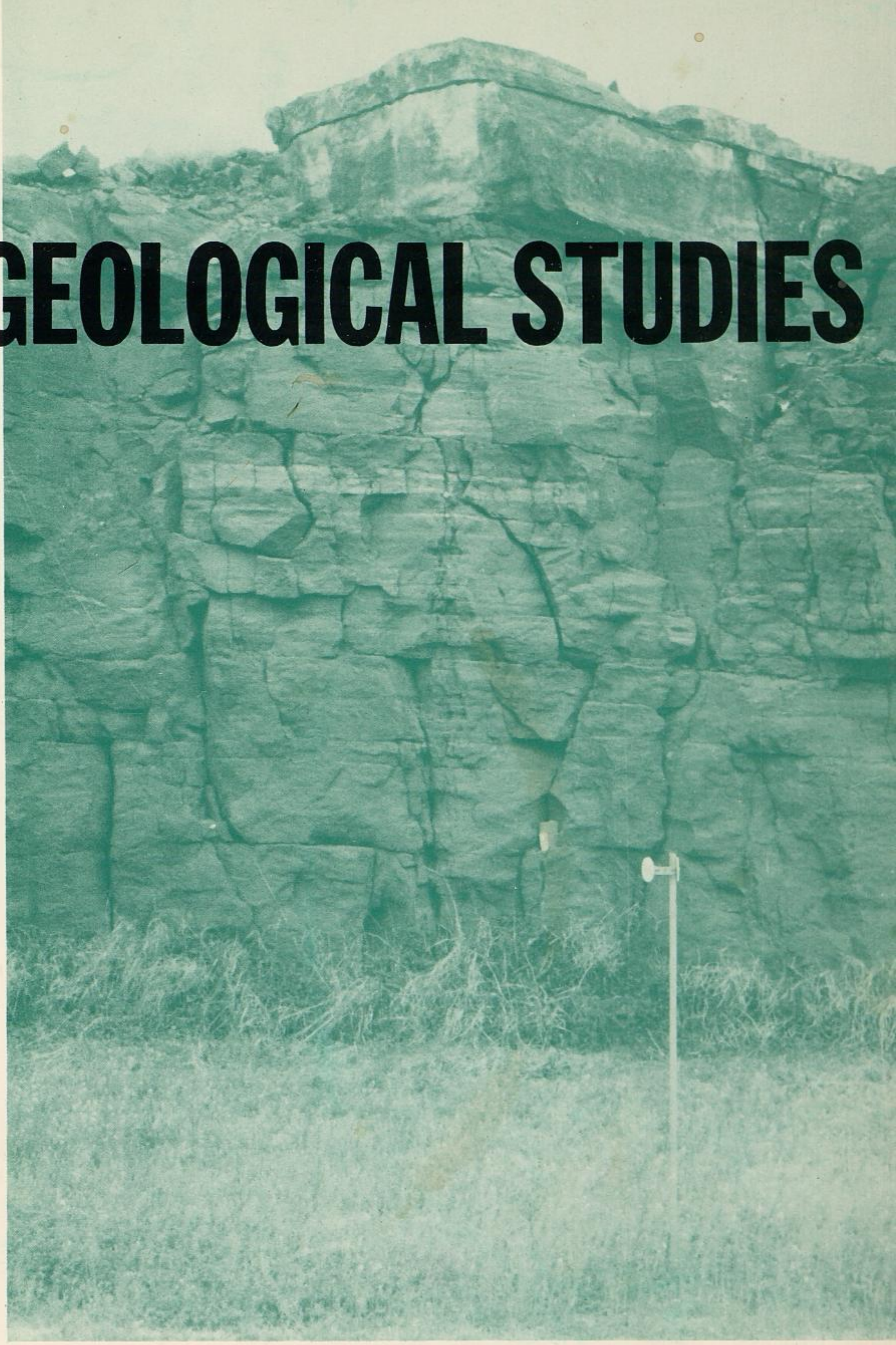
BAYLOR GEOLOGICAL STUDIES



SPRING 1991

Bulletin No. 51

BAYLOR UNIVERSITY - WACO, TEXAS
1845

Geology and Flow Systems of the Hickory Aquifer, San Saba County, Texas

ROBERT J. PETTIGREW, JR.

> *"Creative thinking is more important than elaborate equipment--"*
>
> FRANK CARNEY, PH.D.
> PROFESSOR OF GEOLOGY
> BAYLOR UNIVERSITY
> 1929-1934

Objectives of Geological Training at Baylor

The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

Cover: Upper Hickory Sandstone and overlying Cap Mountain. Limestone exposed in roadcut on U.S. Highway 71, 5 miles east of Valley Spring, Texas.

THE BAYLOR PRINTING SERVICE
WACO, TEXAS

BAYLOR GEOLOGICAL STUDIES

BULLETIN NO. 51

Geology and Flow Systems of the Hickory Aquifer, San Saba County, Texas

Robert J. Pettigrew, Jr.

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Spring 1991

Baylor Geological Studies

The Baylor Geological Studies Bulletin is published by the Department of Geology at Baylor University. The Bulletin is specifically dedicated to the dissemination of geologic knowledge for the benefit of the people of Texas. The publication is designed to present the results of both pure and applied research which will ultimately be important in the economic and cultural growth of the State.

ISSN 0005-7266

Additional copies of this bulletin can be obtained from the Department of Geology, Baylor University, Waco, Texas 76798.

CONTENTS

ILLUSTRATIONS

ABBREVIATIONS AND CONVERSIONS

C.I. - contour interval
cfs - cubic feet per second (2.832 x 10^{-2} m^3/s)
ft/ft - feet per foot (gradient)
gpd/ft - gallons per day per ft
gpd/ft (transmissivity), equal to 1.438 x $10^{-7}m^2s$ (SI)
gpd/ft-ft - gallons per day per foot per foot (hydraulic conductivity, referred to as permeability in this text), equal to 4.720 x $10^{-7}m/s$ (SI)
gpm - gallons per minute (6.309 x $10^{-5}m^3/s$)
msl - mean sea level
pCi/l - picocuries per liter
V.E. - vertical exaggeration

Geology and Flow Systems of the Hickory Aquifer, San Saba County, Texas

Robert J. Pettigrew, Jr.

ABSTRACT

Little is known about the Hickory aquifer in the highly faulted San Saba County area. The aquifer is composed of the Hickory Member of the Cambrian Riley Formation. It overlies an unconformity on the Precambrian rocks which causes the Hickory to regionally thin in eastern San Saba County, locally thin over a ridge on the unconformity northeast of Pontotoc, and locally thicken in a valley on the unconformity around Cherokee.

The Hickory has three distinct facies. The lower, crossbedded, coarse-to-medium-grained facies has an estimated outcrop permeability of 200 to 300 gpd/ft/ft. The middle facies is composed of interbedded sand and shaly sand, has an estimated permeability of less than 30 gpd/ft/ft, and is vertically anisotropic. The upper facies is variably cemented with hematite and appears to have a permeability equal to or greater than the middle facies. The permeability of the upper facies may decrease downdip due to increased cementation and compaction.

The study area is on the northeastern flank of the Llano Uplift. Normal faults with large displacement create two major structural axes separated by a graben. The structure of these axes controls two major flow systems. Faults appear to act as either boundaries or zones of discharge for flow into juxtaposed overlying aquifers. Flow becomes stagnant in northern San Saba County.

In the Hickory outcrop areas around Pontotoc and north of Valley Spring, flow is southward into the fractured Precambrian rocks and mimics topography. In the Hickory outcrop area south of Cherokee, flow is northeastward and into the downdip aquifer.

The study supplies important background information to the Hickory Underground Water Conservation District. It indicates the complexity of the aquifer flow systems and has implications for several areas of acquifer management including well spacing, groundwater exploration, and water quality control.

INTRODUCTION*

PURPOSE

The Hickory aquifer supplies a majority of the groundwater used within parts of McCulloch, San Saba, Mason, Menard, Concho, and Kimble Counties of Texas. In 1982, the Hickory Underground Water Conservation District was formed in order to manage this groundwater resource more efficiently. The district needs general information about the Hickory aquifer, especially in the San Saba County area. This study combines geologic, physiographic and hydrologic data to describe the physical characteristics and flow systems of the Hickory aquifer in the San Saba County area and provides a framework for aquifer management.

LOCATION

CULTURAL

The study area covers most of San Saba and parts of Mason and Llano Counties of Texas (Fig. 1). It includes the eastern portion of the Hickory Underground Water Conservation District #1 and adjacent areas.

There are seven towns within the study area (Fig. 2). They are given with their 1980 census population: San Saba—2,847; Richland Springs—420; Pontotoc—206; Cherokee—175; Bend—115; Fredonia—75; and Valley Spring—50. Residents of Cherokee and Pontotoc depend on water from the Hickory aquifer obtained through individual water wells. The North San Saba Water Supply Corporation depends on water from the Hickory aquifer obtained through a deep water well. The rest of the population within the study area obtains water from other sources.

---

*A thesis submitted in partial fulfillment for the M.S. degree in Geology, Baylor University, 1988.

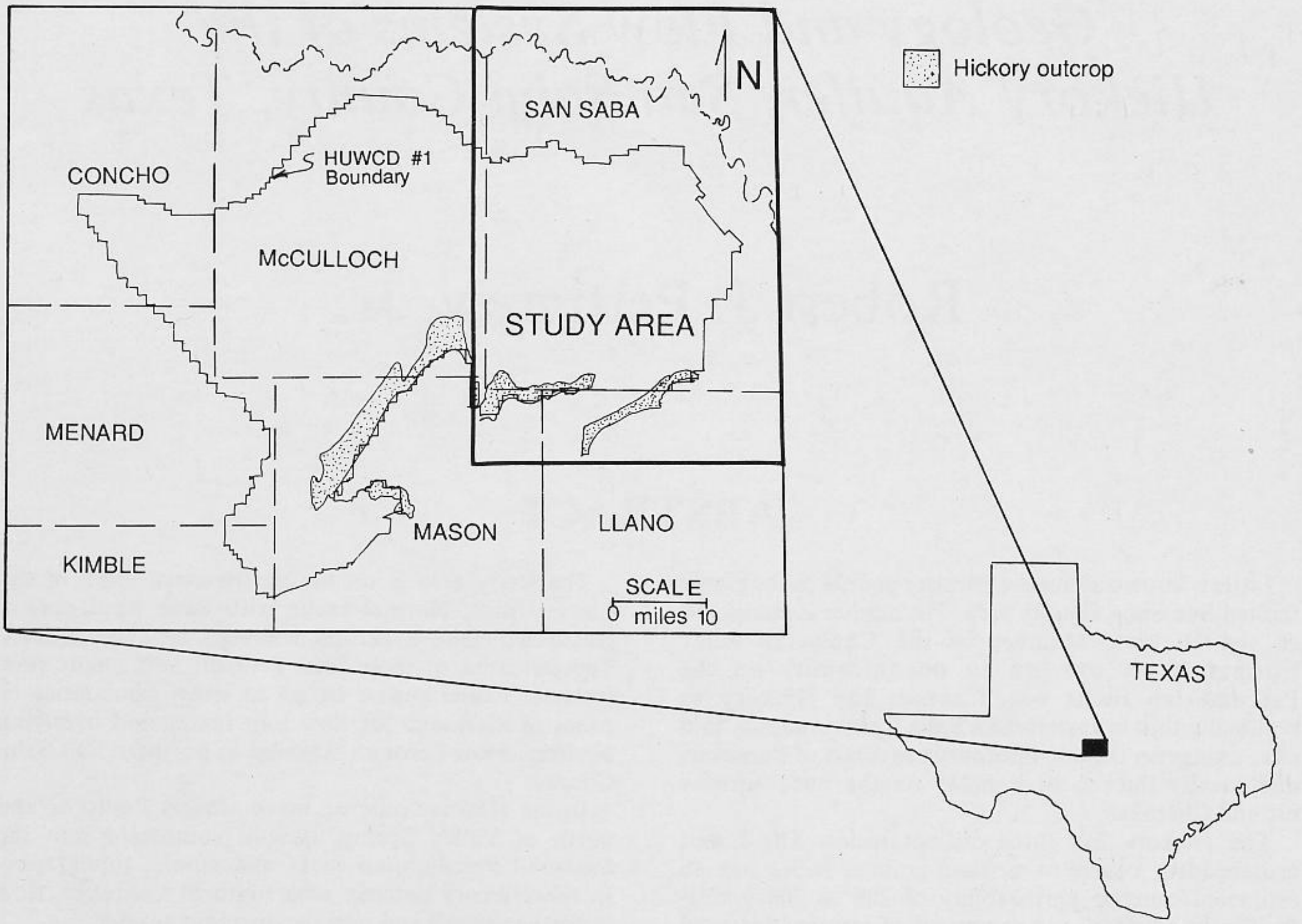


Fig. 1. Location map. The study area covers San Saba and parts of Mason and Llano Counties of Texas. It includes the eastern portion of the Hickory Underground Water Conservation District # 1 (HUWCD # 1) and adjacent areas.

Physiographic

Figure 2 shows the major drainage within the study area. The Colorado River is the major trunk stream in the region. It is fed by two eastward-flowing, perennial tributaries, the San Saba River and Cherokee Creek. In the southern part of the study area is the southward-flowing Llano River drainage. There are four major topograhic features near the Hickory outcrop area: the Pontotoc escarpment; Cold Creek escarpment; Valley Spring escarpment; and the Little Llano River valley.

Geologic

A large section of Paleozoic rocks crops out in the study area and ranges from Cambrian to Pennsylvanian in age (Fig. 3). Precambrian granite, gneiss, and schist are exposed on the southern end of the area and outliers of Cretaceous rocks exist on several high divides.

The study area is on the northeastern flank of the Llano Uplift and the southern end of the Fort Worth Basin (Fig. 4). It is east of the Ouachita Fold Belt. Strata dip northeastward into the Fort Worth Basin at a rate of 90 to 120 feet per mile. Generally northeast-striking, large-throw, normal faults create numerous horsts and grabens in the area.

Climatic

The average annual rainfall at the city of San Saba is 27.55 inches with the wettest part of the year in late spring and early fall (Larkin and Bomar, 1983; Fig. 5). However, the study occurred during an exceptionally dry period in which the total rainfall at San Saba from June 1987 to May 1988 was only 18.35 inches. The average annual pan evaporation is around 70 inches with the maximum potential for evaporation occurring in July and August (Larkin and Bomar, 1983; Fig. 5).

METHODS

A flow chart of steps involved in the development of this study is shown in Figure 6. Several different approaches were needed to obtain primary data about the aquifer. The most beneficial sources of information were well logs, water level measurements, chemical analyses, and topographic maps. In addition to the steps listed in Figure 6, a computer program developed by the author was used to create a cross-sectional, numerical model and is described in Appendix A. An equation derived by Sokol (1963) was used to calculate the head in the Hickory in multi-aquifer completed wells. An equation described by Logan (1964) was used to estimate

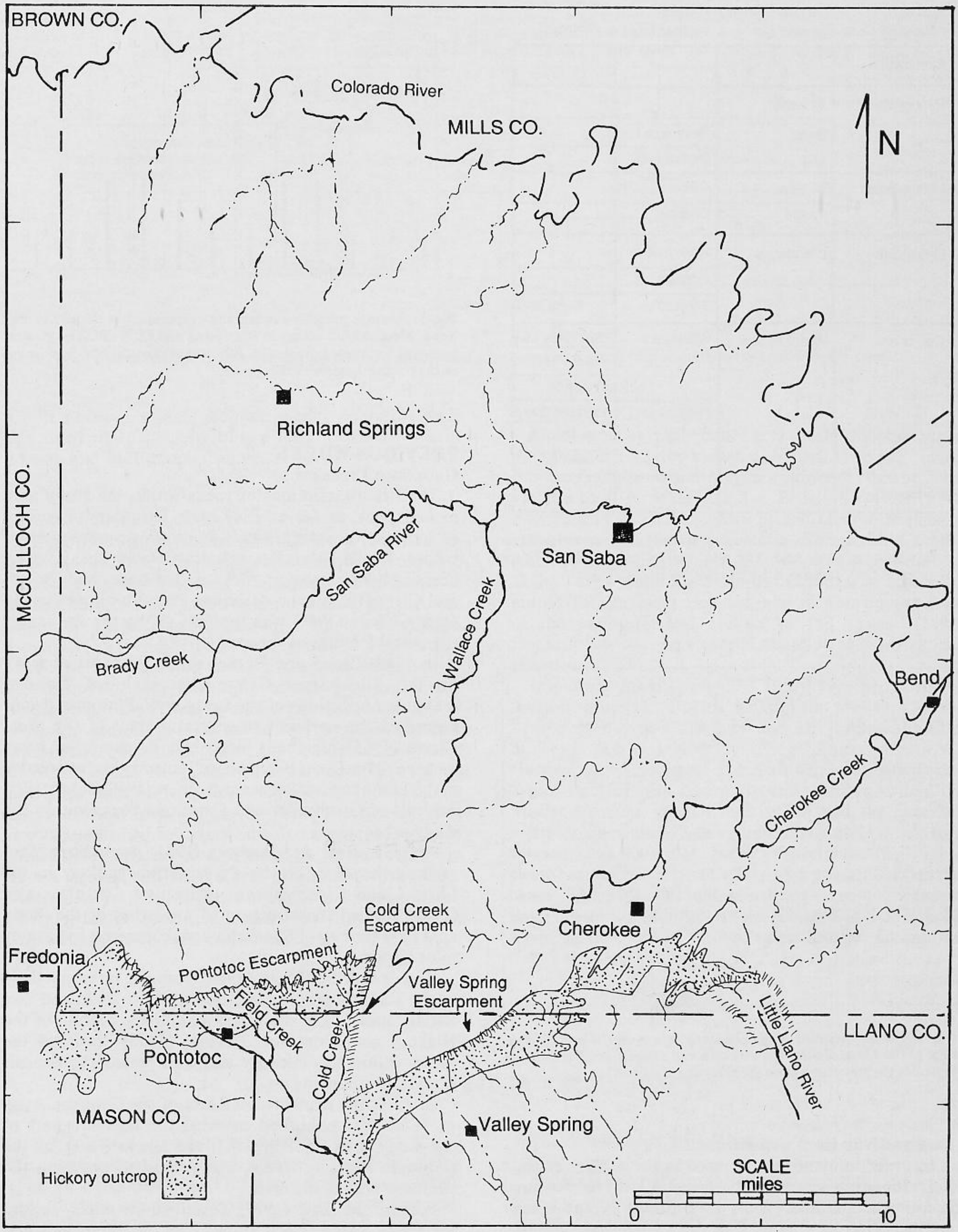


Fig. 2. Drainage map showing towns and topographic features. A drainage divide occurs in the southern part of the study area between San Saba River and Cherokee Creek drainage and southward-flowing Llano River drainage.

