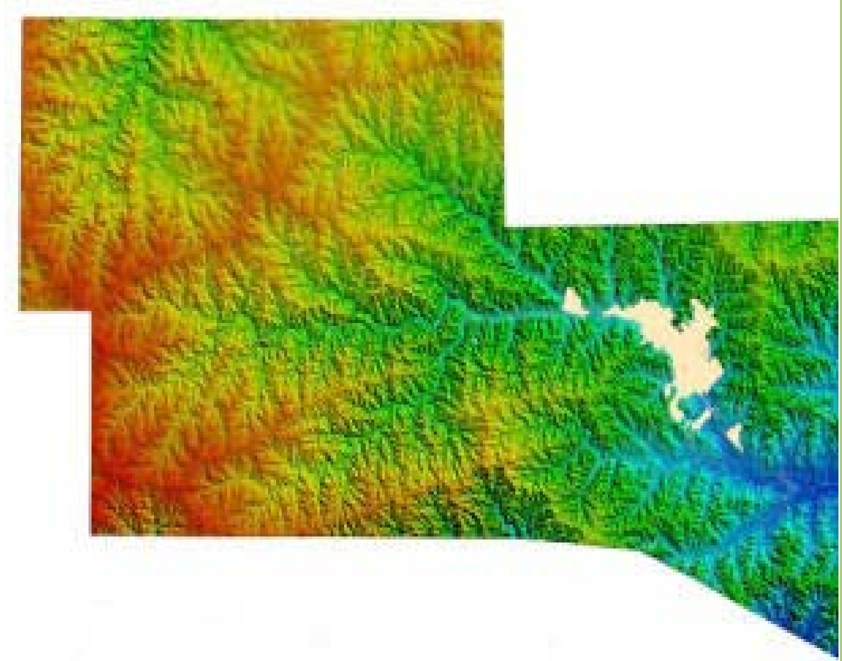
Strata Geological Services

2008

HYDROGEOLOGY OF KERR COUNTY



WILLIAM FEATHERGAIL WILSON, PG # 21

STRATA GEOLOGICAL SERVICES

12/19/2008

December 19, 2008

Headwaters GCD
125 Lehman St.
Kerrville, Texas 78028

RE: ***Hydrogeological Summary Report – 2008***

Dear HGCD and Readers;

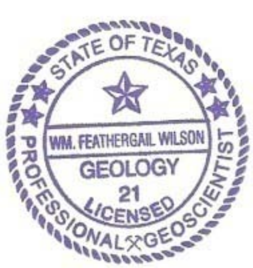
Strata Geological Services is pleased to submit this hydrogeological report summarizing a four year project designed to accomplish a stratigraphic, flow regime and aquifer framework for Kerr County, Texas through drilling, logging mapping, monitoring and consulting for HGCD.

This report is to be viewed as a work in progress. Hydrogeological analysis is a very complex and long term process requiring voluminous amounts of data and interpretation. New data requires modified interpretation. It is on an going process and will remain so for decades to follow.

The drilling that HGCD has initiated added immeasurably to the understanding of the complex stratigraphy existing in Kerr County. It drastically altered the literature and former interpretations that have put forth for the past fifty years. The monitor well and research drilling was the single most important step. Interpretation of the hydrogeological framework could not have been accomplished to the degree that it now represents without the new well index.

Strata Geological Services stands ready to answer any further questions and looks forward to your comments and the comments of other geologists as well as the general public as to the interpretations, data and conclusions reached herein.

William Feathergail Wilson, PG # 21



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I INTRODUCTION

Headwaters GCD launched an ambitious program in 2004 to enhance groundwater conservation and the decision process associated with the mandated goals of a groundwater conservation political entity. The Board decided to set a new management policy by promoting an internal employee, Gene Williams, as the General Manager. The Board realized, based upon experience and consultation with other conservation districts, that a General Manager's time was largely usurped by administration and other details. As a consequence the Board decided to contract the geological requirements and scientific duties to Strata Geological Services.

Strata's direction evolved through time to include local consulting with drillers, home owners, city and county political entities. Strata supervised a very complex drilling program in addition to modeling, mapping, database building and advising the Board on numerous technical issues that arose during the course of the contract term.

Strata continues to educate and inform the general public on the progress of the geological research in Kerr County as well as cooperating and sharing interpretations with other Texas Hill Country groundwater conservation districts. Scientific presentations have been made at the local, regional and national level concerning the research performed across the 1,100 square mile area of Kerr County.

The effort has focused upon data gathering through HGCD drilling, as well as other types of data, along with concomitant interpretation of that data. The interpretations have updated the pre-existing literature and assumptions that will have a long lasting impact on surrounding Hill Country geology. The HGCD drilling program has contributed immensely to the understanding of the complex stratigraphy that is present beneath Kerr County. The drilling program has proved to be the single most important aspect to the entire scientific endeavor. It has paved the way for the present and future data directions through the long term monitoring program and the discoveries that came forth.

The results of this endeavor will hopefully set the stage for an improved decision process based upon scientific investigations and new interpretations of the subsurface both within the boundaries of Kerr County and the surrounding areas

II KERR COUNTY LOCATION, FACTS AND PROJECTIONS

KERR COUNTY IS UNIQUE IN THE FACT THAT IT IS THE LARGEST COUNTY IN THE TEXAS HILL COUNTRY WITH THE LARGEST POPULATION. THE POPULATION RACE MAY SOON BE ECLIPSED BY KENDALL, COMAL AND HAYS COUNTIES, WHICH ARE UNDERGOING ENORMOUS POPULATION INCREASES.

KERR COUNTY IS BLESSED WITH A PLETHORA OF SMALL AND LARGE SPRINGS THAT FEED INTO THE GUADALUPE WATERSHED. THE GUADALUPE RIVER IS THE KEY ECONOMIC INGREDIENT THAT ATTRACTS RETIREES AND PROFESSIONALS TO THE TEXAS HILL COUNTRY AND SPECIFICALLY KERR COUNTY. THE HGCD BOARD IS FULLY AWARE OF THIS ECONOMIC ASSET AND THEY HAVE TAKEN STEPS TO RULE OUT ANY THREAT TO THESE SPRINGS BY PLACING A MORATORIUM ON ALL PERMITTED WELLS TO BE DRILLED INTO THE EDWARDS AQUIFER.

KERR COUNTY LIES ON THE SOUTHEASTERN EDGE OF THE 38,000 SQUARE MILE EDWARDS PLATEAU. APPROXIMATELY TWO-THIRDS OF KERR COUNTY IS COVERED BY THE EDWARDS GROUP OF FORMATIONS. THE REST OF THE COUNTY IS COVERED EITHER BY ALLUVIAL DEPOSITS ALONG THE GUADALUPE WATERSHED OR THE UPPER GLEN ROSE MARLS AND THIN BEDDED LIMESTONES.

SOME KERR COUNTY GEOGRAPHIC AND DEMOGRAPHIC FACTS ARE OUTLINED BELOW.

CATEGORY	NUMBERS
POPULATION (2008) ESTIMATE	49,000
SQUARE MILES	1,107.66
ACRES	708,902.4
ELEVATION RANGE	1,450 - 2,400’
AVERAGE RAINFALL	32.6”
AVERAGE EVAPOTRANSPIRATION	61”
**SURFACE AND GROUNDWATER USE ESTIMATE (2008) ** **	8,233 ACRE FEET

NOTE: APPROXIMATELY ½ OF THE ESTIMATED WATER USE IS DERIVED FROM THE CONJUNCTIVE USE OF THE GUADALUPE RIVER AT THE CITY OF KERRVILLE.

TABLE 1: - DEPICTING KERR COUNTY FACTS AND DEMOGRAPHICS

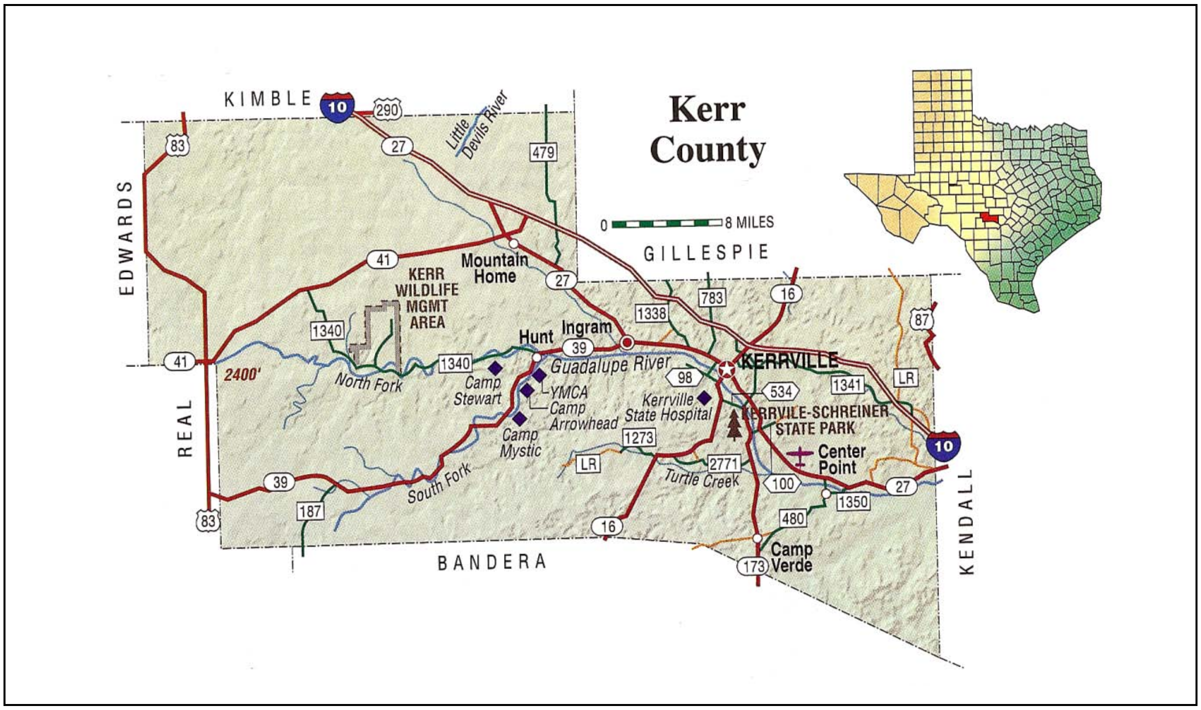


Figure 1: - Kerr County roads, elevation and features.

Kerr County is a mix of landowners and industries, including retirees, commercial ranches, recreational ranches, summer camps, medical facilities, sand and gravel mines and metroplex support retail businesses. Almost one-half of the population resides within the cities of Kerrville and Ingram and surrounding rural subdivisions. Population centers also exist in the unincorporated areas of Center Point and the area near Hwy 27 in the southeast portion of the county. The western portion of the county is occupied by large parcels of ranch land. Recent population shifts have been noted around Mountain Home and the YO and Dominion Ranch areas in the northwest portion of the county. These areas around Mountain Home and the northwest are being cut up into 25-100 acre parcels for retirees and hunting ranches. Most of the population is concentrated in and around Kerrville and southeast along the Guadalupe watershed.

Population is expected to rise to about 100,000 people over the next 40-years placing a larger burden upon the surface water and groundwater resources.

The conjunctive use of surface water is not expected to rise proportionately with the demand for water. Guadalupe River water rights are now over allocated and it is doubtful the City of Kerrville and the Upper Guadalupe River Authority will be able to increase their water rights substantially. During droughts the Texas Commission of Environmentally Quality (TCEQ) has cut back the City of Kerrville in 500,000 gallons per day increments as the flow of the Guadalupe decreases. The water is replaced by increased withdrawal from active city wells. The annual water right limits are now at approximately 6,000 acre feet. The City of Kerrville has recently been pumping water from the river at approximately 4,800 acre-feet per year.

The population of 100,000 people will equate to an average annual usage of approximately 16,802 acre feet. About 64% of that average annual use will probably be allocated to groundwater by 2040.

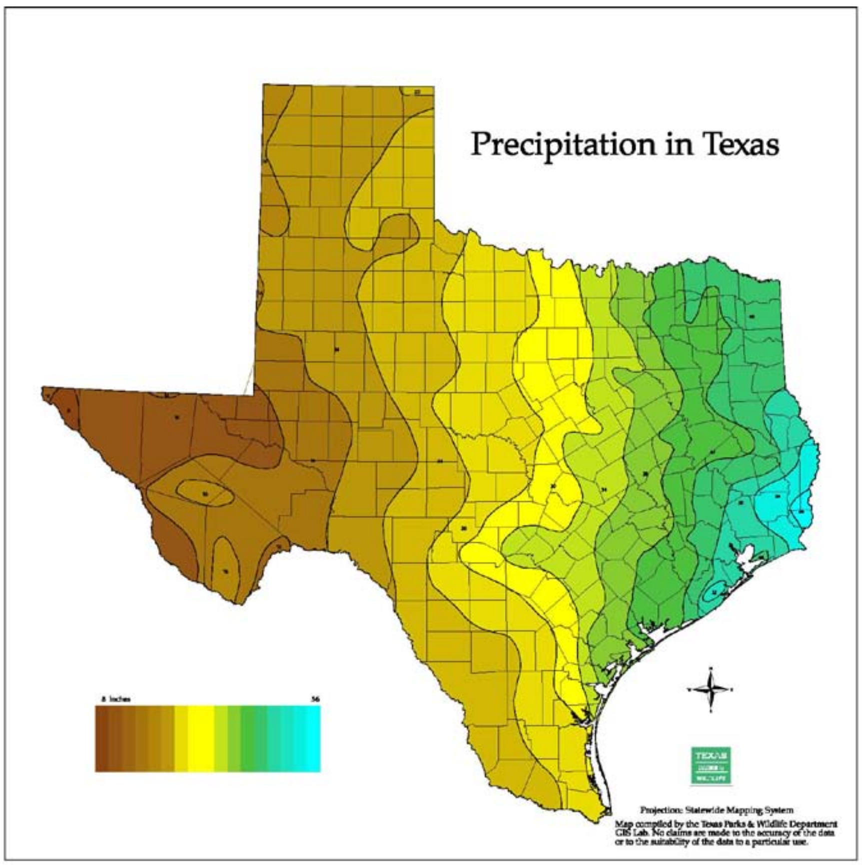


Figure 2: - Annual average Texas rainfall map

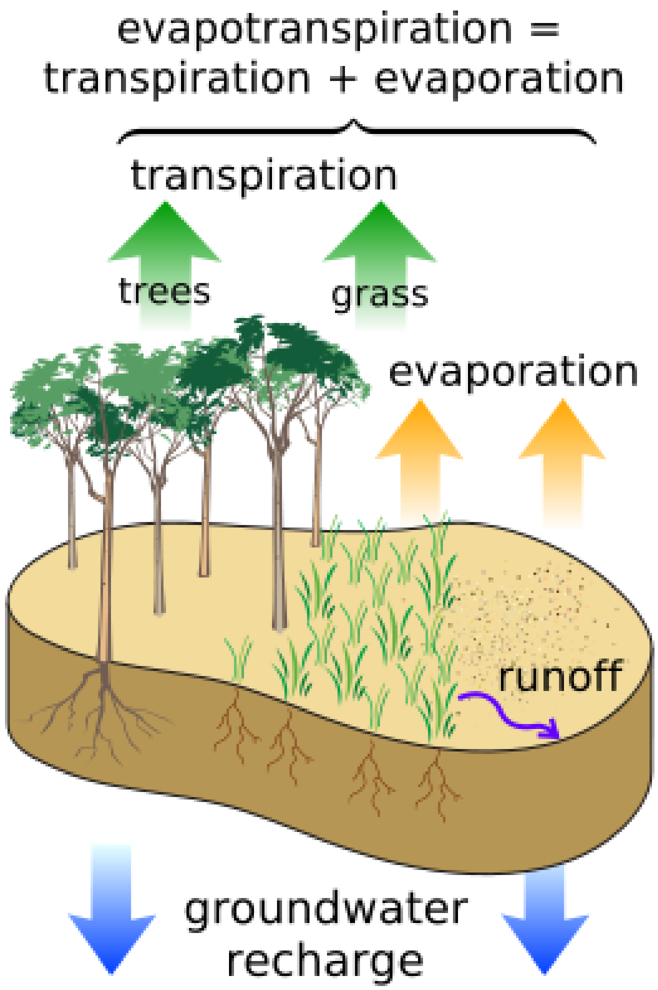


FIGURE 3: - EVAPOTRANSPIRATION CONCEPT. KERR COUNTY HAS AN AVERAGE EVAPOTRANSPIRATION OF APPROXIMATELY 61" PER YEAR AND AN AVERAGE RAINFALL OF 32.6". THIS REPRESENTS AN AVERAGE ANNUAL DEFICIT OF 29.4" OR 2.45 FEET PER YEAR. IF GROUNDWATER IS STORED ON THE SURFACE IN LARGE QUANTITIES, THIS IS NOT A PRUDENT CONSERVATION PRACTICE.

III KERR COUNTY GEOLOGY

The geology of Kerr County is far more complex than depicted in previously published literature. This is especially applicable to the Lower Cretaceous geology that contains the primary aquifers in the county. This study will add appreciably to the distribution and aquifer characteristics found within the county.

Four major geological divisions are present across Kerr County. All of these major divisions have been penetrated across the county. They are tabulated below.

Major Geological Division	Age Ranges	Description
Pleistocene/Holocene	1.8-present million years	Alluvial sands, gravels, silts and clays along the streams and rivers
Cretaceous Period	93-144 million years ago	Surface and subsurface geology: note the missing time
Paleozoic Period	290-543 million years ago	Pennsylvanian black shales and Ordovician dolomites have been drilled
Pre-Cambrian Era	543-1,600 million years ago	Metamorphic and igneous crustal complex, undrilled

Table 2: - Depicting Kerr County crustal layers or gross stratigraphy.

Fresh groundwater (400-1,000 ppm) is thus far confined to the Cretaceous Period aquifers. However, fresh groundwater may also exist in a portion of the unexplored and undeveloped Paleozoic aquifers. Brackish and saline groundwater certainly exists within Paleozoic aquifers. A water classification is presented below in parts per million (ppm) in total dissolved solids (TDS).

Water Category	TDS Range
Fresh water	0-1,000 ppm
Brackish water	1,000- 36,000 ppm
Saline water	36,000-400,000 ppm

Table 3: - Groundwater TDS classification

All of the surface outcrops within the county are attributed to the Cretaceous Period. The surface and subsurface Cretaceous Period in the Kerr County stratigraphic section is presented below.

Period		**Epoch -Age**	**Group-Formation**	**Members**	**Description**
Cretaceous	Upper	Cenomanian 93.5 – 99 million years ago	Buda		Limestone
			Del Rio		Clay
	Lower	Albian 99 – 112 million years ago	Edwards	Salmon Peak	Limestone and dolomite, aquifer
				Fort Terrett	
			Glen Rose	Upper	Marl and thin bedded limestone
				Lower	Limestone and dolomite, aquifer
			Pearsall	Hensel	Sand, sandstone, microdolomite, marl aquifer
		Aptian 112-121 million years ago		Bexar	Marl, clay, sand and paleosol
				Cow Creek	Limestone and sandstone, aquifer
				Hammett	Clay
		Neocomian 121-144 million years ago	Sligo		Limestone, aquifer
			Hosston		Sand and gravel, aquifer

Blue color indicates an aquifer.

FIGURE 4: - AQUIFER AND AQUITARD COLUMNAR SECTION FOR KERR COUNTY.

THE DETAILS OF THE ABOVE STRATIGRAPHIC COLUMN ARE FAR MORE COMPLEX THAN SHOWN ABOVE. DISTRIBUTION OF SOME OF THESE UNITS MERGES INTO OTHERS FROM SOUTH TO NORTH AS WELL AS EAST TO WEST. THE PRESENCE OF THE LLANO UPLIFT ISLAND COMPLEX DISGORGED HUGE AMOUNTS OF SAND AND GRAVEL INTO THE ADVANCING SHALLOW WATER LAGOONAL CRETACEOUS SEAS THROUGH A SERIES OF BRAIDED STREAMS. THIS GREAT CLASTIC DEPOSITIONAL SEQUENCE PUSHED THE LAGOONAL CARBONATES TO THE SOUTH ACROSS THE COUNTY INTO BROAD DISTRIBUTARY LOBES.

BUDA LIMESTONE

THE BUDA LIMESTONE OUTCROPS ACROSS A NARROW AREA IN WEST-CENTRAL KERR COUNTY AS AN UPPER CRETACEOUS REMNANT. THE BUDA IS DESCRIBED AS A CREAM COLORED TINTINID BARING BIOMICRITE. THE TINITINDS ARE THE REMAINS OF FOSSIL GLOBULAR SHAPED PHYTO-PLANKTON. A BIOMICRITE IS A FINE GRAINED APHANITIC LITHIFIED LIME MUD. NO AQUIFERS ARE PRESENT WITHIN THE LIMITED DISTRIBUTION OF THE BUDA LIMESTONE. IT IS INTERESTING TO NOTE THAT SUB-BITUMINOUS AND BITUMINOUS COAL FOUND WITHIN THE SUBSURFACE IN THE CRETACEOUS SYSTEM INDICATES THE PRESENT SURFACE OF KERR COUNTY WAS ONCE BURIED BELOW 3,000-5,000 FEET OF UPPER CRETACEOUS AND TERTIARY SEDIMENTS. THE AREA WAS UPLIFTED APPROXIMATELY 6.5-10.0 MILLION YEARS AGO STRIPPING THE 3,000-5,000 FEET OF OVERBURDEN OFF THE PRESENT SURFACE. THE BUDA IS THE LAST REMNANT OF THIS PERIOD. THE BUDA IS ABOUT 20-40 FEET THICK.

DEL RIO CLAY

THE DEL RIO CLAY IS A THIN UNIT (15-30 FEET) THAT UNDERLIES THE BUDA LIMESTONE AND NOTABLY OUTCROPS IN THE VICINITY OF GARVEN'S STORE IN THE WEST CENTRAL PORTION OF THE COUNTY. A FEW VERY SMALL ISOLATED AND ABANDONED HAY FIELDS REVEAL THE PRESENCE OF THE DEL RIO CLAY. THE LITHOLOGY OF THE CLAY IS DESCRIBED AS FOSSILIFEROUS, TAN, EXPANDABLE CLAY, CONTAINING THE PELECYPOD EXOGYRA ARIENTINA. IT IS A WEATHERING PRODUCT OF THE DEPOSITION OF LARGE AMOUNTS OF VOLCANIC GLASS.

FIGURE 5: – EXOGYRA ARIENTINA

EDWARDS GROUP

THE EDWARDS GROUP WITHIN KERR COUNTY IS COMPOSED OF TWO FORMATIONS. THE LOWER MOST FORMATION IS DESIGNATED AS THE FORT TERRETT, WHILE THE UPPER UNIT IS KNOWN AS THE SALMON PEAK FORMATION. THE DIVISION IS NOT READILY RECOGNIZABLE OVER THE ENTIRE EXPANSE OF THE COUNTY, EVEN THOUGH THEY HAVE BEEN MAPPED BASED UPON ELEVATIONS RATHER THAN LITHOLOGY. THE EDWARDS GROUP CANNOT BE DIVIDED WITH ANY ACCURACY IN THE SUBSURFACE. THE DIVISION MAY NOT BE APPLICABLE TO KERR COUNTY OUTCROPS OR SUBSURFACE DESCRIPTIONS AND THIS MAY BE ONE OF THE NEW REVELATIONS AND REVISIONS TO THE LITERATURE. THE EDWARDS IS KNOWN TO BE AS THICK AS 645 FEET, THINNING TO 0 FEET OVER THE SOUTHEASTERN PORTION OF THE COUNTY. THE EDWARDS IS MAJOR LOW YIELD AQUIFER THAT COVERS ABOUT 2/3 THIRDS OF THE COUNTY. IT IS A KARSTED AQUIFER, WHICH CREATES SOME UNIQUE HYDROGEOLOGICAL PROPERTIES. KARST IS A GERMAN TERM ORIGINALLY ASSIGNED TO GEOMORPHIC FEATURES FOUND ON THE LANDS THAT BORDER THE EASTERN ADRIATIC SEA. THE TERM HAS EVOLVED TO DESCRIBE NOT ONLY THE SURFACE, BUT THE CAVERNOUS NATURE OF THE POROSITY AND PERMEABILITY OF THE SUBSURFACE.

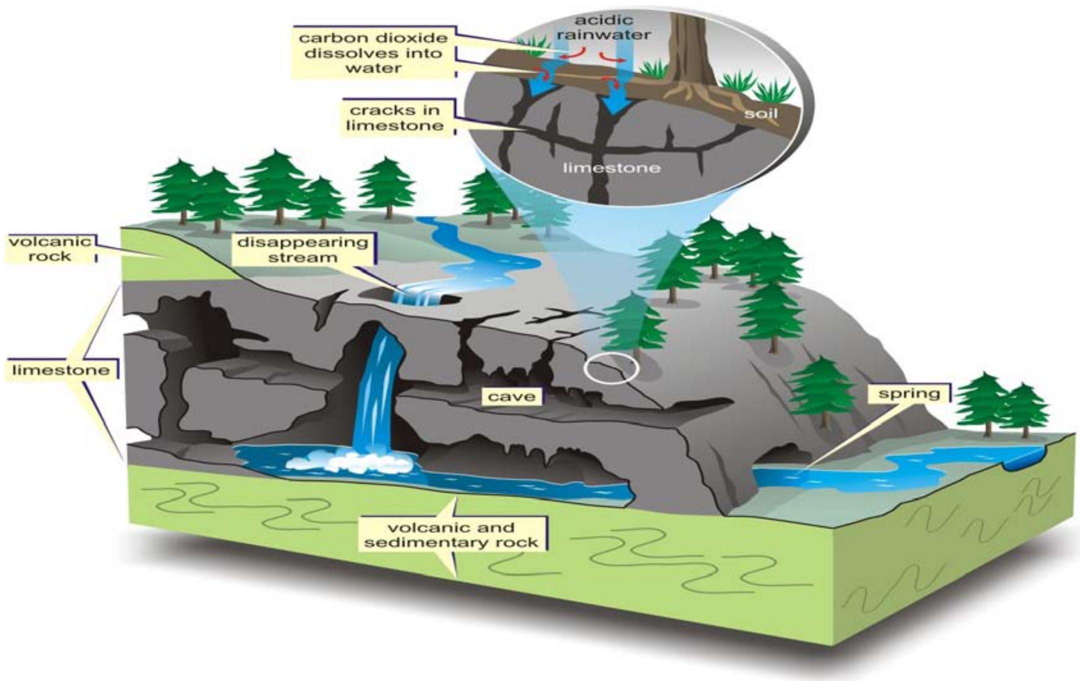


FIGURE 6: – KARSTED TERRAIN AND SUBSURFACE AQUIFER CHARACTERISTICS.

GROUNDWATER WITHIN THE EDWARDS GROUP EMANATES AS SEEPS AND SPRINGS FILLING AND SOURCING THE GUADALUPE RIVER WATERSHED. THE AVERAGE ANNUAL FLOW OF THE GUADALUPE RIVER IS APPROXIMATELY 78,921 ACRE FEET OR ABOUT 7-MILLION GALLONS PER DAY OR 2.57 E+10 MILLION GALLONS PER YEAR IN KERR COUNTY. VIRTUALLY ALL OF THE WATER THAT FLOWS DOWN THE GUADALUPE IN KERR COUNTY IS GROUNDWATER THAT IS DERIVED FROM THE EDWARDS AQUIFER.

THE GUADALUPE WATERSHED WEST OF THE CITY OF KERRVILLE DRAINS A VERY LARGE AREA OF GROUNDWATER BY SPRING FLOW. RUNOFF ONLY OCCURS DURING HEAVY RAINFALL EVENTS. ESSENTIALLY THE BASE FLOW OF THE GUADALUPE RIVER WEST OF KERRVILLE CAN BE TOTALLY ATTRIBUTED TO SPRINGS EMANATING FROM THE BASAL 100 FEET OF THE EDWARDS GROUP OF FORMATIONS. THE EDWARDS'S KARST LIMESTONES AND DOLOMITES RELEASE COPIOUS AMOUNTS OF PRISTINE SPRING WATER ONTO THE UPPER GLEN ROSE MARLS AND THIN BEDDED LIMESTONES ACROSS TWO-THIRDS OF KERR COUNTY.

Flow meters have been set up at key intersections of the Guadalupe watershed by the USGS over the past century that provide yearly, monthly and daily averages. The following table depicts the year of deployment of each USGS flow station.

Station	**Deployment Year**	**Drainage Area Square Miles**	**Mean Average Flow CFS**
Johnson Creek	1941	114	**21.5**
Hunt	1966	288	**67.6**
North Fork	1968	169	**33.6**
Bear Creek****	1978	494	**131**
Kerrville	**1987**	**510**	**109**

**** Intermittent gauging. CFS=cubic feet per second.

Table 4: - Depicting USGS gauging station data.

It is obvious from the above table that records from the Johnson Creek station are the oldest and the only station that crosses the 50's drought of record. If you examine the Johnson Creek records across the 50's drought, it is noted that flow never ceased despite the common belief that the Guadalupe went completely dry during that devastating drought. Some portion of the Guadalupe may have appeared to be dry, but gravel underflow must have been present.

The author has chosen the Kerrville station as the benchmark for this study due to its data consistency and drainage area. Additional spring flow is present east of this station, but it represents the flow from the major springs and it is the most downgradient station in the county.

<u>ASSUMPTIONS & FACTS</u>

Simplification and averages create a necessity for certain assumptions. They are listed below.

1 AVERAGE ANNUAL RAINFALL: 32.6" (2.5')

2 AVERAGE ANNUAL EVAPOTRANSPIRATION: 61" (5.0')

3 RECHARGE AREA CONFINED TO ABOVE THE KERRVILLE STATION: 510 SQUARE MILES ***

4 TRIPLE THE NUMBER OF EDWARDS WELLS IN DATABASE TO: 483 WELLS

5 AN AVERAGE EDWARDS YIELD; 6.2 GPM

*** SOME RECHARGE IS REGIONAL OUTSIDE THE 510 SQUARE MILE AREA THROUGH THE EDWARDS AQUIFER

THE FOLLOWING FACTS AND CONVERSION FACTORS HAVE BEEN UTILIZED.

1 ACRE FOOT = 325,851 GALLONS

2 CUBIC FEET PER SECOND = 646,317 GALLONS PER DAY

3 510 SQUARE MILES OF WATERSHED = 326,400 ACRES

CALCULATIONS

THE FOLLOWING TABLE DEPICTS THE MEAN ANNUAL RECHARGE-DISCHARGE FOR THE EDWARDS GROUP WITHIN THE 510 SQUARE MILE AREA EAST OF THE KERRVILLE GAUGING STATION.

ANNUAL RECHARGE (ACRE FEET)	**ANNUAL EDWARDS PUMPING DISCHARGE (ACRE FEET)**	**ANNUAL EDWARDS SPRING FLOW DISCHARGE (ACRE FEET)**	**TOTAL ANNUAL MEAN DISCHARGE (ACRE FEET)**
530,000	**4,816**	**78,914**	**83,700**

TABLE 5: - EDWARDS RECHARGE AND DISCHARGE STATISTICS.

The ratio of total annual mean discharge to annual recharge of 83,799/816,000 is equal to approximately 10%. Another way of expressing this ratio is that 10% of the mean annual rainfall makes its way into the Edwards aquifer over the 510 square mile watershed area. The remaining 90% of the average annual rainfall is usurped by evapotranspiration and runoff based upon the above referenced assumptions and conversion factors.

It has been calculated that 6% of the Edwards discharge is pumped from the aquifer and therefore, 94% of the Edwards ground water drains from the springs on a mean annual basis.

<u>IMPLICATIONS</u>

1 The Kerrville gauging station is down gradient from the City of Kerrville water treatment plant. The annual mean withdrawal from the water plant is 3,921 acre feet per year (3.5 mg/d) for the City. A minor portion of the water is injected into and recovered fromn the two ASR wells, which are completed in the Hosston sands and gravels. The Bear Creek station is up gradient from the water plant and its mean annual flow rate is 131 cfs, which implies that the city is taking approximately 22 cfs from the river on average. This may be deceiving due to the fact that the time span for the ASR wells is considerable less than the mean annual flow rates. This study utilizes the long range stream flow from the Kerrville station at 109 cfs.

2 It would be prudent to encourage the UGRA, City of Kerrville and the USGS to install two additional gauging stations placing one immediately west of the city and one near the unincorporated City of Comfort. This would allow more spring flow to be measured and any irrigation withdrawal between Center Point and Comfort.

3 The protection of the aquifer and all of the Edwards springs should be the primary long term goal of the Headwaters GCD and the UGRA along with the City of Kerrville.

4 The question that needs to be answered concerning the Edwards aquifer is what is the safe pumping yield to sustain spring flow? If we had another drought of record and the spring flow declined by 68%, the pump-spring flow ratio would equate to 4816/53661 = 9% as compared to the 6% for mean annual pumpage. This is assuming that no additional pumping will occur from this point forward. If pumping were allowed to double, the ratio would equate to 18% of spring flow during a drought of record.

5 Viewing the 1952-1956 data for Johnson Creek, it was concluded that spring flow during this period declined by approximately 6.9 cfs from the mean annual flow of 21.5 cfs or 32% of the mean annual average.

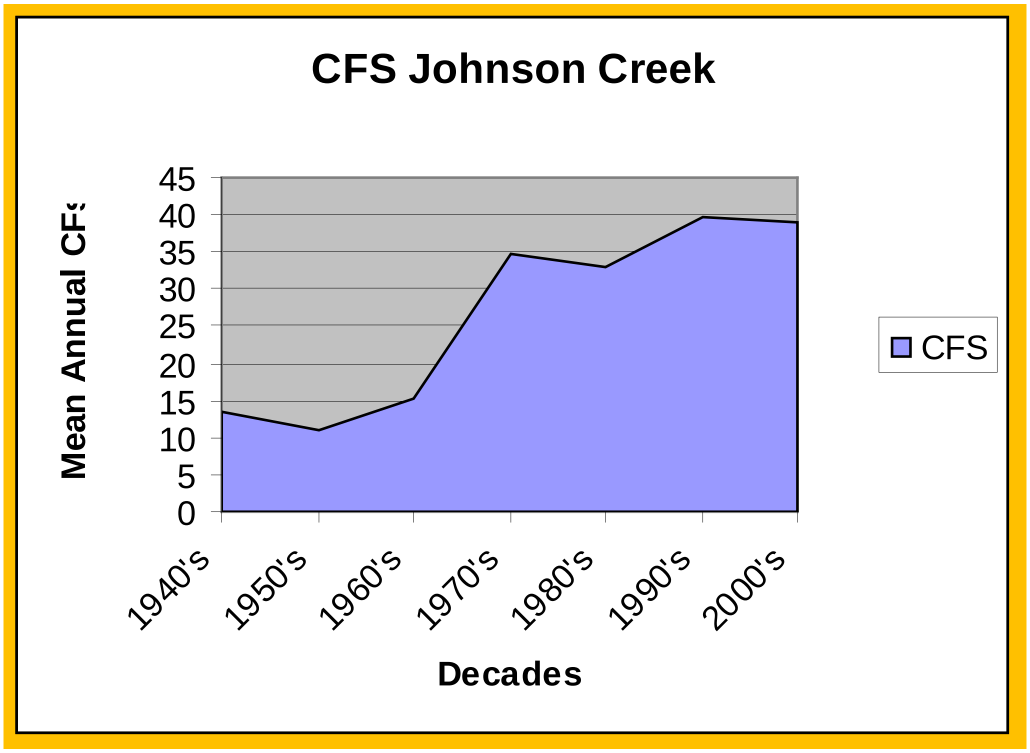


FIGURE 7: - NOTE THE INCREASE IN STREAM FLOW SINCE 1940'S, 1950'S AND 1960'S. IS THIS AN INDICATION OF CLIMATE CHANGE? TEXAS A & M PERFORMED A STUDY FOR THE EDWARDS AQUIFER AUTHORITY IN LATE 2007 AND CONCLUDED THAT THE TEXAS HILL COUNTRY COULD EXPERIENCE A 20-40% DECREASE IN AVERAGE ANNUAL RAINFALL OVER THE NEXT CENTURY. SOME SCIENTISTS BELIEVE THAT GLOBAL WARMING WILL INCREASE THE TEMPERATURE OF THE GULF OF MEXICO AND THE CENTRAL PACIFIC THAT WILL INCREASE RAINFALL ACROSS THE TEXAS HILL COUNTRY OVER THE NEXT CENTURY. THE TWDB IS NOW CONSIDERING A 30% DECREASE IN AVERAGE ANNUAL RAINFALL OVER THE NEXT CENTURY AND POTENTIAL IMPACTS ON GROUNDWATER RECHARGE.

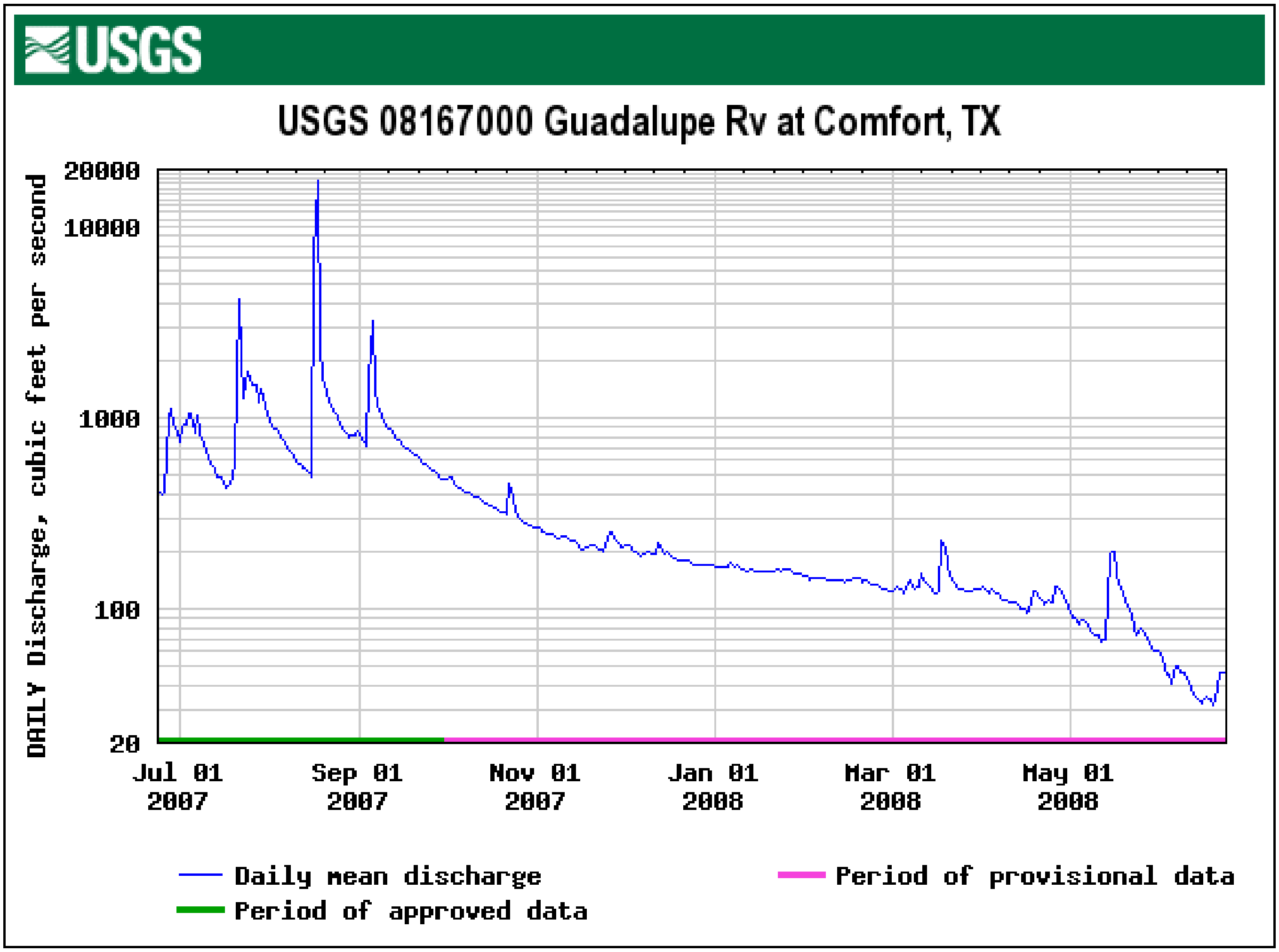


FIGURE 8: - GUADALUPE FLOW RATE 2007-2008 TRENDING INTO DROUGHT.

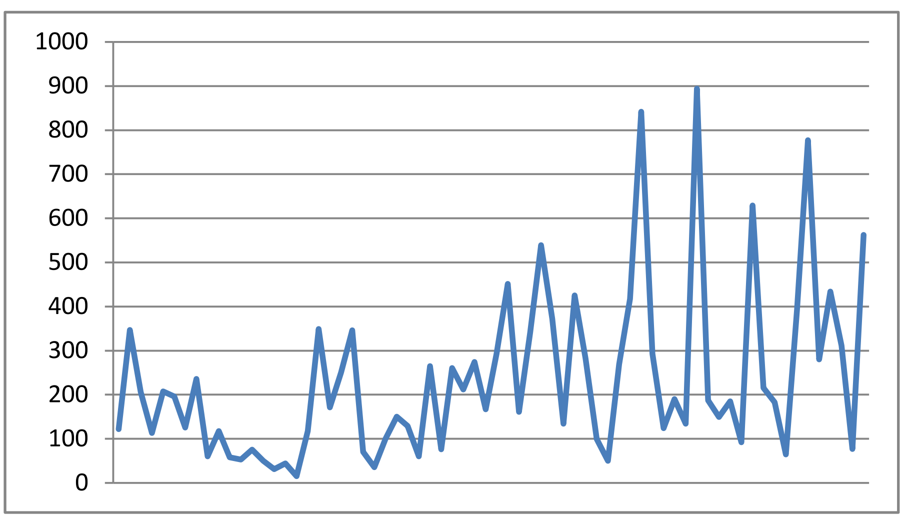


FIGURE 9: - AVERAGE ANNUAL FLOW RATE AT COMFORT 1939-2007, CFS.

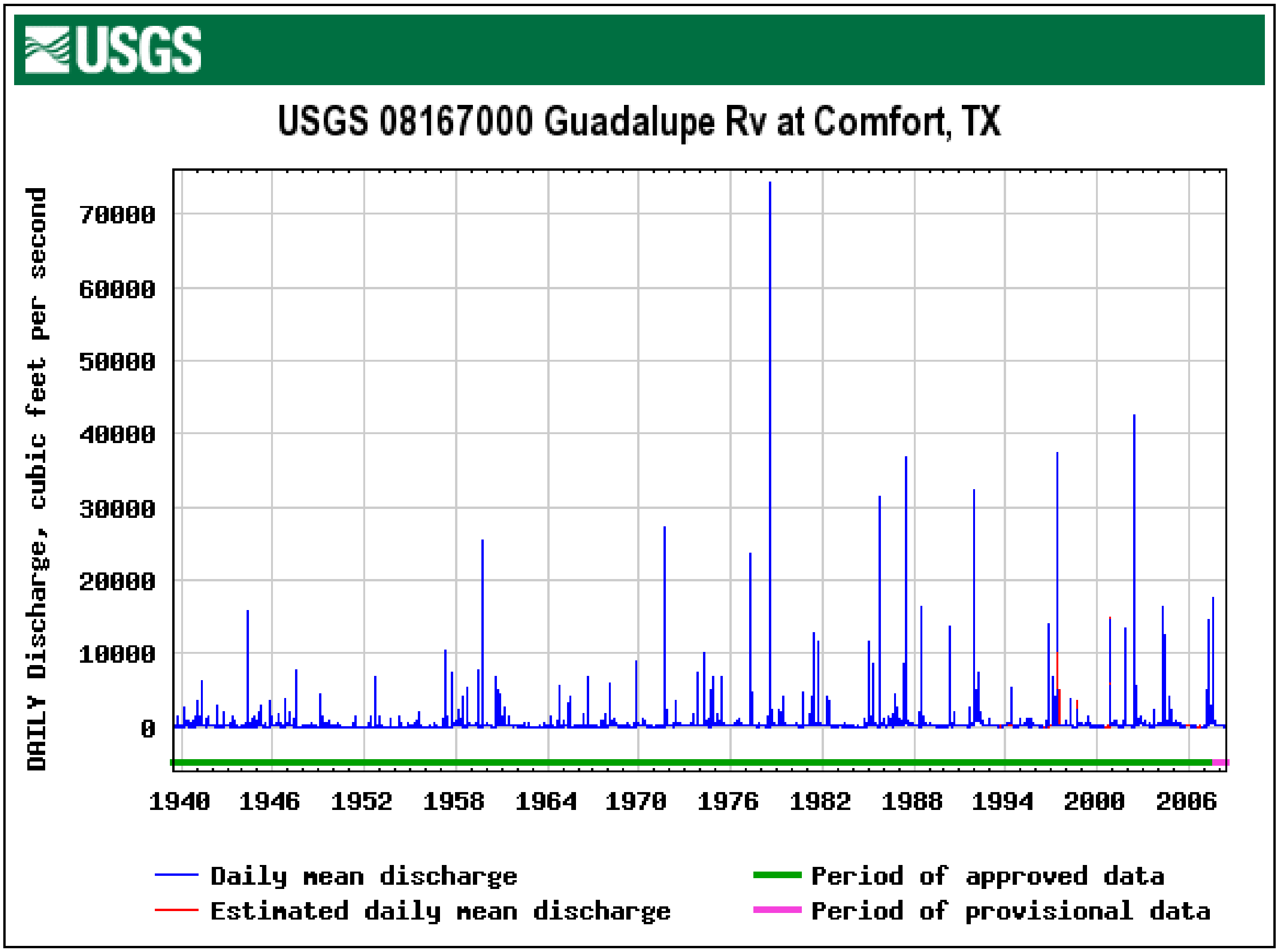


FIGURE 10: - DAILY FLOW RATE OF THE GUADALUPE 1938-2007. NOTE THE INCREASE IN AVERAGE FLOW FROM THE 1950'S THROUGH THE PRESENT.

A COMPARISON WAS MADE DURING THE MIDDLE OF THE 2007-2008 DROUGHT AT THREE USGS STREAM GAUGES ALONG THE GUADALUPE AT 7:45 AM ON JULY 1, 2008. THE FOLLOWING HISTOGRAM DISPLAYS THE DIFFERENCES IN FLOW RATES IN CUBIC FEET PER SECOND. THIS IMPLIES THE GUADALUPE IS LOSING WATER AS IT FLOWS FROM KERRVILLE TO CENTER POINT AND COMFORT. THE PERCENTAGE LOSS IS APPROXIMATELY 27% BETWEEN KERRVILLE AND COMFORT.

Point	CFS Flow 7:45 AM July 1, 2008	Comments
Kerrville	37	None
Center Point	30	Decrease may due to withdrawal by sand and gravel industry, irrigation and evapotranspiration
Comfort	27	Decrease may be due to irrigation and evapotranspiration

Table 6: - Flow rates under drought conditions, 2008.

