technical paper

Precambrian basement aquifer, Llano Uplift, Central Texas

Brian B. Hunt, P.G.
Barton Springs/Edwards Aquifer Conservation District

Abstract

This paper provides an overview and initial conceptual model for the Precambrian Bedrock Aquifer of the Central Texas Llano Uplift. Evaluation of well data from the Texas Water Development Board, a geographic information system, geologic mapping, and fracture-trace analysis were the primary methods used in this study. Results of the study indicate that the Precambrian basement rocks of the Llano Uplift cover approximately 1,290 square miles and provide the sole source of water for an estimated 7,200 people and 73,000 livestock supporting an estimated pumping of 3,600 acre-feet per year. The aquifer is more prolific than previously considered, as fracturing and faulting are more extensive than shown on geologic maps. The Precambrian Basement Aquifer could be considered a minor aquifer of Texas because it supplies "relatively small quantities of water in large areas of the State."

Introduction

The Llano Uplift of Central Texas is a broad structural dome exposing Precambrian granites and metamorphic rocks (basement rocks) through an erosional window of Paleozoic and Mesozoic sediments (Figure 1). Basement rocks of the Llano Uplift cover approximately 1,290 square miles and provide the sole source of water for an estimated 7,200 people and 73,000 livestock in the region. Precambrian basement rocks of the Llano Uplift are currently not listed among the minor aquifers of Texas (Ashworth and Hopkins, 1995). Although the Precambrian Basement rocks do not generally provide prolific water supplies relative to the surrounding Paleozoic and Mesozoic aquifers, they do form an aquifer that can supply modest yields of fresh water when fractured or deeply weathered.

The purpose of this paper is to provide an overview and initial conceptual model for what I am defining as the "Precambrian Basement Aquifer" of the Central Texas Llano Uplift. Few regional water-resource studies have been conducted on the Precambrian rocks of the Llano Uplift. Landers (1972) and Landers and Turk (1973) conducted reconnaissance studies in the eastern Llano County area.

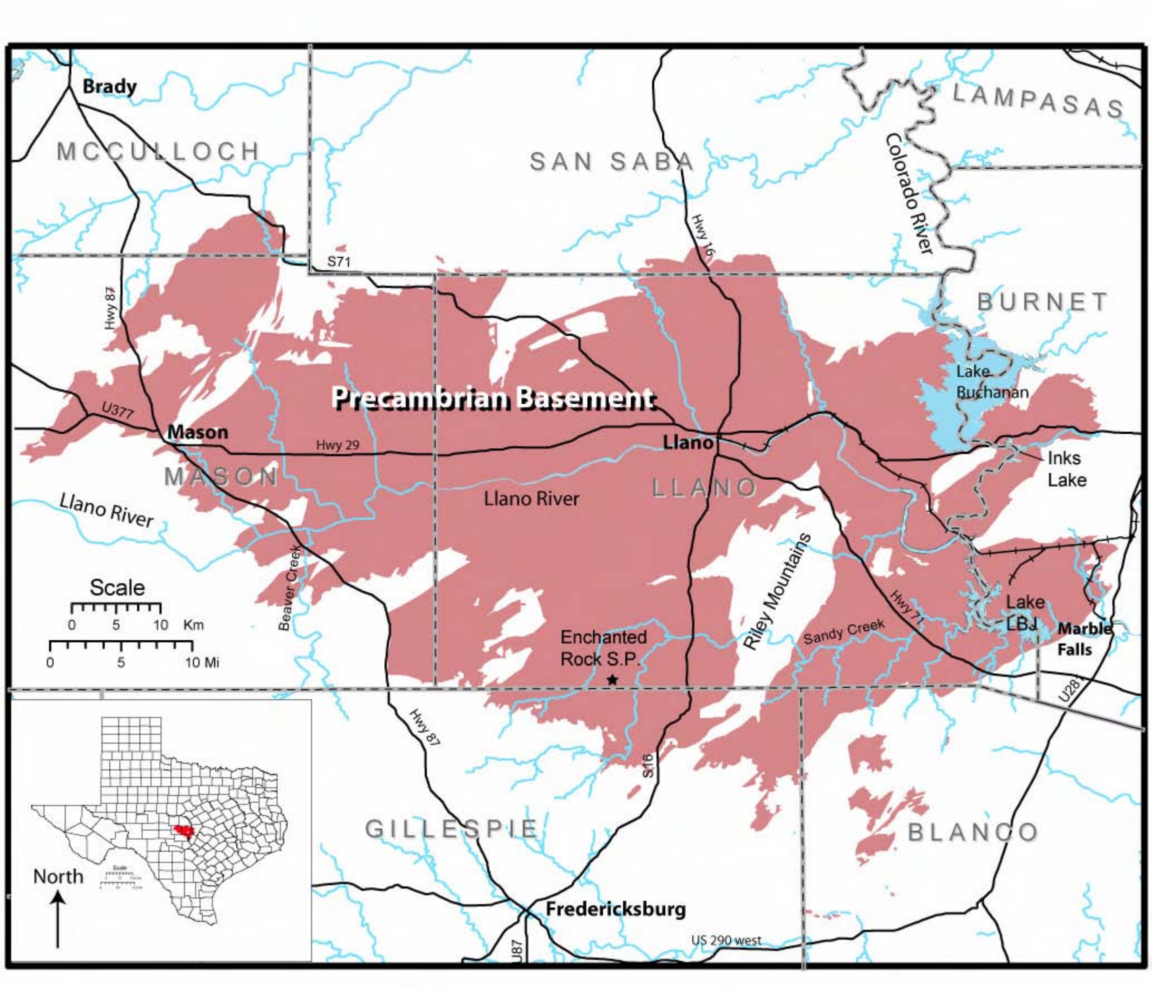

Figure 1. Location of the study area within the Llano Uplift of central Texas. Precambrian basement covers 1,290 square miles in portions of seven counties.

Methods used for this study include evaluation of well data compiled from the Texas Water Development Board's well database. Geographic information systems (GIS) were used for analysis and mapping. Geologic and fault mapping (1:5,000) was conducted by the author (Hunt, 2000) in a portion of the study area. Fracture-trace analysis was performed at the site scale to locate potential sites for water wells.

Results of this study indicate that an estimated 5,900 wells are completed within the aquifer pumping an estimated 3,600 acre-feet per year for domestic and livestock needs. The aquifer could meet the definition of a minor aquifer of the state as defined by Ashworth and Flores (1991) because it supplies "relatively small quantities of water in large areas of the State." Faulting and fracturing are key elements to the availability of groundwater in the Precambrian Basement Aquifer. Detailed geologic mapping has shown that faults and fractures are more prevalent than shown on published geologic maps and can be targeted for groundwater production; therefore, groundwater supplies may be greater than previously considered.

Setting

The study area is in the Llano Uplift physiographic province, also called the Central Mineral Region, or the Central Texas Uplift (Wermund, 1996). The Llano Uplift is a topographic basin floored by Precambrian metamorphic and igneous rocks and rimmed by Paleozoic and Mesozoic sedimentary rocks. The Llano Uplift lies to the northeast of the Edwards Plateau, and west of the Balcones Escarpment physiographic regions (Figure 2). Basement rocks are exposed over about 1,290 square miles (3,350 square kilometers) in an area covering seven central Texas counties. The rocks make up nearly all of Llano County and nearly one third of Mason County with smaller portions within Gillespie, Burnet, Blanco, McCulloch, and San Saba counties (Figure 1).

Despite the name "uplift" the study area is a topographic basin owing to the relatively resistant sediments that surround the igneous and metamorphic units. Sidney Paige (1912) described the Llano Uplift as *"…basin-like being etched below the Edwards Plateau and its form due to a combination of structural and erosional conditions."* Relief of the basement rocks consists of relatively flat to rolling landscape studded with rounded granite hills or domes 400 to 600 feet high (such as Enchanted Rock). Other hills consist of Paleozoic sandstone and limestone such as the Riley Mountains, which are fault-bounded grabens (Figure 1). Topography within the Llano Uplift generally slopes to the east. The range in elevation is from 800 feet along the Colorado River in the eastern study area, up to a maximum elevation of 2,000 feet.

Climate, Soil, and Vegetation

Climate of the study area is characterized as Subtropical Subhumid with hot summers and dry winters (Larkin and Bomar, 1983). The range of average annual rainfall is 26 to 30 inches per year from west to east across the study area (Figure 2**;** Daly, 1998). The topographically low core of the uplift has an effect on annual rainfall that is reflected in the 28- and 30-inch rainfall contours protruding east within the basin (Figure 2). Average gross surface water evaporation is 67 to 71 inches per year (Larkin and Bomar, 1983).