AGE	STRATIGRAPHIC UNITS GROUP	FORMATION	MEMBER
Cretaceous			
Pennsylvanian	Strawn		
	Bend	Smithwick	
		Marble Falls	
Mississippian	Chester	Barnett	
	Osage	Chappel	
Ordovician	Ellenburger	Honeycut	
		Gorman	
		Tanyard	
Cambrian	Moore Hollow	Wilberns	San Saba Ls.
			Point Peak Sh.
			Welge Ss.
		Riley	Lion Mtn. Ss.
			Cap Mtn. Ls.
			Hickory Ss.
Precambrian			

Fig. 3. Stratigraphic column showing the nomenclature of geologic units within the study area. The main unit of study is the Hickory Member of the Cambrian Riley Formation.

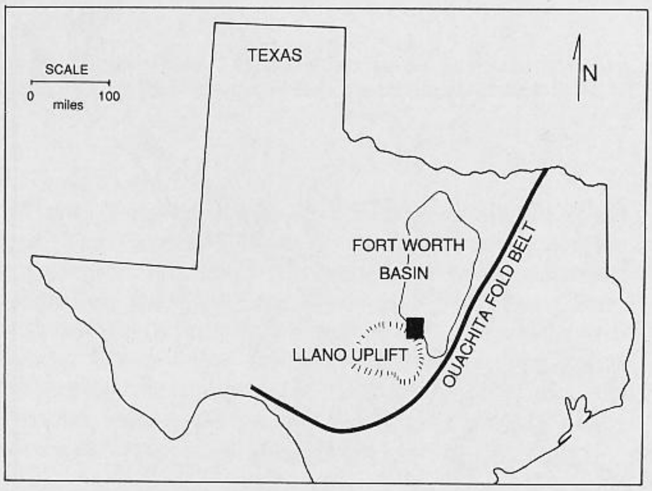


Fig. 4. Tectonic location map. The study area is on the northeastern edge of the Llano Uplift. The southern end of the Fort Worth Basin separates the study area from the Ouachita Fold Belt.

transmissivity from well yield.

In order to identify wells used in the study, the state well numbering system of the Texas Water Development Board was adapted. Wells inventoried by the author are identified by a letter P as the next-to-last digit. An explanation of the well numbering is included in Appendix B.

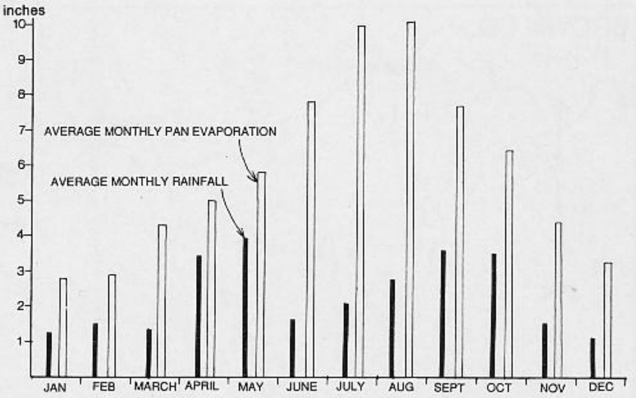


Fig. 5. Average monthly rainfall and evaporation at the city of San Saba. Most rainfall occurs in late spring and early fall. The greatest potential for evaporation is in July and August. (Data from maps in Larkin and Bomar, 1983.)

PREVIOUS WORKS

Geologic Literature

The first descriptions of rocks within the study area extend back as far as 1849 with Ferdinand Roemer. A number of stratigraphic descriptions were written before World War II, including Paige (1911), who described Precambrian rocks in the area, and Bridge and Girty (1937), who described Paleozoic rocks in the area. Cheney (1940) was the first to discuss the major structural features in the area.

In 1948, Cloud and Barnes produced a major work on the Ellenburger Group that included detailed mapping of portions of the study area. Plummer (1950) described the carboniferous stratigraphy of the area. Flawn (1956) regionally described Precambrian basement rocks in Texas based on well cuttings and exposures in the Llano region. Barnes and others (1959) did detailed analysis of Ordovician and Cambrian rocks within the study area.

Almy, Lidiak, and Rodgers (1961) used geophysical methods to describe the Precambrian geology in the Little Llano River valley southeast of Cherokee. Orr (1962) studied the structure of a portion of the study area near the city of San Saba and recognized five major joint trends.

Barnes and Schofield (1964) mapped large portions of the Hickory outcrop in Mason, McCulloch, and San Saba Counties and described a complete section of the Hickory near Pontotoc. Cornish (1975) described the facies within the Hickory and interpreted the depositional environments.

In 1976, the Brownwood Sheet of the Geologic Atlas of Texas was published covering the northern part of the study area and, in 1981, the Llano Sheet of the Geologic Atlas of Texas was published covering the southern part of the area.

Barnes and Bell (1977) described in detail several vertical sections of the Hickory in an extensive study of the Cambrian section. Walper (1982) summarized the tectonic evolution of the Fort Worth Basin and the Llano

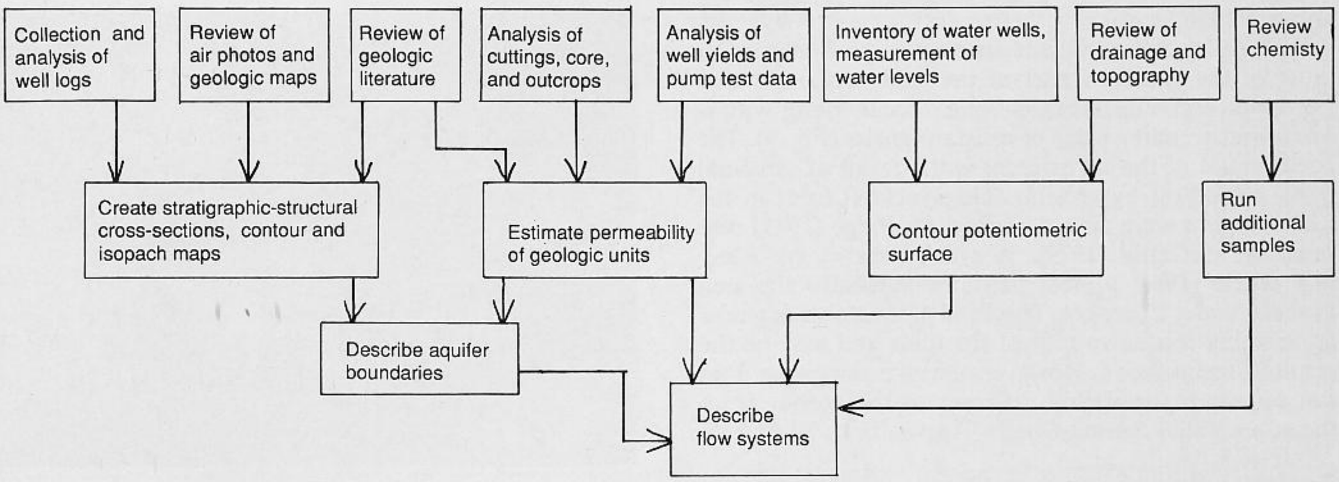


Fig. 6. Flow chart of methods. Geologic, hydrologic and chemical data were collected and analyzed to describe the aquifer flow systems.

Uplift utilizing a plate tectonic model. El-Jard (1982) described the diagenesis of the Hickory Sandstone in Mason and McCulloch Counties.

HYDROLOGIC LITERATURE

Mason (1961) studied the Hickory aquifer in McCulloch County, reporting transmissivities from nine aquifer tests and mapping the general potentiometric surface. Sokol (1963) derived an equation to calculate composite heads from multi-aquifer completed wells and Logan (1964) described a method of estimating transmissivity from well yields. Freeze and Witherspoon (1966) developed a governing equation to evaluate a steady state flow system by numerical methods.

Mount and others (1967) described the major aquifers within the study area as part of a regional reconnaissance of the Colorado River basin. Landers and Turk (1973) presented data on well yields and depths in crystalline rocks in the Llano region. In 1974, Richard Preston drew unpublished aquifer delineation maps for the Texas Water Development Board showing depths to the top of the aquifer and the general potentiometric surface. Black (1988) studied the Hickory aquifer contemporaneously with this study and described flow systems in Mason and McCulloch Counties.

ACKNOWLEDGMENTS

The following individuals generously supplied data for this study: Taylor Virdell of Virdell Drilling, Llano; Bill Jacob of Jacob and Martin Engineers, Abilene; Mr. Watson of J. L. Myers, Dallas; Felicia Boyd of R. W. Harden and Associates, Austin; and George Epperson and Joe Allen Robertson, two San Saba County landowners. Much appreciation goes to Bob Bluntzer of the Texas Water Development Board, who approved money for chemical analyses, and to Jim Boyer, chief of the environmental section of the Texas Health Department, who gave special attention to the chemical analyses.

Important insights into the study were provided by the following: Dr. Robert C. Grayson and Dr. W. G. Brown of Baylor University and Dr. Brann Johnson of Texas A&M University; Ridge Kaiser of R. W. Harden and Associates; and Dan Muller of the Texas Water Development Board. Special thanks goes to Dan Muller for time spent in the office and the field on methodologies used in this study. The author would like to especially thank Dr. Joe C. Yelderman, Jr., for his contributions to the field study and preparation of the thesis. The author would also like to especially thank Rick Illgner for his help with the project and the Hickory Underground Water Conservation District Board for their financial support.

GEOLOGIC FRAMEWORK

The Hickory Sandstone is underlain by Precambrian rocks and overlain by a thick section of Paleozoic rocks. (Fig. 7). All of these rocks influence flow systems within the Hickory aquifer. Therefore, this section describes and relates the lithologic, stratigraphic, and hydrologic characteristics of the Hickory Sandstone and of the underlying and overlying rock units.

PRECAMBRIAN ROCKS

LITHOLOGY

Precambrian rocks in the study area include the Valley Spring Gneiss which is a light-colored, pinkish, quartzofeldspathic rock (Fig. 8), the Packsaddle Schist which is a dark-colored mica and amphibolite schist with some marble, and various coarse-grained granites

(Flawn, 1956, p. 26).

The Valley Spring Gneiss outcrop and subcrop cover most of the southern part of the study area, but two northwest-trending areas of schist occur along with a northwest-trending ridge of resistant gneiss (Fig. 9). The linear trend of the schist areas is the result of synclinal folds planed-off by erosion. The synclinal folds in the Llano region were first described by Paige (1911) and later by McGehee (1979). A gravity survey by Almy and others (1961, p. 468) partially delineated the area of schist under Cherokee. The trend of the resistant gneiss is probably related to that of the folds and may be the result of an intrusion. However, the resistant gneiss does not appear to be visibly different to the author from the other Valley Spring Gneiss (Appendix C, 57-01-8a).

Fracture Permeability and Porosity

Permeability within the Precambrian rocks is created by weathering fractures (Fig. 8). The fractures extend to between 75 and 100 feet below the land surface (Landers and Turk, 1973, p. 7). The fracturing may increase around faulting and be affected by the lithology of the rock. The large number of wells completed in the Precambrian rocks and a median well yield of 14 gpm show that significant amounts of water can be transmitted by the rocks (Landers and Turk, 1973, p. 5).

Because of weathering on the Precambrian unconformity, a significant amount of fracture permeability is believed to exist in the Precambrian rocks under the Paleozoic cover. Although the Precambrian rocks have been deeply buried, the fractures may not be completely closed.

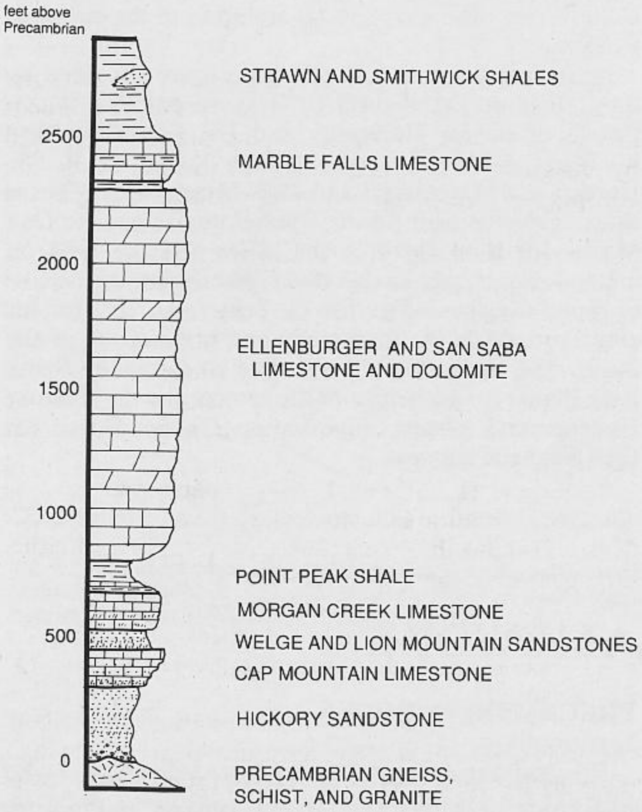


Fig. 7. Weathering profile showing lithology and thickness of the Paleozoic rocks above the Precambrian unconformity.

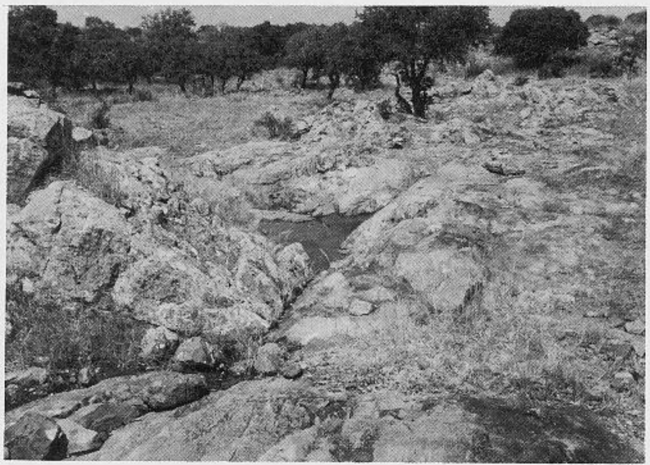


Fig. 8. Photograph of the Valley Spring Gneiss. The gneiss is usually pink colored, fine-grained and quartzofeldspathic. Photo taken at Bush Spring just south of the Hickory outcrop suggesting that water from the Hickory flows into fractures in the Precambrian rocks (App. C, Locality 57-01-5a).

The effective porosity within the Precambrian rocks is also created by weathering fractures. The fractures do not appear closely spaced in most outcrops, suggesting a low effective porosity. The low porosity is evident in comparing the difference in decline in water levels in a Hickory well and a Precambrian well in the same vicinity. From October 1987 to May 1988, a Hickory well (57-02-8P2) declined 1.2 feet while a Precambrian well (57-02-8P1) declined 22.2 feet. The wells were both in the recharge area of a flow system that discharges southward through Precambrian rocks, suggesting that the net difference in recharge and discharge in the area around the two wells is approximately the same. The difference in the water level fluctuations thus appears to be a result of differences in effective porosity. Based on the difference in water level fluctuation, the effective porosity of the Precambrian rocks may be at an order of magnitude less than the Hickory Sandstone. Assuming a 20 percent porosity for the Hickory, the effective porosity of the fractured Precambrian rocks would be less than 2 percent. This agrees with previously estimated porosities for fractured metamorphic rocks (Lewis and others, 1966, p. 533). Although Precambrian rocks can transmit significant amounts of water to or from the overlying Hickory, they have a low specific storage.

HICKORY SANDSTONE

Thickness

Figure 10 is an isopach map of the Hickory Sandstone. Because of the relief on the Precambrian unconformity, the thickness of the Hickory is locally variable but averages 350 feet through most of the area. The Hickory

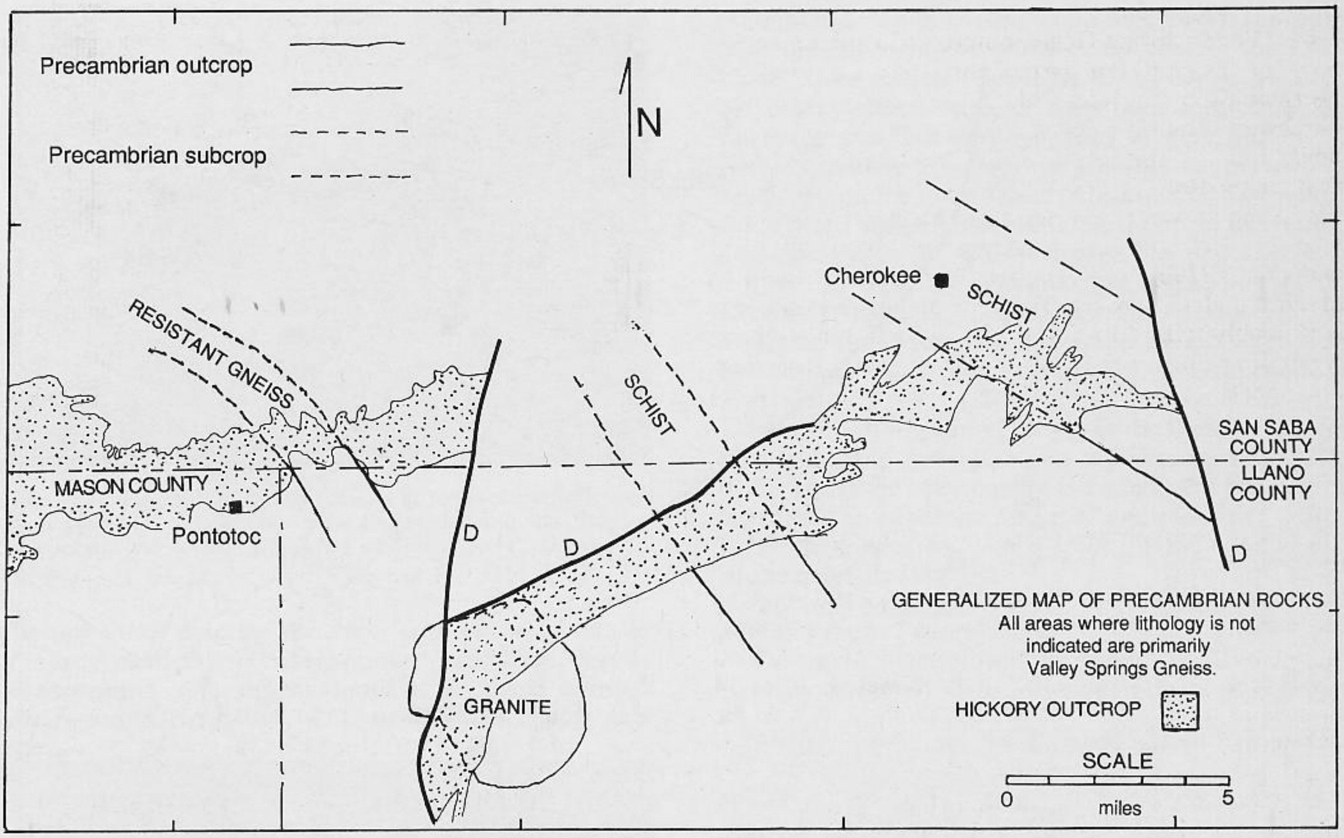


Fig. 9. Subcrop and outcrop of the Precambrian basement in the southern part of the study area. The northwestward trend of the schist and resistant gneiss are due to northwestward trending synclinal axes.

thins in the eastern part of the study area, as was shown by Cornish (1975, p. 23), who indicated a basement high in Mills and Lampasas Counties during Hickory deposition.