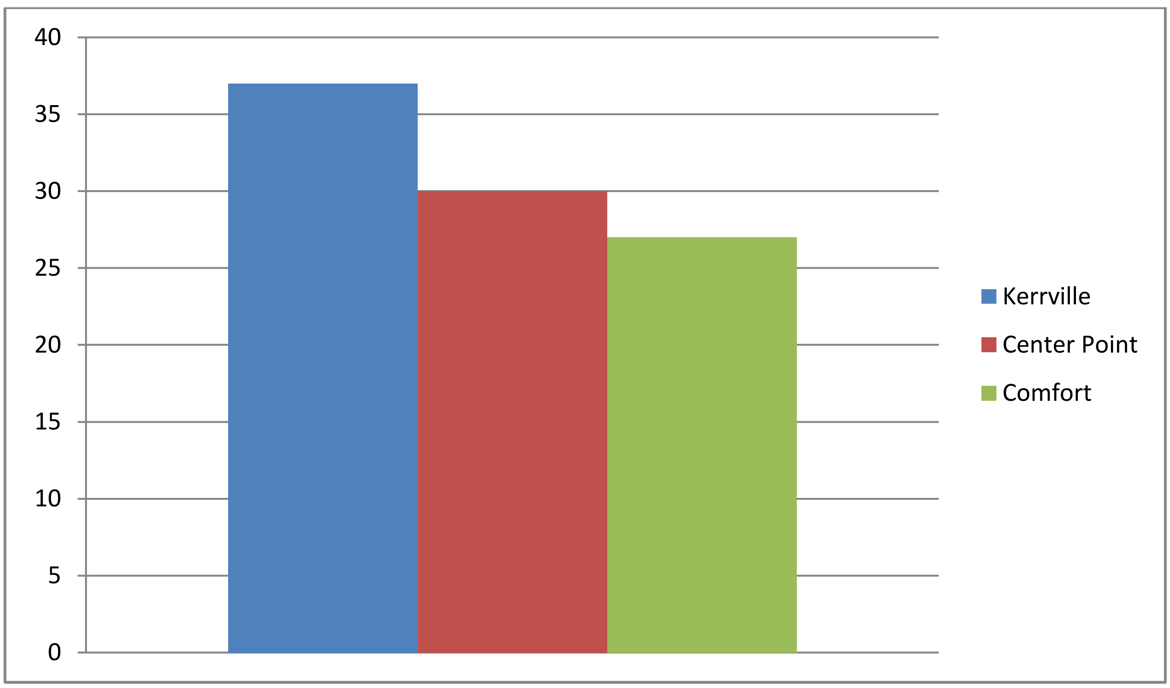


Figure 11: - Flow rates in CFS along the course of the Guadalupe during drought conditions at 7:45 AM, July 1, 2008.

This preliminary study is a broad brush overview of recharge versus discharge for the Edwards Aquifer and is subject to revision as new insights emerge from the hydrogeological maps and GAM that are now being constructed. The limitations center on several unanswered questions including;

1 HOW MUCH WATER COMES INTO THE AQUIFER BEYOND THE COUNTY BOUNDARIES?

2 HOW MUCH WATER SPRINGS FORTH FROM POINTS DOWNSTREAM FROM THE KERRVILLE GAUGING STATION?

3 HOW MUCH OF A FACTOR IS IRRIGATION AND EXERCISED WATER RIGHTS IN THE ALLUVIAL SYSTEM BETWEEN CENTER POINT AND COMFORT?

MOST OF THE EDWARDS SPRINGS OCCUR ABOUT 60 FEET FROM THE BASE OF THE UNIT. HOWEVER, MANY EXCEPTIONS TO THAT RULE OF THUMB ARE ALSO FOUND. YIELDS OF WATER WELLS DRILLED INTO THE EDWARDS TYPICALLY FALL INTO THE 2-10 GALLON PER MINUTE RANGE AND DRY HOLES CAN BE DRILLED INTO THIS KARST AQUIFER.

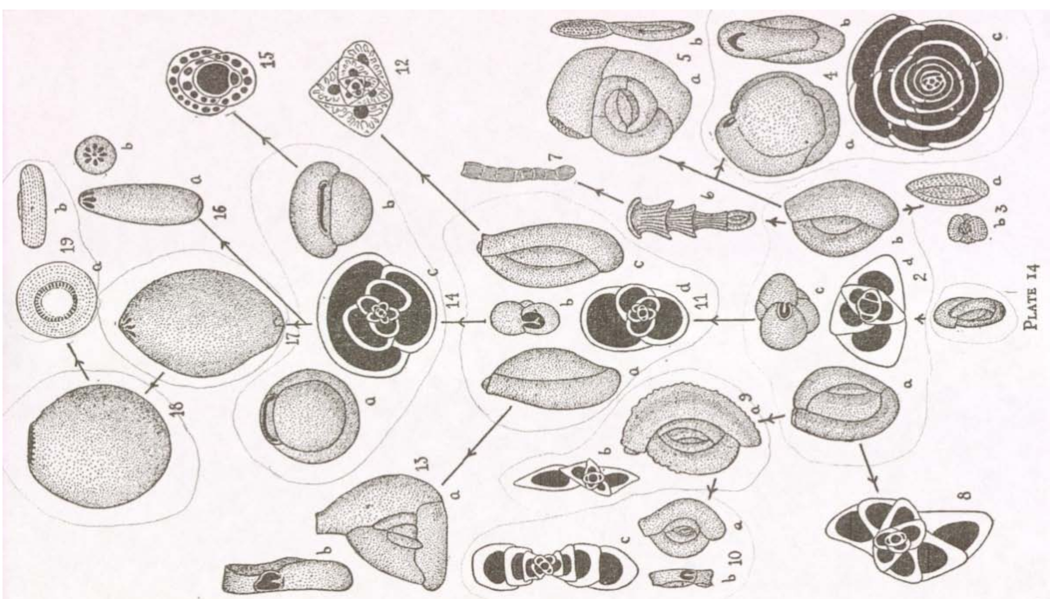


FIGURE 12: - EDWARDS GROUP FORAMINIFERA AS SEEN WITH A HAND LENS OR MICROSCOPE.

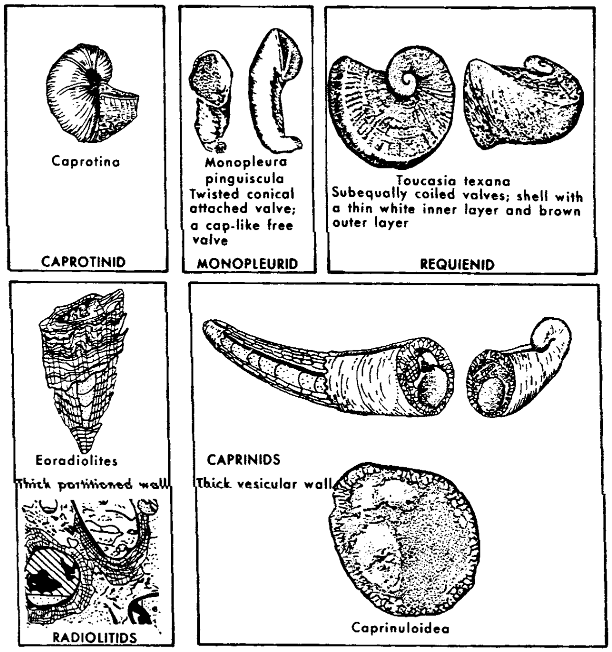


FIGURE 13: - EDWARDS PATCH REEF FOSSILS FOUND THE SW PORTION OF KERR COUNTY PRESERVED IN SILICA.

Glen Rose Formation

The Glen Rose can be easily divided into two members. The Upper Glen Rose Member is a thick sequence of marl and thin discontinuous biomicrite beds. It forms an effective barrier or aquitard to groundwater and surface water from penetrating vertically into the underlying units and aquifers. The Upper Glen Rose is generally found in sharp contact with the overlying Edwards Group. It is known as the"blue clay" by drillers. On the outcrop the Upper Glen Rose weathers to cream colored stair step topography. It is a gray marl in the immediate subsurface. This Upper Glen Rose Member is not an aquifer in Kerr County. Portions of the Upper Glen Rose contain beds of anhydrite and/or gypsum. It commonly contains fossil molds and oyster shells. One very prominent foraminifera is the Orbitolina texana which is not necessarily an index or marker fossil across the width and breadth of the county. It is typically 250-300 feet thick in the western portion of the county thinning to 100 feet or less in the eastern portion of the county.

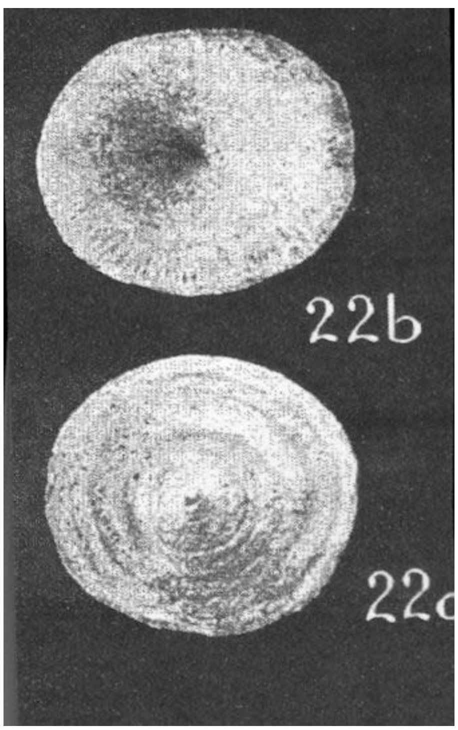


Figure 14: - Orbitolina texana foraminifera found throughout the Glen Rose Formation.

The Lower Glen Rose member of the Glen Rose Formation thins and changes facies from limestone to sand across most of the northern portion of the county. The age equivalent sand is known as the Hensel Member of the Pearsall Formation. This Lower Glen Rose Member is a massive carbonate unit and it does serve as a secondary aquifer in the southeastern portion of the county. It does contain evaporates in the form of anhydrite, gypsum and an orange colored microdolomite. The Lower Glen Rose is interbedded biomicrite, biosparite and microdolomite. The thickness of the Lower Glen Rose amounts to approximately 100-250' feet where present, but it changes facies to a sand across the northern portion of the county. It is transitional with the underlying and adjacent to the Hensel Sand member of the Pearsall Formation. The top of the Lower Glen Rose is often picked on the "Corbula bed" as shown below.

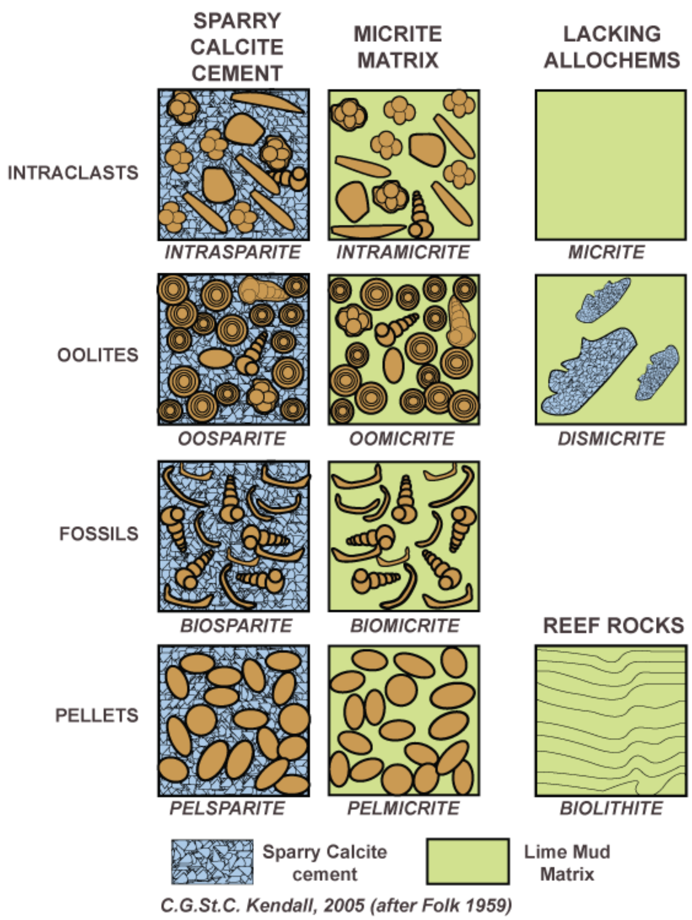
` Figure 15: - Corbula bed at the top of the Lower Glen Rose (20X)

At this point the author introduces a carbonate classification scheme. The R.L. Folk classification is used throughout the report including the lithologic logs found in most of the Chapters. The author was a graduate student at UT @ Austin working under Dr. R.L. Folk.

CLASSIFICATION OF CARBONATES

ROCKS ARE CLASSIFIED IN ORDER TO COMMUNICATE INFORMATION ABOUT THEM. ALL CLASSIFICATIONS OF LIMESTONES ARE ARBITRARY AND THEY FREQUENTLY OVERLAP OR DO NOT FIT ONES PARTICULAR NEEDS. SINCE BINOCULAR MICROSCOPES OR HAND LENSES ARE THE TOOLS THAT ARE COMMONLY AVAILABLE TO THE EXPLORATIONIST, A PRACTICAL CLASSIFICATION SHOULD BE BASED ON DESCRIPTIONS USING THEM. WHEN THESE INSTRUMENTS ARE USED, IT IS USUALLY POSSIBLE TO IDENTIFY THE INDIVIDUAL GRAINS FORMING THE ROCK. THUS MOST CLASSIFICATIONS REQUIRE THAT THE MOST SIGNIFICANT SEDIMENTARY PARTICLE IN THE ROCK BE DESCRIBED. FOR INSTANCE, IF A ROCK IS COMPOSED OF OOIDS, IT IS TERMED AN OOLITIC LIMESTONE. IF THE LIMESTONE ALSO CONTAINS A MINOR ELEMENT SUCH AS SKELETAL FRAGMENTS, THEN IT IS CALLED A SKELETALOOLITIC LIMESTONE.

TWO OF THE MOST WIDELY USED CLASSIFICATIONS ARE THOSE OF FOLK (1959, 1962) AND DUNHAM (1962). BOTH CLASSIFICATIONS SUBDIVIDE LIMESTONES PRIMARILY ON THE BASIS OF MATRIX CONTENT.



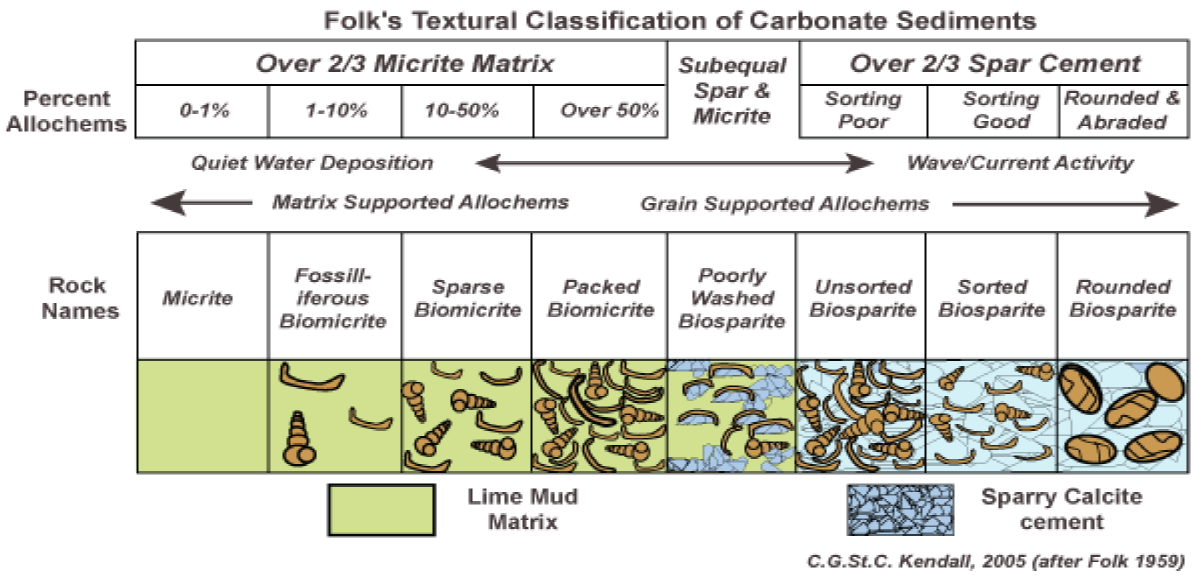


Figure 16: - Dr. R.L. Folk's carbonate classification.

Most limestones are classified by Folk allochemical rocks if they contain over l0% allochems (transported carbonate grains). Based on the percentage of interstitial material, the rocks may be further subdivided into two groups: sparry allochemical limestones (containing a sparry calcite cement of clear coarsely crystalline mosaic calcite crystals) and microcrystalline allochemical limestone (containing microcrystalline calcite mud, micrite, which is subtranslucent grayish or brownish particles less than about 5 microns in size). Further subdivision is based on the allochem ratios of Folk (1962) are shown in Scholle & Ulmer-Scholle (2003).

Thus Folk's classification (figures above) is most suited for thin section study. Remember that he terms rocks with appreciable matrix as micrites while matrix-free rocks that contain sparry calcite cement are termed sparites. As you can see sparites and micrites are further subdivided by means of their most common grains.

The Lower Glen Rose is utilized as an aquifer in a limited area in and around Center Point. It is seldom utilized as an aquifer elsewhere in the county due to the presence of calcium sulphate or anhydrite and/or gypsum beds intercalated with orange microdolomite. These same paleoenvironments of deposition are found in the present day Persian Gulf and these evaporate pans are known as Sabhkas.

THE LOWER GLEN ROSE IS FOUND IN A VERY NARROW BAND ALONG A STREAM BED NEAR COMFORT ON THE SURFACE. ALL THE REST OF LOWER GLEN ROSE IS CONFINED BELOW THE UPPER GLEN ROSE MEMBER.

HENSEL SAND MEMBER, PEARSALL FORMATION

THE HENSEL SAND MEMBER OF THE PEARSALL FORMATION IS THE MOST IMPORTANT AQUIFER IN KERR COUNTY. THIS AQUIFER CONTAINS THE VAST MAJORITY OF WATER IN STORAGE. IT DOES NOT REACH THE SURFACE AND IS ENTIRELY CONFINED BELOW THE UPPER AND LOWER GLEN ROSE MEMBERS. IN FACT, ALL OF THE AQUIFERS BELOW THE UPPER GLEN ROSE ARE CONFINED AQUIFERS.

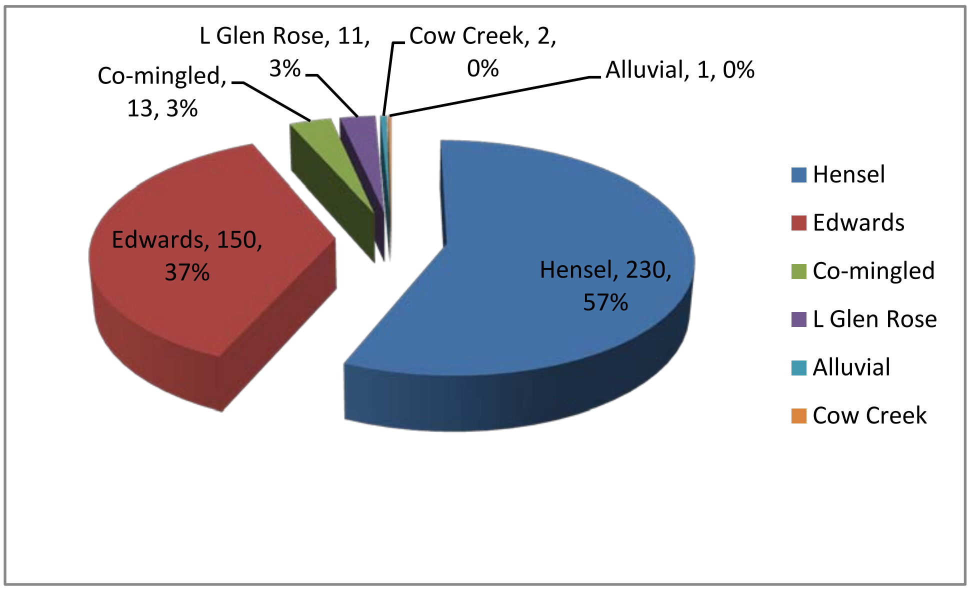


FIGURE 17: – PIE DIAGRAM DEPICTING THE IMPORTANCE OF THE EDWARDS AND HENSEL AQUIFERS IN KERR COUNTY.

THE HENSEL SAND MEMBER IN KERR COUNTY IS COMPOSED OF FINE-COARSE GENERALLY UNCEMENTED LOOSE SAND. GRAVELIFEROUS SAND AND POOR SORTING INCREASE NEAR THE BASE OF THE UNIT. HYDROLOGICAL HEADS ALSO INCREASE AS THE SECTION IS DRILLED AND COMPLETED. IN OTHER WORDS, SIGNIFICANT INCREASES IN WATER LEVEL ELEVATIONS ARE NOTED FROM THE BASE OF THE UNIT IN COMPARISON TO COMPLETIONS AT THE THE TOP OF THE UNIT.

The Hensel varies in thickness from approximately 400 feet near Mountain Home to approximately 150 feet in the southeastern portion of the county. The sand is derived from most of the clastic units that surround the Llano Uplift and in particular the Cambrian Hickory Sandstone. The reworked Hickory is characterized by well rounded chatter marked COURSE grains. No reworked feldspar has been noted in Hensel samples indicating rainfall that would exceed 30-40" per year during the depositional cycle.

The Hensel underlies the Upper Glen Rose marls over the entire county and overlies the Bexar Shale Member in the southern portion of the county. The Hensel is a facies of the Upper Glen Rose, the Lower Glen Rose, Bexar, Cow Creek, Hammett, Sligo and Hosston to the north and northwest portions of the county. The Hensel in this area overlies the Paleozoic surface. The author has designated this northern sand facies as the Hensel North to differentiate it from the Hensel South which is found between the the Lower Glen Rose and the Bexar Shale. The pinch out or facies change of the Hammett Clay Member is partially coincident with Bexar Shale pinch out moving from south to north. This major facies change, with few exceptions, is the change from marine to continental deposition.

The Hensel braided stream aquifer is most well developed along an axis that stretches southwest from Mountain Home to Garven's Store on the Real-Kerr County boundary. The water in storage along this axis far exceeds any other area in the county. It is perhaps the strongest and most abundant aquifer in the Texas Hill Country. It is certainly the most favored completion target over the entire county.

The Hensel aquifer is recharged from the extensive outcrops to the north and northwest. Rainfall falls on the outcrop and moves down gradient beneath the Upper Glen Rose marl. The map below depicts the outcrop and thickness of the Hensel and the recharge routes.

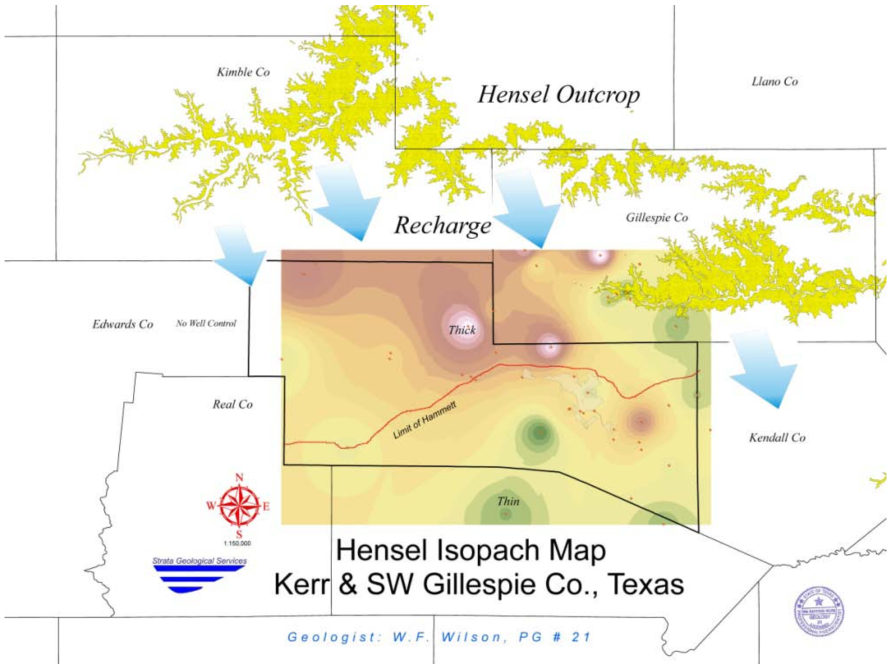


Figure 18: - Hensel aquifer map depicting thickness, flow regimes and outcrops.

Altered weathered volcanic ash forms isolated beds of green bentonite, ten to forty feet thick, within the Hensel in the northwestern portion of the county. This indicates that intrusions were present within the area during the time of depiction as shown above. The braided stream bed nature of the Hensel in this area also indicates that the Llano Uplift island complex was elevated at least 1,000 feet above the braided plain of deposition that extended from Gillespie County, down the axis of Hwy 41 to at least Garven's Store in the west central portion of the county.

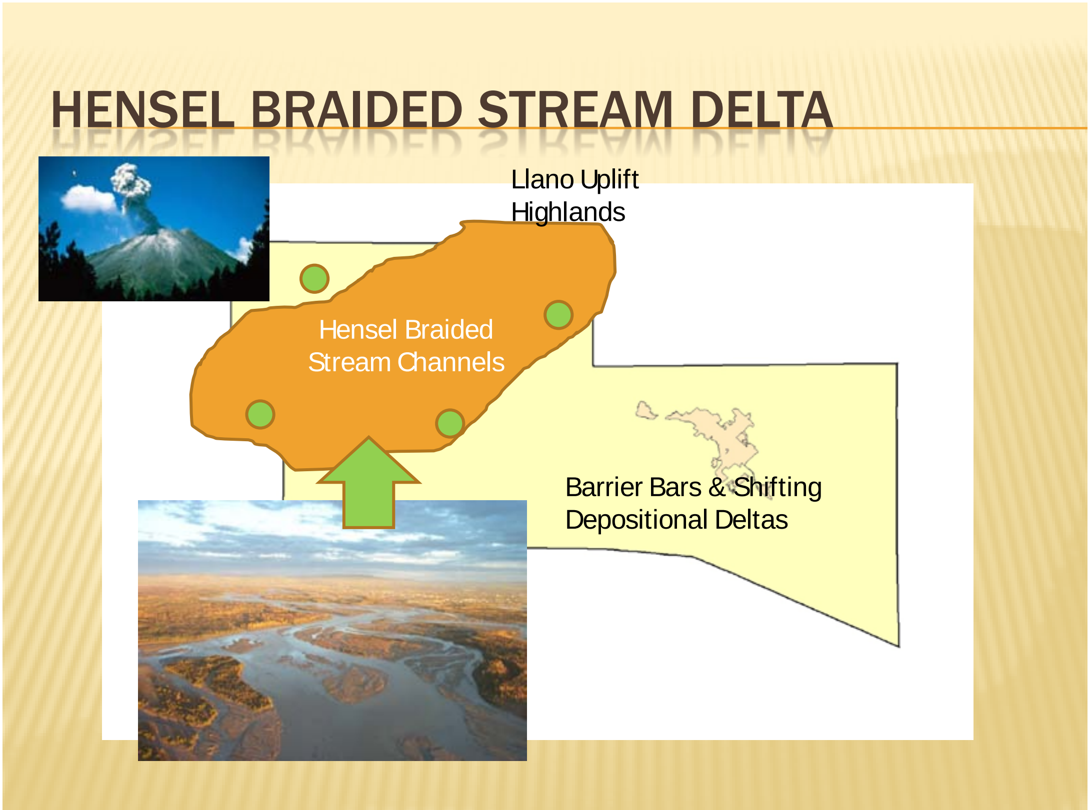


FIGURE 19: - HENSEL BRAIDED STREAM AND THICK SANDS ALONG THE NW PORTION OF KERR CO.

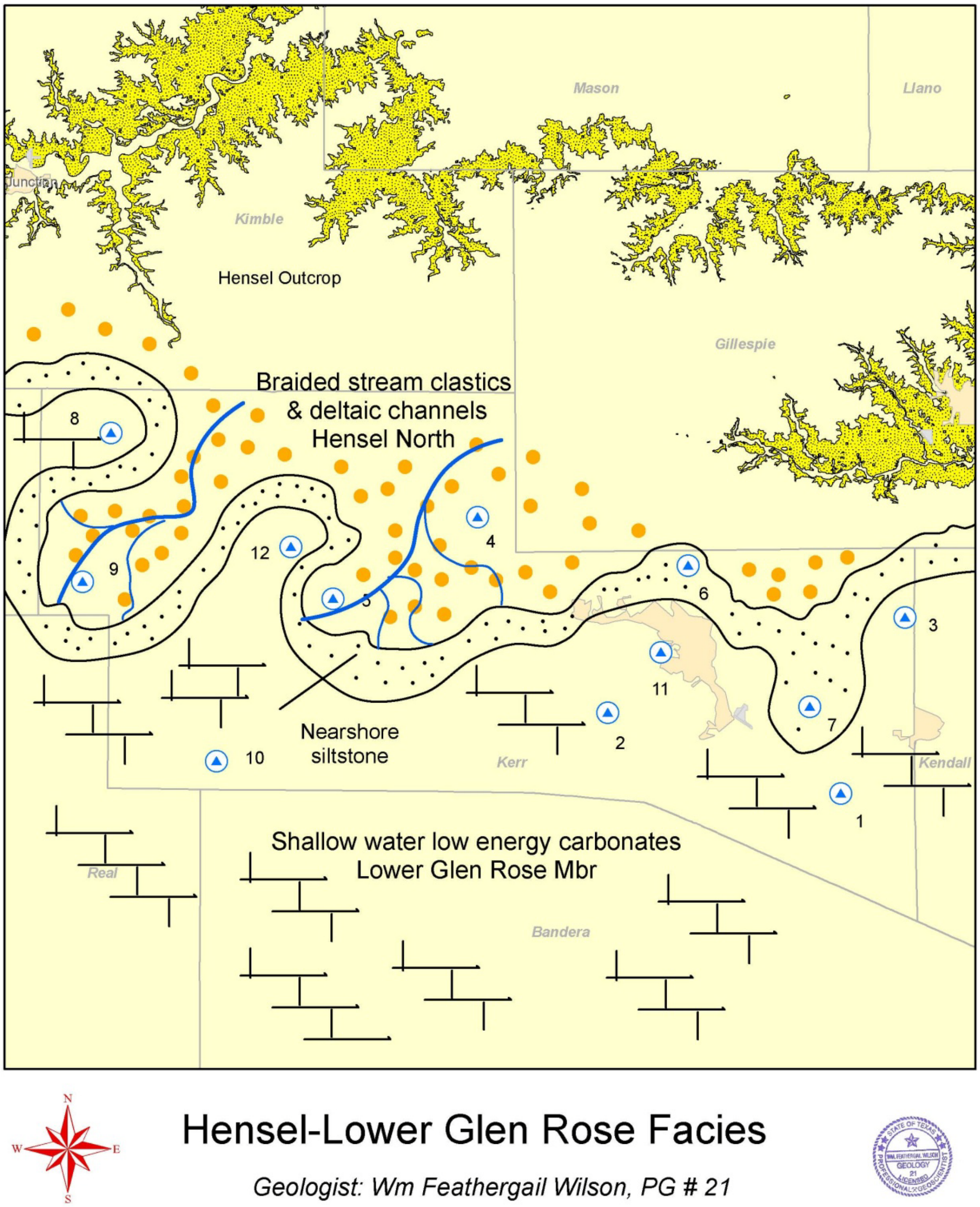


FIGURE 20: - HENSEL – LOWER GLEN ROSE TIME SLICE PALEO-FACIES MAP.

Bexar Shale Member, Pearsall Formation

The Bexar Shale is a misnomer. The unit is composed of marl and clay for the most part and almost no shale has been noted. In some areas the Bexar is organically rich, very fine grained sandy clay. In other areas it is a sand facies, while in other areas it is a red paleosol. In some areas, it is missing entirely due to erosion. Typically, it is about 5-25 feet thick. Typically, it is gray silty marl separating the overlying Hensel Sand from the underlying Cow Creek white biosparite. It is frequently only seen on geophysical logs and almost never described by drillers. The facies equivalent in Center Point area is generally a sand or paleosol. The Bexar Shale pinches out to the north and northwest roughly following the pitchout of the Hammett Member. It may serve as a local time equivalent aquifer in the Center Point area. It has no lithologic significance other than a geophysical log marker bed representing a shallow marine transgression within the Pearsall Formation. It becomes a much more important marker bed south of Kerr County.

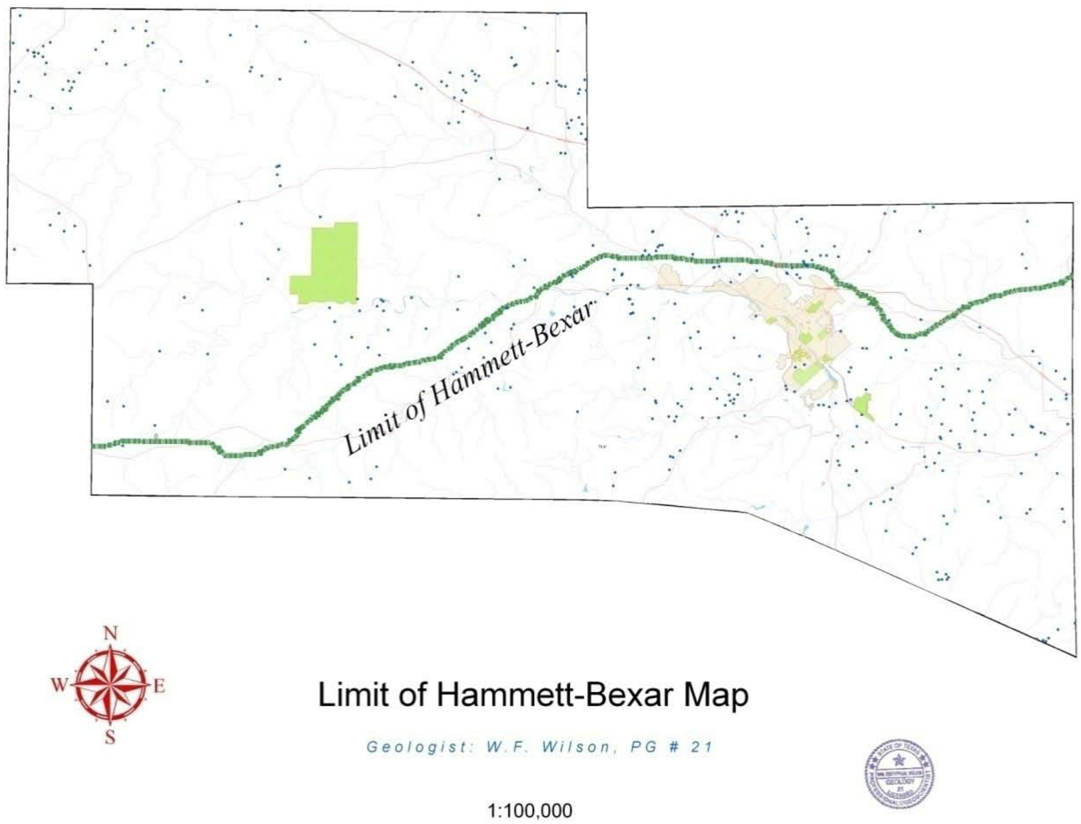


FIGURE 21: - LIMIT OF HAMMETT AND BEXAR UNITS WITH WELLS, ROADS, PARKS AND CITIES.

COW CREEK LIMESTONE MEMBER, PEARSALL FORMATION

THE COW CREEK LIMESTONE MEMBER IS GENERALLY A WHITE POROUS BIOSPARITE THAT BLENDS INTO A LIGHT BROWN MICRODOLOMITE IN THE LOWER HALF. THE TOP OF THE COW CREEK IS OFTEN CHARACTERIZED BY A TIGHT NON-POROUS HARD WHITE MICRITE. IT IS SELDOM DESCRIBED BY DRILLERS EVEN THOUGH IT IS QUITE DISTINCT IN CUTTINGS. IT IS OFTEN COMINGLED AS AN AQUIFER WITH THE HENSEL AS DESCRIBED ABOVE. THE POROUS WHITE BIOSPARITE IS GENERALLY ABOUT 20-30 FEET THICK, WHILE THE ENTIRE UNIT IS APPROXIMATELY 50-60 FEET THICK. THE FOLLOWING IS A PHOTOMICROGRAPH OF A THIN SECTION (~30 MICRONS THICK) IN A POLARIZED TRANSMITTED LIGHT MICROSCOPE. THE BLUE AREA REPRESENTS POROSITY. NOTE THE ROUNDED RE-CRYSTALLIZED FOSSIL FRAGMENTS AND OOIDS.

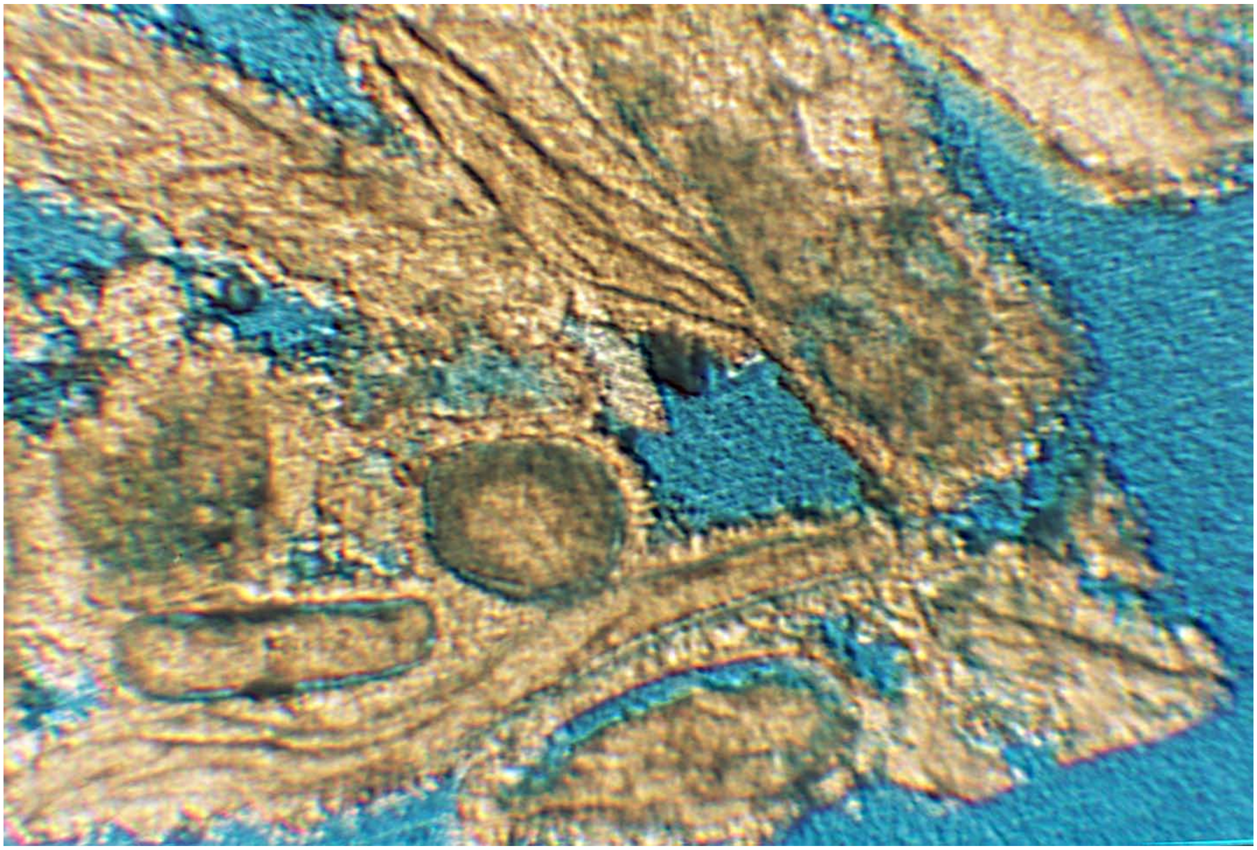


Figure 22: - Cow Creek Limestone thin section cut about 30 microns in thickness. The blue area are porous, while the light tan areas are recrystallized fossil fragments and oolites.

The Cow Creek becomes a sand facies in and around the Center Point area and changes facies to the north becoming the Hensel North time equivalent roughly along the Hammett-Bexar limit as shown in Figure 23.

The Cow Creek is the primary aquifer along with the Hensel and more often than not this unit remains unrecognized by drillers. It may be referred to as "streaks of white limestone" and almost never separated from the sands above the unit.

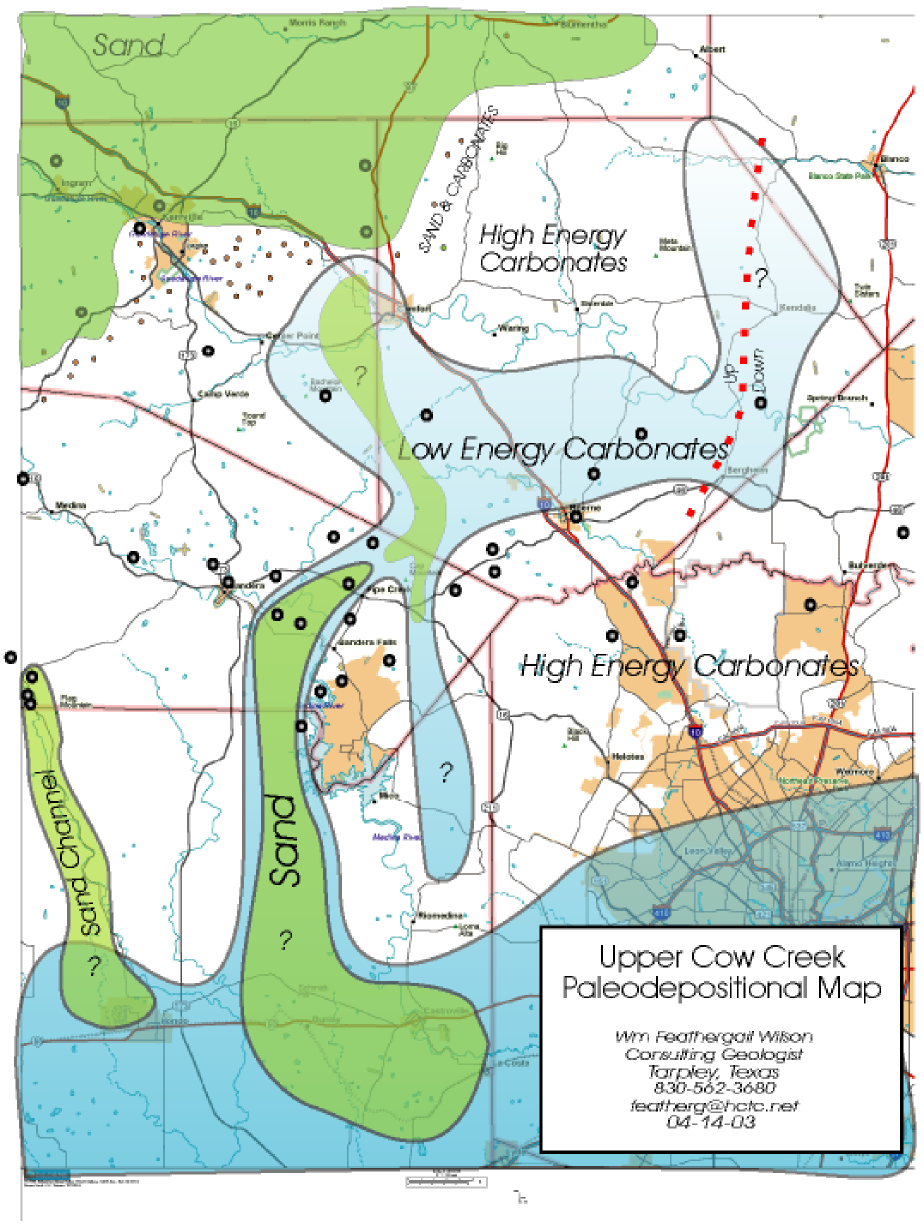


FIGURE 23: - REGIONAL FACIES COW CREEK MAP. THE BLUE AREA DEPICTS LOW POROSITY AREAS, WHILE THE WHITE AREAS DEPICT HIGH ENERGY POROUS AREAS. THE GREEN AREAS REPRESENT QUARTZ SAND FACIES.

Hammett Clay Member, Pearsall Formation

The Hammett Clay represents an advancing anoxic sea that was organically rich and slightly over pressured. It ranges in thickness from 0-60 feet. It often contains numerous oyster fragments in Kerr County indicating an estuary environment of deposition. It is a gray sticky soft clay that expands into large fist sized chunks as it is drilled. It often sticks to drill collars and may completely stop air flow from the bit. In some areas it will crush and or split SDR-17 PVC 4.5" casing. Generally, it is wise to set steel casing through the Hammett, if completing in the Sligo-Hosston couplet. The clay dissolves into a dark gray mud while drilling and often it is not detected by drillers until it blows to the surface as large chunks. Drillers should never leave tools in the hole over night to prevent stuck drill pipe. It often caves into the hole as soon as it is drilled. Geophysical logs must be immediately run after pulling out of the hole across the Hammett Clay. Near the leading edges of the pinch out, silt and coal have been noted in the unit and it becomes somewhat more competent.

Sligo Limestone Formation

The Sligo Limestone is a facies of the underlying Hosston Formation and is limited to the extreme southern boundaries of Kerr County. It is characterized by a sandy poorly washed green phosphate bearing biomicrite and biosparite. It is transitional with the underlying Hosston sands, silts and gravels. It is an aquifer that is seldom, if ever, utilized as a completion target. It ranges from 0-30 feet across very limited areas of the county. Most wells that target the Hosston set casing within the Sligo Limestone or its facies Hosston silty time equivalent. The Sligo becomes a much more important and well developed aquifer in southern Bandera County. It is essentially the marine time equivalent of the underlying continental basal Cretaceous clastics.

HOSSTON FORMATION

THE HOSSTON IS MORE COMMONLY KNOWN BY DRILLERS AND THE GENERAL PUBLIC AS THE "LOWER TRINITY" SANDS. IT BECOMES A FACIES AND CLASTIC CONTINUUM OF THE HENSEL MEMBER NORTH OF THE HAMMETT PINCH OUT. IT HAS BEEN THE PRIMARY PUBLIC WATER SYSTEM TARGET IN AND AROUND THE CITY OF KERRVILLE. IT IS GROSSLY A FINING UPWARD SEQUENCE WITH BASAL GRAVELS RESTING ON THE PALEO-TOPOGRAPHIC PALEOZOIC SURFACE. IT HAS COMMONLY BEEN CO-MINGLED WITH THE HENSEL IN THE SOUTHEASTERN PORTION OF THE COUNTY. THESE COMINGLED COMPLETIONS HAVE BECOME A HYDROGEOLOGICAL PRESSURE PROBLEM IN THE CENTER POINT TO COMFORT AREA. THE AVERAGE THICKNESS OF THE HOSSTON IS APPROXIMATELY 165 FEET THINNING TO 60 FEET IN THE CITY OF KERRVILLE. WELLS DRILLED KERRVILLE SOUTH SELDOM DRILL THE ENTIRE SECTION, THEREBY LIMITING HYDRAULIC HEADS COMPARED TO WELLS DRILLED THROUGH THE ENTIRE SECTION. IF THE WELLS ARE DRILLED WITH MUD IN DEFERENCE TO AIR, THE COMPLETION CONSEQUENCES HAVE PROVED TO BE DISASTROUS. MUD DRILLED HOSSTON WELLS MAY NEVER RECOVER FROM DEEP MUD INVASION INTO THE SANDS AND BASAL GRAVELS AROUND THE BOREHOLE. ONE WELL IN THE CENTER POINT AREA ENCOUNTERED A 40 FOOT BED OF INDURATED VOLCANIC GLASS, ANOTHER WELL DRILLED IN BANDERA COUNTY ENCOUNTERED THIS SAME INDURATED TUFF, WHICH WAS SEEN IN A TWIN WELL DRILLED 300 YARDS TO THE EAST.

