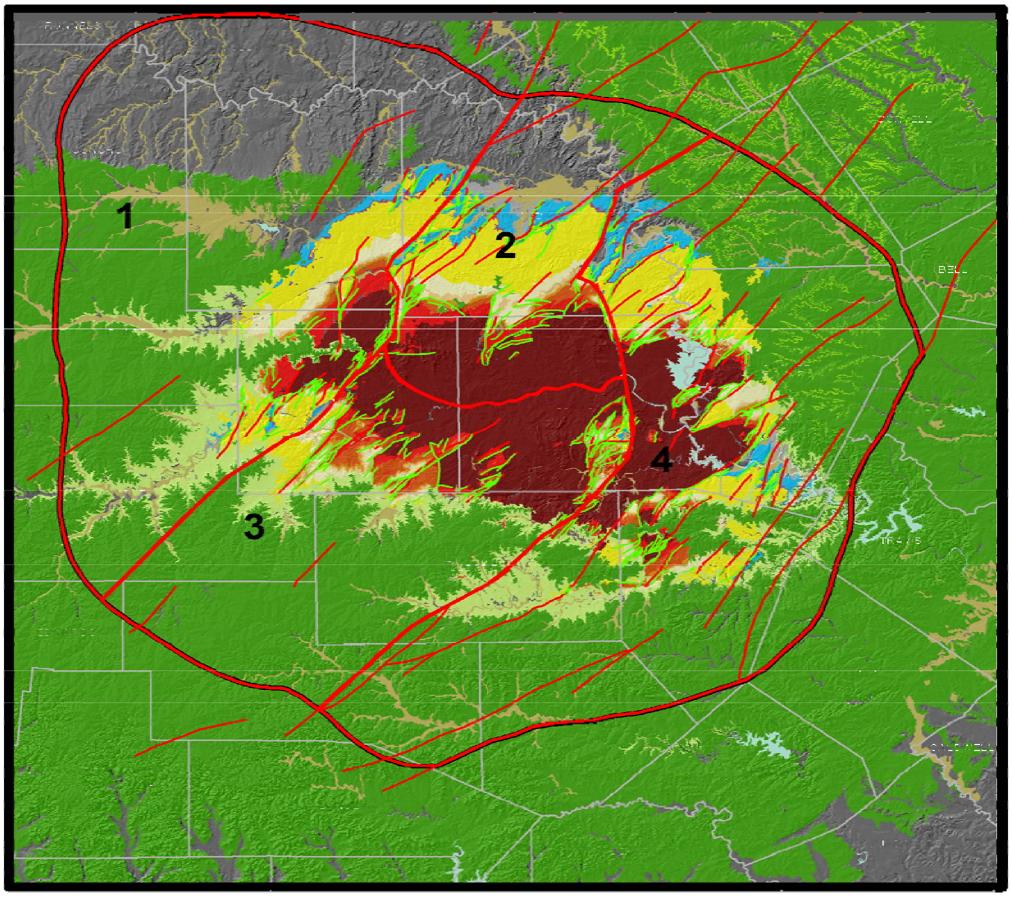
Llano Uplift Aquifers
Structure and Stratigraphy



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Acknowledgements

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Executive Summary

The Llano Uplift area in central Texas is probably the most structurally and stratigraphically complex area in Texas. This project compiled all publicly available data (more than 1,050 locations) to create structural elevation contour surfaces of the base of Marble Falls, top of the Ellenburger, base of the San Saba, top of the Welge and top and base of the Hickory and net sand isopachs of the Welge–Lion Mountain and Hickory aquifers. New up dip and down dip extents were created for all of these aquifer surfaces. The purpose of the project was to provide a framework in which to build future groundwater models of these aquifers. Upon completion of the structural and stratigraphic interpretations, the Daniel B. Stephens & Associates, Inc. team proposed that the Llano Uplift area be subdivided into four areas based primarily on common structural character and geologic history. The boundaries of these regions are delineated by three major through-going faults, in some cases are over 50 miles in length, extending across several counties.

1. Introduction

On behalf of the Texas Water Development Board, Daniel B. Stephens & Associates, Inc. (DBS&A) led an effort to compile information and construct databases that can be used in groundwater availability modeling of aquifers in the Llano Uplift area of Texas. The study area covers approximately 14,000 square miles in central Texas and consists of all or portions of 18 counties, including Concho, Coleman, McCulloch, Brown, Mills, San Saba, Lampasas, Menard, Kimble, Mason, Llano, Burnet, Williamson, Travis, Gillespie, Kerr, Kendall, and Blanco counties (Figure 1). The stratigraphy and structure of three recognized minor aquifers (Marble Falls, Ellenburger–San Saba, and Hickory) and one additional Cambrian-age aquifer (Welge–Lion Mountain) were investigated during this study. These aquifers are collectively referred to as the Llano Uplift Aquifers.

The purpose of this project was to (1) delineate stratigraphic tops and bases of the Hickory (sandstone), Welge–Lion Mountain, Ellenburger–San Saba (carbonate), and Marble Falls (carbonate) aquifers within the Llano Uplift region (study area), (2) compile net sand isopach maps for the Welge-Lion Mountain and Hickory aquifers, and (3) delineate structural faulting that could impact groundwater flow. This information is expected to be used to construct a Llano Uplift groundwater availability model (GAM) at some time in the future. Project deliverables include the following:

- A GAM-compatible GIS geodatabase
- Digital structural elevation surfaces of the Hickory, Welge–Lion Mountain, Ellenburger–San Saba, and Marble Falls aquifers
- Net sand isopach maps of the Welge–Lion Mountain and Hickory aquifers
- Two fault geodatabases that include locations and characteristics of newly identified subsurface faults and selected faults shown in the *Geologic Atlas of Texas* (GAT)
- A report describing methodology, data sources, and results

2. Study Area Geology

2.1 Stratigraphy

2.1.1 Precambrian Basement

The Precambrian basement underlying the Llano Uplift is part of the Grenville orogenic belt that occurs along the southern margin of North America. The stratigraphic sequence of the Llano Uplift is illustrated in Figure 2. The GAT geology illustrated in Figure 1 is indexed to the appropriate stratigraphy in Figure 2. The Llano Uplift rocks represent more than 300 million years of orogenic activity (Mosher, 2004). The Precambrian rocks exposed in the Llano Uplift consist of gneisses, amphibolites, schists, and granites (Barnes and Bell, 1977 and McGhee, 1963).

These Precambrian rocks have undergone uplift and have been eroded, but the timing of these events are unknown (Ewing, 2004). Fracture sets and faults of multiple orientations are common in these basement rocks and some evidence favors pre-Pennsylvanian origin (Johnson, 2004). Extensive erosion has occurred during the Precambrian based on depths and ages of the granitic plutons, over 8 kilometers of overburden between the emplacement of the youngest granite and the deposition of the Hickory Aquifer has been removed (Figure 3). The resultant Precambrian paleotopography has mapped granite knobs up to 800 feet high (Barnes and Bell, 1977). This paleotopography controls the depositional patterns of the Riley Formation, which includes the Hickory, Cap Mountain, and Lion Mountain Members (Krause, 1996).

The Cambrian-age Hickory Member was deposited around the base of these Precambrian knobs, and where the Precambrian knobs were higher than Hickory deposition, the Cap Mountain or even the Lion Mountain Members were directly deposited on the Precambrian basement rocks (Long, 2004). The resultant complex depositional pattern greatly complicates the compilation of accurate isopach maps of the Hickory Member (Krause, 1996).

Figure 4 is comprised of a number of illustrations and tables that help summarize the tectonic, structural, depositional, and erosional events that occurred within the Llano Uplift study area during the Precambrian to Cretaceous time span.

2.1.2 Cambrian Riley Formation of the Moore Hollow Group

The Riley Formation consists of three members, the Hickory, Cap Mountain, and Lion Mountain Members, as discussed below.

Hickory Member. The Cambrian Hickory Member is the oldest member of the Riley Formation; it was deposited directly on the Precambrian irregular surface and forms the largest aquifer in the study area (Figure 2). The Hickory stratigraphy and lithology have been extensively studied by many authors, including Cornish (1975), Barnes, 1963, Barnes and Bell (1977), Black (1988), and Krause (1996).

The Hickory is a mixture of terrestrial and marine sandstones, siltstones, and mudstones (Krause, 1996) and has been subdivided by Black (1988) into three zones (the upper, middle, and lower units) based on sedimentary characteristics. The lower zone generally produces the most groundwater and locally can consist of medium to coarse sandstone and conglomerates (Cornish, 1975; DBS&A, 2005). The lithofacies are gradational both vertically and laterally with the overlying Cap Mountain Limestone Member (Krause, 1996). The average dip of the Hickory Sand is approximately 1.5 degrees, but varies throughout the study area. The Hickory Member pinches out on the Llano Uplift and generally thickens away from the uplift in all directions. Thickness ranges from 0 to 530 feet based on study results. The top and base of the Hickory Member are strong geophysical log correlation surfaces (Figure 2).

Cap Mountain Member. The Cap Mountain Member unconformably overlies the Hickory and consists of thin beds of limestones and considerable amounts of sand. The Cap Mountain grades upward from a calcareous, silty sandstone to a glauconitic limestone (Krause, 1996 and Barnes and others, 1959). Locally the Cap Mountain was directly deposited on the Precambrian Llano Uplift (Figure 2). This member is considered to be a confining unit, or aquitard. Thickness of this unit ranges from 0 to 650 feet in the study area based on study results.

Lion Mountain Member. The Lion Mountain Member consists of glauconitic sandstone, sandy limestone with minor shale, and limestone (Barnes, 1963, and Barnes and Bell, 1977). The Lion Mountain Member is in hydraulic communication with the overlying Cambrian Welge Member of the Wilberns Formation (Figure 2). Bluntzer (1992) and Carrell (2000) combined these two members into one hydrogeologic unit considered an aquifer.

2.1.3 Cambrian Wilberns Formation of the Moore Hollow Group

The Wilberns Formation consists of four members, the Welge, Morgan Creek, Point Peak, and San Saba Members, as described below.

Welge Sandstone Member. The Welge Member is a coarse- to medium-grained, quartz, marine sandstone with some glauconitic areas (Barnes and Bell, 1977) (Figure 2). The combined thickness of the Lion Mountain Member and the Welge Sandstone Member ranges from 15 to 220 feet in the study area based on study results. The top of the Welge Member is a geophysical log correlation surface (Figure 2).

Both the top and base elevations of the Welge and Lion Mountain Members were captured during data compilation. Because Bluntzer (1992) and Carrell (2000) combined these two members into one hydrogeologic unit, this study considered the Welge and Lion Mountain Members as one hydrogeologic unit, referred to as the Welge–Lion Mountain aquifer.

Morgan Creek Limestone Member. The Morgan Creek Limestone Member (Figure 2) unconformably overlies the Welge Sandstone Member and consists of glauconitic limestone with interbeds of fine-grained silty limestone (Krause, 1996; Barnes and Bell, 1977). Thickness of this unit may be as great as 220 feet in the study area based on study results.

Point Peak Shale Member. The Point Peak Shale Member (Figure 2) is a confining unit and consists of laminated siltstones, thinly bedded limestones, and shale (Barnes and Bell, 1977; Carrell, 2000). The thickness of this member ranges from 0 to 265 feet in the study area based on study results. The top of the Point Peak is a strong geophysical log correlation surface (Figure 2).

San Saba Limestone Member. The San Saba Limestone Member is in hydraulic communication with the overlying Ordovician Ellenburger Group and the two units are therefore considered to be one aquifer in this study (Figure 2). The San Saba Member consists of thinly to thickly bedded limestones and dolomite. The dolomite is generally fine-grained (Barnes and Bell, 1977).

2.1.4 Ordovician, Ellenburger Group

The Ellenburger Group is comprised of the Honeycut, Gorman, and Tanyard Formations. The group consists of medium- to coarse-grained dolomite that transitions into massive limestone (Cloud and Barnes, 1948). The Ellenburger has undergone various degrees of erosion and karstification (Figure 4), and local well yields in excess of 1,000 gallons per minute (gpm) have been observed. The thickness of the combined Ellenburger–San Saba aquifer ranges from 0 feet (Menard County) to over 2,400 feet (eastern Burnet and Blanco counties). The top of the Ellenburger Group is a strong geophysical log correlation surface (Figure 2).

2.1.5 Silurian, Devonian and Mississippian Formations

The majority of the Silurian, Devonian, and Mississippian stratigraphic formations were either not deposited or were eroded away in the study area. Thin exposures of these formations outcrop in southern Burnet County and in Lampasas, San Saba, and McCulloch counties. These formations include, from oldest to youngest, the Stibling, Houy, Chappel, and Barnett Shale Formations.

2.1.6 Pennsylvanian Bend Group (Marble Falls and Smithwick Shale Formations)

Geophysical log correlations of the Pennsylvanian Formations were very difficult to construct due to Ouachita (Thrust Belt) tectonism, which extensively faulted and deformed all of the studied geologic section. Alternating periods of deposition and erosion of the Pennsylvanian Formations (Figure 4) were contemporaneous with this tectonic activity. Formation thickness and facies changes combined with active deformation distorted tops and bases and created alternating lithologic facies of these Pennsylvanian Formations.

Marble Falls Formation. The Marble Falls Formation is divided into upper and lower units. The lower unit is a massive limestone. The upper unit is a very fine-grained limestone interbedded with shales (Morey, 1955 and Carrell, 2000). Only the limestone or carbonate intervals of the Marble Falls Formation, the only lithology capable of producing water, were correlated with geophysical logs. Some of these sections contained interfingered shaley beds. Correlated limestone units of the Marble Falls have thicknesses ranging from 0 to 265 feet within the study area based on study results.

Smithwick Shale Formation. The Smithwick Shale Formation unconformably overlies the Marble Falls Formation and Smithwick consists of interbedded claystone, siltstone, and sandstone. The Smithwick is a confining unit (Morey, 1955 and Carrell, 2000). The Smithwick Shale base provided a relatively reliable correlation point in the geophysical logs.

2.2 Structure and Faulting

Johnson (2004) provides an excellent description of the development of the Llano Uplift and related faulting. The following discussion of structure and faulting was extracted from his text.

2.2.1 Structure

The Llano Uplift is a broad structural dome in central Texas with 2 to 3 km of structural relief relative to the subsurface Fort Worth and Kerr basins to the northeast and southwest, respectively. Erosion of gently dipping Cretaceous rocks in the Colorado River drainage exposes middle Proterozoic igneous and metamorphic rocks in the core of the uplift and Paleozoic sedimentary rocks primarily on the flanks of the uplift. Stratigraphic studies indicate that the Llano Uplift and the Fort Worth and Kerr foreland basins formed contemporaneously during early to middle Pennsylvanian time. These structures were positioned along the margin of the North American continent and were formed in association with Ouachita collisional tectonism occurring to the east (Figure 5).

2.2.2 Faulting

Surface and subsurface data show a more than 500-km (310-mile) long northeast-trending zone with syndepostional, dip-slip dominant, high-angle faults associated with the Llano Uplift and Fort Worth and Kerr basins. The largest fault displacements (up to 900 meters, almost 3,000 feet) occur in the Llano region, where a northeast-oriented system of high-angle faults cuts the Precambrian and Paleozoic rocks as young as middle Pennsylvanian.

In the Llano region, faults of Pennsylvanian age are discernable where they offset Paleozoic strata. The faults exhibit a range of attitudes and fault kinematics. Faults generally trend northeast–southwest, but many trend north–northeast and east–northeast, and there are some that trend north, north–northwest, and east–west. Figures 6 (Tybor, 1993) and 7 (Tybor, 1995) illustrate the variable fault displacements in Gillespie County. Most faults have a significant normal dip-slip component. Smaller-scale faulting includes step and en echelon faulting, which occurs throughout the study area (Carrell, 2000).

2.2.3 Hydrogeologic Effects of Faulting

Faults with throws greater than the Hickory Member thickness (up to 530 feet) may result in the juxtaposition of the Hickory aquifer against other aquifer units with different lateral hydraulic conductivities, such as the Welge–Lion Mountain aquifer. Faulting can also lead to compartmentalization of the Hickory aquifer, by down-dropping (graben) the Hickory into the Precambrian strata (Randolph, 1991, Wilson, 2001 and Pettigrew, 1988). Figures 6 and 7 illustrate how faulting can compartmentalize the Hickory, Welge–Lion Mountain, and Ellenburger–San Saba aquifers. Low-permeability fault gouges can cause a two to six orders of magnitude decrease of groundwater flow across faults as compared to undeformed rock (Delaney, 1990). The change in fluid flow across faults and the juxtaposition of the Hickory against other formations has been studied in detail by Zhurina (2003).

3. Data Sources

3.1 Stratigraphy Data Sources

A total of 1,077 subsurface locations (or control points) were used to construct the GIS geodatabase, *Final_Llano_Point_File*, for this study. Subsurface sources of data used in this study include groundwater district databases, Bureau of Economic Geology (BEG) geophysical logs, driller's reports from a local driller, locations from published BEG and Texas Water Development Board (TWDB) reports and cross sections, BEG scout tickets, Texas Commission on Environmental Quality (TCEQ) subsurface casing geophysical logs, various consultant reports, and subsurface information for TWDB wells in the Well Site Remarks Table and Casing Table datasets.

An attempt was made to obtain as much of the Llano Uplift public domain subsurface information as possible. Various entities in the study area were visited during September 2006 to obtain pertinent driller's reports, geophysical logs, and available groundwater databases. During this four-day trip, DBS&A staff met with the managers and/or technical staff from the Blanco-Pedernales Groundwater Conservation District (GCD), the Hickory Underground Water Conservation District (UWCD) No. 1, the Hill Country UWCD, the Kimble County GCD, the Menard UWCD, and the Headwaters GCD. Driller's reports and/or geophysical logs were obtained from all of the districts visited. The Central Texas GCD, Hays Trinity GCD, and Saratoga UWCD were not visited because available data for the Paleozoic formations were very limited. The Virdell Drilling Company was also visited and a day was spent going through the company's file cabinets extracting logs for wells completed in Paleozoic rocks. A total of 68 driller's reports and/or geophysical logs were obtained from these sources.

Mr. Paul Tybor of the Hill Country UWCD provided a large database (Tybor, 2006) of almost 5,000 wells (approximately 2,100 wells included Paleozoic Formations) with geological formation picks. He also provided two large cross sections that he had constructed using his formation picks (modified for this report and included as Figures 6 (Tybor, 1993) and 7 (Tybor, 1995). A total of 646 of the wells from the Hill Country UWCD (or Gillespie County) were used in this study.

Numerous theses and dissertations were reviewed for subsurface information that could be used in this report. Unfortunately, the lack of reliable location information prevented the use of any of the data. Problems with the reliability of the location information included scale issues (very small maps and/or figures with posted locations) and/or no location information being provided.

The BEG Geophysical Log Library was the source of the majority of the geophysical logs used in this study. Approximately 300 geophysical logs were initially selected based on location. Of this initial data set, only 152 logs were used, based on additional screening for details of location data, well depth, and log quality. The BEG also has a petroleum-based scout ticket library, and an additional 11 locations were added to the GIS geodatabase from this data source.

All relevant BEG and TWDB published reports were reviewed and maps were geo-referenced for GIS analysis. Cross sections and maps were reviewed and screened for usable (detailed location and subsurface) data; 50 geophysical logs and 13 outcrop (or columnar section—"columr_sec" in the *Final_Llano_Point_File*) locations were identified and included in the GIS geodatabase (Flawn and others, 1961, Barnes and Bell, 1977, Barnes, 1963, Mason, 1961 and Bluntzer, 1992). The TCEQ's subsurface casing office provided another 5 geophysical logs.

Consultant's reports and cross sections were also used. Geophysical logs were obtained from the San Angelo Hickory Well Field study in McCulloch and Menard Counties (DBS&A, 2005), and 9 wells with Paleozoic data were extracted from Mr. Feather Wilson's cross section interpretations of Kerr County (Wilson, 2005). A total of 15 cross sections were used in this study.