The topography on the unconformity was probably similar to the topography on the Precambrian rocks today with a combination of broad gently rolling areas and rugged areas with steep hills. The effects of the Precambrian topography have been identified in two areas. Northwest of Pontotoc, the Hickory Sandstone thins over a ridge of resistant gneiss shown in Figure 9. The ridge extends from the Precambrian outcrop into the Pontotoc escarpment. In the Precambrian outcrop, High Rock and Panther Rock make up part of the ridge. How far the ridges extend into the sedimentary cover is not known. In the Cherokee area, the Hickory thickens in a valley underlain by the schist trend shown in Figure 9. This valley was probably topographically similar to the present steep-sided Little Llano River valley that exists where the schist crops out southeast of Cherokee (Fig. 2).

Description of Facies

The Hickory Sandstone can be divided into three facies which, in general, overlie one another. The facies thus will be termed the lower, middle, and upper facies.

The lower facies is a fine- to coarse-grained, poorly sorted sand with rounded to subrounded grains and minor amounts of siltstone and shale (Fig. 11; Appendix C, 57-01-7a, 56-08-8a). It has festoon and planer crossbeds with large-scale foresets (Cornish, 1975, p. 30). Beds average six inches thick and many are cut and filled by channel scours. The facies contains granule-size feldspar and quartz grains which decrease in amount upward.

The middle facies interfingers with the lower facies and is composed of layers of coarse- to medium-grained sand interbedded with fine-grained sand, silt, and shale (Fig. 12; Appendix C, 57-01-6a, 57-02-9a). The fine-grained layers have planer-to-wavy laminations and the coarse- to medium-grained layers generally have massive bedding. Numerous fining-upward sequences occur (Cornish, 1975, p. 30).

The upper facies is medium- to coarse-grained, well rounded, hematitic sandstone (Fig. 13; Appendix C, 57-01-4a, 57-0-9a). It is generally thick bedded and either crossbedded or massive. Some thin, silty, and shaly beds occur. The hematitic cementation varies between beds from a thin coating on the sand grains to filling of the pore space, and cementation appears to decrease downward.

The lower facies appears to be continuous throughout the study area. The width of the outcrop area on geologic maps by Barnes and Schofield (1964) suggests the lower facies thins between the ridge northwest of Pontotoc and the Cold Creek escarpment. Barnes and Bell (1977) state that the lower unit or facies is not present in the Little Llano River section southeast of Cherokee,

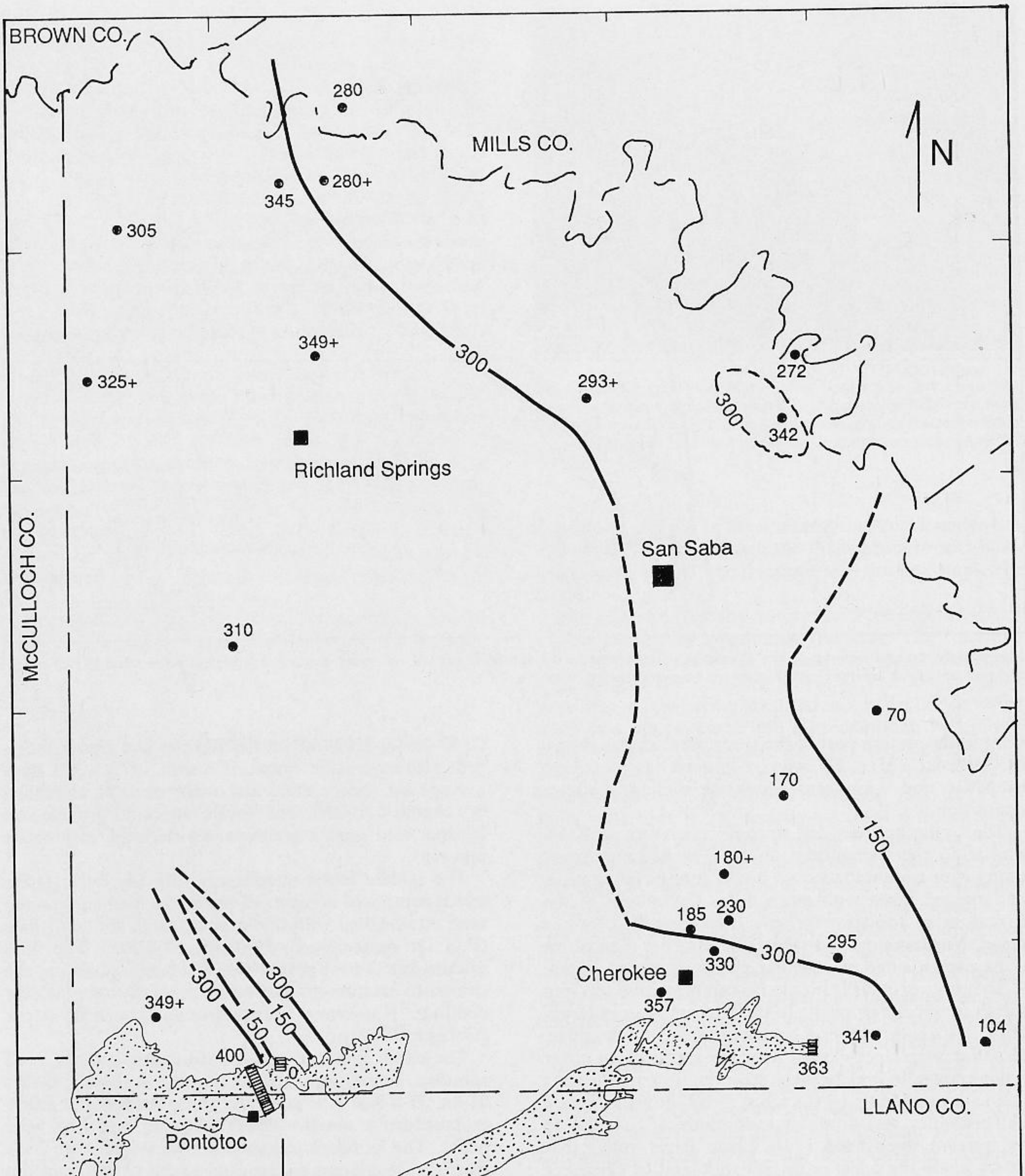


Fig. 10. Isopach map of the Hickory Sandstone. Due to the Precambrian unconformity the thickness of the Hickory is locally variable and regionally eastward thinning. The Hickory thickens around Cherokee and thins northeast of Pontotoc as a result of relief on the unconformity.

Fig. 11. Photograph of the lower facies of the Hickory. The facies is composed of crossbedded, coarse to medium sand with granule-size quartz and feldspar decreasing upward (App. C, Locality 57-03-6a).

however they describe the lower part of the section as "mostly medium- to coarse-grained sandstone, mostly crossbedded, and mostly massive or thick bedded" (Barnes and Bell, 1977, p. 134). This description and examination of part of the section suggest that the lower facies described in this study does occur in the Little Llano River section (Appendix C, 57-03-6a; Fig. 11). No other vertical sections have been located in the Cherokee area, but the topogaphy of a portion of the Hickory outcrop area south of Cherokee appears to be developed on the lower facies (Appendix C, 57-03-4a).

Eastward through the study area, the upper facies thins dramatically. In the Cherokee area, the upper facies is a three- to five-foot hematitic bed at the top of the Hickory (Appendix C, 57-03-2a). The contact with the overlying Cap Mountain is marked by a change from hematitic to calcareous cement (Fig. 13; Appendix C, 57-01-9a).

Because of this change, the top of the Hickory is easily distinguishable on driller's logs and electric logs. On the driller's logs the color change is evident. On geophysical logs both spontaneous potential and resistivity deflect to the left, apparently as a result of the conductance of the hematite (Fig. 14).

Porosity and Permeability

The middle and lower facies of the Hickory are strongly cemented with calcium carbonate as indicated

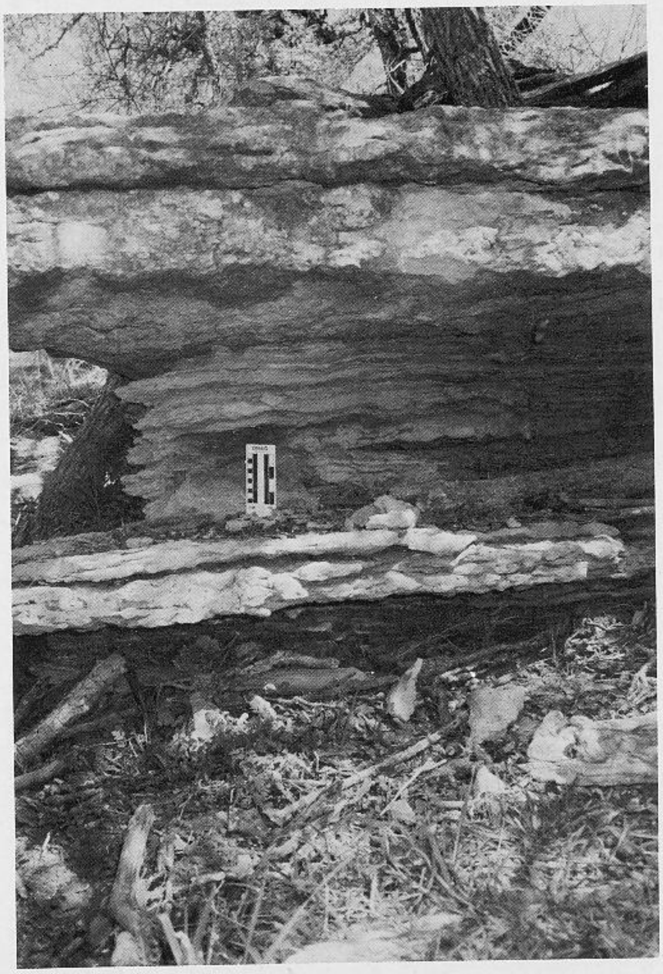


Fig. 12. Photograph of the middle facies of the Hickory. The interbedded coarse- and fine-grained layers and the shaly laminations may produce significant anisotropy (App. C, Locality 57-02-9a).

Fig. 13. Photograph of the upper hematitic unit of the Hickory Sandstone and the overlying Cap Mountain Limestone. Note the contact indicated by the color change caused by a change from hematitic to calcareous cementation (App. C, Locality 57-01-9a).

by the numerous wells in the study area with an open hole completion. The Hickory likely became cemented while deeply buried by overlying sedimentary rocks in late Paleozoic time. Maxwell (1964) has shown that a reduction of porosity due to cementation occurs in standstones as a function of time, overburden pressure, and age. The Hickory's porosity and permeability are probably mostly due to dissolution of the carbonate cement by fresh water. Because more dissolutioning can occur where the original pore space was larger, grain size and sorting still have a large effect on porosity and permeability. Because less circulation of fresh water occurs downdip than in the outcrop, less dissolutioning and a corresponding decrease in porosity and permeability should occur downdip in the aquifer.

Dissolution porosity can be seen in the outcrop and in the core studied from northern San Saba County (Fig. 14; Appendix C, 57-01-7a). Some of the porosity appears to be the result of dissolutioning of small feldspar grains from the Valley Spring Gneiss.

Aquifer Parameters

Mason (1961) reported transmissivities from aquifer tests made on irrigation wells in the Voca area. Two wells appear to be completed only in the lower facies and have transmissivities of 23,000 and 31,000 gpd/ft. Based on probable saturated thicknesses of 100 feet, this would suggest permeabilities of 230 and 310 gpd/ft/ft. Similar values may exist for the lower facies in the Hickory outcrop in the study area due to a similar stratigraphic nature.

Yields from three wells located in the Hickory outcrop and completed in the middle facies show a much lower permeability than the lower facies. Well 57-01-4P1, in the Pontotoc outcrop area, had a saturated thickness of 40 feet. The landowner reported that an old windmill often pumped the well dry. In the Cherokee outcrop area, well 57-03-4P4 had a saturated thickness of 60 feet and was pumped dry in one hour at 100 gpm, and well 57-01-103 had a saturated thickness of 210 feet and was pumped dry at 175 gpm in a few hours. Making some assumptions and using an approximation method by Logan (1964, p. 36), these yields indicate the middle unit to have transmissivities of less than 4,000 gpd/ft and permeabilities of less than 30 gpd/ft/ft (Appendix E). In the study area, wells completed solely in the upper hematitic facies have domestic submersible pumps that are run for long periods of time, suggesting it has permeabilities generally greater than the middle facies.

Data from the well owned by the North San Saba Water Supply Corporation are useful for estimating parameters for the deep confined aquifer. The well was pumped at a constant rate for one week and the initial and final static heads were taken. Based on these data, a transmissivity of 5,270 gpd/ft was estimated (Appendix E). The well has been in operation for 14 years. The original static head, the total volume pumped, and the present static head are known. A theoretical drawdown over the 14 years was calculated from the Theis equation using an estimated transmissivity of 5,270 gpd/ft and assumed storage of 0.00005. The calculated drawdown of 21 feet compared favorably to the actual drawdown of 24.6 feet over 14 years (Appendix E).

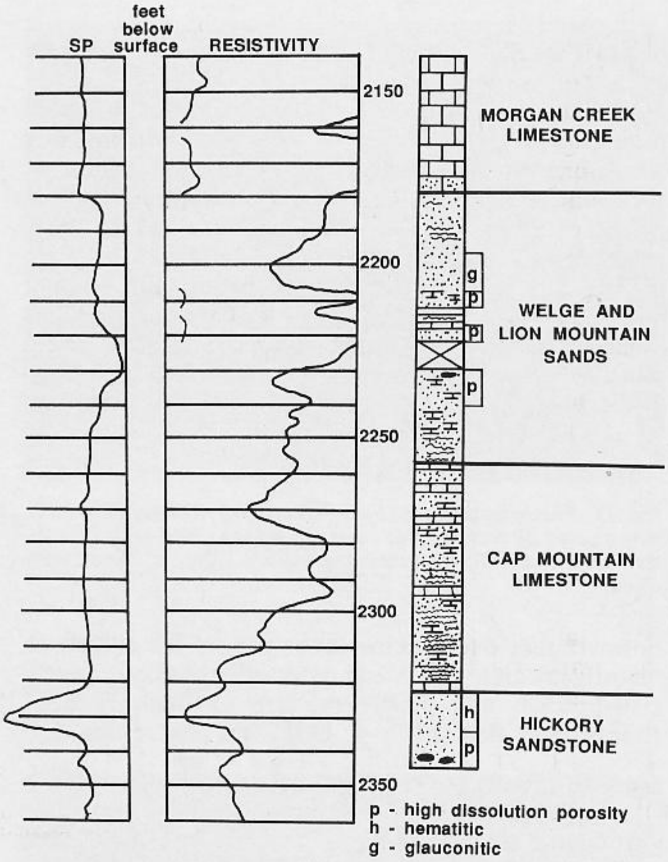


Fig. 14. Correlation of electric log and core from Bobby Griffith Softge # 1 (well 41-33-802). Note the top of the Hickory is marked by a deflection to the left on both the SP curve and the resistivity curve. This response appears to be due to hematitic cementation in the Hickory. A written core description is given in Appendix D.

The North San Saba well has a screened interval of 126 feet entirely in the lower facies, giving a permeability of around 40 gpd/ft/ft for the lower facies. The decrease in the permeability of the lower facies from 230-310 gpd/ft in the outcrop to 40 gpd/ft/ft is probably a result of less dissolutioning downdip.

Anisotropy and Heterogeneity

The entire Hickory Sandstone appears vertically anisotropic due to its layered nature, but the middle facies may be more anisotropic than the other two facies due to its interbedded shaly layers. Because flow to wells is essentially horizontal, the estimated permeabilities above represent only the horizontal permeabilities. The vertical permeabilities are likely much lower.

Because of the hematitic and calcareous cementation of the Hickory, fracturing may enhance permeability. Sand Spring in the Valley Spring area has a concentrated flow from a fracture in the center of an outcrop of the lower facies, suggesting that fractures can create preferred flow paths within the aquifer (Appendix C, 57-02-8a).

UNITS OVERLYING THE HICKORY

Cap Mountain Limestone

Directly overlying the Hickory is the Cap Mountain Limestone which grades upward from a calcareous, silty sandstone into a glauconitic, pure limestone (Fig. 7). The unit is 170 to 200 feet thick on the outcrop, but thins northward and becomes a series of thin limestones interbedded with calcareous sand (Figs. 14, 15).

