	Recoverable Water per Acre (acre-feet)	Recoverable Water per Square Mile (acre-feet)
Bandera County				
Guadalupe	9,823	3,892	0.40	254
Nueces (Plateau Area)	38,709	29,117	0.75	481
Nueces	119,383	103,871	0.87	557
San Antonio (Plateau Area)	89,964	59,951	0.67	426
San Antonio	251,775	224,648	0.89	571
Total		**421,479**		
Kerr County				
Guadalupe (Plateau Area)	344,162	81,311	0.24	151
Guadalupe	154,883	54,542	0.35	225
Nueces	9,622	4,330	0.45	288
San Antonio (Plateau Area)	18,327	7,608	0.42	266
San Antonio	17,651	12,681	0.72	460
Total		**160,472**		
BANDERA AND KERR COUNTIES TOTAL		**581,951**		

* See Figure 1 for location of river basins.

Almost all of the current utilization of the lower Trinity aquifer in the Plateau Region occurs in or very near the Cities of Bandera and Kerrville. The total availability estimate calculated for the entire lower Trinity in Bandera and Kerr Counties cannot be removed by wells located only within the general area of the two cities. A well must compete for the water from the aquifer that is in close proximity to that individual well. If 20 or 30 wells exist in close proximity, then all of those wells must share the volume of water nearby that is retrievable from the aquifer, and they are competing with each other for that water. As a result, the recoverable water per square mile or acre listed in Table 8 may be a more useful estimate of availability for an area.

For future considerations, lower Trinity wells should be spaced an optimal distance apart, and new well fields should be located away from current areas of high production. There are large portions of Bandera and Kerr Counties where the lower Trinity is untapped and therefore untested because the middle Trinity aquifer above it produces more than adequate water for all existing uses in that area. By locating new well production away from existing pumping centers (near cities), it is possible to obtain additional use of the lower Trinity aquifer without having a significant effect on existing withdrawals.

Another way of expressing water-supply availability is with the concept of "sustainable yield," which suggests a quantity of water that can be withdrawn from an aquifer over a given period of time without causing an undesirable amount of aquifer depletion. The sustainable yield of an aquifer is therefore dependent on how the term is defined for its specific intended use. Sustainable yield can mean a quantity of water equivalent to recharge or to lateral underflow such that water is never taken from aquifer storage. Or, it can mean a quantity of water equivalent to recharge plus an agreed-upon quantity taken from storage. A reasonable management assumption of sustainable yield might be one in which recharge is combined with a quantity of water that is allowed to be taken from storage during below average rainfall conditions. This quantity would be equivalent to the volume of recharge water that can be expected to bring the water table back up to a predetermined level during above average rainfall conditions.

Based on municipal well production, annual water-level declines and a recharge of 5-percent of average rainfall, Bluntzer (1992) estimated the sustainable yield for the entire Trinity aquifer in Bandera and Kerr Counties as 6,500 and 7,200 acre-feet/year, respectively. However, Bluntzer did not estimate the sustainable yield for the lower Trinity separately.

A relatively accurate assessment of lower Trinity sustainable yield was not attempted during this study due to the lack of necessary data. As expressed earlier in this report, very few water-level measurements have been made in the past in wells that are completed only in the lower Trinity aquifer. Also, there are no continuous water-level measurements that would allow an analysis of how water levels respond to regional pumpage, recharge events, or even to seasonable fluctuations. Because a reasonably accurate estimate of sustainable yield is an important component of establishing water management guidelines, it is strongly recommended that water-level recording equipment be installed in as many appropriate wells as possible in the near future so that such an analysis can be performed.

SUMMARY

The lower Trinity aquifer is being used at an increasing rate in Bandera and Kerr Counties, mainly for public supply, domestic and livestock purposes. A minimal amount of the water from this aquifer is used for either irrigation or industry. The lower Trinity is the oldest of the Cretaceous formations in the Hill Country area, and is comprised of the Hosston Sand and Sligo Limestone. The Hosston Sand is between 0 and 280 feet thick in the study area. It consists of sandstone, claystone and shale and comprises the bulk of the lower Trinity aquifer. The Hosston grades upward into the Sligo, which is a sandy dolomitic limestone, with dolomite and shale, and pinches out in the middle of the study area. Where present, the Sligo is often difficult to differentiate from the Hosston. Above the lower Trinity is the Hammett Shale, which serves as a confining unit for the lower Trinity where it is present. Where the Hammett is not present, the lower Trinity is difficult to differentiate from the overlying Cow Creek Limestone and Hensell Sand.

The lower Trinity generally produces fresh water to wells in small to very large quantities. Yields of more than 1,000 gpm are possible in properly completed wells in certain areas. Water quality is generally good, with total dissolved solids generally between 300 and 500 mg/l. Water quality in downdip areas (i.e. Bandera County) is slightly different than in updip areas (i.e. Kerr County), with downdip areas having lower concentrations of calcium and magnesium but higher concentrations of sodium, potassium, sulfate and chloride, as well as slightly higher TDS.

Hydraulic characteristics of the lower Trinity aquifer are difficult to estimate for most of the study area because very few wells are completed in the lower Trinity alone. Most wells in the study area either do not penetrate the lower Trinity and are just completed in the middle

Trinity, or are completed in both the lower and middle Trinity aquifers. This lack of wells in the lower Trinity alone makes it difficult to accurately estimate aquifer characteristics.

From the data that were available, it was determined that the lower Trinity showed varying hydraulic characteristics. In the Kerrville area, the aquifer tended to be more transmissive, with transmissivities of 15,000 to 46,000 gpd/ft. Storativities for the lower Trinity in the Kerrville area were in the confined range, generally between 10^{-4} and 10^{-5}. Outside the Kerrville area, the aquifer appears to be less transmissive. No estimates of storativity outside the Kerrville area have been made.

Recharge to the lower Trinity from land surface (i.e. from infiltration of precipitation) does not occur in the study area because the formation does not outcrop in the study area. In fact, very little surficial recharge to the lower Trinity occurs because little of this aquifer outcrops at any location. Instead, most water (recharge) in the aquifer comes from leakage from the overlying middle Trinity. Water-chemistry data (both nitrate and tritium) confirm that none of the water samples collected during this investigation showed any evidence of a recent water component. Eight water samples were collected and analyzed from wells for tritium. All were essentially tritium-free, indicating that the ground water does not contain any water precipitated after the 1940s. However, this does not indicate whether or not water is recharging into the lower Trinity from other aquifers. Leakage to the lower Trinity is probably restricted where the Hammett Shale is present, as this unit provides a fairly tight confining layer over the lower Trinity. Much of the leakage probably occurs updip, where the Hammett is not present. Some leakage appears to occur through the Hammett in the Kerrville area. However, it may be that most of this leakage occurs through well bores rather than through the formation itself.

Ground water in the lower Trinity moves to the south and southeast, generally in a downdip direction similar to the direction of ground-water movement in the middle Trinity. Originally, discharge from the lower Trinity was probably through leakage or ground-water movement downdip. Presently, most or all of the discharge from the lower Trinity is to wells completed in and producing from this aquifer.

Water levels in areas that produce heavily from the lower Trinity have declined significantly in the past. The City of Kerrville relied heavily on the lower Trinity as a water source from the 1920s to the early 1980s, and water-level declines of as much as 250 feet were observed during that time. In 1981 a surface-water treatment plant was brought on-line, and ground-water production was reduced dramatically. This resulted in water levels in the Kerrville area rebounding as much as 200 feet between 1982 and 1990. Since 1990, however, many wells are again showing significant water-level declines as ground-water use increases again. Declines of as much as 100 feet have been recorded since 1990. In the Bandera area, continuous declines in water levels have been observed for decades. Declines of as much as 400 feet have been observed in some wells. Water-level declines in areas outside of the Cities of Kerrville and Bandera are probably not as great due to the fact that very little ground-water production occurs outside of these areas and that aquifer characteristics restrict the impact of heavy pumpage to those areas in the vicinity of the pumpage.

Although there are limited well data available to estimate the availability of ground water from the lower Trinity, data available on the aquifer were used to make a conservative estimate of availability during drought-of-record conditions. The estimate is based on a volume of confined storage, a low specific yield of 1 percent, and 30 percent recoverable water that could be produced because of well distribution. A total of about 582,000 acre-feet is estimated to be available from the lower Trinity in Bandera (421,500 acre-feet) and Kerr (160,500 acre-feet) Counties. However, because all of this water cannot be withdrawn from any single area of the aquifer, the availability on a square-mile or per-acre basis is best for evaluating locally.

RECOMMENDATIONS

Because of the lack of available data on the lower Trinity aquifer, the primary recommendation resulting from this investigation is that further study of the aquifer is needed. The following areas need to be addressed to help answer some of the questions about the lower Trinity in order to help in the appropriate management of this aquifer.

1. Additional lower Trinity wells are needed to better characterize the aquifer, particularly in areas in the western portion of the study area where few, if any, lower Trinity wells exist. Pumping tests should be conducted on all new wells where possible and the data used to develop potential well-yield maps.
2. A complete assessment of existing lower Trinity and lower/middle Trinity wells should be made. The TWDB database should be used as a starting point, and all wells should be field checked to determine the well status, depth and water level. It should also be determined, if possible, how a well has been completed and if it has collapsed or been altered since completion. Any wells located that are completed solely in the lower Trinity should be tested and sampled.
3. Additional isotopic studies should be conducted on lower Trinity ground-water samples to help characterize aquifer recharge by determining the age of the ground water.
4. Water-level recorders should be established at selected wells in the study area to begin collecting long-term water-level data. As many wells as possible should be equipped with continuous water-level recording devices. Continuous water-level measurements will provide the needed data to evaluate seasonal fluctuations, impacts of regional pumping and the effects of drought conditions on the aquifer.

The long-term goal of additional study of the lower Trinity is to develop a good understanding of the distribution of aquifer parameters and of the aquifer sustainability. This information will be used in the future to establish reasonable aquifer-management decisions.

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TABLES

TABLE 1
SUMMARY OF GEOLOGIC AND HYDROLOGIC UNITS

System	Group	Formation	Unit	Approximate Thickness (ft)	Rock Type	Aquifer	Water-Bearing Properties
Quaternary	Recent deposits			0-50	Gravels, silts, and sands.	Local	Able to yield very small to small quantities of water in some areas
Cretaceous	Fredericksburg	Edwards	Segovia	150-400	Massive to thin-bedded limestone and dolomite.	Edwards	Yields small to moderate quantities of fresh water to wells.
			Fort Terrett		Limestone and dolomite.	Confining Bed	Not known to yield water to wells.
	Trinity	Glen Rose	Upper Unit	350-400	Alternating hard to soft limestone, dolomite, nodular marl, gypsum and anhydrite. Thinner bedded than lower Glen Rose.	Upper Trinity	Yields very small to small quantities of mostly slightly to moderately saline water to wells.
			Lower Unit	170-240	Massive limestone and limestone reefs with numerous caves in lower portion. Grades upward into thinner beds.	Middle Trinity	Yields small to very large quantities of fresh to moderately saline water to wells. Well yields of 500+ gpm are possible from this aquifer.
		Travis Peak	Hensell	40-180	Clay, silt, sand, sandstone, conglomerate, with some thin limestone.		
			Cow Creek	30-90	Massive, fossiliferous dolomitic limestone with thin sand, shale, and lignite layers.		
			Hammett Shale	0-60	Dark blue "sticky" clay, thin limestone and sand layers.	Confining Bed	Not known to yield water to wells.
			Sligo	0-80	Sandy dolomite, limestone, and shale.	Lower Trinity	Yields small to very large quantities of fresh to slightly saline water to wells. Well yields of 1,000+ gpm are possible from this aquifer.
			Hosston	0-280	Sandstone, siltstone, claystone, shale, dolomite, limestone, and conglomerate.		

(After Bluntzer, 1992)

TABLE 2
WELLS COMPLETED IN THE LOWER TRINITY AQUIFER IN BANDERA AND KERR COUNTIES

State Well	County	Owner	Date Drilled	Well Depth	Aquifer	Status	Primary Use
Lower Trinity Wells							
6809401	Bandera	Joe H. Berry Well 3	1952	830	Hosston	Unknown	Irrigation
6817101	Bandera	Ard E. Richardson, II	1968	1204	Hosston	Unknown	Stock
6817105	Bandera	Jeff & Michelle Asher	1994	440	Hosston	Unknown	Domestic
6817409	Bandera	Greg & Janet Laura	1994	500	Hosston	Unknown	Domestic
6817410	Bandera	Jack Dean	1993	500	Hosston	Unknown	Domestic
6817414	Bandera	Robert McDonald	1982	470	Hosston	Unknown	Domestic
6817506	Bandera	Herbert Metzger	1991	440	Hosston	Unknown	Domestic
6817702	Bandera	George Hohon	1984	500	Hosston	Unknown	Domestic
6817707	Bandera	Matthew Woods	1993	460	Hosston	Unknown	Domestic
6817708	Bandera	Carlos Cortez	1994	420	Hosston	Unknown	Domestic
6817711	Bandera	Dorothy Ruff	1990	460	Hosston	Unknown	Domestic
6817713	Bandera	Wayne Hildenburg	1973	350	Hosston	Unknown	Domestic
6817810	Bandera	Wesley Kyle	1985	480	Hosston	Unknown	Domestic
6916902	Bandera	Purple Sage Ranch, #4		950	Hosston	Unknown	Irrigation
6922701	Bandera	Paul Kayser	1956	1000	Hosston	Unknown	Domestic
6924102	Bandera	Bandera County WCID #1	1967	805	Hosston	Unknown	Public Supply
6924201	Bandera	Bandera Water Control & Improvement District	1953	900	Hosston	Unknown	Unused
6924202	Bandera	Bandera W.C.I.D. #1	1953	824	Hosston	Unknown	Public Supply
6924204	Bandera	Bandera W.C.I.D. #1 Well 3	1946	896	Hosston	Unknown	Public Supply
6924301	Bandera	J. P. Heinen	1918	422	Hosston	Unknown	Domestic
6924303	Bandera	Lost Valley Resort Ranch		785	Hosston	Unknown	Irrigation
6924504	Bandera	Alkek Elementry School	1986	930	Hosston	Unknown	Public Supply
6924601	Bandera	B. Parker		925	Hosston	Unknown	Irrigation
5663501	Kerr	City of Kerrville, Lois Well	1957	620	Hosston	Active	Public Supply
5663603	Kerr	City of Kerrville	1940	667	Hosston	Inactive, due to be plugged	Public Supply
5663604	Kerr	City of Kerrville		606	Hosston	Observation Well	Public Supply
5663605	Kerr	City of Kerrville Plant Well	1947	600	Hosston	Inactive, due to be redrilled	Public Supply
5663606	Kerr	City of Kerrville, Travis Well	1949	665	Hosston	Active	Public Supply
5663607	Kerr	City of Kerrville		634	Hosston	Inactive, due to be plugged	Public Supply
5663609	Kerr	City of Kerrville	1963	601	Hosston	Test hole only	Unused
5663610	Kerr	City of Kerrville	1967	600	Hosston	Test hole only	Unknown
5663611	Kerr	City of Kerrville, Harper Road Well	1965	610	Hosston	Active	Public Supply
5663614	Kerr	City of Kerrville, Hays Park	1966	603	Hosston	Active	Public Supply
5663901	Kerr	City of Kerrville, H St.	1952	625	Hosston	Active	Public Supply
5663909	Kerr	Riverhill M. U. D.		642	Hosston	Inactive	Public Supply
5663922	Kerr	City of Kerrville			Hosston	Unknown	Unused
5664403	Kerr	City of Kerrville	1965	604	Hosston	Test hole only	Unused
5664407	Kerr	City of Kerrville, Alpine Well	1972	620	Hosston	Active	Public Supply

TABLE 2
WELLS COMPLETED IN THE LOWER TRINITY AQUIFER IN BANDERA AND KERR COUNTIES

State Well	County	Owner	Date Drilled	Well Depth	Aquifer	Status	Primary Use
5664601	Kerr	B.R. Schulz	1952	634	Hosston	Unknown	Irrigation
5664605	Kerr	Texas Department of Transportation		684	Hosston	Active	Public Supply
5664701	Kerr	City of Kerrville, Meadowview Well	1963	638	Hosston	Active	Public Supply
5664702	Kerr	United States Veterans Administration		558	Hosston	Active	Public Supply
5664707	Kerr	Lions Camp	1957	668	Hosston	Abandoned	Public Supply
5664709	Kerr	City of Kerrville	1974	760	Hosston	Abandoned	Unused
6907902	Kerr	T.S. Clements	1952	1000	Hosston	Unknown	Irrigation
6908101	Kerr	City of Kerrville, Airport Well	1956	665	Hosston	Observation Well	Public Supply
6908103	Kerr	Guadalupe Heights Utility Corp.	1962	692	Hosston	Unknown	Public Supply
6908104	Kerr	Guadalupe Heights Util Corp	1967	690	Hosston	Unknown	Public Supply
6908106	Kerr	C. Meek	1954	900	Hosston	Unknown	Irrigation
6908107	Kerr	C. Meek	1954	900	Hosston	Unknown	Domestic
6923501	Bandera	YMCA (Hamman Ranch)	1989	850	Sligo	Unknown	Public Supply
6924211	Bandera	Bandera I.S.D.	1976	1160	Sligo	Unknown	Public Supply
6923601	Bandera	Dixie Dude Ranch	1953	1085	Sligo and Hosston	Unknown	Domestic
6923801	Bandera	J. F. Merrick Estate		1095	Sligo and Hosston	Inactive	Unused
6923803	Bandera	Texas Parks & Wildlife Commission		879	Sligo and Hosston	Inactive	Irrigation
6923901	Bandera	J. S. Morris	1953	1110	Sligo and Hosston	Unknown	Domestic
5663615	Kerr	Upper Guadalupe River Authority-Well #PZ1		635	Sligo and Hosston	Observation Well	Unused
5663906	Kerr	J. Weatherby Riverhill M. U. D.	1964	631	Sligo and Hosston	Abandoned?	Public Supply
5663921	Kerr	Richard Cremer	1979	680	Sligo and Hosston	Unknown	Irrigation
6908108	Kerr	B.L. Wiendenfeld	1937	642	Sligo and Hosston	Unknown	Stock
Middle/Lower Trinity Combination Wells							
5662701	Kerr	Camp Mystic	1986	560	Middle and Lower Trinity	Unknown	Public Supply
5663409	Kerr	Aquasource Ingram WSC Well No. 4	1981	840	Middle and Lower Trinity	Unknown	Public Supply
5663413	Kerr	R. Hansen	1956	614	Middle and Lower Trinity	Unknown	Domestic
5663502	Kerr	W.F. Stelzer	1965	657	Middle and Lower Trinity	Unknown	Domestic
5663507	Kerr	R. Hansen	1956	614	Middle and Lower Trinity	Unknown	Domestic
5663601	Kerr	City of Kerrville	1923	610	Middle and Lower Trinity	Abandoned	Unused
5663602	Kerr	City of Kerrville		650	Middle and Lower Trinity	Abandoned	Unused
5663608	Kerr	City of Kerrville, Lewis Well		619	Middle and Lower Trinity	Monitor Well Only	Public Supply
5663917	Kerr	Hill Country Utilities Lakeview	1985	800	Middle and Lower Trinity	Unknown	Public Supply
6801101	Kerr	G. Walker	1955	668	Middle and Lower Trinity	Unknown	Stock
6801406	Kerr	R.O. Perkins	1953	666	Middle and Lower Trinity	Unknown	Unused
6817411	Bandera	Larry Smith	1994	480	Middle and Lower Trinity	Unknown	Domestic
6817412	Bandera	Howard Dukes	1994	480	Middle and Lower Trinity	Unknown	Domestic
6817413	Bandera	Jim Rasmussen	1985	455	Middle and Lower Trinity	Unknown	Domestic
6817503	Bandera	William & Priscilla Ferguson	1994	440	Middle and Lower Trinity	Unknown	Domestic