The TWDB database was used to establish some formation tops near outcrops where geophysical logs were not available. The TWDB Well Site Remarks Table and Casing Table datasets were searched for Hickory (371HCKR) or Ellenburger (367ELBG) wells that had top picks for screen, slotted, or perforated intervals. Wells with unique top picks (not a multiple of 10) that were deeper than 20 feet and were reported by reliable drillers were selected. Using GIS and a 30-meter digital elevation model (DEM) (used for all elevations in this study), the depth to the top of the screen or producing interval was subtracted from the DEM-estimated land surface elevation to calculate the top elevation of the aquifer. A total of 106 locations with Hickory or Ellenburger tops were derived using this technique. These locations were then compared with outcrop DEM elevations to determine if these calculated aquifer tops seemed reasonable based on distance from outcrop.

The DBS&A team was very selective in choosing which driller's reports and scout tickets were to be used in this study. A phone survey of the local groundwater district managers identified Virdell Drilling as one of the oldest (mid-1940s) and most reliable (consistently produced detailed location and borehole cutting descriptions) in the study area. The visit to the Virdell Drilling office in Llano, Texas confirmed the results of the phone survey. During the driller's report selection process in the Virdell Drilling office, the DBS&A team only selected driller's reports that identify the formation tops. After the geophysical logs were correlated, the driller's report formation tops were integrated into the database and reviewed to determine applicability. The formation tops identified in the Virdell driller's reports were found to be consistently reliable.

The scout tickets obtained from the BEG library were also screened for detailed location and stratigraphic information. The scout tickets were especially critical in Blanco, Kendall, and Kerr counties because of the lack of geophysical logs available for these areas.

Detailed discussions of database construction, descriptions of GIS attribute columns, data screening, location and elevation correction procedures, and quality assurance of the location database (*Final_Llano_Point_File*) and other GIS files for this study are discussed in Appendix A (Geo-referencing and Location Verification), Appendix B (GeoDatabase Construction), and Appendix C (GIS Attribute Definitions).

Digital files of the Llano (Barnes, 1981) and Brownwood (Barnes, 1976) GAT sheets were obtained from the TNRIS FTP site and entered into the GIS geodatabase. The digital GAT files included the surface geology and mapped faults. The surface geology GAT GIS file has been modified by adding an additional attribute column, "Unit," that visually simplifies the geology by grouping the formations and members into hydrogeologic units as shown in the legend of Figure 1. Unfortunately, the Morgan Creek and Welge Members and the Lion Mountain and

Cap Mountain Members were combined together as geologic mapping units in the GAT sheets, making the delineation of the Welge–Lion Mountain aquifer not possible. The GIS file has been renamed *Modified_Geology_GAT*.

3.2 Fault Data Sources

The detail, resolution, and accuracy of the faults in the digital GAT sheets were compared to the original hard copy maps and were determined to be adequate for use in this study. These faults were posted over the digital geology, and all faults located outside of the study area and faults within the study area that did not offset discernable Paleozoic strata were deleted from the GIS geodatabase. All faults less than 1 mile long were also deleted from the geodatabase. The resultant GAT fault GIS file is named *Modified_GAT_Faults*.

Additional sources of fault information for the Llano Uplift study area were two studies by Dr. Thomas Ewing (1991, 2004). These references provided surface traces of regional subsurface faults generated from the interpretation of geophysical logs and other published and unpublished resources. These faults are relatively large-scale faults 5 to 50 miles long. The faults were captured digitally and geo-referenced into the GIS geodatabase *Ewing_Faults*.

Figure 8 illustrates the data locations, the modified GAT faults, and the Ewing faults used in this report.

4. Stratigraphic Interpretation of Geophysical Logs

The correlation of geophysical logs and drillers' reports for such a large, complex stratigraphic section was a challenging and slow iterative process. Fortunately, the DBS&A team had two areas with concentrated stratigraphic control, in addition to published BEG, TWDB, and consultant cross sections with stratigraphic picks.

The first area with concentrated stratigraphic control evaluated was southwestern McCulloch County and far eastern Menard County in the vicinity of the San Angelo Hickory aquifer well field. DBS&A subcontracted Dr. Robert Loucks of the BEG, a recognized expert on the Ordovician Ellenburger Group, to correlate the Paleozoic section (Precambrian through the Pennsylvanian Barnett Shale Formation). This stratigraphic framework provided a reference for correlating east into San Saba County, northwest into Concho County, west into Menard County, and southwest into Kimble County (Figure 8).

The second area with concentrated stratigraphic control was Gillespie County. Data for this county were initially obtained from the Hill Country UWCD well database (Tybor, 2006), constructed by Mr. Paul Tybor and his staff. This dataset included approximately 5,000 wells with stratigraphic picks for tops and bottoms of formations from Precambrian to Cretaceous, of which about 2,100 well locations had stratigraphic picks within the Paleozoic formations. Mr. Paul Tybor had constructed two northwest to southeast cross sections mapping fault blocks within Gillespie County and a few large areas with Cretaceous strata unconformably overlying the Precambrian rocks (Figures 6 (Tybor, 1993) and 7 (Tybor, 1995). Using these cross sections as guides, a total of 646 well locations in Gillespie County were selected for this study, ultimately providing high stratigraphic resolution across nearly two-thirds of Gillespie County (Figure 8). This stratigraphic framework provided a reference for correlating east into Blanco County and south and southwest into Kerr and Kendall Counties (Figure 8).

The Marble Falls Formation was the most challenging formation of the four aquifer systems for correlating surfaces in geophysical logs. The best potential for water production from the Marble Falls Aquifer occurs from the carbonates, such as limestone, with potential for primary and secondary porosity (karstification) enhancing water storage and movement. The top and base of the Marble Falls Formation were selected on each geophysical log in terms of log patterns that best characterize this hydrologic potential. Elsewhere in the formation, the Marble Falls contains low-water-producing lithologies such as silts and clays. Thus, the structural contours developed from these data represent the top and base of the hydrologic Marble Falls (limestone) and not the entire stratigraphic Marble Falls Formation. The degree of local karstification of the Marble Falls limestones is unknown.

The geophysical log surveys of the City of San Angelo Hickory Well Field in McCulloch and Menard Counties were initially used to identify the Marble Falls Formation in the subsurface. Geophysical logs, primarily from oil and gas wells, were then used to laterally correlate the Marble Falls aquifer moving away from the San Angelo Well Field area in all directions.

The log pattern displayed by the Marble Falls Formation commonly changes significantly over short lateral distances, making it difficult to recognize in the subsurface. It was often necessary, therefore, to select other geologic units above the Marble Falls for preliminary correlation purposes prior to identifying the Marble Falls log signature. The most useful unit for this purpose was an approximately 80-foot shale unit above the Pennsylvanian Winchell Formation, which occurs approximately 150 to 200 feet above the Marble Falls in the San Angelo wells. Locally, the base of the Smithwick Shale Formation also provided a geophysical log correlation surface.

Dr. Robert Loucks and Mr. Jeff Kane of the BEG provided assistance during the geophysical log interpretation phase. Dr. Loucks was especially helpful in his guidance with the geophysical log correlations of the Marble Falls. DBS&A was also assisted by Mr. John Ashworth of LBG-Guyton and Associates Inc. during most of the geophysical log interpretation activities.

The other three Paleozoic aquifer systems (Ellenburger–San Saba, Welge–Lion Mountain, and Hickory) were less difficult to correlate throughout the study area. Good stratigraphic correlation surfaces for these systems included the top of the Ellenburger, the top of the Point Peak, and the top and base of the Hickory (Figure 2). Log types used in the correlation were gamma, resistivity, compensated neutron, density, and occasionally, spontaneous potential (SP).

5. Construction of Structural Contour Elevation Surfaces

The construction of gridded structural elevation surfaces of the four aquifers over a 14,000-square mile area for a large stratigraphic sequence that has been intensely faulted and has Precambrian paleotopography, onlapping, unconformities, nonconformities, thinning and thickening intervals, and facies changes was a formidable task. The DBS&A team depended on previous work completed by Dr. Thomas Ewing, a structural expert of Texas geology, to provide the initial template and guide to identifying the major regional subsurface faults. The Ewing (1991) faults were digitized, creating the GIS file *Ewing_Faults*, which was imported into the GIS geodatabase. The Ewing_Fault dataset provided an excellent reference during the interpretation of structural surfaces of the tops and bases of the Marble Falls, Ellenburger, San Saba, Welge, Lion Mountain, and Hickory Formations. Ewing's faults were generally honored even where this study's data density was sparse.

The DBS&A team identified new subsurface faults during the structural contouring process by interpreting apparent offsets of the contours based on the stratigraphic picks from the GIS geodatabase. Faults with throws less than 250 feet were not identified through contouring.

Two GIS fault files were created for the new subsurface fault files. The Hickory, Welge–Lion Mountain, and Ellenburger–San Saba faults and all of Ewing's accepted faults were combined into one GIS fault file named *Hick_to Ellen_Fault_Attrib*. The second new subsurface fault file, *Marble_Falls_Fault_Attrib*, was for the Marble Falls faults and associated Ewing faults, which were separated from the other faults because fault displacements in the Marble Falls appeared to be decreasing in vertical displacement or, in some cases, because vertical displacement was not observed in contouring. Additional information is provided later in this section in the discussion of the faulting in the Marble Falls by Winston (1963) in Sections 5 & 8.

Figure 9 illustrates the updip and downdip extents of the proposed model area using the base of the Hickory Aquifer. The downdip extent used for all gridded structural elevation surfaces for this project is the TWDB's Hickory Aquifer subsurface downdip extent, plus 5 miles. This downdip extent was used because the TWDB's downdip extent of the Hickory Aquifer is based on water quality of 3,000 milligrams per liter (mg/L) total dissolved solids (TDS). Available well data suggest that water quality rapidly deteriorates to 10,000 mg/L TDS (TCEQ's defined limit of usable water) or more within this 5-mile extension.

The DBS&A team made a concerted effort to be consistent in the interpretation of each structure elevation contour surface and to be aware of its interaction with the overlying and underlying structural surfaces, the variation of formation thickness, and fault displacement according to information compiled within the GIS geodatabase while contouring. The DBS&A team made the assumption that all faults are high angle and Pennsylvanian in age and, therefore, that faults identified in the Cambrian formations would be observed through the Ordovician Ellenburger Group and even into the overlying Pennsylvanian Marble Falls Formation.

All structural elevation surfaces were contoured at an interval of 250 feet from 1,500 to –1,500 feet. Although not an ideal interval for all of the aquifers, a 250-foot interval (approximately half the maximum Hickory thickness) was necessary to maintain a conformable shape during structural contouring. Data density was not uniformly distributed, which could have caused perturbations of contours had a tighter interval been used, especially in highly faulted regions with steep dips. This interval allowed capture of faults that exceeded 250 feet of throw. Larger contour spacing was used at elevations below –1,500 feet due to the paucity of data. Additional –2,000 and –3,000 contour lines were added to illustrate the structural surface dip away from the Llano Uplift.

The Hickory sandstone top and base surfaces were contoured taking into consideration a variable thickness across the region. This unit is thinner to the north and reaches a maximum thickness in Menard and Kimble counties. At points of known thickness, contours were conformed to reflect reliable thickness data and similarly extended between well points to indicate a smoothed thickness variance. The Hickory was usually thicker than 250 feet, locally exceeding 500 feet in Menard and Kimble counties. A 250-foot contour interval was determined to be adequate for Hickory definition without including irresolvable noise in the observed data. Structural elevation contours of both the top and base of the Hickory Aquifer were completed for this report.

The top of Welge structural elevation surface was more problematic than the Hickory because the Welge-Lion Mountain interval thickness only ranges from 15 feet to 220 feet. Generally, this interval is thinnest in the north, increasing to a maximum thickness in the west. Accounting for variations in interval thickness and fault throws greater than the interval made it difficult to maintain structural conformance.

The structural contouring of two surface less than 250 feet apart is difficult using 250-foot contour intervals. In addition, there are areas within the study area that have very tightly spaced structural contours created by steeply dipping fault blocks. After a number of attempts, it was determined that it was not possible to construct structural elevation contours without introducing interpretational error into the base of the Lion Mountain structural contours. Therefore, only the top of the Welge structural elevation contour surface was completed for this report.

By contrast, the Ellenburger–San Saba interval ranges in thickness from approximately 50 feet in Gillespie County to 2,400 feet in Burnet and Blanco counties. A large area where the Ellenberger has been nearly totally removed is located in eastern Menard and southwestern McCulloch counties. Johnson (2004) thinks that this area was structurally highest during the Pennsylvanian orogeny. The DBS&A (2005) report for San Angelo confirms this and identified the absence of Ellenburger within a horst block in a portion of southwest McCulloch County. This area (over 400 square miles) is possible evidence of a high “forebulge” created by loading of the continental crust by Ouachitan compression, crustal thickening, and thrusting from the east. The top of the Ellenburger and the base of the San Saba structural elevation contour surfaces were completed for this report.

The top and base of the carbonate interval(s) within the Marble Falls Formation were reliable geophysical log picks (the base was more reliable) as lithologic surfaces. The interval ranged in thickness from 0 to 265 feet. The interval thickness is generally much less than the 250-foot structural contour interval. Again, the structural contouring of two surfaces less than 250 feet apart is difficult using 250-foot contour intervals. In addition, there are areas within the study area that have very tightly spaced structural contours created by steeply dipping fault blocks. After a number of attempts, it was determined that constructing structural elevation contours was not possible without introducing interpretational error into the top of the Marble Falls structural contours. Accordingly, structural elevation contours were created for the Marble Falls base only; the top of the Marble Falls was not contoured in this study.

Winston (1963, Figure 4) presents a photograph showing the Marble Falls being folded and not faulted in the southwest part of the Bluff Creek area of Mason County. This suggests that there may have been areas in the Llano Uplift where the Pennsylvanian faulting did not occur in the Marble Falls or the overlying Smithwick, possibly because the formations had not been lithified.

The updip extent for each of these gridded surfaces was created using the TWDB's aquifer extents when possible and interpreting the digital GAT geology and subsurface geology compiled in the GIS geodatabase (Final_Llano_Point_File). The updip extents of the Marble Falls, Ellenburger, and Hickory aquifers are very different than the existing TWDB's aquifer extents, especially in Gillespie County because of Mr. Paul Tybor's extensive subsurface geological database.

Six contoured surfaces (structural elevation contour maps) were constructed at 250-foot intervals from posted control data points, taking into account known faults and editing or creating faults as data dictated. The contoured area on each surface was clipped by its appropriate updip and downdip aquifer boundaries to exclude extraneous data. These clipped structural contoured surfaces were then converted to Triangulated Irregular Networks (TINs), which were then converted to one square-mile cell grids. The same stock linear color bar was applied to all six aquifer structural surface grids for uniformity. Thus, a total of six gridded structural elevation contour maps were generated:

- Base of Marble Falls (Figure 10)
- Top of Ellenburger (Figure 11)
- Base of San Saba (Figure 12)
- Top of Welge (Figure 13)
- Top of Hickory (Figure 14)
- Base of Hickory or top of Precambrian (Figure 15)

Because the number and distribution of data points for each of the individual structural elevation layers was variable, a few of the smaller faults identified by Ewing (1991) were not presented in these figures. Many new subsurface faults were identified in this study (especially in Gillespie County) and many of Ewing's faults were extended.

Structural contouring of the top of the Hickory (Figure 14) identified more faults than were identified in the overlying structural surfaces (Figures 10 through 13). Data distribution and availability cannot account entirely for all of the additional faults. One explanation for the increased number of faults is made by Johnson (2004), who states that "detailed mapping demonstrates a relation between fractures in the crystalline basement and faults in the overlying Hickory Sandstone. The complex faults systems observed in the Hickory sandstone outcrop are interpreted to reflect highly heterogeneous deformation in the underlying basement."

Another possible explanation for differences in mapped faults on various horizons arises from Precambrian topography. In some places, the erosional remnants or highs of the Precambrian strata have a relief of 800 feet above base surface (Barnes and Bell, 1977). The Hickory, Cap Mountain, Lion Mountain, Welge, and Morgan Creek units onlap this topographic surface. With such an age disparity at the contact, a fault might be interpreted where one does not exist, in the absence of better or more dense data.

6. Proposed Model Areas

The study area has been subdivided into four proposed model areas (Figure 16) based primarily on common structural character and geologic history. The boundaries of these regions are delineated by three major through-going faults, in some cases more than 50 miles long, extending across several counties. Table 1 is a detailed summary of the boundaries, structure characteristics (fault intensity, internal faults, horst-graben pattern), and interpretation of each area. Recommended grid spacing is 1 mile.

Important geologic features that may significantly affect groundwater flow, and should therefore be considered in future three-dimensional groundwater flow models to the extent possible, include the following:

- The Precambrian erosional topography (Krause,1996)
- The Cambrian onlap onto that surface (varying thickness, e.g., Figures 6 and 7)
- The post-Ellenburger unconformity, which is locally significant (removing over 500 feet of Ellenburger in western McCulloch County and thinning of Ellenburger, in Gillespie County [Figure 6, (Tybor, 1993)]
- The non-uniform motion of fault blocks
- Laterally changing structural stress fields and fault styles
- Varying sealing capacity of near-vertical faults
- Lateral depositional facies changes (differing lithology and rock properties)
- Laterally and vertically varying diagenetic alteration (creation or dissolution of inter/intragranular porosity and pore-filling cements)

7. Determination of Net Sand Thickness

Net sand thickness was derived for the Welge–Lion Mountain and the Hickory Sandstone intervals (Figures 17 and 18) by establishing a sand/shale line at approximately the 50 percent shale line determined on the gamma ray curve of geophysical well logs. The sand/shale line was adjusted by lithologic description on drillers' sample logs if available. Driller's reports from Virdell Drilling were also used to determine net sand thickness. If the formation was fully penetrated and the tops and bases of the Welge–Lion Mountain and/or the Hickory were identified, then the sand intervals described by the driller between the top and base surfaces were summed to obtain net sand.

Net sand information could not be derived from the Hill Country UWCD well database. When contouring net sand isopachs within Gillespie County, it was assumed that the total Welge–Lion Mountain and Hickory thicknesses were net sand. According to the data within the study area GIS geodatabase (Final_Llano_Point_File), the net sand divided by the total interval thickness equals 78 percent for the Welge–Lion Mountain, based on 62 locations, and 80 percent for the Hickory, based on 24 locations.

8. Assignment of Fault Characteristics

One of the deliverables for this study was to develop fault characteristics for the existing GAT faults in the study area and the faults identified and delineated from the top and base elevation structure contour maps (Figures 10 through 15). The three fault files—Modified_GAT_Faults and the two new subsurface fault files, Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib—contain all of the faults that were identified and evaluated in this study. An attempt was made to compile fault attributes contained in these files, including fault type, formations impacted (Modified_GAT_Faults only), general dip direction, lateral fault extent, and vertical fault offset. Definitions of GIS file attributes for the Hick_to_Ellen_Fault_Attrib, Marble_Falls_Fault_Attrib, Modified_GAT_Faults, and all other GIS files are provided in Appendix C.

8.1 Fault Types

The faults in the Llano Uplift are predominantly high-angle faults with significant normal dip-slip components that generally trend northeast–southwest (Carrell, 2000; Johnson, 2004). Locally, smaller-scale faulting includes step faulting and en echelon faulting (Carrell, 2000), and it is even possible to find low-angle and high-angle reverse faults (Johnson, 2004). Because field-measured fault dips are not available in the study area, it is assumed for this study that all faults from the GAT sheets and the study subsurface faults are high-angle normal faults.