THE HOSSTON WAS LAID DOWN IN BRAIDED HIGH ENERGY STREAMS UPON THE IRREGULAR ERODED PALEOZOIC SURFACE. THICKER AND MORE COARSE GRAINED CLASTICS WERE LAID DOWN IN THE PRE-EXISTING PALEOZOIC VALLEYS IN DEFERENCE TO THE ADJOINING HILLS. THE PALEO-ELEVATION DIFFERENCES AMOUNT TO AS MUCH AS 200 FEET IN SOME AREAS. IN KERR COUNTY, THE HOSSTON EITHER OVERLIES BLACK ORGANIC RICH PENNSYLVANIAN SHALE OR THE ORDOVICIAN ELLENBURGER DOLOMITE. THE PALEOZOIC FAULTED SURFACE EXHIBITS 2,000-3,500 THROWS GENERALLY TRENDING NE-SW. THIS STRUCTURAL SURFACE CONTROLS THE SEDIMENTARY PATHS AND THICKNESS OF THE OVERLYING HOSSTON.

FIGURE 24: - EXAMPLE OF A BRAIDED STREAM AS IT MAY HAVE APPEARED DURING HOSSTON TIME DEPOSITING SAND AND GRAVEL DERIVED FROM THE LLANO UPLIFT. THESE BRAIDED STREAM CHANNELS WERE LAID DOWN ON A LOW ROLLING PALEOTOPOGRAPHIC SURFACE WITH ELEVATION RANGES FROM 50-200 FEET. THE HOSSTON REMAINS A CONTINENTAL FLUVIAL FACIES UNTIL IT REACHES SOUTHERN BANDERA COUNTY AND NORTHERN MEDINA COUNTY. THE OVERLYING SANDY LIMESTONE SLIGO FORMATION IS FOUND ONLY IN THE SE EXTREME PORTION OF KERR COUNTY AND GRADUALLY INCREASES IN THICKNESS TO THE SOUTH UNTIL IT COMPLETELY REPLACES THE HOSSTON AS A BARRIER REEF IN DEEP SOUTH TEXAS.

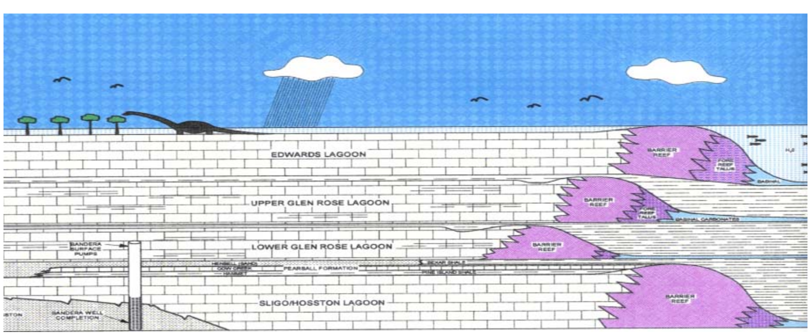


FIGURE 25: - DOWN DIP REEF FACIES OF THE LOWER CRETACEOUS SYSTEM.

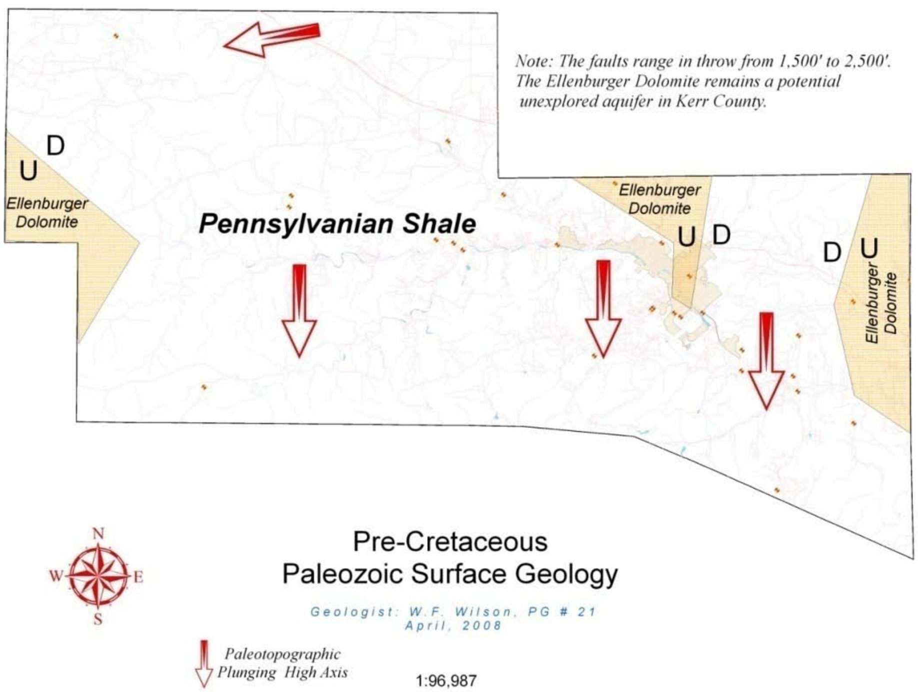


FIGURE 26: - PALEO-GEOLOGY MAP OF THE PALEOZOIC SURFACE PRIOR TO THE DEPOSITION OF THE HOSSTON SAND AND GRAVELS IN BRAIDED STREAMS. THE ARROWS REPRESENT PALEOTOPOGRAPHIC HIGHS OR RIDGES.

FIGURE 27: - A PALEOZOIC RIDGE AND VALLEY SCENE AS IT MAY HAVE BEEN SEEN DURING THE EARLY STAGES OF DEPOSITION OF THE HOSSTON SANDS AND GRAVELS UPON THE PALEOZOIC SURFACE.

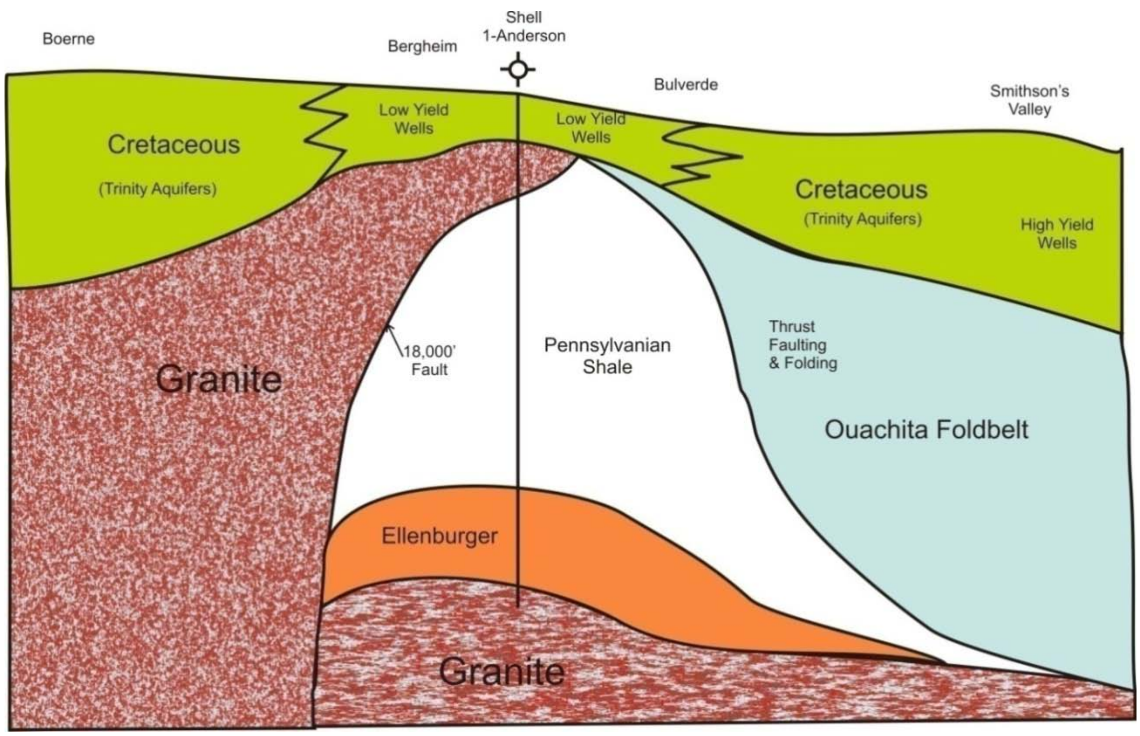


FIGURE 28: - CROSS-SECTION NEAR THE COMAL-KENDALL COUNTY BOUNDARY DEPICTING THE INFLUENCE OF THE UNDERLYING PALEOZOIC STRUCTURE AND PALEO-TOPOGRAPHIC SURFACE ON THE OVERLYING CRETACEOUS LITHOLOGY.

The underlying Paleozoic structural surface and paleo-topography have impacted facies changes within the entire Cretaceous System. In certain places the paleo-topography controls the Hosston thickness and hydraulic conductivity. The paleo valleys allowed braided streams to concentrate coarser and thicker clastics. The intervening paleo hills were high enough is some areas to deposit only silts and entire valley sequences are attenuated or missing completely. The most striking example is the area near Bergheim, Texas (see Figure 28). The Hosston in the northern portion of Kerr County varies in thickness quite markedly within the City of Kerrville and the surrounding areas.

Facies changes within in the entire Cretaceous System are also noteworthy and were strongly influenced by the underlying Paleozoic surface throughout Kerr County and Texas Hill Country.

Paleo-Geographic Time

The paleo-geographic view of the continents and the oceans was quite different from the beginning of the Cretaceous System to the end of Edwards Group time. The following maps depict these different time periods.

The Lower Cretaceous sediments were laid down in a very warm climate with elevated levels of carbon dioxide. Shallow lagoonal seas were spread across the entire Texas Hill Country above the fluvial Hosston sands. These shallow marine lagoonal sediments were dotted with lushly vegetated verdant islands. Very few of the paleosols associated with these islands have been preserved except near the perimeter of the Llano Uplift. Much of the lagoonal areas were just a few feet deep enabling large herbivore and carnivore dinosaurs to wade from island to island. The shallow lagoons were teeming with marine life. Only about 10% or less of the remains of this marine life is preserved as fossil material. The time of this study spanned approximately 50-million years.

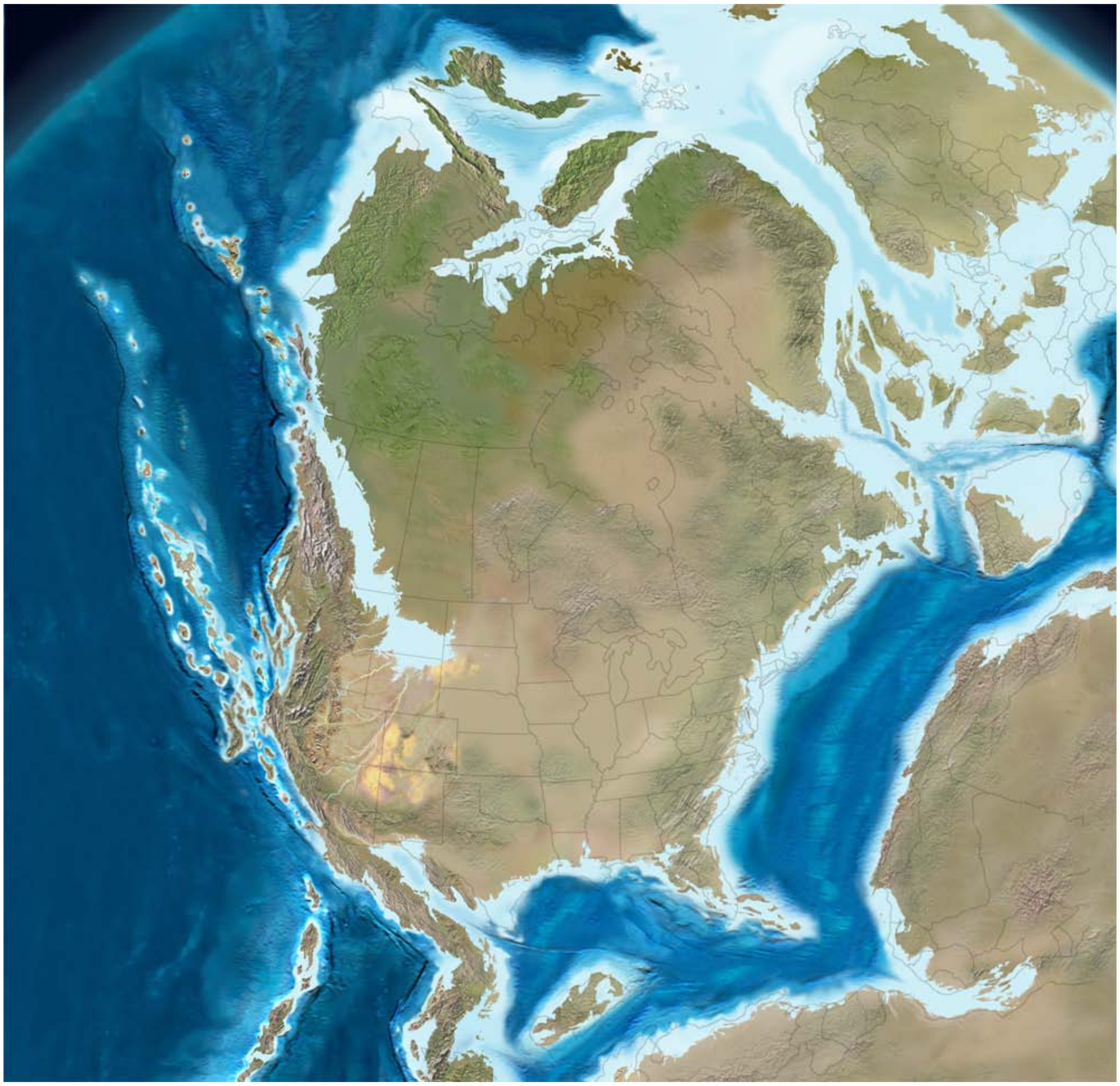


FIGURE 29: - DISTRIBUTION OF THE LANDMASS AND OCEAN BASINS AT THE BEGGING OF HOSSTON DEPOSITION AT 144 MILLION YEARS BEFORE PRESENT (BP), AFTER BLAKEY, ET AL.

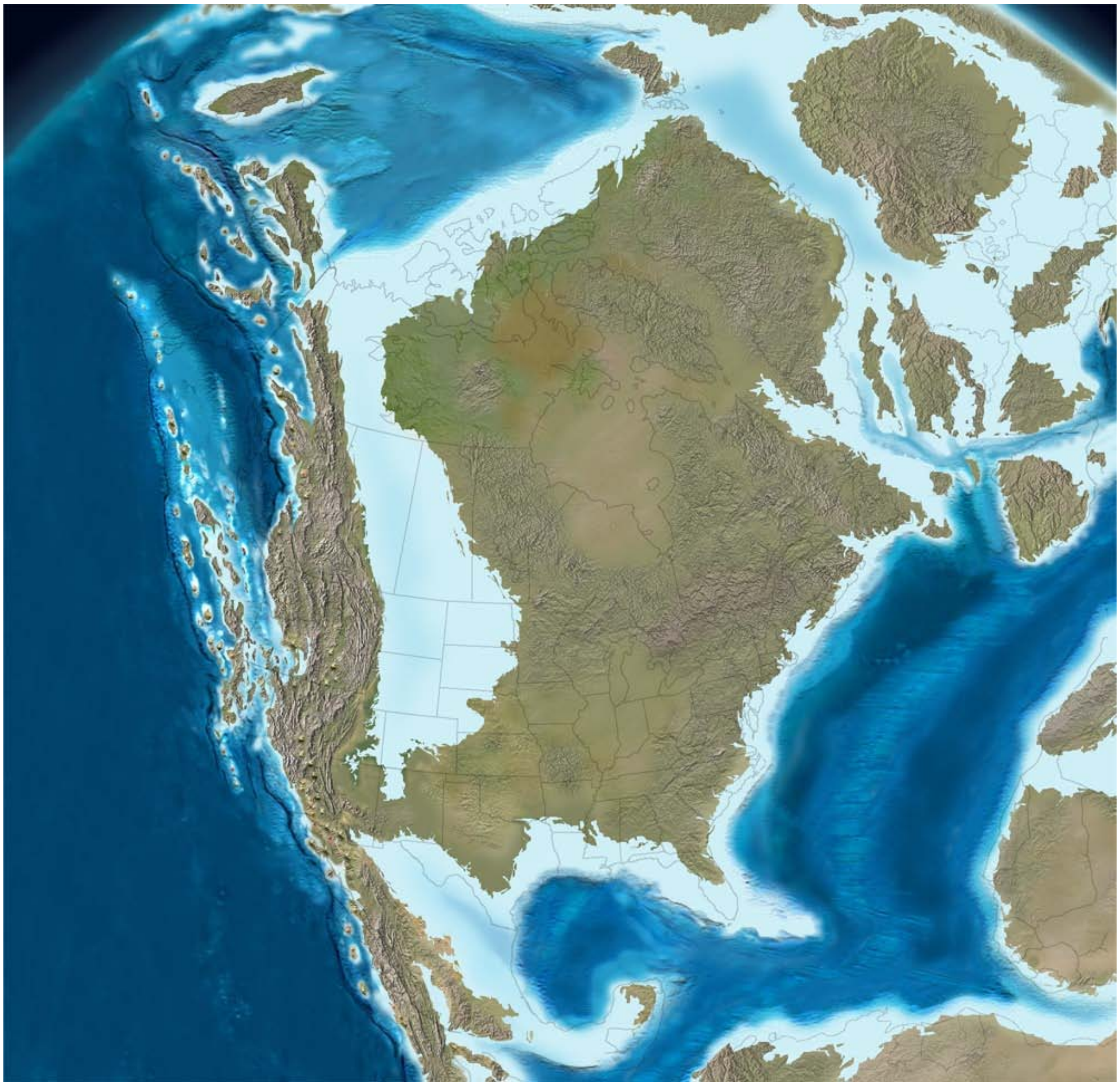


FIGURE 30: - DISTRIBUTION OF THE OCEANS AND LANDMASS AT THE END OF EDWARDS GROUP TIME, AFTER BLAKEY ET AL.

Isotope Studies

A consortium of groundwater districts launched an isotope study in 2006 to ascertain the ages and provenance of groundwater moving through the Texas Hill Country within various aquifers. All of the pre-existing data as well as new data were collected and compared. The results were quite unexpected and surprising.

Isotopes included C-14 and Tritium as well as many others as shown on the following spreadsheet. The gathering and analysis of this data is continuing in the counties of Bandera, Blanco, Gillespie, Kerr, Kimble and Kendall. Paleozoic as well Cretaceous aquifer groundwater was sampled and analyzed.

Recharge and provenance or origin and direction of groundwater flow were the primary goals. The TWDB Groundwater Availability Models assume a rapid vertical component of recharge. Very large recharge numbers were assumed by this method utilized by the TWDB. The subsurface geology within the confined units of Kerr County does not support this interpretation. The Upper Glen Rose marl is an effective aquitard. Groundwater flowing into and through the Hensel North and Hensel South sands is moving latterly and receives very small amounts of vertical recharge due to the thickness of the overlying Upper Glen Rose aquitard. This Upper Glen Rose aquitard covers the entire county. The isotope data proves this to be the case. Hensel groundwater age dates range from 24,000 years to 28,000 years old in the Hensel sands. Movement of the groundwater is very slow and mapping shows that it is moving from the Hensel outcrop areas located in Mason, Kimble and Gillespie Counties. Some Hensel groundwater may originate from the unconfined portion of the Edwards-Trinity aquifer from additional areas to the northwest of Kerr County as the Upper Glen Rose changes facies and becomes the Hensel North. In other words, the unconfined Edwards limestones directly overlie the Hensel sands creating a single leaky aquifer.

The Edwards unconfined age dates in Gillespie County ranged from 2,000 to 10,000 years old. One spring in Bandera County appeared to b approximately 800 years old. Edwards samples in Kerr County have not been taken. The age corrections of "percent modern carbon" (pmc) are far more applicable to carbonate aquifers such as the Edwards in deference to clastic aquifers such as the Hensel. Thus age dates within the Hensel are much more realistic than age dates within the Edwards carbonates.

The following table displays a very small portion of the data and isotopes collected.

County	Well/Spring	Lithologic Unit	Date Sampled	C-14 Age
Kerr	Johnson Creek RV	Hensel Sand North	2006-June	25,880
Kerr	Johnson Creek RV	Hensel Sand North	2006-Dec	28,000
Kerr	Alpine City Well	Hosston Sand	2006-Dec	25,480
Kerr	Hayes Well	Hensel Sand	2006-Dec	25,410
Kerr	1-USGS	Lower Trinity		
Kerr	2-USGS	Lower Trinity		
Kerr	3-USGS	Middle Trinity		
Kerr	4-USGS	Middle Trinity		
Kerr	5-USGS	Middle Trinity		
Kerr	6-USGS	Middle Trinity		
Kerr	7-USGS	Middle Trinity		
Kendall	Jim Schowpe Well	Cow Creek	2006-June	17,080
Kendall	8-USGS	Middle Trinity		
Kendall	9-USGS	Middle Trinity		
Kendall	12-USGS	Lower Trinity		
Bandera	City Well # 5	Hosston Sand	2007-Jun	41,333
Bandera	City Well # 5	Hosston Sand	2006-Jun	25,490
Bandera	P-1020 Medina WSC	Hosston Sand	2007-Jun	35,330
Bandera	Lake Medina Shores #2	Hosston Sand	2007-Jun	43,660
Bandera	17-USGS	Middle Trinity		
Bandera	18-USGS	Middle Trinity		
Bandera	20-USGS	Middle Trinity		
Bandera	22-USGS	Middle Trinity		
Bandera	23-USGS	Middle Trinity		
Bandera	Privilege Creek	Cow Creek	2007-July	22,740
Bandera	AS-68-25-102	Middle Trinity		
Bandera	AS-68-25-505	Middle Trinity		
Bandera	AS-68-25-507	Middle Trinity		
Bandera	AS-68-25-509	Middle Trinity		

Bandera	AS-68-25-511	Middle Trinity		
Gillespie	P. Lambright	Edwards	2007-Oct	
Gillespie	J. Mechler	Edwards	2007-Oct	8960
Gillespie	V. Althaus	Hensel Sand North	2007-Oct	830
Gillespie	Vineyard (Fredericksburg)	Hensel Sand North	2006-Jun	modern
Gillespie	Vineyard (Fredericksburg)	Hensel Sand North	2007-Oct	modern
Gillespie	P. Tybor	Hensel Sand North	2007-Oct	modern
Gillespie	Hidden Springs	Hensel Sand North	2007-Oct	22,940
Gillespie	Harper	Hensel Sand North	2007-Oct	17,020
Gillespie	K-3	Ellenburger	2007-Oct	2,850
Gillespie	Boerner 5	Ellenburger	2007-Oct	16,902
Gillespie	H. Sohner	Ellenburger	2007-Oct	2,880
Gillespie	G. Marburger	Ellenburger	2007-Oct	26,490
Gillespie	L. Tybbor	Hickory	2007-Oct	19,740
Gillespie	D. Johnson	Hickory	2007-Oct	28,700
Gillespie	Ped. River@Fiedler Rd.	Glen Rose Outcrop	2007-Oct	N/A
Gillespie	Ped. River@Goehmann Ln.	Ellenburger Outcrop	2007-Oct	N/A
Gillespie	Rain Precip@ Fbg. Tx.	Hensel Outcrop	8/17/2007	N/A
Gillespie	Rain Precip@ Fbg. Tx.	Hensel Outcrop	9/4/2007	N/A
Blanco	Rockin J Well 1	Hensel-Cow Creek	8/22/2006	4,880
Blanco	Rockin J Well 1	Hensel-Cow Creek	9/26/2007	5,260
Blanco	Mike & Pam Reese Well	Hensel	8/22/2007	1,790
Blanco	Dwayne Hoppe Well	Hensel	8/22/2007	7,140
Blanco	John Stephsenson Well	Hensel	8/21/2007	1,830
Blanco	James Sultemeier LS Well	Hensel	8/21/2007	1,990
Blanco	Robert Keith Well	Ellenburger	8/22/2007	1,780
Blanco	Karen Weber Well	Ellenbuger	8/23/2007	7,120
Blanco	Mavis Lemons Well	Ellenburger	8/27/2007	730
Blanco	BPGCD Monitor Well	Ellenburger	8/15/2007	2,540
Blanco	Larry Hauptriet (old Grote) Well	Hickory	8/23/2007	15,640
Blanco	Sandy Store Well	Hickory	8/28/2007	4,410
Blanco	Blanco River/Crabapple Rd		10/31/2007	N/A
Blanco	Blanco River/Cox Rd.		10/31/2007	N/A
Blanco	Pedernales River Paleozoic		10/31/2007	N/A
Blanco	Ped. R. Hammett's Crossing		10/31/2007	N/A
Blanco	Rain Water		8/16/2007	0
Blanco	Klepac Spring		9/26/2007	1,880
Blanco	Koch Spring		9/26/2007	2,020
Real	15-USGS	Lower Trinity		
Real	16-USGS	Lower Trinity		
Edwards	19-USGS	Lower Trinity		
Edwards	21-USGS	Lower Trinity		
Bexar	10-USGS	Middle Trinity		
Bexar	11-USGS	Middle Trinity		

Bexar	13-USGS	Middle Trinity
Bexar	24-USGS	Middle Trinity
Bexar	25-USGS	Middle Trinity
Comal	14-USGS	Middle Trinity
Comal	26-USGS	Middle Trinity
Medina	TD-68-25-602	Middle Trinity
Medina	TD-68-25-603	Middle Trinity
Medina	TD-68-25-701	Edwards
Medina	TD-68-25-807	Upper Trinity
Medina	TD-68-25-809	Middle Trinity
Medina	TD-68-25-402	Middle Trinity
Medina	TD-68-25-806	Edwards
Medina	TD-68-25-810	Middle Trinity

Table 7: - Isotope groundwater age data, Texas Hill Country.

The following is an outline of the procedures that are followed with regard to the ongoing isotope program.

The analytical approach that is proposed to be taken to conduct an age dating/source provenance study of groundwater within the Texas Hill Country will consist of the following:

AGE DATING

Tritium

Carbon 14

SOURCE/PROVENANCE

Oxygen 18

Deuterium

MAJOR CATION/ANION

PH	FLUORIDE	TEMPERATURE
SILICA	CALCIUM	SODIUM
MAGNESIUM	STRONTIUM	SULFATE
BROMIDE	CHLORIDE	POTASSIUM
ALKALINITY	NITRATE	IRON

ALL GROUNDWATER SAMPLES WILL BE RUN FOR ALL OF THE ANALYSES LISTED ABOVE. IN ADDITION TO GROUNDWATER SAMPLES, SURFACE WATER AND RAINFALL SAMPLES SHOULD BE SAMPLED AND RUN FOR SOURCE/PROVENANCE AND MAJOR CATION/ANION ANALYSES. THIS WILL IDENTIFY AND CHARACTERIZE RECHARGE AREAS FOR GROUNDWATER LOCATED DOWN GRADIENT.

THE MAJOR CATION/ANION ANALYSES ARE NECESSARY TO INPUT THIS DATA INTO THE GEOCHEMICAL MODELING PROGRAM NETPATH TO CALIBRATE THE UNADJUSTED C-14 AGES. THE PROGRAM WILL TAKE INTO ACCOUNT ANY FRACTIONATION AND DILUTION FROM CARBONATES AND SULFATES THAT MAY OCCUR WITHIN THE AQUIFER FROM RECHARGE TO DOWN GRADIENT AREAS.

ADDITIONAL INFORMATION IS PRESENTED IN THE APPENDIX OF THIS REPORT.

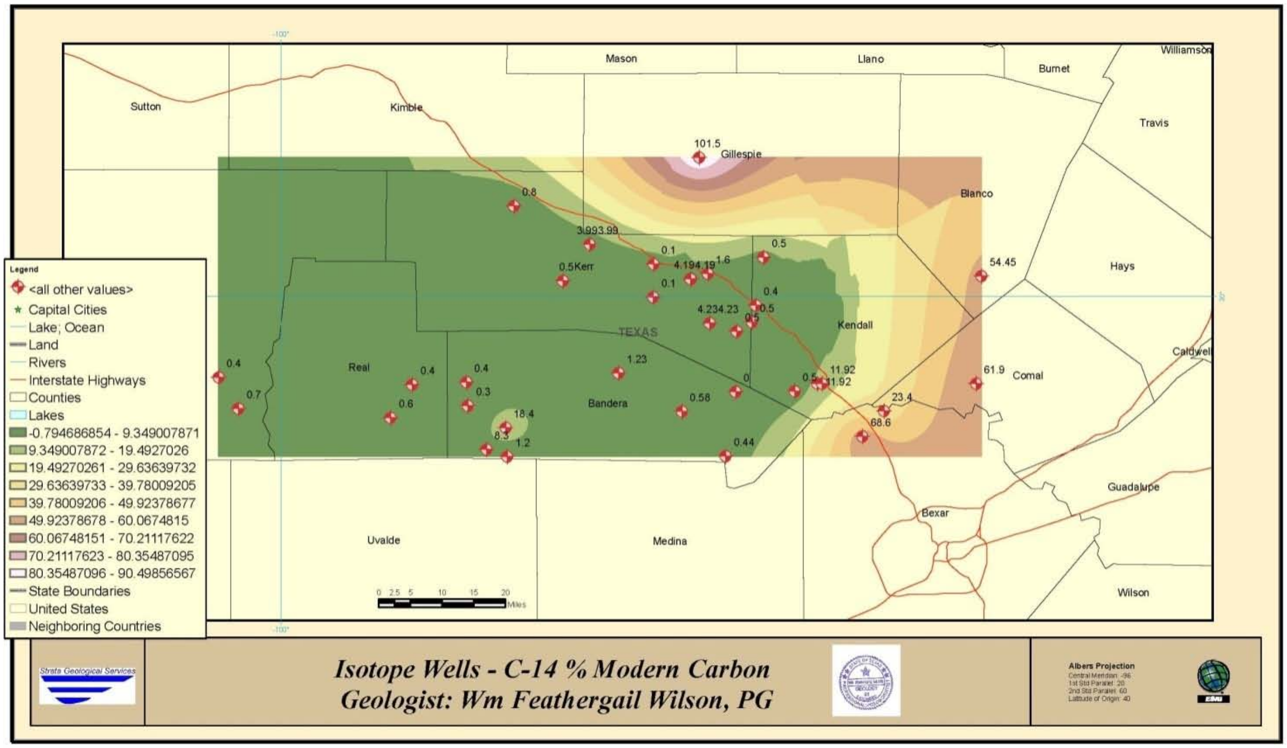


FIGURE 31: - REGIONAL MAP DISPLAYING PERCENT MODERN CARBON WITHIN THE C-14 ANALYSIS

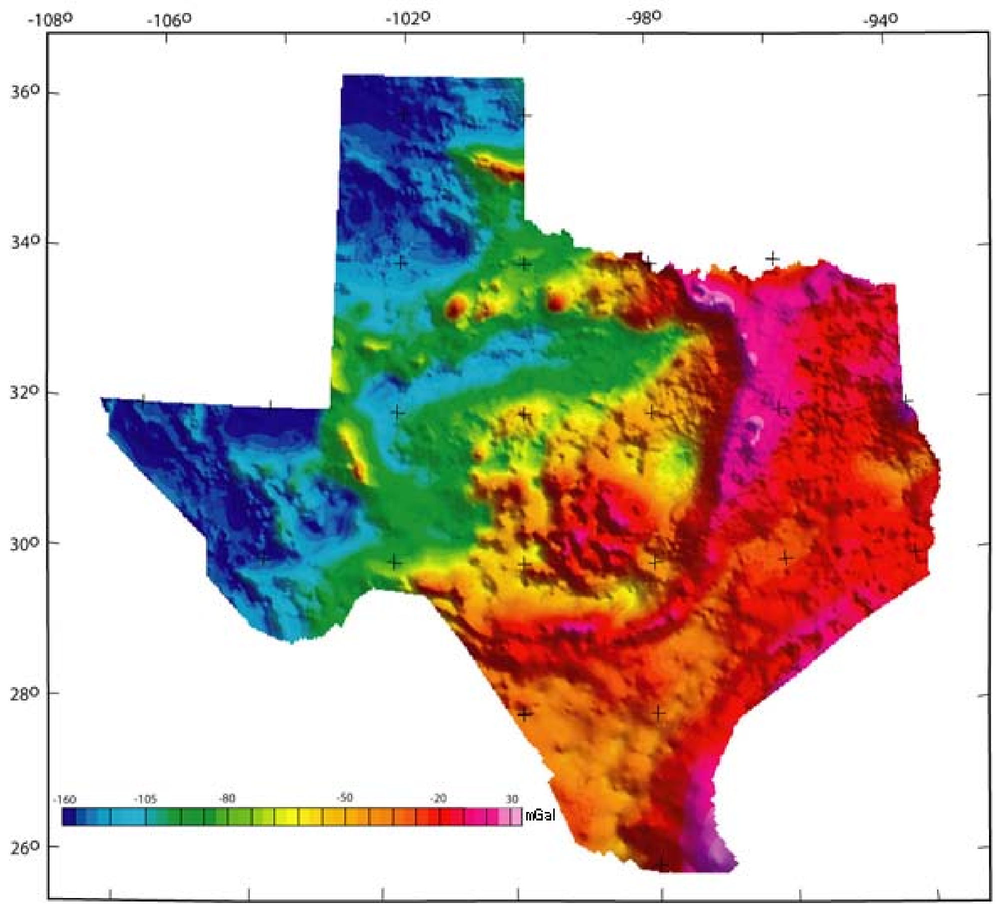


FIGURE 32: - BOUGER GRAVITY MAP OF TEXAS. NOTE THE CENTRAL TEXAS LLANO UPLIFT AREA ADJACENT TO THE OUACHITA FOLDBELT AND THE PENNSYLVANIAN TROUGH, WHICH ARE ALL ELEMENTS OF KERR COUNTY. THE BASINS ARE DEPICTED IN YELLOW NEAR THE GREAT ARC OF THE OUACHITA FOLDBELT THAT EXTENDS FROM DEL RIO TO SAN ANTONIO TO WACO AND DALLAS AND THEN EAST-NORTHEAST INTO A THE SOUTHERN BOUNDARY OF THE APPALACHIANS.

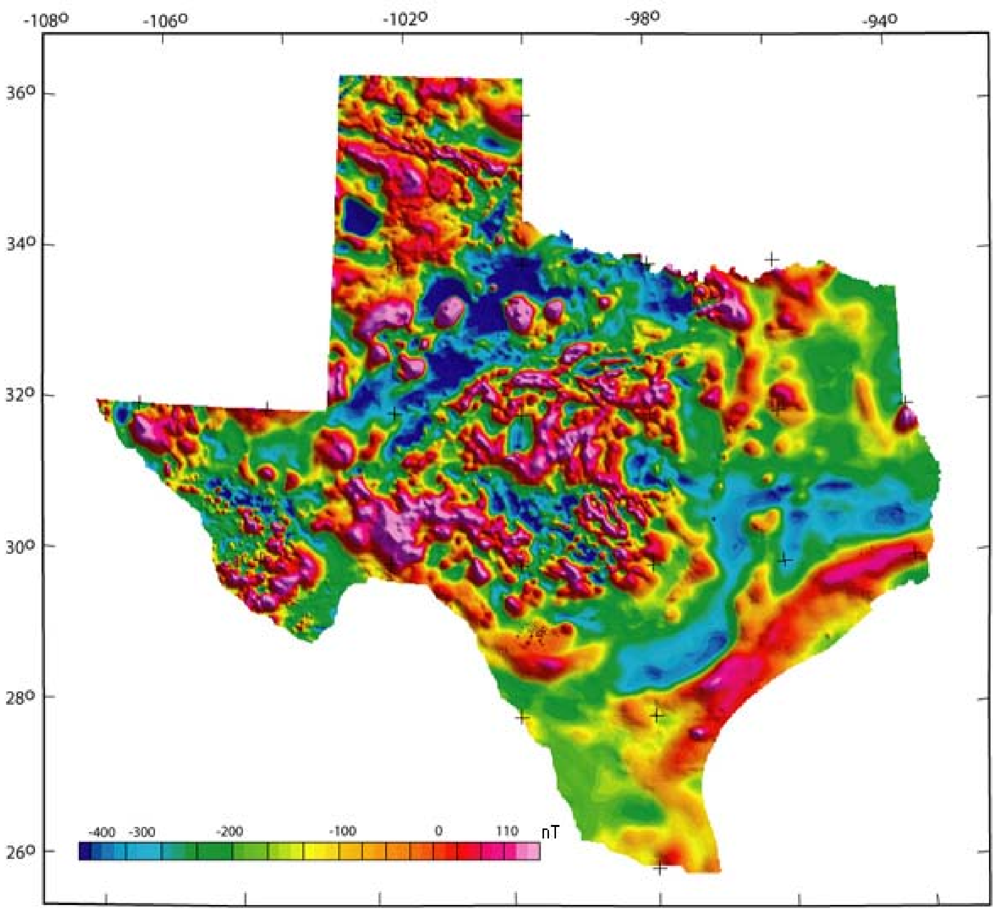


FIGURE 33: - MAGNETIC MAP OF TEXAS. NOTE THE PRONOUNCED LINEAMENTS ACROSS THE TEXAS HILL COUNTRY DEPICTING PRE-CAMBRIAN IGNEOUS AND METAMORPHIC TERRAIN AS WELL AS MORE RECENT IGNEOUS INTRUSIONS IN WEST TEXAS. NOTE THE EAST-WEST LINEAMENT ACROSS THE STATE FROM EL PASO TO LOUISIANA. THIS MAY REPRESENT AN ANCIENT PRE-CAMBRIAN SUTURE ZONE BETWEEN TWO PLATES.

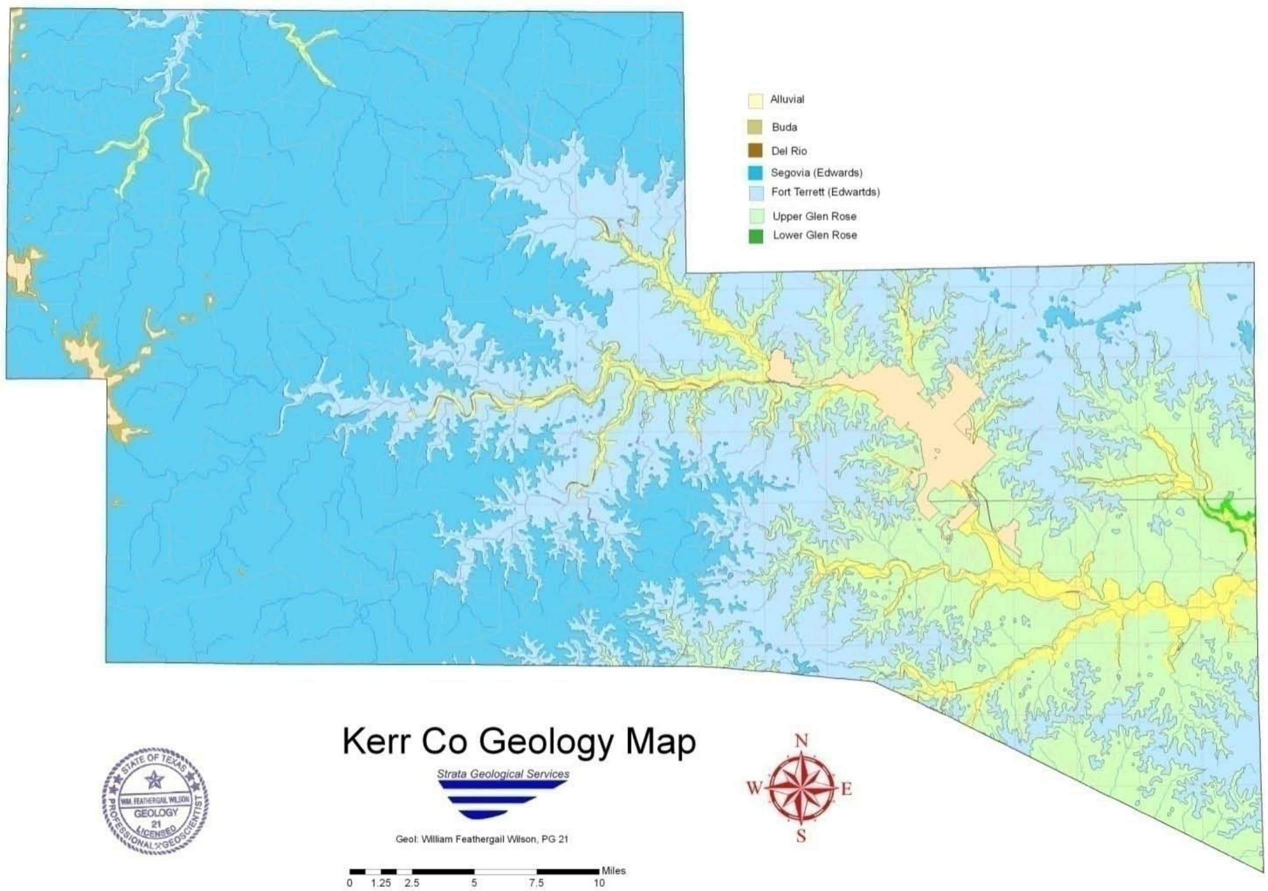


FIGURE 34: - SURFACE GEOLOGIC MAP OF KERR COUNTY.

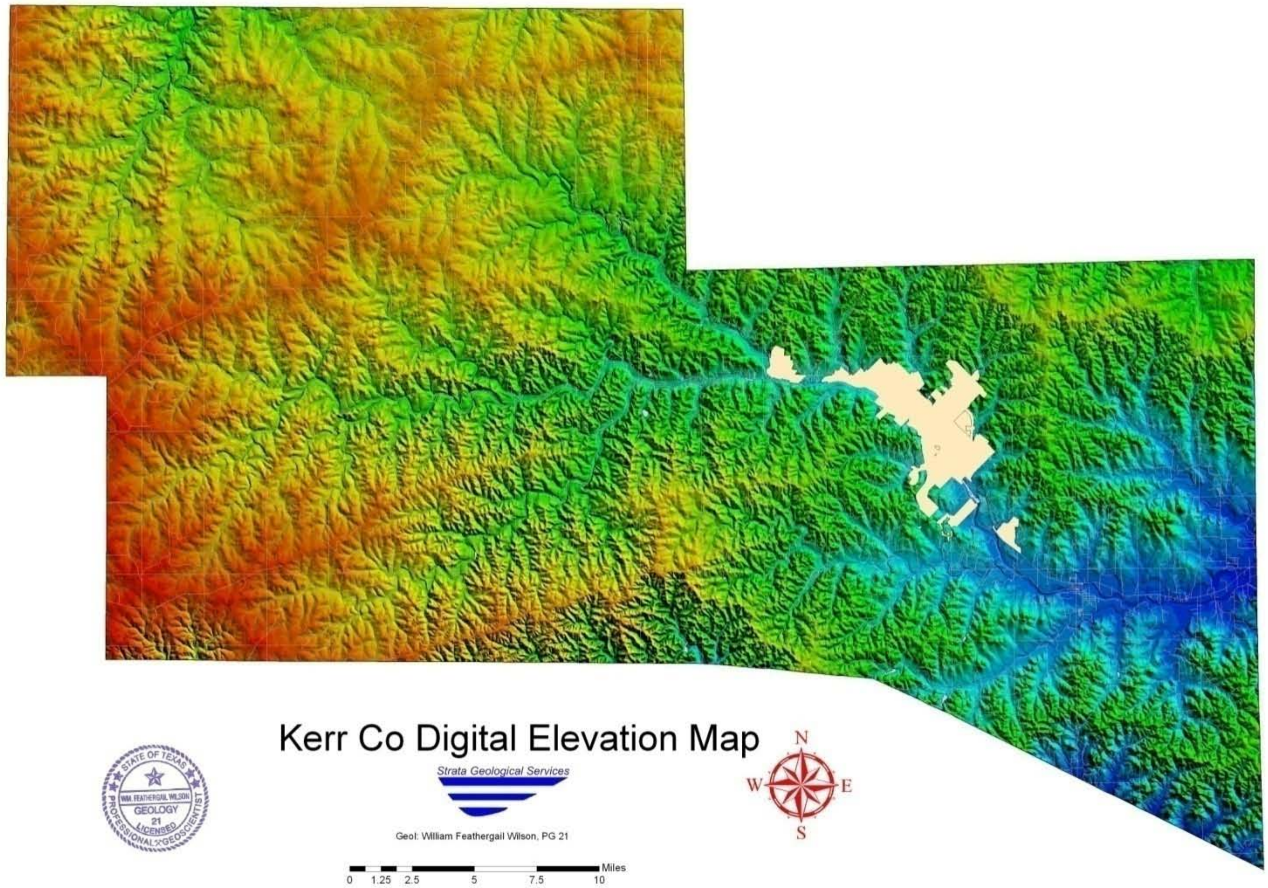


FIGURE 35: - ILLUSTRATION OF A DEM (DIGITAL ELEVATION MODEL) OF KERR COUNTY. THE HIGHER ELEVATIONS DEPICTED IN RED OR ORANGE ARE ABOVE 2,300'. NOTE THE SURFACE DIVIDE ACROSS THE NW PORTION OF THE COUNTY, WHICH IS NOT REFLECTED IN THE SUBSURFACE WITHIN UNITS BELOW THE EDWARDS GROUP. THE TWDB TRINITY-HILL COUNTRY GAM MODEL CUTS OFF AT THE SURFACE DIVIDE.

IV KERR COUNTY HGCD DRILLING

THE HGCD HAS NOW DRILLED AND COMPLETED 12 RESEARCH AND MONITORING WELLS AT THE TIME OF THIS REPORT. ADDITIONAL DRILLING IS PLANNED FOR THE FUTURE. THREE OF THE TWELVE WELLS WERE COMPLETED IN TWO SEPARATE AQUIFERS. THESE ARE KNOWN AS DUAL COMPLETIONS. APPROXIMATELY 30 KERR COUNTY WELLS ARE NOW IN THE HGCD MONITORING PROGRAM AND MORE WELLS HAVE BEEN ADDED EACH YEAR.