The study area is dominated by soils that formed in material weathered from granite and metamorphic units. Generally, many of the soils are moderately deep (20 to 40 inches) sandy loam soils that support grass savannahs scattered with oak trees (Goerdel, 1998). This description is similar to a vegetation map of Texas compiled by McMahan and others (1984) showing the study area as "Live Oak-Mesquite Parks." Live Oak and Mesquite are the dominant large woody species and the term "park" refers to areas where "woody plants grow as clusters or scattered individuals within continuous grass or forbs (11-70% woody canopy overall)."

Surface Water Drainage

The Llano River is a perennial river (except during extreme drought) flowing west to east through the center of the study area joining the Colorado River in the eastern Llano Uplift. Many large streams feed into the Llano River but are intermittent and generally dry or have very low flows during the summer months. However, during large rain events, rivers and creeks are prone to flash flooding. The U.S. Geological Survey and the Lower Colorado River Authority have many stream gauging stations in the Llano Uplift (Figure 3). The U.S. Geological Survey gauging station on the Llano River at Llano has measured a range of flow from 0 cubic feet per second (1952–56, 1964, 1984) to flood peaks of 88,500 cubic feet per second. Average and median flow for the period of record (1939–2004) is 380 and 157 cubic feet per second, respectively (http://waterdata.usgs.gov/tx/nwis/uv?08151500).

Surface water is the primary source of water for the small cities in Llano and Burnet counties in the eastern portion of the study area. Several of the Highland Lakes (Buchanan, Inks, and LBJ) are located along the eastern margin of the Llano Uplift and form a flood control and water supply network of reservoirs managed by the Lower Colorado River Authority.

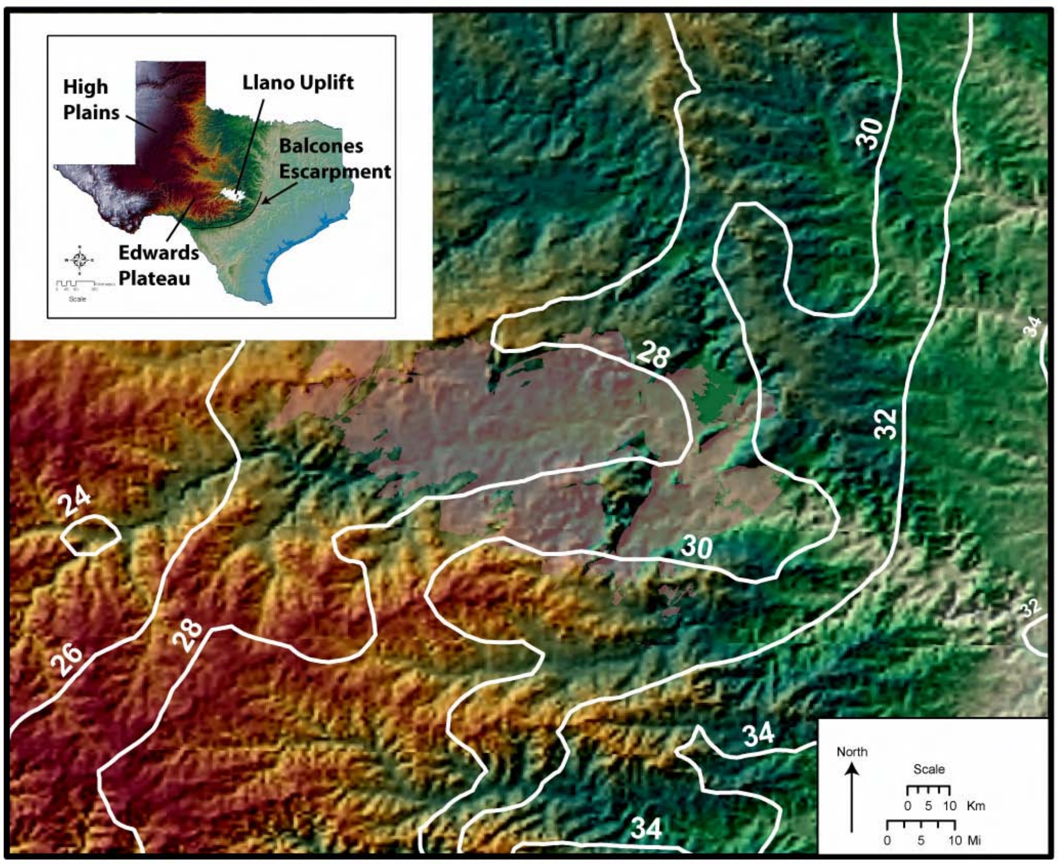

Figure 2. (Inset map) Physiographic map of Texas showing the position of the Llano Uplift relative to other features. (Large map) Texas terrain map of Central Texas with average annual precipitation contours from 1961 to 1990 shown as white lines (from Daly, 1998). The Precambrian Bedrock Aquifer is shown in light shading. Texas terrain color ramp map was obtained from the Texas Natural Resource Information System.

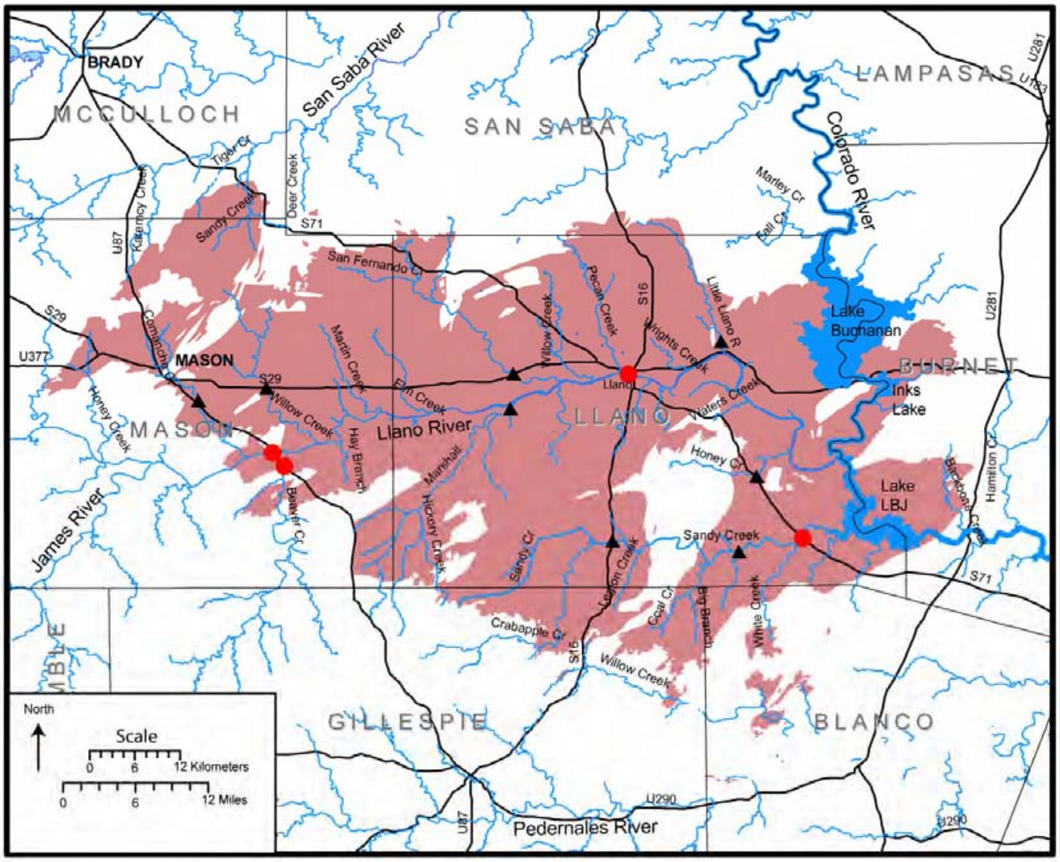

Figure 3. **Map of surface water features within the study area. Circles indicate U.S. Geological Survey stream gauging stations available on the web. Triangles indicate stream gauging stations maintained by the Lower Colorado River Authority.**

Land Use

By the 1880s windmills started to proliferate across the Edwards Plateau (Rose, 2004), allowing ranching and farming to spread throughout the region. Ranching has dominated land use to this day with about 82 percent of the study area, on average, in Llano and Mason counties used as pasture land for ranching (Goerdel, 1998; USDA, 2002; USDA 2002b). Llano and Mason counties have a total of 900 farms (ranches) within the study area with an average size of 825 acres. Livestock include cattle, goats, sheep, hogs, and horses. Cropland makes up 9 percent and 12 percent of the area for Llano and Mason counties, respectively. Cropland includes forage or hay, pecans (Llano), grapes (Llano), and peanuts (Mason) (USDA, 2002; USDA 2002b). Although croplands are present, they are generally not significant over the Precambrian Basement.