8.2 Formations Impacted

The evaluation of formations impacted by faulting is difficult, especially in the subsurface. As is illustrated in Figures 6 (Tybor, 1993) and 7 (Tybor, 1995) which are based on well data from Gillespie County, unconformities and extended erosional periods (Silurian to Mississippian), rotation of fault blocks, Precambrian topography, and other factors can remove a few (Cretaceous on Cap Mountain or Cretaceous on Point Peak) or all (Cretaceous on Precambrian) of the underlying Paleozoic members and formations. In addition, post-depositional unconformities that do not extend across more than one formation, such as the one that occurs within the Ellenburger Group massive carbonates, can obscure the presence of a fault or its throw where wells do not fully penetrate into older formations.

The identification of the formations impacted for the subsurface faults identified during structural contouring (Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files) was attempted but proved not possible for the whole study area. The study area includes many parts with poor data density and/or locations with partial subsurface information (not fully penetrating to the base of the Cambrian formations). Due to the many geological variables (Precambrian paleosurface, onlapping, unconformities, nonconformities, etc.), the interpretation of the formations impacted would be very speculative for the majority of the study area. Therefore, information on formations impacted was not provided for these files. The Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files may contain information to determine the formations impacted for some localized areas (possibly Gillespie and McCulloch counties).

For the Modified_GAT_Faults file, formations that were impacted by faulting were determined by observing the geology on both sides of the fault on the GAT sheets and were recorded in the Form_Imp field in the Modified_GAT_Faults file. Stratigraphic intervals are probably more completely intact in proposed model areas 1 and 2 (Figure 16).

8.3 Dip Direction

As discussed in Section 8.1, field-measured fault dips are not available in the study area. Determination of dip directions for most of the faults in the study area would therefore be speculation. The actual dip of the fault plane for each fault cannot be determined from available information. Based on the predominant fault dip shown in Table 1, a generalized dip direction was assigned to faults within each model area. The predominant fault dip in Table 1 was also used to assign dip direction in the Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files.

8.4 Lateral Fault Extent

The lateral extent or length of faults shown on the GAT sheet has been calculated in miles and is provided as the “Lngth_Mile” field in the Modified_GAT_Faults file. These lateral extents are based on mapping activities and are probably more representative of the actual fault extent than the lateral fault extents in the Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files, which are impacted by digitizing style and structural interpretation of fault extent by the geologist. Due to these factors, the lateral fault extents of the faults in Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files may not accurately represent the true extents and were therefore not included as an attribute in their respective files.

8.5 Vertical Fault Offset

The maximum offset of a fault occurs in the middle, can change along a fault, and decreases to zero at the ends of the fault trace. Schlische and others (1996) determined that the length of faults has a strong correlation (fractal relationship) with fault offsets or displacement and developed a formula using fault length to estimate maximum fault vertical displacement. The coefficient of determination for this formula is $R^2 = 0.97$. The formula is D (vertical displacement of the fault) = 0.03 x L (length of the fault)$^{1.06}$, or 1 mile (5,280 feet) is equal to a fault displacement of 265 feet. Using this formula, the DBS&A team estimated the maximum displacement of throw in the attribute field “Throw_est” for all of the faults in the Modified_GAT_Faults file. In addition to this estimate of fault vertical displacement, a file called “Form_Imp,” discussed in Section 8.2, was created to provide an apparent geologic formation displacement caused by each fault.

Because the lateral extents of the faults in Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files may not accurately represent the true fault extent (Section 8.4), the Schlische and others (1996) technique would not be useful for those files. Fault throws or offsets compiled in the Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files were determined by using both structural contours and posted structural surface elevations from one or more structural elevation surfaces. If one structural elevation surface had sufficient well data to support the estimation of a fault throw, overlying structural surfaces would generally mimic the fault throw, even with no supporting data.

During the structural contouring of the base of the Marble Falls Aquifer (limestones), the DBS&A team became aware that many of the fault displacements appear to be decreasing (or in some cases disappear). A University of Texas thesis by Winston (1963) has a photograph of folded Marble Falls in outcrop, as opposed to being faulted, as might otherwise be expected along a known fault trend that disrupts older formations. Relying on this information, the structural contouring of the Marble Falls, and the difficulty of identifying the Marble Falls in some areas, the DBS&A team decided to create a separate fault file for the Marble Falls and assign estimated fault throws the same as the underlying Hick_to_Ellen_Fault_Attrib fault file but include the word “decreasing,” because the faults are most probably dying out (decreasing fault displacement).

The estimated fault throw intervals were 0 to 250 feet, 250 to 500 feet, and greater than 500 feet, and are located in the “Est_flt_Di” attribute column of the Hick_to_Ellen_Fault_Attrib and Marble_Falls_Fault_Attrib fault files.

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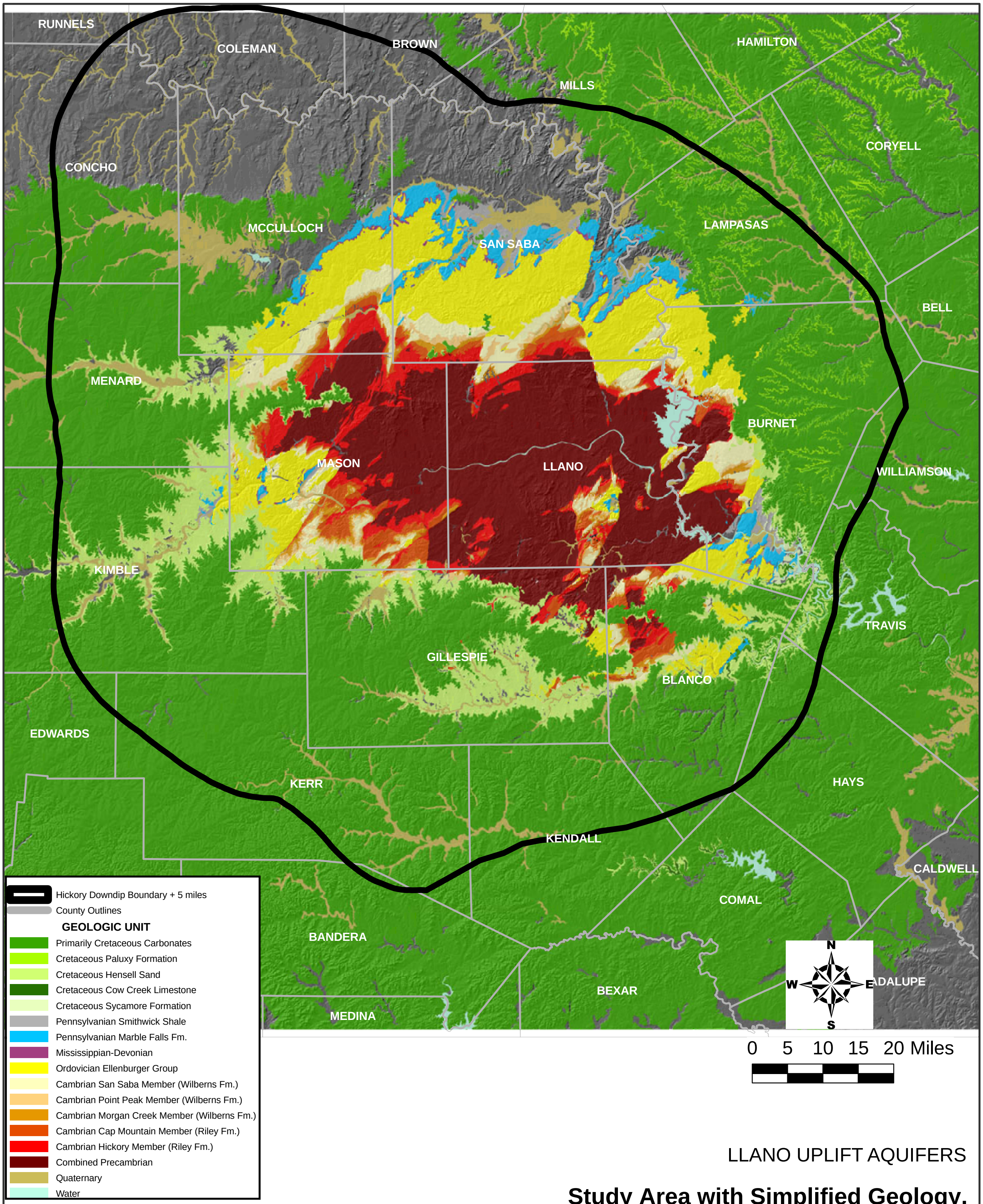

LLANO UPLIFT AQUIFERS

Study Area with Simplified Geology, Geologic Atlas of Texas (GAT)

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10/31/07

Figure 1

Stratigraphic Column

Era	Period	Group	Formation/Unit		Description
Mesozoic	Cretaceous	Fredericksburg	Edwards		Karstified limestone
		Trinity	Hensell		Silt to pebble-sized sediments derived from Paleozoic rocks
Paleozoic	Pennsylvanian	Canyon	Undivided		Limestone, sandstone, shale alternating
		Bend	Smithwick		Sandstone, claystone, siltstone
			Marble Falls Limestone		Limestone with spiculite, oolites
	Ordovician	Ellenburger	Honeycut		Alternating limestone and dolostone; highly karstified
			Gorman		
			Tanyard		
	Cambrian	Moore Hollow	Wilberns	San Saba	Dolomite, limestone; moderately glauconitic
				Point Peak	Siltstone with stromatolic bioherms
				Morgan Creek	Limestone; glauconitic; trilobites common
				Welge Sandstone	Non-glauconitic sandstone grades up to Morgan Creek
			Riley	Lion Mountain	Quartzose green sand; highly glauconitic
				Cap Mountain	Limestone; sparingly glauconitic
				Hickory Sandstone	Red sandstone, eolian and fluvial. Contains Precambrian sediments.
Proterozoic	Precambrian				Pink coarse-grained and aplite granite; Quartzofeldspathic gneisses

━━━ Strong Geophysical log correlation surface

\- - - - Geophysical log correlation surface

🟦 Aquifer

Geologic Unit (Simplified Geology, Geological Atlas of Texas (GAT), Figure 1)

🟩 Primarily Cretaceous Carbonates
🟩 Cretaceous Paluxy Formation
🟩 Cretaceous Hensell Sand
🟩 Cretaceous Cow Creek Limestone
🟩 Cretaceous Sycamore Formation

⬜ Pennsylvanian Smithwick Shale
🟦 Pennsylvanian Marble Falls Fm.
🟪 Mississippian - Devonian - not present everywhere
🟨 Ordovician Ellenburger Group
🟨 Cambrian San Saba Member
🟧 Cambrian Point Peak Member
🟧 Cambrian Morgan Creek Member
🟧 Cambrian Cap Mountain Member
🟥 Cambrian Hickory Member
🟫 Combined Precambrian

Source: Modified after Preston and others, 1996
Modified from Hoh and Hunt, 2004

LLANO UPLIFT AQUIFERS

Study Area Stratigraphy

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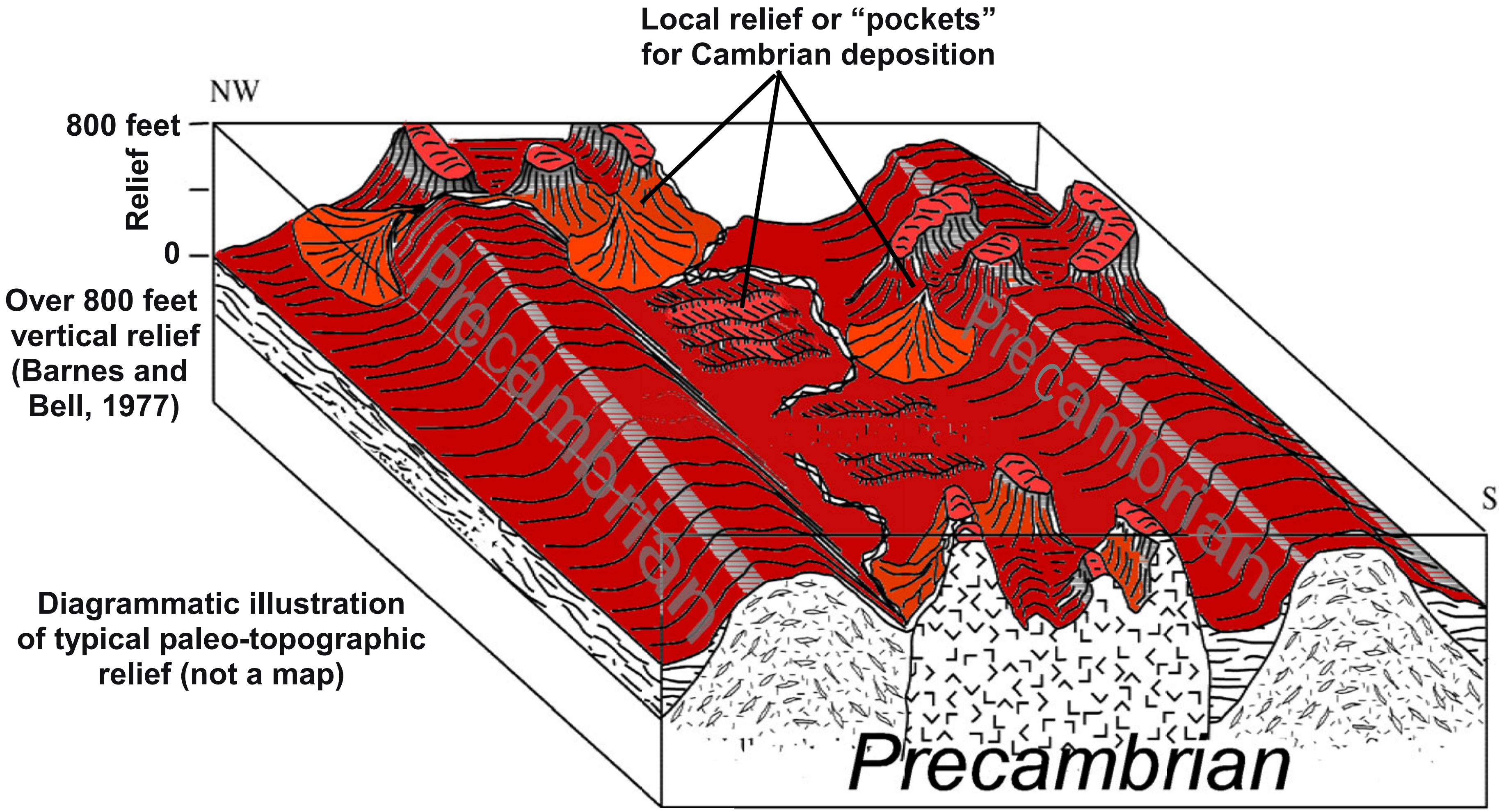
Figure 2

Vertical Relief on Eroded Precambrian Surface



Over 800 feet vertical relief (Barnes and Bell, 1977)

Diagrammatic illustration of typical paleo-topographic relief (not a map)

Source: Modified after Krause, 1996
Modified from Long, 2004

LLANO UPLIFT AQUIFERS

Precambrian Erosional Surface

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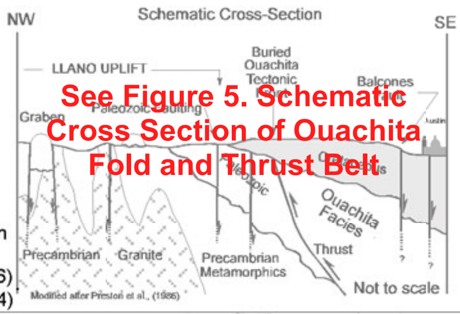
Figure 3

TECTONIC TIME CHART

Millions of Years Ago	TIME SCALE			TECTONIC CYCLES	SELECTED TECTONIC EVENT
0		CENOZOIC	T	(Balcones)	To the east: Subsidence & Progradation
100	MESOZOIC	Cretaceous	K	GULFIAN	Magmatism, uplift Gulf subsidence
200		Jurassic	J		Tethys Ocean rifting
		Triassic	TR		
	PALEOZOIC	Permian	P	OUACHITAN	To the west: Permian Basin subsidence
300		Pennsylvanian	IP		Foreland deformation Thrust faulting
		Mississippian	M		
400		Devonian	D		Nearly complete erosion of Siluro-Devonian in uplift area
		Silurian	S		Minor deformation; Ellenburger erosional surface
500		Ordovician	O		
		Cambrian	Ꞓ		Morgan Creek unconformity Cap Mountain unconformity
600–1000	PROTEROZOIC	Late		(quiescent)	peneplanation; intrusion cores weathered out

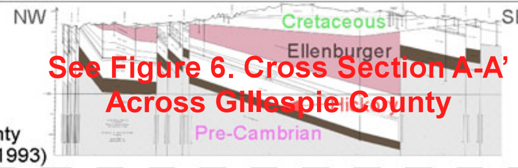
Series	Formation/Group/Erosion West	Formation/Group/Erosion East	Deformation
Missiourian	Canyon	Canyon	Westward Tilting
Des Moines	Strawn, Erosion	Strawn	Faulting
Atoka	Smithwick, Erosion Upper Marble Falls, Erosion	Smithwick	
	Erosion	Erosion	
Morrow	Lower Marble Falls Barnett?	Upper Marble Falls Lower Marble Falls	



See Figure 5. Schematic Cross Section of Ouachita Fold and Thrust Belt

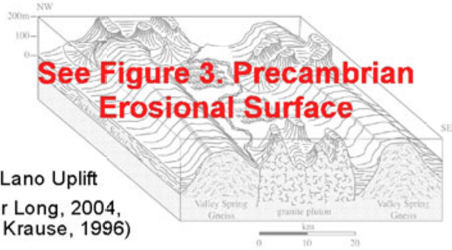
Marble Falls to Austin

(Preston and others, 1996)
(from Hoh and Hunt, 2004)



See Figure 6. Cross Section A-A' Across Gillespie County

Gillespie County
(A-A' after Tybor, 1993)



See Figure 3. Precambrian Erosional Surface

LLano Uplift
(after Long, 2004, and Krause, 1996)

Source: From Ewing, 2004

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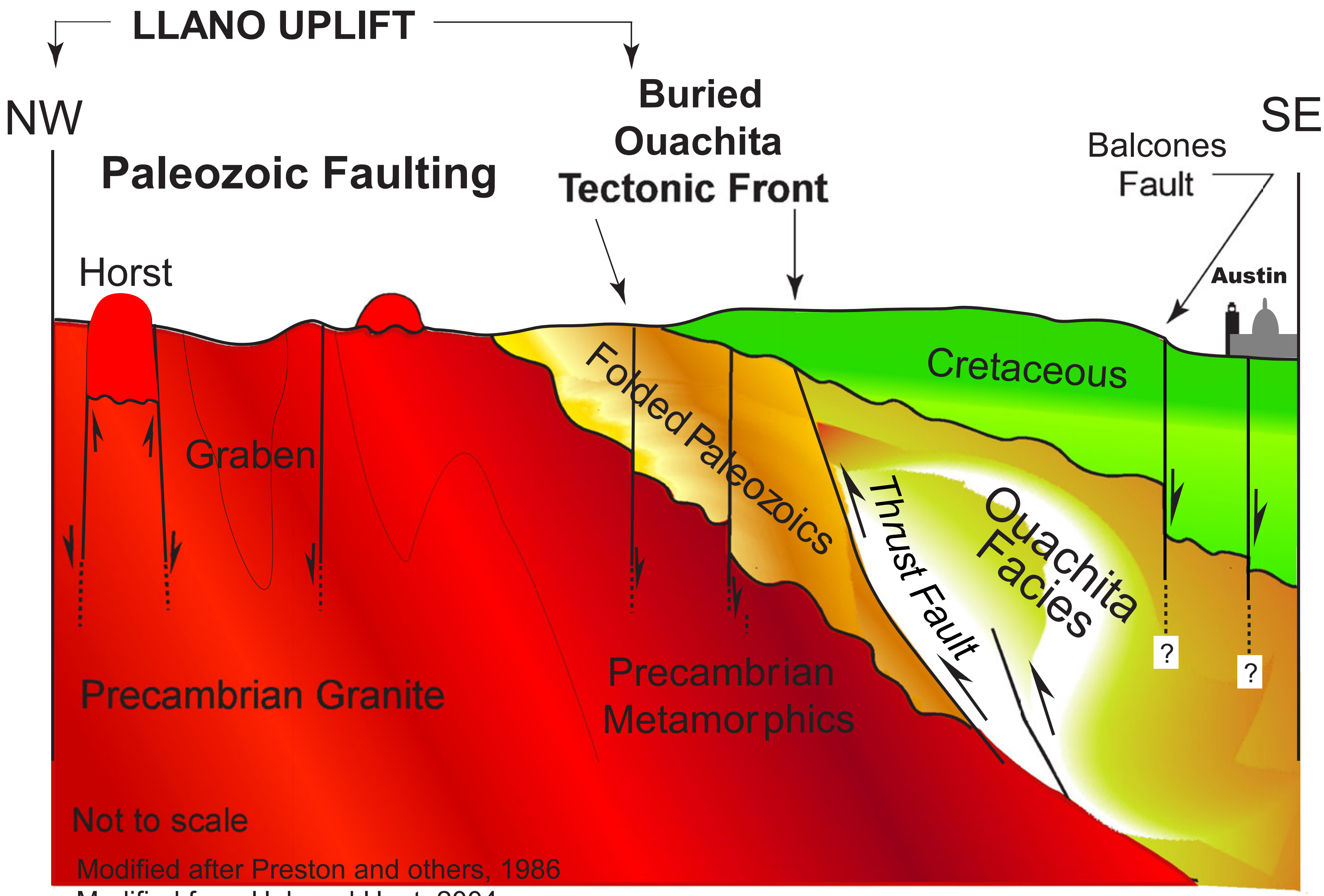
LLANO UPLIFT AQUIFERS
Tectonic Time Chart