The Cap Mountain appears to be a confining unit, probably due to the lower silty zone. The lack of shallow wells in the Cap Mountain outcrop indicates it does not yield significant amounts of water. However, Mount and others (1967, p. 76) suggested that vertical fractures in the Cap Mountain outcrop allow recharge to the Hickory.

Welge Aquifer

Overlying the Cap Mountain are the Lion Mountain Sandstone, the Welge Sandstone, and the Morgan Creek Limestone, in successive order (Fig. 7). The Lion Mountain is a highly glauconitic, fine-grained sandstone with impure limestone beds and minor amounts of shale and siltstone. It averages 60 feet throughout the study area. The Welge is a non-glauconitic, coarse- to medium-grained sandstone that averages 30 feet in the study area. The Morgan Creek Limestone is a granular, silty to sandy glauconitic limestone. It averages 110 feet in thickness throughout the study area.

The Lion Mountain, Welge, and Morgan Creek are all water-bearing and can be considered one aquifer termed the Welge aquifer in this study. The Welge Sandstone has the greatest permeability as a result of its coarse-grained nature, but most wells in the study area usually penetrate all three units and stop at the top of the Cap Mountain. The permeability of the Morgan Creek Limestone is believed primarily to be the result of weathering fractures which may decrease with depth.

Point Peak Shale

The Point Peak overlies the Morgan Creek Limestone and acts as a confining unit separating the Welge aquifer from the Ellenburger aquifer. The Point Peak grades upward from interbedded siltstone, shale, and limestone into massive shale. It averages 140 feet in thickness throughout the study area, and contains approximately 80 feet of massive shale.

Ellenburger Aquifer

Above the Point Peak are the Ellenburger and San Saba Limestones. Together they consist of 1,200 to 1,600 feet of interbedded limestone and dolomite termed the Ellenburger aquifer. Permeability in the units is the result of fracturing and dissolutioning. Dolomitic layers generally have the greatest permeability but are not laterally continuous (Mount and others, 1967, p. 72). Because not all layers are dissolutioned, a number of different confined zones occur, and head levels in the aquifer may vary dramatically with depth.

The top of the Ellenburger is, in most places, separated from the Marble Falls Limestone by the Barnett Shale which ranges from 0 to 40 feet in thickness in the study area (Fig. 7). The Marble Falls averages 150 to 200 feet thick and has a fracture- and dissolution-derived permeability similar to the Ellenburger. Where the Barnett is absent, or where faults occur, the Marble Falls is believed to be hydraulically connected with the Ellenburger aquifer.

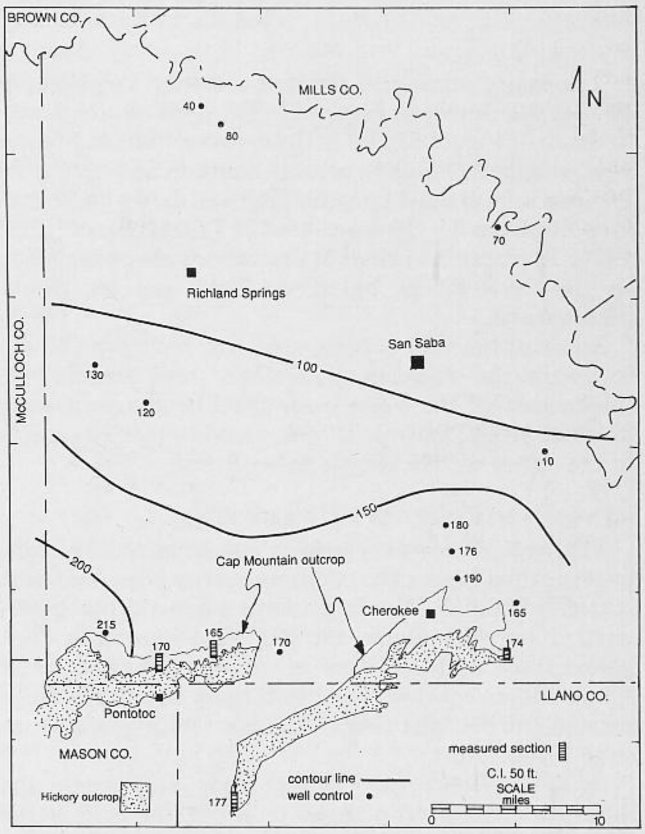


Fig. 15. Isopach map of the Cap Mountain Limestone showing the northward thinning. Northward the Cap Mountain becomes a series of thin limestones interbedded with calcareous cemented sand, making it difficult to distinguish from the overlying Lion Mountain Sandstone.

The top of the Ellenburger was subaerially exposed prior to deposition of the overlying units, and erosional truncation caused the Ellenburger to thin eastward (Fig. 16). Because of exposure to meteoric water, the upper one hundred feet is highly dissolutioned even where covered by overlying rocks. This dissolutioned zone supplies a large quantity of water to a number of springs in the study area, including Richland Springs, San Saba Springs, and springs feeding Wallace Creek (Appendix C, 41-41-7a, 41-51-4a, 41-58-7a). These springs issue from the Marble Falls Limestone, but in each case the top of the Ellenburger is near the land surface.

Smithwick and Strawn Shales

The Marble Falls is overlain by the Smithwick and Strawn shales which thicken to several hundred feet in the northern part of the study area (Fig. 7). They serve as a regional confining unit and transmit little water, The Strawn contains a number of discontinuous bodies of fine-grained, cemented sandstone which yield small amounts of water.

STRUCTURAL GEOMETRY

The major structural features affecting the Hickory aquifer are shown in Figure 17. The features are shown in detail in Figure 23 and in the cross sections in Figures 18 through 21. The structural contour and the cross sections were created by combining well data with surface mapping from the Geologic Atlas of Texas (Barnes, 1976; 1981). In places, additions or corrections have been made to the fault traces based on field and air photo observations.

Some of the well control used was not deep enough to reach the Hickory Sandstone, but because the thicknesses of the units from the Ellenburger Group downward are known, it was possible to extrapolate to the top of the Hickory in many cases.

STYLE AND TREND OF FAULTING

Faulting in the study area is characterized by high-angle normal faults. The maximum throw on some faults is over 1,000 feet. The faults have a general northeastward trend that divides the area into numerous fault blocks tilted northeastward at variable dip rates. Fault splays and en echelon faults with ramp structures occur throughout the area (Fig. 22). Step faulting occurs on large-throw faults.

In the northern part of the study area where the Smithwick and Strawn shales crop out, the fault traces are covered. Faulting in the area was caused by the subsidence of the Fort Worth Basin during early Pennsylvanian time. The Smithwick and Strawn units represent basin fill occurring at the time of subsidence, and faulting thus dies out upward in these units.

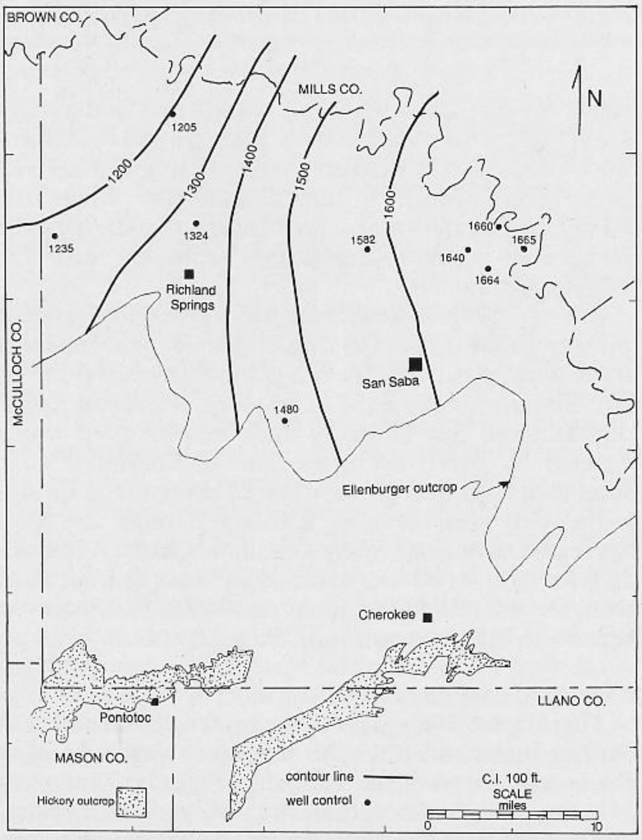


Fig. 16. Isopach of the Ellenburger and San Saba Limestones. The westward thinning is due to erosional truncation of the Ellenburger.

Several faults have trends significantly different from the overall northeast trend. The Little Llano River fault and the Shaw Bend faults have a north-northwest trend. Faults south of Cherokee and north of Pontotoc have roughly east-west trends. Orr (1962, p. 64) recognized five joint sets in the vicinity of the city of San Saba. They had trends of N42E, N43W, N1E, N75E, and N72W. The different trends of the faults and joints may have been caused by breakage along pre-existing stress fabrics within the Precambrian (Brann Johnson, oral communication, November 1987).

MAJOR STRUCTURAL FEATURES

Cheney (1940, p. 105) described and named three northward-dipping structural highs in the study area as the Richland Springs, Pontotoc, and San Saba axes. Intervening grabens were named the San Saba River and Wallace Creek grabens. Later authors have referred

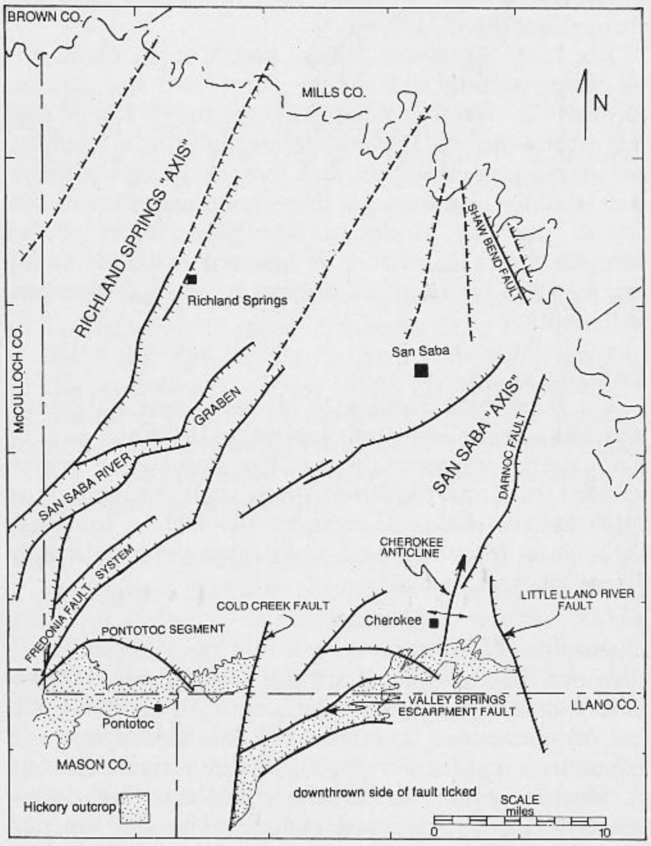


Fig. 17. Major structural features. The Richland Springs axis is separated from the San Saba axis by the intervening San Saba River graben. The Pontotoc segment is bounded by the Cold Creek fault and the Fredonia fault system. The Valley Spring escarpment fault severs part of the Hickory outcrop from the downdip part of the aquifer.

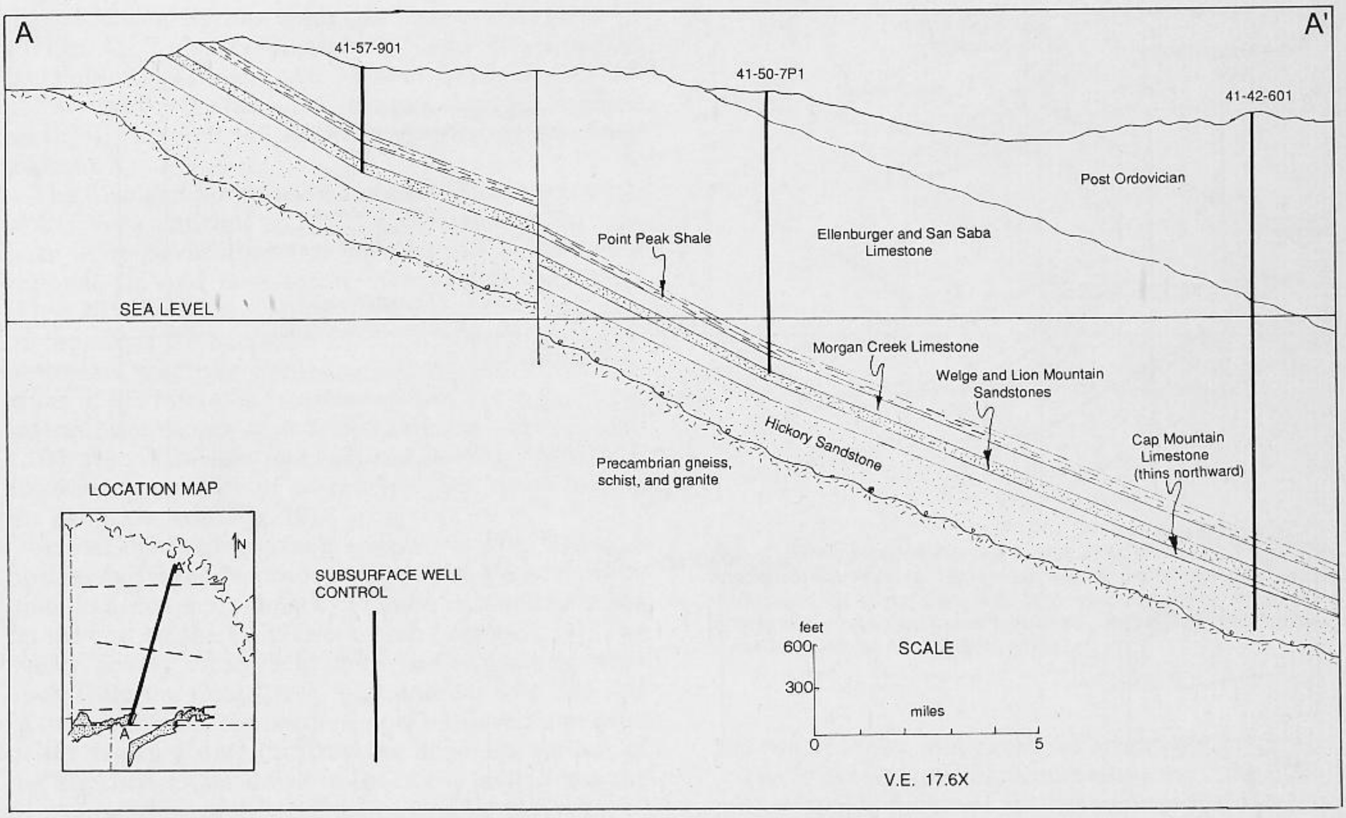


Fig. 18. South to north dip section from the Hickory outcrop to northern San Saba County. The Cap Mountain Limestone thins northward. The dip rate averages 125 feet per mile.

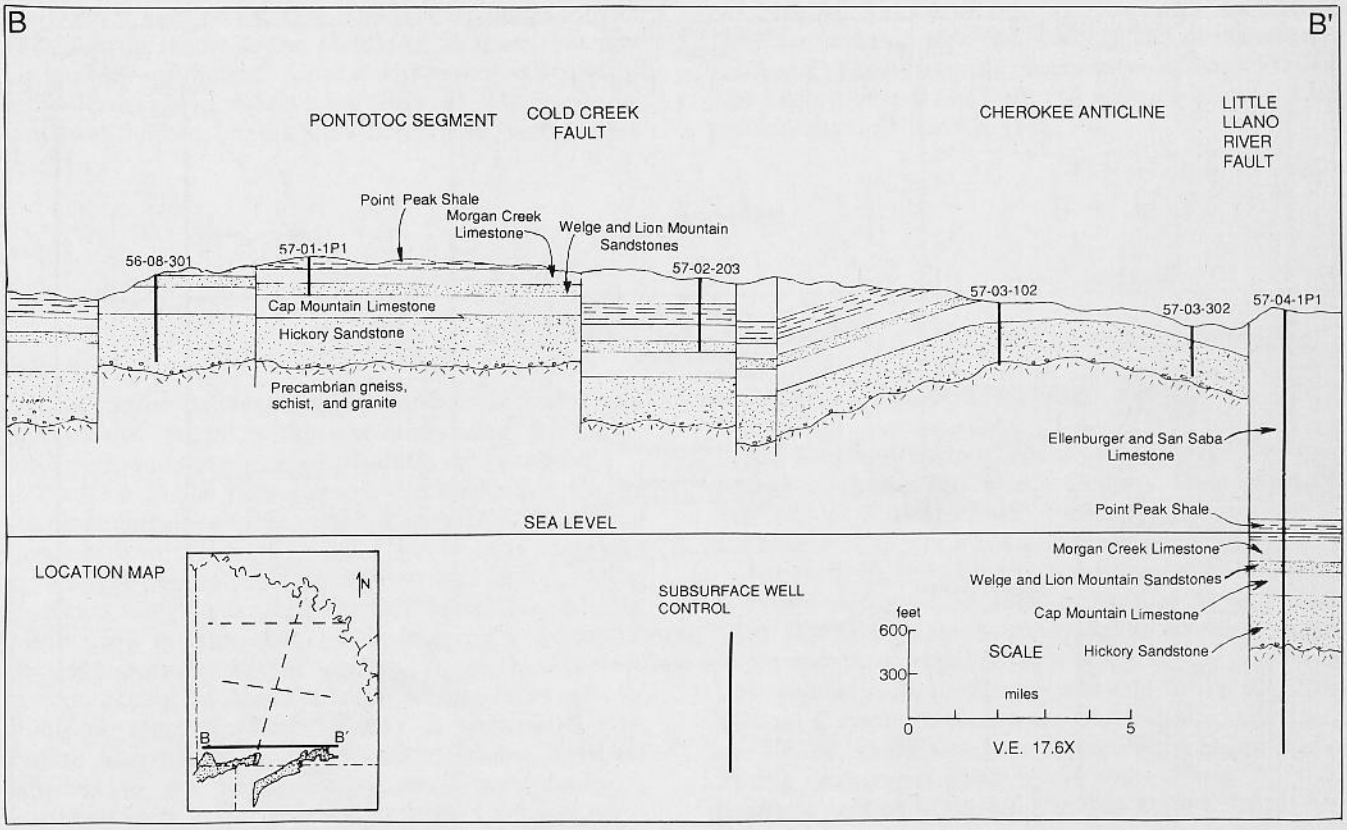


Fig. 19. West to east strike section in southern San Saba County. The Hickory is severed by the Cold Creek and Little Llano River faults. The Pontotoc segment and the Cherokee anticline are fairly unfaulted.