Population and Groundwater Use

A database of 230 wells was compiled for this study, but represents only a sampling (estimated less than 5 percent) of the wells completed in the Precambrian Basement aquifer (Tables 1 and

2). Domestic supply, small public water supply, and livestock supply are the two primary uses of groundwater in the study area. An attempt was made to estimate the number of domestic wells using census (2000) data for Llano and Mason counties since they contain most of the Precambrian Basement Aquifer. However, small cities in Llano County obtain their water from the Colorado River (Highland Lakes), which is reflected in low overall use of groundwater (1,800 acre-feet) representing only 27 percent of total water use in 2000. Conversely, Mason County pumps about 11,602 acre-feet per year, or 97 percent, of its water from groundwater sources in 2000 (Mace and Angle, 2004). However, these estimates, including the City of Mason and two thirds of Mason County, are primarily from Paleozoic aquifers that surround the study area. By excluding populations and households within small cities from the county totals, the number of rural households, and therefore domestic wells completed in the Precambrian Basement Aquifer, is estimated to be 4,100 (Table 3). The number of wells reasonably compares to the total estimated rural population of 7,272 that depend on the Precambrian Basement Aquifer. Livestock wells support an estimated inventory of 72,605 animals (80 percent cattle and 20 percent goats and sheep) in Mason and Llano counties (USDA, 2002; USDA 2002b). Since ranches are often quite large (see land use), they often contain several wells for livestock and domestic purposes. Accordingly, a factor of 2 was applied to the 900 ranches in Mason and Llano counties for an estimated 1,800 livestock wells. Therefore, the estimated total number of domestic and livestock wells within the Precambrian Basement Aquifer is 5,900 (Table 3). A reduction factor of two thirds was applied for Mason County estimates to account for the area of the Precambrian Basement in that county.

Table 1. Number of wells in database.*

County	Number	% of total
Llano	158	68
Mason	25	11
Burnet	20	9
Gillespie	17	7
Blanco	9	4
San Saba	1	0
McCullough	0	

*Data primarily from the Texas Water Development Board (total number of wells = 229)

Table 2. Classification of wells in database.

Classification	Number	% of total
Domestic	94	41
Public supply	54	24
Stock	34	15
Unused	32	14
Irrigation	13	6

To determine the annual pumpage from the aquifer, an estimate is needed for the amount of groundwater used for domestic and livestock purposes. Domestic use was estimated by applying the per capita 200 gallons per day (TWDB, 2002), multiplied by the average 3.2 persons per household, multiplied by the number of rural households (Table 4). Using this method the total annual domestic use equals 961 million gallons (2,949 acre-feet per year). To estimate the volume pumped for livestock, the inventory of livestock is multiplied by the reported water consumption for livestock. Using this method, the estimated annual livestock use is 226.8 million gallons (696 acre-feet per year). The total estimated annual groundwater use from the Precambrian Basement Aquifer is 1.2 billion gallons per year (3,646 acre-feet per year) (Table 4). It is noteworthy that this amount is likely a minimum volume as other counties are not accounted for in those estimates, and irrigation is also not accounted for. It is also noteworthy

Table 3. Estimated number of wells in the study area.

	2000 Census rural population	2000 Census rural households	Estimated number of domestic wells[1]	Estimated number of livestock wells[2]	Total wells
Rural Llano County:	*6,743*	*3,885*	3,885	1,384	5,269
Rural Mason County[3]:	*529*	*229*	229	416	645
Total	**7,272**	**4,114**	**4,114**	**1,800**	**5,914**

[1] Estimated from the number of rural households.
[2] Estimated from two wells for every ranch.
[3] Original value reduced by two thirds

Table 4. Estimated groundwater use in the Precambrian Basement Aquifer.

County	Estimated annual domestic use [millions gallons/yr[1,2] (acre-ft/yr)]	Estimated Annual Livestock Use [millions gallons/yr[3] (acre-ft/yr)]	Total Groundwater Use [millions gallons/yr (acre-ft/yr)]
Llano	907.5 (2,785)	149.3 (458)	131.0 (402)
Mason	53.4 (164)	77.5 (238)	1,056.8 (3,244)
Total	961.0 (2,949)	226.8 (696)	1,187.9 (3,646)

[1] 200 gallons per day per capita (TWDB, 2002)
[2] Household = 3.2 people
[3] Livestock consumption: cattle & horses = 10 gallons per day and goats and sheep = 3 gallons per day (Landefeld, and Bettinger, 2002)
Millions gallons/yr = millions of gallons per year
Acre-ft/yr = acre-feet per year

that this estimated annual volume is greater than the supplies of six other minor aquifers of Texas (TWDB, 2002).

Groundwater Management

The study area falls within Region K and Region F of the regional water planning areas. The majority of the study area lies within Region K, while the western portion of study area (Mason and McCulloch counties) lies within Region F (Figure 4). There are four groundwater conservation districts in the study area. Those districts include the Hickory Underground Water Conservation District #1 (Mason, McCulloch, and San Saba counties), Hill Country Underground Water Conservation District (Gillespie County), Blanco-Pedernales Groundwater Conservation District (Blanco County), and the Central Texas Groundwater Conservation District (Burnet County). There are no groundwater conservation districts in Llano County and portions of San Saba County.

Most studies do not consider the Precambrian Basement Aquifer a major groundwater resource (Follet, 1973; Ashworth and Hopkins, 1995). Regions K and F do not appear to explicitly account for water from the Precambrian Basement Aquifer. Accordingly, groundwater conservation districts do not appear to account for groundwater from the Precambrian Basement Aquifer in their groundwater management plans.

Geologic Setting

The Llano Uplift is a broad structural dome exposing Mesoproterozoic igneous and metamorphic rocks surrounded by an erosional window of Paleozoic and Mesozoic sedimentary rocks (Figure 5 and 6) (Barnes, 1981). The Llano Uplift was created by six broad structural arches, which intersected at the uplift (Ewing, 1991, 2004). The geologic and structural development of the Llano Uplift involves all of the major tectonic cycles to affect Texas, including two major orogenies, a great unconformity, extensional faulting, and erosion (Ewing, 1991). A geologic guidebook to the eastern Llano Uplift contains papers detailing those events (Hoh and Hunt, 2004).

The core of the Llano Uplift consists of Mesoproterozoic (1.0 to 1.3 billion years ago) igneous and metamorphic rocks (Figures 5 and 6). Metamorphic rocks cover about 60 percent of the area and consist of diverse packages of schists, gneisses, marbles, and metaigneous rocks. Polyphase folding, multiple metamorphic fabrics, boudinage, partial melting, shearing, and transposition of most rock types reveal a complex ductile deformation history of those units (Mosher, 1998). Reese and others (2000) have redefined the usage of metamorphic unit names as chronostratographic packages. Three domains, based on the chronostratographic rock packages, have been defined in the southeast uplift (Mosher, 1996, 1998; Reese and others, 2000). From structurally highest to lowest (southwest to northeast) the rock packages are as follows: the island arc Coal Creek domain (CCD); heterogeneous supracrustal, metavolcanic and metaigneous Packsaddle domain (PSD); and the supracrustal and plutonic rocks of the Valley Spring domain (VSD). Metamorphic units are intruded by 1126+5/-4 million year old to 1070±2 million year old syn- to post-tectonic granites comprising about 40 percent of the Precambrian rocks (Reed, 1999). These basement rocks record a 300 million year history of orogenic activity