TABLE 2
WELLS COMPLETED IN THE LOWER TRINITY AQUIFER IN BANDERA AND KERR COUNTIES

State Well	County	Owner	Date Drilled	Well Depth	Aquifer	Status	Primary Use
6817504	Bandera	John Forsythe	1975	465	Middle and Lower Trinity	Unknown	Domestic
6817505	Bandera	Jack Trenkelbach	1974	470	Middle and Lower Trinity	Unknown	Domestic
6817515	Bandera	Paul Chandler	1994	540	Middle and Lower Trinity	Unknown	Domestic
6817703	Bandera	Ollie Fuller	1990	475	Middle and Lower Trinity	Unknown	Domestic
6817704	Bandera	Damon Lee	1989	460	Middle and Lower Trinity	Unknown	Domestic
6817705	Bandera	E.D. Lansford	1984	425	Middle and Lower Trinity	Unknown	Domestic
6817808	Bandera	Dewitt Leibold	1955	670	Middle and Lower Trinity	Unknown	Domestic
6817811	Bandera	Paul & Rachel Olson		460	Middle and Lower Trinity	Unknown	Domestic
6817812	Bandera	Bill Araiza	1984	635	Middle and Lower Trinity	Unknown	Domestic
6817813	Bandera	Shirley Boone	1985	450	Middle and Lower Trinity	Unknown	Domestic
6818701	Bandera	Pete Knowles	1956	1120	Middle and Lower Trinity	Unknown	Unused
6825507	Bandera	Bandera County Park & State Boat Ramp	1979	575	Middle and Lower Trinity	Unknown	Public Supply
6907304	Kerr	Weidenfeld Water Works Silver Creek Estates	1979	880	Middle and Lower Trinity	Unknown	Public Supply
6907904	Bandera	T. S. Clements	1955	750	Middle and Lower Trinity	Unknown	Irrigation
6908102	Kerr	Guadalupe Heights Util. Corp.		600	Middle and Lower Trinity	Unknown	Unused
6908510	Kerr	Wiedenfeld Water Works	1987	500	Middle and Lower Trinity	Unknown	Public Supply
6908511	Kerr	Texas Orchards	1990	500	Middle and Lower Trinity	Unknown	Unused
6908611	Kerr	R.B. Nowlin	1920	550	Middle and Lower Trinity	Unknown	Unused
6914601	Bandera	Medina Water Supply Corp.	1967	800	Middle and Lower Trinity	Unknown	Public Supply
6914604	Bandera	Medina Water Supply Corp.	1980	406	Middle and Lower Trinity	Unknown	Public Supply
6914605	Bandera	Camp Corpus Christi Catholic Diocese of CC	1985	494	Middle and Lower Trinity	Unknown	Public Supply
6914903	Bandera	Camp Corpus Christi Catholic Diocese of CC	1985	560	Middle and Lower Trinity	Unknown	Public Supply
6914904	Bandera	Camp Corpus Christi			Middle and Lower Trinity	Unknown	Public Supply
6914905	Bandera	Camp Corpus Christi	1983	420	Middle and Lower Trinity	Unknown	Domestic
6916702	Bandera	Texas Department of Transportation		798	Middle and Lower Trinity	Unknown	Public Supply
6916901	Bandera	Purple Sage Ranch	1954	780	Middle and Lower Trinity	Unknown	Domestic
6924103	Bandera	Bandera W.S.C.	1979	430	Middle and Lower Trinity	Unknown	Public Supply
6924207	Bandera	Flying L. Ranch Well 1	1972	817	Middle and Lower Trinity	Unknown	Unused
6924208	Bandera	Flying L. Ranch Well 2	1972	790	Middle and Lower Trinity	Unknown	Irrigation
6924210	Bandera	Flying L. Ranch	1945	960	Middle and Lower Trinity	Unknown	Public Supply
6924214	Bandera	Enchanted River Est.	1980	390	Middle and Lower Trinity	Unknown	Public Supply
6924215	Bandera	Flying L Ranch	1985	855	Middle and Lower Trinity	Unknown	Irrigation
6924216	Bandera	Flying L Ranch			Middle and Lower Trinity	Unknown	Unused
6924218	Bandera	William F. Garms	1970	380	Middle and Lower Trinity	Unknown	Domestic
6924219	Bandera	Louis Kieschnick	1980	438	Middle and Lower Trinity	Unknown	Unknown
6924505	Bandera	San Julian Estates Hill Country Utilities	1985	885	Middle and Lower Trinity	Unknown	Public Supply

TABLE 3
SUMMARY OF HYDRAULIC CHARACTERISTICS OF THE LOWER TRINITY AQUIFER IN BANDERA AND KERR COUNTIES

State Well	Owner	Well Number	Aquifer	Transmissivity	Storativity	Source
Kerr County						
5663615	UGRA	PZ-1	Sligo and Hosston	9,600-11,128	ND	CH2M Hill, 1989
None	UGRA	R-1	Sligo and Hosston	7,000	7.00E-04	CH2M Hill, 1992
5663501	City of Kerrville	No. 10	Sligo and Hosston	21,500	ND	CH2M Hill, 1992
5663501	City of Kerrville	No. 10	Sligo and Hosston	24,400	ND	Guyton, 1973
5663603	City of Kerrville	No. 3	Sligo and Hosston	21,500	3.10E-03	Guyton, 1973
5663603	City of Kerrville	No. 3	Sligo and Hosston	23,500	6.00E-04	Guyton, 1973
5663603	City of Kerrville	No. 3	Sligo and Hosston	22,000	5.00E-05	Reeves, 1969
5663604	City of Kerrville	No. 4	Sligo and Hosston	23,500	9.20E-04	Guyton, 1973
5663604	City of Kerrville	No. 4	Sligo and Hosston	24,800	1.40E-05	Guyton, 1973
5663604	City of Kerrville	No. 4	Sligo and Hosston	24,000	ND	Reeves, 1969
5663604	City of Kerrville	No. 4	Sligo and Hosston	19,000	5.00E-05	Ashworth, 1983
5663605	City of Kerrville	No. 5	Sligo and Hosston	23,500	ND	CH2M Hill, 1988
5663605	City of Kerrville	No. 5	Sligo and Hosston	34,343	ND	Guyton, 1973
5663606	City of Kerrville	No. 14	Sligo and Hosston	14,000	1.90E-04	CH2M Hill, 1992
5663607	City of Kerrville	No. 7	Sligo and Hosston	24,800	2.00E-05	CH2M Hill, 1988
5663607	City of Kerrville	No. 7	Sligo and Hosston	16,500	1.90E-04	Guyton, 1973
5663607	City of Kerrville	No. 7	Sligo and Hosston	20,000	2.00E-05	Reeves, 1969
5663608	City of Kerrville	No. 8	Cow Creek, Sligo and Hosston	40,000	ND	CH2M Hill, 1988
5663608	City of Kerrville	No. 8	Cow Creek, Sligo and Hosston	23,200	ND	Guyton, 1973
5663608	City of Kerrville	No. 8	Cow Creek, Sligo and Hosston	46,000	7.40E-04	Reeves, 1969
5663611	City of Kerrville	No. 12	Sligo and Hosston	20,000	ND	CH2M Hill, 1992
5663614	City of Kerrville	No. 13	Sligo and Hosston	16,000	ND	Guyton, 1973
5663614	City of Kerrville	No. 13	Sligo and Hosston	19,000	5.00E-05	Reeves, 1969
5663901	City of Kerrville	No. 9	Sligo and Hosston	14,900	ND	CH2M Hill, 1992
5663901	City of Kerrville	No. 9	Sligo and Hosston	15,000	3.00E-05	Reeves, 1969
5664407	City of Kerrville	No. 15	Sligo and Hosston	1,450	ND	CH2M Hill, 1992
5664701	City of Kerrville	No. 11	Sligo and Hosston	22,000	ND	Guyton, 1973
None	The Woods	No. 3	lower Trinity	1,010	ND	Current investigation
Bandera County						
6819501			Hosston	900		Ashworth, 1983
6923803	Hill Country Preserve	None	lower Trinity (Sligo only?)	61	ND	Current investigation
6924219	Bandera Downs	None	lower Trinity?	6,080	ND	Current investigation
6924220	Flying L Ranch	No. 2	middle/lower Trinity	1,960	ND	Current investigation

ND- Not determined

TABLE 4
SUMMARY OF SELECTED WATER-CHEMISTRY RESULTS FOR LOWER TRINITY SAMPLES IN BANDERA AND KERR COUNTIES

State Well Number or Well Name	Aquifer	Date		Analyte Concentration (mg/l)								pH
		Month	Year	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	
Bandera County												
6817101	Hosston	11	1975	41	25	95	13	353	49	50	466	8.5
6818701	Trinity	12	1956	304	180	46	--	316	1260	20	1979	7.4
6825507	Trinity	1	1996	137	80	25	8	308	412	20	855	7.2
6907904	Trinity	2	1957	54	49	49	--	338	129	22	474	7.8
6914601	Hosston, Sligo, Cow Creek	9	1991	77	52	45	18	355	205	39	636	7.3
6914903	Trinity	6	1994	83	58	42	19	344	256	36	688	7.0
6916702	Trinity	6	1994	50	32	63	15	371	52	42	455	7.2
6916902	Hosston	7	1977	68	48	43	16	369	120	39	528	7.7
6922701	Hosston	11	1975	34	20	140	14	371	79	72	553	8.3
6923601	Sligo	1	1957	32	21	134	--	360	51	73	503	7.6
6923801	Sligo	1	1957	39	20	137	15	364	70	85	560	7.7
6923803 **	Lower Trinity	5	2000	20	20	107	15	210	72	62	431	--
6923901	Sligo	7	1977	35	20	116	14	348	48	68	484	7.8
6924102	Hosston	6	1988	44	22	95	13	378	48	52	473	7.6
6924103	Other Lower/Middle Trinity	9	1991	77	53	41	17	361	177	30	599	7.3
6924202	Hosston	9	1991	36	22	100	15	354	56	56	477	7.5
6924204	Hosston	2	1952	55	30	96	--	372	81	57	519	8.2
6924208	Other Lower/Middle Trinity	8	1996	70	54	42	14	334	149	36	552	7.0
6924211 **	Lower Trinity	5	2000	33	20	101	11	290	49	62	423	--
6924214	Other Lower/Middle Trinity	6	1995	71	49	46	--	364	131	36	514	7.7
6924219 **	Lower Trinity	5	2000	61	46	41	14	288	135	37	533	--
6924220 **	Lower Trinity	5	2000	62	43	41	13	287	130	36	503	--
6924221 **	Lower Trinity	5	2000	36	21	100	11	287	48	66	450	--
6924301	Hosston	3	1986	65	46	45	15	369	114	36	515	8.1
6924303	Hosston	11	1975	43	26	94	13	370	51	51	473	7.9
6924504	Hosston	9	1991	39	25	100	14	369	51	58	486	7.5

TABLE 4
SUMMARY OF SELECTED WATER-CHEMISTRY RESULTS FOR LOWER TRINITY SAMPLES IN BANDERA AND KERR COUNTIES

State Well Number or Well Name	Aquifer	Date		Analyte Concentration (mg/l)								pH
		Month	Year	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	
Kerr County												
5663501	Hosston	10	1973	57	38	33	--	376	30	23	367	7.7
5663502	Other Lower/Middle Trinity	4	1966	29	31	24	20	288	24	12	293	7.8
5663602	Other Lower/Middle Trinity	11	1945	79	45	11	7	368	79	20	437	7.9
5663603	Hosston	6	1966	74	46	16	4	376	105	17	460	7.2
5663604	Hosston	8	1968	74	43	12	--	365	67	19	396	7.5
5663605	Hosston	5	1966	61	43	17	7	379	44	20	391	7.0
5663606	Hosston	12	1968	81	45	18	--	382	29	55	417	7.3
5663606	Hosston	8	1970	68	46	25	--	367	28	57	405	7.6
5663606	Hosston	9	1972	59	56	36	--	360	28	91	448	7.7
5663606	Hosston	10	1973	73	49	42	--	362	28	109	480	7.5
5663606	Hosston	2	1976	85	55	72	--	360	34	200	624	8.0
5663607	Lower Trinity	8	1963	55	43	22		366	38	19	540	7.5
5663608	Hosston	8	1968	84	40	16	--	362	102	13	435	7.4
5663608	Hosston	9	1972	76	44	17	--	360	86	16	417	7.3
5663608	Hosston	5	1979	75	42	18	--	362	80	16	423	7.7
5663608	Hosston	7	1987	156	66	21	8	365	381	23	864	7.9
5663608	Hosston	4	1993	197	61	23	10	394	409	28	956	7.0
5663611 **	Hosston	5	2000	60	43	17	6	288	27	38	349	--
5663614 **	Hosston	5	2000	58	41	20	6	296	39	23	368	--
5663615	Hosston	9	1989	58	48	37	8	331	24	96	583	7.3
RA Well R-1	Hosston	3	1991	59	35	44	6	347	36	40	421	7.3
5663901	Hosston	6	1988	65	39	23	6	383	48	19	401	7.2
5664407	Hosston	4	1993	63	45	18	8	369	26	25	387	7.0
5664601	Hosston	6	1966	76	45	95	8	374	43	168	629	7.2
5664605 **	Hosston	5	2000	75	43	62	9	284	115	98	528	--
5664701	Hosston	10	1973	70	45	23	--	388	44	45	419	7.7
5664702 **	Hosston	5	2000	56	40	21	7	299	37	17	357	--
5664707	Hosston	12	1965	62	38	27	--	377	32	18	364	7.1
6907902	Hosston	4	1985	72	44	31	11	370	111	19	484	8.2
6908101	Hosston	4	1993	58	40	33	9	377	34	15	394	7.2
6908103	Hosston	9	1972	58	42	23	7	392	43	15	382	7.1

TABLE 4
SUMMARY OF SELECTED WATER-CHEMISTRY RESULTS FOR LOWER TRINITY SAMPLES IN BANDERA AND KERR COUNTIES

State Well Number or Well Name	Aquifer	Date		Analyte Concentration (mg/l)								pH
		Month	Year	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	
69-08-10X **	Lower Trinity	5	2000	55	40	25	8	300	48	13	366	--
6908107	Hosston	4	1985	96	39	22	9	372	128	17	508	7.9
Woods #3 **	Lower Trinity	8	1999	53	36	26	8	296	32	14	309	--

TABLE 5
SUMMARY OF LOWER TRINITY WATER CHEMISTRY IN BANDERA, KERR, AND KENDALL COUNTIES

Bandera County

	Ca	Mg	Na	K	HCO3	SO4	Cl	TDS	pH
Average	43	27	97	14	342	70	58	492	7.9
Median	39	22	100	14	362	51	58	485	7.9
Minimum	20	20	41	11	231	46	36	423	7.5
Maximum	68	48	140	16	378	135	85	560	8.5

Kerr County

	Ca	Mg	Na	K	HCO3	SO4	Cl	TDS	pH
Average	67	43	29	7	351	56	41	451	7.5
Median	62	43	23	7	366	39	19	401	7.5
Minimum	53	35	9	4	284	24	13	309	7.0
Maximum	97	55	95	11	392	173	200	710	8.2

Bandera and Kerr Counties

	Ca	Mg	Na	K	HCO3	SO4	Cl	TDS	pH
Average	57	37	56	10	348	61	47	467	7.7
Median	58	40	37	9	365	48	38	467	7.7
Minimum	20	20	9	4	231	24	13	309	7.0
Maximum	97	55	140	16	392	173	200	710	8.5

Kendall County

	Ca	Mg	Na	K	HCO3	SO4	Cl	TDS	pH
Average	81	46	252	8	335	206	337	1172	7.6
Median	58	44	262	8	328	200	335	1129	7.5
Minimum	30	24	37	0	275	24	96	717	6.9
Maximum	249	108	449	20	404	362	830	1936	8.3

TABLE 7
SUMMARY OF TRINITY AQUIFER WATER USE IN BANDERA AND KERR COUNTIES, 1980-1996

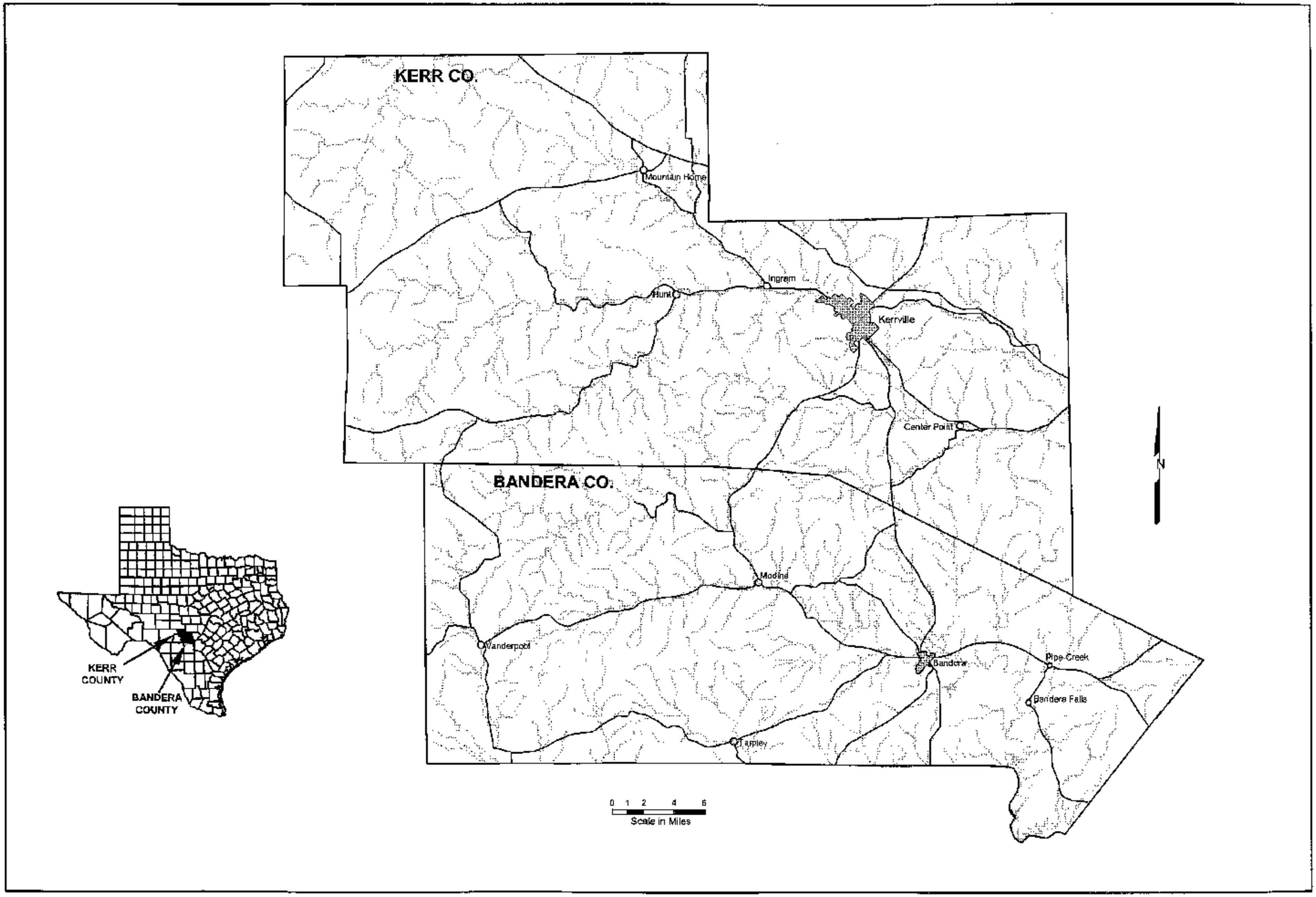
Bandera County

Year	Pumpage (acre-feet/year)						
	Municipal	**Manufacturing**	**Power**	**Mining**	**Irrigation**	**Stock**	**Total**
1980	885	8	0	0	99	263	1,255
1984	1,129	0	0	24	61	222	1,436
1985	1,121	0	0	24	89	199	1,433
1986	1,179	0	0	72	36	185	1,472
1987	1,192	0	0	20	162	198	1,572
1988	1,263	0	0	21	162	230	1,676
1989	1,359	0	0	20	133	228	1,740
1990	1,424	0	0	23	151	228	1,826
1991	1,425	0	0	23	151	231	1,830
1992	1,349	12	0	23	151	231	1,766
1993	1,517	43	0	23	290	216	2,089
1994	1,595	13	0	23	55	250	1,936
1995	1,699	0	0	23	50	251	2,023
1996	1,791	18	0	23	53	203	2,088
Percent of Total	71-86%	0-2%	0%	1-5%	2-14%	10-21%	