Figure 4



Modified after Preston and others, 1986

Modified from Hoh and Hunt, 2004

LLANO UPLIFT AQUIFERS

Schematic Cross Section of Ouachita Fold and Thrust Belt

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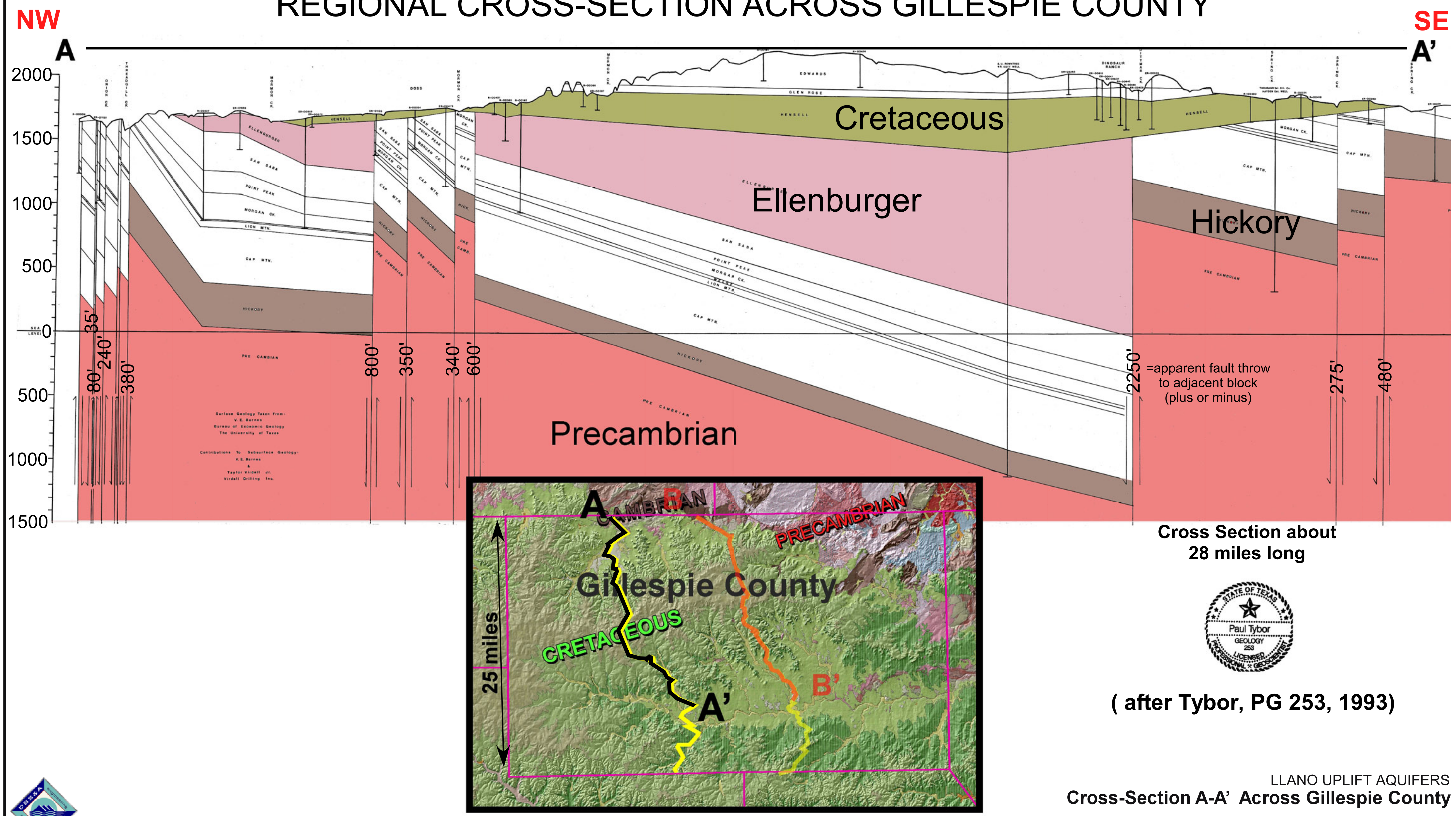
Figure 5

REGIONAL CROSS-SECTION ACROSS GILLESPIE COUNTY



Cross Section about 28 miles long

Paul Tybor
253

(after Tybor, PG 253, 1993)

LLANO UPLIFT AQUIFERS

Cross-Section A-A' Across Gillespie County

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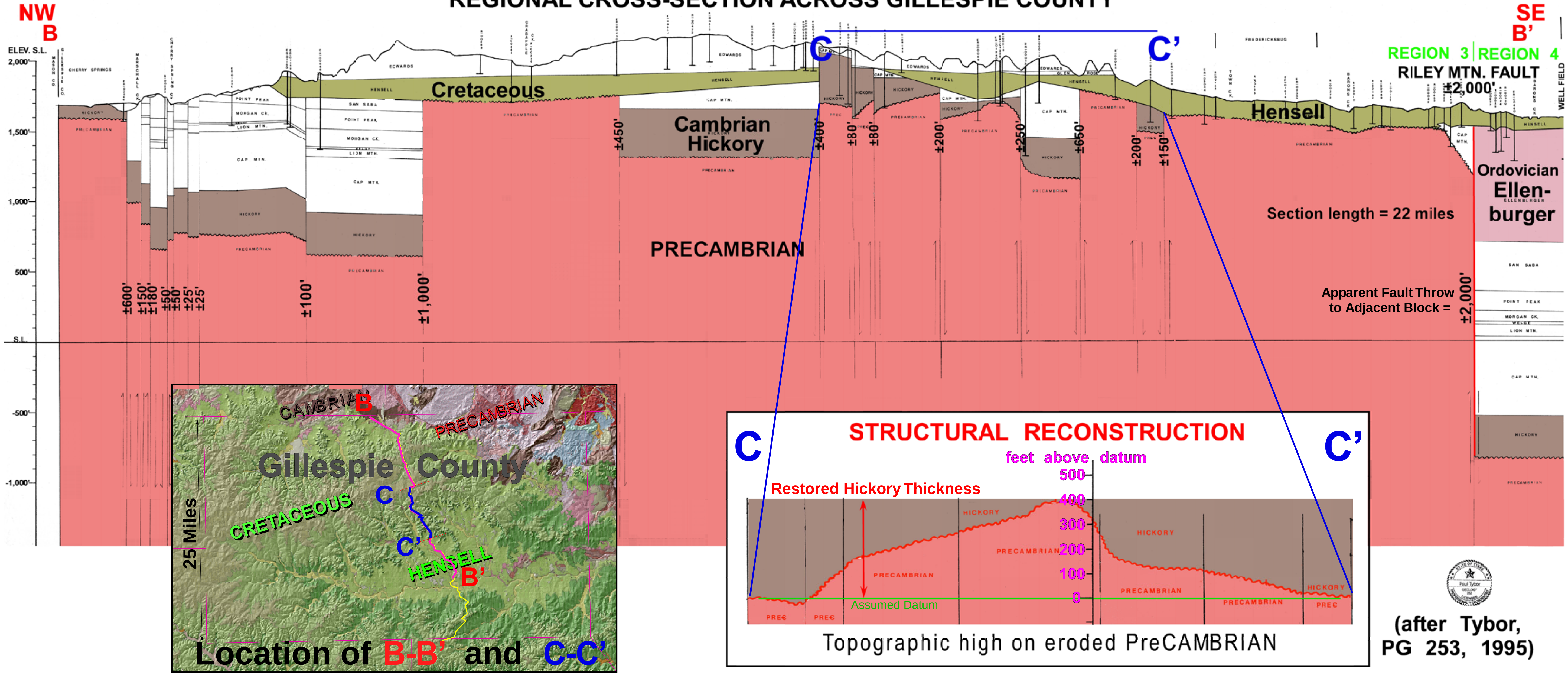
Figure 6

REGIONAL CROSS-SECTION ACROSS GILLESPIE COUNTY



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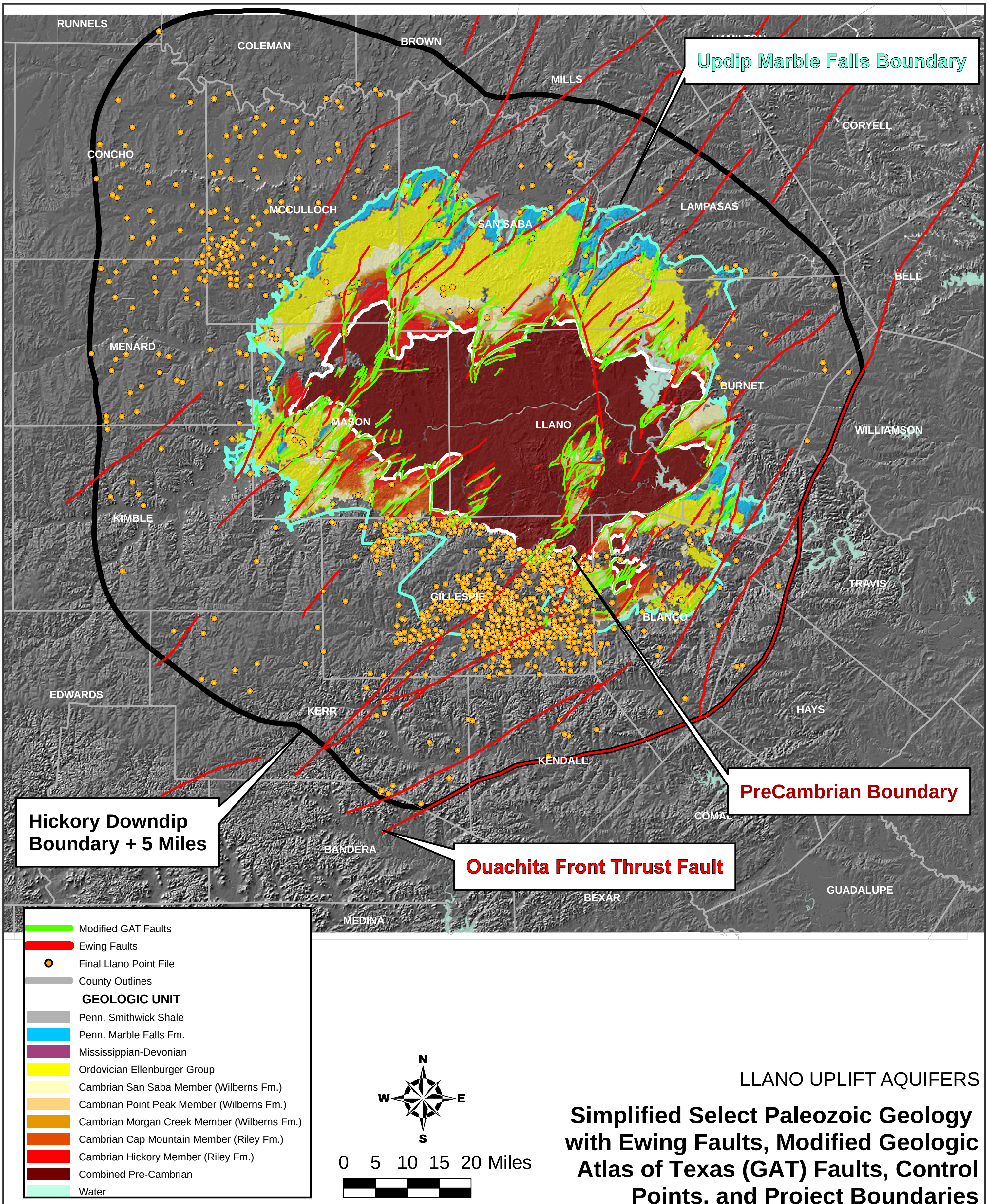
10-31-07

LLANO UPLIFT AQUIFERS

Regional Cross Section Across Gillespie County

Figure 7



LLANO UPLIFT AQUIFERS

Simplified Select Paleozoic Geology with Ewing Faults, Modified Geologic Atlas of Texas (GAT) Faults, Control Points, and Project Boundaries on Topographic Relief

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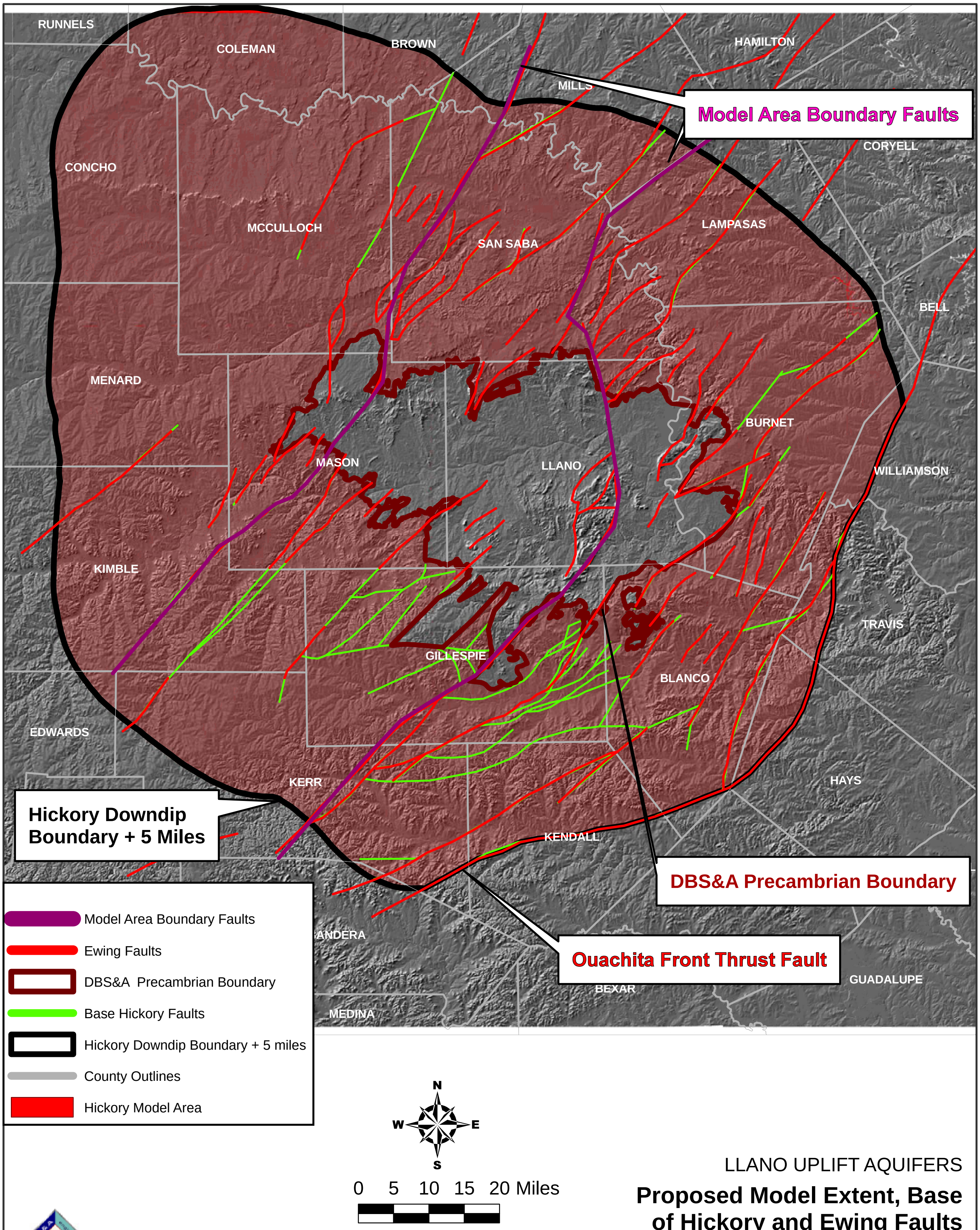
Figure 8



LLANO UPLIFT AQUIFERS

Proposed Model Extent, Base of Hickory and Ewing Faults

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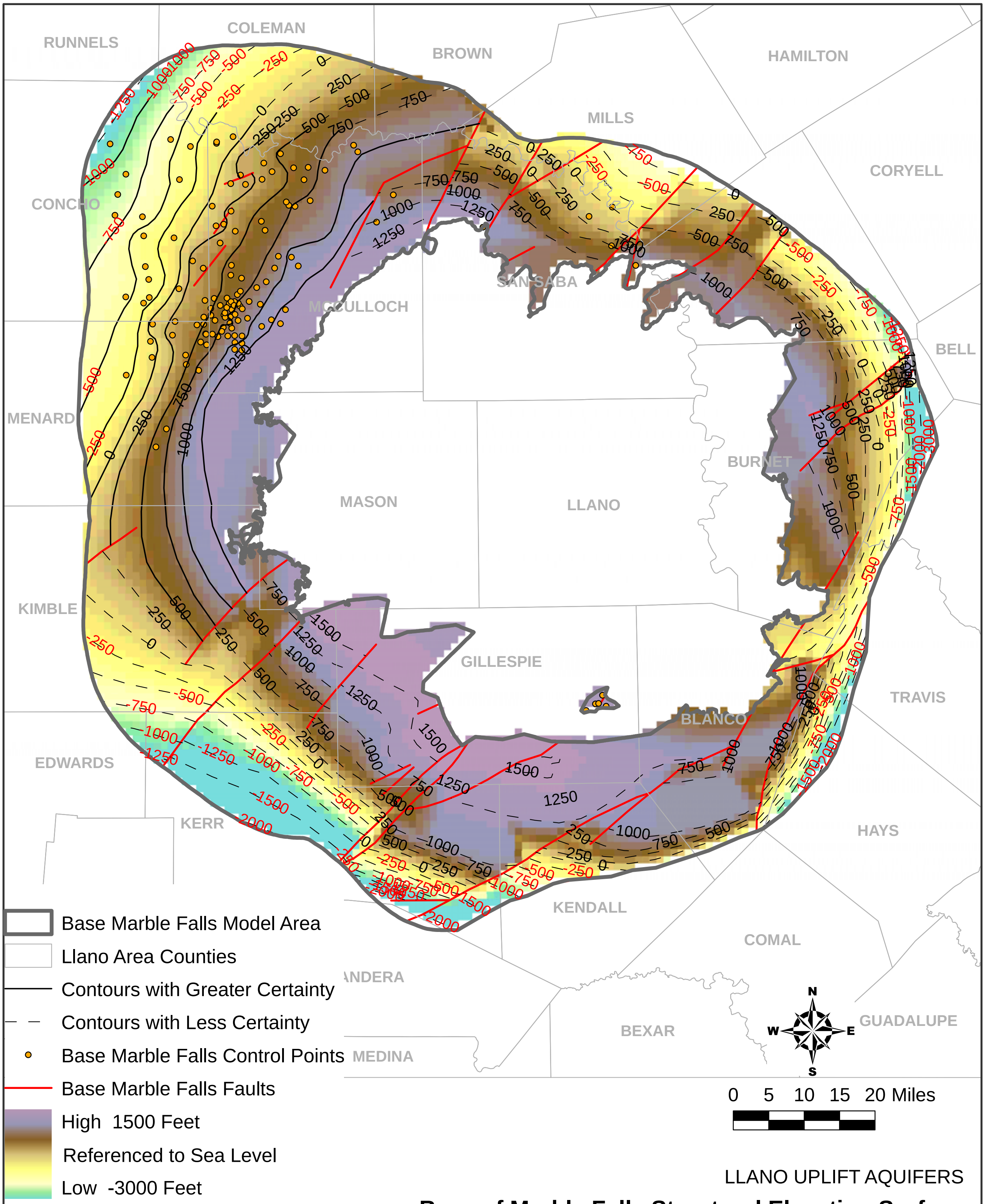
Figure 9