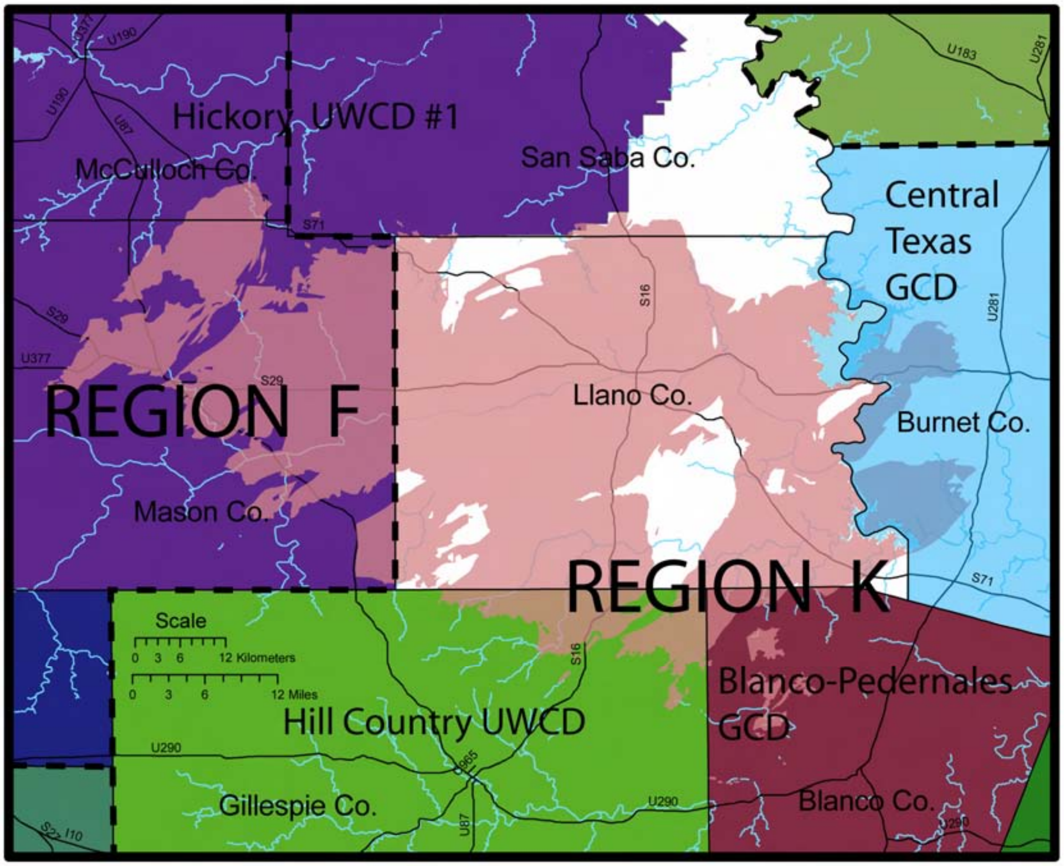

Figure 4. Map showing boundaries of management areas and jurisdictions that overlay the Precambrian Basement Aquifer. Regional water planning areas F and K are shown as dashed boundaries. The study area contains four groundwater conservation districts. Llano County and portions of San Saba County shown in white do not have a groundwater conservation district. The study area is divided into three groundwater management areas: Blanco County is in Area 9, Burnet County is in Area 8, and the remaining counties of the study area are in Area 7. GIS data sources are from the Texas Water Development Board.

culminating in continent-continent collision of the Mesoproterozoic Grenville orogeny and the formation of the super-continent Rodinia, (Mosher, 1998).

Following termination of Grenville orogeny, deep erosion during the next 0.6 billion years removed many kilometers of crust in the Llano Uplift region. By the mid- to late-Cambrian Period (at ~500 million years ago) the region had been reduced to a hilly area having topographic relief similar to that in the Llano Uplift today (Long, 2004).

The Paleozoic Era was dominated by marine sedimentation blanketing the igneous and metamorphic rocks with sandstones, shales, and limestones. Many of those units make up the Paleozoic aquifers that surround the Llano Uplift such as the Hickory, Marble Falls, and Ellenberger-San Saba (Preston et al., 1996).

The late Paleozoic Era was dominated by the Ouachita Orogeny related to the formation of the supercontinent Pangea. Ouachita-related, dominantly northeast-trending normal faults cut all

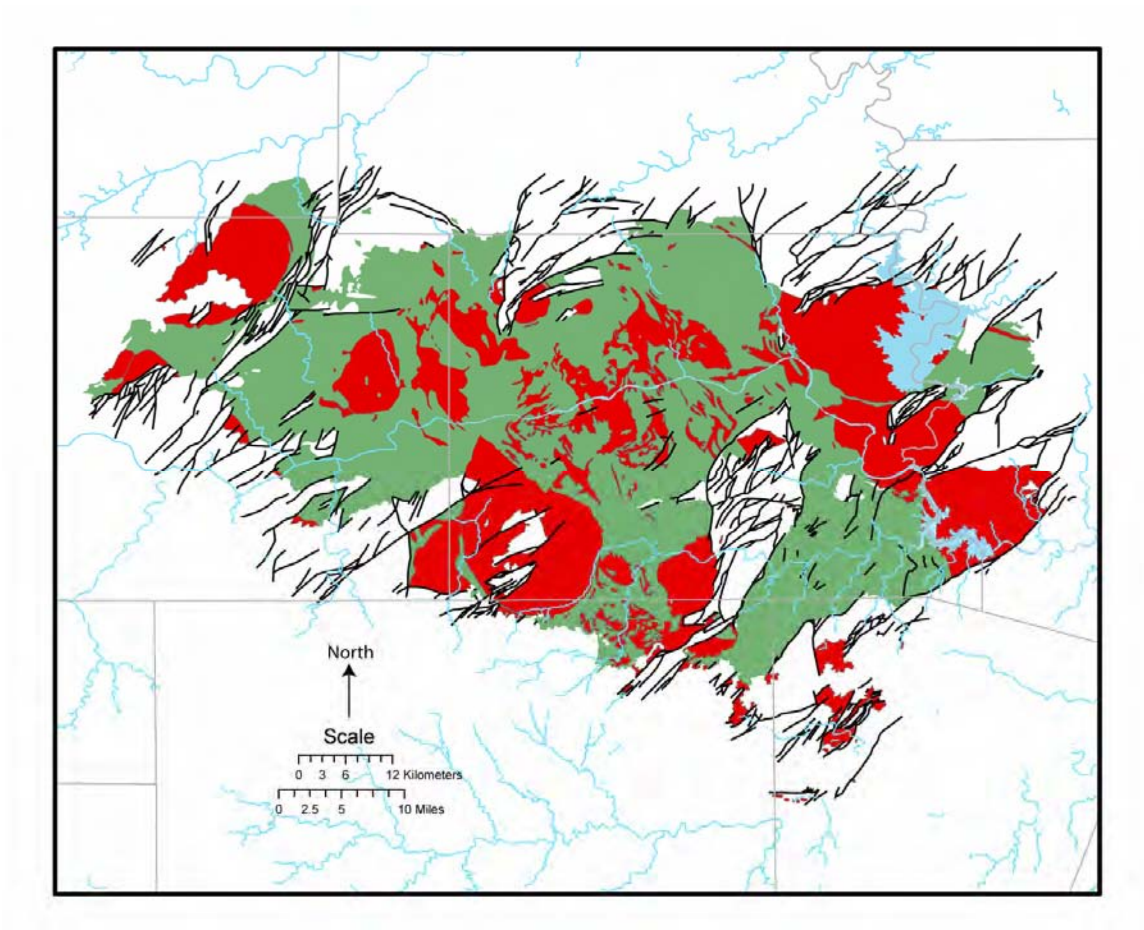

Figure 5. **Simplified geologic map of the Precambrian Basement of the Llano Uplift. Granites (40 percent of total area) are shown in red and metamorphic units (60 percent of total area) are shown in green. Paleozoic-age faults are shown as black lines (geology digitized by Dr. Mark Helper [The University of Texas at Austin]; map originally from Barnes, 1981).**