Kerr County

Year	Pumpage (acre-feet/year)						
	Municipal	**Manufacturing**	**Power**	**Mining**	**Irrigation**	**Stock**	**Total**
1980	4,682	0	0	0	500	184	5,366
1984	2,876	0	0	81	374	151	3,482
1985	2,847	0	0	81	204	139	3,271
1986	2,458	0	0	0	136	105	2,699
1987	2,032	0	0	71	136	116	2,355
1988	2,373	0	0	78	136	134	2,721
1989	2,809	0	0	73	191	132	3,205
1990	2,478	0	0	73	187	130	2,868
1991	2,402	0	0	170	187	136	2,895
1992	2,861	0	0	170	187	179	3,397
1993	3,109	0	0	167	396	166	3,838
1994	2,951	0	0	167	406	167	3,691
1995	3,240	0	0	167	355	161	3,923
1996	3,688	0	0	167	396	147	4,398
Percent of Total	80-91%	0%	0%	0-6%	5-11%	3-5%	

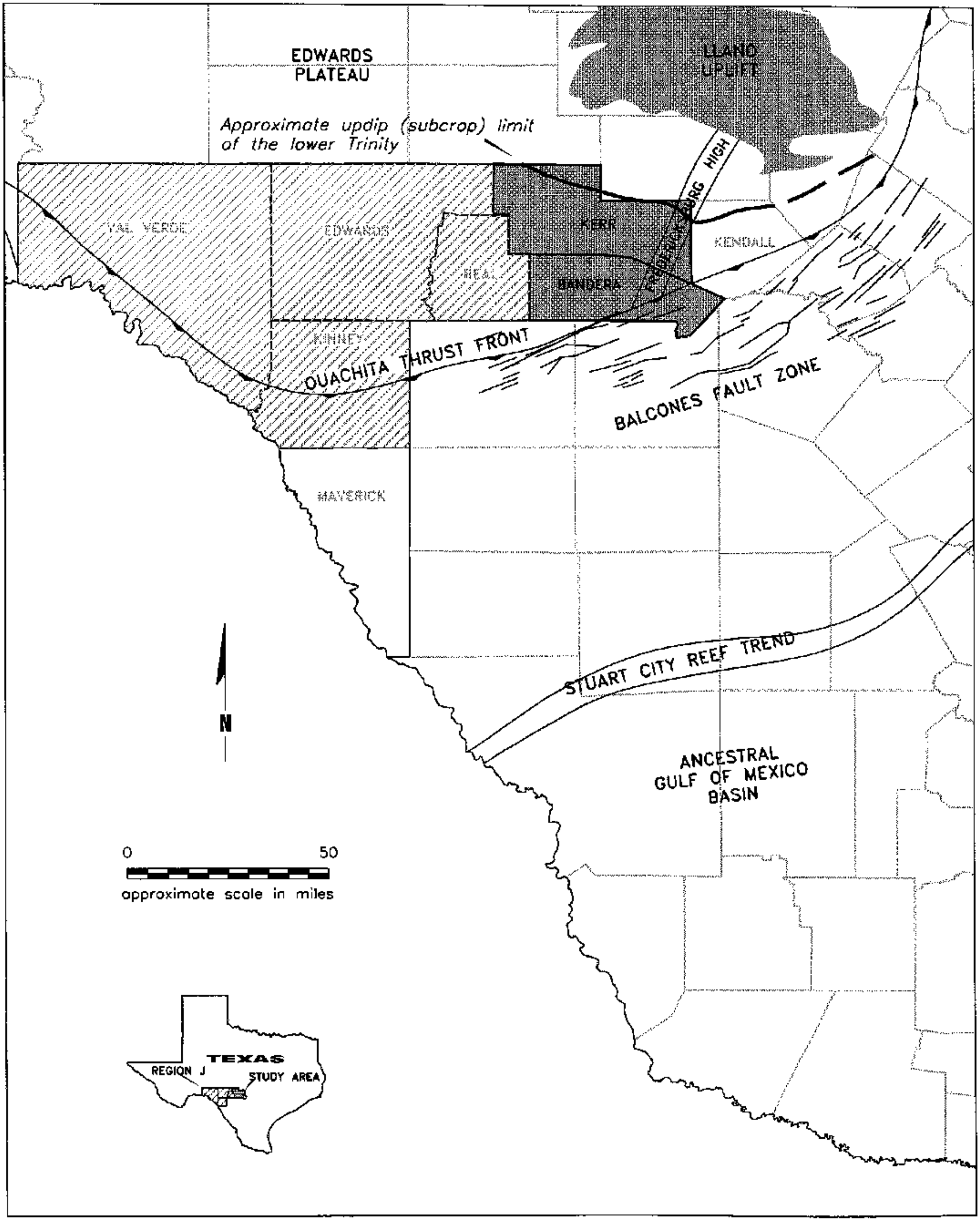
FIGURES



LOCATION OF THE STUDY AREA

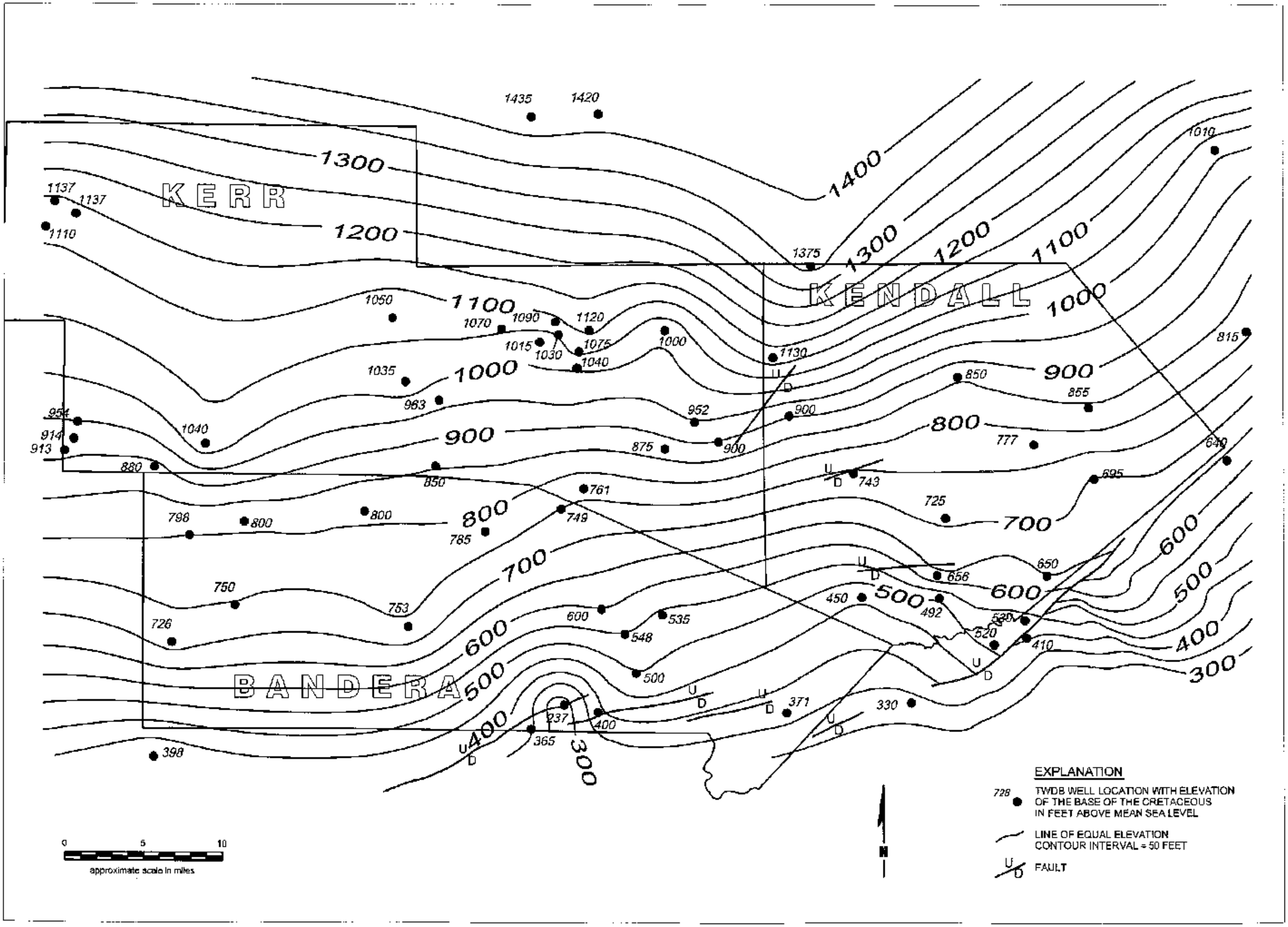
FIGURE 1

LBG-GUYTON ASSOCIATES



GENERAL STRUCTURAL FEATURES IN THE STUDY AREA

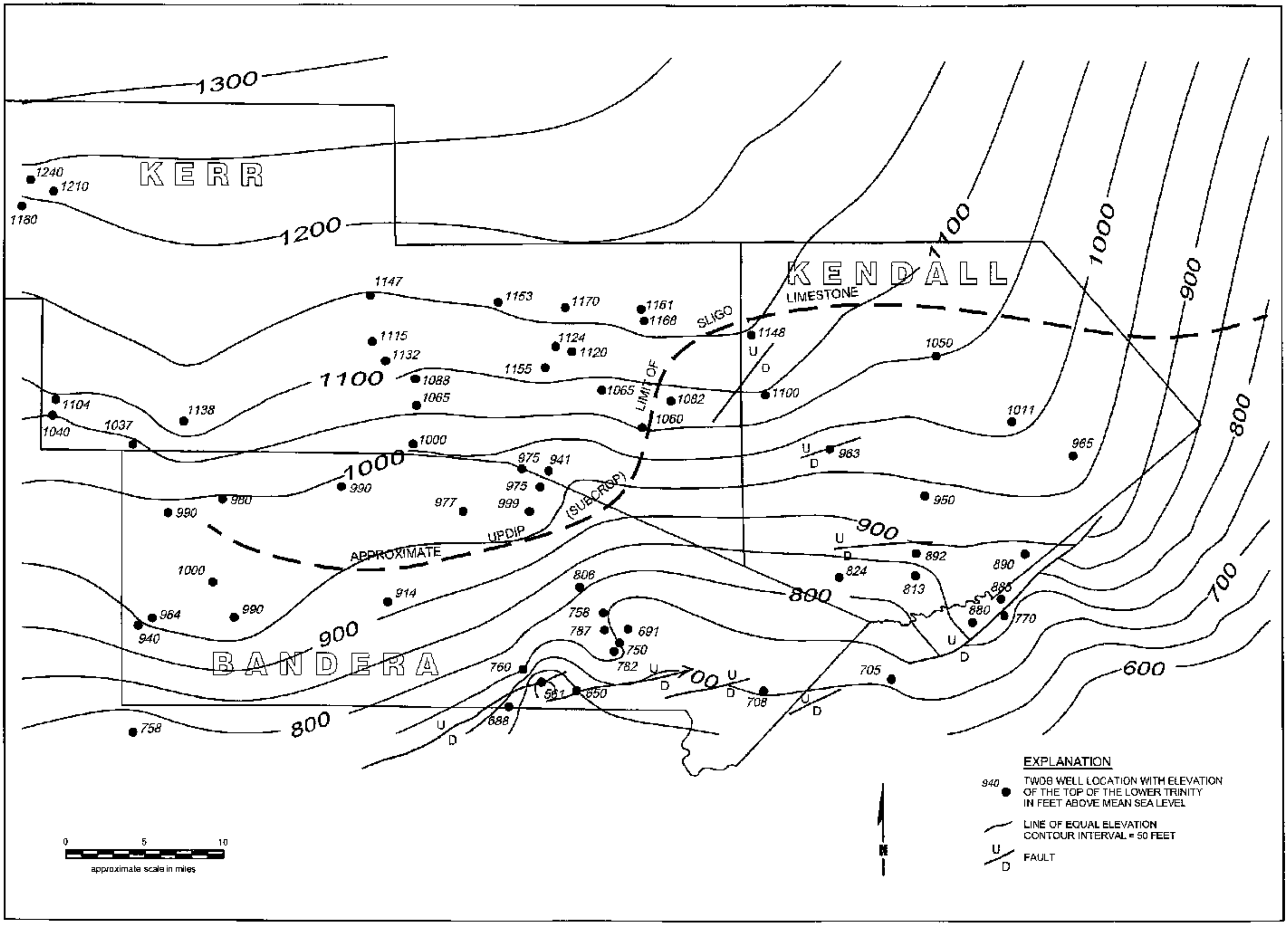
FIGURE 2
LBG-GUYTON ASSOCIATES



BASE OF CRETACEOUS FORMATIONS