LLANO UPLIFT AQUIFERS

Base of Marble Falls Structural Elevation Surface with Contours, Faults, and Control Points

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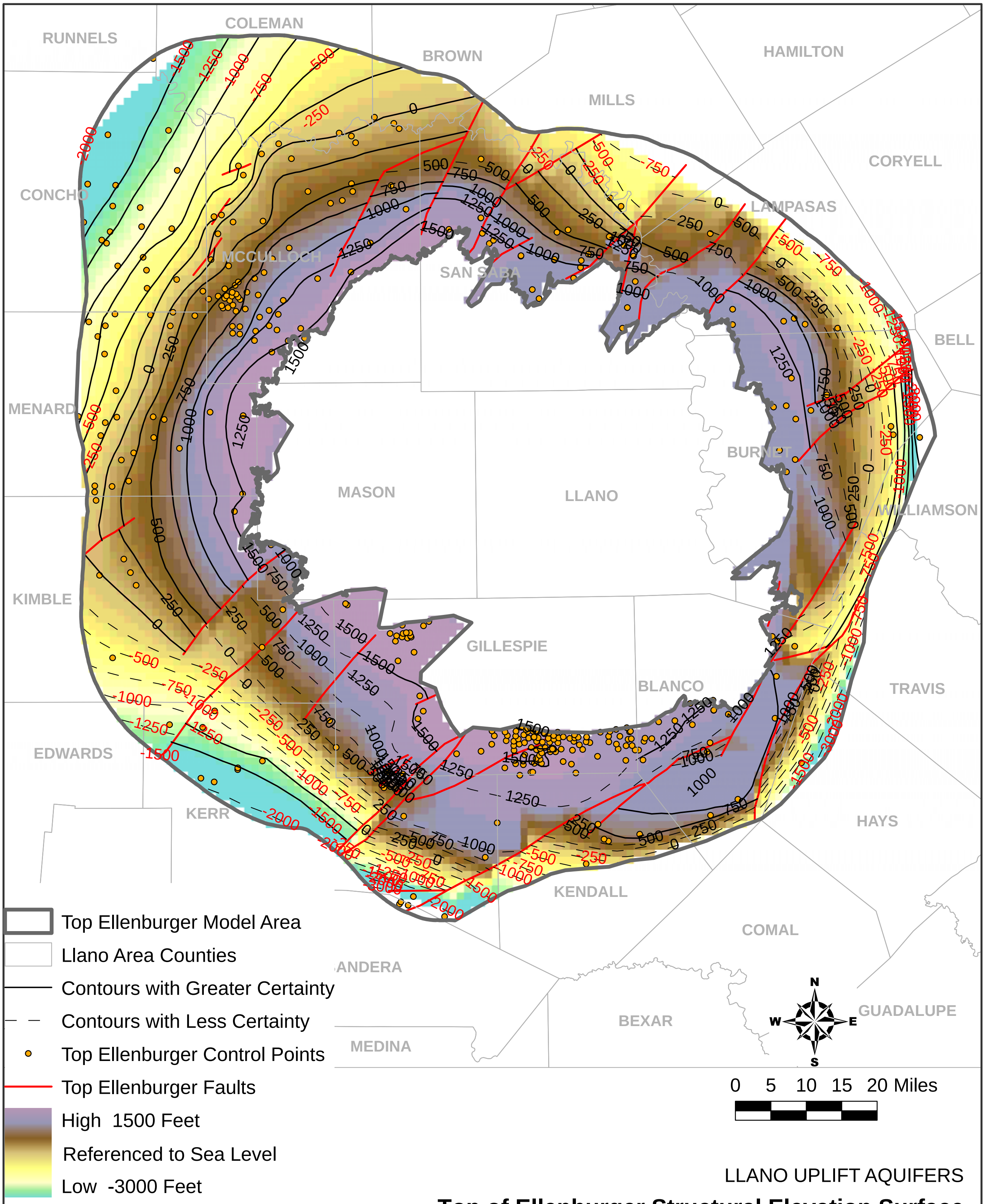
Figure 10



LLANO UPLIFT AQUIFERS

Top of Ellenburger Structural Elevation Surface with Contours, Faults, and Control Points

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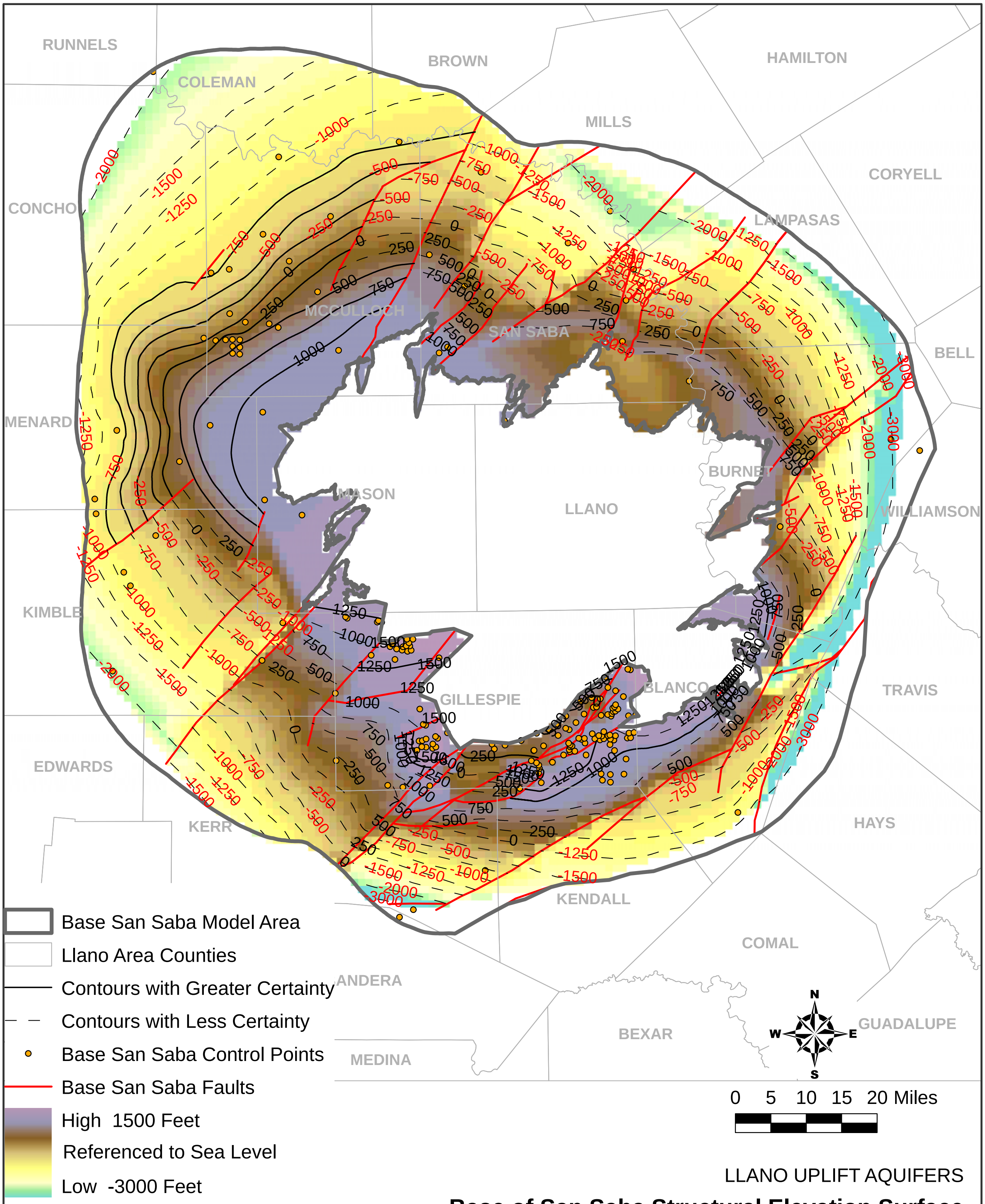
Figure 11



LLANO UPLIFT AQUIFERS

Base of San Saba Structural Elevation Surface with Contours, Faults, and Control Points

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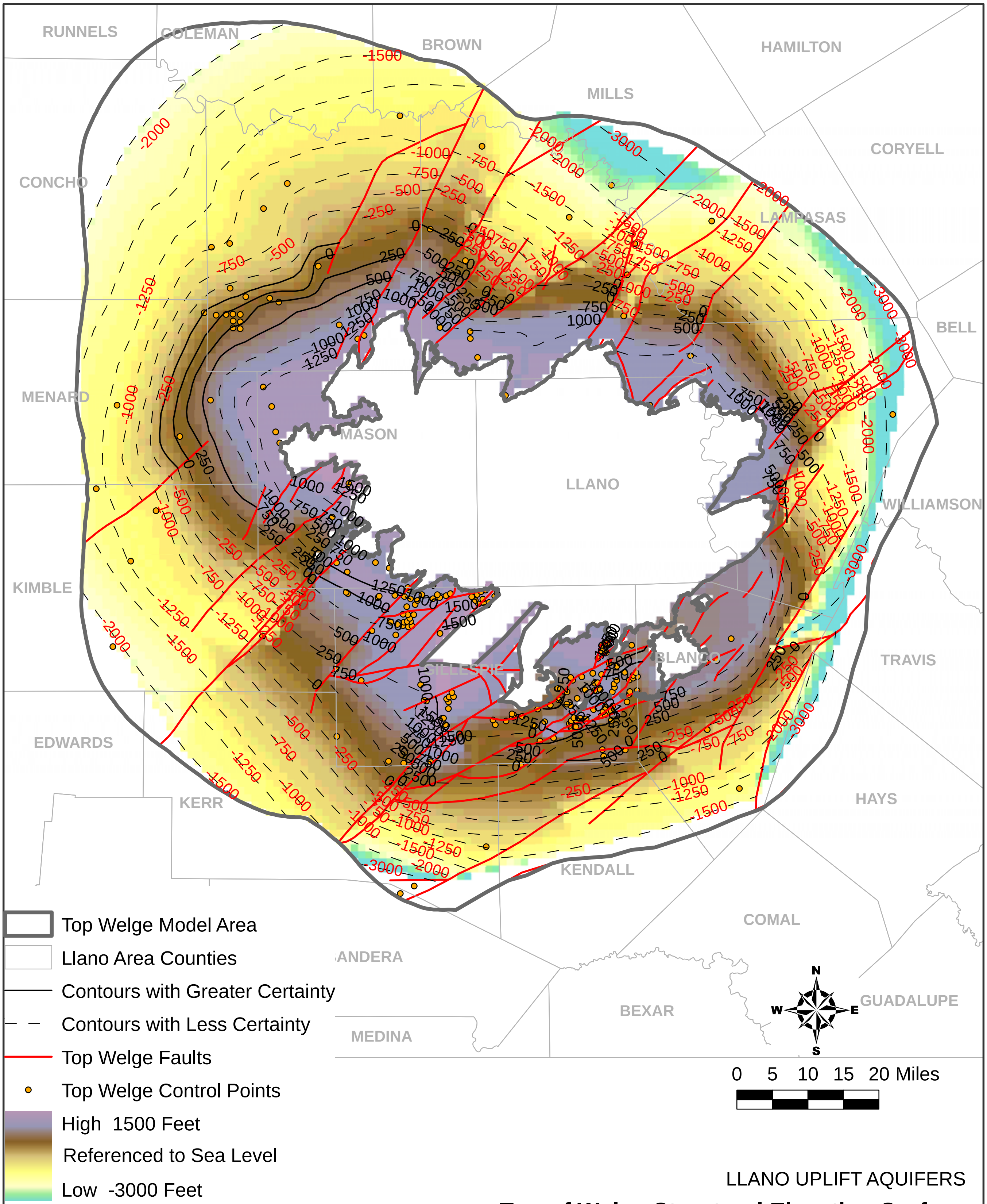
Figure 12



LLANO UPLIFT AQUIFERS

Top of Welge Structural Elevation Surface with Contours, Faults, and Control Points

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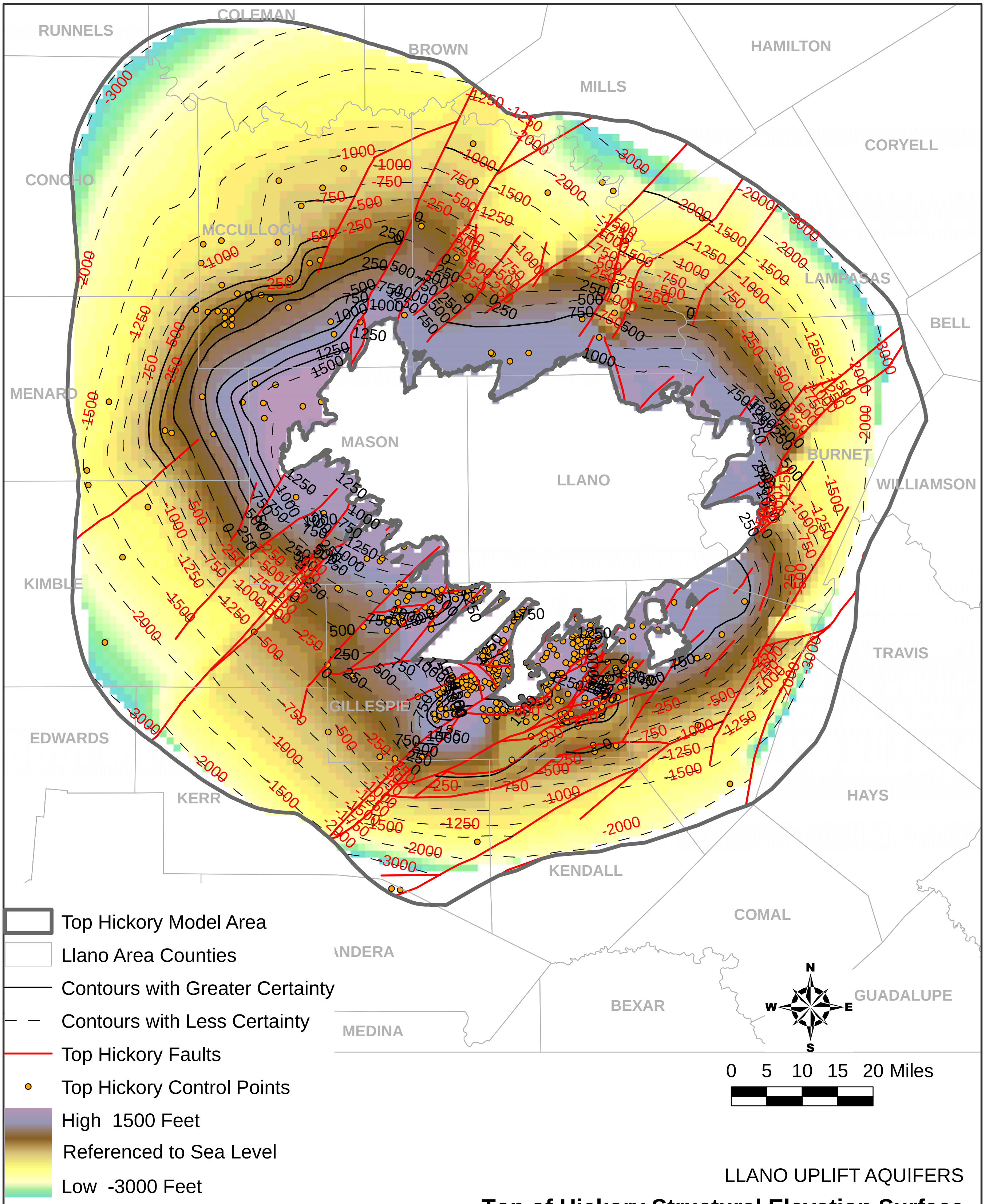
Figure 13



LLANO UPLIFT AQUIFERS

Top of Hickory Structural Elevation Surface with Contours, Faults, and Control Points

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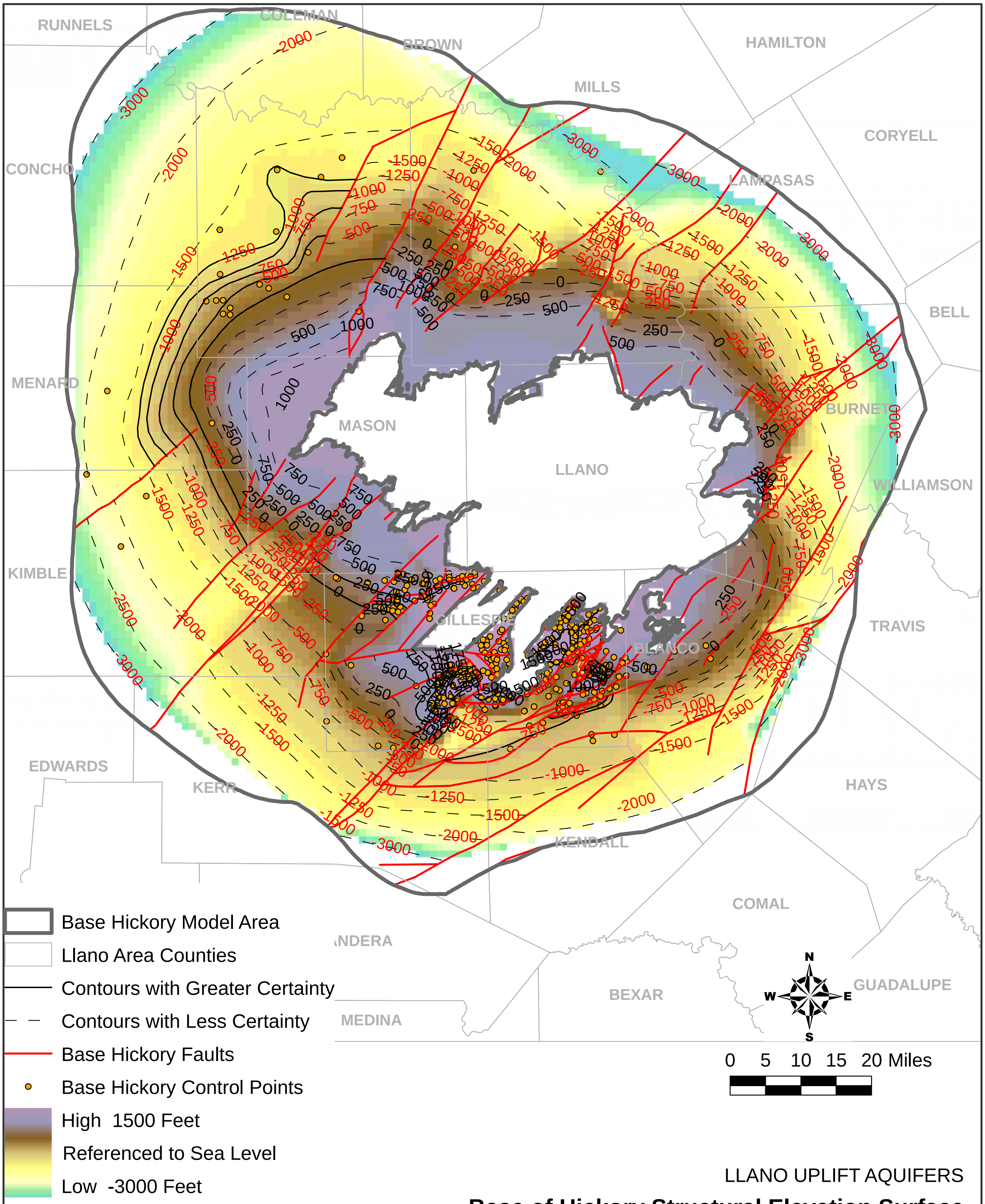
Figure 14