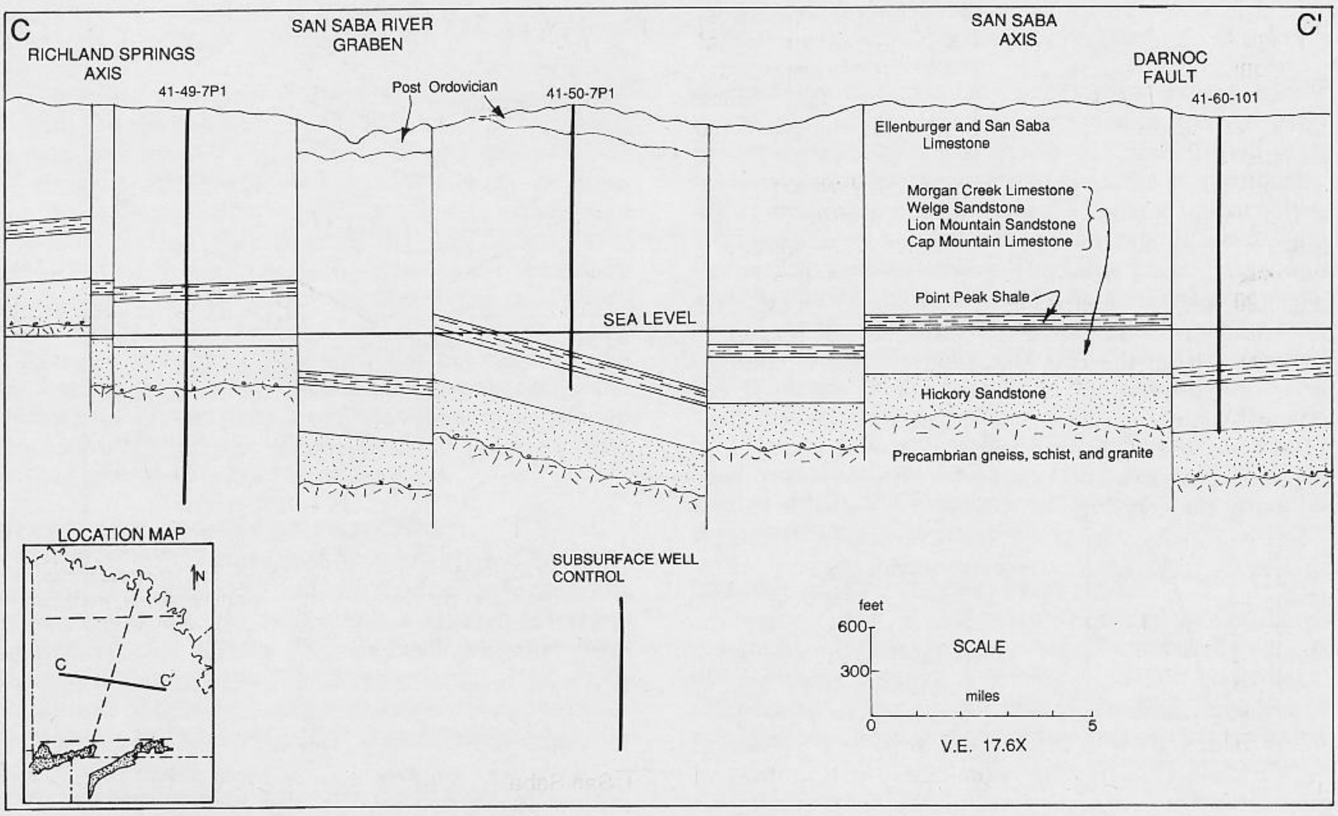


Fig. 20. West to east strike section in central San Saba County. The San Saba River graben is east of the Richland Springs axis. The Darnoc fault forms the eastern boundary of the San Saba axis.

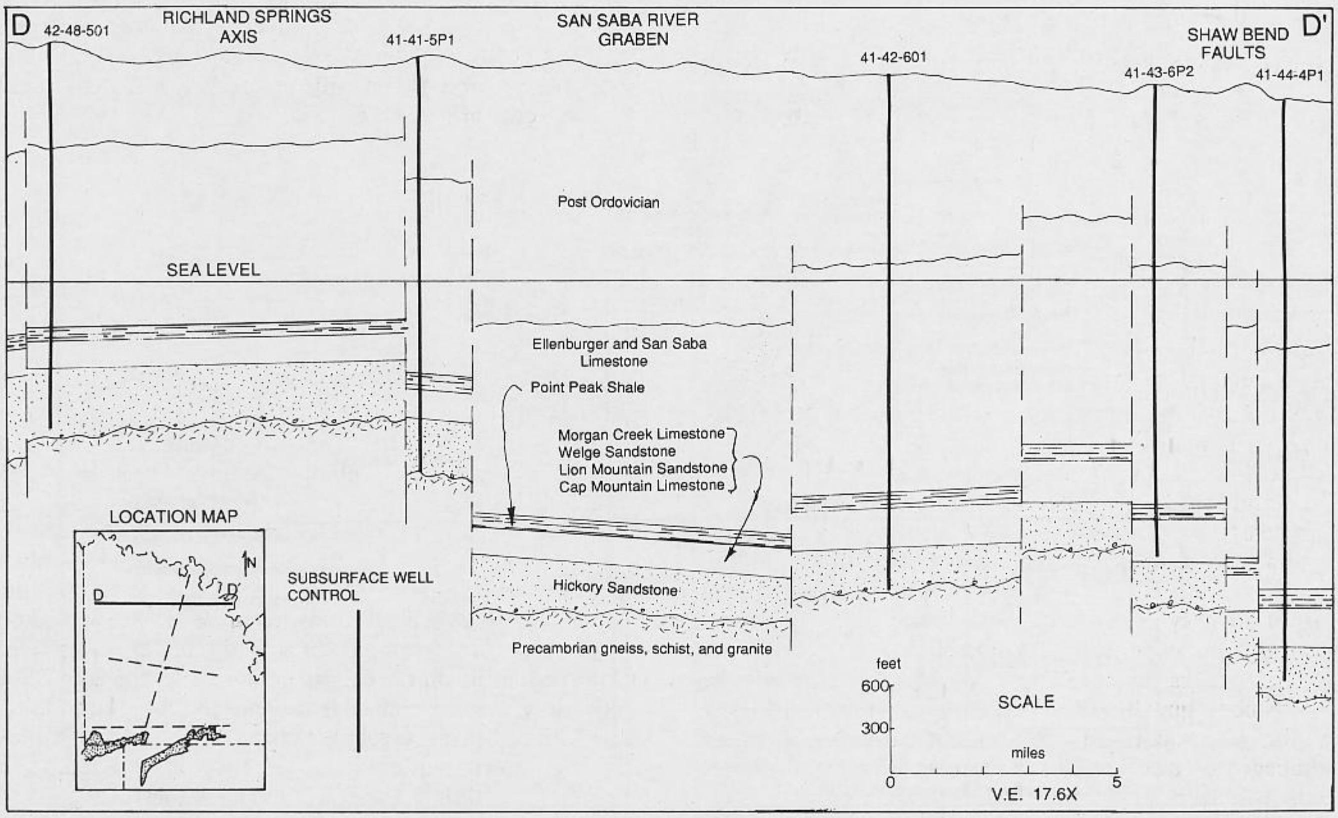


Fig. 21. West to east strike section in northern San Saba County. The Shaw Bend faults form the eastern boundary of an unnamed structural high north of the San Saba axis.

to the Richland Springs axis as the Cavern axis (Belforte, 1971, p. 45; Walper, 1982, p. 247). Figure 23 shows that the Pontotoc axis and the Wallace Creek graben are not well-defined structural features. The fault block north of Pontotoc will be referred to as the Pontotoc segment.

The Richland Springs axis is the northward extension of the Voca anticline in McCulloch County. The axis is an asymmetric structural high formed by westward regional dip and large-throw, down-to-the-east faults (Figs. 20, 21, 23). Bounding the Richland Springs axis on the east is the San Saba River graben which extends northward from the Fredonia fault system. Numerous faults in the Fredonia fault system and San Saba River graben have throws of over 500 feet and some of over 1,000 feet. The San Saba River graben "steps up" eastward in a series of en echelon step faults toward the San Saba axis (Fig. 20).

Across the Fredonia fault system from the Richland Springs axis is the Pontotoc segment which is a relatively unfaulted area approximatley 11 miles wide and bounded on the east by the Cold Greek fault (Figs. 17, 19). The Valley Spring escarpment fault heads northeastward away from the Cold Creek fault and has over 500 feet of throw, down to the north (Fig. 17). It severs a portion of the Hickory outcrop from the downdip portion of the Hickory. Other down-to-the-north faults form the southern border of the Hickory outcrop in that area.

The San Saba axis is a horst block that dies out northeastward due to an increasing rate of dip. The horst is bounded by the Simpson Creek fault on the west and the Darnoc fault on the east. The Darnoc fault has over 1,000 feet of throw in the middle of its trace, but dies out quickly southward. A horst with a more northward trend occurs north of San Saba (Figs. 21, 23). The horst is not well defined, but the Shaw Bend faults, with around 500 feet of throw, may represent one boundary.

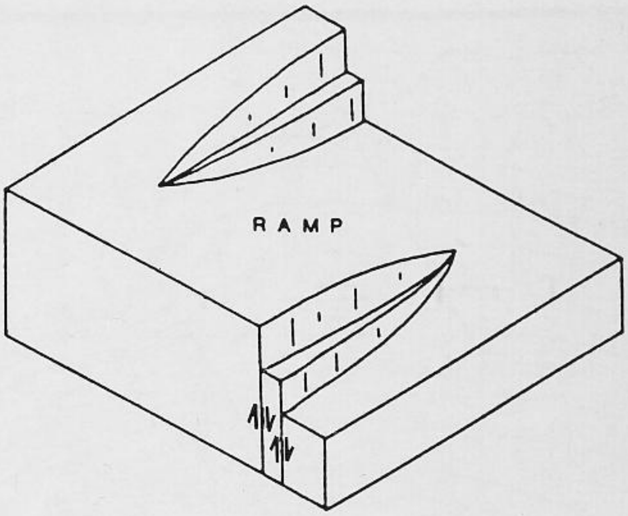


Fig. 22. Block diagram showing a ramp structure between en echelon faults with step faulting. This type of faulting and structure is common throughout the study area. One large example occurs northeast of Cherokee between the Darnoc fault and Little Llano River fault (from Grimshaw and Woodruff, 1986, p. 85).

The Cherokee anticline occurs along the southern end of the Darnoc fault and the northern end of the Little Llano River fault (Fig. 17). It has a broad, gently dipping anticlinal shape near the Hickory outcrop, and is faulted along its axis by the Darnoc fault a few miles north of Cherokee. The northern end of the Little Llano River fault is en echelon with the southern end of the Darnoc fault, and a ramp structure occurs between the two faults. The Little Llano River fault has a throw of over 1,500 feet due east of Cherokee (Fig. 19).

FLOW SYSTEMS

This section delineates and describes the major and minor flow systems within the study area. Recharge, discharge, and the effects of structure are discussed.

The two major flow systems are controlled by the Richland Springs and San Saba structural axes and flow northeastward (Figs. 17, 24). The flow systems are separated by complex, large-scale normal faulting of the Fredonia fault system and the San Saba River graben. Minor flow systems occur in the outcrop and shallow confined portions of the aquifer. A southward flow system occurs in the Hickory outcrop area of the Pontotoc segment (Figs. 17, 24). A southward flow system also occurs in the Hickory outcrop segment adjacent to the Valley Spring escarpment fault. A northeastward flow system occurs in the Cherokee area. This flow system is a part of the larger San Saba axis system, but is discussed separately.

REGIONAL FLOW SYSTEMS

Recharge

The Richland Springs axis flow system receives most of its recharge in McCulloch County. The recharge in McCulloch County flows northeastward toward the study area as shown by Mason (1961, p. 29; Fig. 24).

The recharge area for the San Saba axis flow system is shown in Figure 25. Very little recharge to the San Saba axis flow system comes from the Hickory outcrop in the Pontotoc segment as a result of the southward flow system in that area. No recharge to the San Saba axis flow system comes from the Hickory outcrop in the Valley Spring escarpment area because the Valley Spring escarpment fault severs the outcrop from the downdip portion of the aquifer. The highest water levels in the area occur in the covered portions of the aquifer indicating that most recharge for the San Saba axis flow

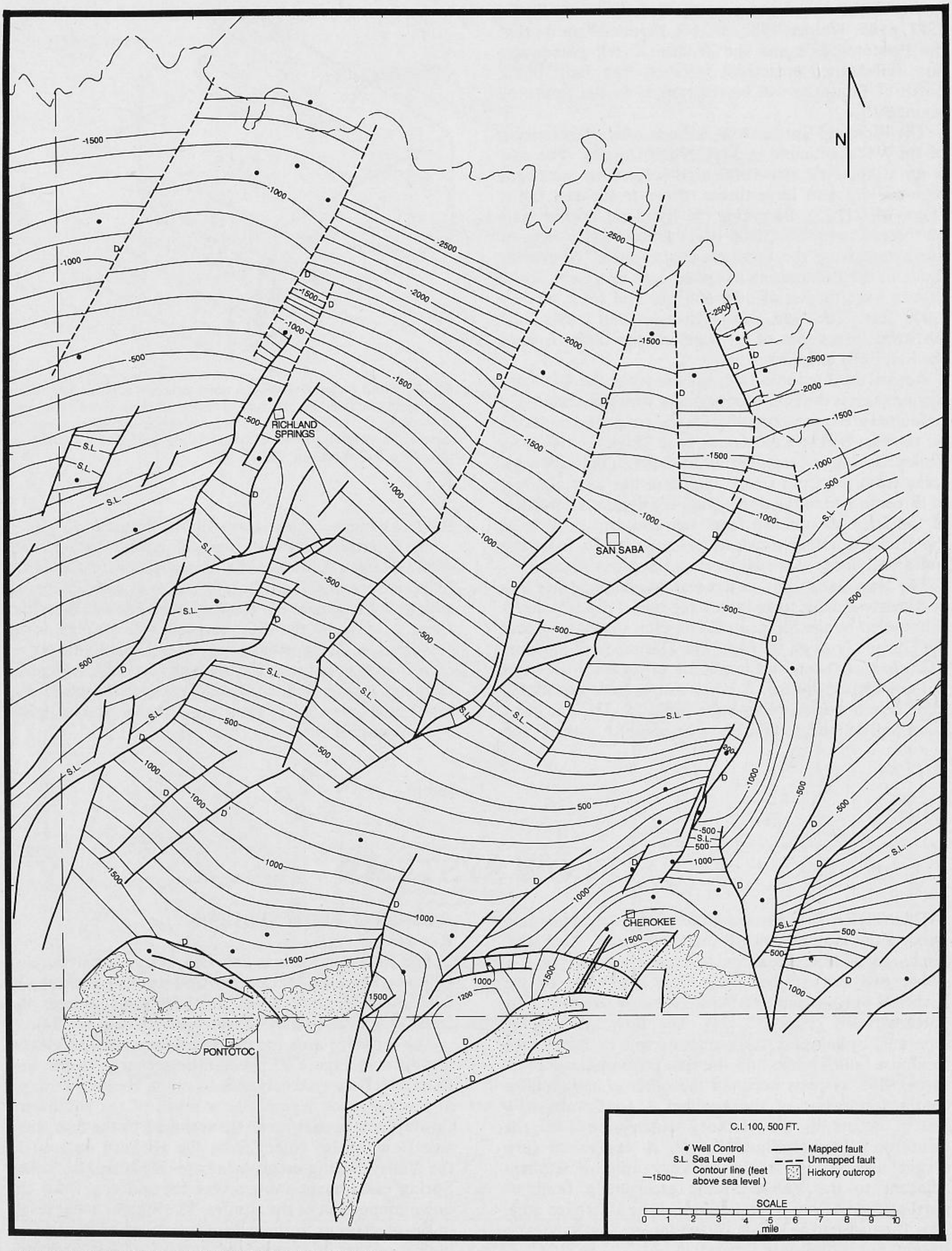


Fig. 23. Structural contour on top of Hickory Sandstone.