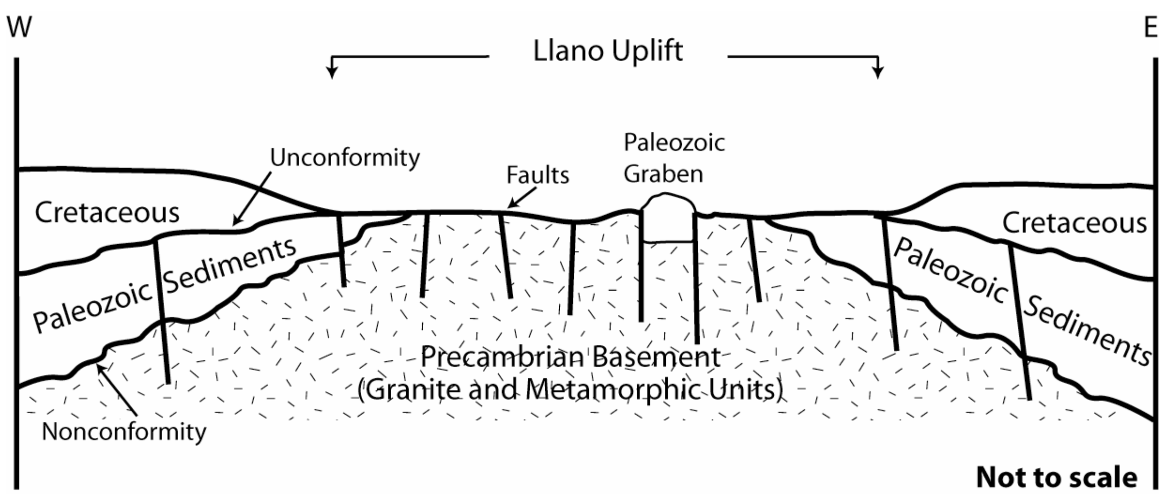

Figure 6. **Schematic cross section of the Llano Uplift (modified from Preston and others, 1996).**

Precambrian and Paleozoic units in the Llano Uplift. These faults are critical to the secondary porosity and permeability development of the Precambrian Basement and the formation of the aquifer and are discussed in the next section. However, until recently the origin of the pervasive extensional (normal) faults in close proximity to a convergent margin had not been fully discussed in the literature. Johnson (2004) writes "…that (normal) faulting from bending of the continental plate results from increased vertical loads near to, and parallel to, the continental margin as a consequence of thrust-induced crustal thickening and enhanced foreland sediment accumulation."

During the Mesozoic Era the Llano Uplift was a structural high and either provided detrital material or influenced deposition of many lower Cretaceous units in central Texas. Islands of Precambrian and Paleozoic-age sediments surrounded by a Cretaceous ocean provided the source for some Trinity units in Central Texas (Stricklin and others, 1971). Ultimately marine limestones blanketed most of the Llano Uplift until the seas retreated at the end of the Cretaceous.

During the Miocene (~15 million years ago), the Llano Uplift is thought to have achieved its present form. The Edwards Plateau region was uplifted and stripped of much of its sedimentary overburden. The uplifting is thought to be the result of thermal doming during the formation of the Rio Grande Rift and the Basin and Range province (Ewing, 2004).

Unconsolidated alluvial sediments and weathered granitic bedrock, also called "grus," are also significant geologic materials in the Llano Uplift.

Faulting and Fracturing

Faulting and fracturing are critical to the porosity and permeability development of the Precambrian Bedrock aquifer. Johnson (2004) has a detailed discussion of the nature and origin of the cataclastic faults and fractures in the Llano Uplift.

Paleozoic-age normal faulting crosscuts the Precambrian and Paleozoic rocks of the Llano Uplift and generally trend to the northeast, but also at nearly all other orientations (Figure 7) (Barnes, 1981). Most faults have a significant normal dip-slip component with moderate throws. Johnson (2004) notes at least nine faults have a stratigraphic throw of greater than 1,640 feet and have oblique-slip, left-lateral and right-lateral strike slip components.

Field observations within the basement rocks reveal faults that generally consist of planar features with steep dips (greater than 80 degrees) and little relief (Figure 8). Fault zones often contain gouge, sparry calcite, and, less commonly, layered sedimentary carbonate filling. Sense-of-motion indicators, such as slickensides, are not common; however, offset intrusive units locally reveal a relative sense of motion (Figure 8; Mosher, 1996; Hunt, 2000). Individual fault zones range in thickness from a few inches to greater than 15 feet. Fractures generally increase in frequency upon approaching fault zones and are useful to determine orientation and attitude of faults, as most fault planes are not exposed. Qualitative observations from well-exposed fault and fracture zones indicate there is good lateral connectedness among the fractures within individual fault zones. Locally, fractures or faults offset one another, although no chronology could be established between faults of different orientations in the field (Hunt, 2000). Johnson (2004) notes that many fractures appear to have existed prior to deposition of the Hickory Sandstone,

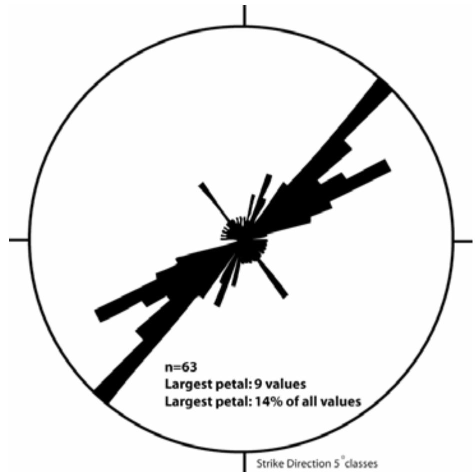

Figure 7. **Rose diagram of fault trends within a 10-mile transect in the western portion of the Llano Uplift along the Llano River in Precambrian Metamorphic Units, Mason County (modified from Hunt, 2000).**

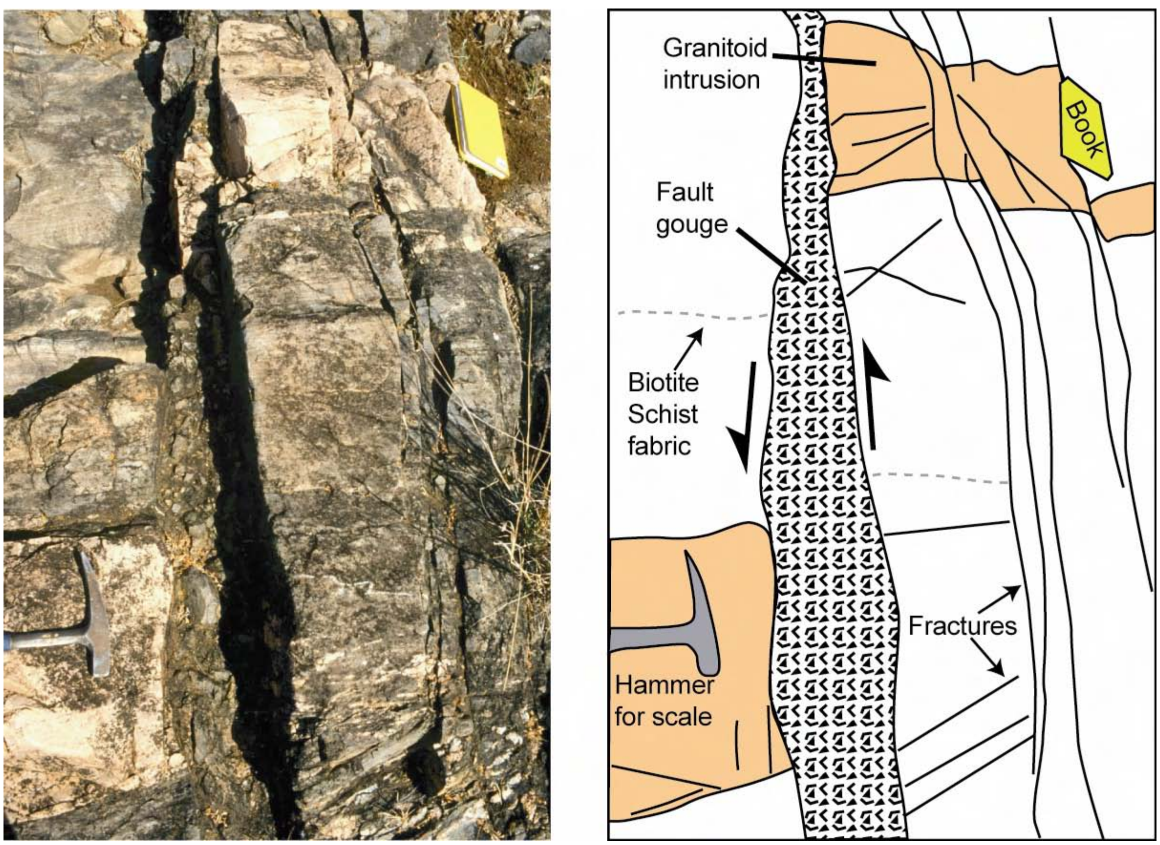

Figure 8. **Photograph and sketch of a fault zone in a biotite schist within the Packsaddle Schist. The fault offsets a pink granite dike with left-lateral offset of about 3 feet (from hammer to notebook). Metamorphic fabric is normal to fault gouge. Faults correlate locally to vegetation lineaments on aerial photographs and extend more than two kilometers. The fault is not on any published maps.**

the basal Paleozoic unit, making them related to some other structural occurrence (such as uplift). Additionally, Johnson (2004) notes the possibility of some Paleozoic faults resulting from reactivation of Precambrian structures.