LLANO UPLIFT AQUIFERS

Base of Hickory Structural Elevation Surface with Contours, Faults, and Control Points

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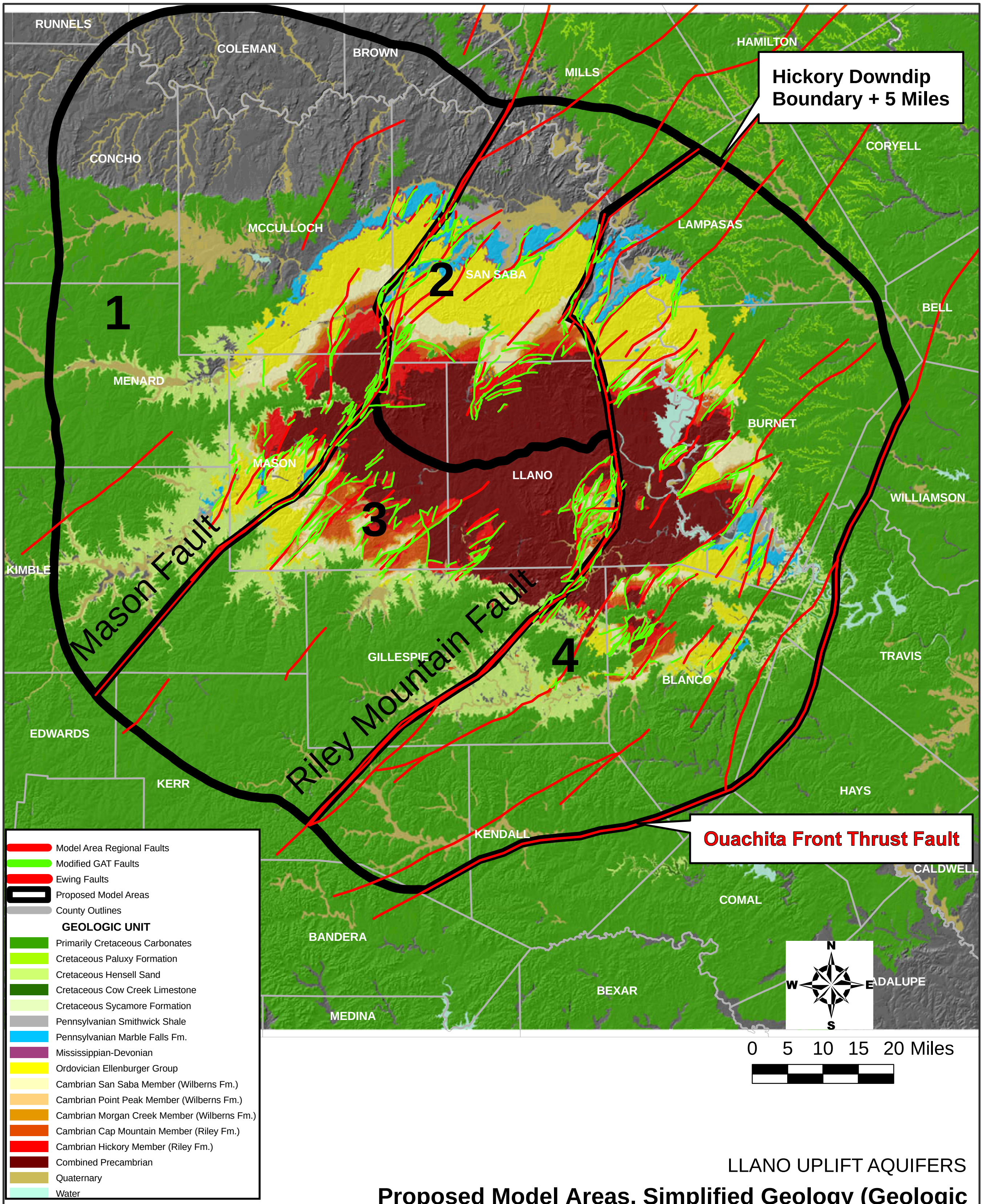
Figure 15



LLANO UPLIFT AQUIFERS

Proposed Model Areas, Simplified Geology (Geologic Atlas of Texas, GAT), Major Faults and GAT Faults

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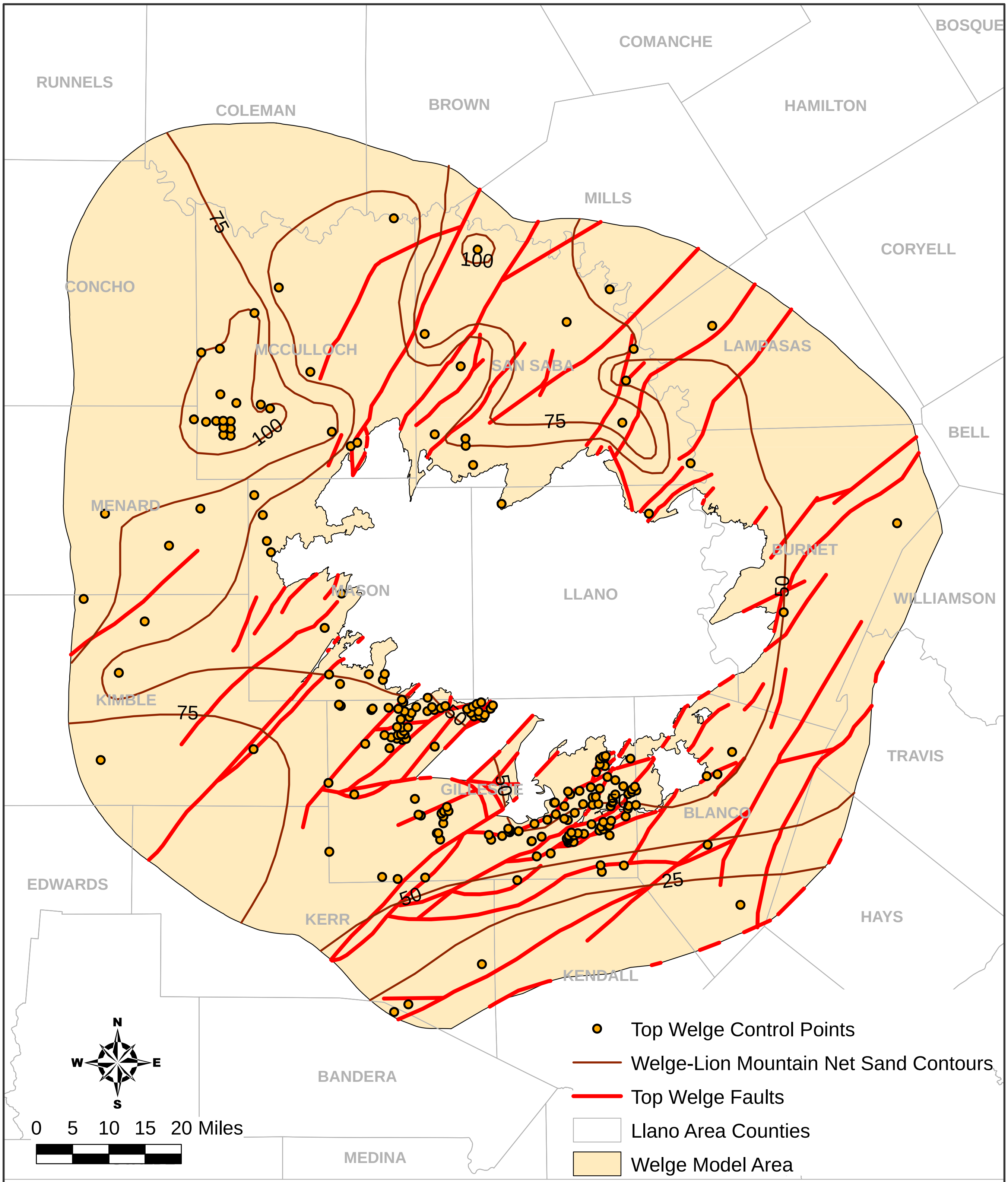
Figure 16



LLANO UPLIFT AQUIFERS

Welge - Lion Mountain
Net Sand Contours

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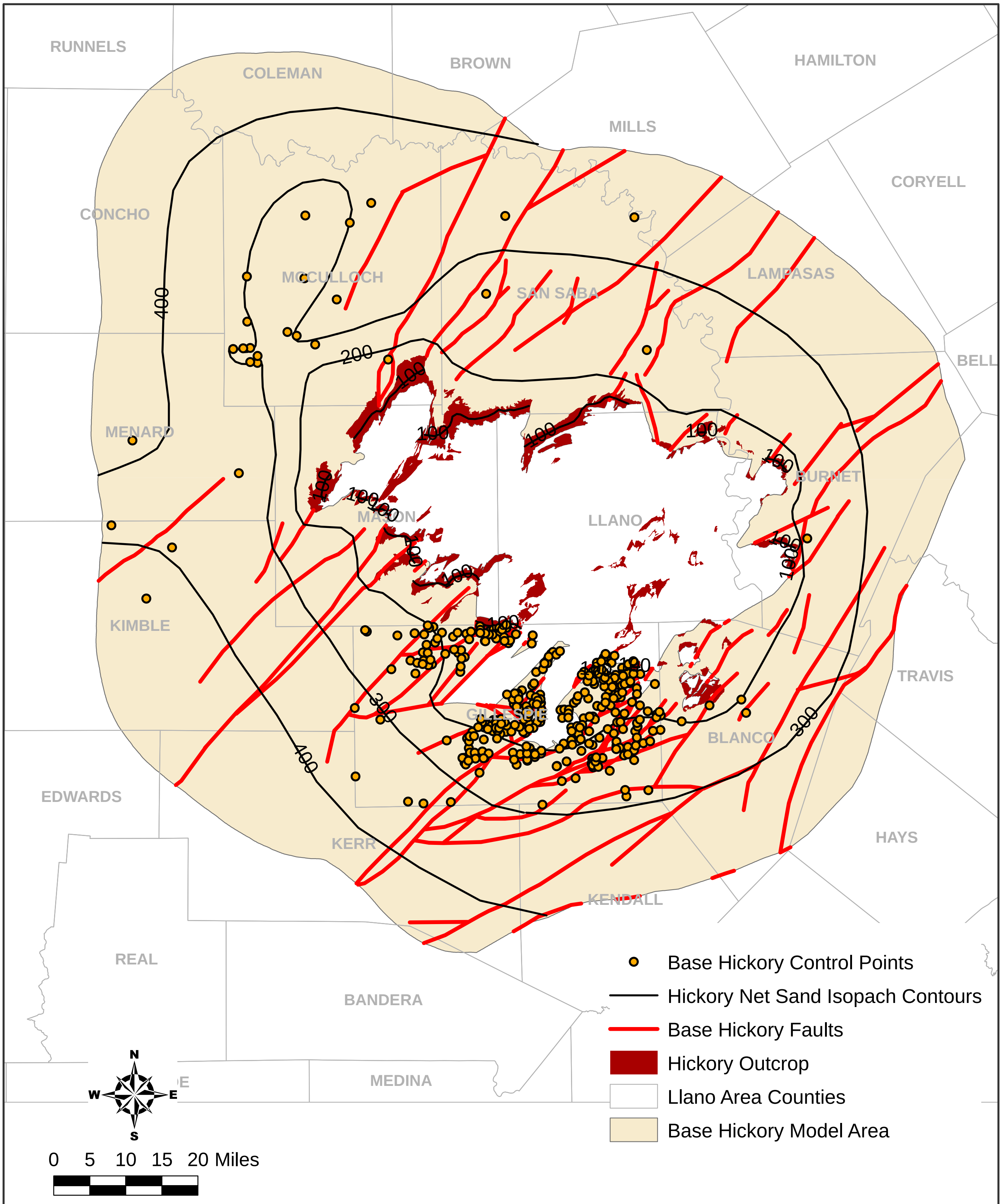
Figure 17



LLANO UPLIFT AQUIFERS

Hickory Net Sand Contours

Figure 18

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Table 1. Structural Summary of Proposed Model Areas

Characteristic	Proposed Model Areas			
	1	2	3	4
Boundaries	Mason Fault to east	Riley Mountain Fault to east; Mason Fault to west	Riley Mountain Fault to east; Mason Fault to west; steep dip of Ouachita downwarp to south	Riley Mountain Fault to west and to northwest; steep dip of Ouachita downwarp to east; steep dip of Ouachita downwarp to east and south (Johnson, 2004) in subthrust section
Overall faulting intensity	Least faulted; basically one large block (20 miles wide at outcrop), increasing to the south	Moderate; three broad blocks comprised in one larger graben	Moderate but more than Area 3	Highly faulted, with faulting increasing to the south
Internal faults	Short, small offset; extremely little cross-faulting most distant from uplift point (Region 4); more numerous faults to the south	Little cross-faulting	Little cross-faulting	Major downthrown toward coast block (southeast-down); southeast-down faults thrown 3,000+ feet (Johnson, 2004); moderate to extreme cross-faulting at uplift point in southern half of area
Predominant fault dip	Northwest-down	Northwest-down	Northwest-down	Northwest-down to Riley Mountain Fault (northern and western); southeast-down (southern and eastern)
Horst-graben pattern	Mostly within 20 miles of Mason Fault and longer than in Area 6, subparallel (northwest-southeast) to Mason Fault, more small grabens to the south	Three broad blocks (each 5 to 9 miles wide) stepwise downdropping (approx. 500 feet per step) from Riley Mountain Fault west toward Mason Fault; northwestern-most graben deepest	Grabens deepen toward the northwest; deepest against the Mason Fault, preserving more young section	Grabens deepen toward the north, deepest against the Riley Mountain Fault, preserving more section in southeast and south. Alternating horst-graben pair within 1 mile; oldest rocks (Precambrian) in core of grabens; outcrop becomes younger toward northeast and also to southeast away from uplift center
Interpretation	Distant to uplift focus; area of deeply eroded Ellenburger (Johnson, 2004, Fig. 4) likely axis of forebulge during flexuring phase (Edwards Arch, Ewing, 2004 and Johnson, 2004)	Somewhat distant to Uplift focus, larger graben like Areas 3 and northern 4	Lateral to area of uplift focus, larger graben like Areas 2 and northern 4	In southeast and northwest, lateral to area of uplift focus, larger graben like Areas 2 and 3. To the southeast, focal uplift; uplift of Precambrian rocks, oldest in core of grabens

Appendix A. Geo-referencing and Location Verification

Location work began with geo-referencing 18 cross section maps from the Bureau of Economic Geology (BEG), Texas Water Development Board (TWDB) and consultant reports (Barnes and others, 1959 and 1977; Bluntzer, 1992; Flawn and others, 1961; Morey, 1955; Tybor, 1993, 1995; Wilson, 2005). Once entered, well points or columnar section points could be digitized and attributes entered. Cross section points were initially assigned an accuracy value of 2. This value would be later updated if the point had to be relocated or additional geographic information was found. The number of each cross section was entered into the CRS_SECT_N column and the source of the cross section SOURCE_ref column in the GIS geo-database.

The next step was to enter location points for scout tickets and drillers' reports. To do this, the team would attempt to locate the well using any land survey, attached map, or directional information provided on each report or ticket. In rare cases, latitude and longitude values were given. Most often, however, the team used the given information and attempted to locate the point in ArcMap using the state well grid layer, county survey data, and county roads. If the report or ticket had sufficient information to locate the point, it was digitized and then assigned an accuracy value from 1 to 3 based on the detail level of the location information provided.

Location accuracy values were assigned to each point in the database:

- A value of 1 corresponds to those points that were plotted using latitude and longitude from sources such as drillers' reports and geophysical logs, the Hill Country UWCD database wells, and the BEG geophysical logs. It represents an estimated location error of less than ½-mile radius.

- A value of 2 was initially assigned to most points digitized from geo-referenced cross sections and many points entered from scout tickets and drillers' reports. It represents an estimated location error between ½ and 1 mile radius.

- A value of 3 represents a location error of 1 to 1.5 miles and was assigned to points that the team had difficult locating with any accuracy.

To verify elevations, a 30-meter digital elevation model (DEM) was added and geo-referenced for the study area to allow the team to extract DEM elevation values for all points that fell within its boundaries. These values allowed the team to check the accuracy of the elevation recorded on the geophysical log, driller's report, or scout ticket, if provided, against the DEM elevation for that location. Additionally, these values would later play a critical role in point relocation. Locations outside the boundaries of the study area DEM were determined by using Google Earth™ after location issues had been resolved, and the elevation from Google Earth™ was entered into the spreadsheet as the DEM elevation value.

DEM elevations extracted from the point locations were compared to the recorded elevation on the geophysical log, driller's report, or scout ticket. The team determined that differences greater than 20 feet had to be addressed in some fashion. In some cases, no elevation had been given for the point so no correction was required for that point. However, the DEM elevation for those points should be considered only as accurate as the point location itself. If the difference between the recorded value and the DEM value was greater than 20 feet, the point was relocated spatially in ArcMap to an area close to the original location that matched the original elevation value. In the case of point relocations, the accuracy value for the location was lowered by a factor of one unless it was already at the lowest value.

Columnar sections and composite columnar sections (mapped outcrops) posed a different problem. Some columnar sections were treated as wells on the cross sections with depth to unit interfaces given as if the point had been drilled. This is only a virtual depth since the columnar sections were mapped from outcrop bottom to top. Other columnar sections began with a basal value of zero and increased from there to the top of the section. In both cases, the amount of section presented often exceeded the amount of relief actually present in the study region. Further, the composite columnar sections were pieced together as one unit on the cross section but had actually been mapped from several separate locations to create a generalized section for an area.

The team decided to use only the basal section of each composite section for picking unit tops and bottoms. Though upper units appeared to be present, the team often had no way of knowing the location from which the upper units were mapped or the starting elevation of the upper units. In cases where the geo-referenced cross section maps gave locations for each portion of the composite section, the point for that location was moved to correspond with the basal unit and DEM elevations extracted for that location. Elevations with respect to sea level for unit interfaces within that basal unit were then derived using the new DEM values as the base of the outcrop from which the columnar section was mapped.

Other location issues are the vintage differences of some of the data gathered from the Texas Water Development Board (TWDB) and other sources and scale issues with some of the cross section maps. If gathered data were referenced to the NAD 27 datum versus the NAD 83 datum, this would cause some error in the point location and, thus, an error margin between any given elevation and elevation extracted from the DEM. Map scaling issues arose because some geo-referenced cross sections (specifically from Flawn and others [1961, Plate 2] and Barnes and others [1959, 1977]) were of such a small scale that when brought into ArcMap and geo-referenced, it became difficult to pick the correct point when viewed at a large scale. The team worked to match point locations in ArcMap to those given in the source data by comparing given elevation values for the points and the DEM elevation values in the area. These points were assigned a lower location accuracy value.