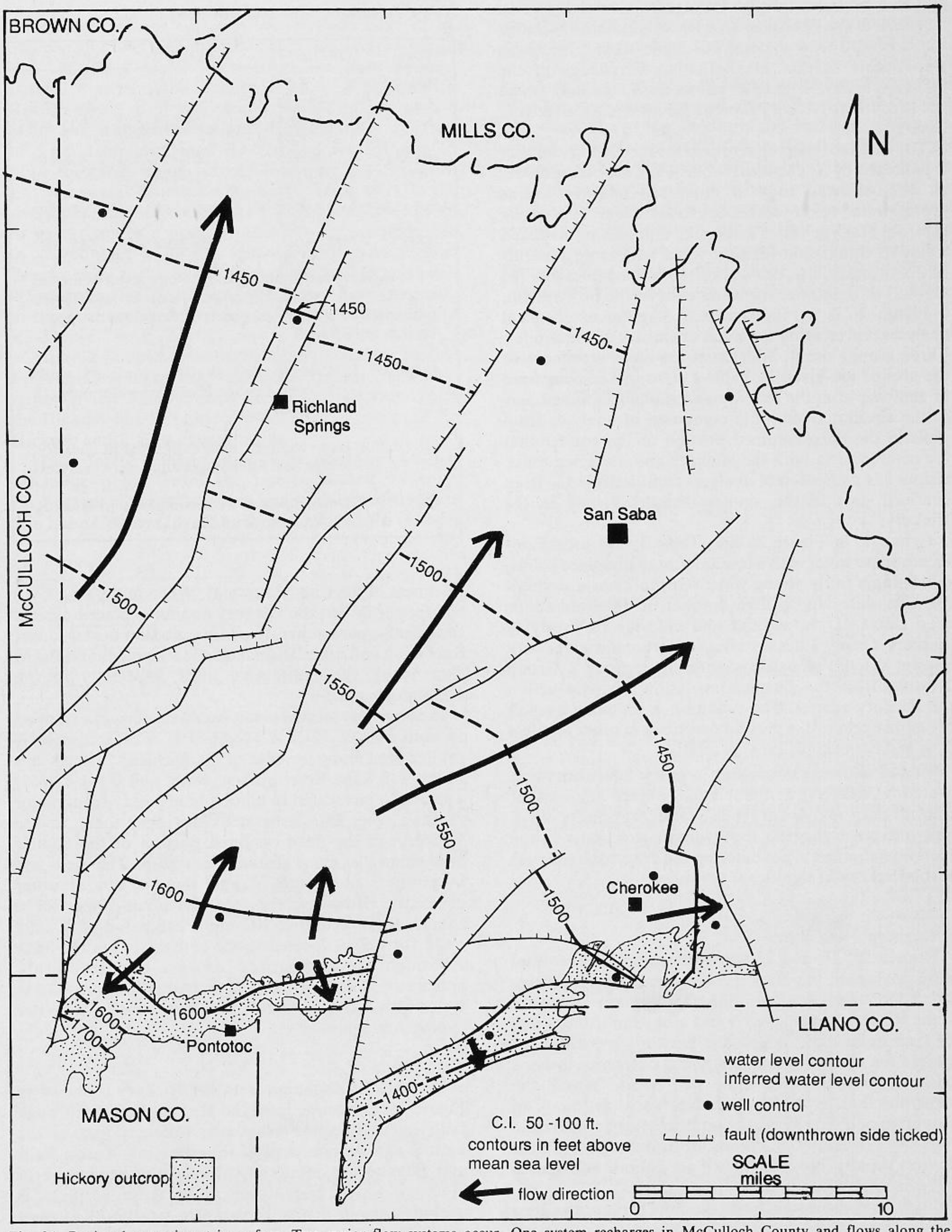


Fig. 24. Regional potentiometric surface. Two major flow systems occur. One system recharges in McCulloch County and flows along the Richland Springs axis. The other system recharges north of Pontotoc and flows along the San Saba axis. Minor flow systems occur in parts of the Hickory outcrop. (See Figure 36 for well numbers and Appendix F for water level measurements).

system is probably through leakage from overlying units. Portions of the Cherokee area Hickory outcrop recharge the downdip flow system, but some leakage recharge also occurs in that area. The northern edge of the recharge area in Figure 25 shows approximately where the head in the Hickory exceeds the head in the overlying aquifers.

The extent of the recharge area for the Hickory aquifer is indicated by its chemical evolution. Chebotarev (1955, p. 210) showed that in most sedimentary basins groundwater undergoes an ion evolution from a young bicarbonate-type water with small amounts of dissolved solids to an old chloride-type water with large amounts of dissolved solids. The age of the water represents the amount of time since the water entered the flow system.

Figure 26 is a Piper trilinear diagram of chemical analyses representing the water chemistry of the aquifer. Three groups occur. Ranges of ion concentrations for the groups are given in Table 1. Group 1 is composed of analyses from the outcrop and shallow confined part of the aquifer. Group 2 is composed of analyses from wells in the deep confined portion of the aquifer that are completed in both the Hickory and overlying units. Group 3 is composed of analyses from wells in the deep confined part of the aquifer completed only in the Hickory.

Group 1, in Figure 26 and Table 1, has a calcium-bicarbonate water with a low amount of dissolved solids, indicating a fairly young water. Group 2 has a sodium-chloride water and a high amount of dissolved solids as a result of the sodium and chloride in overlying aquifers. Group 3 has a sodium-bicarbonate water with a lower amount of dissolved solids than group 2. Group 3 results from the chemical evolution downdip within the Hickory aquifer. The evolution is probably a result of cation exchange, a process described in other aquifers (Lee and Strickland, 1988, p. 299).

Table 1 shows that analyses in group 2 (Hickory and overlying aquifers) contain much greater amounts of chloride than analyses in group 3 (Hickory aquifer only). This difference suggests that chloride-rich water in the overlying aquifers is not entering the deep confined part of the Hickory in significant amounts.

Table 1. Ranges of concentrations in mg/ 1.

ION	GROUP 1	GROUP 2	GROUP 3
Mg	5-53	1-12	1-2
Ca	43-113	1-14	1-2
Na	7-360* (27)	25-310	225-348
HCO_3	104-425	267-456	438-666
SO_4	7-213* (25)	15-124	1-24
Cl	12-522* (26)	277-1550	76-283
TDS	375-1404* (375)	902-2989	568-1095

*The high concentration appears to be a result of human activity. An estimated upper limit in unaffected groundwater is given in parentheses below the upper limit in the data set.

GROUP 1: Outcrop and shallow confined wells completed in the Hickory aquifer only (18 analyses)

GROUP 2: Deep confined wells completed in Hickory, Welge, and Ellenburger aquifers (4 analyses)

GROUP 3: Deep confined wells completed in Hickory aquifer only (4 analyses)

Effects of Faulting

Figures 20, 21, and 23 show that large-scale normal faults juxtapose the Hickory with the overlying Welge and Ellenburger aquifers along the eastern boundary of the Richland Springs axis and along faults bounding the San Saba axis. Where the Hickory is juxtaposed against the overlying aquifers and a difference in head exists, flow across the fault will occur. Where the overlying unit is less permeable, such as the Cap Mountain or Point Peak, the fault will form a hydraulic boundary. Because the amount of throw of most faults changes rapidly, most faults will act as both boundaries and discharge zones in different locations.

Significant discharge from the Hickory aquifer into the Welge aquifer can take place when faults have between 100 and 400 feet of throw (depending on the thickness of the Cap Mountain). When faults have over 600 feet of throw, the Hickory aquifer is placed against the Ellenburger aquifer. In addition to flow across faults, fracturing and brecciation may allow significant upward flow along the fault zone itself, especially in the Ellenburger aquifer.

In complexly faulted areas, water may become trapped in fault blocks. Well A (41-41-5P1) is in a complexly faulted area along the edge of the Richland Springs axis in the San Saba River graben, while well B (41-42-601) appears to be located in a horst block away from major faulting (Fig. 24). Both wells are open only to the Hickory, in the deep confined portion of the aquifer and about the same distance downdip. The wells are in group 3 in Figure 26 and show a similar water chemistry. However, the total dissolved solids for a sample from well B is 707 mg/ 1 compared with 1095 mg/ 1 for well A located in the complexly faulted area. Although the comparison of two analyses is not conclusive, it suggests complexly faulted areas may have water with more dissolved solids because of older water in stagnant zones.

Discharge

The area of discharge from the Hickory is shown in Figure 25. Discharge from the Hickory aquifer through fault interconnection eventually becomes part of the natural surface discharge of the overlying Marble Falls and Ellenburger aquifers. Although the percentage of Hickory water discharging from these aquifers is probably small, it may represent a significant amount of the total discharge from the regional Hickory flow systems. Most of the natural discharge points for the

Ellenburger aquifer occur at the northern edge of its outcrop area and feed into the San Saba River.

A sample of water taken from San Saba Springs showed a gross alpha activity of 13 ± .4 pCi/l and a Ra-226 of 6.5 ± .2 pCi/l and a Ra-228 of less than 1 pCi/l. This is above the national drinking water standard of 5 pCi/l for combined Ra-226 and Ra-228 and 15 pCi/l for gross alpha activity including Ra-226 (U.S. Environmental Protection Agency, 1986, p. 527). In the study area, only water from the Hickory aquifer is known to have significant natural radioactivity, probably due to its contact with the igneous and metamorphic Precambrian rocks. Water from well 41-42-601, located 7.5 miles north of San Saba Springs and completed only in the Hickory, had a gross alpha of 21 ± 7 pCi/l, a Ra-226 of 7.8 ± .2 pCi/l, and a Ra-228 of 8.4 ± .7 pCi/l; while samples from the Ellenburger and the Marble Falls aquifers taken near San Saba Springs showed no radioactivity. This supports the idea of discharge from the Hickory through interconnected flow systems of the Hickory and Ellenburger aquifers.

Water in the Hickory that flows under the natural discharge points from the interconnected Hickory-Ellenburger flow system becomes stagnant in northern San Saba County (Fig. 25). Figure 27 shows the changes in chloride concentration and static head, and the volume of water pumped over the past 14 years in well B (41-42-601; Fig 24). The chloride concentration has quadrupled since the well began pumping. This shows that the expanding cone of depression around the well has encountered high sodium and chloride concentrations around the well and indicates that flow may become sluggish a short distance downdip from the well.

Although the Colorado River is the base level for surface drainage, it does not represent a major discharge point for the Hickory or overlying aquifers. The Smithwick and Strawn shales are over 1,000 feet thick beneath the Colorado River, have a low permeability, and retard upward leakage from the underlying aquifers.

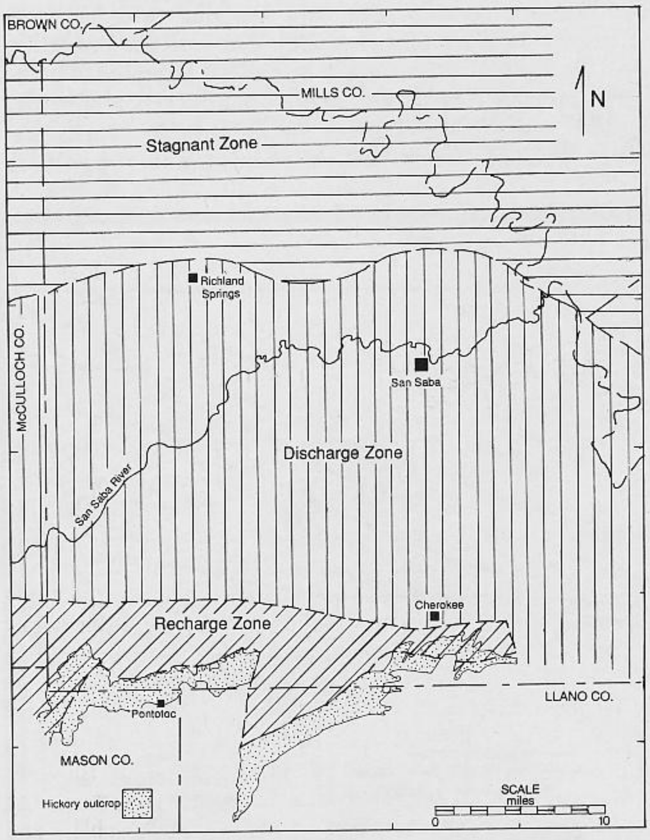


Fig. 25. Recharge, discharge, and stagnant zones for the regional confined flow systems. Recharge is primarily by leakage in the shallow confined and covered portion of the aquifer. Discharge flows upward, across and along faults into overlying aquifers and eventually into the San Saba River. In the area covered by the Smithwick and Strawn Shales, flow in the Hickory becomes stagnant.

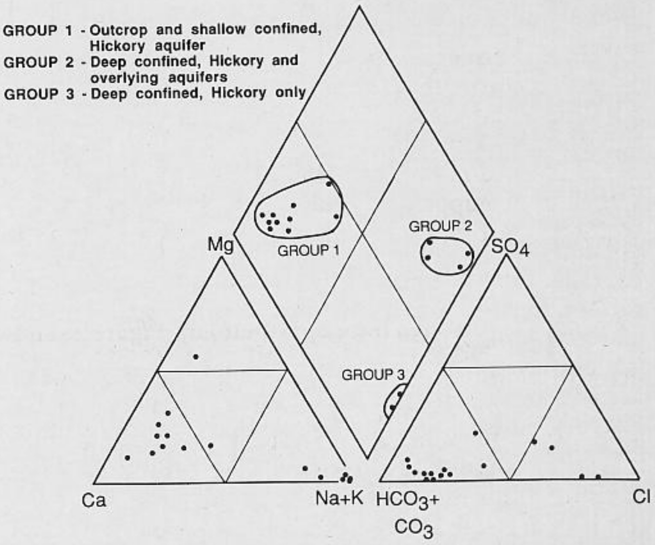


Fig. 26. Piper trilinear diagram of chemical analyses from wells open to the Hickory. The difference between groups 1 and 3 shows the chemical evolution of water in the Hickory from calcium bicarbonate to sodium bicarbonate. The difference between groups 2 and 3 is a result of large chloride concentrations in overlying units. The bicarbonate-type water in the Hickory aquifer in northern San Saba County supports the interpretation of a discharge zone (data in Appendix G).

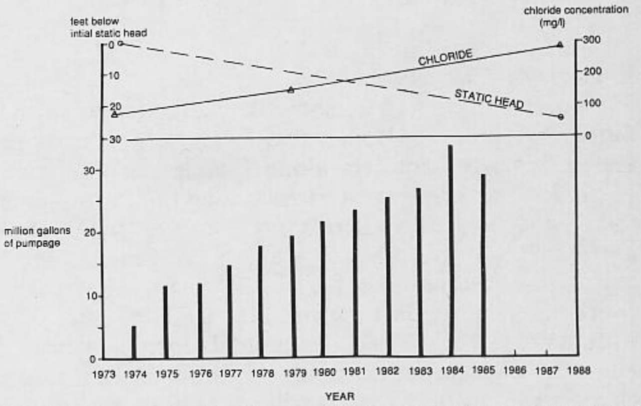


Fig. 27. Changes in chloride concentration and static head correlated to the amount of pumpage from well 41-42-601 in northern San Saba County. The chloride concentration has quadrupled as the static head has declined nearly 25 feet. This suggests that the expanding cone of depression around the well has encountered a high concentration gradient of chloride downdip from the well.

VALLEY SPRING ESCARPMENT OUTCROP AREA

A southward flow system occurs in the Valley Spring escarpment outcrop area (Fig. 24). The area is severed from the covered portion of the Hickory aquifer by the Valley Spring escarpment fault (Fig. 17). Recharge occurs as direct infiltration of rainfall through the highly permeable lower facies of the Hickory which crops out in most of the area. Flow in the outcrop area generally follows the land surface, but a number of faults cut through the outcrop area perpendicular to the southward flow direction and create complex flow paths. For example, Sand Spring issues out of a fracture in the middle of the outcrop area as a result of faulting. Water levels suggest that water slowly discharges into the fractured Precambrian rocks across faults bounding the Hickory outcrop and flows southward toward the Llano River.

PONTOTOC AREA

Local Flow Systems

The Pontotoc area includes the Hickory outcrop extending from just east of Fredonia to the Cold Creek escarpment. Figure 28 shows the water table and potentiometric surface in the Pontotoc area on May 24-25, 1988. Flow is generally southward following the land surface in most of the Hickory outcrop area. In the extreme southwestern portion of the outcrop area, there is a northeastward flow system also mimicking the land surface. A groundwater divide occurs just north of the Hickory outcrop and the potentiometric surface has a low northward gradient indicating downdip flow under confined conditions. Figure 29 is a cross section of the water table and potentiometric surface and shows that the aquifer becomes confined about 3,000 feet north of where it is covered by the Cap Mountain Limestone.

Because of the dry spring season of 1988, Figures 28 and 29 represent relatively low water levels for the Pontotoc area. Although changes in water levels occur, the general shape and direction of the flow systems is believed to remain the same throughout the year because of the topographic control.

Water levels in the Pontotoc escarpment area undergo large fluctuations. Figure 30 compares the water table surface in May 1988 with its approximate position in September 1987. Well 57-01-4P2, located on top of the escarpment, had the largest fluctuation. It declined nearly 11 feet from April 1988 to May 1988, and probably declined 30 to 40 feet from September 1987 to May 1988. In comparison, well 57-01-4P1, located at the base of the escarpment, declined only two feet from September 1988 to May 1988.

Even at relatively low water levels, a steep gradient of approximately 0.03 ft/ft exists between wells 57-01-4P1 and 57-01-401 (Fig. 29). The steep gradient appears to be the result of both topographic control and a low vertical permeability in the middle facies of the Hickory.

Vertical Flow Net

Figure 31 is a vertical flow net based on the cross-section in Figure 29. The flow net was obtained from a steady state numerical model. The bottom boundary for the model is a no-flow boundary representing the Precambrian rocks. The upper boundary is a constant head boundary representing the water table. Horizontal and vertical permeabilities and anisotropy were

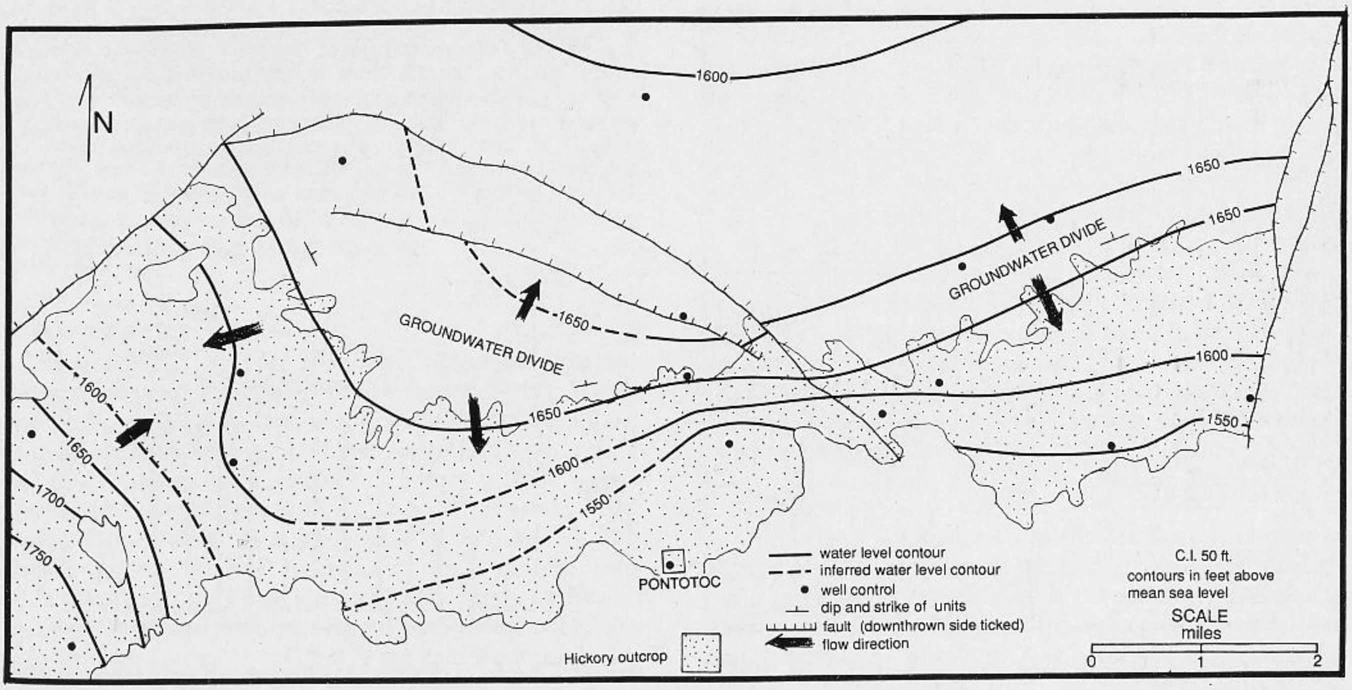


Fig. 28. Water table and potentiometric surface map of the Hickory aquifer in the Pontotoc area in May 1988. A groundwater divide exists along the Pontotoc escarpment at the northern edge of the Hickory outcrop. Flow is southward into the Hickory outcrop and northward downdip. A northward flow system occurs in the southwestern portion of the outcrop area. See Figure 38 for well numbers and Appendix F for water level measurements.

estimated for the three facies of the Hickory and assigned to the nodes in the model. Although the program only approximates the actual conditions, variation of the parameters through a realistic range of values does not drastically alter the shape of the flow net. A description of the program and various outputs for different amounts of anisotropy are given in Appendix H.