THE HGCD DRILLING PROGRAM BEGAN IN 2001 AND WILL CONTINUE INTO THE FORESEEABLE FUTURE. EACH WELL WAS DESIGNED TO PENETRATE THE ENTIRE CRETACEOUS SYSTEM OF AQUIFERS AND AQUITARDS. THE DEEPEST WELL DRILLED THUS FAR PENETRATED 1,330 FEET OF ROCK IN THE FAR SOUTHWESTERN CORNER OF KERR COUNTY.(HGCD-10)

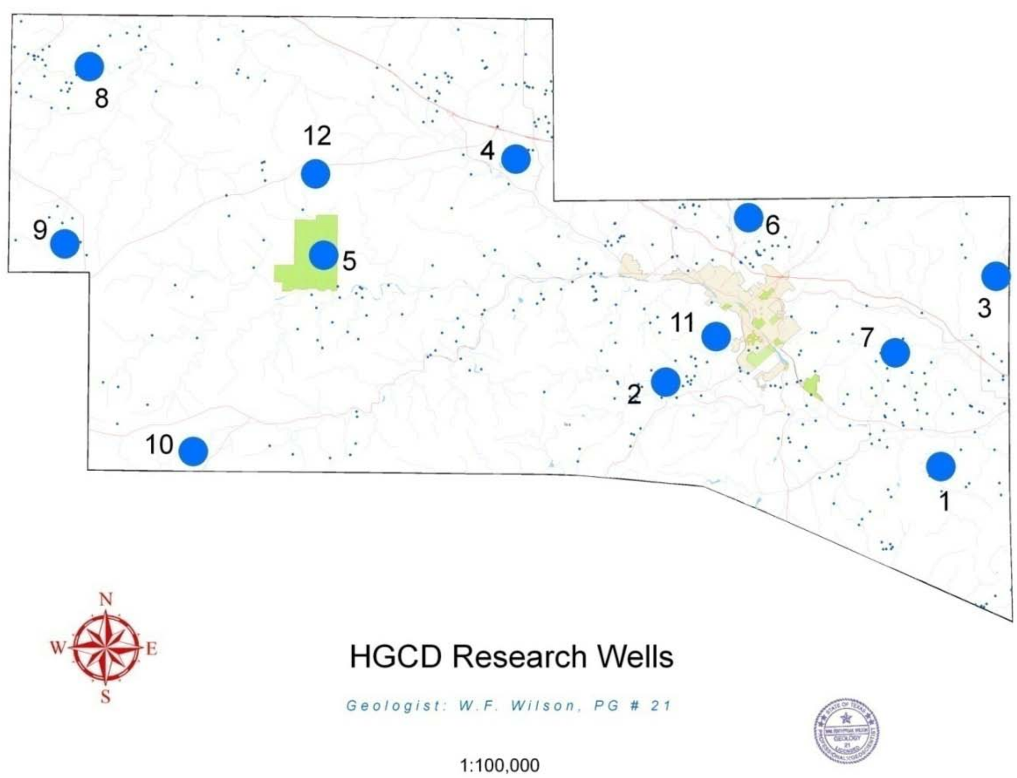


FIGURE 36: - HGCD RESEARCH AND MONITOR WELL DRILLING, 2001-2008.

The concept of the drilling program is to establish an index of scientifically controlled series of research wells that would establish new and very detailed stratigraphic and structural data points in three-dimensions of the entire Cretaceous System of aquifers and aquitards. The placement of the wells was designed to establish a geographic statistical representation of the subsurface geology for Kerr County. One notable blank area lies in the south-central portion of the county and along the northern edges of the county. New locations will be placed within these areas.

HGCD MW-12 encountered tar and heavy oil possibly mixed with natural gas. The well casing was viewed with a video camera on 10-27-08 and found a few inches of very heavy oil floating on the water table at a depth of 645'. Considerable scale was noted building up on the inside of the casing from the water table down to approximately 916'. The camera could not get past an obstruction at that depth. The asphalt of heavy oil is believed to originate in the Ellenburger dolomite found at the base of the Cretaceous sands at 1,036 to 1,110 feet. Water samples were taken and dried. A distinct oil odor was noted in the sample bottles. The dried residue resembles Gilsonite ®, which is an asphaltic ingredient used in oil well cement and paint.

Figure 37: - HGCD-MW-12 Gilsonite® or asphalt residue.

FIGURE 38: - COMMERCIAL GILSONITE®, VERNAL UTAH, GREEN RIVER OIL SHALE.

FIGURE 39: - HGCD-MW-12 OIL AND WATER EMULSION.

Gilsonite® has a density of 1.04-1.06 which will sink in fresh water. However, some volatiles are still escaping from the asphalt due to the oil/water interface. Gas bubbles were noted a few feet below the oil/water interface rising toward the surface of the water table.

The drilling program has substantially revised the pre-existing literature and added immeasurably to the understanding of the complex facies changes as well as clearing up recharge issues. The list of benefits is outlined below.

1. The well index allows drillers, landowners, realtors, political entities and others to review the detailed geology and data associated with one or more of the wells.
2. The data allows monthly and/or daily water level information transmitted to the HGCD office via satellite communication thereby establishing long term trends for individual aquifers.
3. The water level data is also a new legal requirement to support the *"Managed Available Groundwater"* number that will be set in place by September 1, 2010.
4. The stratigraphic data set forth by lithologic and geophysical logging allows the construction of regional cross-sections and a variety of geologic maps including groundwater gradient maps, thickness maps, structural maps, paleo-depositional maps, flow regime maps and many others for each layer in the Cretaceous System of rocks.
5. It enhances the ability of the HGCD Board to base their policy decisions on solid scientific data in deference to no-data-decisions for the present and far into the future.
6. The new well data allows the revision of pre-existing or non- existing literature that will impact the entire Texas Hill Country region.
7. The data also allows an analysis of recharge sustainability, which in turn allows estimates to be made of the water in storage at one given time period.

In summary, the drilling program has been the most integrally important contribution to the Headwaters goal of conservation and knowledge that will extend well into future.

V LOGGING

HGCD has logged the twelve monitoring wells as well as many other deep wells in Kerr County. It is a policy to geophysically log and lithologically log selected private or public wells across the entire county. A collection of these logs are now being added to the HGCD files and database.

The geophysical log shown in Figure 18 depicts the depth plotted against a four point resistivity series of curves on the right side of the log. Resistivity electrodes spaced at 8-16-32-64" induce current into area adjacent to the open borehole and record the response. Movement to the right indicates fresh water, relative porosity and lithologic indicators.

The left hand side of the log records three parameters including a Self Potential curve, a Self Potential Resistivity curve and a Natural Gamma Ray log. The red line is gamma ray curve. As this curve increases to right, it is recording more radiation associated with organic matter associated with uranium; thorium and radium trapped within the finer grained sediments and clays. Less gamma radiation indicates a clean sand or carbonate lithology. The gamma ray curve is calibrated in counts per minute.

Geophysical logs may be used as a correlation tool between widely spaced wells. It is prudent to use this type of correlation method with carefully constructed lithologic logs. If lithologic logs are not used, miss-correlations are possible. Pre-existing literature incorporating only geophysical logs often made some erroneous picks utilizing the clay units. This is one of the observations made by the author based upon the detailed studies described herein. The Hammett Clay was frequently mapped too far north. The Sligo Formation was seldom differentiated from the Hosston Formation in pre-existing literature due to the lack of lithologic logs.

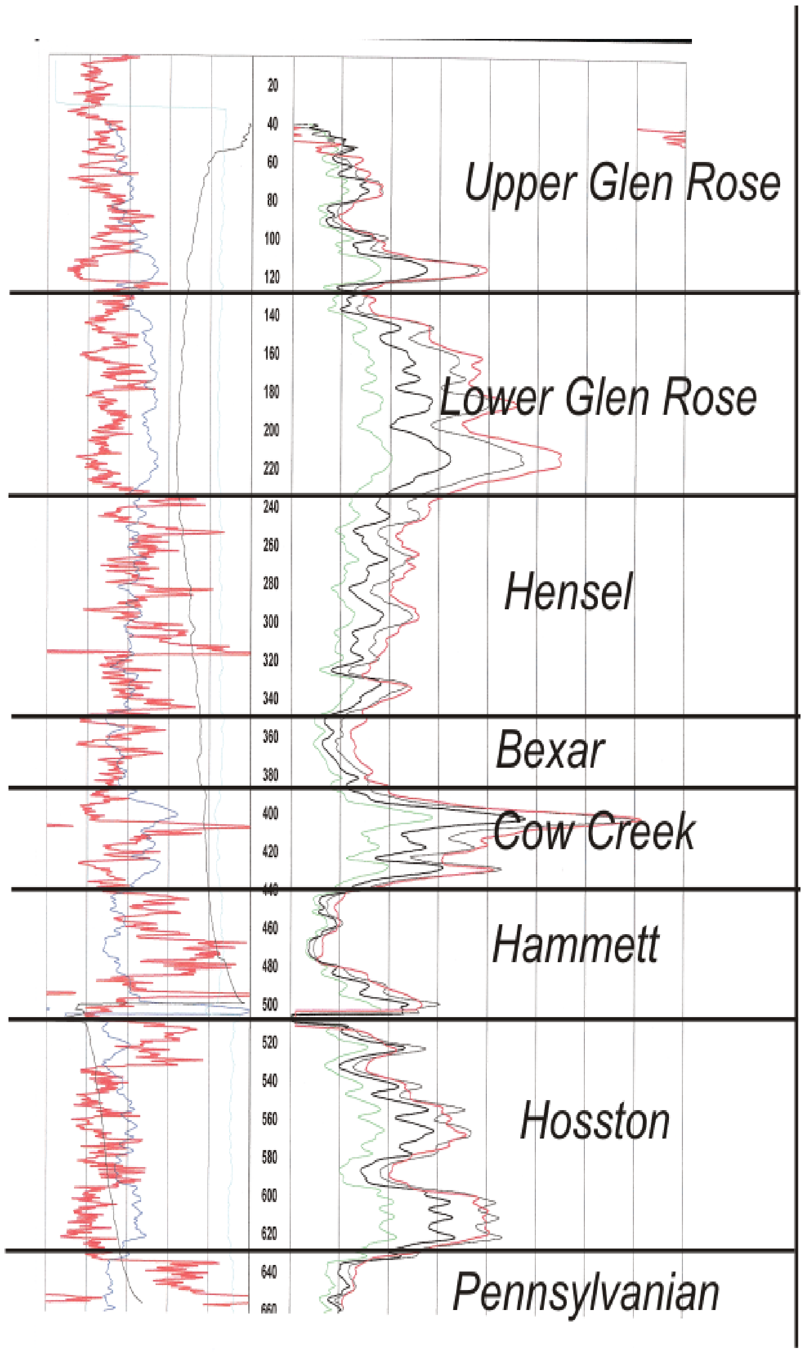


FIGURE 40: - AQUA TEXAS NO. 3 GEOPHYSICAL LOG AT CENTER POINT DEPICTING THE ENTIRE CRETACEOUS SERIES OF AQUIFERS AND AQUITARDS.

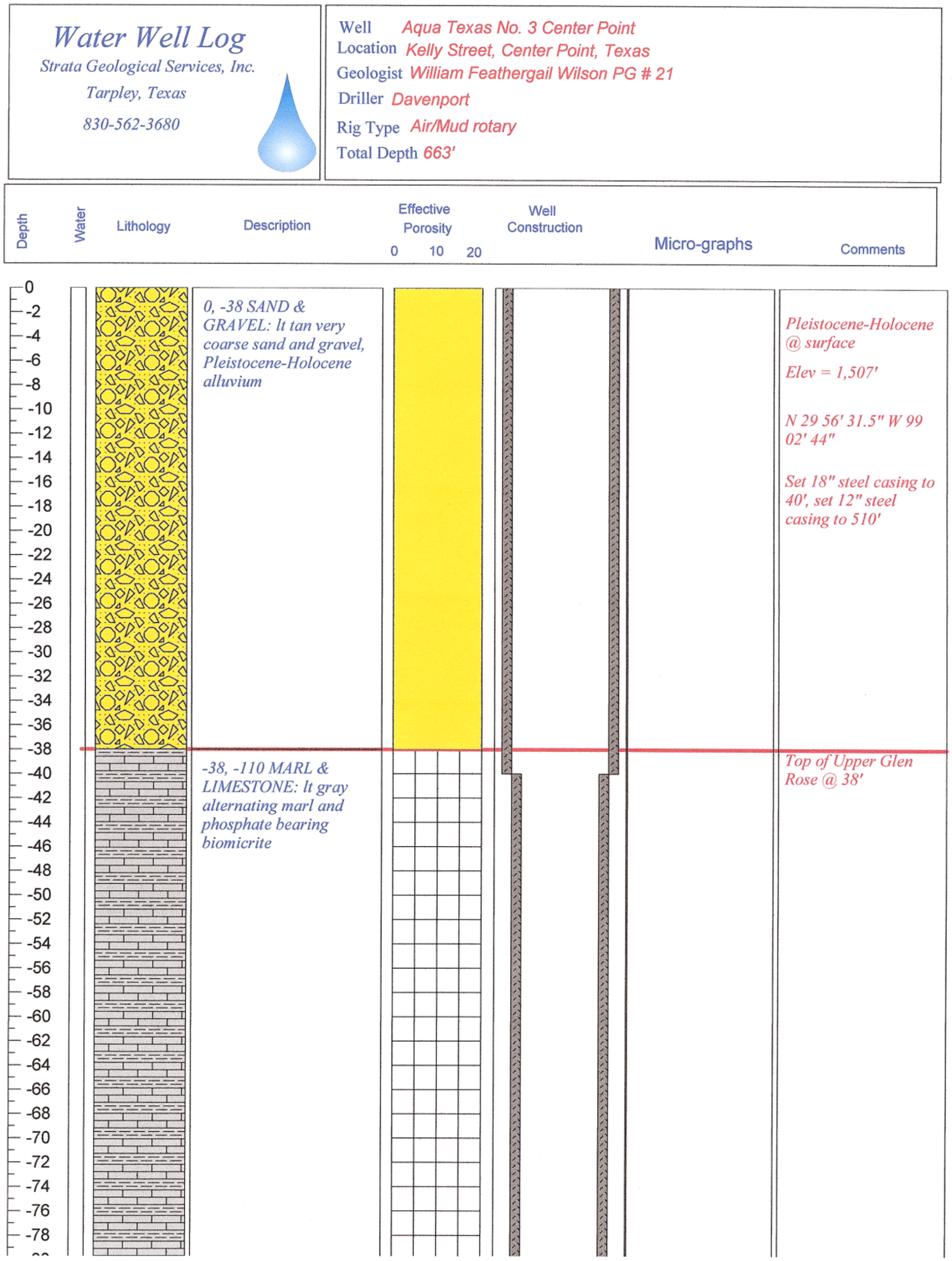


FIGURE 41: - EXAMPLE OF A PARTIAL DETAILED LITHOLOGIC LOG OF THE FIRST 80' OF THE AQUA TEXAS NO. 3 SHOWN IN THE FIGURE 40 GEOPHYSICAL LOG. DETAILED DESCRIPTIONS WERE MADE OF THE SAMPLES RECOVERED FROM THIS WELL AT INTERVALS OF 10 WITH A STEREOSCOPIC MICROSCOPE

VI MAPPING & HYDROGEOLOGY

Subsurface and surface maps allow the depiction of thickness, structure, flow directions, predictions, provenance, paleotopography, geophysics, contours, outcrops, digital elevation models and countless other geological features. The use of mapping programs such as ArcGIS has greatly enhanced map making or cartography along with detailed databases. ArcGIS databases can be sorted and selected to isolate individual aquifers and surfaces to create distinct and colorful maps. State and federal databases and shape files are readily available for little or no cost that are compatible with ArcGIS programs. Special mapping ad-on programs such as Spatial Analyst and 3-D Analyst were also utilized. The author freely uses all of these tools to create the maps found in this report. Many hand drawn maps were utilized at both the local and regional scale to supplement the final ArcGIS depictions.

Hydrogeology is the primary subject of this report and cannot be easily explained without the use of extensive maps. ArcGIS allows the user to calculate volumes of rock and aerial extents that plug into recharge and discharge calculations. Estimates of water in storage in each individual aquifer is an important parameter of hydrogeology. Estimates of where the sustainability points are greatly aided by many types of maps.

The maps presented in this report will also serve as a foundation for the addition of new data and new interpretations as new data is discovered. The author and the General Manager, Gene Williams, have instituted new handouts and driller requirements to encourage the reporting of better driller's descriptions of samples and sections drilled. The driller's reports are the single most important documents that may ever exist historically. The more education and encouragement HGCD can provide drillers in Kerr County, the better the data will be into the future. That will translate into more accurate maps and subsequent interpretations.

The following paragraphs will outline some of the basic questions, solutions and goals of the study of hydrogeology of Kerr County. This introduction will allow the reader to more fully understand the complexities of the data that mapping has revealed\

HYDROGEOLOGY INTRODUCTION

IF YOU LEARN NOTHING ELSE, REMEMBER THAT WATER IS ALWAYS MOVING. IT MOVES FROM THE OCEANS INTO THE ATMOSPHERE AND THEN FALL TO THE GROUND AS RAIN, SNOW, ICE OR DEW. IT REMAINS IN THE ATMOSPHERE ABOUT TWO WEEKS FROM EVAPORATION THAT OCCURS IN THE GULF OF MEXICO AND THE PACIFIC OCEAN. AFTER THE WATER FALLS TO THE GROUND IT MOVES DOWN THE STREAMS AND INTO THE SHALLOW SUBSURFACE. THE MOVEMENT INTO THE SUBSURFACE IS OUR PRIMARY INTEREST AND THAT FALLS INTO THE ARENA OF HYDROGEOLOGY. WATER MOVING IN THE SUBSURFACE, MOVES AT DIFFERENT SPEEDS FROM FEET PER DAY TO CENTIMETERS PER DECADE OR SLOWER.

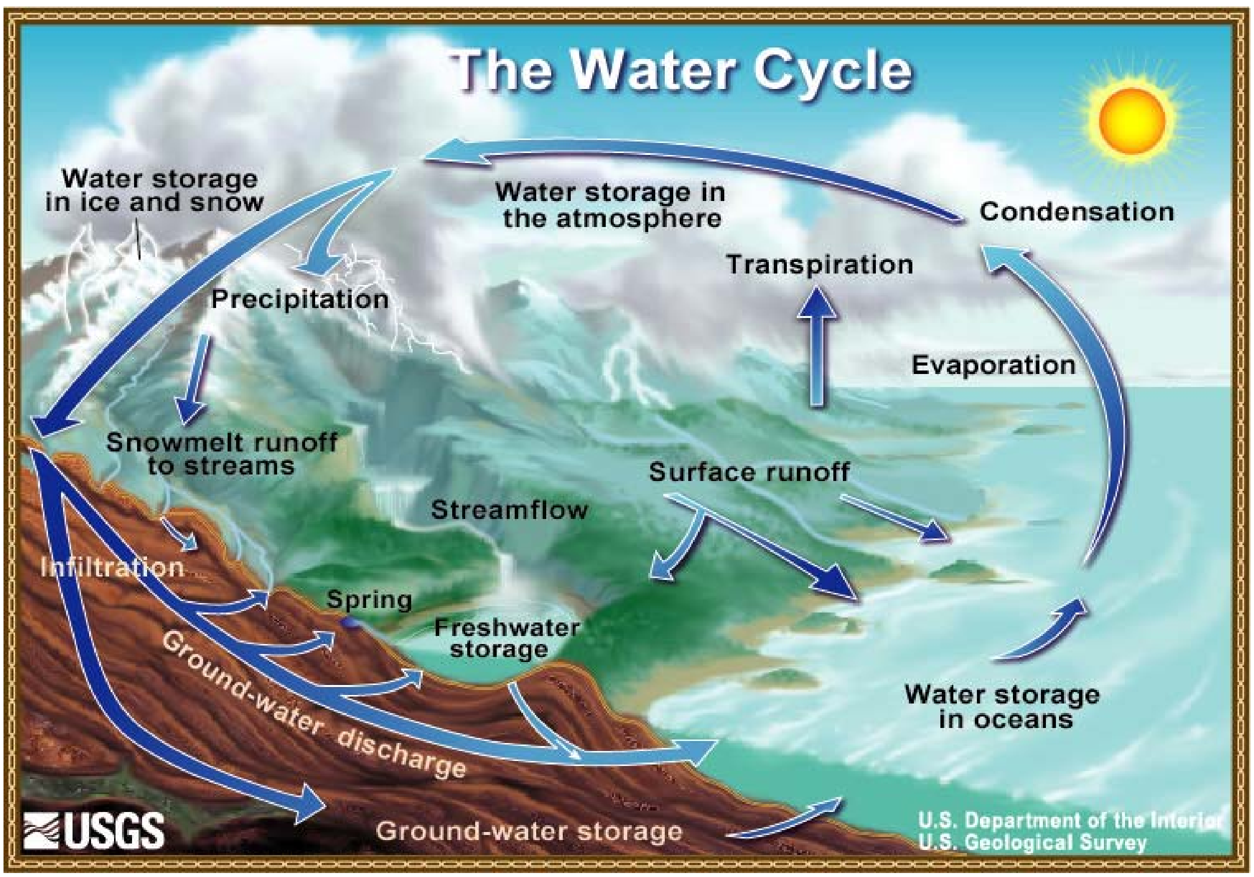


FIGURE 42: - THIS DRAWING DISPLAYS THE WATER CYCLE AS PREVIOUSLY DESCRIBED.

Subsurface water moves back to the surface by spring flow, or if it is deeply buried, it is squeezed back into the oceans. The water that moves deep in the subsurface, picks up minerals as travels down to thousands of feet and becomes saline. Water is known to exist to at least 30,000 feet below the surface in sedimentary aquifers. However, at about 18,000-20,000 feet water begins to be squeezed out by the overlying sediments. Above those depths water is so incompressible that it actually holds up those sediments and holds a steady pressure gradient of 0.43 psi per foot of depth. Below about 18,000-20,000 that pressure gradient begins to increase approaching 1.0 psi per foot. Water is a universal solvent being a bi-polar molecule. Water also transports oil and gas into structural and stratigraphic traps.

Subsurface water flow speed is of great interest to the hydrogeologist and should be of great interest to the policy maker. The speed of groundwater is critical to sustainability. If too much water is allowed to be produced because of the slowness of recharge, it can become a non-sustainable resource. Eventually people will just have to move, import or desalinize water if sustainability is ignored. Understanding hydrogeology will allow policy makers and political leaders to make better decisions on the use or misuse of groundwater.

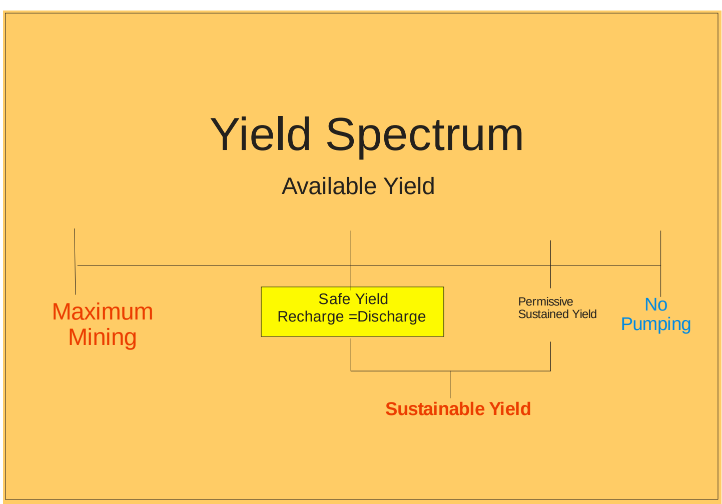


Figure 43: - The Yield Spectrum is a diagram of sustainability or the complete mining of groundwater.

Sustainability can be viewed from the simple standpoint of recharge = discharge as shown above in Figure 43. One sustainability axiom may be stated as follows and applicable to groundwater or any other natural resource (Peak Everything, Richard Heinberg, 2008).

1. "Any society that continues to use critical resources, unsustainably, will collapse."

The future of groundwater usage in Kerr County will necessitate conservation measures such as:

- Rainwater harvesting - mandated with tax incentives
- Water availability studies for each new proposed subdivision
- Managed Available Groundwater permit limits (MAG's)
- Pipelines to move groundwater from the NW portion of the county the SE portion of the county
- Conjunctive use of surface water and groundwater
- Growth limits

Fresh groundwater as defined by a TDS range of 0-1,000 ppm is first captured by an unconfined aquifer. The Edwards Group in Kerr County is an example of an unconfined aquifer. Rain simply falls upon the Edwards outcrop and seeps into the fractures and holes with no confining units above it.

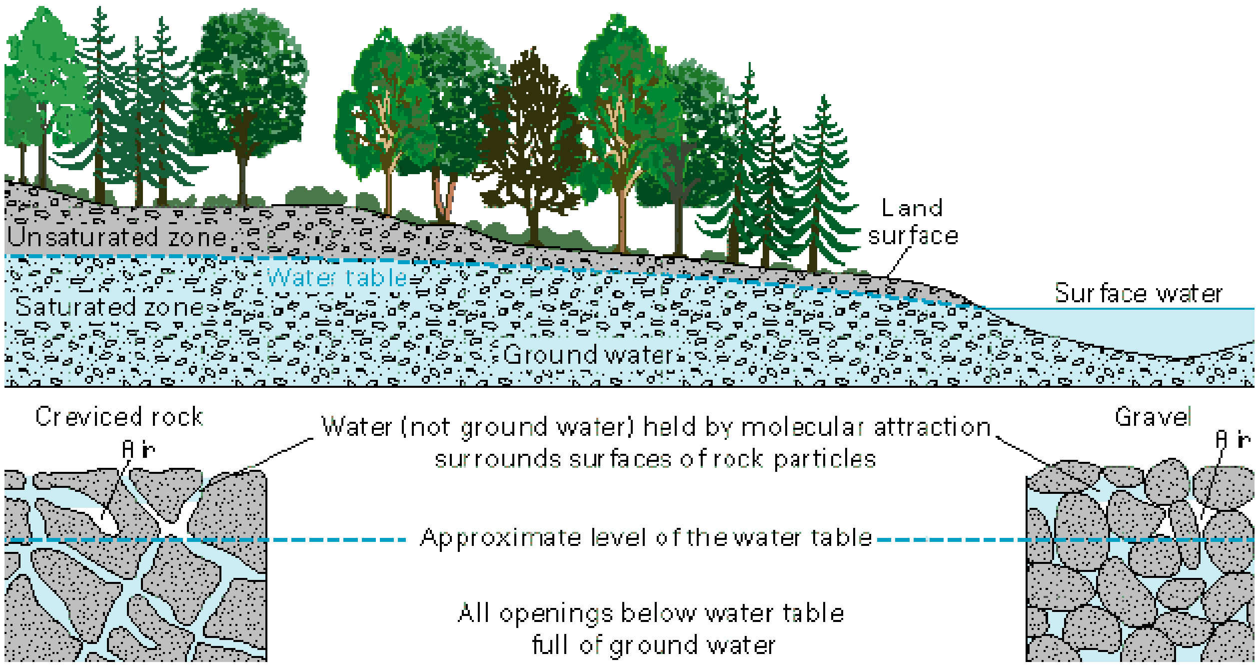


FIGURE 44: - EXAMPLE OF AN UNCONFINED AQUIFER WITH NO CONFINING UNIT (AQUITARD). THE CREVICED ILLUSTRATION ON THE LEFT IS APPLICABLE TO THE EDWARDS, WHILE THE ILLUSTRATION ON THE RIGHT WOULD BE APPLICABLE TO THE ALLUVIUM ALONG THE GUADALUPE WATERSHED.

THE THREE PARAMETERS THAT FORM THE BASIS FOR ESTIMATING AND CALCULATING HOW FAST THE WATER MOVES AND HOW MUCH WATER MOVES AND FINALLY HOW MUCH WATER IS IN STORAGE IS TABULATED BELOW.

PARAMETER	**DESCRIPTION**
STORAGE COEFFICIENT	A NUMBER WITHOUT UNITS REFLECTING THE AMOUNT OF WATER IN STORAGE WITHIN AN AQUIFER AT ONE GIVEN TIME. IT DOES NOT REPRESENT A SUSTAINABLE NUMBER OF RECHARGE = DISCHARGE.
HYDRAULIC CONDUCTIVITY	A UNIT PRISM REFLECTING HOW FAST WATER IS MOVING THROUGH THAT UNIT PRISM EXPRESSED AS FEET/DAY OR EQUIVALENTS
TRANSMISSIVITY	HYDRAULIC CONDUCTIVITY TIMES THE THICKNESS OF THE AQUIFER EXPRESSED AS FEET^2/DAY OR EQUIVALENTS

TABLE 8: - DEPICTING THE THREE HYDROGEOLOGICAL PARAMETERS USED TO CALCULATE GROUNDWATER MOVEMENT AND STORAGE.

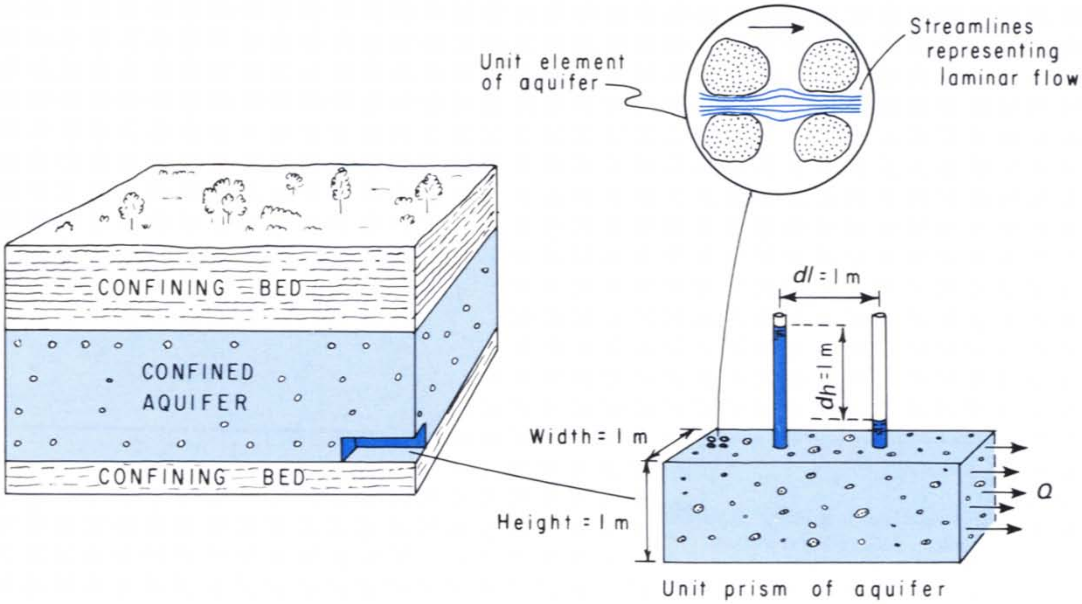


FIGURE 45: - ILLUSTRATION OF HYDRAULIC CONDUCTIVITY UNIT PRISM.

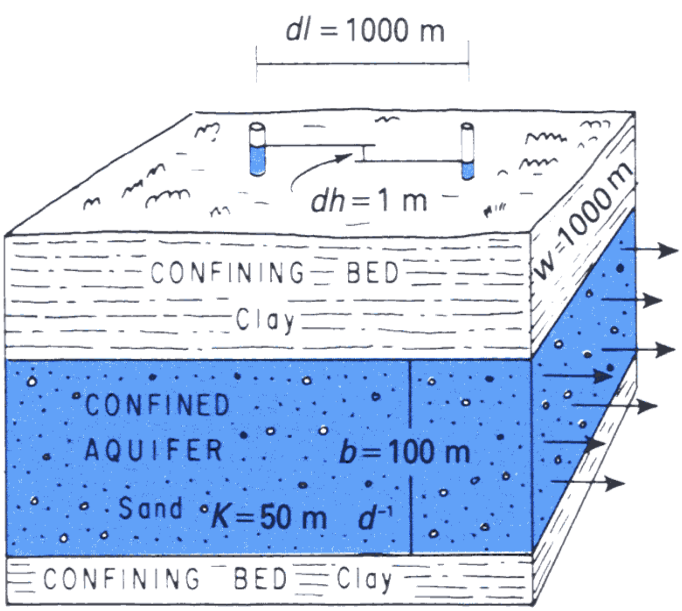


FIGURE 46: - ILLUSTRATION OF THE CONCEPT OF TRANSMISSIVITY.

STORAGE COEFFICIENT NOTES

INTRODUCTION

THERE IS A SMALL AND ELUSIVE NUMBER USED IN GROUND WATER STUDIES THAT ON THE SURFACE APPEARS TO BE SO SMALL THAT IT BECOMES MEANINGLESS. IT IS A VERY IMPORTANT NUMBER BECAUSE IT DESCRIBES THE WATER THAT IS IN STORAGE WITHIN AN AQUIFER AT ANY ONE INSTANT IN TIME. ANOTHER DESCRIPTION THAT MIGHT BE APPLIED IS *"THE VOLUME OF WATER THAT AN AQUIFER RELEASES FROM OR TAKES INTO STORAGE PER UNIT SURFACE AREA OF THE AQUIFER PER UNIT CHANGE IN HEAD"*. THE SIZE OF THE STORAGE COEFFICIENT DEPENDS UPON WHETHER THE AQUIFER IS CONFINED OR UNCONFINED. IT CHANGES BY AN ORDER OF MAGNITUDE. AN ORDER OF MAGNITUDE CHANGE RESULTS IN AN EXPONENTIAL INCREASE OR DECREASE IN THE VOLUME OF WATER STORED. THE EQUATION GIVEN BELOW IS A VERY SIMPLIFIED FORM (HEATH, R.C., USGS WATER SUPPLY PAPER 2220, BASIC GROUND-WATER HYDROLOGY).

.

$$Storage_{coeff} = \frac{volume\ of\ \ water}{(unit\ area)(unit\ head\ change)} = \frac{m^3}{m^3}$$

NOTE THE TERM "UNIT HEAD CHANGE". THAT IS DERIVED FROM A PUMP TEST. THE "UNIT AREA" WILL BE A THREE DIMENSIONAL AREA.

STORAGE COEFFICIENT IN CONFINED AQUIFERS RANGE BETWEEN 10^{-6} (0.00001) TO 10^{-3} (0.001), WITH AN AVERAGE OF 10^{-4} (0.0001). THE RANGE IN UNCONFINED AQUIFERS GENERALLY VARIES FROM 10^{-3} TO 10^{-1}. WHEN DEALING WITH UNCONFINED AQUIFERS THE TERM IS USED INTERCHANGEABLY WITH ***"SPECIFIC YIELD"***. THE TERMS ARE ALSO REFERRED TO AS ***"STORATIVITY"***.

A MORE RIGOROUS EQUATION CONSIDERS ALL OF THE VARIABLES AND IS ALSO KNOWN AS "SPECIFIC STORAGE".

$$Storage_{specific} = \rho_w g(\phi + n\beta)$$
$$\beta = compressibilty\ of\ water$$
$$\phi = compressibility\ of\ aquifer\ matrix$$
$$g = acceleration\ of\ gravity$$
$$\rho_w = density\ of\ water$$
$$n = porosity$$
$$\psi = specific\ weight\ of\ water$$
$$b = aquifer\ thickness$$

IT IS ESSENTIALLY A SOPHISTICATED MEASUREMENT OF ***POROSITY (N)***. IN OTHER WORDS, IT IS THE TOTAL VOLUME (100%) OF WATER THAT IS IN STORAGE WITHIN THE PORE SPACE OF A UNIT VOLUME OF ROCK.

GROUND WATER IS GOVERNED BY ANOTHER PARAMETER KNOWN AS ***"SPECIFIC RETENTION"***. MOST OF THE WATER IS NOT AVAILABLE FOR PRODUCTION. MUCH OF THE WATER IS TRAPPED WITHIN THE ROCK MATRIX DUE TO CAPILLARY PRESSURE. THE PERCENTAGE OF WATER THAT CAN BE EXTRACTED FROM THE 100% GENERALLY FALLS WITHIN THE RANGE OF 5-35% DEPENDING UPON SIZE SORTING, CLAY AND SILT CONTENT, PACKING, CEMENTATION, COMPACTION AND GRAIN SIZE. SMALLER SIZE SEDIMENT RETAINS A HIGHER PERCENTAGE OF WATER THAN GRAVEL SIZE SEDIMENT.

REASONS TO USE STORAGE COEFFICIENT

DESPITE THE ELUSIVE AND COMPLEX NATURE OF STORAGE COEFFICIENTS, THEY ARE VERY USEFUL AND NECESSARY WHEN CALCULATING WATER AVAILABILITY OF AN INDIVIDUAL AQUIFER OR SERIES OF AQUIFERS. THE EQUATION THAT GOVERNS THE AVAILABILITY OF WATER FROM ANY GIVEN AQUIFER AT ANY GIVEN INSTANT IS SHOWN BELOW.

$$Water_{available} = S_{coeff}\ x\ aquifer\ thickness\ x\ \%\ of\ water\ released\ x\ acres = acre\ feet\ x\ 325,851 = gallons$$

FOR EXAMPLE, A STORAGE COEFFICIENT OF 2.3 X 10^{-4} DERIVED FROM A PUMP TEST COMBINED WITH AN AQUIFER THICKNESS OF 20' AND A 25% RECOVERY FACTOR OVER 50-ACRES WILL YIELD:

$$Water_{available} = 2.3\ x 10^{-4}\ x\ 20'\ x\ 0.25\ x\ 50 = 0.0575 acre\ feet\ x\ 325,851 = 18,736\ gallons$$

LET'S CHANGE THE ORDER OF MAGNITUDE BY -1;

$$Water_{available} = 2.3\ x10^{-3} x\ 20'\ x\ 0.25\ x\ 50 = 0.575 acre\ \ feet\ x\ 325,851 = 187,736\ gallons$$

NOTE THE AMOUNT OF WATER AVAILABLE INCREASED BY 10 TIMES BY INCREASING THE ORDER OF MAGNITUDE BY +1. IF THE ORDER OF MAGNITUDE WERE DECREASED BY -1, IT WOULD HAVE DECREASED THE GALLONS TO 1,873 GALLONS.

2.3×10^{-3}	187,736 GALLONS
2.3×10^{-4}	18,736 GALLONS
2.3×10^{-5}	1,873 GALLONS

.

WITH THIS EQUATION YOU CAN ESTIMATE THE DEMAND AND COMPARE THIS TO THE AMOUNT OF WATER THAT IS AVAILABLE FROM ANY GIVEN AREA EXPRESSED IN ACRE FEET OR GALLONS. THESE NUMBERS CAN BE USED IN WATER AVAILABILITY STUDIES, GROUND WATER MODELING AND REGULATORY PUMPING LIMITS. ***THIS NOT AN ACADEMIC SMALL AND MEANINGLESS NUMBER; IT IS THE GOVERNING NUMBER FOR WATER AVAILABILITY.***

HOW IS STORAGE COEFFICIENT DERIVED FROM A PUMP TEST?

Storage Coefficient is derived from a pump test utilizing the time-drawdown curve utilizing the following equation after the transmissivity is obtained. There are other variations based upon different methods both for drawdown and recovery curves (Kasenow, M., Introduction to Aquifer Analysis)

$$Storage_{coeff} = \frac{2.25Tt_o}{r^2}$$

$T = Transmissivity$

$t_0 = Time$

$r = distnace\ to\ observation\ well$

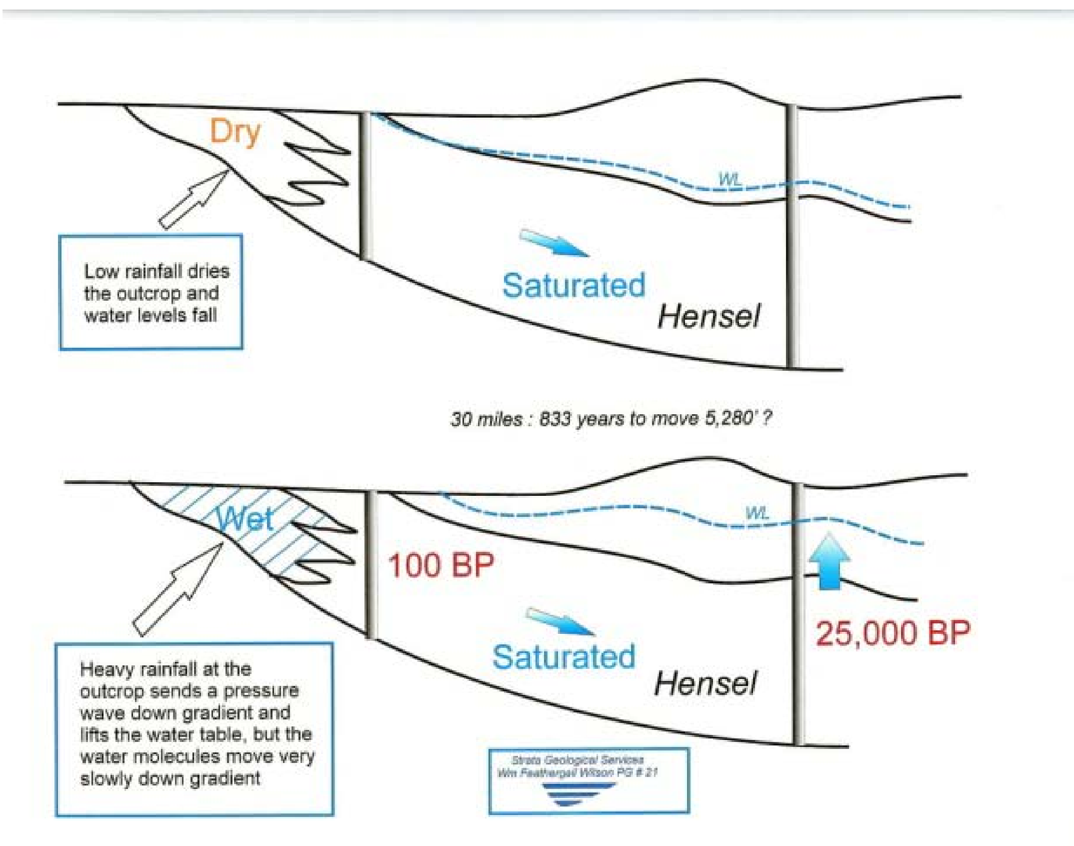


Figure 47: - Illustration of groundwater movement from the outcrop into the subsurface.

Figure 48 is a surface outcrop map of the Edwards unconfined aquifer in Kerr County depicted in two shades of blue. The white area represents the Upper Glen marl aquitard or confining unit that underlies the Edwards. The edges of the Edwards outcrop allow the water to drain out of the unconfined unit as spring flow. This is an example of a surface geologic map created with ArcGIS software.

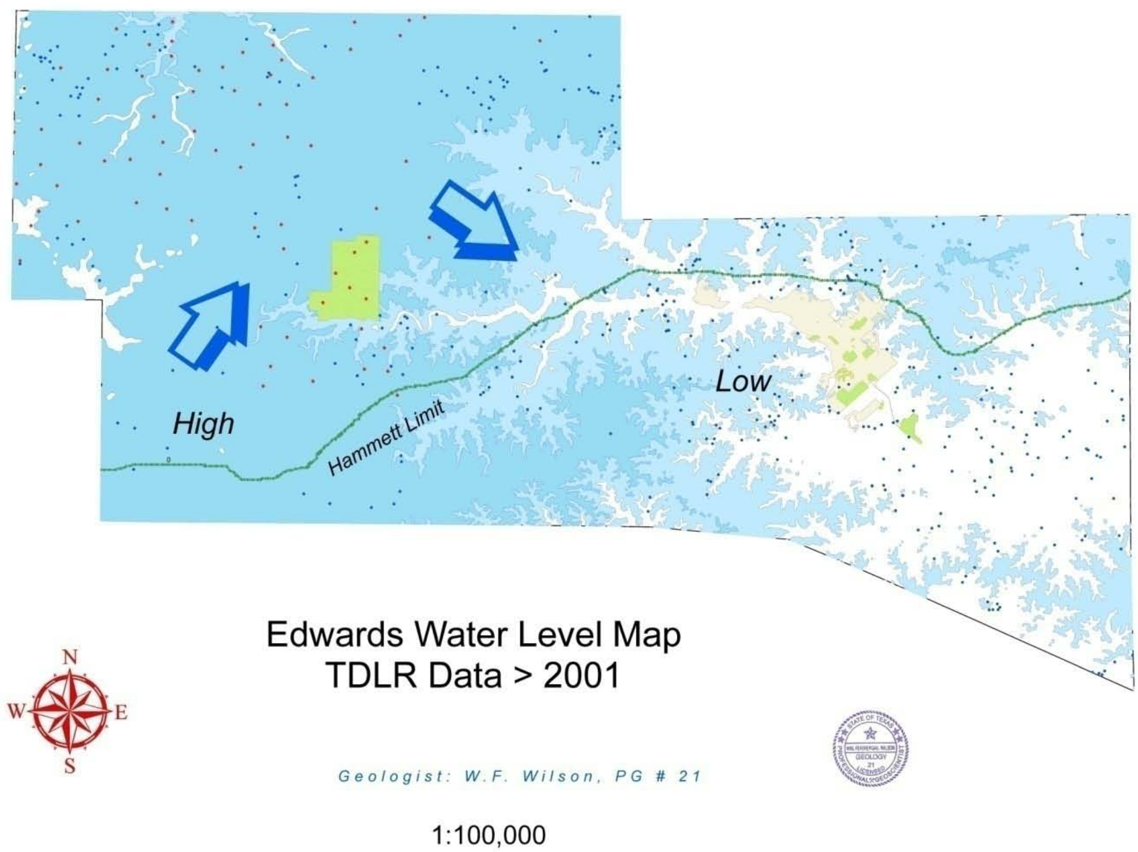


Figure 48: - Edwards Group surface geology map

The amount of water stored in the Edwards is approximately 530,000 acre feet at any one given time. The derivation of this number is far more difficult to ascertain due to the karst nature of the aquifer. We know that groundwater is moving into Kerr County from Real, Bandera, Edwards, Gillespie and Kimble counties. We know that water is moving out of the Edwards at an average rate of 216 acre feet per day. The water moving out of the Edwards is exiting through spring flow about 60' above the base of the Edwards. That is not always the case for every spring, but it is a good approximation. The Edwards covers about three-fourths of the county or approximately 530,000 acres. We assume the water table saturates about 10% of the Edwards aquifer. This figure is complicated by the fact that all of the water is trapped in fractures and caves in deference to the matrix of the limestone. Thus, the trapped water is considerably less than 10%. It is virtually impossible to calculate the volume of these karsted pores unlike a sand or sandstone. Thus, an estimate must be made.

Since water wells completed in the Edwards seldom exhibit any appreciable drawdown and the average annual discharge from wells and springs equates to approximately 83,700 acre feet, a figure about five times this number is chosen for the water in storage. This number amounts to about 530,000 acre feet at any one given time. This approximation is considered a very conservative figure and the Edwards may store considerable more water. The storage of water on the Edwards Plateau cannot be compared with the Edwards along the Balcones Fault Zone, where literally caves of water exist and well yields of 1,500 – 3,000 gpm are common. The Edwards contains more water than any other aquifer in Kerr County.

The well yields within the Edwards Plateau seldom exceed 25 gpm and most yield within a range of 2-5 gpm. The unconfined Edwards range in thickness from 0-645 feet and averages about 250 feet thick.

The City of Kerrville recovered about 3,000 acre feet of water from the Guadalupe River in 2007. The City has about 5,852 acre feet of water rights. The UGRA has about 2,000 acre feet of unused water rights. Almost all of these water rights are considered "junior" water rights compared to others. During a drought the junior water rights will be curtailed sooner than senior water rights.

THE ONLY OTHER UNCONFINED AQUIFER IN THE COUNTY IS ATTRIBUTED TO THE ALLUVIUM ALONG THE STREAMS OF THE GUADALUPE WATERSHED.