Appendix B. GeoDatabase Construction
(Final Llano_Point_File)

B.1 Data Screening Criteria

Selected data for the database were originally entered into an Excel spreadsheet, which was imported into the GIS geodatabase (Final_Llano_Point_File); this original Excel spreadsheet has subsequently undergone numerous iterations and corrections. Most of the work in building the spreadsheet involved simple data capture from picked units or entering source information. Unit tops and bottoms were entered from cross sections or from drillers' reports, and scout tickets if units were specifically broken out on the latter two. The team picked tops and bottoms from geophysical log points using correlation techniques, and these picks were also entered into the spreadsheet. Columnar section picks were entered "as-is" from the cross sections. If the columnar section point was not an elevation, elevations with reference to sea level were later derived by beginning at the bottom of the mapped section, using the DEM elevation for that point, and adding the footage of rock above that base for each pick.

DEM elevations from the 30-meter DEM were extracted for each point that lies within its boundaries. These were the elevation values used to calculate top and bottom elevations with reference to sea level for each applicable unit pick. If an elevation pick for a top or bottom of a unit was given from the source, those numbers were adjusted according to the difference between the DEM elevation and the given elevation.

The Unit Source column was added to the spreadsheet to keep track of whether the original values for the point picks were depths or elevations. Using this, the user can perform his/her own calculations to either ascertain elevation with reference to sea level for the top or bottom or determine at what depth the driller encountered the unit. An entry of "depth" indicates that the original data is depth to unit. An entry of "Elev" indicates that the original data was the top or bottom with reference to sea level. If elevation values were initially given for unit tops and bottoms, the DEM surface elevation was used to back-calculate depth to unit in that well.

The columns labeled CS_SP_1, CS_SP_2, and CS_SP_3 were meant to serve as a way to cross-reference any points that were used in multiple cross-sections. In this manner, the user can determine which points were used on multiple sections and then reference those sections to determine the context of the point. The last number is simply a repeat of the cross section from which the point was initially digitized.

Originally, 18 cross-sections were scanned and georeferenced. Each cross-section location was examined for pertinent data, specifically, for any unit picks that are part of this study. After the DBS&A team had reviewed the data quality and had established the downdip extent of the model area (TWDB Hickory downdip plus 5 miles), only 15 cross-sections were used for this report. Those data were captured and later brought into ArcMap. An assumption made by the team in dealing with these points is that the top of the Paleozoic is equivalent to the base of the Cretaceous.

Points digitized from cross-section, scout tickets, and driller’s Reports originally had survey or location descriptions associated with them. The team used ArcMap to determine X and Y coordinate values for these points once they had been digitized. These points were then reprojected in a layer using the NAD 83 decimal degree geographic coordinate system, which allowed the team to determine latitude and longitude values for these points. In the case of the points that were brought into ArcMap using the provided latitude and longitude values, the team used ArcMap to determine X and Y GAM values for these points. Thus, each point used in the project has both X and Y GAM coordinates and latitude/longitude decimal degree coordinates.

B.2 Quality Assurance of Database

Quality assurance (QA) and quality control (QC) were ongoing during the construction of the geodatabase. Daily comparisons of data were made between the most current dataset and reference databases to catch any sorting errors that might have occurred. The comparisons were made by copying several columns, such as ID, LAT, DEM_ELEV, and T_HICK_EL, from both sets of data into a new spreadsheet and comparing them to ensure that the data entered for each unique ID number matched both data sets.

Removal of duplicate entries was another QA/QC check performed by the team. The team already recognized that duplicate points existed for the cross sections and removed the duplicates for those points that had the least value informationally, spatially, or both. Duplicates were also found by sorting the data by the Total Depth column. If duplicates were found in this column, the rest of the data for those points was examined. If those points were found to be duplicates, the one with the least information was deleted from the database. Finally, once map generation began in earnest, duplicate entries began to show up that had been missed in earlier checks. In this case, the team used ArcMap to query those points and delete the one with the least value if they were duplicates.

The generation of structural contour maps provided another layer of QA/QC for the team. Anomalies identified during contouring were investigated in ArcMap. In some cases, data density in the area in question was sufficient to exclude the anomalous point and it was removed from the database. In other cases, data from that point for only that specific unit was removed because the point contained data for other formations that did not appear to be anomalous. A third, rarer instance occurred when the point in question was in a region with sparse data. Often, that point only had data for that one specific formation and that was the data in question. In this case, the point was removed from the database.

A final QA/QC check came when the team calculated thicknesses of the Marble Falls, Ellenburger-San Saba, Welge-Lion Mountain, and Hickory aquifers. Using the elevation values for the top and bottom of each formation or package, the team subtracted the base from the top in ArcMap using the Field Calculator. It was anticipated that this calculation would result in all positive values, and it did, indicating that none of the bottom picks had a higher elevation with reference to sea level than the top pick. Note that if the unit did not have a top or bottom pick, thickness could not be calculated.

Appendix C. GIS Attribute Definitions

C.1 Point Files

Data Sources:

- Final_Llano_Point_File
- Base_Marble_Falls_Control_Points
- Top_Ellenburger Control_Points
- Base_San_Saba_Control_Points
- Top_Welge_Control_Points
- Top_ Hickory_Control_Points
- Base_Hickory_Control_Points
- Hickory_Net_Sd_Points
- Welge_Net_Sd_Points

All of the GIS files have the same attributes with the exception of the Final_Llano_Point_File, which has one additional attribute: data confidence (DAT_CONFD)

Attribute	Definition
ID	Unique identification number assigned to that point
DAT_CONFD	Overall confidence level of geological interpretation and general reliability of the data: 1 = high confidence level 2 = moderate confidence level 3 = acceptable confidence level
LAT	Latitude in decimal degrees
LONG	Longitude in decimal degrees
GAM_X	The X-coordinate position in GAM projected coordinate system.
GAM_Y	The Y-coordinate position in GAM projected coordinate system.
ACCUR	The Accuracy Value assigned to that point’s location on a scale of 1 to 3 where 1 is accurate to less than a ½-mile radius, 2 is accurate to within ½ to 1 mile radius, and 3 is accurate to within 1 to 1.5 mile radius.

Attribute	Definition
CRS_SECT_N	Cross section number. The number assigned by the team to the cross section from which that point was taken.
SOURCE_REF	The source or reference that provided information about that specific point.
CS_SP_1, 2, 3	If the cross section point is used by multiple cross sections, the other cross section numbers are listed here with the original cross section number repeated as the last value.
CS_DIR	Cross section direction. The general trend of the cross section using compass directions.
COUNTY	The county in Texas where the point is located.
COLUMR_SEC	The name of the applicable columnar section for that point from the cross section.
OP_WELL_NO	The operator and well number of that well.
ELEV	The given elevation with reference to sea level for that point from its source data.
ELEV_CODE	Elevation code: A code assigned to indicate what the elevation value references. Codes are: GL = ground level DF = drilling floor outcrop = outcrop base elevation est = elevation estimated by source GL_DEM = ground level from DEM (if point lies within DEM)
DEM_ELEV	Elevation with reference to sea level for that point extracted from the DEM based on that point's location.
TD	Total depth of well, if given.
UNIT_SRC	Unit source: A column that indicates whether the tops and bottoms for that point were originally depth to unit (Depth) or elevation referenced to sea level (Elev).
B_K	Depth to base of Cretaceous
B_K_EL	Elevation with reference to sea level to the base of the Cretaceous.
T_SMITH	Depth to top of the Smithwick Formation.
T_SMITH_EL	Elevation with reference to sea level to the top of the Smithwick Formation.

Attribute	Definition
B_SMITH	Depth to base of the Smithwick Formation.
B_SMITH_EL	Elevation with reference to sea level to the base of the Smithwick Formation.
T_MRBFA	Depth to top of the Marble Falls Formation.
T_MRBFA_EL	Elevation with reference to sea level to the top of the Marble Falls Formation.
B_MRBFA	Depth to base of the Marble Falls Formation.
B_MRBFA_EL	Elevation with reference to sea level to the base of the Marble Falls Formation.
T_BARN	Depth to top of the Barnett Formation.
T_BARN_EL	Elevation with reference to sea level to the top of the Barnett Formation.
B_BARN	Depth to base of the Barnett Formation.
B_BARN_EL	Elevation with reference to sea level to the base of the Barnett Formation.
T_ELBG	Depth to top of the Ellenberger Formation.
T_ELBG_EL	Elevation with reference to sea level to the top of the Ellenberger Formation.
B_ELBG	Depth to base of the Ellenberger Formation.
B_ELBG_EL	Elevation with reference to sea level to the base of the Ellenberger Formation.
T_ELBG_TWD	Depth to the top of the screen of the Ellenberger from the TWDB database.
T_SSAB	Depth to top of the San Saba Formation.
T_SSAB_EL	Elevation with reference to sea level to the top of the San Saba Formation.
B_SSAB	Depth to base of the San Saba Formation.
B_SSAB_EL	Elevation with reference to sea level to the base of the San Saba Formation.
T_POPK	Depth to top of the Point Peak Formation.

Attribute	Definition
T_POPK_EL	Elevation with reference to sea level to the top of the Point Peak Formation.
B_POPK	Depth to base of the Point Peak Formation.
B_POPK_EL	Elevation with reference to sea level to the base of the Point Peak Formation.
T_MRGCRK	Depth to top of the Morgan Creek Formation.
T_MRGCRK_L	Elevation with reference to sea level to the top of the Morgan Creek Formation.
B_MRGCRK	Depth to base of the Morgan Creek Formation.
B_MRGCRK_L	Elevation with reference to sea level to the base of the Morgan Creek Formation.
T_WELG	Depth to top of the Welge Formation.
T_WELG_EL	Elevation with reference to sea level to the top of the Welge Formation.
B_WELG	Depth to base of the Welge Formation.
B_WELG_EL	Elevation with reference to sea level to the base of the Welge Formation.
T_LIMTN	Depth to top of the Lion Mountain Formation.
T_LIMTN_EL	Elevation with reference to sea level to the top of the Lion Mountain Formation.
Wlg_LM_Net	Net sands for the Welge-Lion Mountain package.
B_LIMTN	Depth to base of the Lion Mountain Formation.
B_LIMTN_EL	Elevation with reference to sea level to the base of the Lion Mountain Formation.
T_CPMTN	Depth to top of the Cap Mountain Formation.
T_CPMTN_EL	Elevation with reference to sea level to the top of the Cap Mountain Formation.
B_CPMTN	Depth to base of the Cap Mountain Formation.

Attribute	Definition
B_CPMTN_EL	Elevation with reference to sea level to the base of the Cap Mountain Formation.
T_HICK	Depth to top of the Hickory Formation.
T_HICK_EL	Elevation with reference to sea level to the top of the Hickory Formation.
B_HICK	Depth to base of the Hickory Formation.
B_HICK_EL	Elevation with reference to sea level to the base of the Hickory Formation.
T_HICK_TWD	Depth to the top of the screen of the Hickory from the TWDB database.
Hick_Net_S	Net sands for the Hickory Formation.
T_PCAMB	Depth to top of the pre-Cambrian.
T_PCAMB_EL	Elevation with reference to sea level to the top of the pre-Cambrian.
COMMENT	Comments that are pertinent to that point.
HICK_ISO	Thickness, in feet, of the Hickory Formation for that point.
MRBFA_ISO	Thickness, in feet, of the Marble Falls Formation for that point.
ELSS_ISO	Thickness, in feet, of the Ellenberger-San Saba package for that point.
WLG_LM_ISO	Thickness, in feet, of the Welge-Lion Mountain package for that point.

C.2 Polyline Files

C.2.1 Fault Files, Structural Contouring

- Base_Marble_Falls_Faults
- Top_Ellenburger_Faults
- Base_San_Saba_Faults
- Top_Welge_Faults
- Top_Hickory_Faults
- Base_Hickory_Faults

Attribute	Definition
SOURCE	Aquifer structural elevation contours in which were used with the faults
AQUIFER	Aquifer system
SHAPE_LENGTH	Length of fault in feet

C.2.2 Fault Characteristics Files

Modified_GAT_Faults

Attribute	Definition
FAULT_CD	1 = unspecified, 2 = normal
LNGTH_MILE	The length of the fault trace in miles, determined by taking SHAPE_LENG and dividing by 5,280
THROW_EST	This is the resultant calculation in feet of estimating the fault throw or displacement using Schlische and others 1996 formula based on the mapped length of the fault;
D (fault displacement)	0.03L (length of fault) $^{1.06}$ The length of the fault was obtained from SHAPE_LENG.
MDL_AREA	The study area was subdivided into four proposed model areas (Figure 16) based on similarities of geology and structural characteristics.
FORM_IMP	Determined by observing the geology on both sides of the GAT_fault using the digital GAT geology
SOURCE	Source of digital data either Brownwood or Llano GAT sheet
AREA_DIP	Determined by qualitatively determining the dominant dip direction of the faults and fault blocks within a model area (Figure 16)
TYPE	Fault type, normal or thrust
SHAPE_LENG	Length of fault in feet

C.2.3 New Subsurface Fault Characteristics Files

- Marble_Falls_Fault_Attrib
- Hickory_to Ellen_Fault_Attrib files

Attribute	Definition
AQUIFER	aquifer system
SOURCE	aquifer fault files included
MODEL_AREA	The study area was subdivided into four proposed model areas (Figure 16) based on similarities of geology and structural characteristics.
FLT_TYPE	Fault type, normal or thrust
EST_FLT_DI	Estimated fault displacement, in feet, determined by using both structural contours and posted control point structural surface elevations
EST_DIP_DI	Determined by qualitatively determining the dominant dip direction of the faults and fault blocks within a model area (Figure 16)

C.2.4 Structural Elevation Contour Files

- Base_Marble_Falls_Contours
- Top_Ellenburger_Contours
- Base_San_Saba_Contours
- Top_Welge_Contours
- Top_Hickory Contours
- Base_Hickory_Contours

Attribute	Definition
ELEV	Elevation of structural contour
TYPE	Certainty (or confidence level) of structural contour interval 1 = greater certainty 2 = lesser certainty

C.2.5 Net Sand Isopach Contours

- Welge_LM_Net_Sd_Isopach_Contours
- Hickory_Net_Sd_Isopach_Contours files

Attribute	Definition
CONT_THK	Thickness on net sand in feet
RELIABIL	Reliability (or confidence level) of structural contour interval 1 = greater confidence 2 = lesser confidence

C.3 Polygon Files

Model_Areas file

Attribute	Definition
AREA_NAME	The study area was subdivided into four proposed model areas (Figure 16) based on similarities of geology and structural characteristics. Areas are numbered 1 through 4

Appendix D. Llano Uplift Structure and Stratigraphy, Central Texas (TWDB Contract #0604830614)

By Daniel B. Stephens & Associates, Inc

Review by Roberto Anaya, Doug Coker and Cindy Ridgeway.

General comments

Please seal the document, appropriate figures, and follow the protocol for geoscience related work in Texas to comply with the Texas Board of Professional Geoscientists rules and regulations per http://www.tbpg.state.tx.us/chapter-851c.html#6 §851.156. Geoscientist's Seals, subsection (i) and (j).
Response: Seals of authors and major contributors are provided on the continuation of the title page; principal authors' names appear on the title page.

Please make sure data provided in Appendix B is cross-referenced in geodatabase as metadata.
Response: Metadata provided in geodatabase (Structural_Surfaces.mdb).

Please verify that all attribute fields are defined in the metadata.
Response: Metadata provided in geodatabase (Structural_Surfaces.mdb).

If scanned images of geophysical logs are not included, please provide enough information in the appropriate Llano_Point_File so TWDB staff has sufficient information to acquire original logs.
Response: Geophysical logs included on DVD, Llano_Uplift_Structure_&_Stratigraphy, as .TIF image files (Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160).

Technical comments:

Please list author names instead of company name on cover and title page.
Response: Author names included on continuation of title cover (seal page) and included more clearly on the enclosed Adobe Acrobat PDF of the text report.

Section 2.1.1, page 2, paragraph 1, 3rd sentence: References Mosher (2005). Please update References section with this citation or adjust the year in the text to agree with the citation listed in the References section of the report.
Response: Deleted. Reference to Mosher (2004) corrected in text.

Section 2.1.1, page 2, paragraph 1, 4th sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text as Barnes and Bell (1977).

Section 2.1.1, page 2, paragraph 2, 1st sentence: References Ewing (2005). Please update References section with this citation or adjust the year in the text to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Ewing (2004).

Section 2.1.1, page 2, paragraph 2, 2nd sentence: References Johnson (2005). Please update References section with this citation or adjust the year in the text to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Johnson (2004).

Section 2.1.1, page 2, paragraph 2, 4th sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 2.1.1, page 2, paragraph 3, 1st sentence: References Long (2005). Please update References section with this citation or adjust the year in the text to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Long (2004).

Section 2.1.2, page 3, paragraph 1, 2nd sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 2.1.2, page 3, subsection Cambrian, Lion Mountain Member (Riley Formation), paragraph 1, 1st sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 2.1.3, page 4, subsection Cambrian, Welge Sandstone Member (Wilberns Formation), paragraph 1, 1st sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 2.1.3, page 4, subsection Cambrian, Morgan Creek Limestone Member (Wilberns Formation), paragraph 1, 1st sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 2.1.3, page 4, subsection Cambrian, Point Creek Shale Member (Wilberns Formation), paragraph 1, 1st sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 2.1.3, page 4, subsection Cambrian, San Saba Limestone Member (Wilberns Formation), paragraph 1, 3rd sentence: References Barnes (1977). Please update References section with this citation or possibly adjust the text to Barnes and Bell (1977), if appropriate, to agree with the citation listed in the References section of the report.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 3.1, page 8, paragraph 1, 1st sentence: States "A total of 1,162 subsurface locations were used to construct the geodatabase." Only 1,161 were actually found in the Llano point feature class. Please make correction to database or text.
Response: Updated in text more correctly as Barnes and Bell (1977).

Section 3.1, page 9, paragraph 1, 3rd sentence: States "only 154 geophysical logs were used" from BEG sources. The geodatabase contains 156 logs from BEG. Please make correction to database or text.
Response: The geodatabase has been updated with the correct wells labeled "BEG" and BEG logs are included in a folder on the DVD, Llano_Uplift_Structure_&_Stratigraphy, (Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160).

Section 3.1, page 9, paragraph 2, 2nd sentence: States "All relevant BEG and TWDB published reports were reviewed and maps were geo-referenced for GIS analysis. … 100 geophysical logs and 20 outcrop locations were identified and included into the geodatabase." No BEG or TWDB published report maps were found within the geodatabase nor were there 20 outcrop locations attributed or found within the geodatabase. Please make corrections to database or text.
Response: The geodatabase was corrected for relevant geophysical logs and other data. Surface data and geophysical logs were included in folders on the DVD, Llano_Uplift_Structure_&_Stratigraphy, (Logs: Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160; Geodatabase: Llano_Uplift_Structure_&_Stratigraphy\Structural_Surfaces.mdb).

Section 3.2, page 10: Discussion implies that three feature classes were developed -1) Modified_Geology_GAT, 2) Modified_GAT _Faults, and 3) Ewing_Faults_GAM. None of these feature classes were found within the geodatabase. Please provide these GIS data within geodatabase and appropriate metadata as applicable.
Response: The geodatabase has been reorganized to contain the feature class "Simplified_Geology" which is a modified Geologic Atlas of Texas (GAT) map, and from a feature dataset "Fault_Attribute_Dataset" the following three fault files: "Modified_GAT_Faults"containing information on faults largely outside the Precambrian outcrop, "Hick_to_Ellen_Fault_Attrib" specific to Hickory through Ellenburger surfaces, and "Marble_Falls_Fault_Attrib" specific to the Marble Falls interval. Metadata appropriate to each is included in the geodatabase.

Section 4, page 11, paragraph 2, 2nd sentence. Please correct the spelling of Ellenburger.
Section 4, page 11, paragraph 3, 5th sentence: States "A total of 665 well locations in Gillespie County were selected for this study." Only 664 were actually found in the Llano point feature class. Please make correction to database or text.
Response: The spelling of "Ellenburger" has become standardized in geologic literature and has been corrected in all references. The geodatabase has been corrected to include all germane Gillespie County wells.