IN KERR, BANDERA, AND KENDALL COUNTIES

FIGURE 3

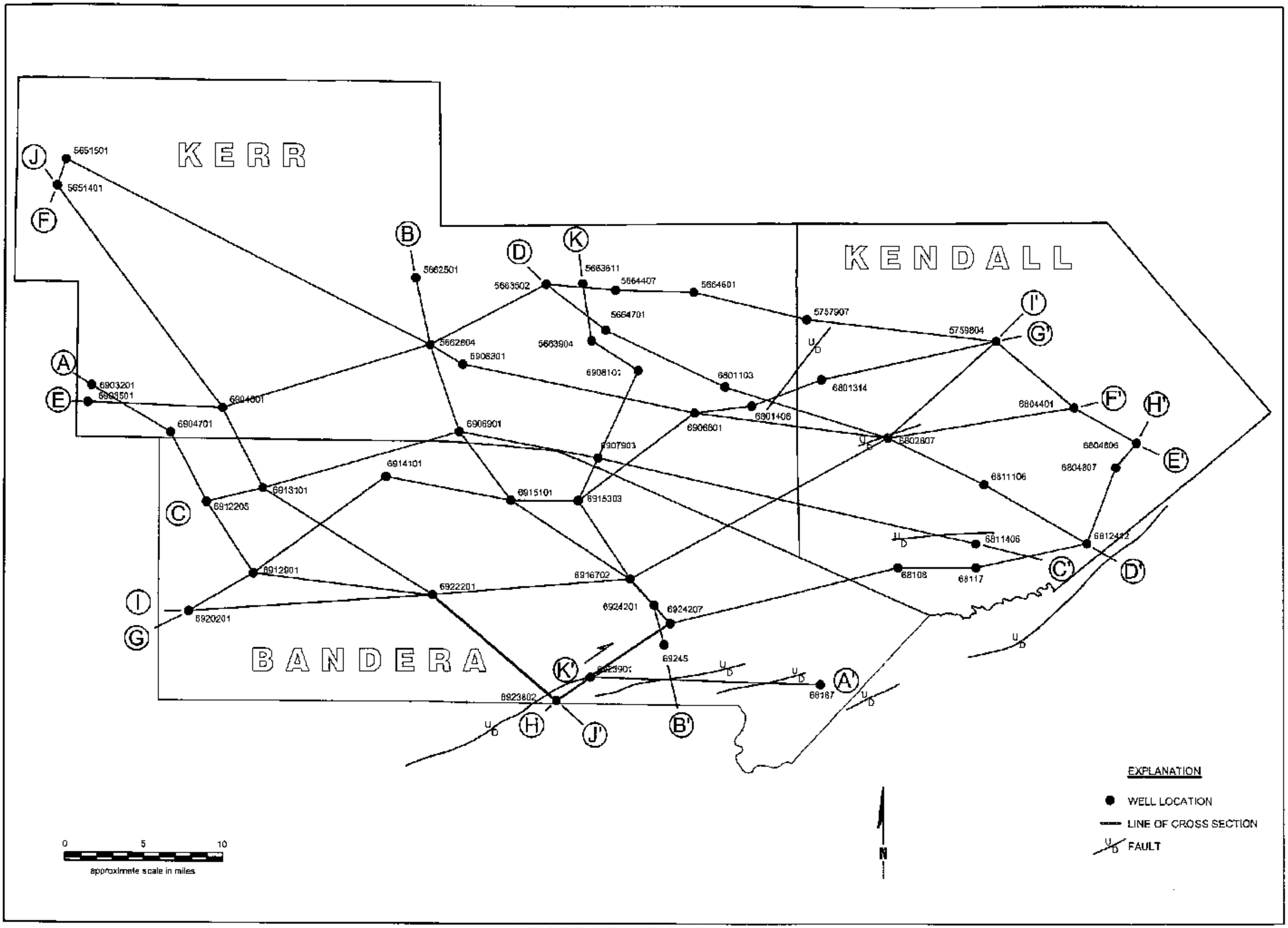
LBG-GUYTON ASSOCIATES



TOP OF LOWER TRINITY AQUIFER
IN KERR, BANDERA, AND KENDALL COUNTIES

FIGURE 4

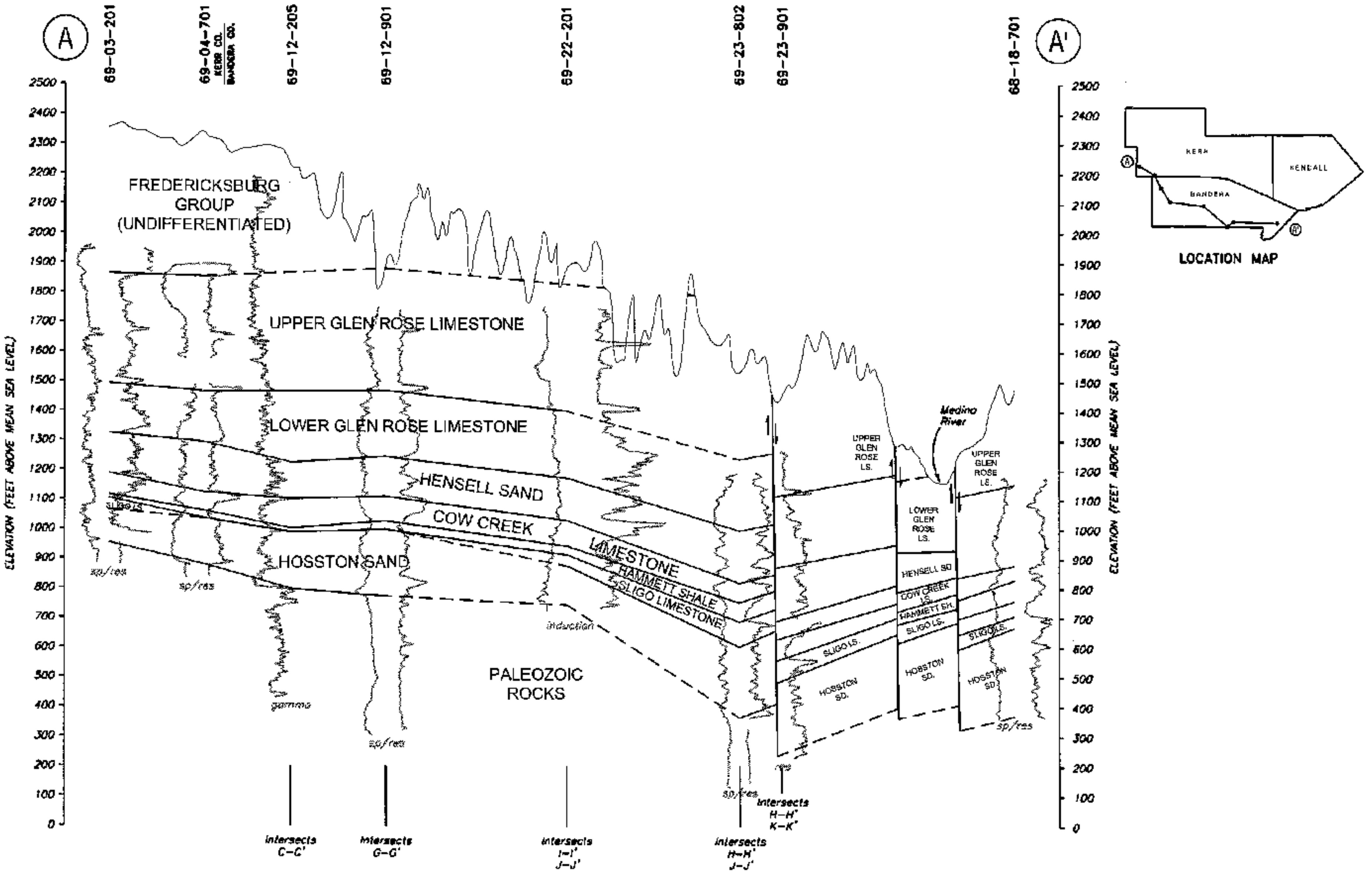
LBG-GUYTON ASSOCIATES



LOWER TRINITY AQUIFER
CROSS SECTION LOCATION MAP

FIGURE 5

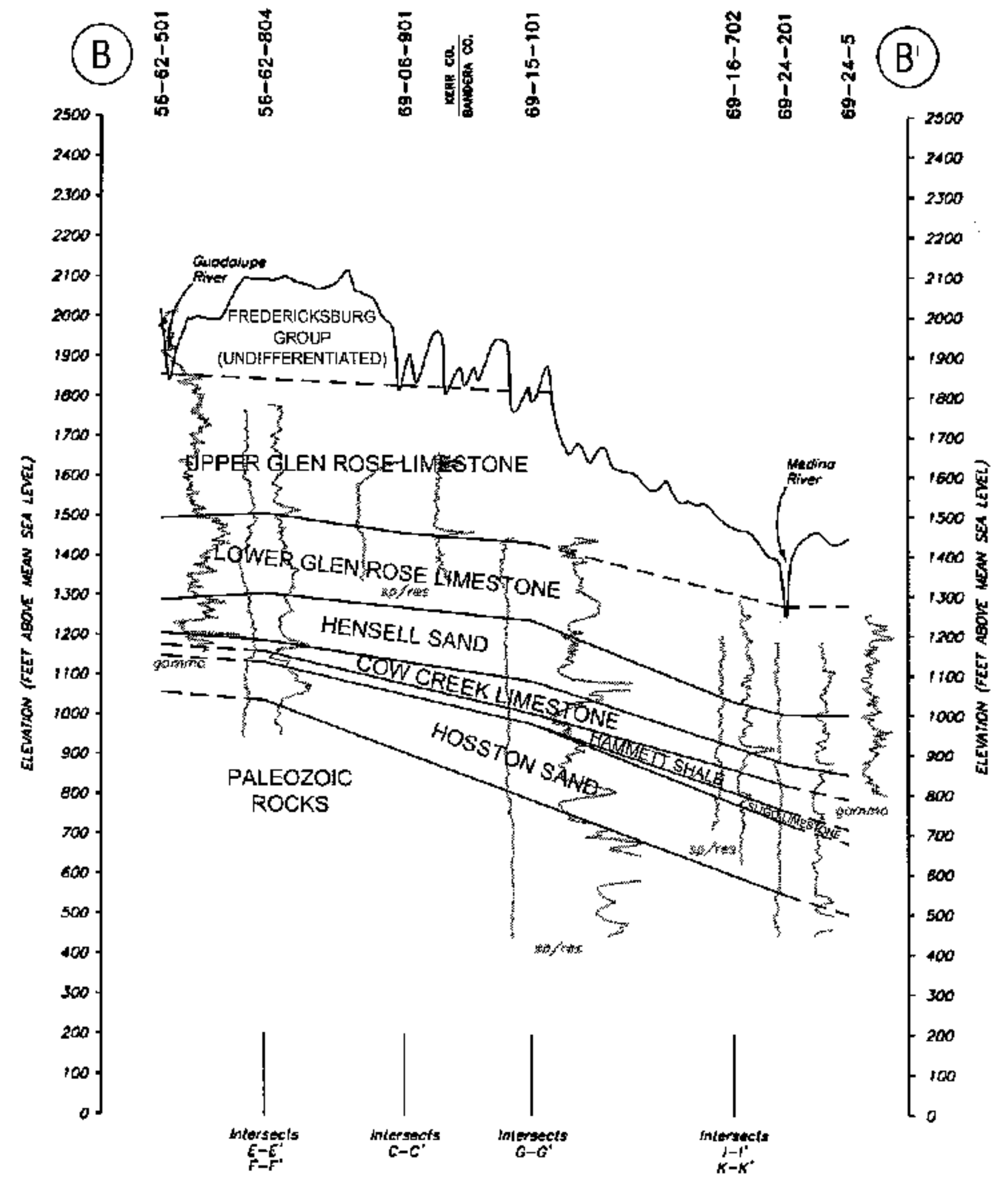
LBG-GUYTON ASSOCIATES

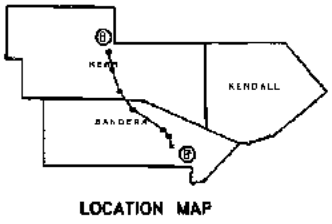


VERTICAL EXAGGERATION = 100x
Cross section adopted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION A - A'

FIGURE 6
LBG-GUYTON ASSOCIATES





LOCATION MAP

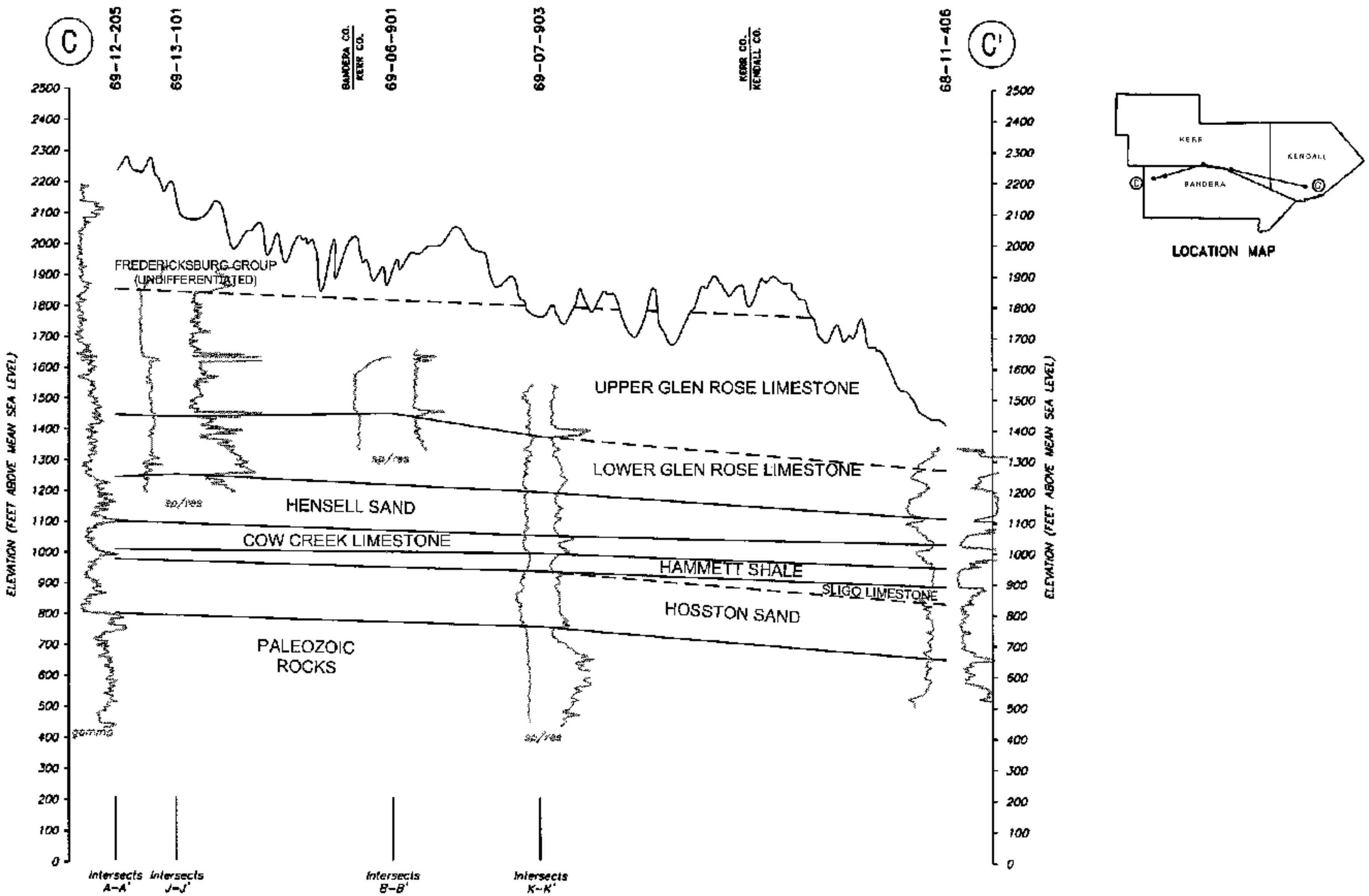
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION B - B'

FIGURE 7

LBG-GUYTON ASSOCIATES



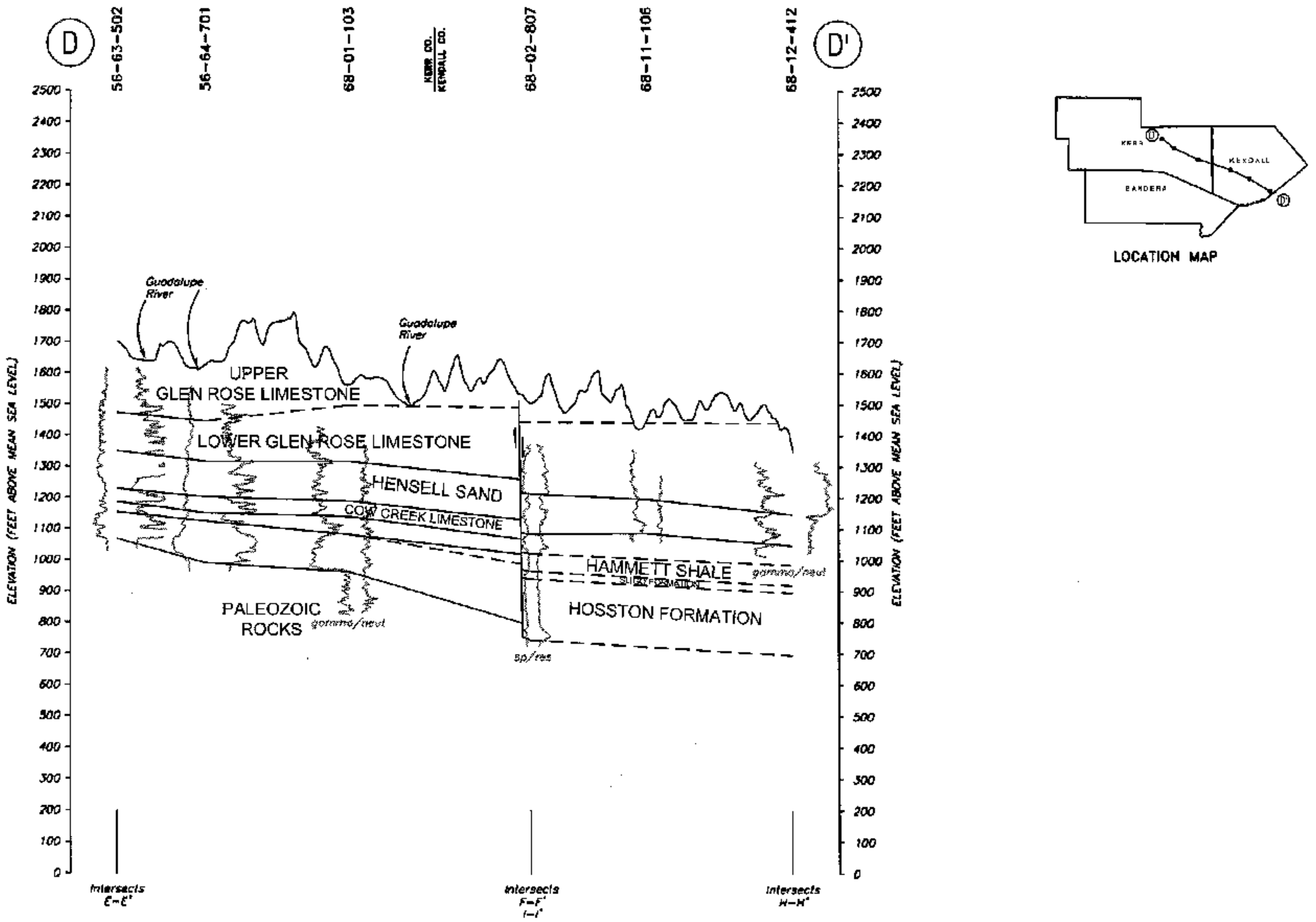
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION C - C'

FIGURE 8

LBG-GUYTON ASSOCIATES



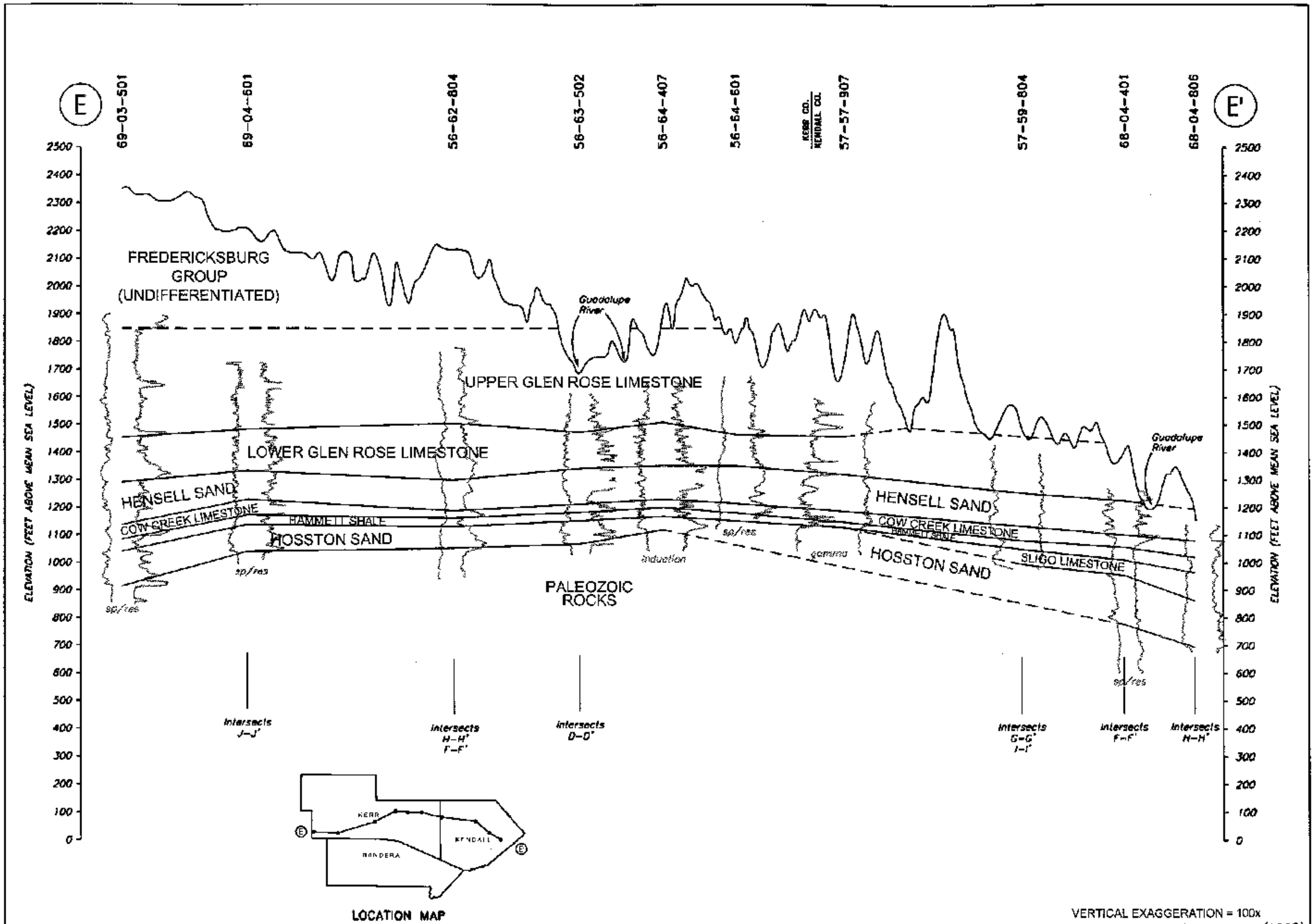
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION D - D'