Most faults mapped by Barnes (1981) are within the Paleozoic units of the Uplift. Hunt (2000) mapped 63 faults within a ten-mile transect of basement rocks in the western Llano Uplift (Figure 7), an area with no mapped faults at the 1:500,000 scale (Barnes, 1981). Faulting within the basement rocks is therefore much more prevalent than shown on published maps. Metamorphic basement rocks are faulted and fractured more pervasively on closely spaced, small throw faults, whereas the granitic basement deforms on widely spaced, large throw faults (Schmittle, 1987; Johnson, 2004). Thus, the fabric within the metamorphic rocks appears to have influenced the structural evolution and ultimately the hydrogeology of the study area.

An important feature of faults and fracture systems in the Llano Uplift are their prominent appearance as vegetation lineaments on aerial photos. Therefore, this characteristic can be used to help locate wells by fault-trace analysis within the Precambrian Basement rocks.

Hydrogeology

Few regional water-resource studies have been conducted on the Precambrian rocks of the Llano Uplift. A reconnaissance study by Landers (1972) and Landers and Turk (1973) looked at the occurrence and quality of groundwater in crystalline rocks of the Llano area. Follett (1973) stated that fractured Precambrian rocks provide very small to small quantities of fresh water to wells.

Precambrian Basement Aquifer

A total of 230 wells make up a database of wells from the Texas Water Development Board (Figure 9). Six aquifer units are identified by the Texas Water Development Board within the study area (Table 5). Where faulted and fractured, the Precambrian Basement rocks form an aquifer, defined here as the “Precambrian Basement Aquifer.” Additionally, weathered granites, called “grus,” can locally create a thick “C” soil horizon that can be a significant aquifer material. Alluvium along the Llano River and its tributaries locally provides a source of water for some wells.

Table 5. Tabulation of aquifers, wells, and springs in the Precambrian Basement.

Aquifer	TWDB code	# of wells	% of total	# of springs
Precambrian Erathem (undifferentiated)	400PCMB	86	38	4
Precambrian Granite	400GRNT	77	34	2
Valley Spring Gneiss	400VSPG	34	15	1*
Packsaddle Schist	400PCKD	21	9	1
Granite Wash	371GRNT	10	4	
Alluvium and Granite	110AGRT	1	0	

*from Brune, 1975
TWDB = Texas Water Development Board

There are eight known springs (five in Gillespie County, two in Llano County, and one in Mason County) in the Texas Water Development Board database or reports (Brune, 1975). The springs are relatively minor with reported flow of 2 to 10 gallons per minute. Most of the springs are located within contributing creeks and one within the Llano River (Figure 9). The author has observed several unmapped small springs and seeps associated with faults within the Llano River and its tributaries.

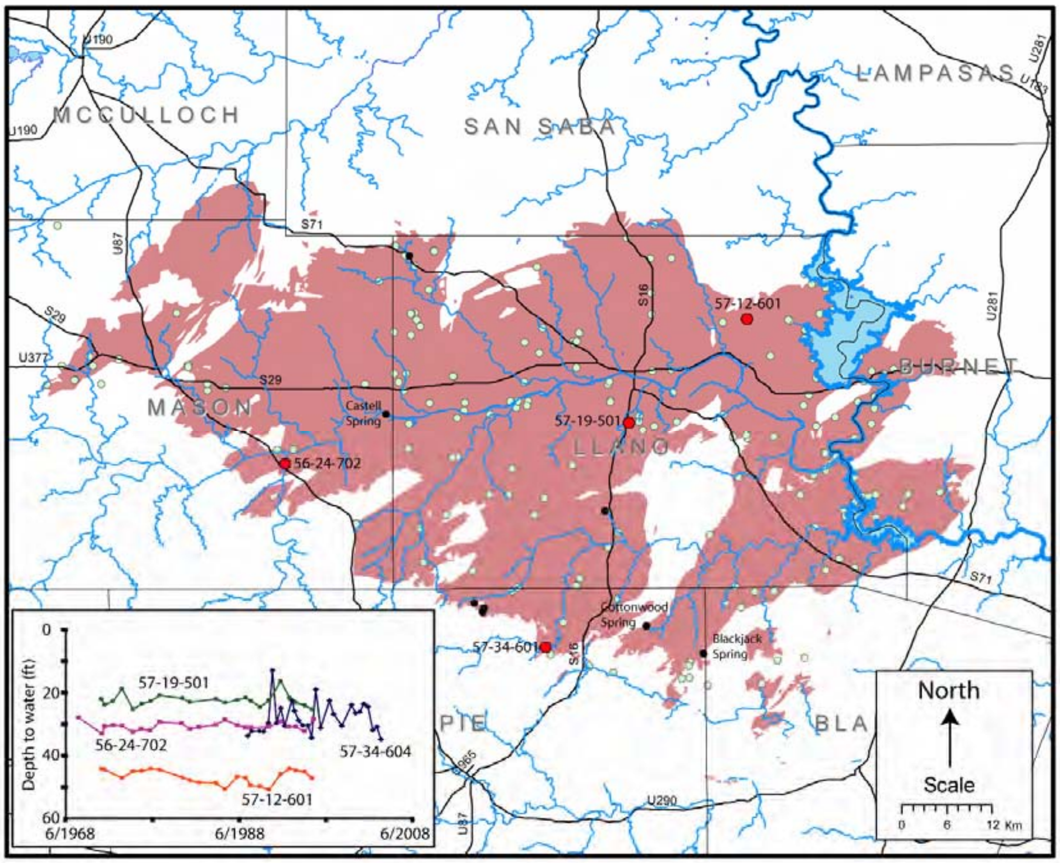

Figure 9. Locations of wells and springs of the Basement Aquifer. Wells (a total of 230) are shown as small green circles. Selected observation wells with state well numbers are shown as large red circles with their hydrographs in the inset. Springs are shown as black circles (a total of 8). Water-level and well data are from the Texas Water Development Board. Geology digitized by Dr. Mark Helper [The University of Texas at Austin]; map originally from Barnes, 1981.

Hydraulic Parameters

Plutonic and metamorphic rocks have little primary porosity ranging from 0.1 to 0.79 percent (Heath, 1983; Barker and others, 1996) and generally do not have good aquifer properties unless faulted or highly weathered. Few hydraulic parameters have been measured in the study area, so values from the literature are reported here. Hydraulic conductivity values for unfractured igneous and metamorphic rocks range from 1.0×10^{-8} to 6.0×10^{-5} feet per day (Bouwer, 1978; Domenico and Schwartz, 1990). Hydraulic conductivity of fractured and weathered igneous and metamorphic rocks range from 0.05 to 14.0 feet per day (Morris and Johnson, 1967; Bouwer, 1978).

Wells in the Precambrian Basement Aquifer have a median well yield of 12 gallons per minute (based on information from 136 wells), indicating their relatively low permeability. The range in yield is from 0.5 gallons per minute up to 200 gallons per minute (Table 6). Granitic rocks have a higher well yield than metamorphic rocks. Water well drillers also observe better yield from wells drilled within granitic basement rocks (Taylor Virdell, Virdell Drilling, personal communication, 2006). This may be due to the fact that large granite bodies can have horizontal joint systems (Morris and Johnson, 1967) or perhaps due to the larger fault and fracture zones reported to occur within granites (Schmittle, 1987) providing increased porosity and permeability. Only four specific capacity values are known for the study area (Table 6). Transmissivity values for one single-well test in the Packsaddle Schist were calculated using the Cooper-Jacob and Theis solutions and averaged 1,400 gallons per day per foot (187.6 feet squared per day).

Average well depths in the study area are 132 feet (median 100 ft; based on information from 222 wells), with no correlation between yield and depth. Yield would not be expected to correlate to depth as fracture aperture and degree of weathering is expected to decrease with depth (Landers, 1972). "Dry holes" are commonly drilled in the study area (five noted in the Texas Water Development Board database and another seven from the author's knowledge) indicating the heterogeneous nature of the aquifer. The fractured nature of the aquifer makes the aquifer highly anisotropic.