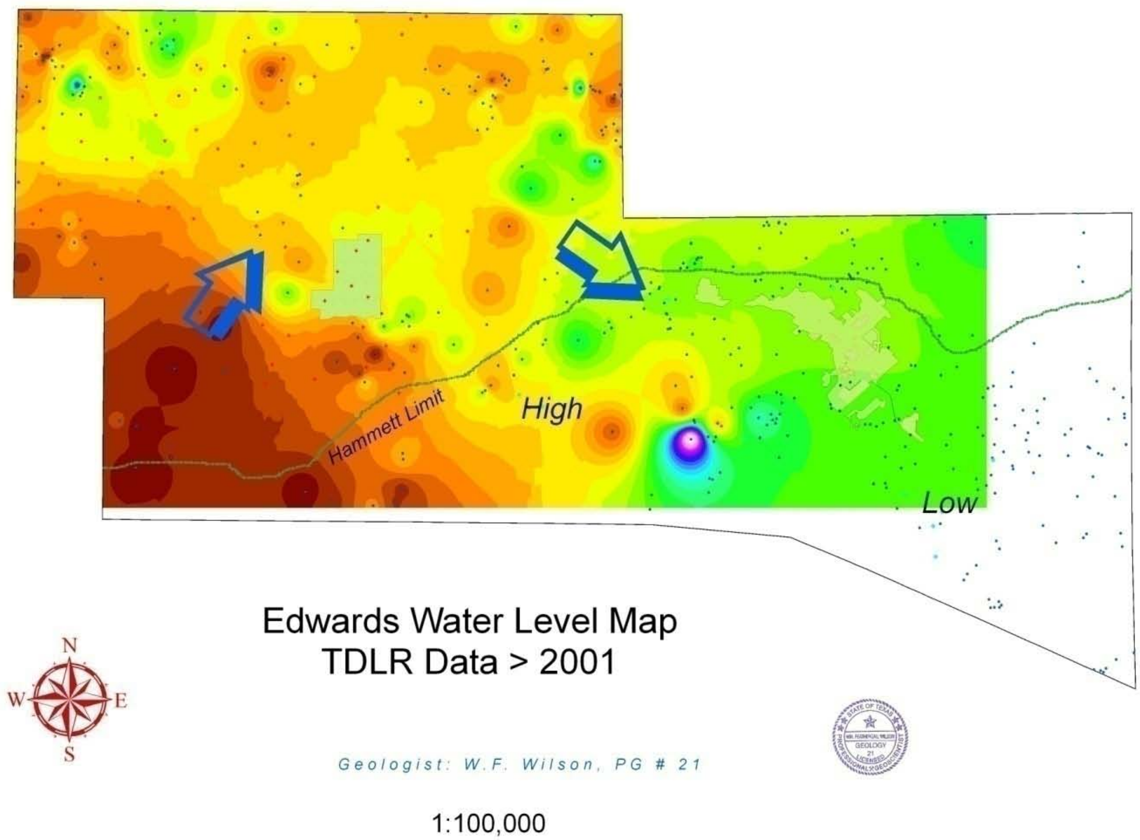


FIGURE 49: - EDWARDS GROUP WATER LEVEL MAP.

CONFINED AQUIFERS

ALL OF THE REMAINING AQUIFERS IN KERR COUNTY ARE CONFINED BY THE 250 FOOT UPPER GLEN ROSE BLANKET OF MARL. RECALL THE TERM "MARL" REFERS TO CLAY THAT CONTAINS ABOUT 50% CALCIUM CARBONATE.

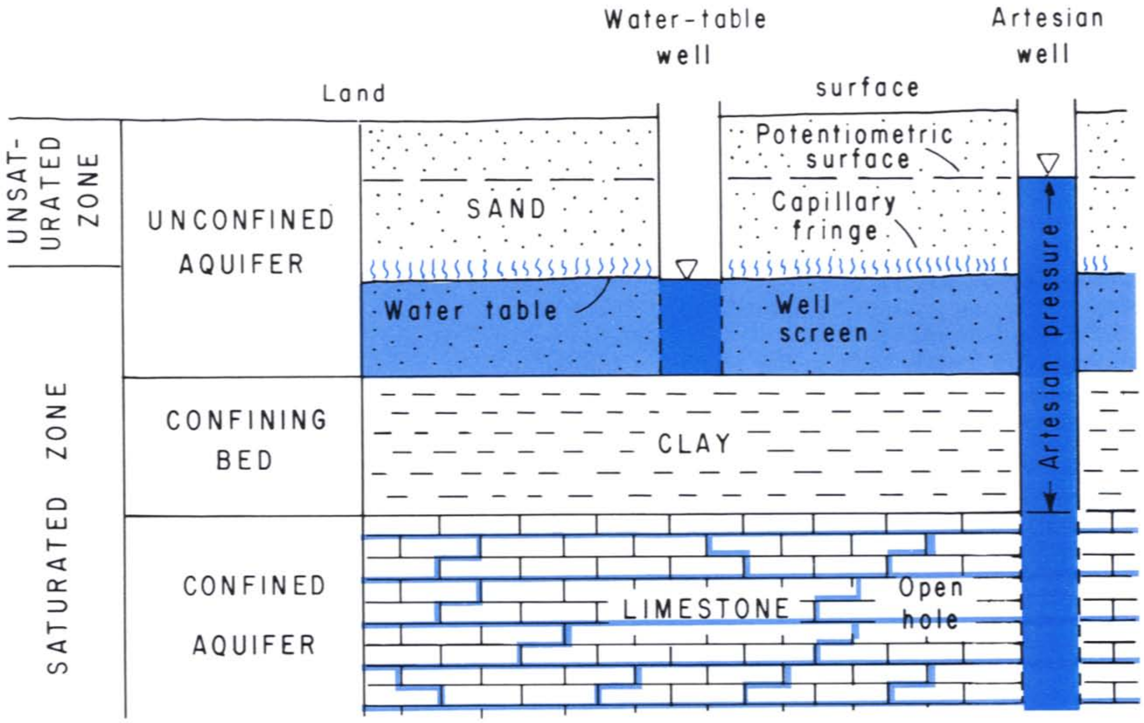


FIGURE 50: - EXAMPLE OF CONFINED AND UNCONFINED AQUIFERS. NOTE THE CLAY LAYER ACTS AS THE CONFINING UNIT OR AQUITARD. THE WELL ON THE LEFT IS COMPLETED IN THE UNCONFINED AQUIFER ABOVE THE CLAY.

<u>HYDROGEOLOGY OF THE HENSEL CONFINED AQUIFER</u>

THE CONFINED HENSEL SAND AQUIFER COVERS THE ENTIRE COUNTY. IT IS THE MAIN PRODUCING HORIZON FOR DOMESTIC WELLS FOLLOWED BY THE EDWARDS AQUIFER. FAR MORE WATER IS PRODUCED FROM THE HENSEL THAN ANY OTHER UNIT.

AVERAGE YIELDS FOR DOMESTIC WELLS ARE ABOUT 15-25 GPM. THERE ARE PUBLIC WATER WELLS THAT PRODUCE IN EXCESS OF 150 GPM IN THE SOUTHEAST PORTION OF THE COUNTY. VERY LARGE YIELD WELLS COULD THEORETICALLY BE DRILLED AND PRODUCED IN THE NORTHWEST PORTION OF THE COUNTY EXCEEDING 1,000 GPM. THE NORTHWEST QUADRANT OF THE COUNTY REMAINS THE BEST AREA FOR HENSEL PRODUCTION. THUS FAR, THIS AREA HAS NOT BEEN DRILLED OR EXPLORED TO ANY APPRECIABLE DEGREE, DESPITE ITS POTENTIAL.

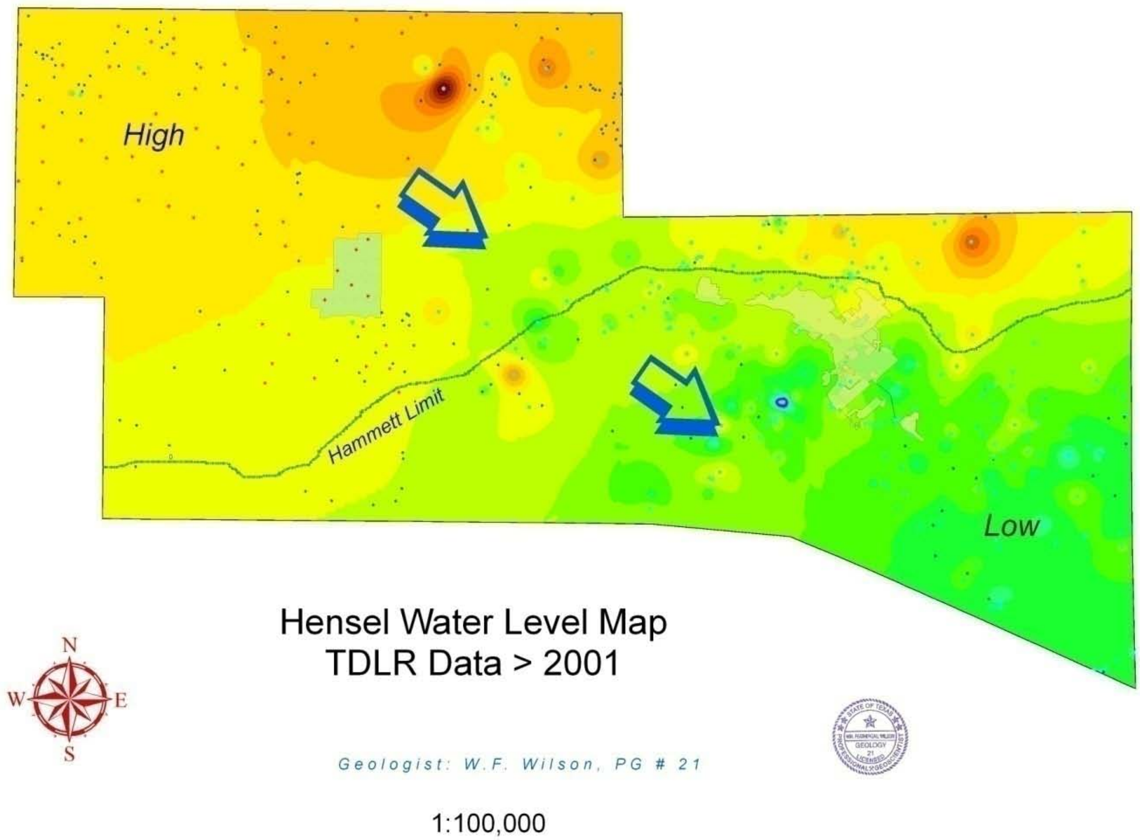


FIGURE 51: - HENSEL WATER LEVEL MAP BASED UPON THE TDLR DATABASE. NOTE THE GRADIENT IS ROUGHLY NW TO SE. GROUNDWATER IS MOVING FROM KIMBLE AND GILLESPIE COUNTY INTO KERR COUNTY BENEATH THE LOWER GLEN ROSE MARLS.

THE HENSEL AQUIFER HAS AN AVERAGE THICKNESS OF APPROXIMATELY 225 FEET AND COVERS 708,902 ACRES IN KERR COUNTY. THE FOLLOWING CALCULATION DEPICTS THE AMOUNT OF WATER IN STORAGE AT ANY ONE GIVEN MOMENT IN TIME.

$$225.44' \, x \, 5E-4S_c \;\; x \; 708{,}902 \; acres \; x \; 0.15\% \; rec = 11{,}986 \; ac \;\; ft$$

THIS FIGURE DOES NOT REPRESENT RECHARGE. IT IS THE ESTIMATE OF WATER IN STORAGE WITHIN THE AQUIFER IF YOU COULD PUMP IT DRY IN ONE DAY. THE AMOUNT OF RECHARGE INTO THE HENSEL IS A MUCH LOWER NUMBER, WHICH WILL BE DISCUSSED SUBSEQUENTLY.

THE FOLLOWING TABLE DEPICTS THE 2008 STORAGE, RECHARGE AND DISCHARGE FOR EACH AQUIFER IN KERR COUNTY. AS THE POPULATION INCREASES LESS PROPORTIONATE WATER WILL BE AVAILABLE FROM THE GUADALUPE RIVER DUE TO THE LIMITATION OF WATER RIGHTS CONTROLLED BY THE CITY OF KERRVILLE. CONJUNCTIVE USE OF RIVER WATER AND SUBSURFACE WATER WILL NOT RISE PROPORTIONATELY, THEREBY PLACING MORE PRESSURE ON THE AQUIFERS. IF THE PRESENT POPULATION RISES TO 100,000 PEOPLE, THE DEMAND WILL RISE TO APPROXIMATELY 16,802 ACRE FEET, LESS APPROXIMATELY 5,000 ACRE FEET FROM THE RIVER EQUALING ABOUT 11, 802 ACRE FEET FROM THE AQUIFERS TABULATED BELOW. IT IS EVIDENT THAT THE 2008 DIFFERENCE BETWEEN RECHARGE AND DISCHARGE IS ALMOST BALANCED DIFFERING BY 1,381 ACRE FEET. AN INCREASE IN POPULATION TO 60,000 PEOPLE WOULD OVERCOME THAT BALANCE. THE POPULATION OF KERR COUNTY IS EXPECTED TO REACH THAT NUMBER WITHIN THE NEXT 10-YEARS.

NUMBERS ASSOCIATED WITH THE FOLLOWING TABLE ARE DEFINITELY SUBJECT TO CHANGE. THAT IS ESPECIALLY TRUE FOR THE LOWER GLEN ROSE, COW CREEK AND SLIGO-HOSSTON AQUIFERS. BETTER ESTIMATES EXIST FOR THE EDWARDS AND HENSEL AQUIFERS DUE TO A MUCH HIGHER LEVEL OF DATA.

CARE SHOULD BE TAKEN TO REVIEW THE EDWARDS NUMBERS. SPRING FLOW REPRESENTS APPROXIMATELY 90% OF THE ESTIMATED ANNUAL DISCHARGE. IT IS DOUBTFUL THAT NO MORE THAN 10% OF THAT FLOW WILL BE ALLOWED TO RECOVER AS CONJUNCTIVE USE. THE WATER RIGHTS OF THE GUADALUPE WATERSHED ARE OVER-SUBSCRIBED AND DURING A DROUGHT, CONJUNCTIVE USE WILL BE INCREMENTALLY CUT BACK.

AQUIFER	AMOUNT OF GROUNDWATER IN STORAGE - ACRE FEET	ANNUAL RECHARGE ESTIMATE – ACRE FEET	ANNUAL DISCHARGE ESTIMATE - ACRE FEET
EDWARDS	530,000	83,700	83,700 (SPRING FLOW & WELLS)
HENSEL	11,986	8,708	4,133 (~1/2 OF KERR COUNTY'S POPULATION UTILIZES

			River water from the Edwards)
Lower Glen Rose	266	50	6
Cow Creek	250	40	28
Sligo-Hosston	1,500	750	4,000
Totals	543,752	93,248	91,867

Table 9: - Depicting the Kerr County aquifer recharge, discharge and storage estimates.

Lower Glen Rose Hydrogeology

The Lower Glen Rose aquifer is limited to the southern quarter of the county. It is a massive carbonate lithologic unit with limited hydraulic conductivity and limited production. Part of the reason for limited production is the poor quality of the water. A small number of shallow wells have been completed in the Lower Glen Rose in the Center Point and Comfort areas of Kerr County. It is considered a minor aquifer in the county compared to the Edwards and Hensel.

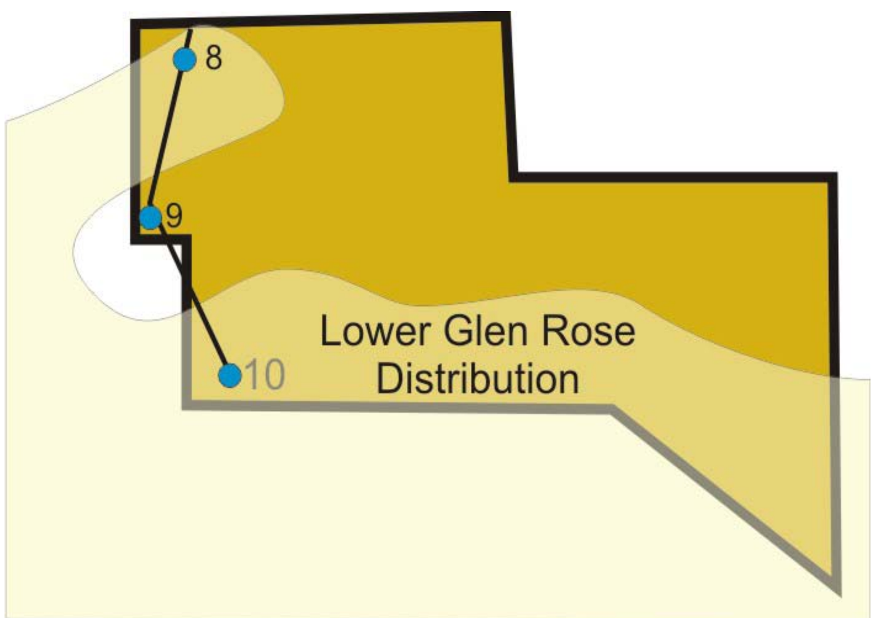


Figure 52: - Lower Glen Rose distribution in Kerr County.

Cow Creek Hydrogeology

The Cow Creek Limestone is a very thin aquifer and is spread across the southern quarter of Kerr County similar to the Lower Glen Rose. The porous section of the Cow Creek is generally less than 20 feet thick. In some areas it is indistinguishable from the Hensel sands. The only division between the Hensel and the Cow Creek is a thin marl unit known as the Bexar Shale. Reference is made to Table 9 for Cow Creek storage, recharge and discharge estimates.

Sligo-Hosston Hydrogeology

The Sligo and Hosston are facies of each other. The Sligo is very limited in distribution and is simply lumped into the Hosston as one aquifer. The Hosston has historically been the primary completion target for the Cities of Kerrville and Ingram and adjacent areas. The Hosston is a fining upward sequence of gravel, sand and silt. Most of the water is stored near the base of the unit in the graveliferous sands. The top one-third of the Hosston is generally a fine silt. Certain areas of the Hosston have proven to be tightly cemented exhibiting lower than normal hydraulic conductivity. These areas have witnessed regional drawdowns due to low recharge and heavy pumping. The Hosston is defined as the clastic unit that underlies the Hammett Clay. The Hammett Clay pinches out across the county as shown on several maps in this report. North of that line the Hosston becomes a facies of the Hensel.

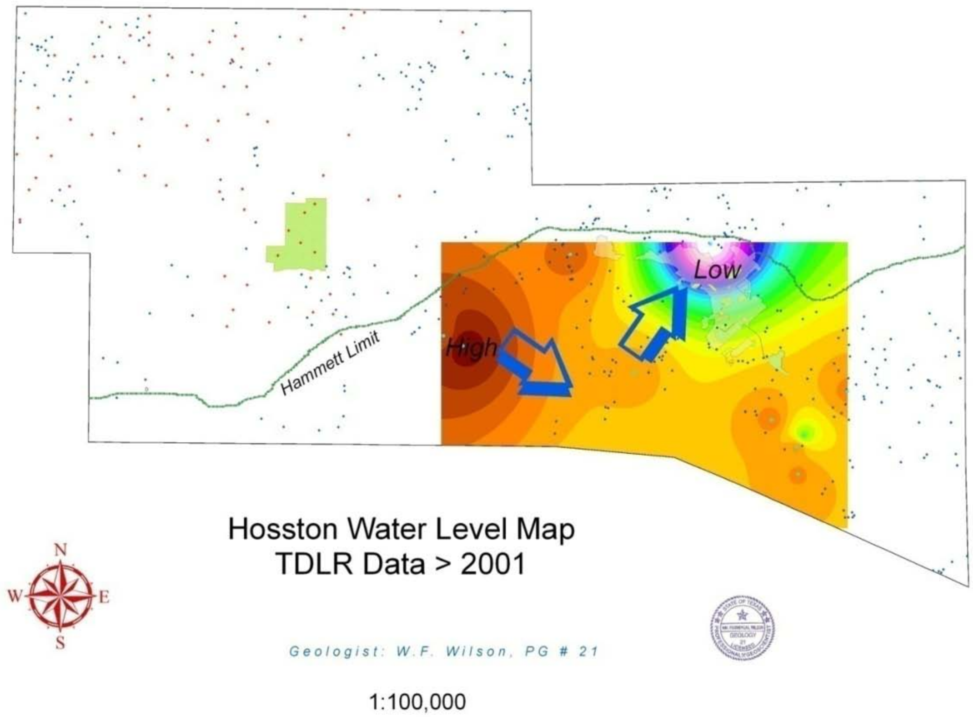


FIGURE 53: - ILLUSTRATION OF THE HOSSTON WATER LEVEL MAP BASED UPON THE TDLR DATABASE. NOTE THE LACK OF DATA TO THE SOUTHWEST AND EAST. ADDITIONAL MONITORING WELLS HAVE BEEN RECOMMENDED IN THESE AREAS.

GROUNDWATER AVAILABILITY MODELING (GAM)

A GROUNDWATER AVAILABILITY MODEL (GAM) HAS BEEN CONSTRUCTED FOR KERR COUNTY BY THE AUTHOR. THE MODEL INCORPORATES 10-LAYERS WITHIN A SQUARE MILE GRID COVERING 708,360 ACRES. THE MODEL UTILIZED HAND DRAWN INTERPRETIVE MAPS OF EACH AQUIFER AND AQUITARD. THE MODEL DID CONVERGE WITH SEVERAL DRY CELLS.

A GAM IS ONLY AS GOOD AS THE DATA. DATA IS STILL BEING DEVELOPED FOR KERR COUNTY AS MORE RESEARCH WELLS ARE DRILLED AND LOGGED ALONG WITH AN AGGRESSIVE PROGRAM TO ENCOURAGE BETTER DRILLER'S LOG INFORMATION. IN ADDITION ADDITIONAL MONITORING WELLS HAVE ADDED TO THE PROGRAM OVER THE LAST FEW YEARS.

Geology is not a science that can be conveniently set on a laboratory table and tested. Geology requires widespread use of well and outcrop data coupled to geophysics. Geology is a long term test, verify and observe endeavor. Kerr County is still in the data gathering stage. HGCD is a long way ahead of other Texas Hill Countries in sophisticated and scientific gathering of data due mainly to the research drilling program as evidenced by this report.

The Kerr County GAM is an ongoing project and as new data becomes available the model will be updated and maintained.

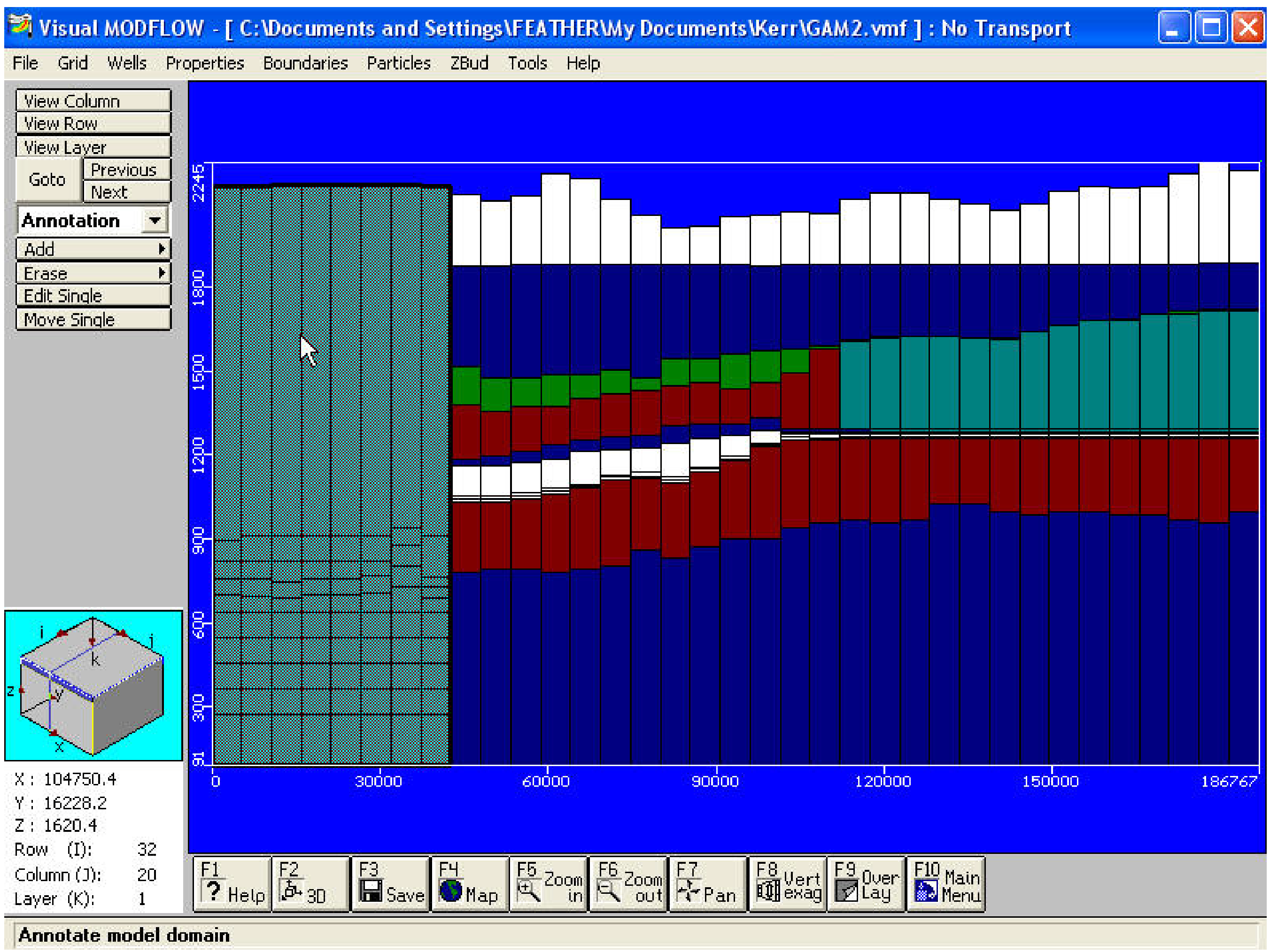


Figure 54: - An illustration of a single column in a portion of the Kerr County GAM.

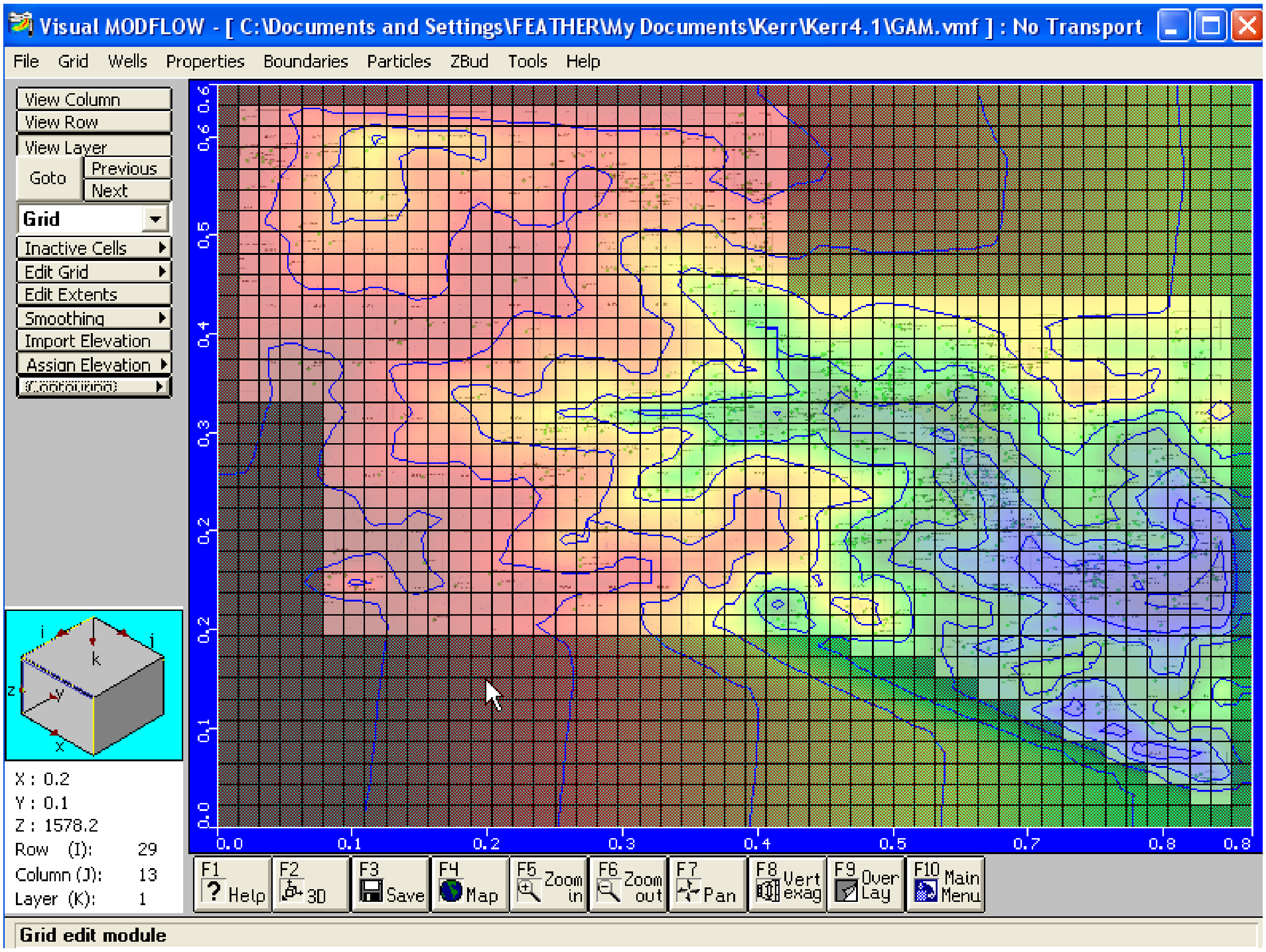


FIGURE 55: - ILLUSTRATION OF CONTOUR THICKNESS MAP OF THE KERR COUNTY GAM.

VII CROSS-SECTIONS

A series of cross-sections have been constructed across Kerr County from carefully controlled lithologic and geophysical logs. Additional cross-sections and revisions will be forthcoming as new well data is accumulated. The following figures illustrate the critical cross-section data for Kerr County.

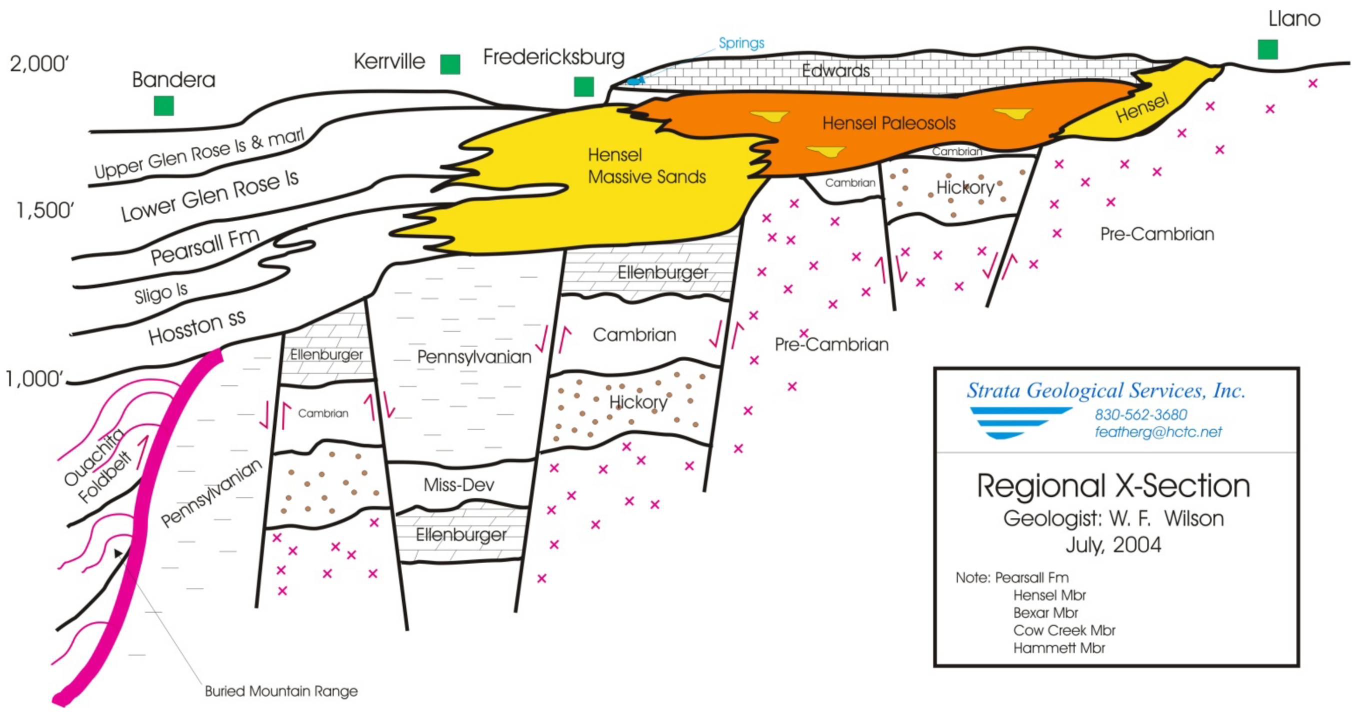


Figure 56: - Regional cartoon cross-section depicting the regional aquifer characteristics of the Cretaceous System and the underlying Paleozoic structural complexities running from the Llano Uplift southward to the vicinity of the City of Bandera in Bandera County. The structural faults that underlie the Cretaceous System range in throw from hundreds of feet to thousands of feet.

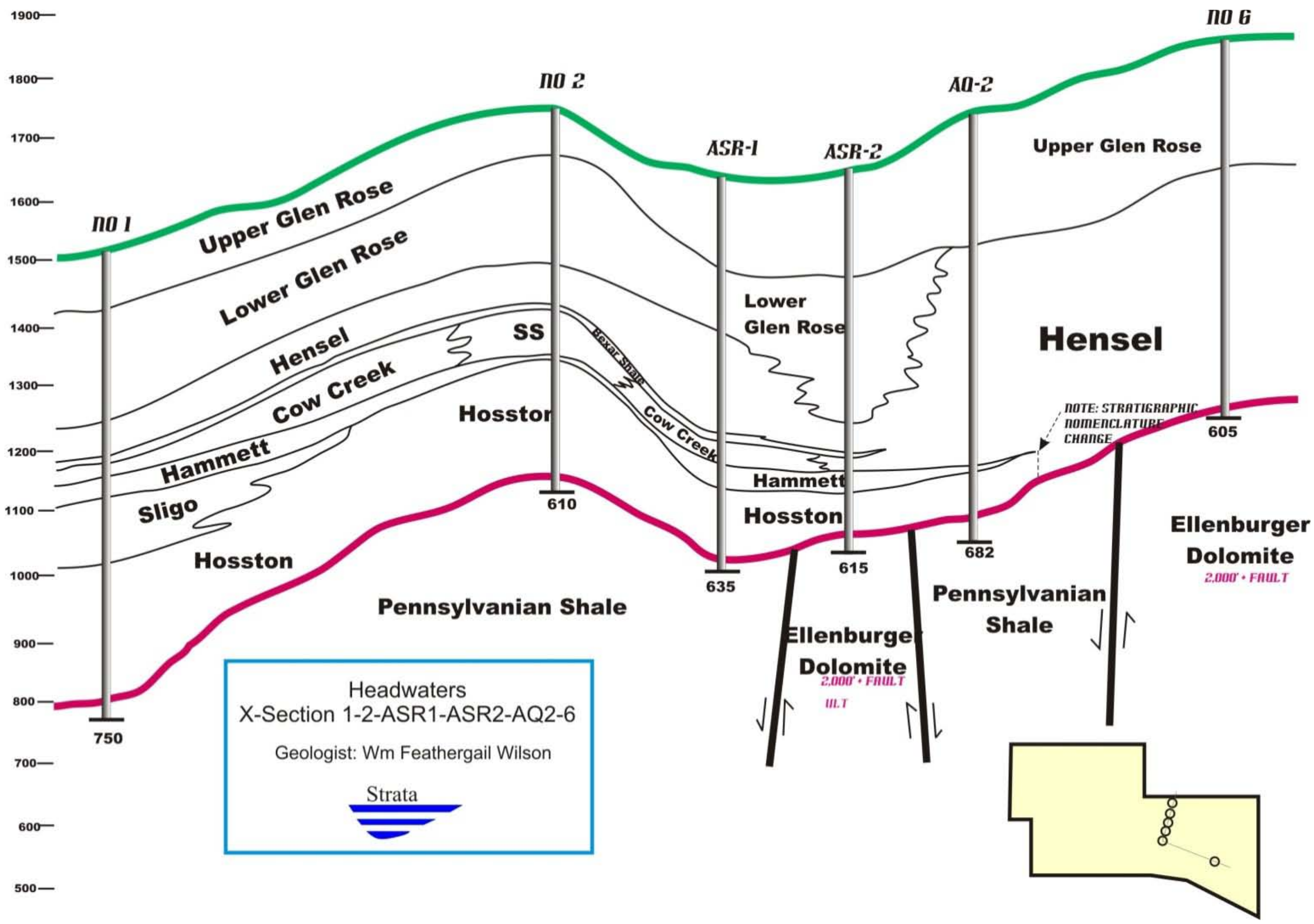


FIGURE 57: - CROSS-SECTION FROM THE CENTER POINT AREA NORTH AND NORTHWEST TO THE GILLESPIE COUNTY LINE.

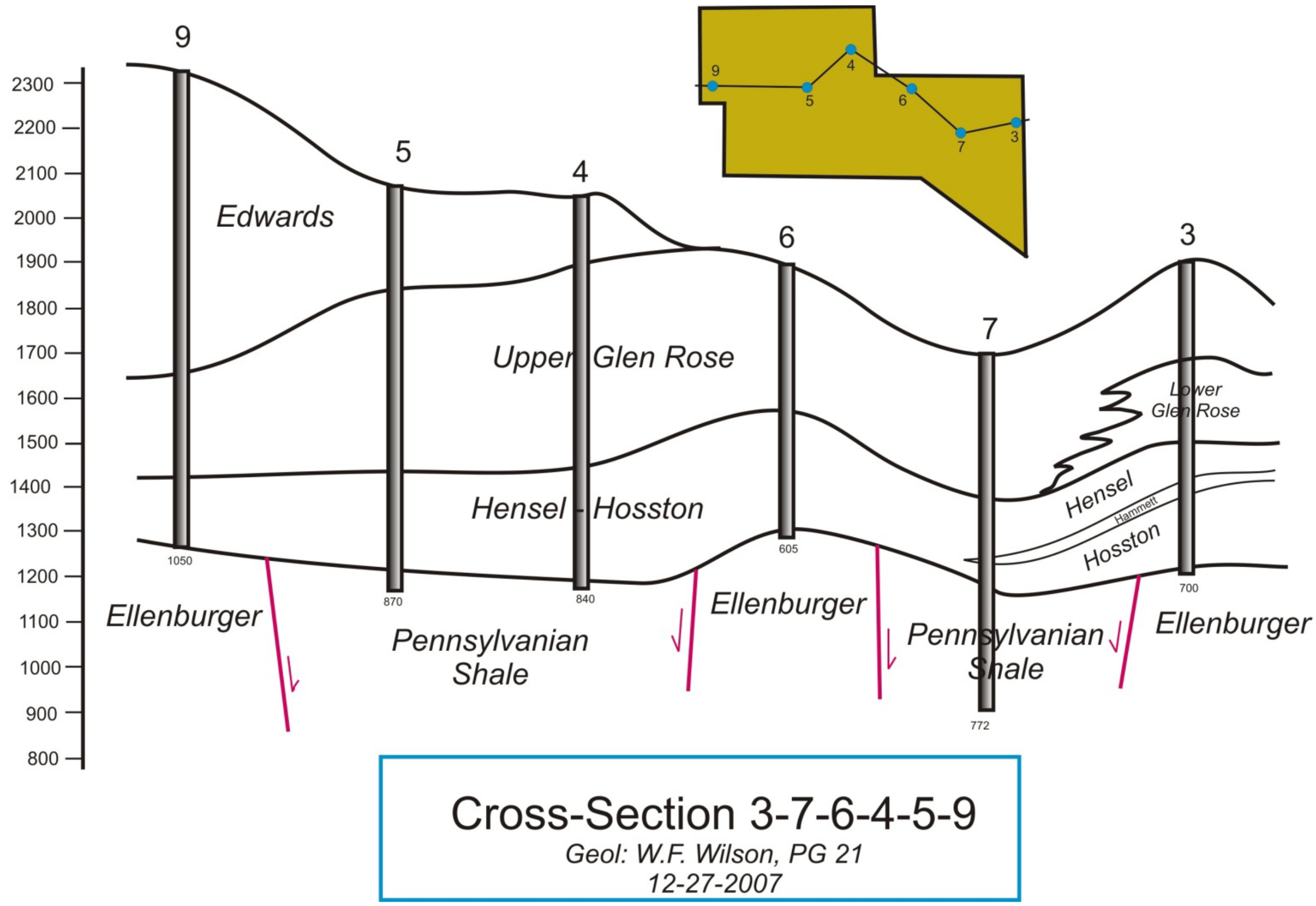


FIGURE 58: - CROSS-SECTION FROM THE EASTERN COUNTY LINE WEST TO THE WESTERN BOUNDARY OF KERR COUNTY.

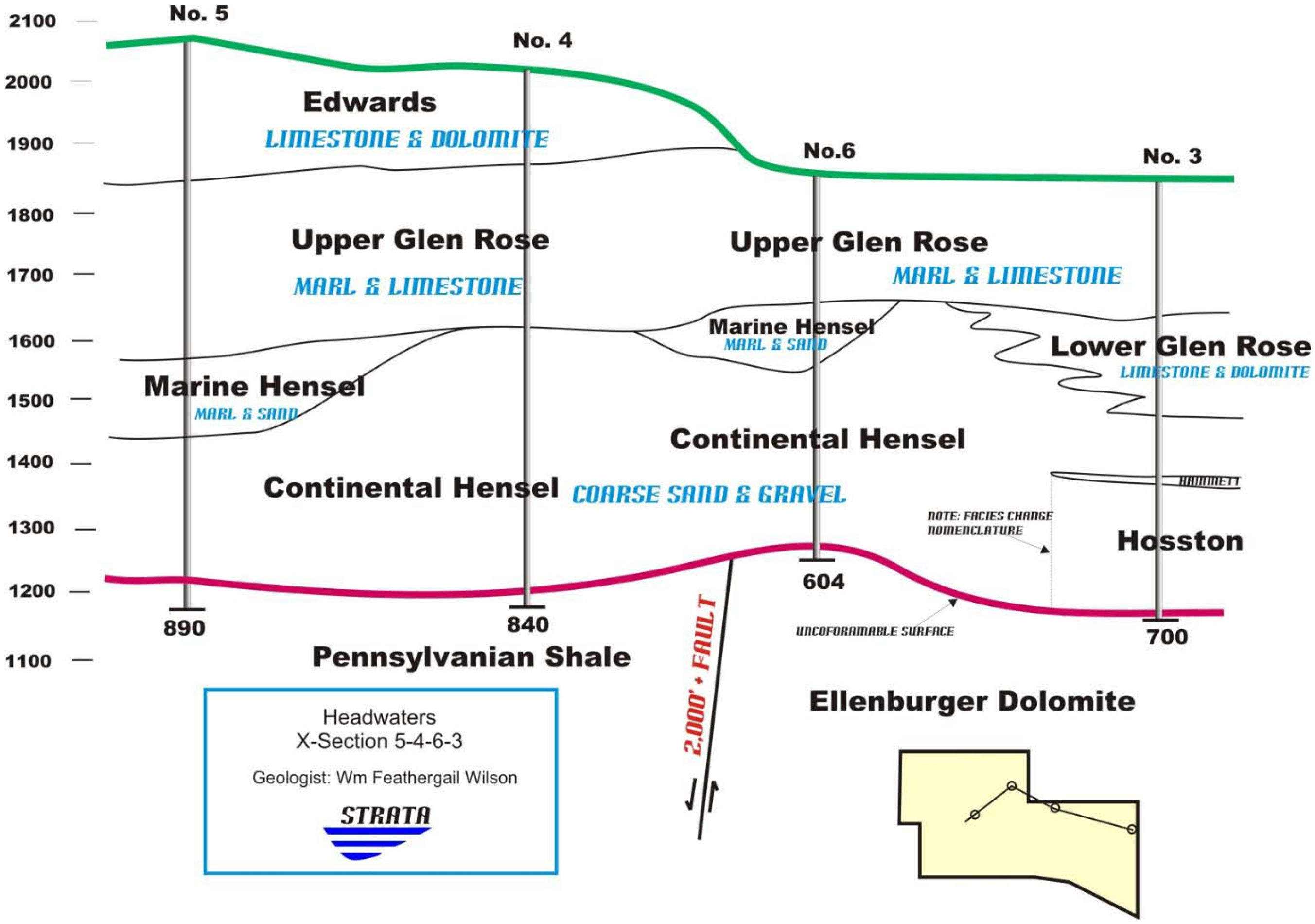


FIGURE 59: - CROSS-SECTION FROM THE EASTERN BOUNDARY TO THE KERR COUNTY WILDLIFE PARK.

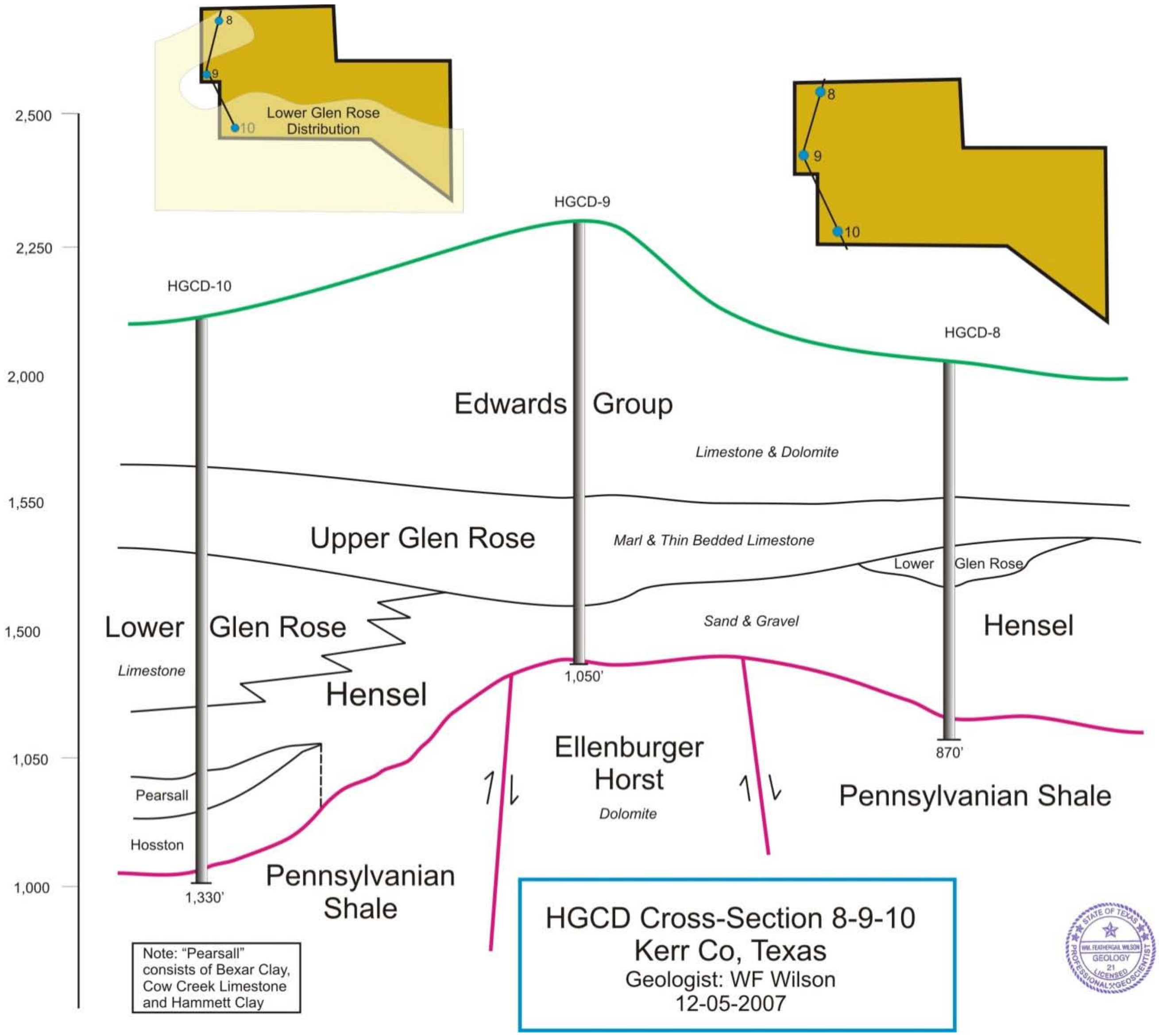


FIGURE 60: - CROSS-SECTION ALONG THE WESTERN BOUNDARY OF KERR COUNTY.