FIGURE 9

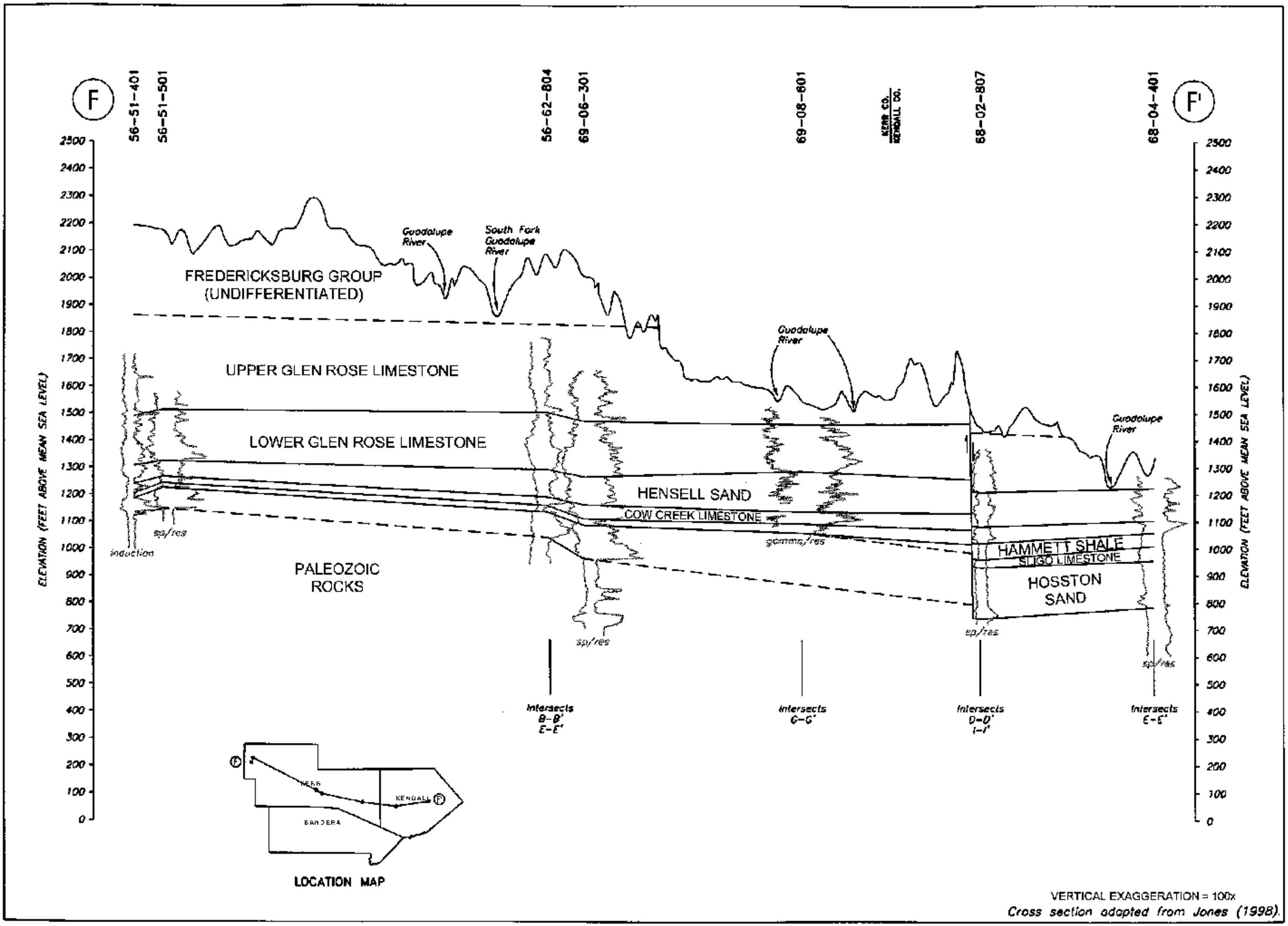
LBG-GUYTON ASSOCIATES



VERTICAL EXAGGERATION = 100x
Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION E - E'

FIGURE 10
LBG-GUYTON ASSOCIATES



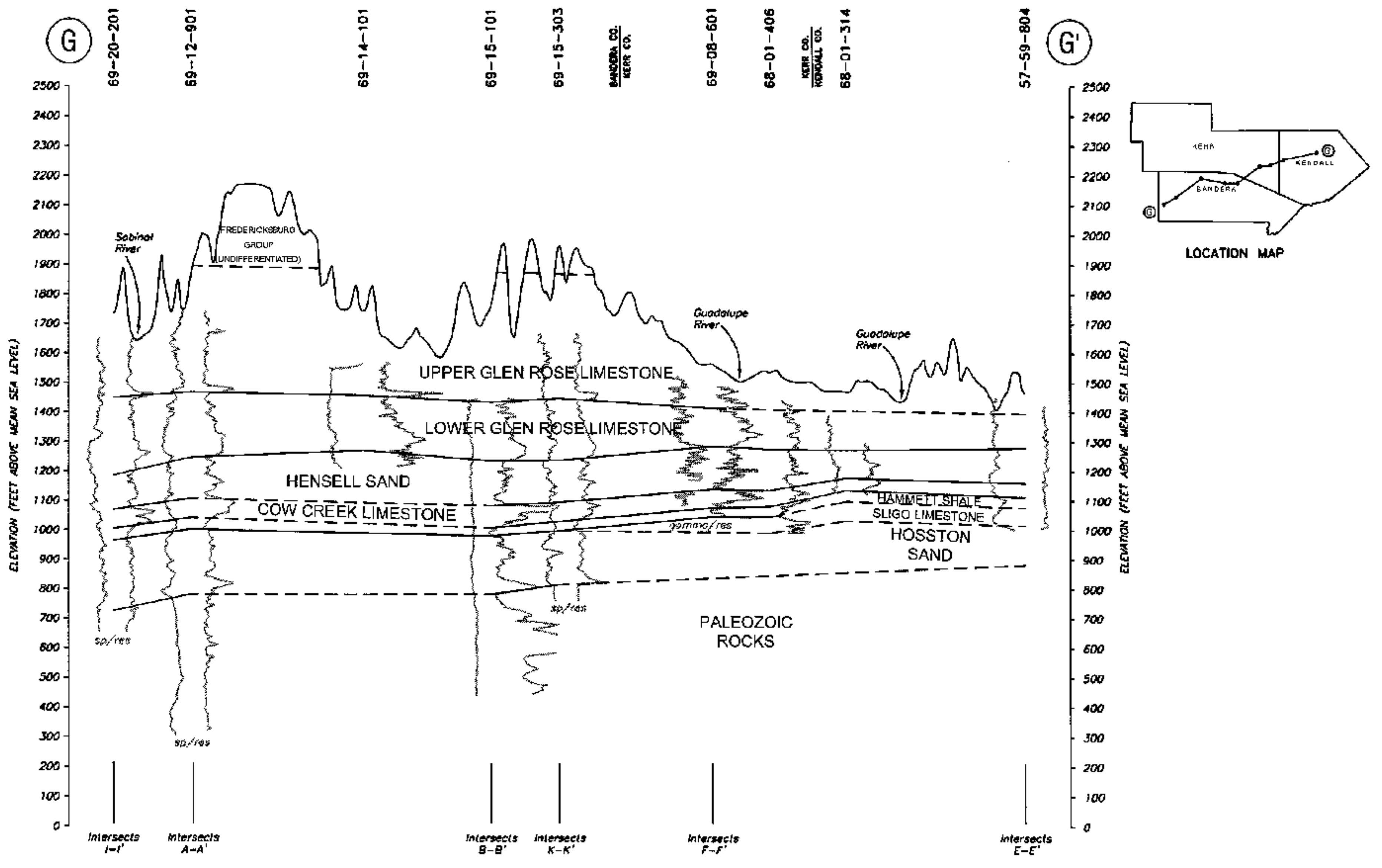
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION F - F'

FIGURE 11

LBG-GUYTON ASSOCIATES



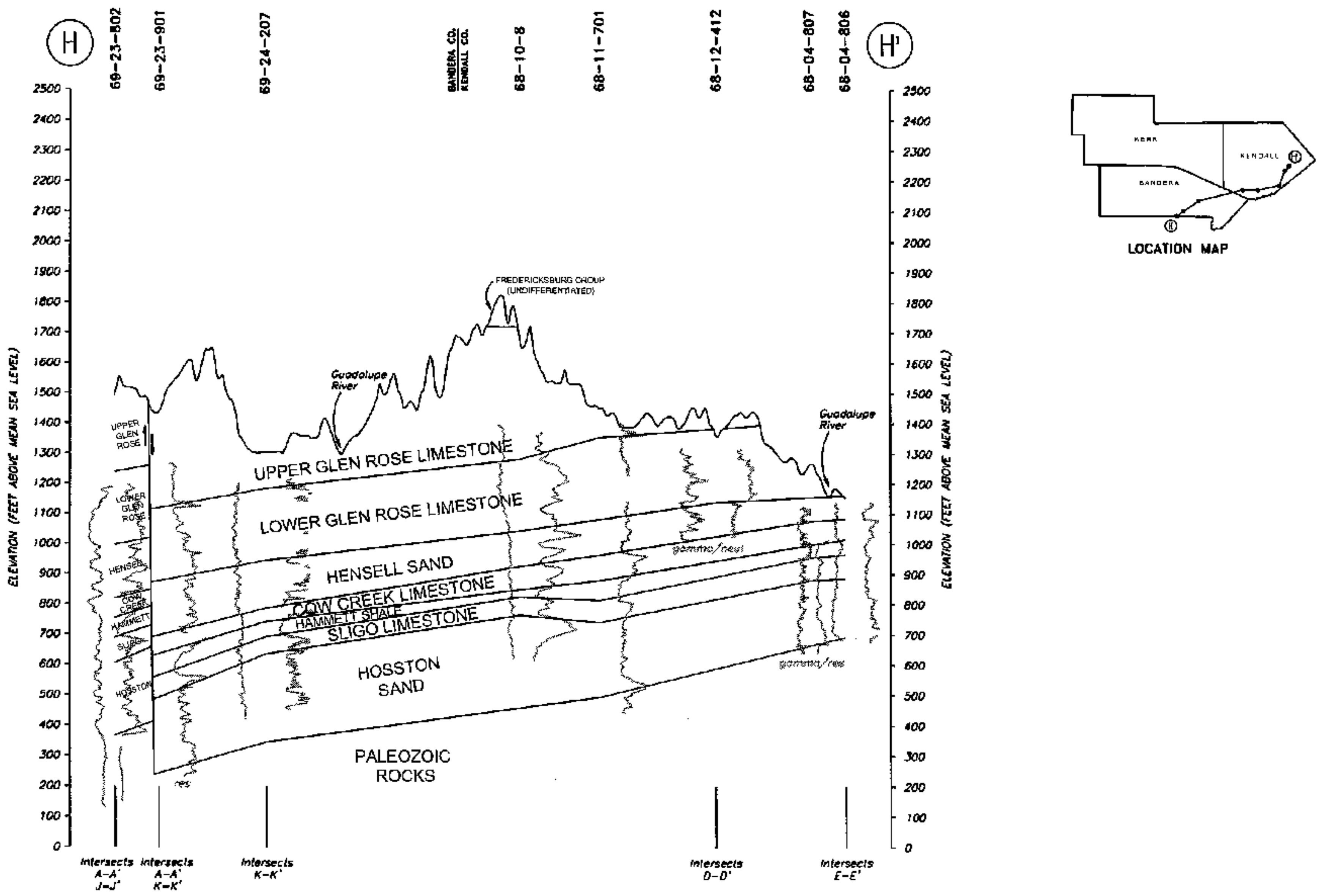
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION G - G'

FIGURE 12

LBG-GUYTON ASSOCIATES



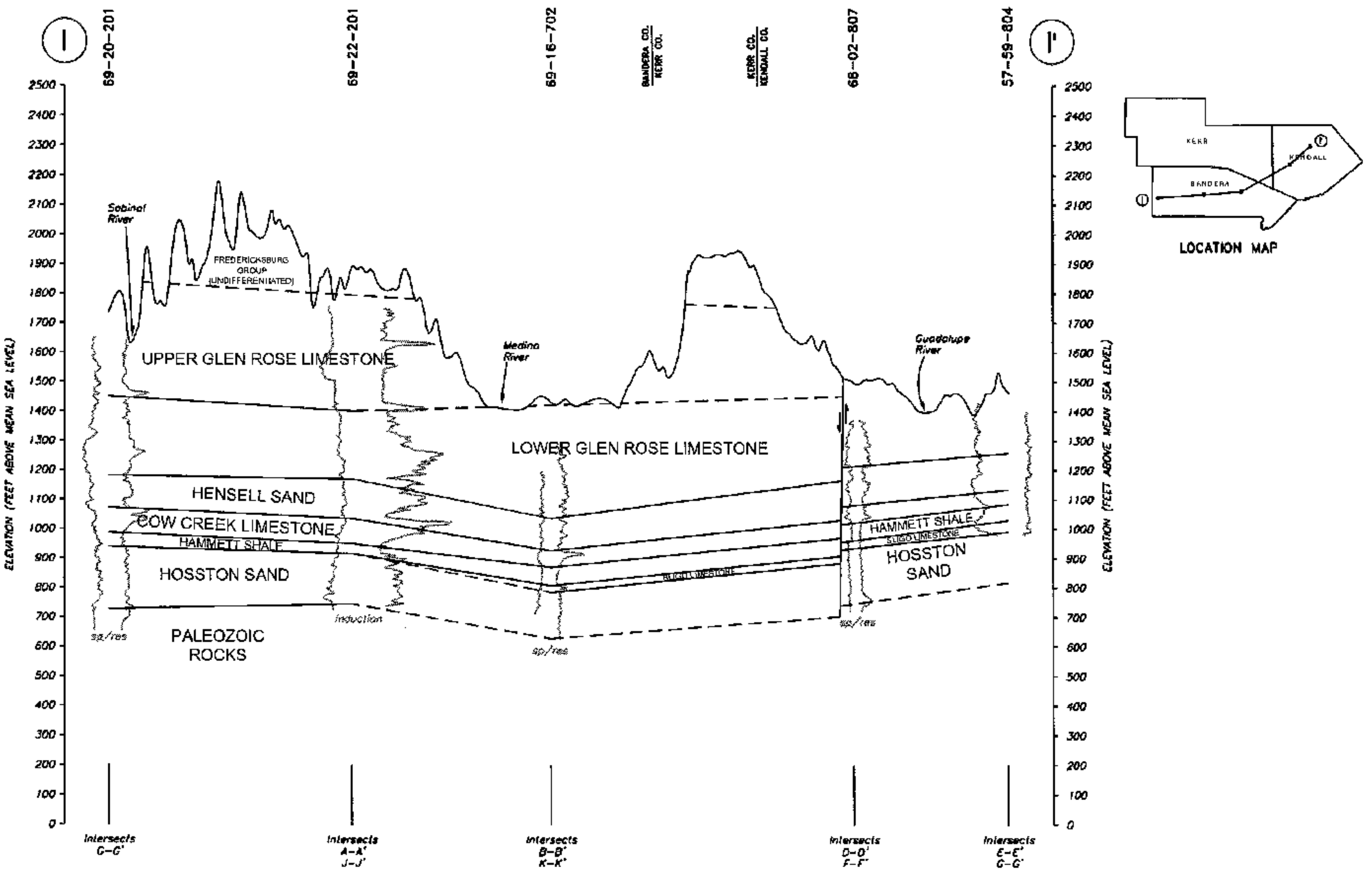
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION H - H'

FIGURE 13

LBG-GUYTON ASSOCIATES



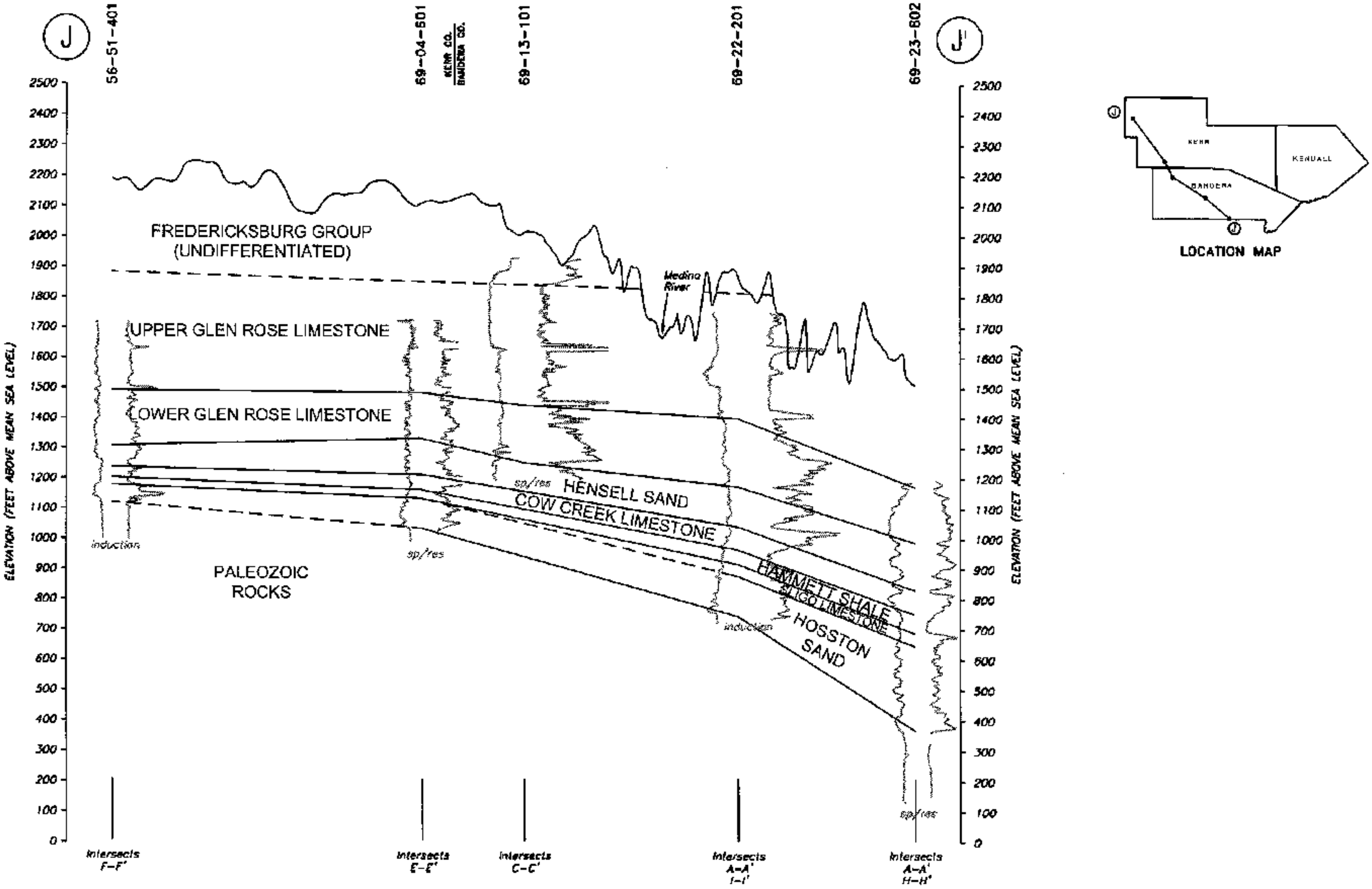
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION I - I'