Table 6. Summary of reported well yields.

Yield (gpm)	All	Precambrian Erathem	Granite Wash	Granite	Valley Spring Gneiss	Packsaddle Schist	Alluvium and Granite
Average	21.8	28.8	25.9	22.8	12.9	10.3	--
Median	12.0	18.0	30.0	12.0	8.0	8.0	--
Max	200.0	200.0	40.0	115.0	70.0	25.0	39.0
Min	0.5	1.5	2.5	0.5	0.5	0.8	--
n	136	49	7	48	24	15	--
Specific capacity (gpm/ft)	--	1.0	--	17.5	--	0.93	0.26

gpm = gallons per minute
Max = maximum value
Min = minimum value
n = number of well yield measurements
gpm/ft = gallons per minute per foot of drawdown

Recharge, Water Levels, and Groundwater Flow

Recharge rates and processes are not known or poorly understood for the study area. However, within the outcrop area, recharge to the Precambrian Basement Aquifer most likely occurs through the sandy loam soils and then migrates along the bedrock-soil interface before entering into faults, fractures, and weathered bedrock. Streams and rivers are often points of discharge, although they may also be areas of recharge under certain conditions.

Depth to the water table throughout the Precambrian Bedrock aquifer is shallow with a median depth to water of 23 feet (based on information from 501 wells). The water table may be a subdued reflection of the surface topography. Hydrographs from four selected historical observation wells are presented in Figure 9. Changes in water levels for these wells range from 5 to 26 feet. Wells completed within the Precambrian Bedrock Aquifer are very susceptible to dry conditions and drought suggested by the relatively shallow well depths and relatively low well yields.

Due to the heterogeneous and anisotropic nature of the aquifer, groundwater flow is likely very complicated. However, groundwater flow can generally be described as occurring along faults and fractures at relatively shallow depths. Influence of the metamorphic fabric on groundwater flow is thought to be minimal; however, the fabric appears to have indirectly influenced flow through its effect on fault and fracture development.

Water Quality

Groundwater quality is generally good with average values for water constituents generally within the U.S. Environmental Protection Agency's maximum contaminant levels and secondary standards. However, the quality can be erratic with locally high total dissolved solids, chloride, sulfate, sodium, nitrate, and some metals (Table 7). Landers (1972) reports that schists generally produce harder water with higher sulfate content than other units, although the data in Table 7 does not necessarily support that. Average values for nitrates are elevated above federal drinking water standards. Landers and Turk (1973) attribute high nitrate values to wells proximal to septic drain fields or livestock pens. This suggests that the groundwater resources may be vulnerable to contamination due to their fractured nature (transmissive) and relatively shallow water table. Samples for naturally occurring radioactive materials are generally below federal drinking water standards.

Factors Contributing to Well Yield

Locating a productive well within the Precambrian Basement Aquifer can be challenging because water-bearing fractures that generate sufficient yield can be difficult to locate due to their poor exposure. However, fracture trace analysis can identify potential areas of faulting and fracturing, and thus potential areas for high-yielding wells. In addition, other geologic and physiographic factors can be used to help evaluate and weigh, in a qualitative sense, potential well sites. Studies within similar geologic and structural settings (fractured bedrock) offer insight

Table 7. Water quality.

	Si (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Sr (mg/l)	Carb. (mg/l)	Bicarb. (mg/l)	$S0_4$ (mg/l)	Zn (mg/l)	Fe (mg/l)	Cu (mg/l)	
Max	65.0	384.0	117.0	940.0	47.0	0.6	13.0	634.6	750.0	1500	102	10.6	
Min	6.0	15.0	4.0	1.0	1.0	0.2	0.0	48.8	3.0	4.99	4	1.15	
Avg	28	100	31	67	5	0	0	308	68	--	--	--	
n	97	118	118	116	50	5	118	118	118	4	2	2	
EPA Std	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	
2^{nd} EPA Std	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*250*	*5*	*0.3*	*1.0*	
TCEQ Surface Water Std	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	
	Cl (mg/l)	**Fl (mg/l)**	**Nitrate (mg/l)**	**pH**	**TDS (mg/l)**	**Phen. alk. (mg/l)**	**Tot. alk. (mg/l)**	**Tot. hard. (mg/l)**	**Conduct. (uS/cm)**	**Raduim 226 (pCi/l)**	**Raduim 228 (pCi/l)**	**Alpha (pCi/L)**	**Beta (millirims/ yr)**
Max	2240.0	9.0	915.0	8.4	3822.0	10.8	520.0	1373.0	8200.0	1.9 +/- 0.3	2.1 +/- 1.1	9.7 +/- 2.3	10 +/- 7
Min	6.0	0.1	0.0	5.6	138.0	0.0	40.0	74.0	255.0	0.2 +/- 0.1	2.1 +/- 0.5	2.5 +/- 1.4	4.4
Avg	120	1	44	7	593	0	252	377	1239	--	--	5.4	--
n	118	112	119	114	116	118	118	118	117	2	2	7	2
EPA std	*NR*	*4*	*10*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*5*	*5*	*15*	*4*
2^{nd} EPA	*250*	*2*	*NR*	*5.6-8.5*	*500*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*
TCEQ surface water std	*NR*	*0.5*	*1*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*	*NR*

Table 7. Water quality (continued).

Water quality data from Texas Water Development Board; filtered samples.

2nd EPA = secondary drinking water standard set by the U.S. Environmental Protection Agency
Avg = average value
Bicarb = bicarbonate
Carb = carbonate
Conduct. = conductivity
EPA Std = primary drinking water standard set by the U.S. Environmental Protection Agency
Max = maximum value
mg/l = milligrams per liter
millorims/yr = millirims per year
Min = minimum value
n = number of samples
NR = nor regulated
pCi/l = picocuries per liter
Phen. alk. = phenol alkalinity
TCEQ surface water std = surface water standard as set by the Texas Commission on Environmental Quality
TDS = total dissolved solids
Tot. alk. = total alkalinity
Tot. hard. = total hardness
uS/cm = microsiemanns per centimeter

into the hydrogeology of the Llano Uplift. In particular, a study by Moore and others (2002) discusses factors that contribute to well yield in a fractured bedrock aquifer of New Hampshire. Factors that can positively relate to well yields include:

- proximity to exposed fault or fracture zone,
- correlation to the strike of mapped fault or fracture zones,
- correlation to vegetation or topographic lineations,
- proximity to the intersection of lineaments or fracture zones,
- located within low slopes or swales,
- proximity to water bodies, and
- large contributing surface drainage area.

Combined, these factors can determine areas of highest probability to supply a well with sufficient yield and have been successfully applied to fieldwork by the author. The geologist must weigh the factors together to identify areas of highest potential. These positive well factors are also helpful in the understanding of the conceptual model of the aquifer.

Future Work

The amount of available water within the Precambrian Basement Aquifer is poorly understood but could be important for water resource planning. More data on the aquifer and wells are needed. In addition, detailed lineament and hydrogeologic studies could help generate better estimates of aquifer parameters, availability, groundwater flow, and recharge. Quantitative studies of well yield and positive contributing factors of yield using GIS and other statistical (multivariate) analyses are needed and could also help better define the conceptual model. Lastly, a detailed study of the fractures and faults is also needed to better understand flow in the system. Quantitative information on fractures such as lateral and vertical connectedness, density, frequency, and apertures would help characterize the system.

Conclusions

The Precambrian Basement rocks of the Llano Uplift cover approximately 1,290 square miles and provide the sole source of water for an estimated 7,200 people and 73,000 livestock with estimated pumping of 3,600 acre-feet per year. Faulting and fracturing are important elements to the availability of groundwater in the Precambrian Basement Aquifer of the Llano Uplift. Detailed geologic mapping has shown that faults and fractures are more prevalent than shown on published geologic maps and can be targeted for groundwater production; therefore, groundwater supplies may be greater than previously considered.

The Precambrian Basement Aquifer could be considered a minor aquifer of Texas because it supplies “relatively small quantities of water in large areas of the State.”