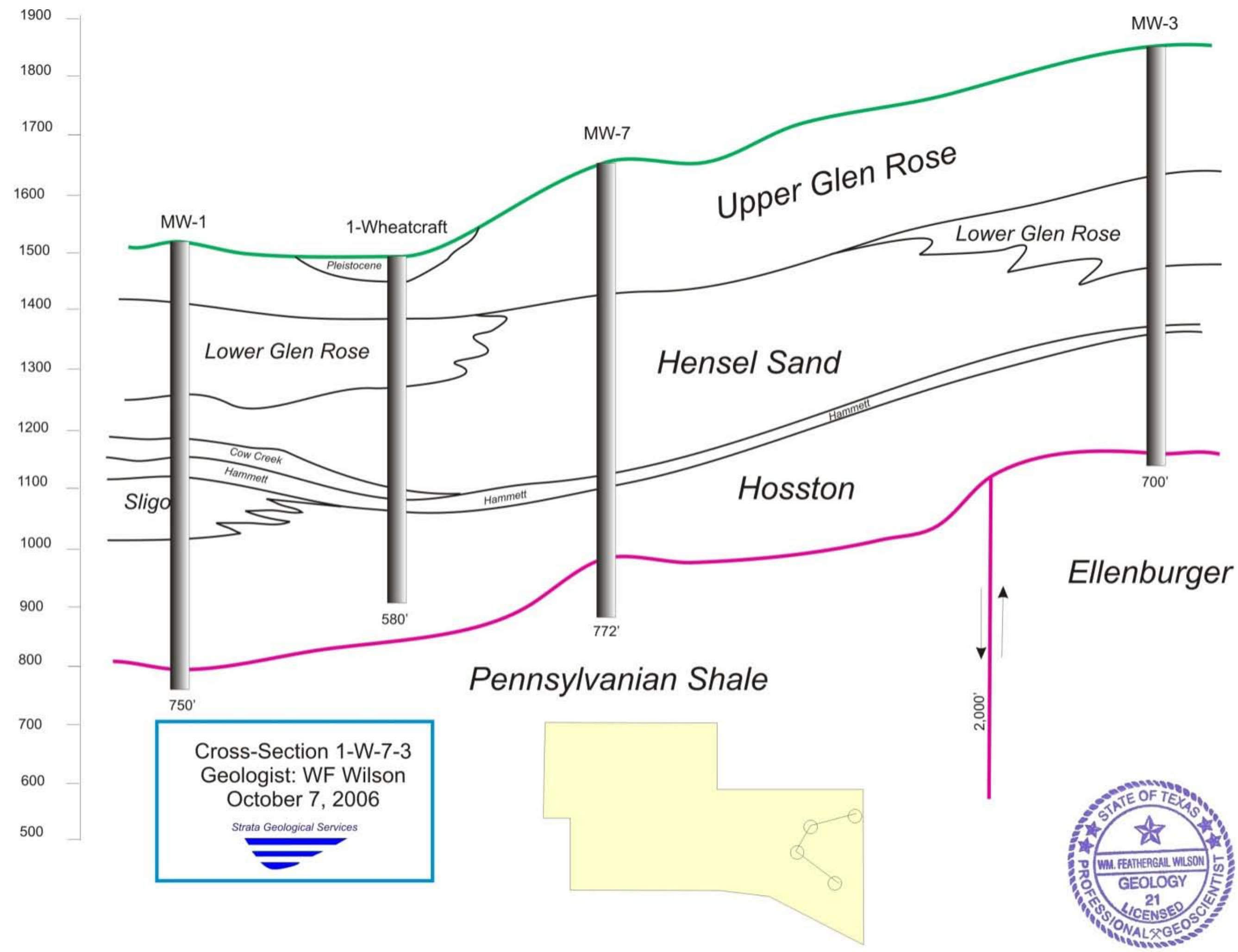


FIGURE 61: - CROSS-SECTION ALONG THE EASTERN BOUNDARY OF KERR COUNTY.

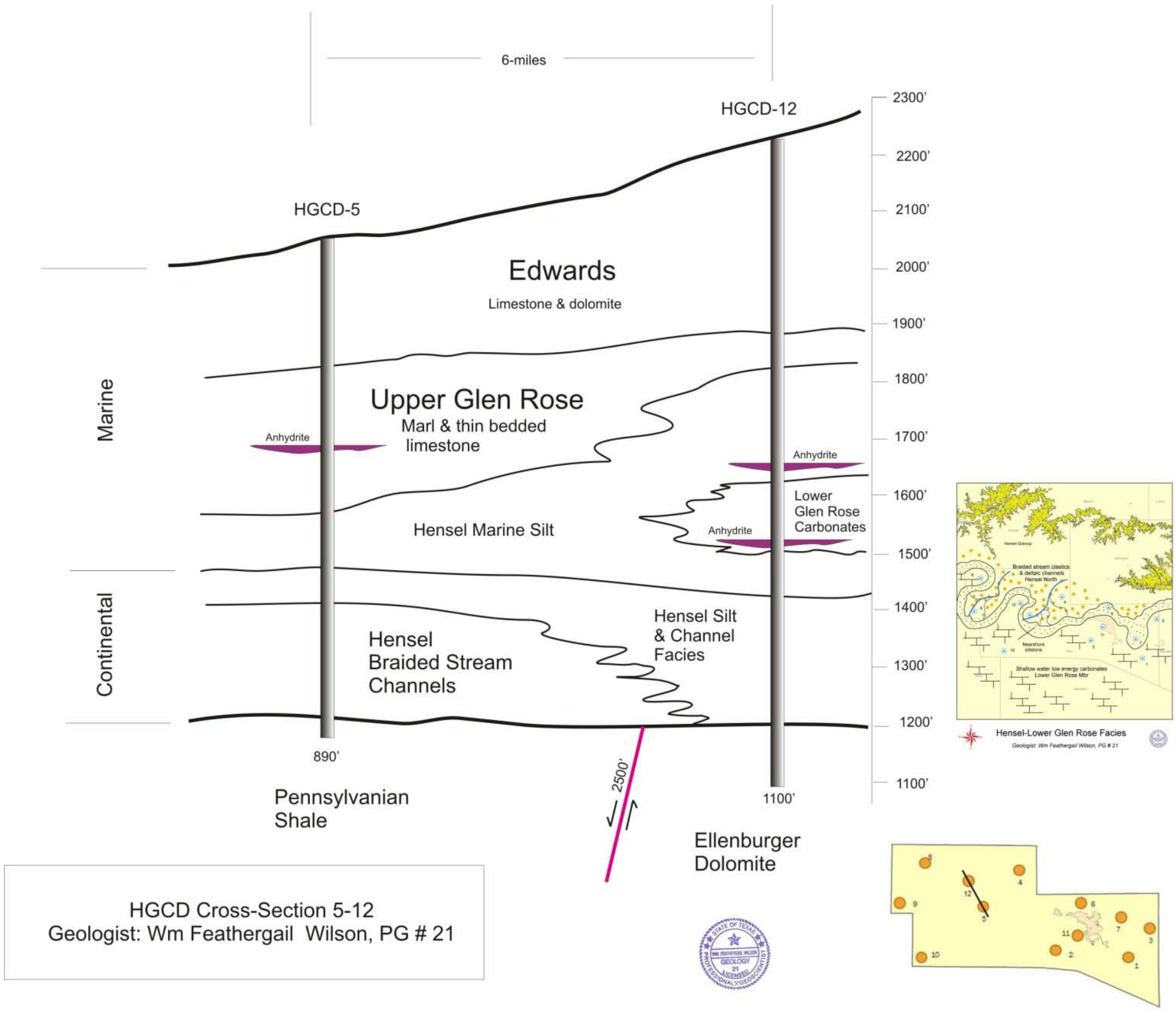


FIGURE 62: - CROSS-SECTION 5-12 DEPICTING THE COMPLEX FACIES RELATIONSHIPS BETWEEN THE HENSEL AND LOWER GLEN ROSE MEMBER.

VIII SUMMARY & CONCLUSIONS

NUMEROUS MAPS, CROSS-SECTIONS AND LOGS HAVE BEEN PREPARED IN THE COURSE OF THIS INVESTIGATION BUT ARE NOT INCLUDED IN THIS REPORT. MOST OF THESE INTERPRETATIONS ARE AVAILABLE AT THE HGCD OFFICE. THIS REPORT IS STRUCTURED TO BE THE BASIS FOR FUTURE UPDATES AS MORE DATA BECOMES AVAILABLE. IT IS PRIMARILY A SUMMARY OF THE ONGOING GEOLOGIC EFFORT BEING PUT FORTH TO UNRAVEL THE GEOLOGICAL DETAIL OF GROUNDWATER THAT IS MOVING THROUGH KERR COUNTY.

THE REPORT IS RICHLY ILLUSTRATED WITH MAPS, TABLES, EXPLANATORY DRAWINGS AND CROSS-SECTIONS. THE REPORT IS A SUMMATION OF THE GEOLOGIC KNOWLEDGE THAT HAS BEEN GATHERED AND INTERPRETED OVER A FOUR-YEAR PERIOD. THE DATA AND SUBSEQUENT INTERPRETATIONS ARE BY NO MEANS SET IN STONE. AS MORE DATA IS RECEIVED BETTER INTERPRETATIONS WILL FOLLOW.

THE CITY OF KERRVILLE HAS PRACTICED CONSERVATION OF GROUNDWATER THROUGH CONJUNCTIVE USE OF THE GUADALUPE RIVER AND SUBSEQUENTLY THE SPRING FLOW FROM THE EDWARDS AQUIFER. THE 5,852 ACRE FEET OF WATER RIGHTS, THE CITY HAS AT ITS DISPOSAL, WILL NOT PROPORTIONATELY INCREASE WITH INCREASING POPULATION AND DEMAND. MORE AND MORE GROUNDWATER WILL HAVE TO BE PRODUCED IN THE FUTURE TO KEEP UP WITH DEMAND.

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X APPENDIX

GROUND WATER AGE

&

PROVENANCE ISOTOPES

GROUND WATER AGES RANGE FROM 0 TO MILLIONS OF YEARS. THE AGES OF INTEREST FOR FRESH WATER GENERALLY RANGE FROM 0 TO ABOUT 30,000 YEARS. AN AGE CLASSIFICATION HAS BEEN DEVISED PRIMARILY BASED UPON THE ISOTOPES AND MOLECULES THEMSELVES.

YOUNG GROUND WATER ISOTOPES (0 – 60 YEARS)

1 HYDROGEN-3 (TRITIUM)

2 HYDROGEN-3/HELIUM-3

3 KRYPTON-85

4 CFC'S – CHLOROFLUOROCARBONS

5 SF-6 – SULFUR HEXAFLUORIDE

OLD GROUND WATER ISOTOPES (60 – 50,000 YEARS)

1 SILICA – 32

2 Argon – 39

3 Carbon – 14

4 Hydrogen – 2/Oxygen – 18 (indirect method)

Very Old Ground Water Isotopes (50,000 – 100,000 years

1 Helium – 4

2 Chlorine – 36

3 Argon – 40

4 Krypton – 81

5 Iodine – 129

In addition, provenance "fingerprints" can be discerned from various molecule and elemental natural combinations. Each combination can be plotted on various types of diagrams to compare one water sample to another.

Cross-sections and maps can be constructed depicting age and provenance gradients across regional areas to calculate the rate of water movement and recharge.

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SELECTED LITERATURE

Paleodepositional Facies, Lower Cretaceous Cow Creek Member, Texas Hill Country

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Abstract

This study addresses the fresh water aquifer characteristics of the Cow Creek Member of the Pearsall Formation within the Texas Hill Country focusing on the paleodepositional elements of the unit. The varied facies of the Cow Creek Member are described and mapped based upon the examination of samples from recently drilled water wells across the study area. This study represents the first of several ongoing mapping programs to define the various aquifer units within the Cretaceous System across the Texas Hill Country. Paleodepositional environments have been found to be closely associated with the aquifer characteristics and well yields. The underlying, deeply buried, structural elements are believed to have controlled the subtle facies changes found in the Cow Creek Member and subsequently controlled the water yields found today.

Introduction

The Lower Cretaceous Cow Creek Member of the Pearsall Formation (Forgotson, 1957) is a commonly drilled aquifer in the Texas Hill Country. The author is mapping and defining the aquifer characteristics of each Lower Cretaceous aquifer within the counties of Bandera, Bexar, Blanco, Comal, Gillespie, Kendall, Kerr and Medina Counties in the Texas Hill Country. This study addresses the paleodepositional and aquifer elements of the Cow Creek. Other aquifers under study include the Edwards Formation, Glen Rose Formation, Hensel Member, Sligo Formation and the Hosston Formation of the Lower Cretaceous System (Fig. 1).

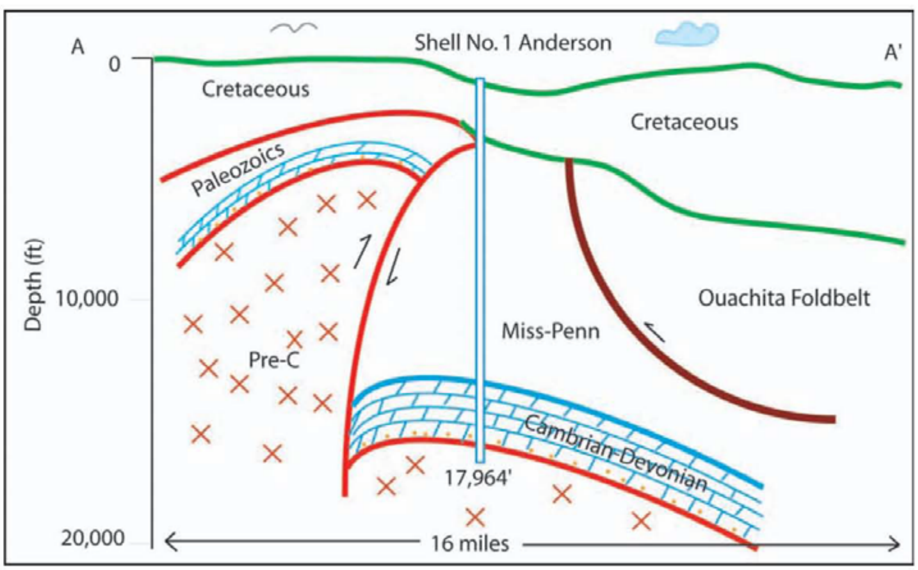

Figure 1. Cross-section A-A' depicting Cretaceous thinning over a large fault system near Bergheim, Texas, Kendall and Comal Counties.

The author has examined sample cuttings from recently drilled water wells with a stereoscopic microscope. Thin sections were prepared on selected samples and examined with a petrographic microscope. This investigation involves a working relationship with landowners and drillers over a number of years. The maps, cross-sections and interpretations should be viewed as "work in progress." New data points are added each year, as new information becomes available.

Paleodepositional characteristics were chosen that best define the associated aquifer characteristics. Primary and secondary porosities were found to mainly correlate with original high and low energy areas of deposition with some exceptions. Experienced water well drillers in local areas frequently describe the geology as "low yield" or "high yield" areas of water availability, which correspond to low and high energy paleodepositional facies. For example, drillers who work around the Bergheim area of Kendall County know that the Cow Creek may yield water at rates that rarely exceed 2–5 gallons per minute on 1.5 HP household pumps. Conversely, drillers who work in the Pipe Creek area of Bandera County expect yields in the 25–50 gallon per minute range from the same pumps at the same depth ranges. The author has found that differences in water well yields generally relate to the energy levels of the original depositional environments, whether primary or secondary porosities are dominant.

The Cow Creek Member of the Pearsall Formation is not a simple model of high and low energy carbonates. It is a record of very complex and varied depositional settings with very limited outcrops. It is perhaps the most important domestic water bearing unit in the Texas Hill Country, but it is seldom exposed. It is uncommon for drillers to take samples at intervals less than the length of the drill stem, which is twenty feet. A few wells that are drilled for water availability studies are electrically logged. There is no substitute for sample examination as the well is being drilled. It is difficult, if not impossible, to correlate carbonate paleoenvironments of deposition from the electrical logs employed by the water well industry. Electrical log data is correlated with the sample data whenever possible. The author employed R.L. Folk's (1959) carbonate classification scheme throughout the study.

Previous outcrop and subsurface stratigraphic and lithologic studies include Amsbury (1966), Loucks (1977) and Lozo and Stricklin (1956), Wilson (2001) and others. This literature is important, but is not the focus of this paper.

Cow Creek Stratigraphy and Paleodepositional Facies

The Cow Creek Member of the Pearsall Formation consists of lithologies that include high and low energy carbonates, coal, unconsolidated quartz and carbonate sands (Fig. 2). In some places it is entirely represented by a quartz sand facies and in other places it is represented entirely by an unconsolidated carbonate sand facies. Isolated evaporites have also been observed within the Cow Creek, including anhydrite, gypsum and salt. However, it is mainly a carbonate unit commonly associated with thin sub-bituminous coal beds. It is primarily a shallow-water or possibly an inter-tidal complex carbonate unit.

The Cow Creek Member is sharply overlain by a relatively thin, silty, oyster-bearing clay unit known as the Bexar Shale (Table 1; Fig. 3). It is underlain by the very sticky oyster-bearing clayey unit known as either the Hammett Shale or Pine Island Shale. The Cow Creek is transitional with the underlying Hammett or Pine Island. The transitional zone (Fig. 3) consists of a clay-bearing silty microdolomite near the top, gradually grading into pure carbonaceous clay near the bottom. The clay unit is usually referred to as the Hammett in the northern portion of the study area and the Pine Island in the southern portion of the study area. The difference in the stratigraphic nomenclature is attributed to the academic arena versus the nomenclature employed by the petroleum industry. Another piece of inconsistent stratigraphic nomenclature that can be attributed to the water well industry is the use of the term "Trinity." The Cow Creek member of the Pearsall Formation is placed in the Middle Trinity Division in the water well industry. The term "Middle Trinity" is used to describe the aquifers within the Lower Glen Rose Member of the Glen Rose Formation as well as the Pearsall Formation. The "Trinity Division" was first defined by R. T. Hill (1889, 1901). The multiple aquifers within this Middle Trinity are often lumped together as one aquifer by regulators, which is not the physical case. This is not the only problem with stratigraphic nomenclature within the Lower Cretaceous System of the Texas Hill Country, but it is representative of some of the inconsistencies and confusion.

The author believes the Hensel Sand is a unit that is genetically related to the Pearsall Formation. It is transitional with the underlying Bexar Shale Member and is commonly in sharp contact with the overlying Glen Rose Formation. This interpretation is subject to additional scientific inquiry. The basal Cretaceous sands, conglomerates and sandstones begin to merge near the Llano Uplift and may be locally equivalent to the Lower Glen Rose, Hensel, Bexar and Cow Creek. Farther away from the Llano Uplift the basal sands, sandstones and conglomerates differentiate into distinct stratigraphic units, where they are separated by mapped carbonates and clastics.

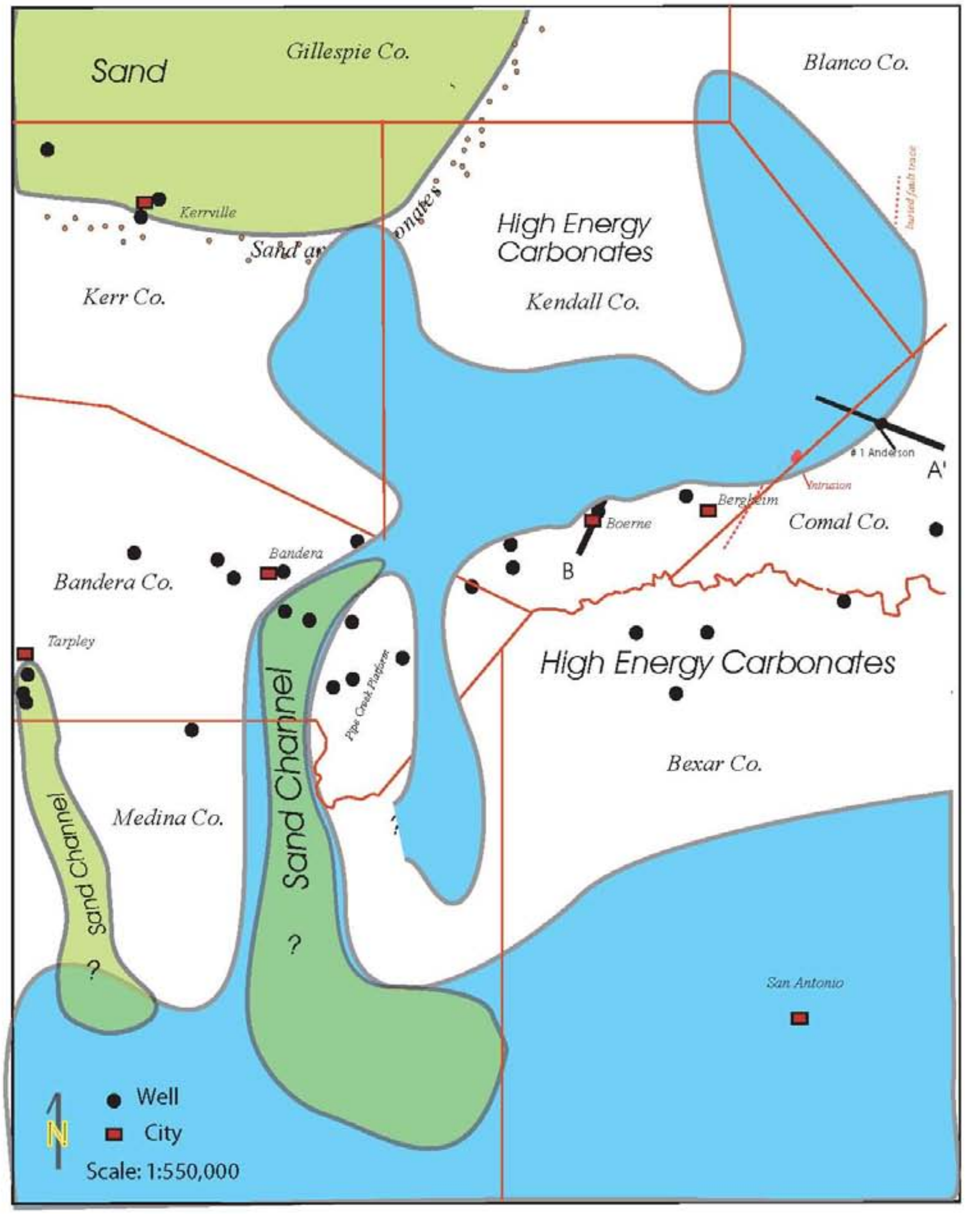

Figure 2. Paleodepositional map of the Cow Creek Member, Pearsall Formation.

Table 1. Stratigraphy of the Cow Creek Limestone

System	Age	Formation	Member
Lower Cretaceous	Aptian	Pearsall	Hensel Sand Bexar Shale Cow Creek Limestone Hammett-Pine Island Shale

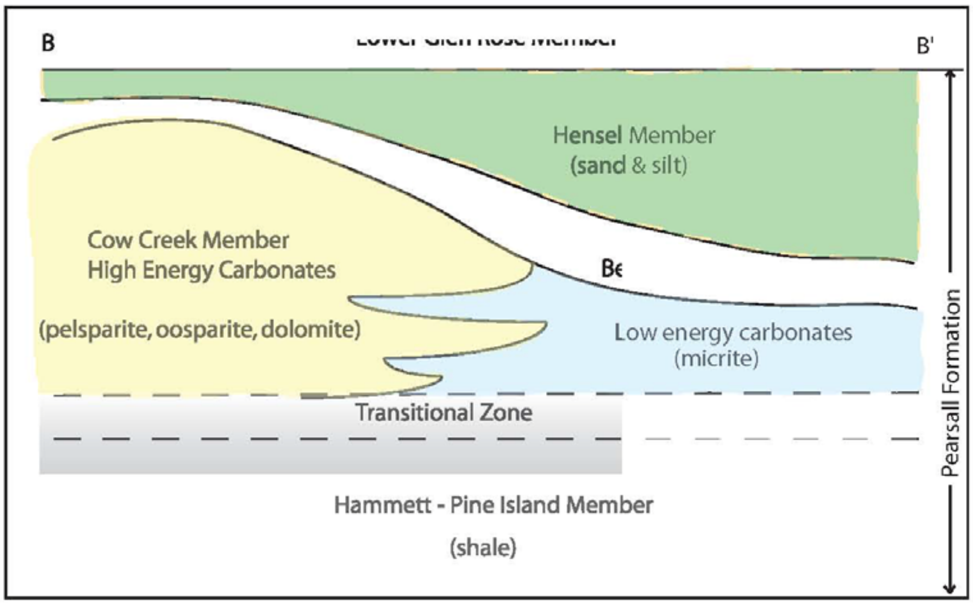

Figure 3. Cross-section B-B' depicting stratigraphic thinning into a starved low energy facies of the Cow Creek Member of the Pearsall Formation near Boerne, Texas, Kendall County (not drawn to scale).

The top of the Cow Creek is often highly indurated and is drilled very slowly for the first few feet. A very sharp contact is present between the Cow Creek and the Bexar Shale Member. This may correspond to a bored disconformable indurated surface across much of the Texas Hill Country.

The high energy Cow Creek facies is typically a loosely cemented pelsparite, oosparite, biosparite and intrasparite. In some places, this high energy facies is partially dolomitized with micro-crystalline dolomite; however in most areas, it is a white clean well washed or winnowed well rounded coarse carbonate sand composed of intraclasts, oolites, pellets and shell fragments that are partially cemented with calspar (see Fig. 4). This usually grades downward into microdolomite that may have originally been a biomicrite or primary dolomite. Below the indurated zone thin sub-bituminous coal beds are commonly found, which may have been low-lying mangrove type lagoonal islands, as potential equivalents of inter tidal, transgressive, prograding high energy carbonate sands. The coal beds are also found associated with low-energy carbonate facies at the same approximate stratigraphic position. Isolated evaporites are also found in this stratigraphic position suggesting the presence of local prograding barriers.

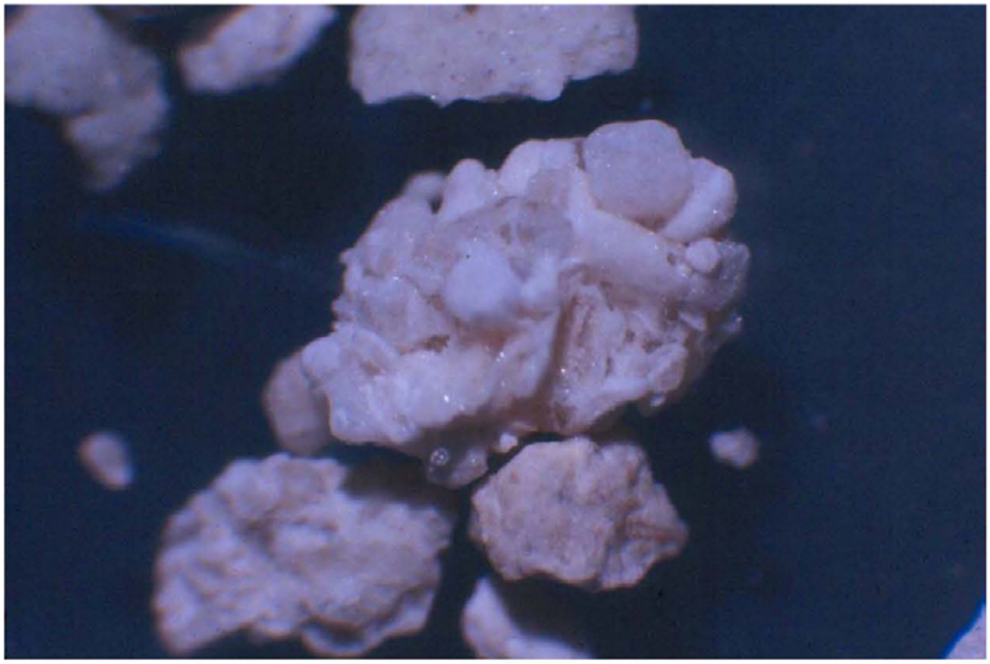

Figure 4. Photomicrograph of a typical sample of Cow Creek high energy carbonate sand facies.

The low energy carbonate environments are characterized by white-flour-colored micrites and biomicrites, which are seldom associated with dolomite. Sub-bituminous coal is more commonly associated with this Cow Creek facies. These low energy carbonates are often thinner than the high energy facies (20-30 feet) suggesting a deeper water environment or series of miniature lagoonal sub-basins bounded by barrier islands.

Two notable departures from these predominant low and high energy carbonate facies are noted in Bandera County as unconsolidated sand facies deposited in channels. These two channels are oriented approximately north-south as shown on the paleodepositional map (Fig. 2). One of these channels is located in southeastern Bandera County and one is located near Tarpley in south central Bandera County. The sand channel in southeastern Bandera County is medium to coarse grained quartz sand, while the channel near Tarpley is associated with coarse-grained uncemented carbonate rock fragment sand with subordinate amounts of quartz. It is not known whether or not these sand channel facies are the age equivalents to the Cow Creek or younger sediments filling incised channels that are cut into the underlying units. In southeastern Bandera County the sand channel extends into the underlying Sligo and Hosston couplet. In the Tarpley area the channel is cut into the Hammett. In either case the typical Cow Creek facies is not present within narrow channels.

A distinct siliciclastic facies is present as the Llano Uplift is approached in northern Kerr County. This facies is composed of quartz silt and sand with some metamorphic rock fragments. Farther to the north, the entire Cow Creek merges into a sand unit surrounding the Llano Uplift and is variously known as the Hensel, Sycamore or Travis Peak Formation. Immediately south and bounding this facies is a mixed carbonate and clastic facies mapped as the Cow Creek.

Each black dot on the paleodepositional map may represent one well, a set of wells, or an outcrop (Fig. 2). Water availability studies require two twin wells to be drilled one-hundred feet apart on each one-hundred acres. Transducers are lowered into both wells to record drawdowns for twenty-four-hour periods of pumping. The resulting data is then used to calculate hydraulic conductivity, transmissivity and storativity. Thus, one dot in Figure 2 may represent a set of wells drilled at very close spacing in certain counties. Other wells and outcrops are single points of data. The author has observed rapid facies changes over distances of hundreds of feet in some areas.

Structure and Paleodepositional Facies

Facies changes within the Cow Creek are believed to be controlled at least in part by underlying structural elements. These structural elements are associated with several salient mega-features.

The Llano Uplift acted as a giant buttress to the advancing Ouachita Mountain Front during the Pennsylvanian and early Period Permian Periods. Deltas and turbidites were rapidly shedding clastics toward the Llano Buttress and forming a narrow trough that connected the Fort Worth and Kerr Basins. As the Ouachita Front advanced toward the Llano Buttress, the sediment load began to compress the Pre-Cambrian and thin Paleozoic section. The compression of the Ouachita Foldbelt (Flawn, 1961), combined with the deepening and advancing frontal basin, set up a series of very large faults downthrown to the southeast, east and northeast forming an arc around the Llano Buttress. The throws on these faults ranged from 10,000 to 18,000 feet based upon unpublished proprietary seismic data from various oil companies and subsequent drilling. This arc of faulting began to bifurcate near northwestern Burnet County with one extension trending northwest into Mills County and the other trending towards McLennan County. The thrust belt overstepped the fault zone in most areas near the Llano Uplift. In an area near Bergheim in Kendall County, a window of Mississippian-Pennsylvanian undeformed section was left open between the thrust belt and the underlying basin. All of this complex structure was eroded into low rolling hills during the Permian, Triassic and Jurassic Periods. The Lower Cretaceous seas then advanced over the unconformable surface.

The buried structural elements then influenced the sedimentation of the Lower Cretaceous sediments and lagoonal sub-basins. The downthrown block along a fault with a 17,000 throw was drilled by Shell Oil Company in 1968-69 near the Bergheim area of Comal County. The wildcat was drilled to a deeply buried Ellenburger anticline that was crushed against the downthrown wall of the fault by the advancing Ouachita front (Fig. 1). The Shell No. 1 Anderson was drilled to a total depth of 17,964 feet. The well penetrated the Cretaceous Hosston Formation and continued through the underlying unconformity at 530 feet. The fault was believed to be cut at 670 feet, where it drilled into Pennsylvanian shale (Fig. 1).

Flawn (1961) described the samples from the Roland Blumberg No. 1 D.C. Knibbe a few miles northeast of the No. 1 Anderson (Fig. 2). and concluded that the Knibbe well drilled out of the Hosston into the Ouachita Foldbelt.

The fault plain is intruded by basalt, which crops out on the surface near the Comal-Kendall County (Fig. 2) line and has been mapped by several previous authors. The entire Cretaceous System thins markedly over this faulted area near Bergheim. The thinning is believed to be characterized by a lack of preserved porosity and permeability in most of the Cretaceous section with the exception of a few patch reefs developed in the Lower Glen Rose Member. There are other exceptions to this general statement, but most wells in the Cow Creek, Hensel, Sligo and Hosston units are low yield water wells. The wells become less productive as the fault zone is approached.

Three water wells drilled in south central Bandera County near Tarpley drilled out of the Hosston Formation into the underlying foreland facies of the Ellenburger Group. This area has previously been mapped in the 1930's as a very broad structural uplift and is probably related to an underlying horst block. Basaltic intrusions are found both immediately east and north of the Tarpley area. These intrusions are believed to be related to this north-south-trending anticline. The Cow Creek facies in this area is a carbonate and quartz sand facies oriented roughly north-south. It is eroded into the underlying Hammett Shale irregular surfaces evidenced from closely drilled wells. This sand facies is interpreted to be a paleo-topographic low developed over the pre-existing Ellenburger horst. The Ouachita Foldbelt wrapped around this feature. The sand facies of the Cow Creek and the subsequent erosion of the underlying Hammett Shale followed this paleo-topographic low. This is believed to be another example of the underlying structure influencing facies development of the Cow Creek. Other examples surely exist, but they are undefined until more data can be obtained through subsequent drilling over the next few decades. For example, there must be an underlying structural reason for the Pipe Creek High, which is associated with a thick and very high energy, high yield Cow Creek facies. This is also an area characterized by patch reefs within the Lower Glen Rose Member. The thick overlying Hensel sands appear to have been diverted around this high, as well as the Cow Creek sand facies (Fig. 2). More data may be required to support this hypothesis.

Low Energy Sub-basinal Thinning

The low energy Cow Creek facies appears to thin into sub-basins, as if they were starved of high energy carbonates sands. This is evidenced by Cross-section B–B', that extends from the City of Boerne in a northeast direction into an area of several rural subdivisions. The thinning is not dramatic, but it does occur. The sub-basinal sediments are characterized by low energy whitish micritic carbonates that may have been winnowed "flour" from nearby high energy environments of deposition (Fig. 3).

Conclusions

This first report addresses the aquifer characteristics of the Cow Creek Member of the Pearsall Formation, as these aquifer parameters relate to the paleodepositional facies of the unit. It is surmised that these facies are in some degree related to underlying structural elements that originate from the Llano Uplift, the Ouachita Foldbelt, basin formation and concomitant faulting. These structural elements created the subtle underlying framework for the overlying Cretaceous environments of deposition that finally controlled where low and high yield water wells are found within the Texas Hill Country. Additional papers are planned to address the remaining aquifers within the study area.

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APPLICATIONS OF HYDROCHEMISTRY TO EVALUATE RECHARGE AND FLOW PATHS IN THE EDWARDS-TRINITY AQUIFER SYSTEM, TEXAS

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5 DECEMBER 2003

ABSTRACT

ROUTINELY ACQUIRED HYDROCHEMICAL ANALYSES OF EDWARDS AQUIFER WELL WATER FROM THE EDWARDS PLATEAU (EDWARDS-TRINITY AQUIFER SYSTEM) OF WEST-CENTRAL AND WEST TEXAS IS USED TO IDENTIFY PREFERENTIAL RECHARGE ZONES AND FLOW PATHS, AND TO ESTIMATE LOCAL RECHARGE VOLUMES. RAINFALL AND WET CHLORIDE DEPOSITION DATA WERE INTEGRATED WITH GROUNDWATER CHLORIDE DATA AND ESTIMATES OF DRY CHLORIDE DEPOSITION IN AN ARCGIS ENVIRONMENT TO PRODUCE FINE-SCALE MAPS OF PREFERENTIAL RECHARGE AREAS AND RECHARGE VOLUMETRIC ESTIMATES BASED ON A CHLORIDE MASS-BALANCE APPROACH. GROUNDWATER CHLORIDE, CALCIUM, MAGNESIUM, AND SODIUM DATA WERE ALSO IMPORTED INTO ARCGIS AND MANIPULATED TO SELECT WELLS THAT PRODUCED RELATIVELY YOUTHFUL GROUND WATER AS SUGGESTED BY SIMULTANEOUSLY LOW VALUES OF CHLORIDE CONCENTRATION, MG/CA, AND LOW EXTENTS OF CATION-EXCHANGE REACTIONS. MAPS BASED ON THESE DATA SHOWED REASONABLE PATTERNS OF IMPLIED RAPID FLOW ORIENTED NORMAL TO POTENTIOMETRIC TRENDS IN AREAS WITH HIGHER POTENTIOMETRIC GRADIENTS.

INTRODUCTION

IDENTIFICATION OF PREFERRED AQUIFER RECHARGE AREAS AND RELIABLE RECHARGE ESTIMATES ARE CRITICAL FOR INFORMED MANAGEMENT OF GROUNDWATER RESOURCES. RECHARGE AREAS MUST BE PROTECTED FROM POLLUTION OR ESTABLISHMENTS OF IMPERVIOUS COVER. GROUNDWATER RESOURCES MUST BE PROTECTED FROM OVER-EXPLOITATION SO THAT PLANTS, ANIMALS, AND PEOPLE WHO DEPEND ON GROUNDWATER, WHETHER BY PRODUCTION FROM WELLS, TRANSPIRATION ALONG SEEPS, OR UPTAKE AT SPRINGS CAN CONTINUE TO THRIVE INDEFINITELY. OFTEN ESTIMATES OF RECHARGE VOLUMES ARE BASED UPON MEASUREMENTS OF DISCHARGE AT SPRINGS AND BY BASE FLOW ALONG STREAMS. ESTIMATES OF DISCHARGE BASED ON THESE CRITERIA ARE ASSUMED TO REFLECT A SIMILAR RATE OF RECHARGE, A CONCLUSION BASED UPON A STEADY-STATE VIEW OF AQUIFER PERFORMANCE. THIS APPROACH DOES NOT RECOGNIZE THE POTENTIAL TRANSIENCE OF RECHARGE RATES AND THE POSSIBILITY THAT MODERN DISCHARGE RATES REFLECT RECHARGE DURING TIMES WHEN THE CLIMATE WAS SIGNIFICANTLY DISSIMILAR TO THAT OBSERVED RECENTLY. SUCH ESTIMATES ALSO DEPEND ON A COMPLETE ACCOUNTING OF ALL FORMS OF DISCHARGE, INCLUDING GROUNDWATER PRODUCTION FROM WELLS. FURTHER, IDENTIFICATION OF PREFERENTIAL RECHARGE AREAS MAY BE BASED ON EXTENSIVE HIGH-RESOLUTION SOIL-TYPE AND THICKNESS ANALYSES ON A REGIONAL SCALE. FINALLY, THE NATURE OF LOCAL RECHARGE AVENUES IN THE AQUIFER ROCK IS USUALLY VERY POORLY KNOWN. THIS IS CERTAINLY TRUE OF THE EDWARDS-TRINITY AQUIFER SYSTEM OF WEST-CENTRAL AND WEST TEXAS. THE MOST RECENT ATTEMPTS TO MODEL GROUNDWATER RECHARGE AND FLOW IN THE EDWARDS-TRINITY AQUIFER SYSTEM (KUNIANSKY, 1989; KUNIANSKY AND HOLLIGAN, 1994) USED DISCHARGE ESTIMATES AND ASSUMPTIONS OF STEADY-STATE CONDITIONS.

DELINEATION OF PREFERENTIAL PATHWAYS FOR GROUNDWATER FLOW IS ALSO IMPORTANT FOR INTELLIGENT RESOURCE MANAGEMENT. RELIABLE INTERPRETATIONS OF PREFERENTIAL FLOW PATHS CAN FACILITATE EFFICIENT SITING OF PRODUCTION WELLS AND PROVIDE A BASIS FOR SITING GROUNDWATER REMEDIATION MEASURES IN THE UNFORTUNATE EVENT OF CONTAMINATION.

HYDROCHEMISTRY MAY PROVIDE INDEPENDENT METHODS OF IDENTIFYING RECHARGE AREAS, ESTIMATING RECHARGE RATES, AND DELINEATING PREFERENTIAL FLOW PATHS. GROUNDWATER CARRIES THE CHEMICAL SIGNATURES OF RECHARGE PRECIPITATION AND OF INTERACTIONS ALONG FLOW PATHS WITH AQUIFER ROCK. KNOWLEDGE OF THE SOURCES OF HYDROCHEMICAL CONSTITUENTS AND RATES OF HYDROCHEMICAL DEVELOPMENT CAN PROVIDE CONSTRAINTS ON INTERPRETATIONS OF GROUNDWATER HISTORY. GROUNDWATER UNDERGOES SOMEWHAT PREDICTABLE EVOLUTIONARY STAGES OVER TIME. BY IDENTIFYING THE LOCATIONS OF WELLS WHERE GROUNDWATER APPEARS TO HAVE UNDERGONE THE LEAST AMOUNT OF EVOLUTION WE MAY BE ABLE TO MAP LIKELY AREAS WHERE RECHARGE AND FLOW ARE THE MOST RAPID.

STUDY AREA, DATA AND METHODS

THE EDWARDS-TRINITY (PLATEAU) AQUIFER SYSTEM IS A MAJOR TEXAS AQUIFER (ASHWORTH AND HOPKINS, 1995) AND PROVIDES A VALUABLE NATURAL LABORATORY FOR EXPLORING THE POTENTIAL VIABILITY OF USING HYDROCHEMICAL METHODS TO RESOLVE ISSUES OF GROUNDWATER RECHARGE AND FLOW (FIG. 1). THE PLATEAU AQUIFER SYSTEM IS LOCATED IN THE EDWARDS PLATEAU AND ENCOMPASSES AN AREA OF 24,000 SQ. MI (62,000 SQ. KM). ELEVATION RANGES FROM 1000 FT (305 M) IN THE SOUTHEAST TO 3,300 FT IN THE NORTHWEST. FROM EAST TO WEST ITS CLIMATE RANGES FROM SUB-HUMID TO SEMI-ARID. MEAN ANNUAL RAINFALL RANGES FROM 34 TO 14 IN. PRECIPITATION EVENTS TEND TO BE FLASHY. SOILS ARE GENERALLY THIN AND STONY BUT ARE BETTER DEVELOPED ALONG STREAMS. THE AQUIFER SYSTEM IS DEVELOPED IN LOWER CRETACEOUS SEDIMENTARY ROCKS AND CONSISTS OF A LOWERMOST INTERVAL OF TRINITY DIVISION SILICICLASTIC (ANTLERS AND ASSOCIATED SANDSTONES) AND CARBONATE ROCKS (GLEN ROSE AND ASSOCIATED LIMESTONE AND DOLOMITE). FREDERICKSBURG AND WASHITA DIVISION CARBONATE ROCKS (SO-CALLED EDWARDS AND ASSOCIATED LIMESTONES) OVERLIE THE TRINITY SECTION (BARKER AND ARDIS, 1996A; FIG. 2). MINOR GYPSUM OCCURS IN THE EDWARDS AND PROVIDES AN ECONOMIC RESOURCE VERY LOCALLY. STRATAL ATTITUDES (DIPS) ARE GENERALLY LOW (SEVERAL DEGREES DOWN TOWARD THE SOUTHEAST) BUT STEEPEN (UP TO 27 DEGREES) IN THE SOUTH TOWARD THE RIO GRANDE. THE SYSTEM IS MORE-OR-LESS CONFINED AT ITS BASE BY MORE STEEPLY DIPPING STRATA OF PRE-CAMBRIAN TO TRIASSIC AGE (BARKER AND ARDIS, 1996B). LOCALLY, SOME OF THESE STRATA ALSO PRODUCE GROUND WATER. ROCKS OF NEOGENE (OGALLALA FM.) TO RECENT AGE OVERLIE THE PLATEAU SYSTEM. THE TRINITY AQUIFER IS GENERALLY HYDRAULICALLY CONFINED (DATA FROM TWDB, 1969) AND MORE SALINE THAN THE GENERALLY UNCONFINED EDWARDS INTERVAL.

THE POTENTIOMETRIC SURFACE SUBTLY REFLECTS BOTH TOPOGRAPHY AND STRATAL ATTITUDE (FIG. 3). A GROUNDWATER AND SURFACE DRAINAGE DIVIDE TRENDS NORTHWEST-TO-SOUTHEAST ALONG THE CREST OF THE PLATEAU. APPROXIMATELY 75% OF DRAINAGE IS TOWARD THE COLORADO RIVER AND ITS TRIBUTARY STREAMS (WALKER, 1979). GROUNDWATER EXPLOITATION IS ACCOMPLISHED BY THREE AREA-SPECIFIC STRATEGIES (FIG. 4) THAT REFLECT THE POSITION OF THE POTENTIOMETRIC SURFACE. IN THE SOUTHEASTERN HALF OF THE AQUIFER WELLS ARE COMPLETED IN THE EDWARDS INTERVAL. IN THE NORTHWESTERN ONE-QUARTER OF THE AREA WELLS ARE COMPLETED IN THE ANTLERS INTERVAL. WELLS ARE COMPLETED IN BOTH INTERVALS IN AREAS INTERMEDIATE TO THE EDWARDS AND ANTLERS COMPLETION AREAS.