FIGURE 14

LBG-GUYTON ASSOCIATES



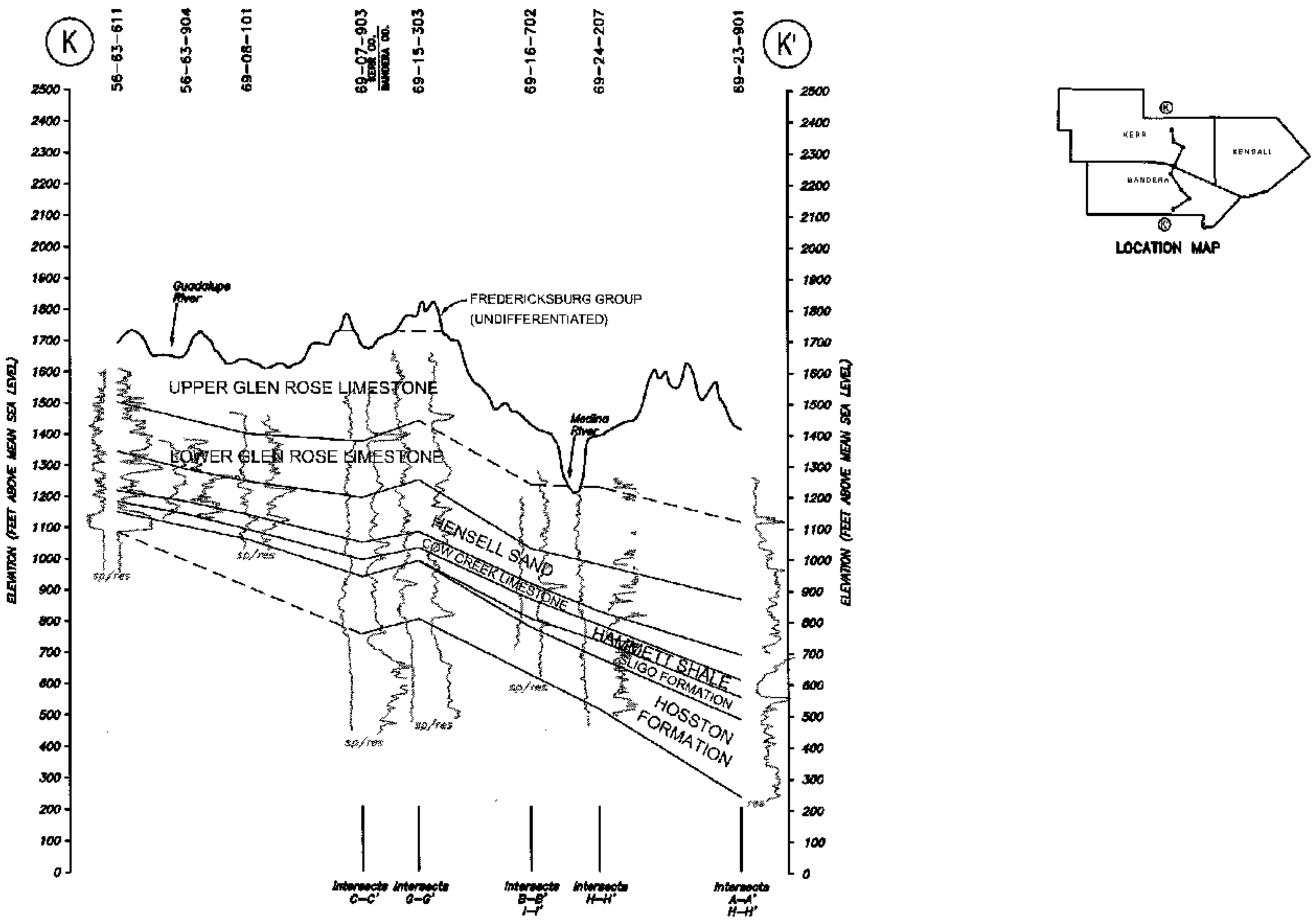
VERTICAL EXAGGERATION = 100x

Cross section adapted from Jones (1998).

LOWER TRINITY AQUIFER
CROSS SECTION J - J'

FIGURE 15

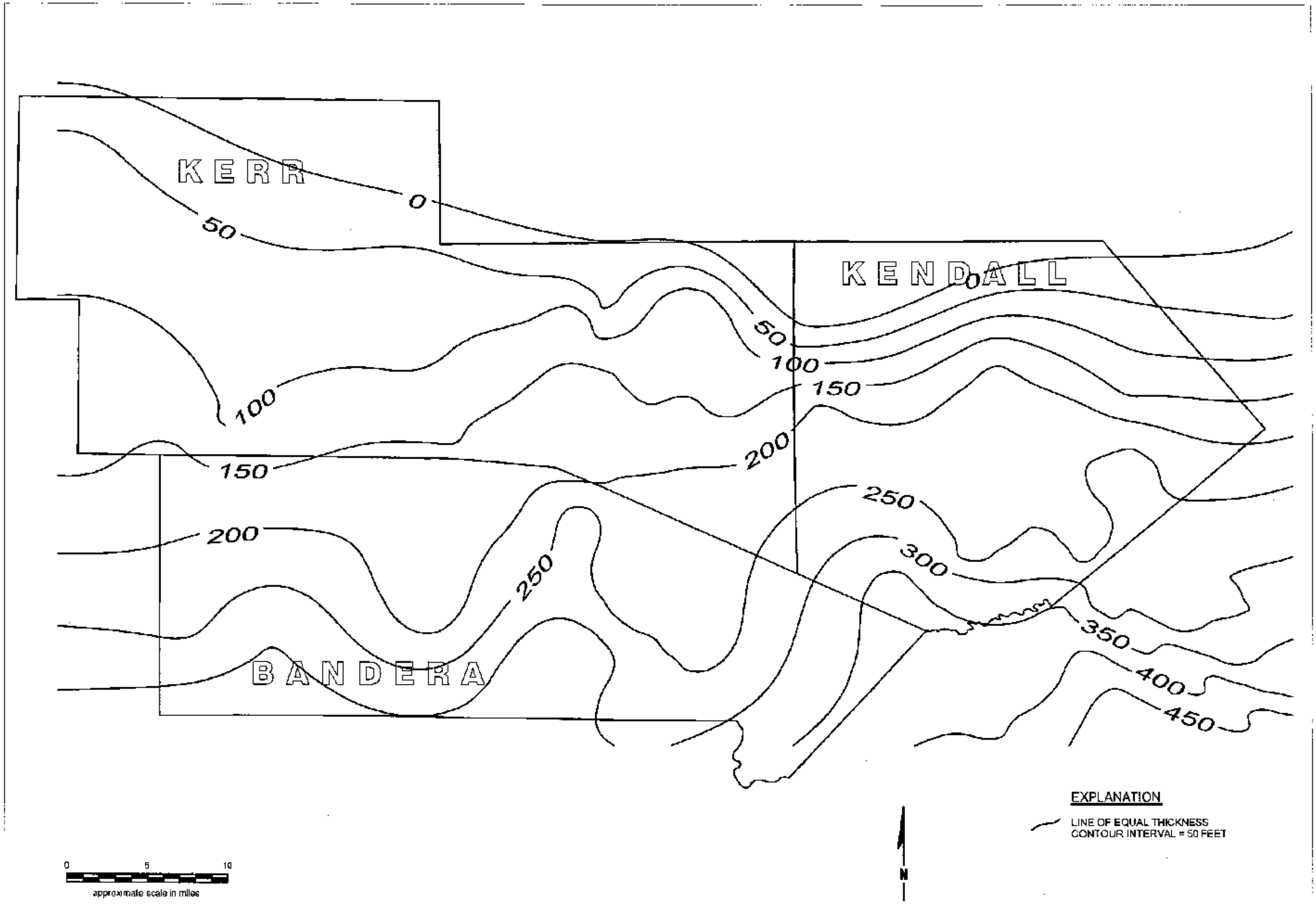
LBG-GUYTON ASSOCIATES



VERTICAL EXAGGERATION = 100x

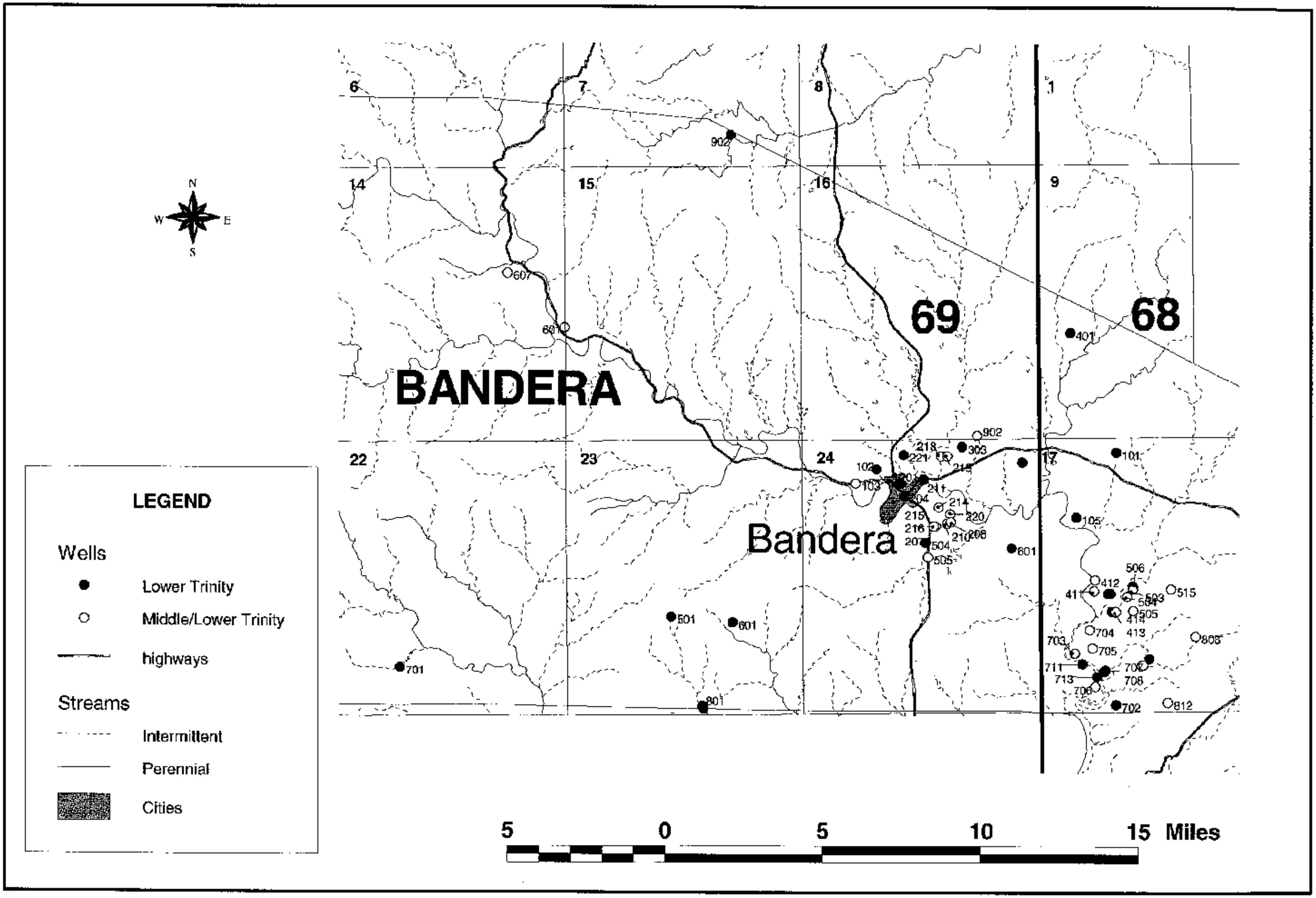
LOWER TRINITY AQUIFER
CROSS SECTION K - K'