Section 5, page 16, paragraph 3, last sentence, mentions six larger faults; however, Figure 4 only labels five: Mason, Riley Mountain, Darnoc, Marble Falls, and Ouachita Thrust faults. Please update figure 4 with the location of the sixth major fault. Also please cite Figure 4 in the text on page 16 regarding faults.
Section 5, page 16, paragraph 2, 3rd sentence. Johnson (2004), Figure 4. Should be Figure 3.

Please correct text.
Response: The use of non-standard names of faults has been corrected. All large-throw faults in the region are not within the study area, so not all are labeled. The important boundary faults to the modeling process are the Mason, Riley Mountain, and Ouachita Faults (Figure 16).

Section 6, page 18, paragraph 1, 1st sentence: Refers to Figure 4 for proposed model areas. Suggest creating a separate figure for these areas.
Response: The figure was separated and the proposed model areas appear in Figure 16.

Section 8: References two fault files (Modified_GAT Faults and Study_Subsurface_Faults) whereas Modified_GAT Faults and Study Ewing_Faults_GAM files are referenced in Section 3.2 and we received none of these data files. Please revise for consistency and provide the appropriate GIS feature class files and appropriate metadata as applicable.
Response: Three fault files (feature classes) are included in the Fault_Attribute_Dataset: Hick_to_Ellen_Fault_Attrib (attributes of Hickory, Welge, and Ellenburger aquifer faults), Marble_Falls_Fault_Attrib (attributes of Marble Falls aquifer interval), and Modified_GAT_Faults (attributes of the faults appearing on the Geologic Atlas of Texas (GAT) within the area bounded by the downdip edge of the Precambrian outcrop and updip of the Hickory aquifer downdip limit as defned by the TWDB expanded by three miles). Metadata for these feature class files is included in the geodatabase.

Section 8.2, page 21: Second sentence refers to Figure 5 in Gillespie County and "(proposed model area 4)" followed by more detailed discussion of complexity of unconformities. The detailed discussion also includes geology within proposed model area 6. Please revise text to include proposed model area 6.
Response: The geology of the revised four model areas is summarized in "Table 1, Summary of Proposed Model Areas" and discussed more fully in Section 6, "Proposed Model Areas", page 19.

Section 8.5, page 23 and Figure 7 source reference: Please use "and others" instead of "et al." in the citation for Schlische and others (1996).
Response: The use "and others" has been changed to "et al." in figures and references.

References, page 26: please resubmit References in alphabetical order, for example McGehee (1963) should appear after Mason (1961) and Schlische and others (1996) should appear before Schmittle (1987). Also please update the References Section with the citations listed in Figure 7.
Response: The "References" section has been resubmitted in alphabetical order and citations updated to be more complete.

Figure 1: Please spell out Geologic Atlas of Texas followed by the (GAT) acronym in the caption as figures should be able to stand alone from the text and also include source reference(s). In addition, please update the References section with the citation, if needed. Please clarify why the Welge Sandstone and Lion Mountain units were not combined in Figure1 as the text and Figure 2 suggest they were considered as one hydrogeologic unit for this study. Suggest regrouping formations and units in a manner consistent with the aquifers and confining units outlined in Figure 2.
Response: "GAT" has been expanded to "Geologic Atlas of Texas (GAT)" where possible. A correlation of geologic unit within the GAT map to aquifer unit studied is provided in revised Figure 2, "Study Area Stratigraphy". The geology of the aquifer units is discussed in the text from section 2.1.2 to 2.1.6.

Figure 2: Please use "and others" instead of "et al." in the citation, please update the References section with Preston and others (1996), please correct spelling of Honeycut, please expand the description of the Smithwick Shale Formation to include claystone, siltstone and sandstone to agree with text in Section 2.1.5 (pages 5-6), and please spell out "mod." in the description for the San Saba unit.
Response: These recommended changes have been made in Figure 2.

Figure 3: please footnote full spelling of abbreviations, such as “MYA” and “Miss.”and please update References section with Tybor (2006) or adjust the year in the figure to agree with the citation listed in the References section of the report.
Response: The abbreviations are removed and the Tybor reference is corrected in “References”.

Figure 3: Small inset figures are very difficult to read. Suggest placing them as separate figures and make appropriate changes to text in section 2.1.1.
Response: New Figure 4 inserts are referenced to full-sized Figures 3, 5, and 6 and the text is updated as appropriate.

Figure 4: Please spell out Geologic Atlas of Texas followed by the (GAT) acronym in the caption as figures should be able to stand alone from the text and also include source reference(s). In addition, please update the References section with the citation, if needed.
Figure 4: Please exclude “Proposed Model Area” from this figure as it does not pertain to Figure caption or text from which it is referenced. In addition, suggest making outer most boundary of proposed model areas coincide with down-dip aquifer extent(s) rather than with county boundaries.
Response: The acronym “GAT” has been spelled out where possible. The proposed model areas are displayed in Figure 16 and explained in Figure 16, page 19, using aquifer boundaries as suggested with the outer most extent of all aquifers assumed to be the TWDB downdip limit of the Hickory extended by three miles.

Figure 5: Please update References section with Tybor (2006) or adjust the year in the figure to agree with the citation listed in the References section of the report.
Figure 5: Small inset figures for C to C’ reconstruction is very difficult to read. Suggest placing it as separate figure and make appropriate changes to text in section 2.2.3. The inset map for lines of section would should be enlarged and placed outside of the actual cross section(s).
Response: References to Paul Tybor’s work have been updated, the reconstruction has been enlarged and updated for readability.

Appendix A: Please expand legend to include highways and roads. Also please clarify or simplify the statement in Section 5, page 14, paragraph 1, 1st sentence that states Appendix A is a map of the study area that is structurally contoured. The Appendix A map appears to be a map of the general study area and not a map that is structurally contoured.
Response: The study area is now provided in Figure 1 and excludes highways and roads. Structural contoured maps of the aquifers are provided in Figures 10 through 15.

Appendix B, page B-2, paragraph 2, 2nd sentence: Cites Flawn (1961). Please update References section with this citation or possibly adjust the text to Flawn and others (1961), if appropriate, to agree with the citation listed in the References section of the report.
Appendix B, page B-3, paragraph 3, 1st sentence. Please correct the spelling of Ellenburger.
Appendix B, pages B-5 and B-6. Please correct the spelling of Ellenburger.
Appendix B, page B-1, paragraph 1, 1st sentence: Refers to use of Excel spreadsheet as part of source data. This source data was not received by TWDB. Please provide as table within geodatabase or within a separate folder.
Appendix B, page B-2, paragraph 2, 1st sentence: Refers to 18 georeferenced cross sections as part of source data. This source data was not received by TWDB. Please provide as feature class within geodatabase and also the actual cross sections as image files or as digitized vector files.
Appendix B, page B-7: Refers to Modified_GAT Faults and Study_Subsurface_Faults feature classes. Please provide these GIS data sets within geodatabase and appropriate metadata as applicable.

Response: The information from Appendix B is now contained in Appendix A. “Ellenburger” is now consistently spelled. A geodatabase, “Structural_Surfaces”, containing the file “Final_Llano_Point_File”, the feature class of well information, is included in the data DVD. The georeferenced cross sections are included as image files (.tif) in the “Digital_Hardcopy” folder of the data DVD and the GIS location files as well points and vector files are contained in “Cross_Sections_Dataset”.

Appendix C, page C-1, paragraph 1, 1st sentence: Please review citations and adjust text or References Section, as needed.

Appendix C, page C-3, paragraph 2, 3rd sentence: Please review citations and adjust text or References Section, as needed.
Response: “References” section is corrected.

Appendix C, page C-1, paragraph 4, 1st sentence: Refers to 30-meter DEM. Please provide DEM within geodatabase raster catalog or as single raster and appropriate metadata as applicable.
Response: The 30-meter DEM is provided in the geodatabase as “Llano_DEM”.

Appendix D through Appendix M: Please update figures to comply with the Texas Board of Professional Geoscientists rules and regulations. Please include an outline of the estimated extent of the related aquifer. In other words, enclose the contours.
Response: Aquifer surfaces are contoured within the boundaries of their respective updip outcrop and all to the TWDB downdip extent of the Hickory aquifer plus a buffer of three additional miles.

Appendix H: Please clarify if the elevation of the top of the Welge Formation represents the correlation point between the San Saba and Point Peak units or the contact between the Morgan Creek and Welge Sandstone units.
Response: Aquifer boundaries and Geologic Atlas of Texas (GAT) correlations are provided in Figure 2.

Appendix I: Please clarify if the base of the Lion Mountain represents the correlation point between the Cap Mountain and Hickory Sandstone units or the contact between Lion Mountain and Cap Mountain.
Response: Aquifer boundaries and Geologic Atlas of Texas (GAT) correlations are provided in Figure 2.

Appendix L: Please clarify if the map Welge-Lion Mountain Net Sand Isopach Map also includes Point Peak, Morgan Creek, and Cap Mountain or just the Welge Sandstone and Lion Mountain units.
Response: Aquifer boundaries and Geologic Atlas of Texas (GAT) correlations are provided in Figure 2.

From CD: Geophysical logs – some tif images do not appear. Please correct.
04933356
04935052
08332803
09530408
09530655
09530804
09531045
09531117
09531194
09531212
09531354
09531443
19531618
19531649

Response: Geophysical logs are included in a folder as .TIF image files on the DVD, Llano_Uplift_Structure_&_Stratigraphy, (Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160).

Editorial comments:

Acknowledgements. Page v, paragraph 2, 3rd sentence: Sentence contains incomplete parenthesis, please revise sentence structure.
Please adjust capitalization of "counties" to lower case.
Response: These corrections have been made to "Acknowledgements".

Additional comments as per Statement of Qualifications

I.6. General Information

Page 1, 1st sentence: Will delineate structural features that impact groundwater flow.
No GIS data for structural features that impact groundwater flow were found as shown in Figures 4, 5, or 6. Please provide.
Response: Structural surface, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb).

2nd sentence: Will delineate the Welge and Lion Mountain members of the Moore Hollow Group.
No surface geologic delineations in geodatabase. Please provide.
Response: Structural surface, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb).

3rd sentence: Data collected and compiled will be integrated into ArcGIS in accordance with the recently developed GAM data model.
Incomplete, please see Task 5 below.
Response: Structural surface, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb).

II.2 Detailed Scope of Work

II.2.2 Scope of Work, Task 2 and 3 – Data Collection and Delineation of Structure.

Page 4, paragraph 1, 4th sentence: …..theses and dissertations….will be reviewed and pertinent data will be extracted and/or digitized.
No data from dissertations or theses found within the geodatabase. Suggest including any source data used from these sources in digital format.
Response: Appropriate structural surface, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb). Other image files are provided in the Digital_Hardcopy folder.

Task 5 – GIS/Database Implemention,

Page 5, 1st sentence: The same data model developed by the TWDB for the current GAM projects will be used to organize, store and document the information used to delineate the structure and net sand thickness of the Llano uplift aquifers.
Incomplete GIS data and metadata.
Response: Structural surface, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb).

Page 5, 4th sentence: All source data and derivative data will be included in the geodatabase.
Not all source data was provided. No georeferenced maps or lines of section were provided as stated in report, no geologic contact points, only 22 geophysical logs provided (>50% corrupted tif files).
Response: Geophysical logs are included in a folder as .TIF image files on the DVD, Llano_Uplift_Structure_&_Stratigraphy, (Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160).

Page 6, paragraph 1, 2nd sentence: Raster data…will be managed…as a raster catalog.
No raster data or raster catalog found.
Response: Geophysical logs are included in a folder as .TIF image files on the DVD, Llano_Uplift_Structure_&_Stratigraphy, (Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160). Other image files are provided in the Digital_Hardcopy folder.

3rd sentence: Hard copy geologic maps will be georeferenced and managed within the geodatabase raster catalog.
Only polygon "outcrop" geology from GAT found … no raster data found.
Response: Geophysical logs are included in a folder as .TIF image files on the DVD, Llano_Uplift_Structure_&_Stratigraphy, (Llano_Uplift_Structure_&_Stratigraphy\Digital_Hardcopy\Geophysical_Logs_860_to_41130160). Other image files are provided in the Digital_Hardcopy folder.

5th sentence: Spatial information will be interpolated onto a uniform grid developed for the study area.
No grids found. Suggest providing gridded surfaces referenced to USGS 3-arc meter second DEM.
Response: Appropriate structural surface grids, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb). Other image files are provided in the Digital_Hardcopy folder.

6th sentence: The grid size will be determined during the study, but will not exceed 1 square mile, to facilitate GAM development.
No grids found. Suggest providing gridded surfaces referenced to USGS 3-arc meter second DEM.
Response: Appropriate structural surface grids, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb). Other image files are provided in the Digital_Hardcopy folder.

Paragraph 2, 2nd sentence: …GIS data set will include estimated fault characteristics…which will include…
Type – *None attributed, please attribute accordingly.*
Formations impacted – *No feature class found for faults for Lion Mountain.*
Dip direction – *None attributed. Please explain why there are no attributes, or remove from dataset.*
Lateral extent – *Only Ellenburger fault feature class had this attribute. Please provide for all others.*
Vertical offset – *None attributed. Please provide.*
Assigned reliability code – *None attributed. Please provide.*
Response: Three fault files (feature classes) are included in the Fault_Attribute_Dataset: Hick_to_Ellen_Fault_Attrib (attributes of Hickory, Welge, and Ellenburger aquifer faults), Marble_Falls_Fault_Attrib (attributes of Marble Falls aquifer interval), and Modified_GAT_Faults (attributes of the faults appearing on the Geologic Atlas of Texas (GAT) within the area bounded by the downdip edge of the Precambrian outcrop and updip of the Hickory aquifer downdip limit as defned by the TWDB expanded by three miles). Metadata for these feature class files is included in the geodatabase.

3rd sentence – Land-surface elevations as derived from USGS 3-arc second digital elevation models will be used to describe the top of the layer in outcrop areas.
No DEM found. Please provide.
Response: Appropriate structural surface grids, fault, point, cross section path, elevation – DEM, and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb). Other image files are provided in the Digital_Hardcopy folder.

Paragraph 3, 3rd sentence: Derivative net sand contour lines and interpolated grid of net sands will be included in the appropriate location within the geodatabase.
No grids found. Suggest providing gridded surfaces referenced to USGS 3-arc meter second DEM.
Response: Appropriate structural surface grids, net sand maps, fault, point, cross section path, elevation and other data, as well as metadata, are provided in the geodatabase (Structural_Surfaces.mdb). Other image files are provided in the Digital_Hardcopy folder.

Paragraph 4, 1st sentence – Metadata will be provided for each layer that documents…
Data descriptions – *Except for point feature class, description abstracts do not sufficiently describe the. data. Please provide separate abstract that will allow user to determine what the specific data set is.*
Response: Metadata for feature class files is included in the geodatabase

Attribute information – *The last 9 or 10 attributes of the Llano_point feature class are not described or defined. Attribute information for all other feature classes are not provided. Please provide definitions for each attribute of each feature class.*
Data reliability – *Except for point feature class, data reliability is not stated for the other feature classes. Please provide.*
Sources – *Data sources are adequately defined or described within the abstract. Please provide.*
2nd sentence – All metadata will be developed within the metadata editor in ESRI ArcCatalog and will comply with Federal Geographic Data Committee standards.
Only one point feature class included significant metadata. Other GIS feature classes included insufficient metadata.
Response: The geodatabase, “Structural_Surfaces”, containing the file “Final_Llano_Point_File”, the feature class of well and other point information, is included in the data DVD. Metadata for feature class files is included in the geodatabase. The structure of the database is as follows:

Llano_Uplift_Structure_&_Stratigraphy

Structural_Surfaces.mdb

Name	**Type**
Final_Llano_Point_File	Personal Geodatabase Feature Class
Llano_Area_Counties	Personal Geodatabase Feature Class
Model_Areas	Personal Geodatabase Feature Class
Simplified_Geology	Personal Geodatabase Feature Class
Base_Hickory	Personal Geodatabase Feature Dataset
Base_Hickory_Contours	Personal Geodatabase Feature Class
Base_Hickory_Control_Points	Personal Geodatabase Feature Class
Base_Hickory_Faults	Personal Geodatabase Feature Class
Base_Hickory_Model_Area	Personal Geodatabase Feature Class
Top_Hickory	Personal Geodatabase Feature Dataset
Top_Hickory_Contours	Personal Geodatabase Feature Class
Top_Hickory_Control_Points	Personal Geodatabase Feature Class
Top_Hickory_Faults	Personal Geodatabase Feature Class
Top_Hickory_Model_Area	Personal Geodatabase Feature Class
Top_Welge	Personal Geodatabase Feature Dataset
Top_Welge_Contours	Personal Geodatabase Feature Class
Top_Welge_Control_Points	Personal Geodatabase Feature Class
Top_Welge_Faults	Personal Geodatabase Feature Class
Top_Welge_Model_Area	Personal Geodatabase Feature Class

Base_San_Saba	Personal Geodatabase Feature Dataset
Base_San_Saba_Contours	Personal Geodatabase Feature Class
Base_San_Saba_Control_Points	Personal Geodatabase Feature Class
Base_San_Saba_Faults	Personal Geodatabase Feature Class
Base_San_Saba_Model_Area	Personal Geodatabase Feature Class
Top_Ellenburger	Personal Geodatabase Feature Dataset
Top_Ellenburger_Contours	Personal Geodatabase Feature Class
Top_Ellenburger _Control_Points	Personal Geodatabase Feature Class
Top_Ellenburger_Faults	Personal Geodatabase Feature Class
Top_Ellenburger_Model_Area	Personal Geodatabase Feature Class
Base_Marble_Falls	Personal Geodatabase Feature Dataset
Base_Marble_Falls_Contours	Personal Geodatabase Feature Class
Base_Marble_Falls_Control_Points	Personal Geodatabase Feature Class
Base_Marble_Falls_Faults	Personal Geodatabase Feature Class
Base_Marble_Falls_Model_Area	Personal Geodatabase Feature Class
Cross_Sections_Dataset	Personal Geodatabase Feature Dataset
Final_CrossSection_Lines	Personal Geodatabase Feature Class
Final_CrossSection_Locations	Personal Geodatabase Feature Class
Fault_Attribute_Dataset	Personal Geodatabase Feature Dataset
Hick_to_Ellen_Fault_Attrib	Personal Geodatabase Feature Class
Marble_Falls_Fault_Attrib	Personal Geodatabase Feature Class
Modified_GAT_Faults	Personal Geodatabase Feature Class
Hickory_Net_Sand_Isopach	Personal Geodatabase Feature Dataset
Hickory_Net_Sd_Isopach_Contours	Personal Geodatabase Feature Class
Welge_Lion_Mtn_Net_Sand_Isopach	Personal Geodatabase Feature Dataset
Welge_Lion_Mtn_Net_Sand_Isopach_Contour	Personal Geodatabase Feature Class
Bs_Hickory	Personal Geodatabase Raster Dataset
Bs_Marble_Falls	Personal Geodatabase Raster Dataset
Bs_San_Saba	Personal Geodatabase Raster Dataset
Llano_DEM	Personal Geodatabase Raster Dataset
Llano_Hillshade	Personal Geodatabase Raster Dataset
Top_Ellenburger	Personal Geodatabase Raster Dataset
Top_Hickory	Personal Geodatabase Raster Dataset
Top_Welge	Personal Geodatabase Raster Dataset

Digital_Hardcopy

Geophysical_Logs_860_to_41130160
Drillers_Reports_104_to_856_not_in_order
CrossSections

.lyr symbology files

Contours.lyr
Faults.lyr
Faults & axial traces.lyr
Llano_Area_Counties.lyr
Simplified Llano Geology.lyr
StructureSurfaceGrids.lyr