Recharge

Figure 31 shows that north of the Pontotoc escarpment a large downward vertical gradient occurs in the middle facies of the Hickory which separates flow in the upper and lower facies. The divide between northward and southward flow in the lower facies is downdip of the divide in the upper facies and is in the covered portion of the aquifer. The flow net shows that little recharge to the downdip regional system comes from the Hickory outcrop in the Pontotoc area and that most recharge to the downdip system is the result of leakage from the covered and confined portion of the aquifer.

Figure 29 shows the Welge and Lion Mountain Sandstones overlying the Cap Mountain north of the Pontotoc escarpment. Cretaceous outliers with basal sands also overlie the Cap Mountain in places. As a result of their topographic position, these sandstones can store water with a greater total head than water in the Hickory, and provide a constant source for leakage through the Cap Mountain. Figure 29 shows that a head difference of approximately 100 feet occurs between the Welge and the Hickory. This creates a large vertical gradient across the Cap Mountain, which causes significant amounts of leakage to the downdip regional system despite the low permeability of the Cap Mountain compared to the adjacent units.

Most of the recharge to the southward outcrop flow system occurs as direct infiltration into the Hickory outcrop. Many outcrop areas underlain by the lower and middle facies of the Hickory have a flat topography and lack incised stream channels, indicating that more rainfall infiltrates than becomes runoff.

Discharge

The southward flow system discharges into streams in the outcrop area. In April of 1988, despite a long period of dry weather, several streams in the Hickory outcrop carried a small amount of baseflow including the lower part of Field Creek, Cold Creek, and Pontotoc Creek. Pontotoc Creek and Cold Creek were noted to have growths of marsh grass, indicating that their channels remain wet throughout the year (Appendix C, 57-01-6b, 57-01-7b). The water table in the western part of the outcrop converges toward local drainage indicating an area of discharge (Fig. 28).

Bush Spring is located in Precambrian rocks a few hundred yards south of the Hickory outcrop and 2.4 miles northeast of Pontotoc (Appendix C, 57-01-5a). The spring suggests that some water from the Hickory flows directly into fractures in the Precambrian rocks. The shallow water in the Precambrian rocks then flows southward following the land surface and discharges by evapotranspiration or baseflow.

CHEROKEE AREA

Local Flow Systems

Figure 32 shows the water table and potentiometric surface in the Cherokee area. Flow in most of the area is northward and eastward, following the slope of the land surface rather than the structural dip. This is evident in the western part of the Hickory outcrop area where flow is northeastward and the dip is northwestward.

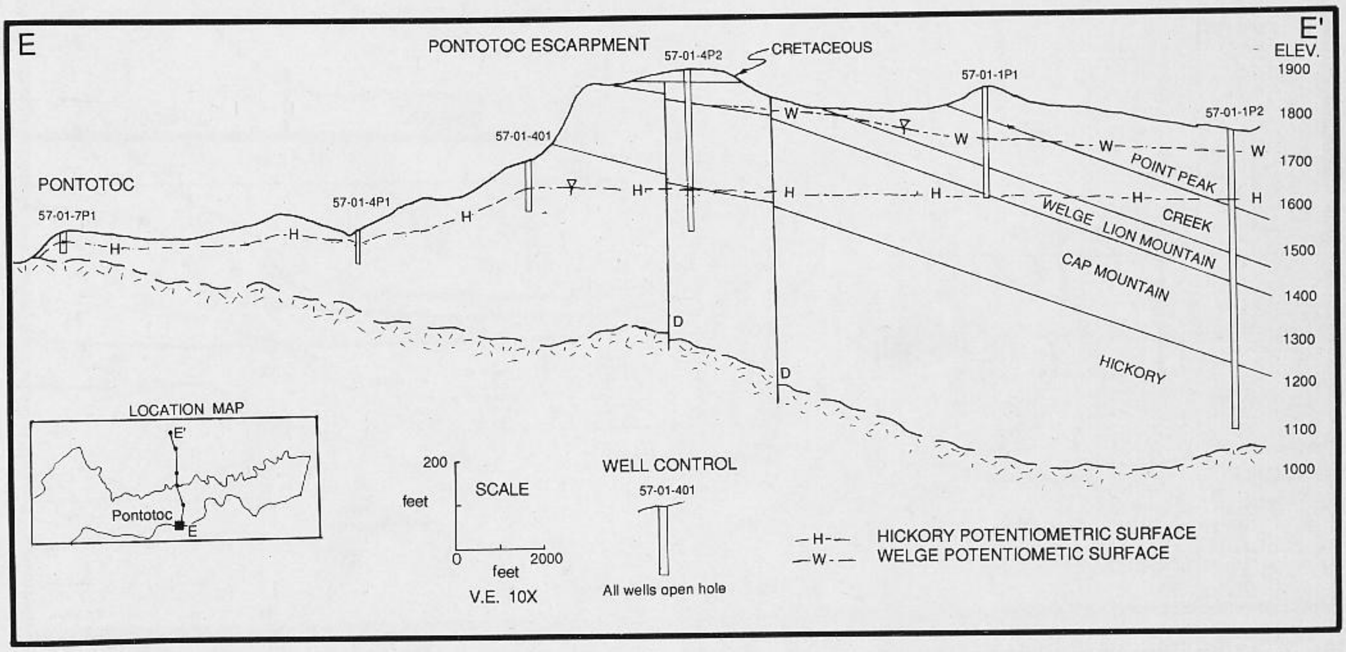


Fig. 29. South to north dip section in the Pontotoc area showing water levels in the Hickory and Welge aquifers in May 1988. A head difference of over 100 feet exists between the Welge and Hickory providing the potential for leakage through the Cap Mountain to recharge the Hickory downdip flow system.

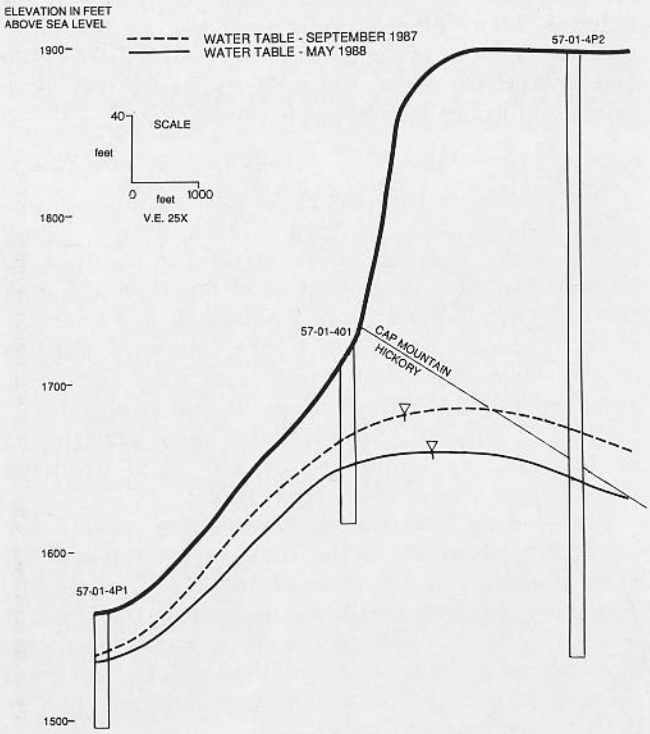


Fig. 30. Decline in the water table in Pontotoc escarpment area from September 1987 to May 1988. The greatest drop in water level occurs in well 57-01-4P2 at the top of the escarpment due to confined conditions. In May 1988, the gradient between wells 57-01-401 and 57-01-4P1 was 0.03 ft/ft. The steep gradient is a result of the low permeability of the middle facies of the Hickory and the steepness of the land surface.

Groundwater divides occur in the southern part of the outcrop near the drainage divide between Cherokee Creek drainage and Little Llano River drainage.

Effects of Fault Boundaries

Fault A in Figure 32 cuts through the western portion of the outcrop area. It has over 150 feet of throw and places the middle part of the Hickory against the lower part (Fig. 33). A steep gradient occurs on the potentiometric surface around the fault suggesting it acts as a partial barrier to flow. This is probably due to reduction in permeability from the lower to the middle part of the Hickory, but commutation of the sand grains along the fault zone may also have an effect.

Water level data are insufficient to show whether other faults in the outcrop area act as barriers to flow, but the amount of throw on the faults is similar to fault A, suggesting they may.

The southern end of the Darnoc fault and fault B are believed to act as boundaries to flow in the downdip part of the aquifer. Fault B is downthrown to the west placing the Hickory against the Precambrian rocks, and forming a barrier to flow. This may explain why well 41-59-702, located near the fault on the downthrown side, was reported to yield poor quality water when other Hickory wells in the area produce good quality water.

Recharge

The Hickory outcrop area south of fault A lacks developed stream channels and has deep sandy soils suggesting an area of little concentrated runoff and high infiltration. The water table surface in this area is higher than its surroundings showing the area to be a definite

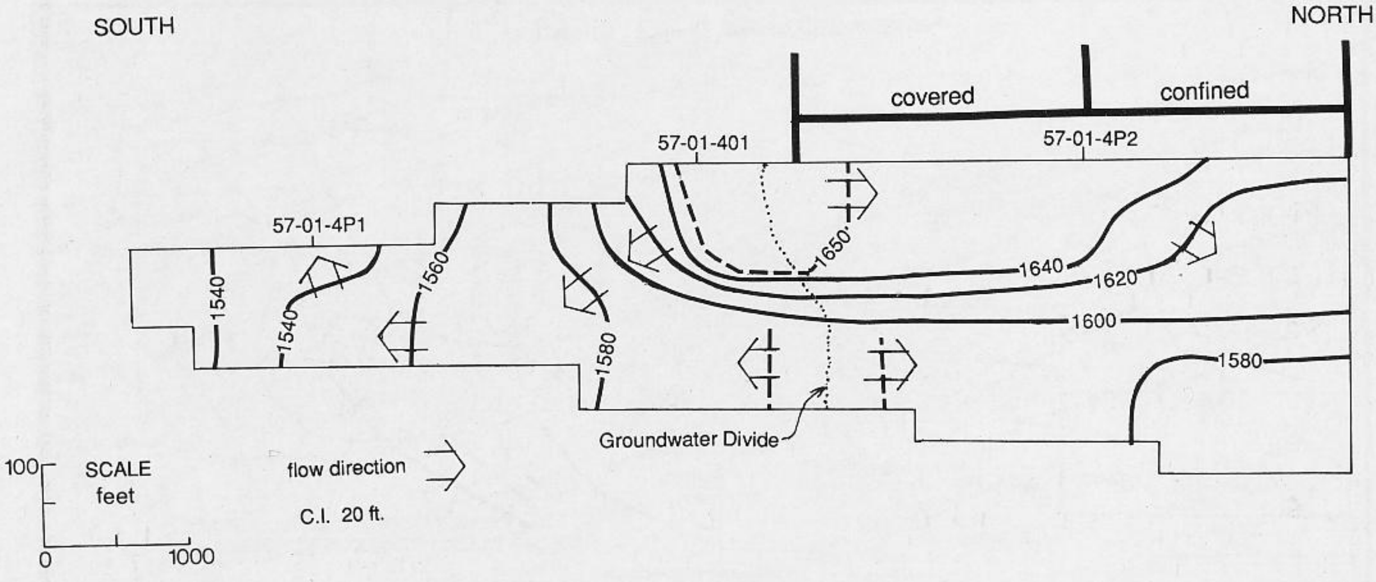


Fig. 31. Vertical flow net obtained from numerical model based on cross section in Figure 29. A downward gradient occurs north of the well 57-01-401 indicating a recharge area. An upward gradient occurs in the outcrop area indicating a discharge area. The position of the groundwater divide shows that most of the recharge to the northward downdip flow system comes from leakage in the covered and confined portions of the aquifer.

recharge area. However, bounding faults may reduce the amount of water flowing northward to the downdip part of the acquifer.

Figure 34 shows chloride concentrations from analyses of Hickory wells in the Cherokee area along with the month and year of the analysis. The increasing chloride concentration with time in wells 57-03-501 and 57-03-4P2 indicates that chloride is being introduced through recharge in the outcrop by recent human activities. Decreasing concentrations of chloride from the outcrop

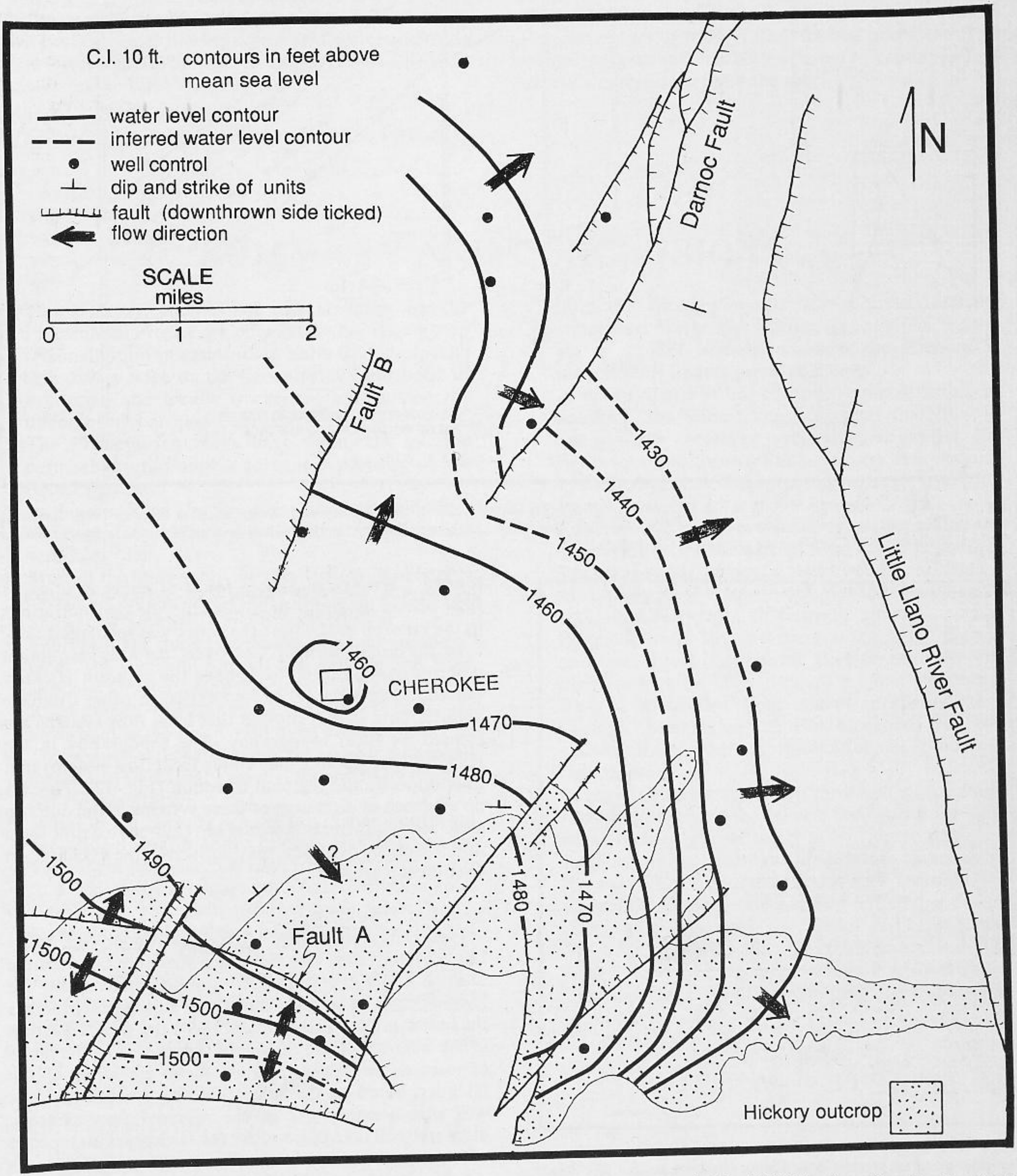


Fig. 32. Water table and potentiometric surface map of the Hickory aquifer in the Cherokee area in May 1988. Flow is northward and eastward toward the Darnoc and Little Llano River faults. Some flow is southward into the Precambrian rocks. Faults A and B appear to act as barriers to flow. A cone of depression occurs under Cherokee. See Figure 39 for well numbers and Appendix F for water level measurements.