FIGURE 16
LBG-GUYTON ASSOCIATES



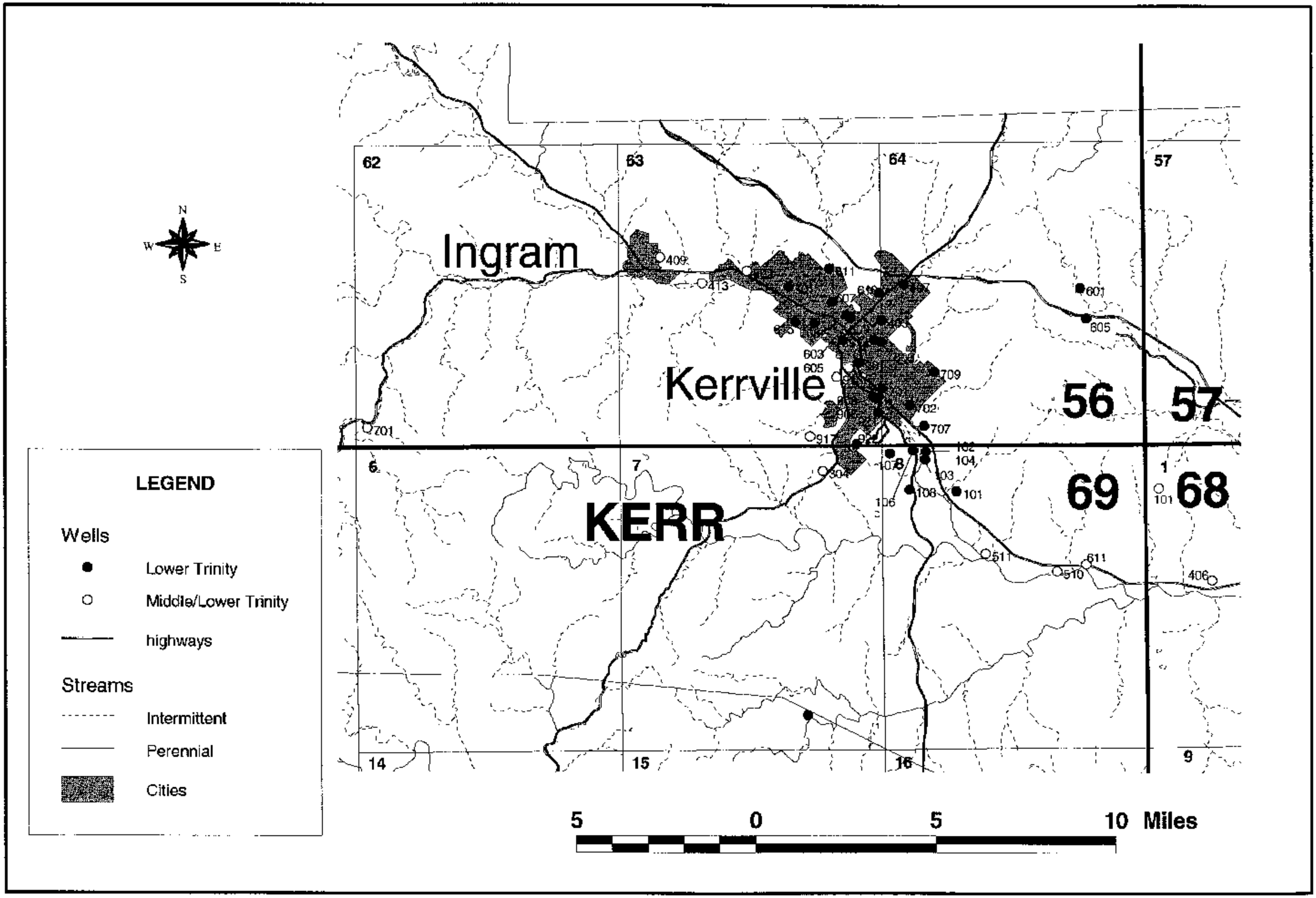
NET THICKNESS OF LOWER TRINITY AQUIFER
IN KERR, BANDERA, AND KENDALL COUNTIES

FIGURE 17



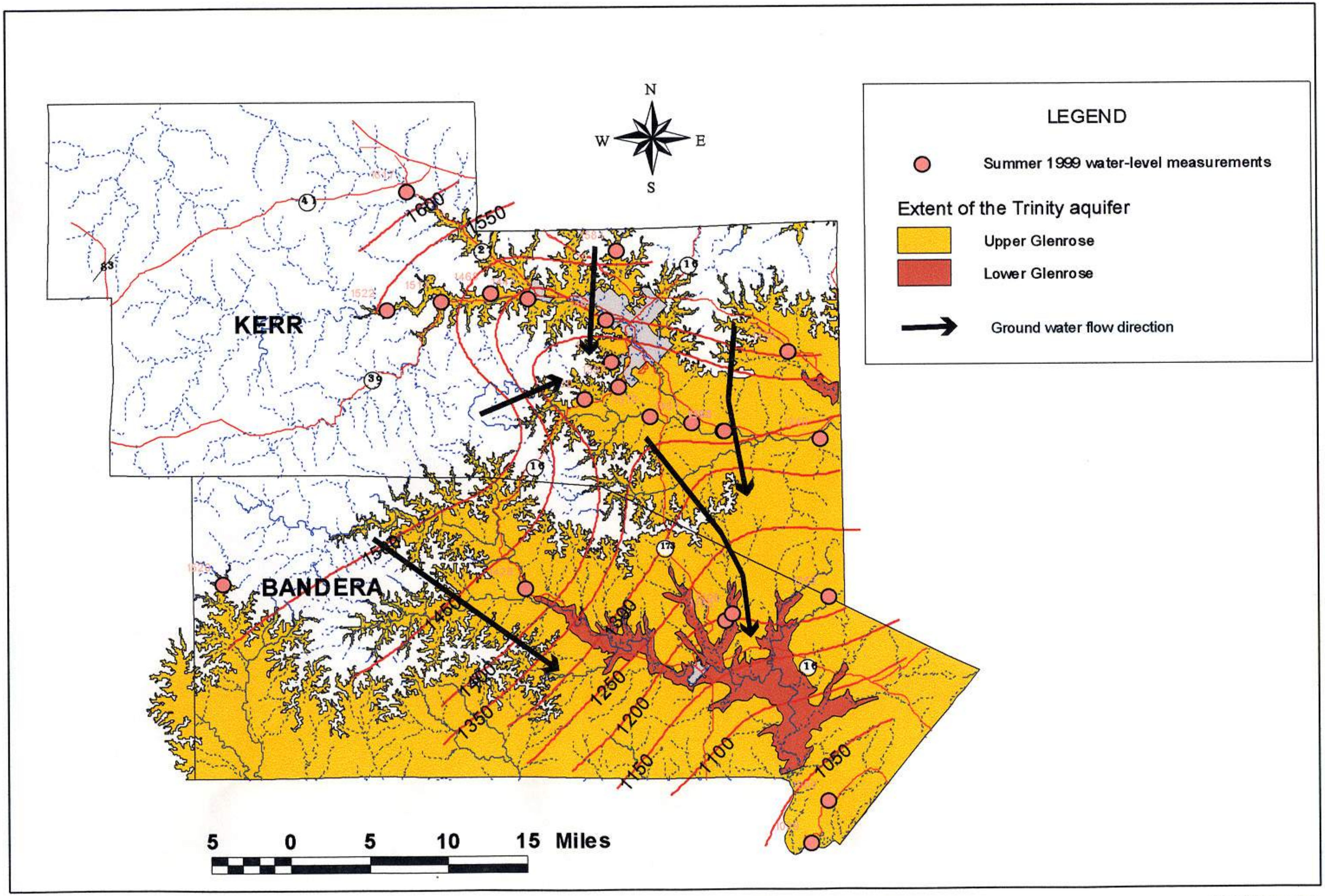
WELLS COMPLETED IN THE LOWER TRINITY IN BANDERA COUNTY

FIGURE 18



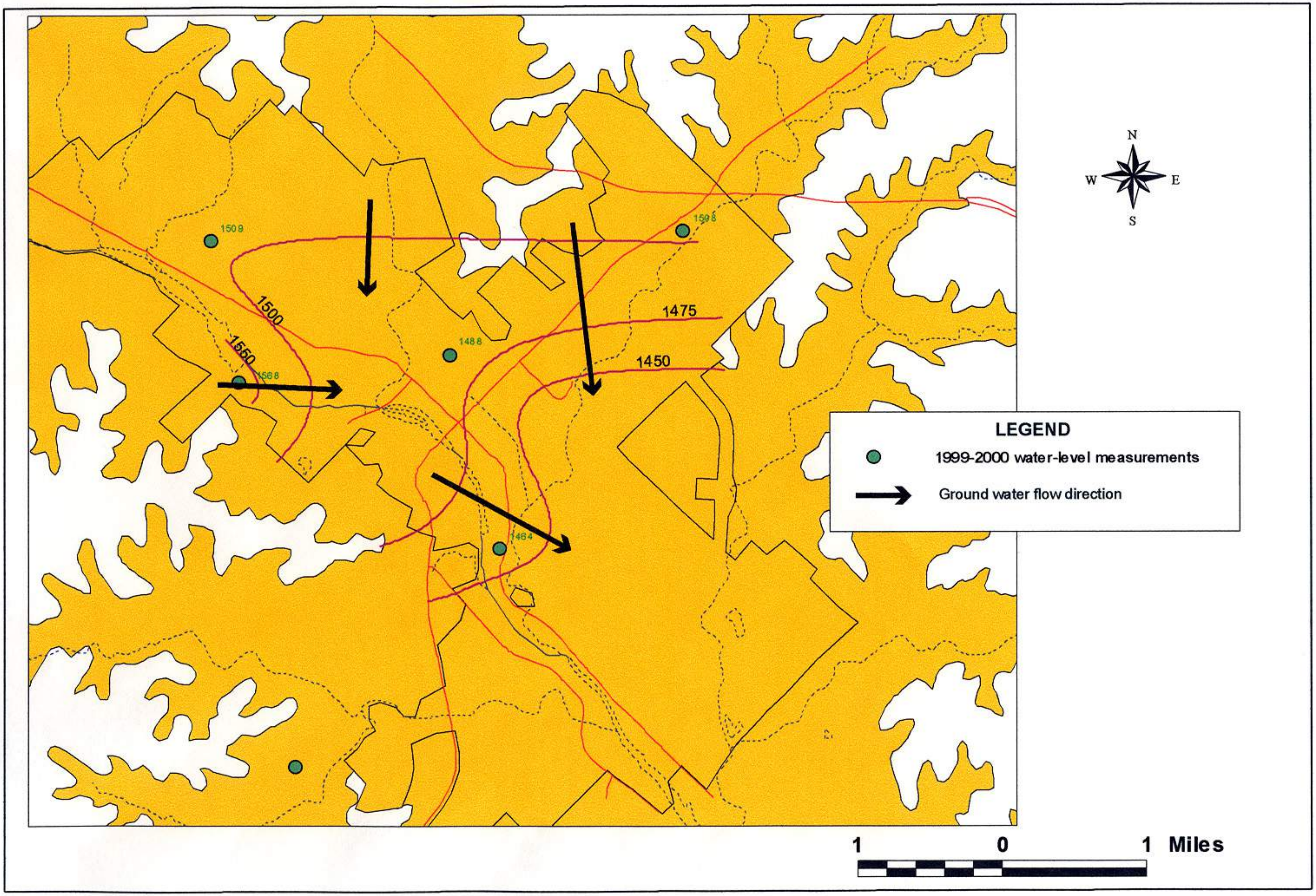
WELLS COMPLETED IN THE LOWER TRINITY IN KERR COUNTY

FIGURE 19



MIDDLE TRINITY AQUIFER SUMMER 1999 WATER LEVELS

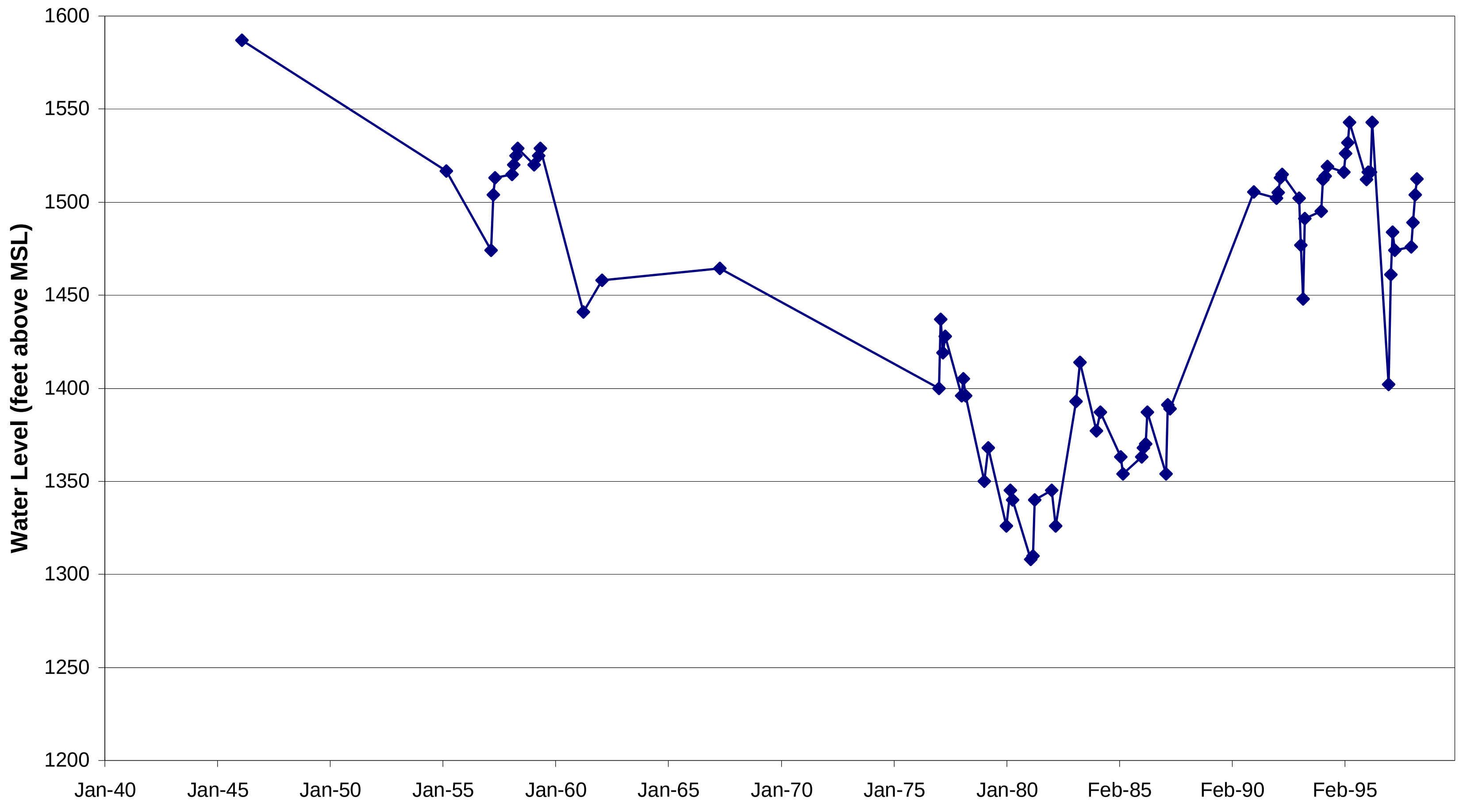
FIGURE 20



LOWER TRINITY AQUIFER WINTER 1999-2000 WATER LEVELS (HIGH), CITY OF KERRVILLE

FIGURE 21

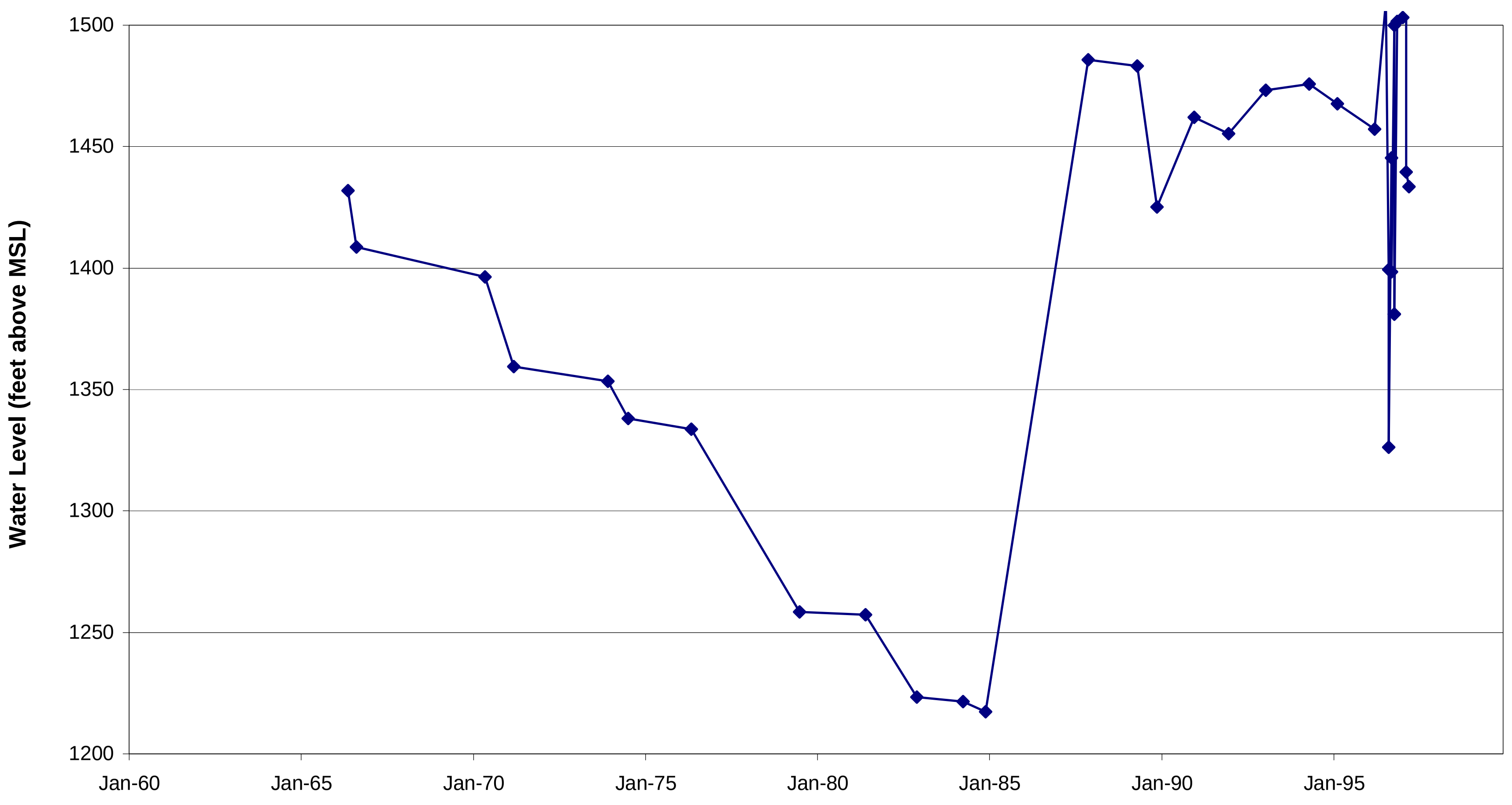
LBG-GUYTON ASSOCIATES



HYDROGRAPH OF SELECTED WINTER DATA FOR KERRVILLE WELL NO. 4 (56-63-604)

FIGURE 22

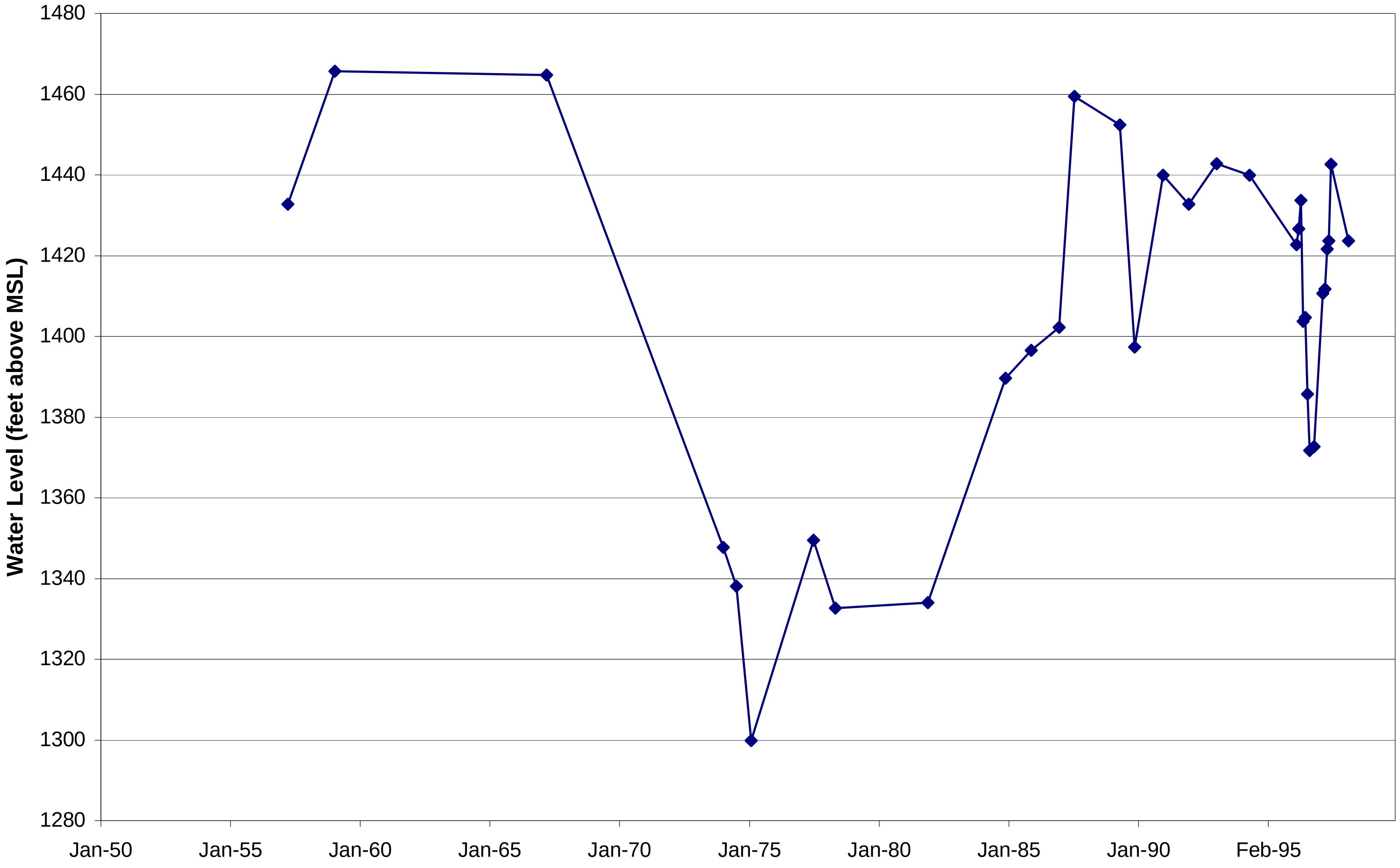
LBG-GUYTON ASSOCIATES



HYDROGRAPH FOR CITY OF KERRVILLE WELL NO. 11 (56-64-701)

FIGURE 23

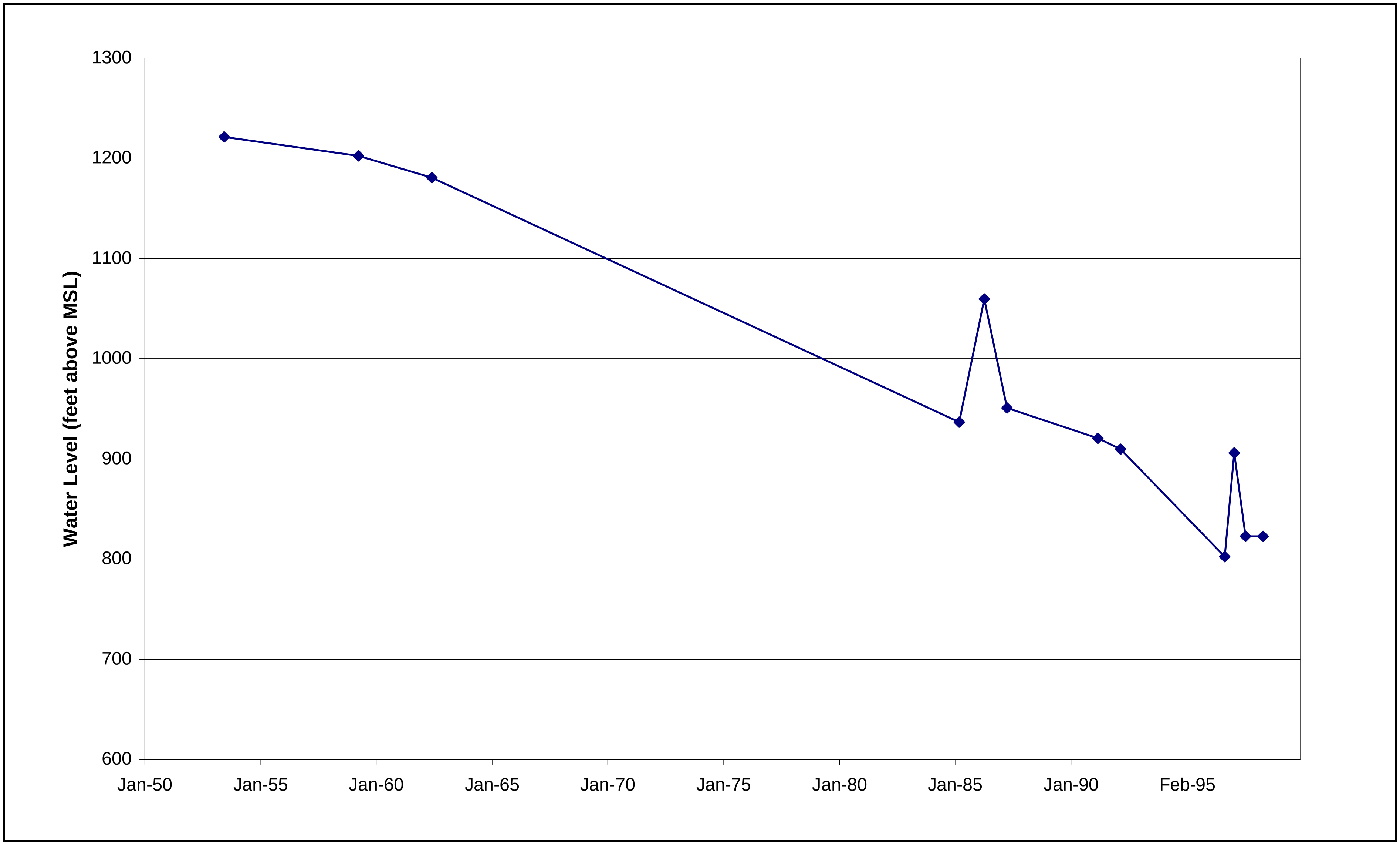
LBG-GUYTON ASSOCIATES



HYDROGRAPH FOR CITY OF KERRVILLE AIRPORT WELL (69-08-101)