The Edwards aquifer interval is the focus of this report. Recharge is mainly from precipitation. The Edwards is fractured and karstified (Freeman, 1968); Wermund and others, 1978; Webster, 1982; Elliot and Veni, 1994; Kastning, 1983). Sub-vertical fractures in the Edwards carbonates probably provide the most efficient avenues for

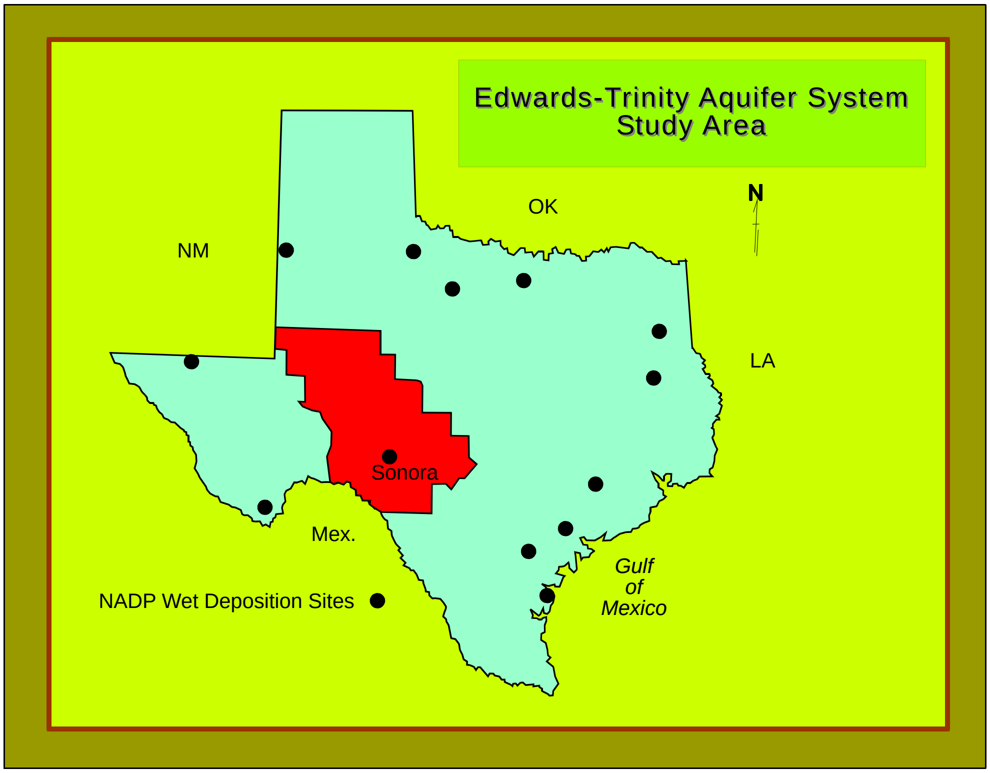
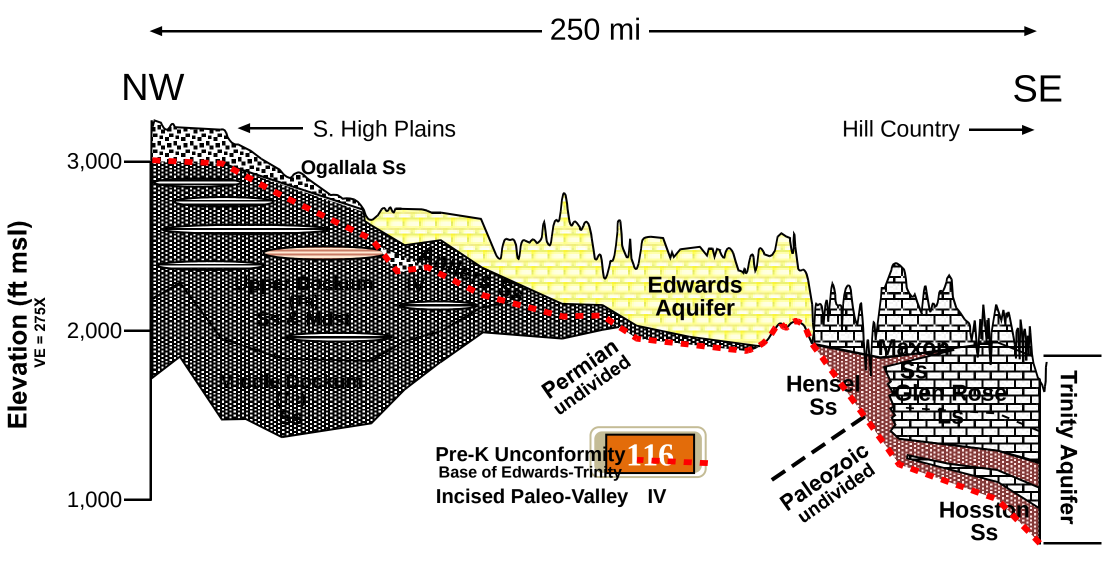


Figure 1. Edwards Plateau study area and location of NAPD sample sites



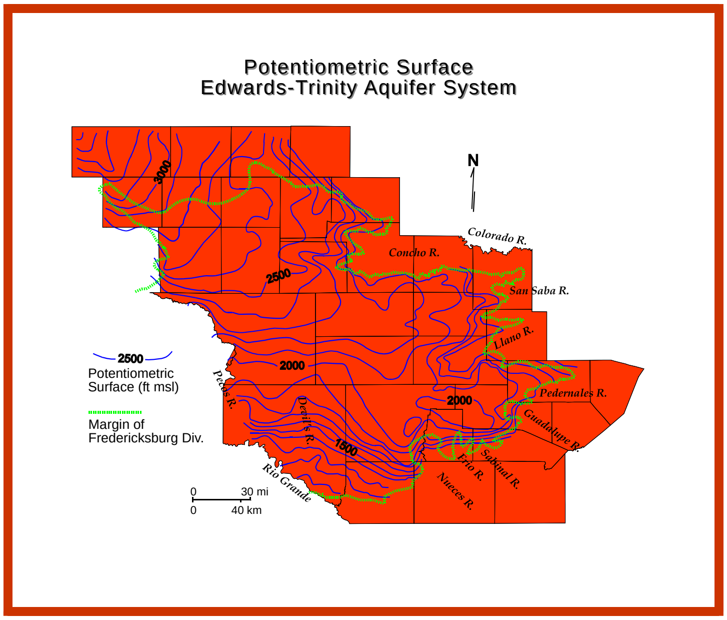
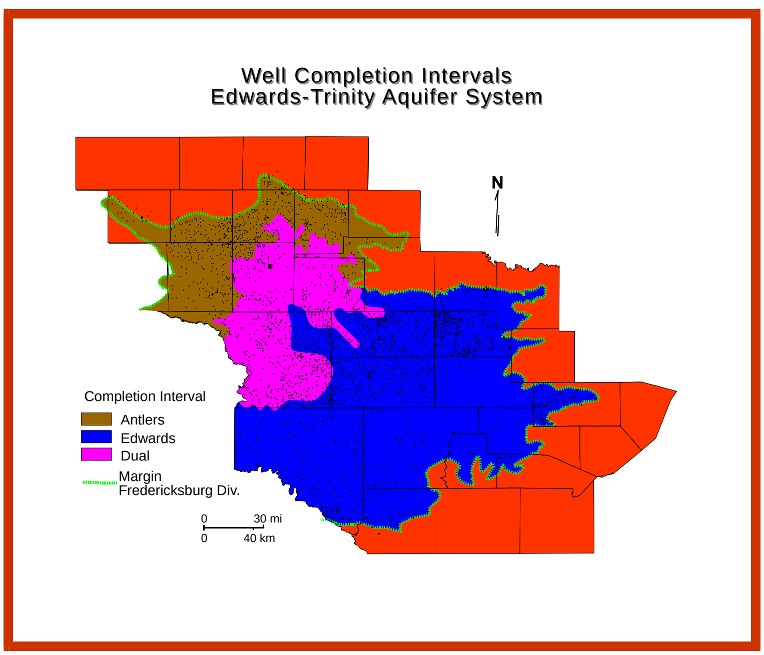


Figure 3. Potentiometric surface, Edwards-Trinity aquifer system

recharge. Flow in the Edwards is probably concentrated in its lowermost strata (Rose, 1972). Carbonate dissolution has produced stratiform flow conduits in particularly solution-susceptible intervals and along bedding planes. These features probably focus most groundwater advection.

Well locations and associated hydrochemical data was provided on-line by the Texas Water Development Board. The records span a time from the late 1930's to the present. Most of the data dates from the late 1960's to the late 1980's. A survey of the hydrochemical histories of several sufficiently monitored well suggests that water quality has not changed over time to an extent that would preclude using data of mixed vintage for the present analysis. Precipitation hydrochemical (mean annual wet chloride deposition) data was provided by the NADP (2003) and represents over 20 years of record ending in 2002 (figure 1). The data for mean annual rainfall is from Bomar, 1995 (fig. 5). Potentiometric surface data is from Kuniansky, 1990 (fig. 3).

IDENTIFICATION OF RECHARGE AREAS AND RECHARGE VOLUMES ARE BASED ON A CHLORIDE MASS-BALANCE APPROACH (FIG. 6). CHLORIDE IS CONCENTRATED IN THE SOIL BY WET (RAIN) AND DRY DEPOSITION. NUMEROUS RAIN EVENTS DELIVER WATER AND SOLUTES TO THE SOIL WHERE THEY REMAIN AS THE WATER EVAPORATES. CHLORIDE IS EXTREMELY SOLUBLE AND PERCOLATES THROUGH THE UNSATURATED ZONE AND TOWARD THE SATURATED ZONE DURING SUFFICIENTLY LARGE RAINFALLS OR DURING LONGER PERIODS OF RAINY WEATHER. THE SLUG OF CHLORIDE THAT ARRIVES AT THE WATER TABLE, THEREFORE, REPRESENTS CHLORIDE DEPOSITION FROM NUMEROUS RAINFALLS AND DRY DEPOSITIONAL EVENTS. ASSUMING THAT CHLORIDE CONTRIBUTIONS FROM THE SATURATED AQUIFER MATRIX AND FROM ADMIXED GROUNDWATER IS RELATIVELY NEGLIGIBLE, THE CONTRIBUTIONS OF SURFACE CHLORIDE AND THE CONCENTRATION OF GROUNDWATER CHLORIDE CAN BE USED TO ESTIMATE THE VOLUME OF RAIN REQUIRED TO PRODUCE THE OBSERVED CHLORIDE CONCENTRATION IN GROUND WATER BY SOLVING THE EQUATION SHOWN IN FIGURE 7. THIS METHOD HAS BEEN USED CONVINCINGLY BY ERIKSSON AND KHUNAKASEM (1969) IN THE ISRAEL COASTAL PLAIN. IN THE PRESENT STUDY DRY CHLORIDE DEPOSITION WAS ASSUMED TO BE EQUAL TO THAT OF WET DEPOSITION. DRY DEPOSITION DISTRIBUTION VALUES ARE UNKNOWN ON THE PLATEAU. HOWEVER, LIMITED STUDIES IN ARIZONA (HOPE AND OTHERS, 2001) INDICATE THAT DRY DEPOSITION MAY VARY FROM AMOUNTS THAT LOCALLY ARE LESS THAN HALF THAT OF WET DEPOSITION TO AMOUNTS THAT ARE MORE THAN TWICE AS GREAT AS THOSE PROVIDED BY WET DEPOSITION. THE ASSUMPTION OF EQUAL CONTRIBUTIONS BY BOTH PROCESSES IS A REASONABLE COMPROMISE FOR THE PRESENT PURPOSE. HOWEVER, A COMPREHENSIVE MULTI-YEAR REGIONAL SURVEY OF CHLORIDE DEPOSITION BY BOTH PROCESSES IS ULTIMATELY CRITICAL FOR THE CONVINCING USED OF THE CHLORIDE MASS-BALANCE APPROACH TO ESTIMATE RECHARGE.



For this project maps of mean annual rainfall (fig. 5) and wet chloride deposition (fig. 8) were digitized, loaded into ArcGIS, spatially interpolated by kriging, and converted to raster formats. Groundwater chloride data was loaded into ArcGIS, kriged, and converted to raster format (fig.9). Raster calculations (division) were performed between the groundwater chloride and wet deposition rasters to produce a recharge percentage map (fig. 10) that was corrected to reflect a dry deposition contribution that was assumed to be equal to that of the wet deposition. The percentage recharge raster was then multiplied with the mean annual recharge raster to produce a map of mean annual recharge (fig. 11).

For the delineation of preferred flow paths wells were selected whose analyses reflected three attributes that are assumed to reflect relative youth of ground water. The

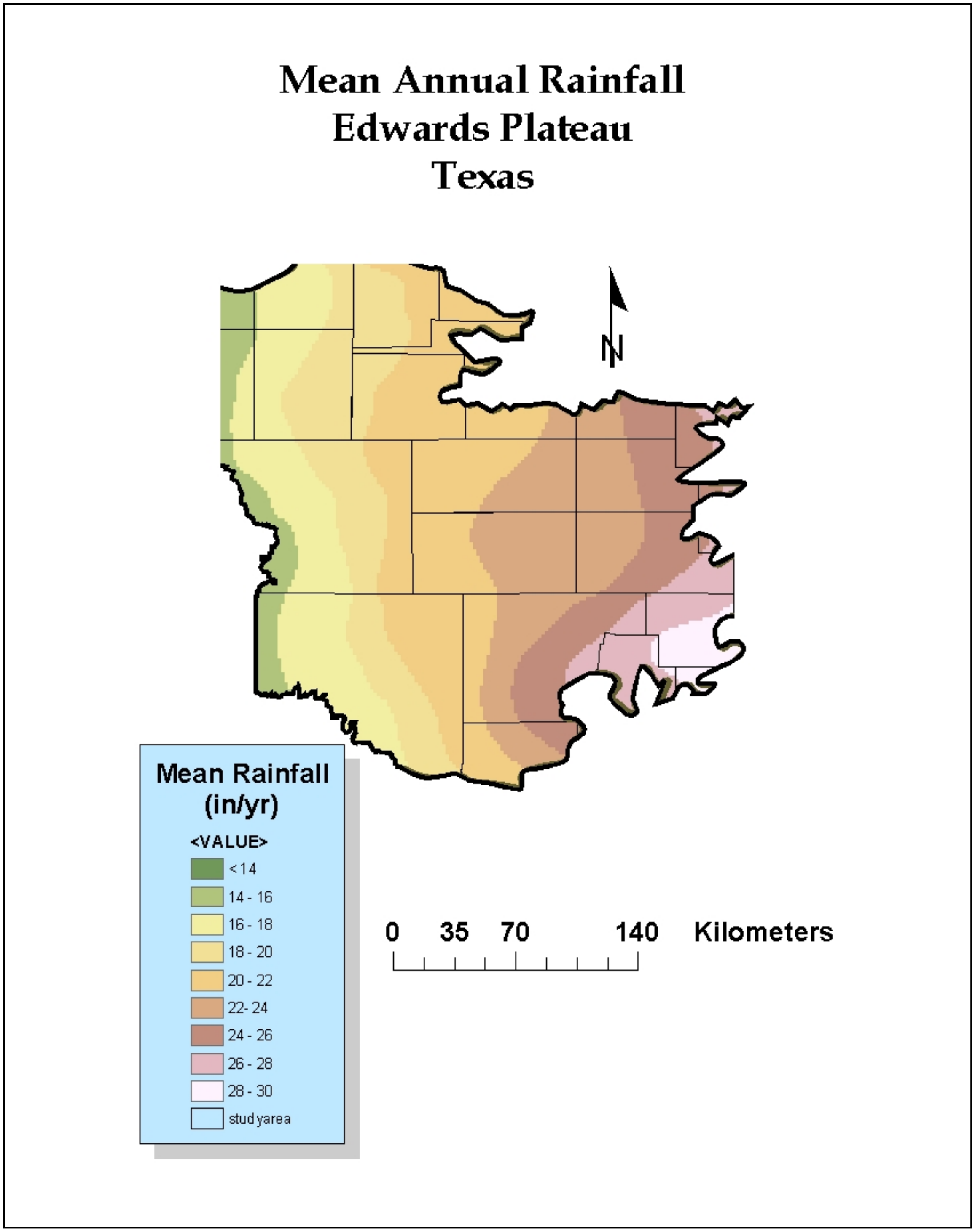


FIGURE 5. MEAN ANNUAL RAINFALL, 1960-1990 (FROM BOMAR,

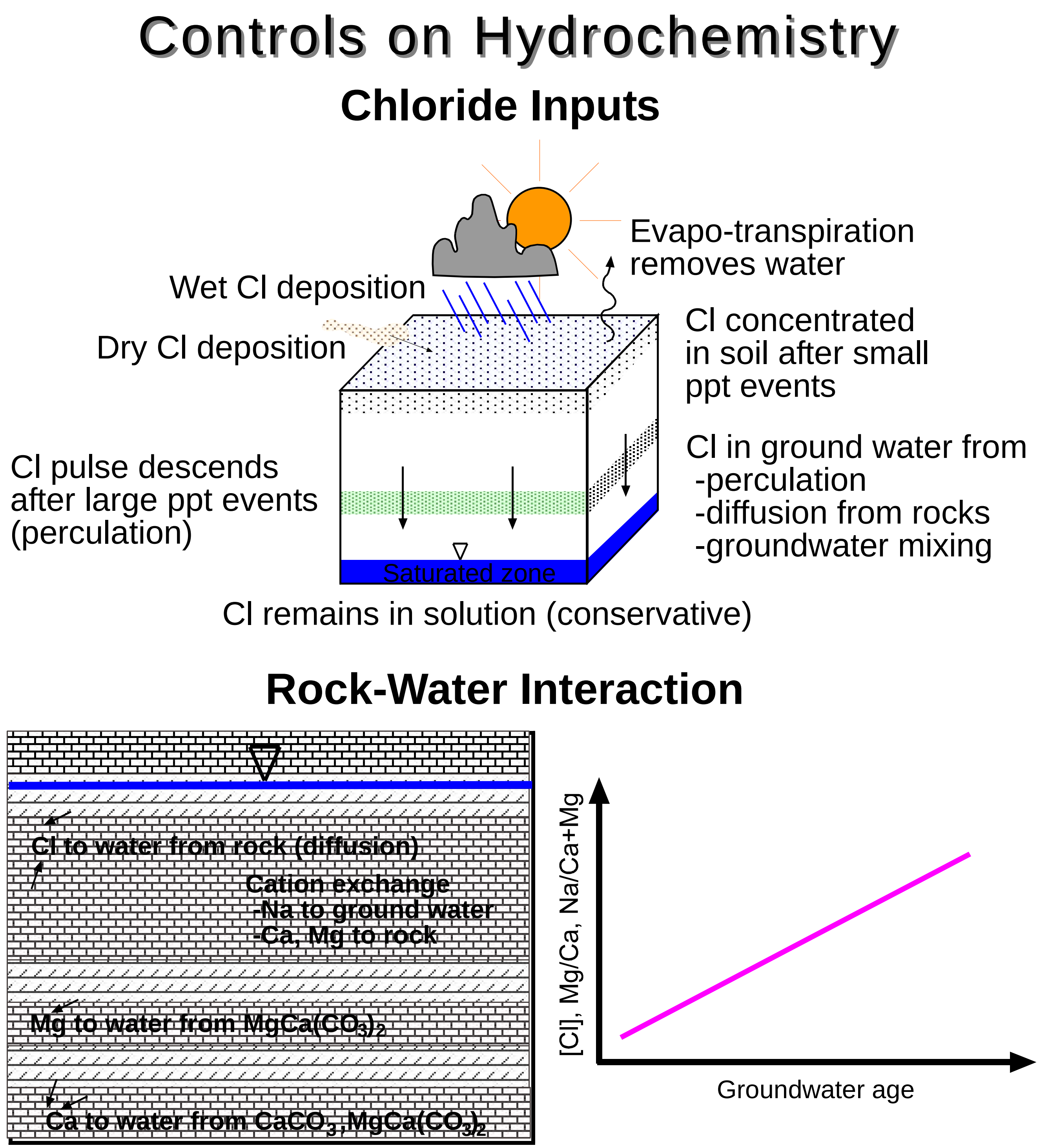


FIGURE 6. DIAGRAMS OF HYDROCHEMICAL CONCEPTS USED IN RECHARGE AREA IDENTIFICATION, RECHARGE VOLUME ESTIMATES, AND DELINEATION OF FLOW PATHS.

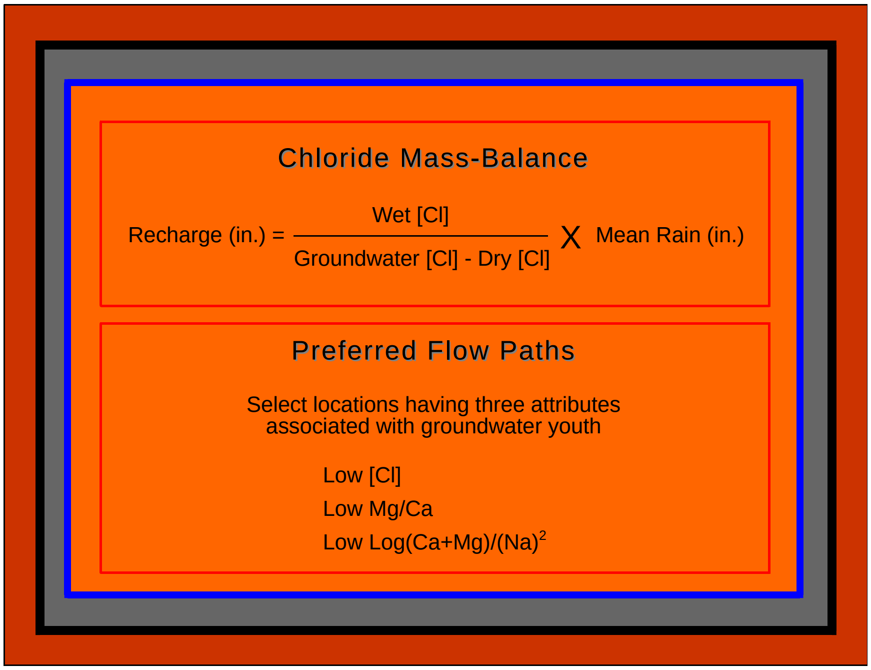


FIGURE 7. EQUATION FOR MEAN ANNUAL RECHARGE ESTIMATION FROM CHLORIDE DATA AND ATTRIBUTES USED TO SELECT WELLS LOCATED ALONG

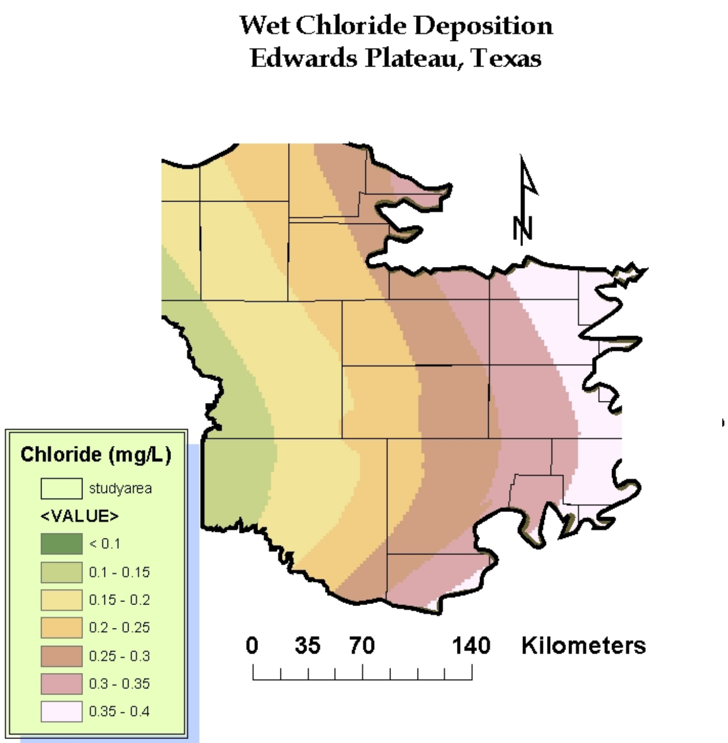


FIGURE 8. CONTOUR MAP OF WET CHLORIDE DEPOSITION (DATA FROM NADP,

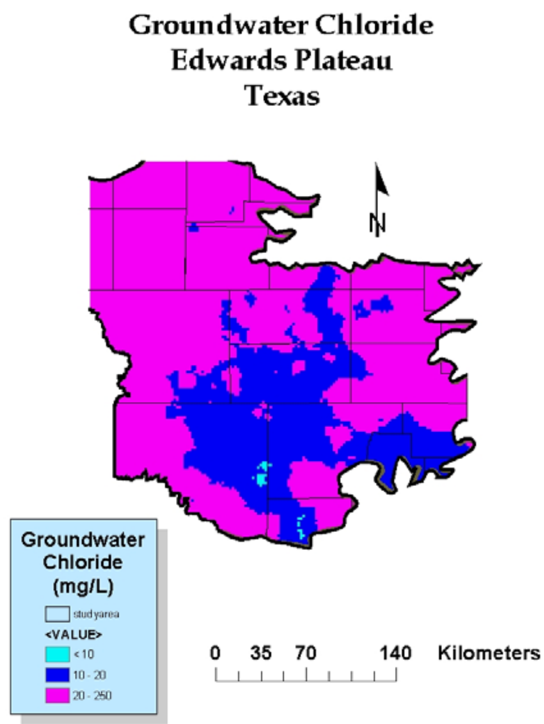


FIGURE 9. MAP OF CHLORIDE CONCENTRATION IN GROUND WATER (DATA FROM TWDB, 2003).

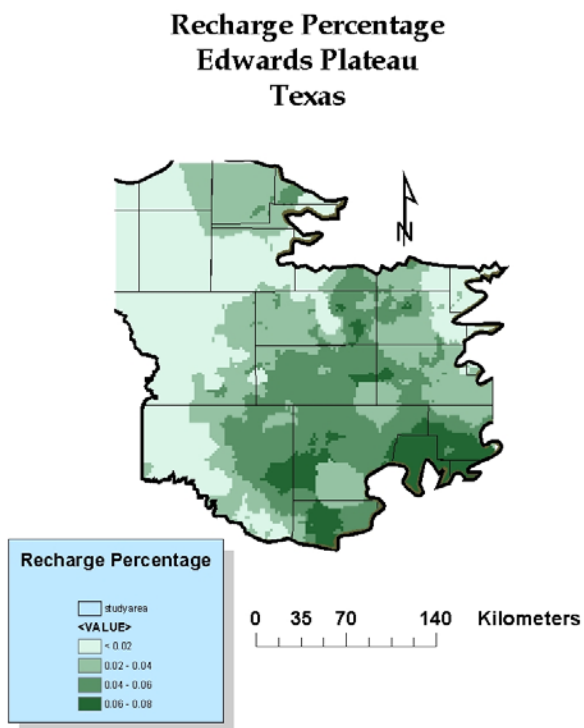


FIGURE 10. MAP OF RECHARGE PERCENTAGE PRODUCED BY RASTER DIVISION OF FIGURE 8 BY FIGURE 9 AND SUBSEQUENT CORRECTION (SEE TEXT) FOR DRY

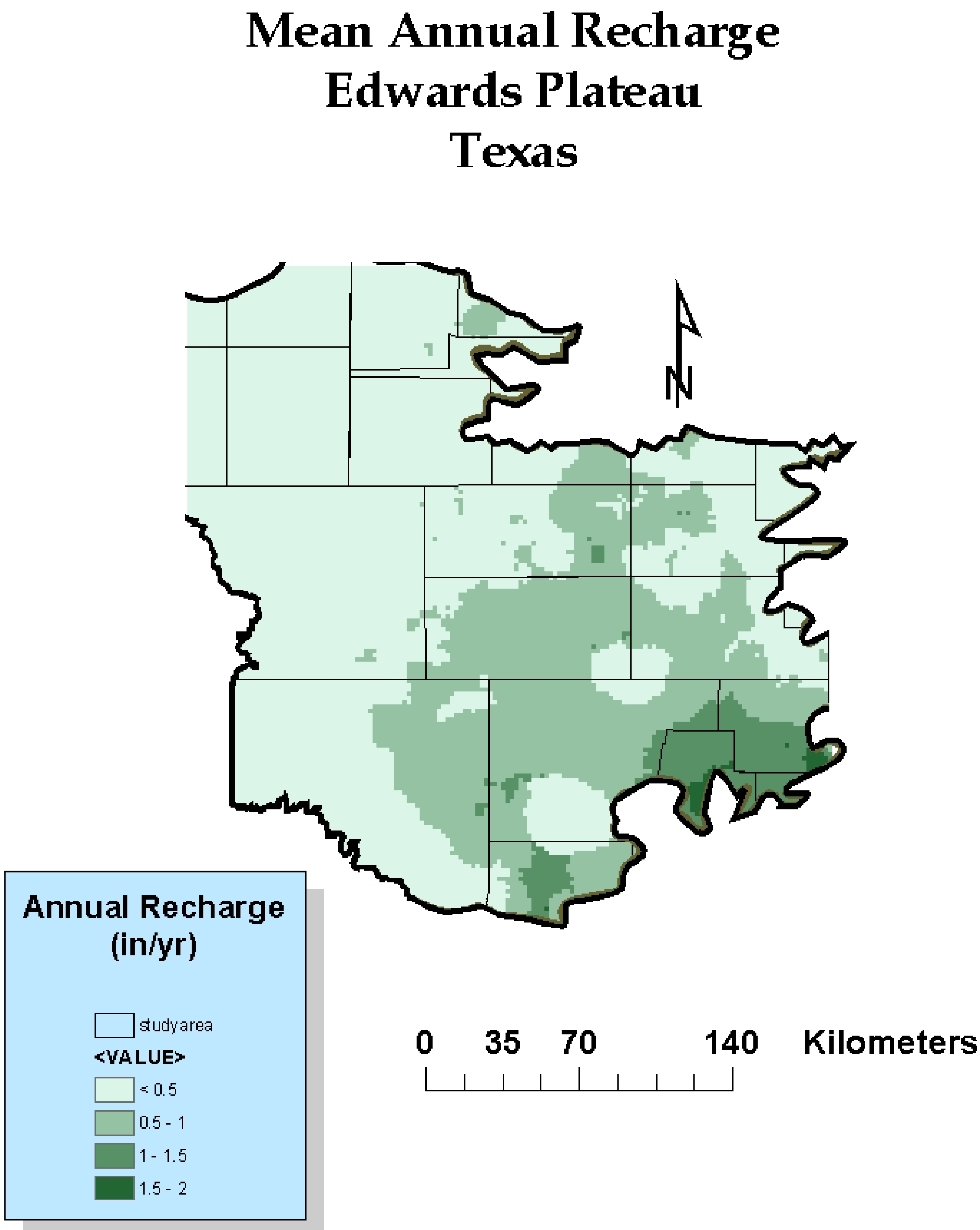


Figure 11. Map of mean annual recharge produced by raster multiplication of figures 5 and 10.

most recently recharged, fastest flowing waters should also be younger than slower moving waters that have resided longer in the aquifer. Over time groundwater increases in chloride concentration that is caused by diffusion of chloride from aquifer rocks. Ground water also generally exhibits increases in Mg/Ca (Freeze and Cherry, 1979) that is caused by the slow dissolution of dolomite $(MgCaCO_3)_2$, Mg-calcite, and de-dolomitization (dolomite converted to calcite in the presence of water with high Ca/Mg) (Moore and others, 1968; DeGroot, 1967). Finally, fresh ground water increases in Na concentration by cation exchange whereby Ca^{2+} and Mg^{2+} substitute for Na^{+} on grain surfaces, especially clay particles. The extent of cation exchange has been characterized by an operational parameter $\log(Ca+Mg)/(Na)^2$. and mapped for two sandstone aquifers in Montana by Henderson (1984) who demonstrated its relationship to groundwater flow direction. In Henderson's study the value of the operational parameter decreased (cation exchange extent increased) along flow paths that were interpreted from potentiometric data. In the present study, therefore, ground water with simultaneously low values of chloride, Mg/Ca, and $\log(Ca+Mg)/(Na)^2$ should generally be younger than waters with significantly higher values for these parameters. For this analysis three attributes were overlain on a single map: (1) chloride values less than 20 mg/L, (2) Mg/Ca values of less than 0.5, and (3) $\log(Ca+Mg)/(Na)^2$ values that were above average for their corresponding Mg/Ca values. The third attribute was determined in the following way. A cross plot was generated in Excel of Mg/Ca values and the corresponding $\log(Ca+Mg)/(Na)^2$ values. A best-fit (regression) line was generated. Then, samples that exhibited $\log(Ca+Mg)/(Na)^2$ values greater than the values along the regression line were selected. In other words, samples with Mg/Ca values less than 0.5 were selected that exhibited apparently lesser extents of cation exchange. The map showing distribution of the wells for which groundwater youth was interpreted from these criteria is shown in figure 12.

RESULTS

The results of the recharge estimates are shown in figures 10 and 11. Recharge ranges from 8% to less than 2% of mean annual rainfall, generally decreasing from east to west. The areas with highest recharge percentages occur in the southern and southeastern parts of the area. The patterns of recharge largely reflect the distribution of groundwater chloride values shown in figure 9. The calculated values for mean annual recharge range from 2 in (50.8 mm) in the southeast part of area to less than 0.5 in (12.7 mm) in the west and northwest. The patterns of recharge volumes reflect the patterns of recharge percentage, of course, coupled with the pattern of regularly decreasing rainfall volumes from east to west over the region. The volume estimates allow a first approximation of the volumes of ground water than can be produced from a specified area without lowering the potentiometric surface. However, knowledge of actual distributions of dry chloride deposition volumes will significantly enhance the viability of recharge estimates produced by the chloride mass-balance approach.

The interpreted flow path map is shown in figure 13 where an envelope has been drawn around the well locations that exhibit the three hydrochemical criteria. The linear trends of low Mg/Ca wells generally trend perpendicular to potentiometric contours in the west-central and western part of the area and suggest a relationship between low Mg/Ca and flow paths. In areas in the south where most of the wells exhibit low Mg/Ca the cation-

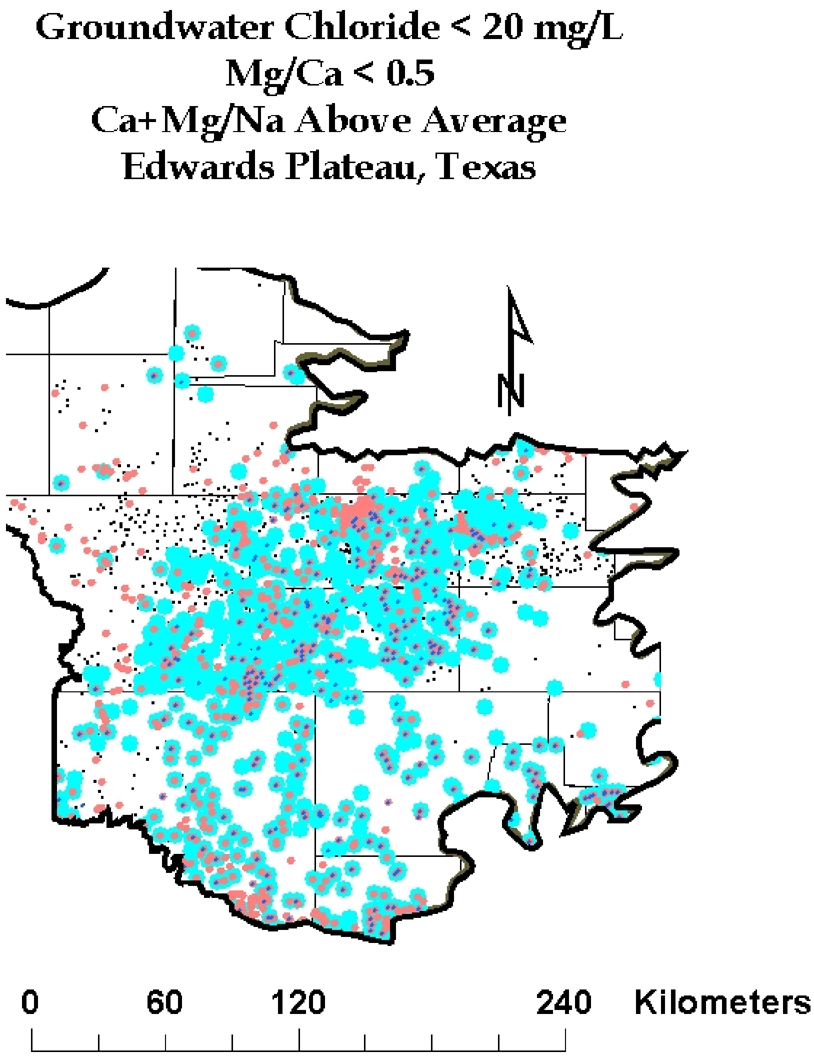


FIGURE 12. DISTRIBUTION OF WELLS CHARACTERIZED BY HYDROCHEMICAL CRITERIA INTERPRETED TO REPRESENT RELATIVELY YOUTHFUL AGE: CHLORIDE LESS THAN 20 MG/L (BLUE SPOTS), MG/CA < 0.5 (PINK SPOTS), AND BELOW AVERAGE VALUES OF $LOG(Ca+Mg)/(Na)^2$ (BLUE DOTS ON BLUE OR PINK SPOTS, REFLECTING LOW EXTENT OF CATION EXCHANGE REACTIONS).

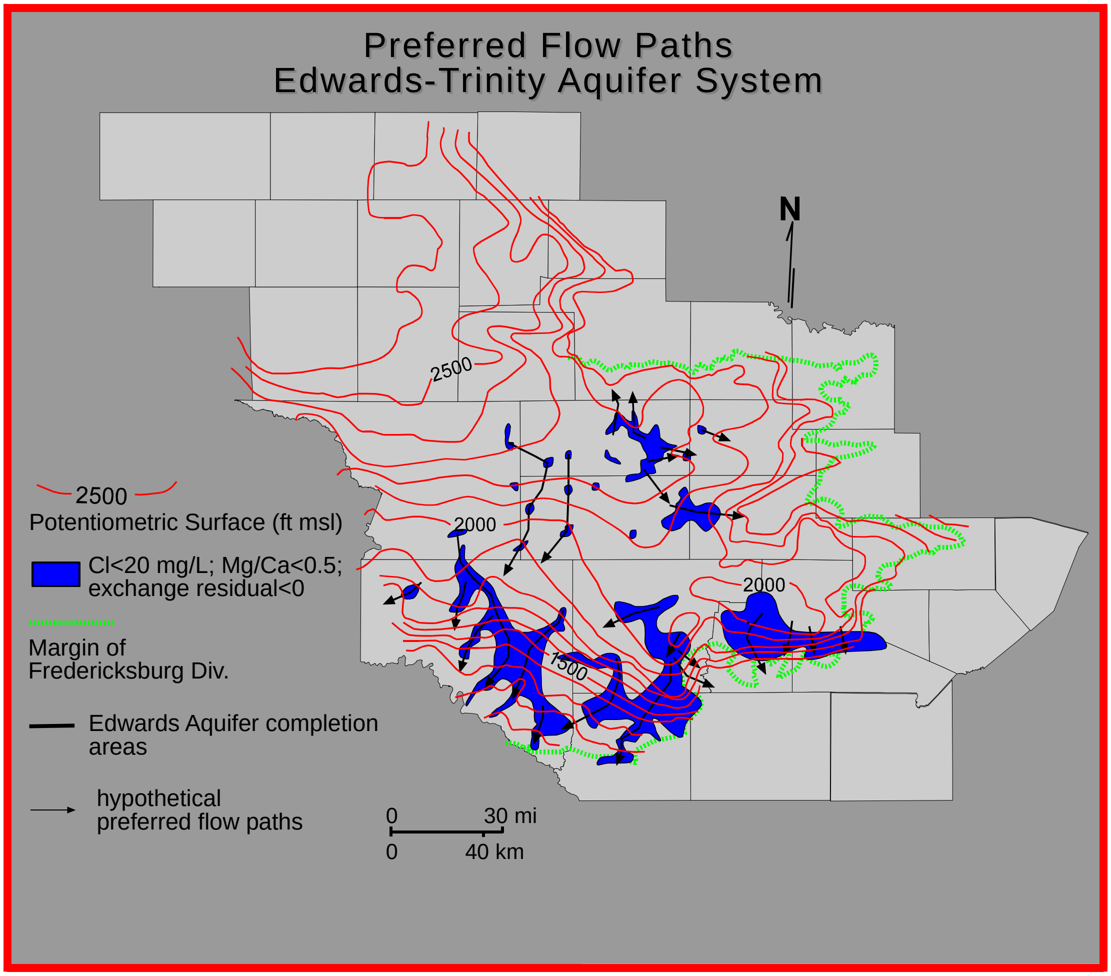


FIGURE 13. INTERPRETED PREFERENTIAL FLOW PATHS DEFINED BY WELLS THAT PRODUCE RELATIVELY YOUTHFUL WATERS DEFINED BY LOW VALUES OF CHLORIDE CONCENTRATION, MG/CA, AND EXTENT OF

exchange criteria provide some guidance for flow path interpretation and also suggests trends that run perpendicular to potentiometric contours. The digitate patterns in some areas suggest that groundwater flow may be locally channelized. This is a reasonable expectation in karstic terrain where dissolution will continue most aggressively in areas where water may have been focused along a lithologic discontinuity (e.g., a fracture) early in the aquifers history. The directions of the interpreted flow paths in the southwest part of the area (along the Rio Grande) parallel dominant fracture trends (Wermund and others, 1978; Webster, 1982) and cavern trends (Kastning, 1983; Elliot and Veni, 1994) in the southern part of the Plateau.

Figure 13 depicts interpreted flow patterns mainly in areas with higher potentiometric gradients. Wells in areas with lower gradients generally do not meet the Mg/Ca or cation exchange criteria for inclusion in flow path depictions, although chloride values are sufficiently low. These circumstances probably reflect relatively slower flow and longer residence times for water in lower-gradient areas.

DISCUSSION AND CONCLUSIONS

Determining in detail groundwater recharge areas, recharge volumes, and preferential flow paths is generally limited severely by data that is insufficiently focused to satisfactorily resolve critical features in the four dimensions. Wells that provide hydrochemical and hydrodynamic information are often completed over depth intervals that include several hydrogeologically distinct flow units. In these cases waters from multiple sources may be intermingled and characteristics that are potentially diagnostic of flow conditions for any given unit are obscured. A partial solution to this issue is a well-designed survey of selected wells whereby packer tests are conducted to ascertain the distribution of hydrochemical and hydrodynamic heterogeneities in the aquifer system. This is an ambitious undertaking but perhaps the only way to significantly reduce the "educated" guesswork that is a mainstay of hydrogeological analysis.

The economics of ground water production have also been insufficient to stimulate comprehensive surveys of hydrochemical constituents, (namely, the radio-isotopes ^{14}C and ^{3}H), that potentially reveal preferential recharge areas and flow paths by demonstrating groundwater-age distributions. Such analyses cost hundreds of dollars apiece in the commercial marketplace and groundwater entrepreneurs are hard pressed to make such investments.

Pending the attainment of transcendental social enlightenment concerning the real-world importance of environmental investigation (it is undoubtedly more critical than going to Mars) we must squeeze maximum benefit from the commonly acquired data that is available. Abundant routine hydrochemical analyses that are available for many aquifer systems have not been fully exploited to broaden our insights into the hydrogeological behavior of aquifers. The Edwards-Trinity aquifer system is a perfect example.

With the chloride mass-balance approach we combine readily available information about rainfall distribution and chloride with groundwater chloride data we can make first approximations at a fairly local scale of the most effective recharge areas and also constrain the range of probable recharge volumes. This information can provide guidance to resource managers for regulating groundwater production such that the resource is maintained indefinitely. The chloride mass-balance approach is apparently limited by poor information about the distribution of dry chloride deposition- critical data for the adjustment of groundwater chloride values to allow estimation of recharge volumes from rainfall. A regional survey of the relative contributions of wet and dry chloride deposition is highly desirable and need not be expensive because high-tech equipment is not required and chloride analyses are not expensive. Although diffusion of chloride from aquifer rocks is also an unknown factor, the aquifer has been bathed in fresh meteoric water for millions of years and groundwater flow rates are probably sufficiently high to negate the relative importance of this potential input.

By using hydrochemical criteria that may allow the sorting of wells into groups that probably reflect relative ages of the ground water that they produce we may be able to resolve preferred flow paths at a finer scale than is usually attempted in a regional investigation. The results of the trial presented in this report are reasonable in that interpreted preferred flow paths are located in areas with higher potentiometric gradients where flow rates are potentially faster than elsewhere. Also, where narrow paths are interpreted the digitate patterns shown on the flow-path map (fig. 13) trend normal to potentiometric contours. This is an encouraging indication that the approach is reasonable. This method can be extended into more up-gradient areas where flow is probably slower, as evidenced by lower potentiometric gradients toward the crest of the potentiometric surface. By raising the Mg/Ca criteria to higher cutoff values patterns similar to those produced with an Mg/Ca cutoff value of 0.5 are revealed. Continued work along these lines is in progress but is insufficiently complete for inclusion in this report. Ultimately, application of isotopic age-dating techniques to selected areas is desired to corroborate the approach reported here for the delineation of groundwater flow paths.