Acknowledgments

The Texas Water Development Board and the Texas Natural Resource Information System provided many geographic information system coverages and data sets used in this evaluation. Dr. Robert Reed digitized the Precambrian geology of the Llano Uplift from the Llano Geologic Atlas Sheet of Barnes (1981). Dr. Mark Helper painstakingly converted those digital data into geographic information system files, which were used in this paper. Jen Garcia (Lower Colorado River Authority) provided geographic information system coverages of surface streams in the study area. Ron Fieseler and Paul Babb (Blanco-Pedernales Groundwater Conservation District) provided well and water-quality data. Angelina Bonetti (Hickory Underground Water Conservation District #1) provided well and water quality data. The author benefited from the observations of the drillers of Virdell Drilling Inc., and discussions with Taylor Virdell. Brian A. Smith, P.G., and John Dupnik, P.G., reviewed this paper and provided helpful suggestions and comments. April Hoh and Eddie Collins provided constructive review and commentary that improved the quality of this paper. Finally, the author would like to thank Robert Mace for his formatting and editorial work.

References

Ashworth, J.B., and Flores, R.R., 1991, Delineation criteria for the major and minor aquifer maps of Texas: Texas Water Development Board Limited Publication LP-212.

Ashworth, J.B. and Hopkins, J., 1995, Aquifers of Texas: Texas Water Development Board Report 345.

Barker, D.S., Muehlberger, W.R., Reed, R.M., 1996, Stop 12: Coarse-grained granite at Wirtz Dam: *in* Mosher, S., editor, Guide to the Precambrian geology of the eastern Llano Uplift, South-Central GSA Fieldbook, 78 p.

Barnes, V.E., 1981, Geologic atlas of Texas—Llano sheet: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

Bouwer, H., 1978, Groundwater hydrology: McGraw-Hill, New York, 480 p.

Brune, G., 1975, Major and historical springs of Texas: Texas Water Development Board Report 189, 94 p.

Daly, C., 1998, Annual Texas precipitation, geospatial data presentation form: vector digital data from http://www.ocs.orst.edu/prism/

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley and Sons, 824 p.

Ewing, T.E., 1991, The tectonic framework of Texas: Text accompanying "The Tectonic Map of Texas" The University of Texas at Austin, Bureau of Economic Geology.

Ewing, T., 2004, Phanerozoic development of the Llano Uplift: *in* Hoh, A., and Hunt, B., coordinators, Tectonic History of Southern Laurentia: A look at Mesoproterozoic, Late-Paleozoic, and Cenozoic Structures in Central Texas, Austin Geological Society Fieldtrip Guidebook 24, 90 p.

Follet, C.R., 1973, Ground-water resources of Blanco County, Texas: Texas Water Development Board Report 174, 95 p.

Goerdel, A., 1998, Soil survey of Llano County, Texas: U.S. Department of Agriculture, Natural Resource Conservation Services, 196 p.

Heath, R.C., 1983, Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220.

Hoh, A., and Hunt, B., coordinators, 2004, Tectonic history of Southern Laurentia: A look at Mesoproterozoic, Late-Paleozoic, and Cenozoic Structures in Central Texas, Austin Geological Society Fieldtrip Guidebook 24, 90 p.

Hunt, B.B., 2000, Mesoproterozoic structural evolution and lithologic investigation of the western Llano Uplift, Mason County, central Texas: [unpublished M.A. thesis], The University of Texas at Austin, 138 p.

Johnson, B., 2004, Late-Paleozoic Structures: *in* Hoh, A., and Hunt, B., coordinators, Tectonic history of Southern Laurentia: A look at Mesoproterozoic, Late-Paleozoic, and Cenozoic structures in Central Texas: Austin Geological Society Fieldtrip Guidebook 24, 90 p.

Landefeld, M. and Bettinger, J., 2002, Agriculture and natural resources: Ohio State University Fact Sheet, http://ohioline.osu.edu/anr-fact/0013.html.

Landers, 1972, Ground-water resources of the crystalline rocks, Llano Area, Texas: M.S. Thesis, The University of Texas at Austin. 99 p.

Landers and Turk, 1973, Occurrence and quality of ground water in crystalline rocks of the Llano area, Texas: Groundwater, v. 11, p. 5–10.

Larkin, T.J., and Bomar, G.W., 1983, Climatic atlas of Texas: Texas Department of Water Resources Limited Publication LP-192.

Long, L., 2004, Middle to Late Cambrian nonconformity in the Llano Uplift, *in* Hoh, A., and Hunt, B., coordinators, Tectonic history of Southern Laurentia: A look at Mesoproterozoic, Late-Paleozoic, and Cenozoic structures in Central Texas: Austin Geological Society Fieldtrip Guidebook 24, 90 p.

Mace, R.E. and Angle, E.S., 2004, Aquifers of the Edwards Plateau, *in* Mace, R.E., Angle, E.S., and Mullican, W.F., III, editors, Aquifers of the Edwards Plateau, Texas Water Development Board Report 360, 366 p.

McMahan, C.A., Frye, R.G., and Brown, K.L., 1984, The vegetation types of Texas, including crop land: Texas Parks and Wildlife Department, 40 p.+map.

Mosher, S., 1996, Guide to the Precambrian geology of the eastern Llano Uplift, central Texas: *in* Mosher, S., editor, Field trip guide for the Geological Society of America 30th Annual South-Central Section Meeting, Austin, TX, Spring 1996.

Mosher, S., 1998, Tectonic evolution of the southern Laurentian Grenville orogenic belt: Geological Society of America Bulletin, v. 110, no. 11, p. 1357–1375.

Moore, R., Schwarz, G., Clark, S., Walsh, G., and Degnan, J., 2002, Factors related to well yield in fracture-bedrock aquifer of New Hampshire: U.S. Geological Survey Professional Paper 1660, 51 p.

Morris, D.A., Johnson, A.I., 1967, Physical properties of rock and soil material, as analyzed by the hydrologic laboratories of the U.S. Geological Survey, 1948–1960: U.S. Geological Survey Water-Supply Paper 1839-D.

Paige, S., 1912, Description of the Llano and Burnet quadrangles: U.S. Geological Survey, Geologic Atlas of Texas, Burnet Folio, Texas, No. 183, 16 p.

Preston, R.D., Pavlicek, D.J., Bluntzer, R.L., and Derton, J., 1996, The Paleozoic and related aquifers of Central Texas: Texas Water Development Board Report 346, 85p.

Reed, R.M., 1999, Emplacement and deformation of late-syn-orogenic, Grenville-age granites in the Llano Uplift, central Texas: The University of Texas at Austin, unpublished Ph.D. dissertation.

Reese, J.F., Mosher, S., Connelly J., and Roback, R.C., 2000, Mesoproterozoic chronostratigraphy of the southeastern Llano uplift, Central Texas: Geological Society of America Bulletin, v. 112, p. 278-291.

Rose, P., 2004, Regional perspectives on the Edwards Group of Central Texas—Geology, geomorphology, geohydrology and their influence on settlement history; in Edwards water resources in Central Texas: Retrospective and Prospective; Symposium Co-hosted by the South Texas Geological Society and the Austin Geological Society, San Antonio, Texas, May 21, 2004.

Schmittle, J.M., 1987, Brittle deformation and cataclasis on the southwest flank of the Llano Uplift, Mason County, Texas: Texas A&M University, College Station, M.S. thesis, 141p.

Stricklin, F.L, Smith, C.I. and Lozo, F.E., 1971, Stratigraphy of lower Cretaceous Trinity deposits of Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations71, 63 p.

TWDB, 2002, Water for Texas—2002: State Water Plan published by the Texas Water Development Board, January 2002, Austin, Texas.

USDA [U.S. Department of Agriculture], 2002, Census of agriculture, county profile, Llano, Texas http://www.nass.usda.gov/census/census02/profiles/tx/cp48299.PDF.

USDA [U.S. Department of Agriculture], 2002b, Census of Agriculture, County Profile, Mason, Texas http://www.nass.usda.gov/census/census02/profiles/tx/cp48319.PDF.

Wermund, E.G., 1996, Physiographic map of Texas: The University of Texas at Austin, Bureau of Economic Geology, Factsheet, 2 p.

Biography:Brian was born in Austin, Texas, and is a fifth generation Texan and a hydrogeologist at the Barton Springs/Edwards Aquifer Conservation District in Austin. Brian earned a B.S. and M.S. from The University of Texas at Austin. Brian spends his free time in Mason County at a small cabin on the Llano River that he and his wife, Sophie, have built. The cabin is supplied by water from a well drilled into the Packsaddle Schist along a fault zone. Locating this well marked the beginning of Brian's interest into the groundwater resources of the Precambrian Basement Aquifer.

South Rim, Big Bend (photo by Brian Hunt)