FIGURE 24

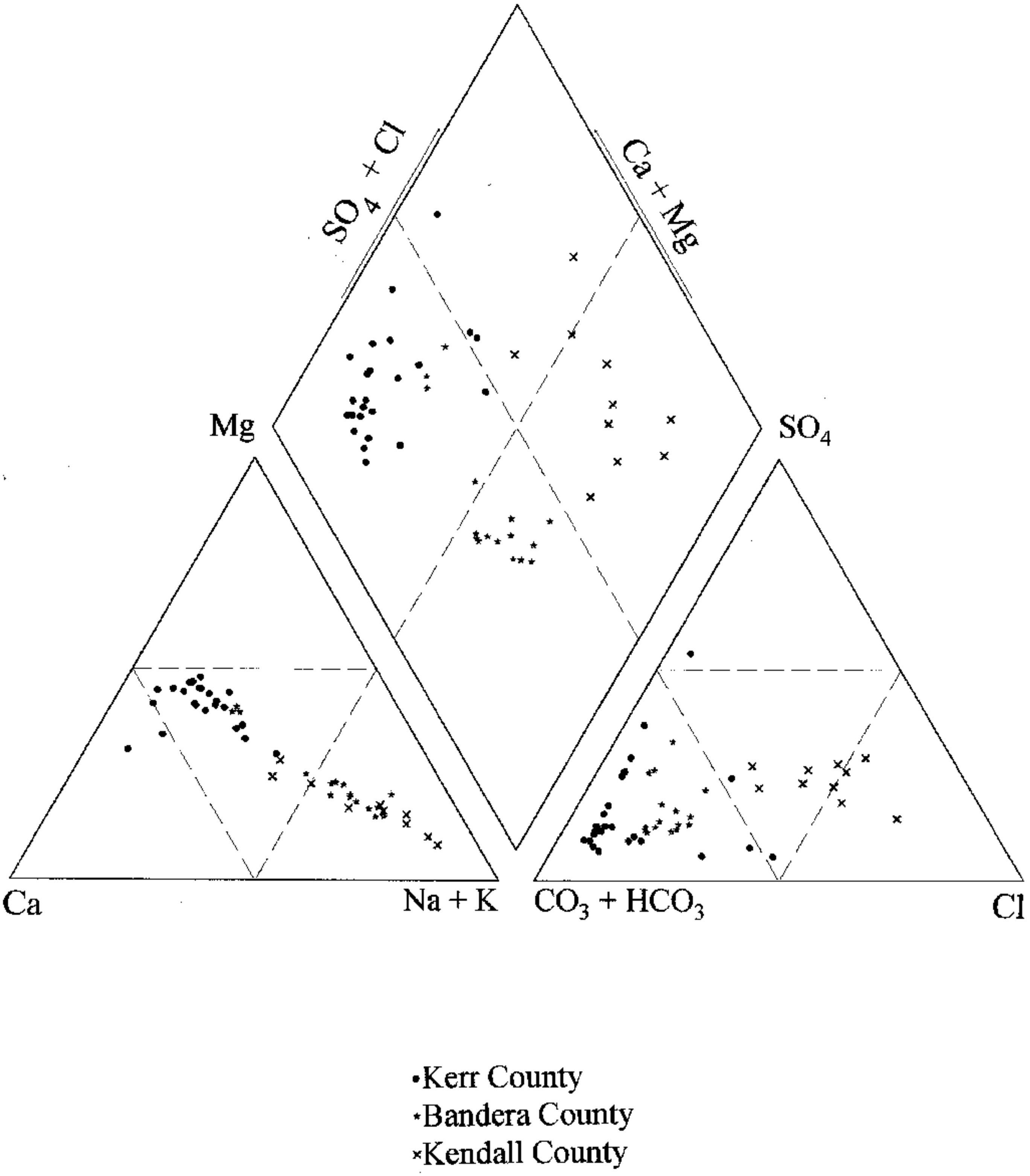
LBG-GUYTON ASSOCIATES



HYDROGRAPH FOR CITY OF BANDERA WELL 69-24-202

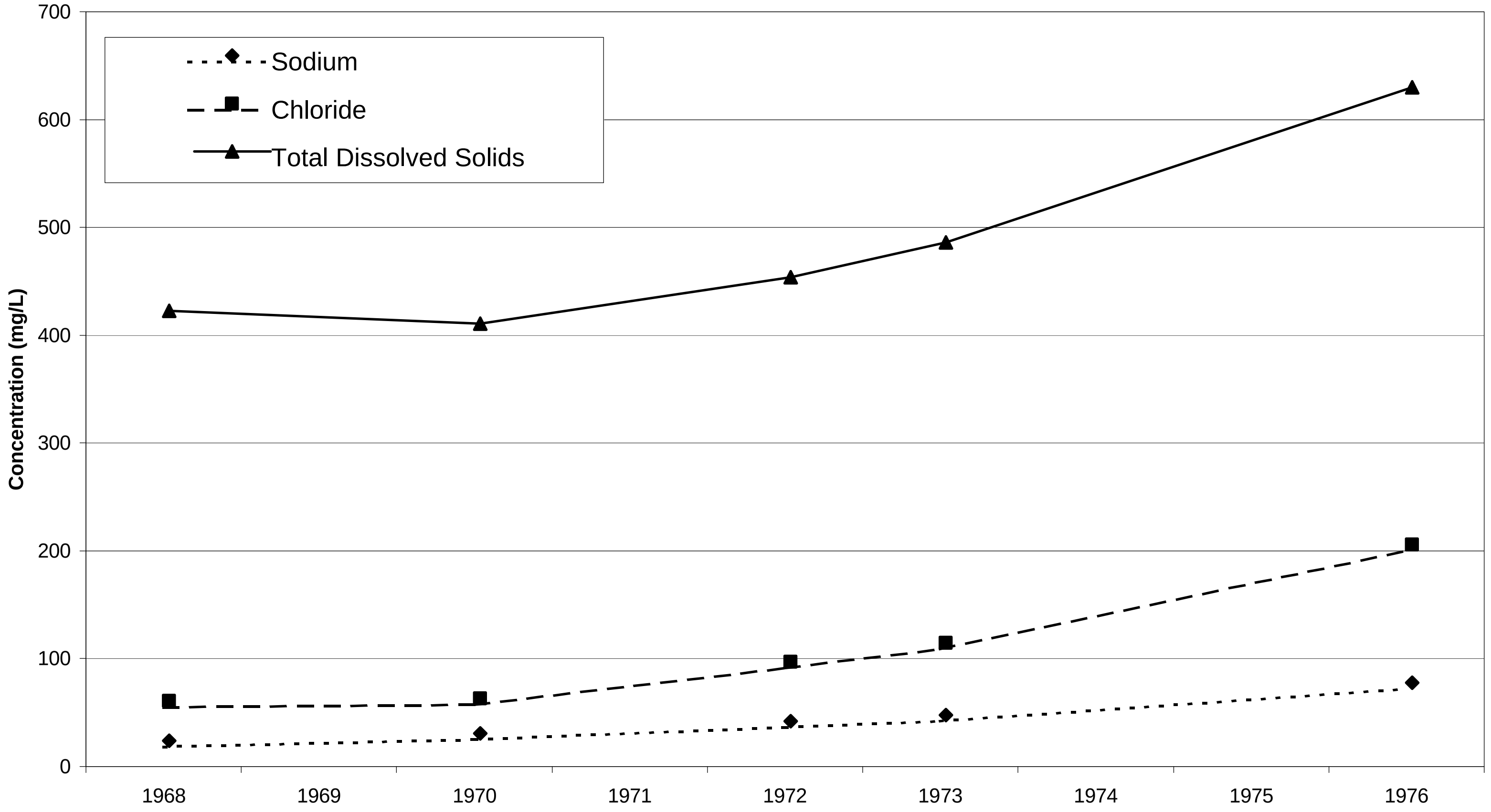
FIGURE 25

LBG-GUYTON ASSOCIATES



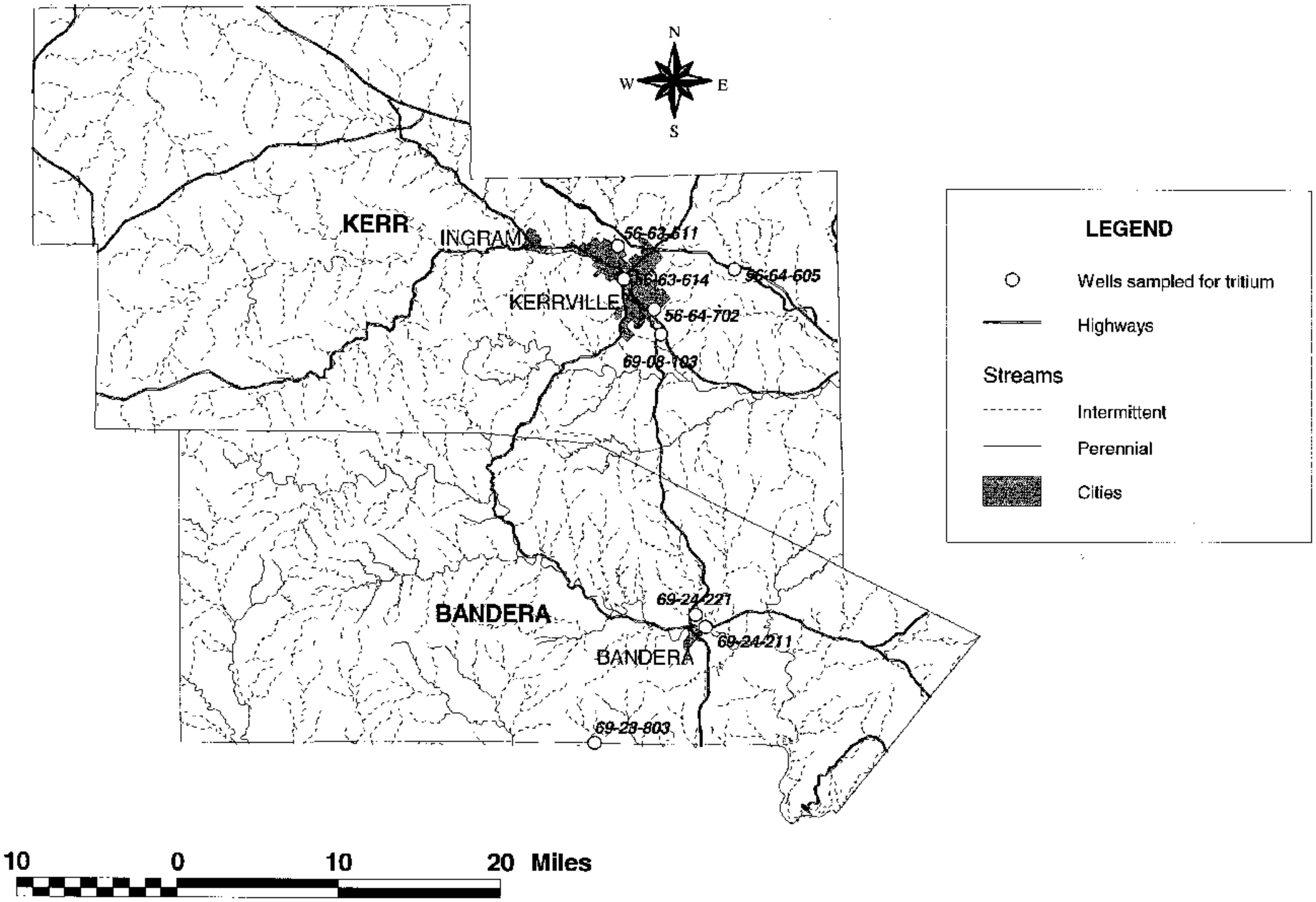
PIPER DIAGRAM OF LOWER TRINITY WATER FROM BANDERA, KERR, AND KENDALL COUNTIES

FIGURE 26



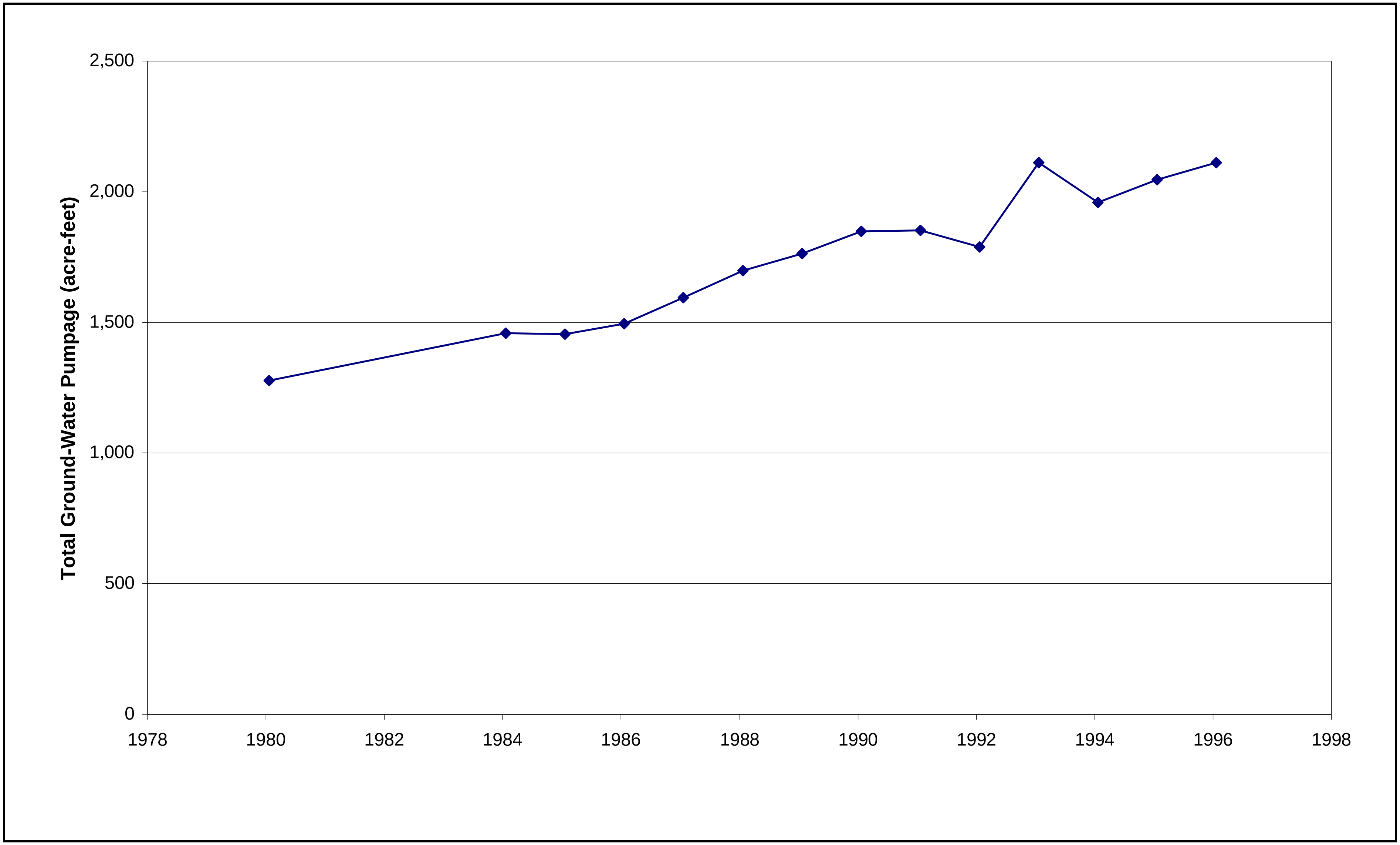
CONCENTRATIONS OF SODIUM, CHLORIDE AND TDS FROM 1968 TO 1976 IN KERVILLE WELL 56-63-606 (TRAVIS WELL)

FIGURE 27



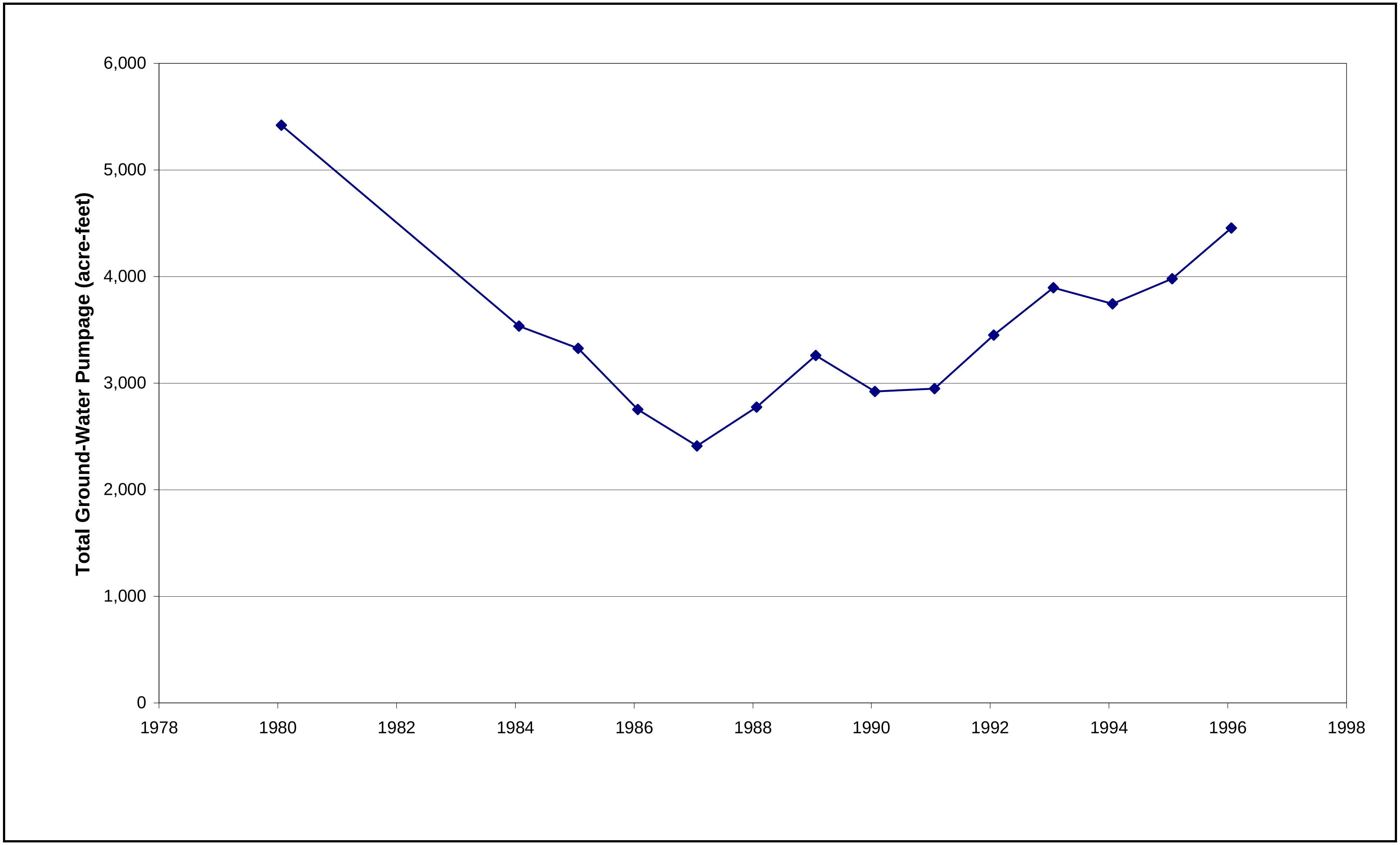
LOCATION OF WELLS SAMPLED FOR TRITIUM

FIGURE 28



TOTAL TRINITY AQUIFER USE IN BANDERA COUNTY FROM 1980 TO 1996

FIGURE 29



TOTAL TRINITY AQUIFER USE IN KERR COUNTY FROM 1980 TO 1996

FIGURE 30

LBG-GUYTON ASSOCIATES