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WATER RIGHTS ABOVE LAKE CANYON. (SOURCE: TCEQ WATER RIGHTS DATABASE, MARCH 2008)

WAM IDENTIFIER	WATER RIGHT NUMBER	WATER RIGHT TYPE	SEQUENCE	APPLICATION NUMBER	ISSUE DATE	OWNER	ANNUAL DIVERSION AC FT
C2006	2006	6	5		7/17/1981	1967 SHELTON TRUSTS PART ET AL	106.9
C2006	2006	6	6		7/17/1981	1967 SHELTON TRUSTS PART ET AL	50.1
C2036	2036	6	1		7/17/1981	46 SKYLINE DRIVE LLC	50
C2036	2036	6	2		7/17/1981	46 SKYLINE DRIVE LLC	75
P5107	5107	1	1	5107	1/20/1987	46 SKYLINE DRIVE LLC	518
P5107	5107	1	2	5107	1/20/1987	46 SKYLINE DRIVE LLC	
C2040	2040	6	1		7/17/1981	A C & DOROTHY PFEIFFER	10
C1978	1978	6	1		7/17/1981	A J RUST	33
C1980	1980	6	1		7/17/1981	A L MOORE	12
C2058	2058	6	2		7/17/1981	A W WRIGHT FAMILY LIMITED PARTNERSHIP	23.47
C2041	2041	6	3		7/17/1981	ALAN R SPARGER III ET UX	64
P4298	4096	1	1	4298	4/17/1984	ALISON B MENCAROW LIVING TRUST	11.52
C1992	1992	6	2		7/17/1981	ALLIE B BURTON	9.9
C1976	1976	6	1		7/17/1981	APACHE SPRINGS LP	29
C1976	1976	6	2		7/17/1981	APACHE SPRINGS LP	
C1972	1972	6	3		7/17/1981	ARANSAS BAY COMPANY	0.05
P5060	5060	1	1	5060	8/18/1986	AUSTEX PROPERTIES LTD	10
C1940	1940	6	1		7/17/1981	B E QUINN III ET AL	28
C1940	1940	6	2		7/17/1981	B E QUINN III ET AL	4
P5501	5501	1	1	5501	2/28/1995	BARRY T & KATHRYN B NALL	5
C2006	2006	6	11		7/17/1981	BEDROCK MATERIALS LTD	100
C2022	2022	6	2		7/17/1981	BELINDA LEE MOSTY STANUSH ET AL	
C2014	2014	6	2		7/17/1981	BENNO OOSTERMAN ET UX	6.36
C2449	2449	6	1		3/8/1983	BILLIE ZUBER ET AL	17
P5490	5490	1	1	5490	8/22/1994	BILLY J & KARAN R BOLES	10
C2446	2446	6	1		3/8/1983	BOB/KAT INC	20
C1969	1969	6	1		7/17/1981	BOBBY DON BLACKBURN	15
C1969	1969	6	2		7/17/1981	BOBBY DON BLACKBURN	49
C1969	1969	6	3		7/17/1981	BOBBY DON BLACKBURN	59
C1969	1969	6	4		7/17/1981	BOBBY DON BLACKBURN	
P5352	5352	1	1	5352	7/19/1991	BONITA OWNERS ASSN INC	2
C1937	1937	6	1		7/17/1981	BOY SCOUTS- ALAMO AREA	

C2444	2444	6	1		3/8/1983	BRUCE F HARRISON	6
C2444	2444	6	2		3/8/1983	BRUCE F HARRISON	
P5348	5348	1	1	5348	7/16/1991	BRYON DONZIS	5
P5122	5122	1	1	5122	6/10/1987	BUCKLEY LP	75
C2025	2025	6	3		7/17/1981	BYNO SALSMAN ET UX	57.35
C2447	2447	6	1		3/8/1983	CAMP LA JUNTA INC	26
C2447	2447	6	2		3/8/1983	CAMP LA JUNTA INC	14
C2447	2447	6	3		3/8/1983	CAMP LA JUNTA INC	
C2445	2445	6	1		3/8/1983	CAMP MYSTIC INC	5
C2445	2445	6	2		3/8/1983	CAMP MYSTIC INC	7
C2445	2445	6	3		3/8/1983	CAMP MYSTIC INC	14
C3815	3815	6	1		7/16/1985	CANYON LAKE WSC	3
C1970	1970	6	1		7/17/1981	CARL HAWKINS	10
C1970	1970	6	2		7/17/1981	CARL HAWKINS	32
C2060	2060	6	1		7/17/1981	CHADEAUX INVESTMENTS LTD	90
C2060	2060	6	2		7/17/1981	CHADEAUX INVESTMENTS LTD	
C2060	2060	6	3		7/17/1981	CHADEAUX INVESTMENTS LTD	
P4230	3925	1	2	4230	12/1/1982	CHARLES MICKAN ET UX	
P4486	4181	1	3	4486	2/1/1985	CHESTER C HURST ET UX	18.76
C2034	2034	6	1		7/17/1981	CHESTER P HEINEN ET AL	2
C2033	2033	6	1		7/17/1981	CHRISTOPHER L HAVENS ET UX	90
C2063	2063	6	3		7/17/1981	CHRISTOPHER P HILL	8.097
C2014	2014	6	1		7/17/1981	CINDI SHARP	6.36
C2002	2002	6	2		7/17/1981	CITY OF KERRVILLE	
P3769	3505	1	1	3769	10/14/1977	CITY OF KERRVILLE	3603
P3769	3505	1	2	3769	10/14/1977	CITY OF KERRVILLE	
P3904	3635	1	1	3904	2/12/1979	CITY OF KERRVILLE	80
P3904	3635	1	2	3904	2/12/1979	CITY OF KERRVILLE	
P5394	5394	1	5	5394	10/12/1993	CITY OF KERRVILLE	761
P5394	5394	1	6	5394	10/12/1993	CITY OF KERRVILLE	339
P5394	5394	1	7	5394	10/12/1993	CITY OF KERRVILLE	1069
P5536	5536	1	4	5536	10/20/1995	CITY SOUTH MANAGEMENT CORP	84.3
C3817	3817	6	1		7/16/1985	CLARENCE B ANDERSON ET AL	79
P4491	4163	1	1	4491	1/4/1985	COMAL CO FRESH WSD #1	
P4491	4163	1	2	4491	1/4/1985	COMAL CO FRESH WSD #1	120
C2002	2002	6	1		7/17/1981	COMANCHE TRACE RANCH & GOLF CL	136
C2448	2448	6	1		3/8/1983	COOL CREEK LLC	6
C1958	1958	6	1		7/17/1981	COOL WATER LLC	20
C1958	1958	6	2		7/17/1981	COOL WATER LLC	
P5846	5846	1	1	5846	4/1/2005	CORDILLERA RANCH POA	
P5846	5846	1	2	5846	4/1/2005	CORDILLERA RANCH POA	
C1971	1971	6	1		7/17/1981	COUNTY OF KERR	
C2004	2004	6	1		7/17/1981	COUNTY OF KERR	
C2017	2017	6	1		7/17/1981	COUNTY OF KERR	

C2017	2017	6	2		7/17/1981	COUNTY OF KERR	
C1952	1952	6	1		7/17/1981	CYPRESS COVE MAINTENANCE ASSN	
C2439	2439	6	1		3/8/1983	DALE B AND MARSHA G ELMORE	8
C2437	2437	6	1		3/8/1983	DAN W BACON MD ET UX	
P5315	5315	1	1	5315	10/29/1990	DANA G KIRK TRUSTEE	
C1997	1997	6	1		7/17/1981	DARRELL G LOCHTE ET AL	143
C1997	1997	6	2		7/17/1981	DARRELL G LOCHTE ET AL	2
C2025	2025	6	2		7/17/1981	DAVID B WRAY	57.35
C1983	1983	6	3		7/17/1981	DAVID J COPELAND ET UX	
C1983	1983	6	4		7/17/1981	DAVID J COPELAND ET UX	
C2066	2066	6	1		7/17/1981	DAVID M ERNSBERGER ET UX	5
C1941	1941	6	1		7/17/1981	DELMAR SPIER AGENT	6
P5531	5531	1	2	5531	9/15/1995	DIANE DEMPSEY	50.9
C1995	1995	6	2		7/17/1981	DON E WOODWORTH ET AL	7.973
C2016	2016	6	1		7/17/1981	DORIS J HODGES	8
C1990	1990	6	1		7/17/1981	DOROTHY L JENKINS ET AL	3
C2069	2069	6	1		7/17/1981	DOUBLE U-SPRING BRANCH	30
P5331	5331	1	4	5331	3/19/1991	DR CURTIS S MCCUBBIN	10
P5322	5322	1	1	5322	2/14/1991	E RAND SOUTHARD ET UX	
C2035	2035	6	1		7/17/1981	EARL PANKRATZ ET UX	2
C2064	2064	6	1		7/17/1981	EARL S DODERER ET UX	4.38
C2043	2043	6	2		7/17/1981	EDGAR SEIDENSTICKER ET UX	16.85
C2054	2054	6	1		7/17/1981	EDMUND BEHR ESTATE	80
C2072	2072	6	1		7/17/1981	ELOY GARCIA JR ET UX	35
P5474	5474	1	1	5474	2/14/1994	ELTON RUST	10
C2053	2053	6	1		7/17/1981	ERNO SPENRATH	32
C2050	2050	6	1		7/17/1981	ERWIN KLEMSTEIN	102.84
C2050	2050	6	2		7/17/1981	ERWIN KLEMSTEIN	
C2050	2050	6	3		7/17/1981	ERWIN KLEMSTEIN	
P5444	5444	1	1	5444	7/13/1994	EUGENE D ELLIS ET UX	10
C2013	2013	6	1		7/17/1981	FELIX R & LILLIAN STEILER REAL	11
C1967	1967	6	1		7/17/1981	FORD SMITH TRUSTEE	20
C1967	1967	6	2		7/17/1981	FORD SMITH TRUSTEE	
C1967	1967	6	3		7/17/1981	FORD SMITH TRUSTEE	
C1967	1967	6	4		7/17/1981	FORD SMITH TRUSTEE	
C2020	2020	6	1		7/17/1981	FOUR SEASONS GROWERS LTD	60
C2070	2070	6	1		7/17/1981	FRANK A STANUSH	22
C2070	2070	6	2		7/17/1981	FRANK A STANUSH	98
C2065	2065	6	2		7/17/1981	FRASHIER LAND PARTNERSHIP II LTD	10
C2039	2039	6	1		7/17/1981	FRED SAUR	7
C2006	2006	6	7		7/17/1981	FRITZ FAMILY ENTERPRISES LP	34.04
C2006	2006	6	8		7/17/1981	FRITZ FAMILY ENTERPRISES LP	15.96
C2063	2063	6	1		7/17/1981	FROST-LANCASTER PROPERTIES	33.223
C2010	2010	6	1		7/17/1981	G ROBERT SWANTNER JR ET UX	7

C2037	2037	6	1		7/17/1981	GENE ARTHUR ALLERKAMP	5
C1995	1995	6	1		7/17/1981	GEOFFREY WRIGHT	3.027
P4590	4255	1	1	4590	11/4/1985	GEORGE M WILLIAMS SR ET AL	50
C1947	1947	6	1		7/17/1981	GUAD VALLEY LOT OWNERS ASSN	6
C1947	1947	6	2		7/17/1981	GUAD VALLEY LOT OWNERS ASSN	3
C2071	2071	6	1		7/17/1981	GUADALUPE RIVER RANCH & CATTLE	1
C2074	2074	6	1		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	62900
C2074	2074	6	2		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	3		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	4		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	5		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	6		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	57100
C2074	2074	6	7		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	8		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	9		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
C2074	2074	6	10		7/17/1981	GUADALUPE-BLANCO RIVER AUTHORITY	
P4445	4167	1	1	4445	1/11/1985	GUADALUPE-BLANCO RIVER AUTHORITY	
C2065	2065	6	1		7/17/1981	GUY BODINE III ET UX	10
C2047	2047	6	1		7/17/1981	H C SEIDENSTICKER	20
P5401	5401	1	1	5401	6/16/1992	H E BUTT GROCERY CO	
C2005	2005	6	1		7/17/1981	HARRIET BOCKHOFF ESTATE	59
C2038	2038	6	1		7/17/1981	HARRY E REEH	15
C1930	1930	6	1		7/17/1981	HERSHEL REID ET UX	69
P5749	5749	1	1	5749	10/15/2003	HILLTOP HOLDINGS INC	
P5749	5749	1	2	5749	10/15/2003	HILLTOP HOLDINGS INC	
P5749	5749	1	3	5749	10/15/2003	HILLTOP HOLDINGS INC	
C2028	2028	6	1		7/17/1981	HOWARD E BUTT	
P5536	5536	1	1	5536	10/20/1995	J W COLVIN III	92
C2006	2006	6	9		7/17/1981	J W COLVIN III ET AL	74.9
C2006	2006	6	10		7/17/1981	J W COLVIN III ET AL	35.1
P5479	5479	1	1	5479	10/21/1994	J W COLVIN III ET AL	566
P5536	5536	1	2	5536	10/20/1995	J W COLVIN III TRUSTEE	18
P5536	5536	1	3	5536	10/20/1995	J W COLVIN III TRUSTEE ET AL	190
P5536	5536	1	5	5536	10/20/1995	J W COLVIN III TRUSTEE FOR FM 1092 CTR	15.7
C1981	1981	6	1		7/17/1981	JACK D CLARK JR ET AL	32
C1981	1981	6	2		7/17/1981	JACK D CLARK JR ET AL	143
C2015	2015	6	1		7/17/1981	JAMES E NUGENT	27
P5208	5208	1	1	5208	9/6/1989	JAMES F HAYES & MARY K HAYES	40
C2037	2037	6	2		7/17/1981	JANICE CHARLOTTE BULLARD	4.46
C2438	2438	6	2		3/8/1983	JAY DICKENS	3.45
C2030	2030	6	3		7/17/1981	JAY H HEIZER ET UX	11.57
P4486	4181	1	1	4486	2/1/1985	JAY L POTH JR	25.86
C2030	2030	6	1		7/17/1981	JERRY BROCK	180
C2030	2030	6	2		7/17/1981	JERRY BROCK	

C1988	1988	6	1		7/17/1981	JIMMIE L QUERNER SR ESTATE	128
C2440	2440	6	1		3/8/1983	JOANNE SCHERER SMITH TRUST	1
C2025	2025	6	1		7/17/1981	JOCELYN LEVI STRAUS ET AL	40.3
C1998	1998	6	1		7/17/1981	JOE M PRUNEDA III ET AL	26.48
C1998	1998	6	2		7/17/1981	JOE M PRUNEDA III ET AL	
C2050	2050	6	4		7/17/1981	JOHN C MCCALEB	16.58
C2007	2007	6	1		7/17/1981	JOHN G WRIGHT ET AL	31
C1948	1948	6	1		7/17/1981	JOHN H DUNCAN	7
C1950	1950	6	1		7/17/1981	JOHN H DUNCAN	6
C1950	1950	6	2		7/17/1981	JOHN H DUNCAN	
C2443	2443	6	1		3/8/1983	JOHN H DUNCAN	40
C2014	2014	6	3		7/17/1981	JOHN M LEBOLT TRUSTEE	9.02
C1945	1945	6	1		7/17/1981	JOHN P HILL	25
C1946	1946	6	1		7/17/1981	JOHN P HILL ADMINISTRATOR	11
C2031	2031	6	1		7/17/1981	JOSEPH PAUL MILLER ET UX	115
C2051	2051	6	1		7/17/1981	JOSHUA CREEK RANCH INC	2
C2051	2051	6	2		7/17/1981	JOSHUA CREEK RANCH INC	260
C2051	2051	6	3		7/17/1981	JOSHUA CREEK RANCH INC	
C1934	1934	6	1		7/17/1981	KATHY JAN FREEMAN	1.55
C1979	1979	6	1		7/17/1981	KEITH S MEADOW	18
C2042	2042	6	1		7/17/1981	KENDALL WATER SUPPLY	209
C2063	2063	6	4		7/17/1981	KENDALL WATER SUPPLY	3.06
C2049	2049	6	1		7/17/1981	KENNETH M & CYNTHIA RUSCH	5
P3896	3625	1	1	3896	1/3/1979	KENNETH W & MARCIA C MULFORD	
P3896	3625	1	2	3896	1/3/1979	KENNETH W & MARCIA C MULFORD	
C2026	2026	6	3		7/17/1981	KENNETH WHITEWOOD ET UX	1.225
C2026	2026	6	4		7/17/1981	KENNETH WHITEWOOD ET UX	52
C2026	2026	6	5		7/17/1981	KENNETH WHITEWOOD ET UX	100
C1999	1999	6	1		7/17/1981	KERRVILLE STATE HOSPITAL	
C1996	1996	6	1		7/17/1981	KERRVILLE, CITY OF	150
C1996	1996	6	2		7/17/1981	KERRVILLE, CITY OF	75
P5528	5528	1	1	5528	8/4/1995	KEVIN SCOTT PETERMANN ET UX	49
C1955	1955	6	1		7/17/1981	KRAUSE FAMILY LTD PARTNERSHIP	10
C2068	2068	6	1		7/17/1981	KWW RANCHES LTD	72
C2043	2043	6	3		7/17/1981	L J MANNERING ET UX	3.58
C2073	2073	6	1		7/17/1981	LAKE OF THE HILLS PROP OWNERS	
C2073	2073	6	2		7/17/1981	LAKE OF THE HILLS PROP OWNERS	
C2073	2073	6	3		7/17/1981	LAKE OF THE HILLS PROP OWNERS	
P5321	5321	1	1	5321	10/31/1991	LARRY J LANGBEIN	150
C1953	1953	6	1		7/17/1981	LAURA B LEWIS ET VIR	40
C1961	1961	6	1		7/17/1981	LAVERNE CRIDER MOORE ET VIR	3
C1961	1961	6	2		7/17/1981	LAVERNE CRIDER MOORE ET VIR	1
C1954	1954	6	1		7/17/1981	LAWRENCE D KRAUSE	5
C1954	1954	6	2		7/17/1981	LAWRENCE D KRAUSE	15

C1963	1963	6	1		7/17/1981	LAWRENCE L GRAHAM ET AL	2
C1963	1963	6	2		7/17/1981	LAWRENCE L GRAHAM ET AL	
C2062	2062	6	1		7/17/1981	LAYNE L PULS	30
C1991	1991	6	1		7/17/1981	LAZY HILLS GUEST RANCH INC	21
C2061	2061	6	3		7/17/1981	LEANING R RANCH FAMILY LTD PARTNERSHIP	15.65
C2018	2018	6	1		7/17/1981	LEE ANTHONY MOSTY	154
P5531	5531	1	1	5531	9/15/1995	LEE ROY COSPER ET UX	29.1
C2044	2044	6	1		7/17/1981	LION'S LAIR LLC	16.38
P5495	5495	1	1	5495	3/1/1995	LOIS & JOSEPH WESSENDORF ET AL	
P5541	5541	1	1	5541	2/16/1996	LONGCOPE FAMILY LTD	14
C1968	1968	6	1		7/17/1981	LOUIS DOMINGUES	10
C1939	1939	6	1		7/17/1981	LOUIS H STRUMBERG	3
C1938	1938	6	1		7/17/1981	LOUIS H STUMBERG	2
C1938	1938	6	2		7/17/1981	LOUIS H STUMBERG	15
C2008	2008	6	1		7/17/1981	LUTHERAN CAMP CHRYSALIS	11
C2438	2438	6	1		3/8/1983	LUTZ ISSLIEB ET AL	26.55
C1994	1994	6	1		7/17/1981	M H & MARY FRANCES MONTGOMERY	5
C2061	2061	6	2		7/17/1981	MARJORIE RANZAU INGENHUETT	17.61
C2056	2056	6	1		7/17/1981	MARK E WATSON JR ET UX	20
C2057	2057	6	1		7/17/1981	MARK E WATSON JR ET UX	25
P5641	5641	1	1	5641	5/15/2001	MARLIN R MARCUM	1
C2045	2045	6	1		7/17/1981	MARSHALL STEVES	8
C2043	2043	6	1		7/17/1981	MARY LEE EDWARDS	19.57
P5521	5521	1	1	5521	5/22/1995	MEYERSTEIN FAMILY TRUST	30
C1984	1984	6	1		7/17/1981	MICHAEL E & GAIL SEARS	1
C1983	1983	6	1		7/17/1981	N V MAMIMAR	32
C1983	1983	6	2		7/17/1981	N V MAMIMAR	67
C2058	2058	6	1		7/17/1981	OTTO KASTEN	16.53
C2037	2037	6	4		7/17/1981	OWNER VERIFIED BUT PENDING	5
C2063	2063	6	5		7/17/1981	OWNERSHIP UNVERIFIED	37.91
C2030	2030	6	4		7/17/1981	OWNERSHIP VERIFIED BUT PENDING	58.14
C2063	2063	6	2		7/17/1981	OWNERSHIP VERIFIED BUT PENDING	22.71
C2044	2044	6	2		7/17/1981	PATRICIA GALT STEVES	1.62
C2061	2061	6	1		7/17/1981	PATRICK DAVID VANDERWILT ET UX	36.74
P4007	3714	1	1	4007	1/22/1980	PECAN VALLEY RANCH OWNERS ASSN	
C1932	1932	6	1		7/17/1981	PRESBYTERIAN MO-RANCH ASSEMBLY	60
C1932	1932	6	2		7/17/1981	PRESBYTERIAN MO-RANCH ASSEMBLY	14
C1932	1932	6	3		7/17/1981	PRESBYTERIAN MO-RANCH ASSEMBLY	
C1932	1932	6	4		7/17/1981	PRESBYTERIAN MO-RANCH ASSEMBLY	5
P4607	4291	1	1	4607	1/30/1986	PURALLOY INC	50
C2006	2006	6	1		7/17/1981	R B COLVIN	104.16
C2006	2006	6	2		7/17/1981	R B COLVIN	
C2006	2006	6	3		7/17/1981	R B COLVIN	
C2006	2006	6	4		7/17/1981	R B COLVIN	48.84

C2059	2059	6	1		7/17/1981	RANCH BRANCH LLC	39
C2052	2052	6	1		7/17/1981	RANCHO KENDALL INC	232
C2021	2021	6	1		7/17/1981	RAYMOND F MOSTY ET AL	102.66
C1957	1957	6	1		7/17/1981	RAYMOND M BOWEN JR ET AL	
C1987	1987	6	1		7/17/1981	REGINALD E WARREN JR	90
C2023	2023	6	1		7/17/1981	RICHARD A GREEN ET UX	7
C1992	1992	6	1		7/17/1981	RICHARD A SMITH ET UX	13.1
C1943	1943	6	1		7/17/1981	RIO NORTE LTD	14
C1956	1956	6	1		7/17/1981	RIVER INN ASSN OF UNIT OWNERS	
C1956	1956	6	2		7/17/1981	RIVER INN ASSN OF UNIT OWNERS	10
C2000	2000	6	1		7/17/1981	RIVERHILL COUNTRY CLUB INC	135
C2000	2000	6	2		7/17/1981	RIVERHILL COUNTRY CLUB INC	215
C2050	2050	6	5		7/17/1981	ROBERT & MARGARET STEVEN (UNVERIFIED)	16.58
P5331	5331	1	1	5331	3/19/1991	ROBERT E BARTELL ET AL	15
P5331	5331	1	2	5331	3/19/1991	ROBERT E BARTELL ET AL	
P5331	5331	1	3	5331	3/19/1991	ROBERT E BARTELL ET AL	86
P5737	5737	1	1	5737	9/23/2002	ROBERT E SIEKER ET AL	1
C2450	2450	6	1		3/8/1983	ROBERT L MOSTY JR	80
C2450	2450	6	2		3/8/1983	ROBERT L MOSTY JR	78
C2027	2027	6	1		7/17/1981	ROBERT L PARKER SR ET AL	8
P3825	3567	1	1	3825	5/2/1978	ROBERT L PARKER SR ET AL	
P5125	5125	1	1	5125	3/14/1988	ROBERT L SCHWARZ	40
C2022	2022	6	3		7/17/1981	ROBERT LEE MOSTY JR	
C2022	2022	6	1		7/17/1981	ROBERT LEE MOSTY JR ET AL	17
C1935	1935	6	1		7/17/1981	ROBERT P MICHEL ET UX	8.45
C1935	1935	6	2		7/17/1981	ROBERT P MICHEL ET UX	6.33
C2037	2037	6	3		7/17/1981	ROMAN Q LUNA ET UX	10
C2026	2026	6	2		7/17/1981	RONNIE W SCHLOTTMAN ET UX	17.83
C2001	2001	6	1		7/17/1981	ROSEMARY HUNT MEEK	41
C2001	2001	6	2		7/17/1981	ROSEMARY HUNT MEEK	100
C2001	2001	6	3		7/17/1981	ROSEMARY HUNT MEEK	154
C2012	2012	6	1		7/17/1981	SANDRA BLAIR	1
C1982	1982	6	1		7/17/1981	SAVOY LTD	133
P4223	4100	1	1	4223	4/18/1984	SHELTON RANCHES INC	20
C1973	1973	6	1		7/17/1981	SHELTON RANCHES INC	10
C1974	1974	6	1		7/17/1981	SHELTON RANCHES INC	70
P4034	3743	1	1	4034	7/8/1980	SHELTON RANCHES INC	
P4230	3925	1	1	4230	12/1/1982	SHIRLEY ANN BEZDEK	
C2441	2441	6	1		3/8/1983	SILAS B RAGSDALE	21
P5647	5647	1	1	5647	7/19/2002	SOUTHERLAND PROPERTIES INC	350
P5647	5647	1	2	5647	7/19/2002	SOUTHERLAND PROPERTIES INC	
P5528	5528	1	2	5528	8/4/1995	STEVES BROTHERS	49
C2442	2442	6	1		3/8/1983	SUMMER DREAMS	28
C2442	2442	6	2		3/8/1983	SUMMER DREAMS	

C2062	2062	6	2		7/17/1981	SUSAN J PULS	30
C2048	2048	6	1		7/17/1981	SUSAN ROSE DURDEN	100
C2041	2041	6	1		7/17/1981	SUSSEX PARTNERS LTD	25
C2041	2041	6	2		7/17/1981	SUSSEX PARTNERS LTD	45
C2064	2064	6	2		7/17/1981	SYBIL R JONES CO-TRUSTEE ET AL	7.62
C1985	1985	6	1		7/17/1981	T & L CAUTHEN LLC	80
P3846	3651	1	1	3846	2/27/1979	T & R PROPERTIES	
C1977	1977	6	1		7/17/1981	TEXAS CATHOLIC BOYS CAMP	23
C1975	1975	6	1		7/17/1981	TEXAS PARKS & WILDLIFE DEPT	400
C1975	1975	6	2		7/17/1981	TEXAS PARKS & WILDLIFE DEPT	5380
P4106	4125	1	1	4106	7/10/1984	TEXAS PARKS & WILDLIFE DEPT	25
P4486	4181	1	2	4486	2/1/1985	THOMAS D POTH	25.38
P5402	5402	1	1	5402	1/16/1992	TURTLE CREEK INDUSTRIES INC	
C2067	2067	6	1		7/17/1981	TY RAMPY ET AL	20
C2067	2067	6	2		7/17/1981	TY RAMPY ET AL	20
P5394	5394	1	1	5394	10/12/1993	UPPER GUADALUPE RIVER AUTHORITY	1661
P5394	5394	1	2	5394	10/12/1993	UPPER GUADALUPE RIVER AUTHORITY	339
P5394	5394	1	3	5394	10/12/1993	UPPER GUADALUPE RIVER AUTHORITY	
P5394	5394	1	4	5394	10/12/1993	UPPER GUADALUPE RIVER AUTHORITY	
C2032	2032	6	1		7/17/1981	VERA L SALVATORE	10
C1964	1964	6	1		7/17/1981	VIRGINIA MOORE JOHNSTON	10
C2029	2029	6	1		7/17/1981	WALTERS INVESTMENTS LP	25
C2029	2029	6	2		7/17/1981	WALTERS INVESTMENTS LP	16.29
C2037	2037	6	6		7/17/1981	WAYNE KLEIN ET UX	0.54
C1972	1972	6	2		7/17/1981	WELCH CREEK PARTNERS LTD	5.15
C2037	2037	6	5		7/17/1981	WERNER WAYNE ALLERKAMP	5
C1993	1993	6	1		7/17/1981	WES H WAGNER ET AL	50
C1972	1972	6	1		7/17/1981	WESLEY ELLEBRACHT	0.8
C2003	2003	6	1		7/17/1981	WHEATCRAFT INC	52
C2003	2003	6	2		7/17/1981	WHEATCRAFT INC	
C2024	2024	6	1		7/17/1981	WHEATCRAFT INC	114
C2024	2024	6	2		7/17/1981	WHEATCRAFT INC	
C3816	3816	6	1		7/16/1985	WHITEWATER SPORTS INC	1460
C3816	3816	6	2		7/16/1985	WHITEWATER SPORTS INC	
C2011	2011	6	1		7/17/1981	WILLIAM ALAN GRUY	80
C2009	2009	6	1		7/17/1981	WILLIAM C NORTON ET UX	5
C2046	2046	6	1		7/17/1981	WILLIAM G & MILDRED D SPROWLS	28
P5534	5534	1	1	5534	12/15/1995	WILLIAM G JOHNSON III ET AL	20
C1936	1936	6	1		7/17/1981	WILLIAM I HENDERSON ET AL	17
C1936	1936	6	2		7/17/1981	WILLIAM I HENDERSON ET AL	134
C1949	1949	6	1		7/17/1981	WILLIAM O CARTER TRUSTEE	6
C1949	1949	6	2		7/17/1981	WILLIAM O CARTER TRUSTEE	27
C2026	2026	6	1		7/17/1981	ZANE H ROBINSON ET UX	53.945

KERR COUNTY LITHOLOGIC LOGS

ALL SAMPLES WERE OBTAINED AT 10' INTERVALS AND EXAMINED WITH A STEREO ZOOM MICROSCOPE BY THE AUTHOR. DETAILED LOGS ARE AVAILABLE AT THE HGCD OFFICE IN KERRVILLE, TEXAS.


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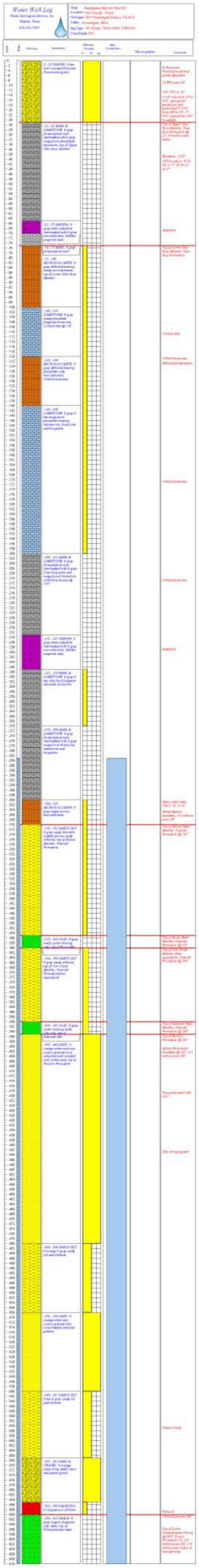
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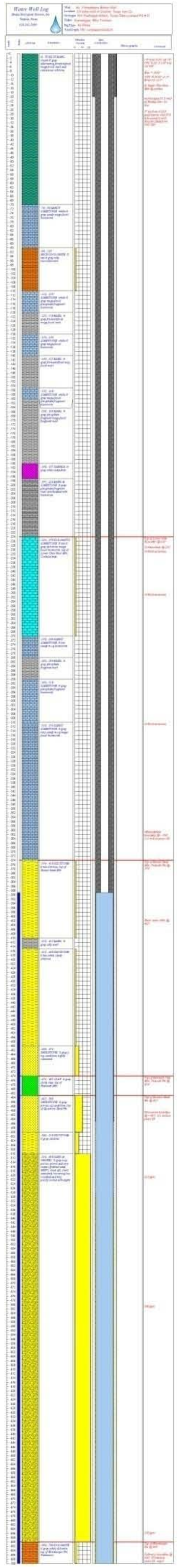
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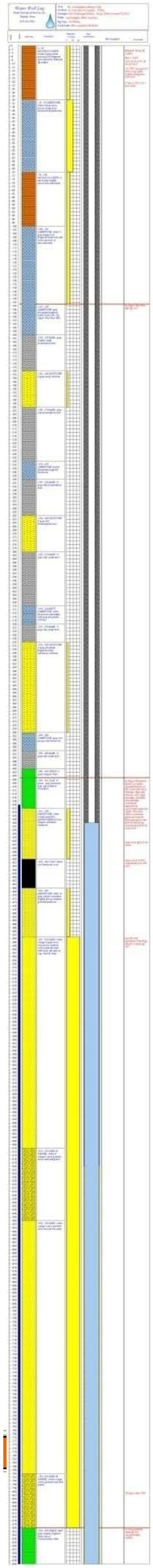
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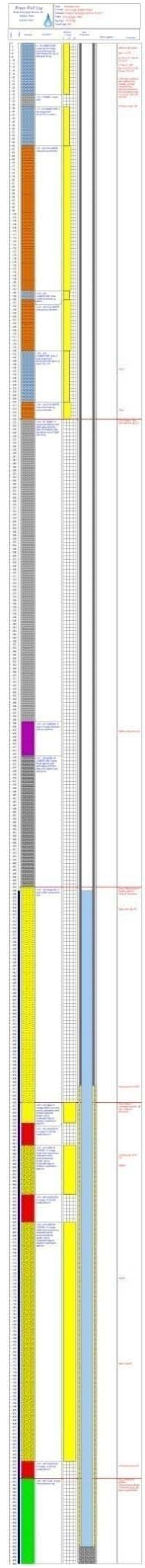
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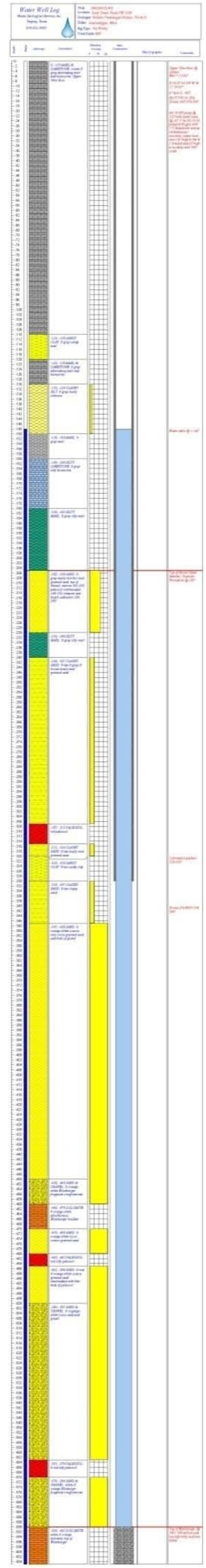
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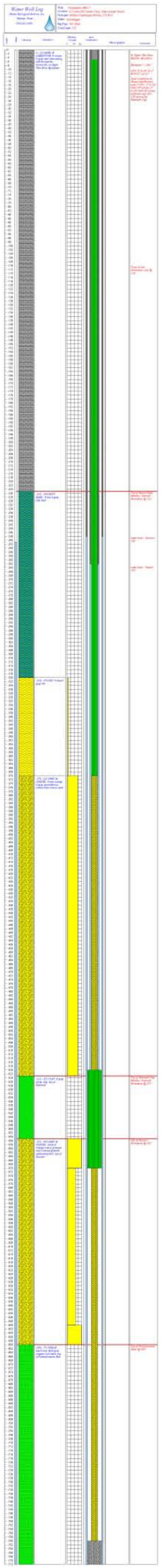
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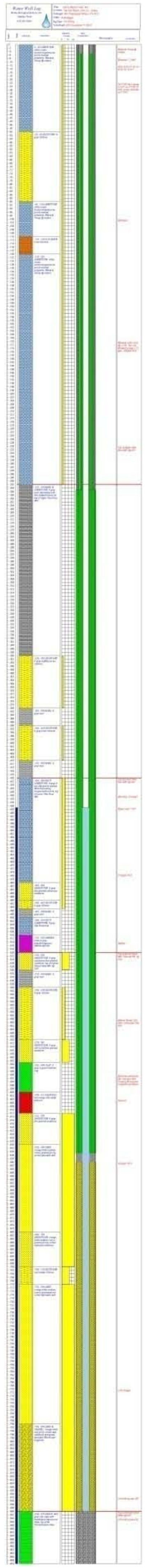
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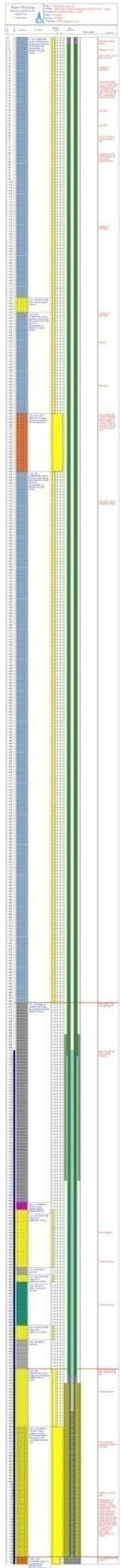
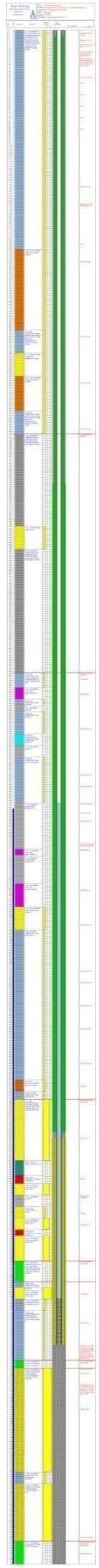
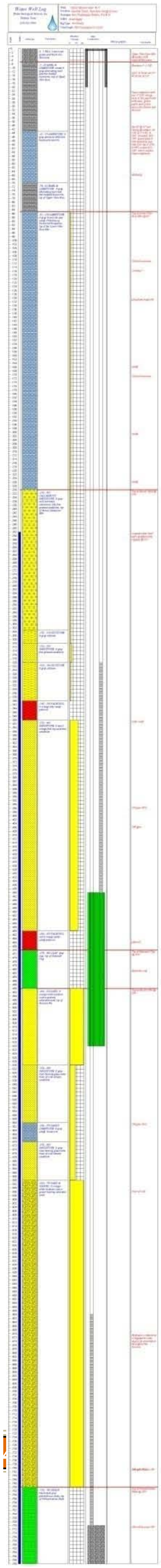
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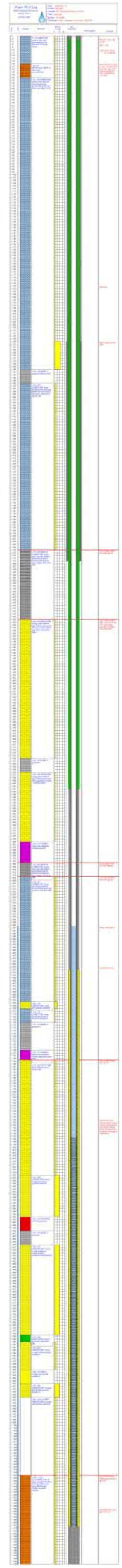
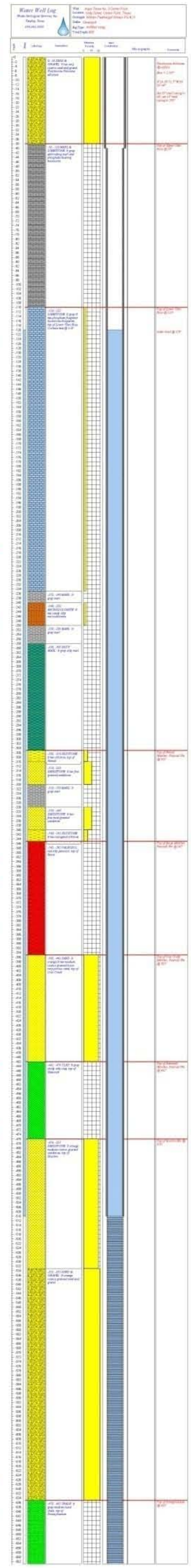
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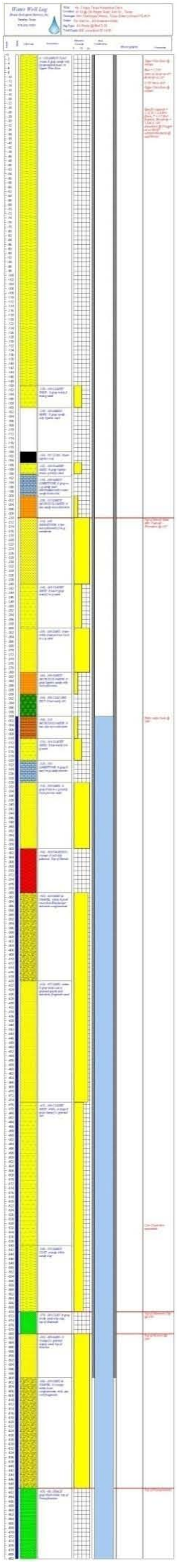
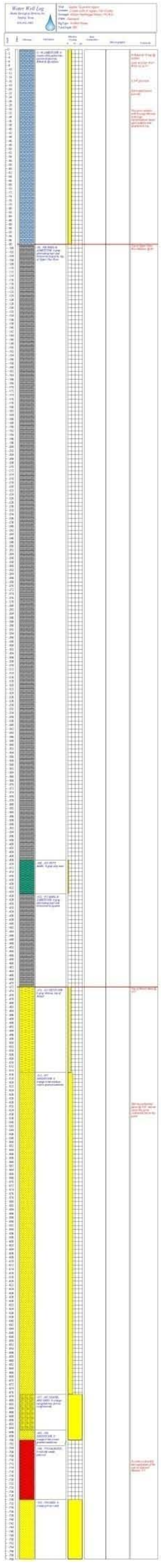
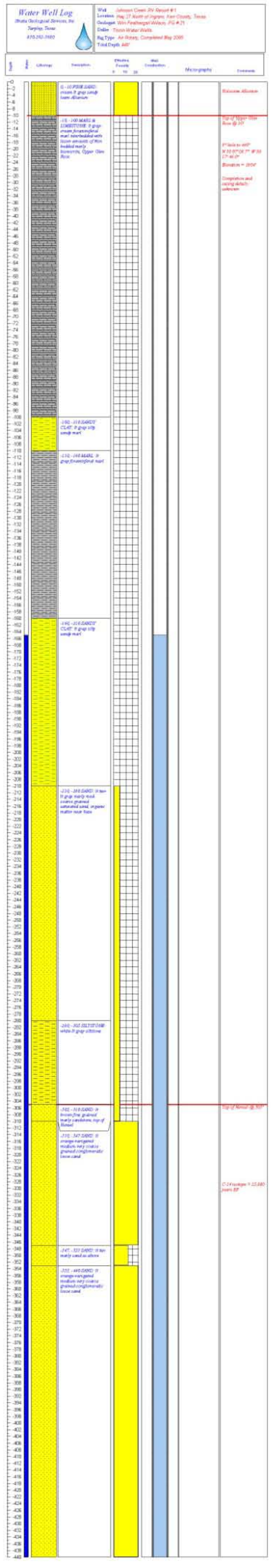
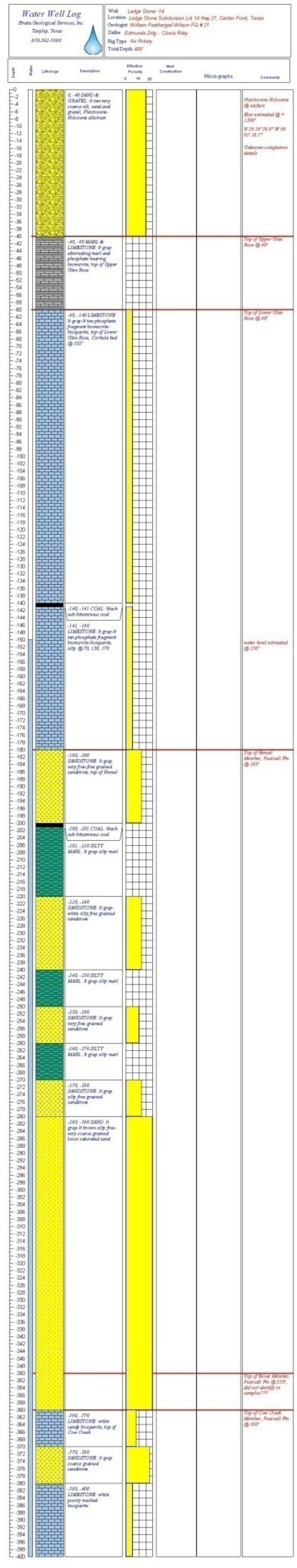
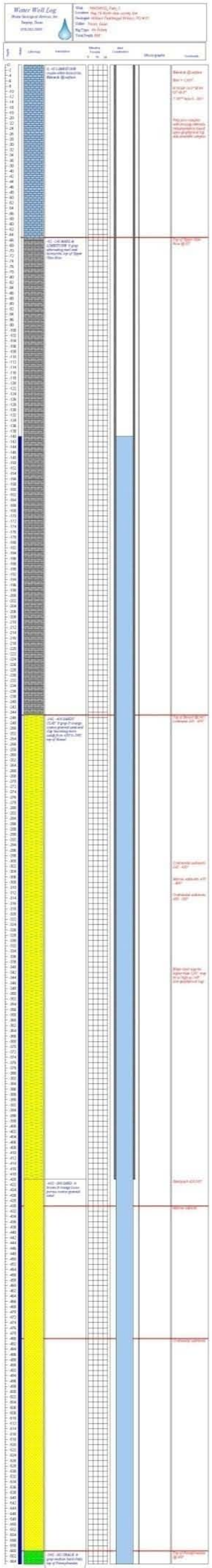





Water Well Log
Well
Location
Geologist
Driller
Rig Type
Total Depth
Depth
Water
Lithology
Description
Effective Porosity
0 10 20
Well Construction
Micro-graphs
Comments
Holocene Alluvium


Water Well Log
Strata Geological Services, Inc.
Tarpley, Texas
830-562-3680
Well Ledge Stone -14
Location Ledge Stone Subdivision Lot 14 Hwy 27, Center Point, Texas
Geologist William Feathergail Wilson PG # 21
Driller Edmunds Drlg - Clovis Riley
Rig Type Air Rotary
Total Depth 400'
Depth
Water
Lithology
Description
Effective Porosity
0 10 20
Well Construction
Micro-graphs
Comments
0, -40 SAND & GRAVEL: lt tan very coarse silt, sand and gravel, Pleistocene-Holocene alluvium
Pleistocene-Holocene @ surface
Elev estimated @ = 1500'
N 29 56' 59.8" W 99 01' 28.1"
Unknown completion details
-40, -60 MARL & LIMESTONE: lt gray alternating marl and phosphate bearing biomicrite, top of Upper Glen Rose
Top of Upper Glen Rose @ 40'
-60, -140 LIMESTONE: lt gray-lt tan phosphate fragment biomicrite-biosparite, top of Lower Glen Rose, Corbula bed @ 105'
Top of Lower Glen Rose @ 60'
-140, -141 COAL: black sub-bituminous coal
-141, -180 LIMESTONE: lt gray-lt tan phosphate fragment biomicrite-biosparite, silty @ 70, 150, 170
water level estimated @ 150'
-180, -200 SANDSTONE: lt gray very fine-fine grained sandstone, top of Hensel
Top of Hensel Member, Pearsall Fm @ 180'
-200, -201 COAL: black sub-bituminous coal
-201, -220 SILTY MARL: lt gray silty marl
-220, -240 SANDSTONE: lt gray-white silty fine grained sandstone
-240, -250 SILTY MARL: lt gray silty marl
-250, -260 SANDSTONE: lt gray very fine grained sandstone
-260, -270 SILTY MARL: lt gray silty marl
-270, -280 SANDSTONE: lt gray silty fine grained sandstone
-280, -360 SAND: lt gray-lt brown silty fine-very coarse grained loose saturated sand
Top of Bexar Member, Pearsall Fm @ 350', did not identify in samples???
-360, -370 LIMESTONE: white sandy biosparite, top of Cow Creek
Top of Cow Creek Member, Pearsall Fm @ 360'
-370, -380 SANDSTONE: lt gray coarse grained sandstone
-380, -400 LIMESTONE: white poorly washed biosparite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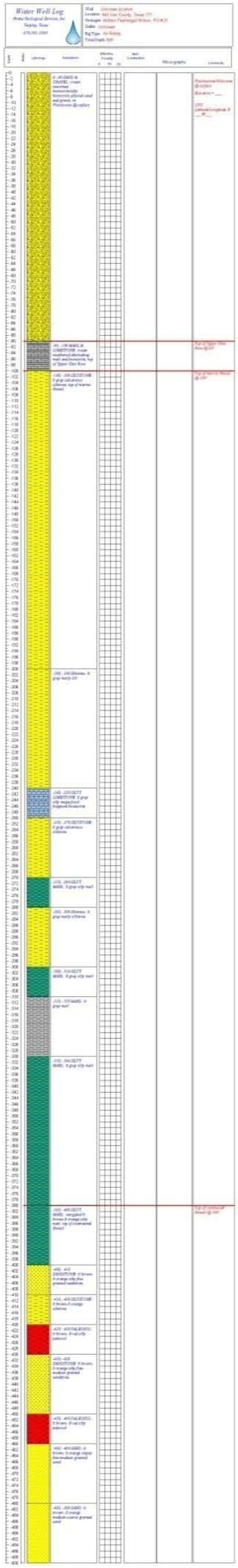
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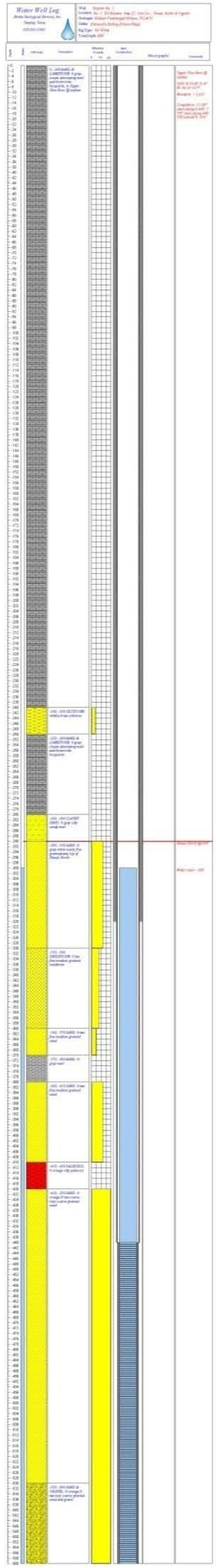
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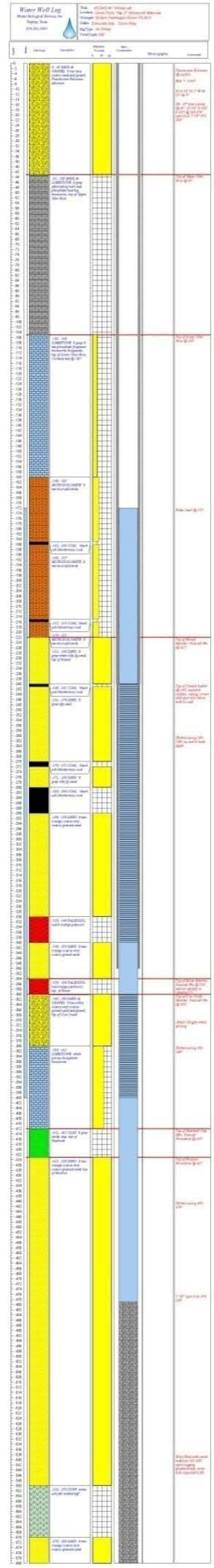
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