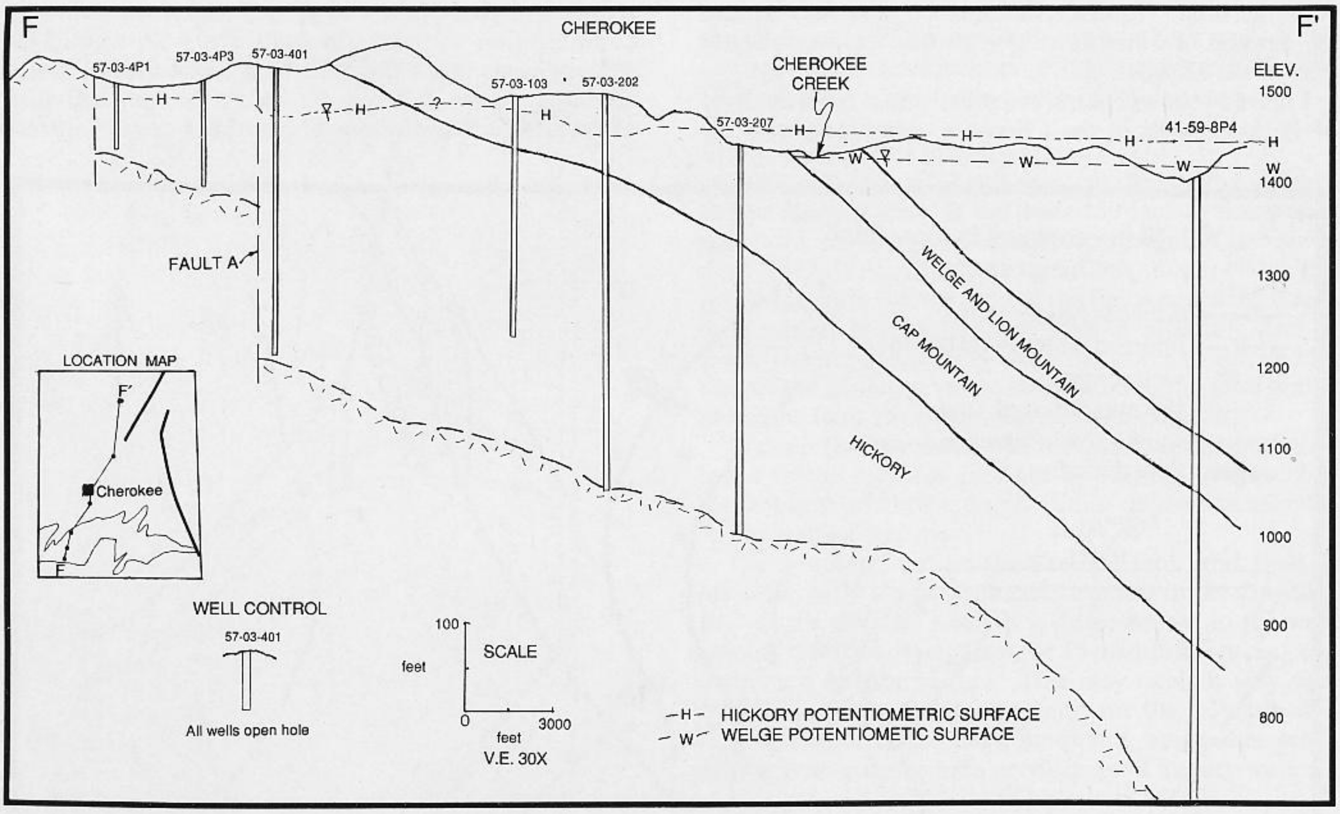


Fig. 33. South to north dip section in the Cherokee area showing water levels in the Hickory and Welge aquifers in May 1988. Recharge occurs in the outcrop and possibly as leakage from the Cap Mountain Limestone. Fault A in the Hickory outcrop acts as a partial barrier to flow. Wells north of Cherokee are artesian to the surface.

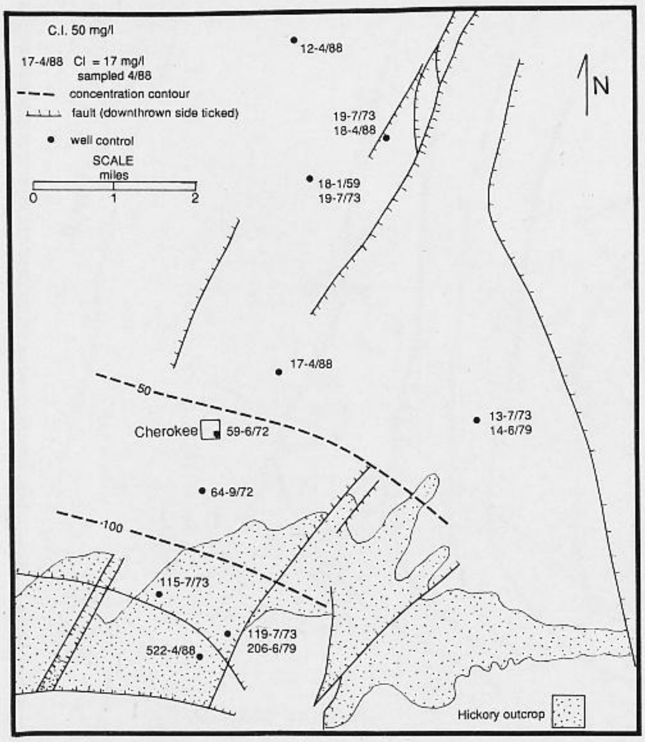


Fig. 34. Chloride concentrations in the Cherokee area. The concentrations are greatest in the Hickory outcrop, suggesting chloride is being introduced with recharge. The lower chloride concentrations around Cherokee appear to be due to the downdip flow of water that infiltrated when chloride concentrations were less.

toward Cherokee may be a result of either dilution as flow occurs downdip or lower chloride concentrations in the outcrop at the time the water was recharged.

In the area south of Cherokee, the Cap Mountain outcrop rises 50 to 60 feet above the adjacent Hickory outcrop. The same relief also exists on other drainage divides. Toth (1963) showed that local flow systems are created by local topography. The topography in the Hickory outcrop area may create local flow systems that flow opposite the regional direction (Fig. 32). There is no evidence of discharge of these systems in the outcrop area. More information would be required to define local flow systems, but they may influence the recharge in the outcrop area.

NATURAL DISCHARGE

Figure 32 shows flow directions toward the Little Llano River fault, into the ramp structure between the Darnoc and Little Llano River faults and toward the Darnoc fault. The flow directions suggest flow across the faults into the Ellenburger. The water table elevation in the Ellenburger on the downthrown side of the faults appears to be lower than the head elevation of the Hickory, based on the lack of flowing streams and one well measurement. As in the regional flow systems, discharge will take place where the Hickory is juxtaposed with permeable zones in the Ellenburger.

Some water also may discharge from the Hickory as vertical leakage upward through the Cap Mountain Limestone into the Welge aquifer. North of Cherokee, a difference in head of about 40 feet occurs between the Welge and the Hickory resulting in an upward vertical gradient (Fig. 33). Discharge from the Welge also appears to be into the Ellenburger across the Darnoc and Little Llano River faults.

Cherokee Creek is a major discharge point for the Ellenburger aquifer in southeastern San Saba County. Most Hickory water flowing across the Darnoc and Little Llano River faults is believed to discharge into Cherokee Creek from the Ellenburger aquifer.

ARTIFICIAL DISCHARGE

The cone of depression around Cherokee appears to be the result of artificial discharge through an estimated 30 to 40 domestic wells in the town (Fig. 32, 33). The decline in the potentiometric surface is probably between 10 and 20 feet in the middle of town. Well 57-03-2P1 is near Jackson Branch and about 2,500 feet from the cluster of wells in town. It is reported by the landowner to have flowed often in the past, but now to have ceased. The current water level is 8 to 10 feet below the land surface, suggesting it has been affected by the expanding cone of depression around the town.

SUMMARY AND CONCLUSIONS

1. The Hickory overlies an unconformity on the Precambrian rocks which causes the Hickory to regionally thin in eastern San Saba County, locally thin over a ridge on the unconformity northeast of Pontotoc, and locally thicken in a valley on the unconformity around Cherokee.
2. The Precambrian rocks have significant fracture permeability but appear to have a porosity of less than 2 percent.
3. In the San Saba County area, the Hickory aquifer has three facies which generally overlie each other vertically.
4. Most of the units overlying the Hickory are aquifers except for the Cap Mountain Limestone, Point Peak Shale, and Smithwick and Strawn Shales.
5. Faulting in the study area creates two main structural highs, the Richland Springs axis and the San Saba axis, and an intervening structural low, the San Saba River graben. Faulting severs the Hickory in several areas and juxtaposes it with overlying units.
6. The two major flow systems in the area are controlled by the two structural axes and separated by the San Saba River graben.
7. Water in the Hickory aquifer undergoes a chemical evolution downdip from a calcium-bicarbonate type water with less than 500 mg/l total dissolved solids to a sodium-bicarbonate type water with less than 1200 mg/l. The sodium-bicarbonate water has a lower amount of total dissolved solids and a different chemical composition from the sodium-chloride water in overlying aquifers. This indicates a lack of leakage into the Hickory aquifer in central and northern San Saba County.
8. Both regional flow systems are believed to discharge from the Hickory aquifer across faults into the juxtaposed Welge and Ellenburger aquifers. Faults act as aquifer boundaries when the Hickory is juxtaposed with less permeable units.
9. A sharp increase in chloride concentration in northern San Saba County suggests that flow in the Hickory becomes very sluggish under the Smithwick and Strawn Shale outcrop area because of limited natural discharge through the overlying shales.
10. The Valley Spring escarpment fault separates the Hickory outcrop area from the downdip aquifer. Recharge to the outcrop area is by direct infiltration of rainfall. Flow is southward into the Precambrian rocks and away from the downdip aquifer.
11. A groundwater divide occurs along the Pontotoc escarpment just north of the Hickory outcrop. The divide separates the northward major flow system from a southward flow system in the Hickory outcrop. Streams in the Pontotoc area Hickory outcrop act as discharge points for the southward flow system.
12. In the Cherokee area, flow is mostly northward and eastward following the general land surface. Faults in the outcrop appear to act as barriers to flow.
13. Recharge in the Cherokee area occurs primarily in the outcrop, but some leakage may occur in the adjacent Cap Mountain outcrop. Discharge occurs primarily as flow across the Darnoc and Little Llano River faults into the Ellenburger aquifer.
14. A 10-20 foot cone of depression has developed under Cherokee as a result of pumping from domestic wells.

RECOMMENDATIONS FOR FURTHER STUDY

1. Conduct a lineament analysis using aerial photographs in the Smithwick and Strawn outcrop areas to identify areas of faulting and possible horst blocks. Such a study could suggest sites for new deep wells in the area. The wells can avoid faulted areas where poor quality water might occur and where faults might create impermeable boundaries to the cone of depression around the well.
2. Conduct a study of the Welge aquifer by identifying Welge wells, creating potentiometric surface maps, collecting chemical analyses, and conducting aquifer tests. An aquifer test could be conducted at "Deep Creek at Pontotoc," a real estate development on FM 501 that will be entirely dependent on the Welge aquifer for water.
3. Conduct an aquifer test in the outcrop west of Pontotoc to determine transmissivity for irrigation well spacing in the area.
4. Conduct an aquifer test and well inventory at Cherokee to model the long-term drawdown under the town. Also install nested piezometers in order to help understand the flow system.
5. Study the water chemistry around Cherokee to determine the rate and causes of declining water quality in the Hickory outcrop in that area.
6. Develop a water budget for the water-bearing section from the Hickory through the Marble Falls based on the concept of one large interconnected flow system.
7. Sample for radioactivity in the Hickory and overlying aquifers to help interpret the flow systems and determine if excessive radioactivity occurs.

APPENDIX A

CALCULATION OF HEAD IN WELLS OPEN TO BOTH THE HICKORY AND WELGE AQUIFERS

Sokol (1963) showed that unpumped multi-aquifer wells will equilibrate to a composite head and that the head in each aquifer will affect the composite head proportional to the transmissivity of the aquifer. Based on Sokol's equation, the head in the Hickory was calculated in four wells open to both the Hickory and the Welge aquifers. The head in the Welge was extrapolated from a nearby well open only to the Welge. Because permeability in the aquifers is roughly equal, the transmissivity of the aquifer was assumed directly proportional to the thickness of the interval open to the aquifers. The table below gives the known data and the calculated head in the Hickory.

$$\frac{T1 \cdot H1 + T2 \cdot H2}{T1 + T2} = H1$$

or

$$\frac{Hw \cdot (T1 + T2) - T2 \cdot H2}{T1} = H1$$

Hw - head in the well
H1 - head in aquifer 1 (Hickory)
H2 - head in aquifer 2 (Welge)
T1 - transmissivity of aquifer 1 (Hickory)
T2 - transmissivity of aquifer 2 (Welge)

Data in Feet

Well no.	head in well	head in Welge	thickness of open interval in Hickory	thickness of open interval in Welge
41-59-8P3	1431.6	1419	230	60
41-59-8P4	1440.4	1428	180	68
57-01-1P2	1650.0	1720	150	70
57-03-1P6	1463.4	1464	115	60

Calculations

Head in Hickory above mean sea level

Well 41-59-8P3:

$$\frac{1431.6\ \text{ft} \cdot (230\ \text{ft} + 60\ \text{ft}) - 60\ \text{ft} \cdot 1419\ \text{ft}}{230\ \text{ft}} = 1435\ \text{ft}$$

Well 41-59-8P4:

$$\frac{1440.4\ \text{ft} \cdot (180\ \text{ft} + 68\ \text{ft}) - 68\ \text{ft} \cdot 1428\ \text{ft}}{180\ \text{ft}} = 1445\ \text{ft}$$

Well 57-01-1P2:

$$\frac{1650.0\ \text{ft} \cdot (150\ \text{ft} + 70\ \text{ft}) - 70\ \text{ft} \cdot 1720\ \text{ft}}{150\ \text{ft}} = 1617\ \text{ft}$$

Well 57-03-1P6:

$$\frac{1463.6\ \text{ft} \cdot (115\ \text{ft} + 60\ \text{ft}) - 60\ \text{ft} \cdot 1464\ \text{ft}}{115\ \text{ft}} = 1464\ \text{ft}$$

APPENDIX B

WELL NUMBERING SYSTEM AND WELL LOCATION MAPS

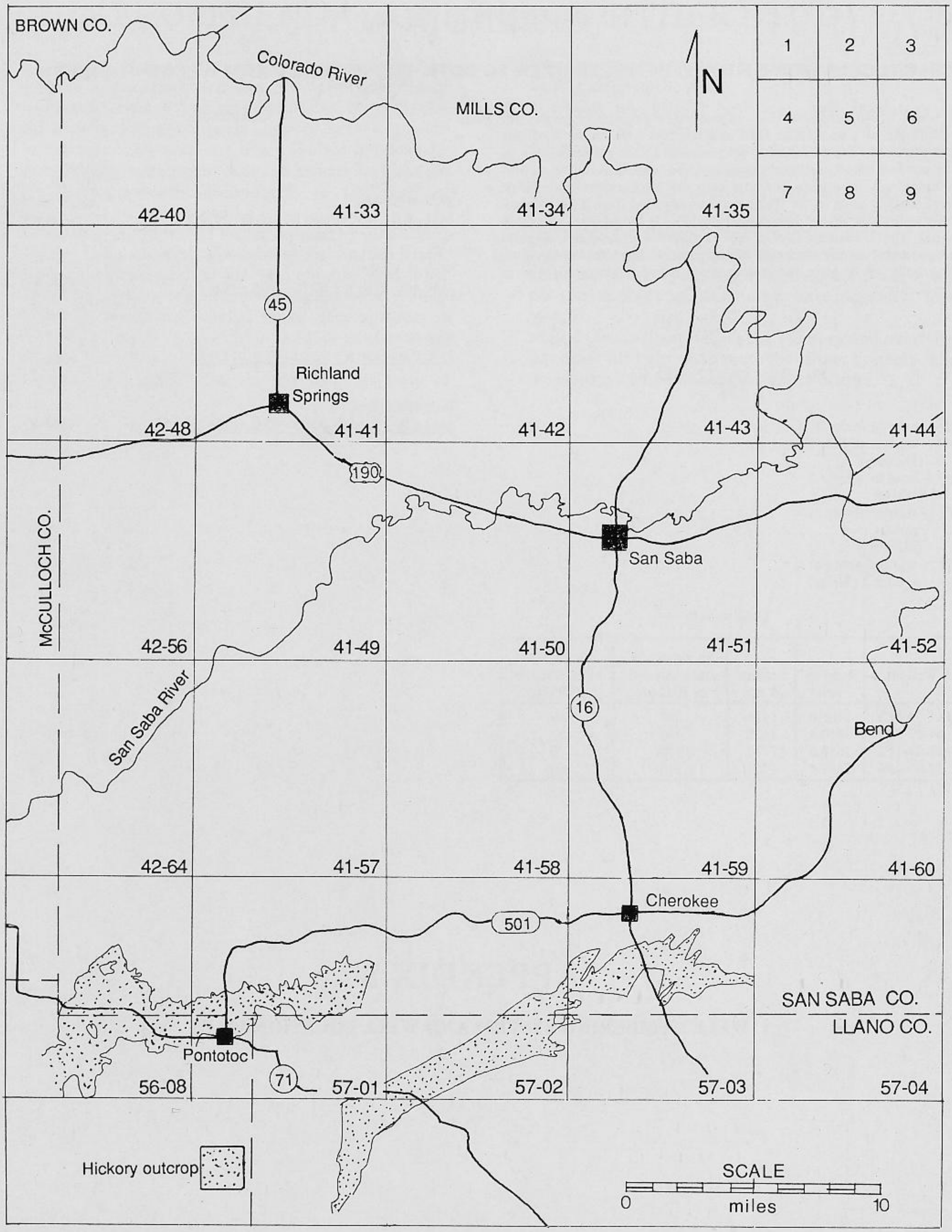


Fig. 35. State well numbering system. Each 7.5 minute quadrangle is divided into nine 2.5 minute areas numbered in the upper right corner of the map. Wells are numbered by the 7.5 minute and 2.5 minute areas they are in and a two-digit number. Well 2 in area 5 of quadrangle 41-49 would be well 41-49-502.

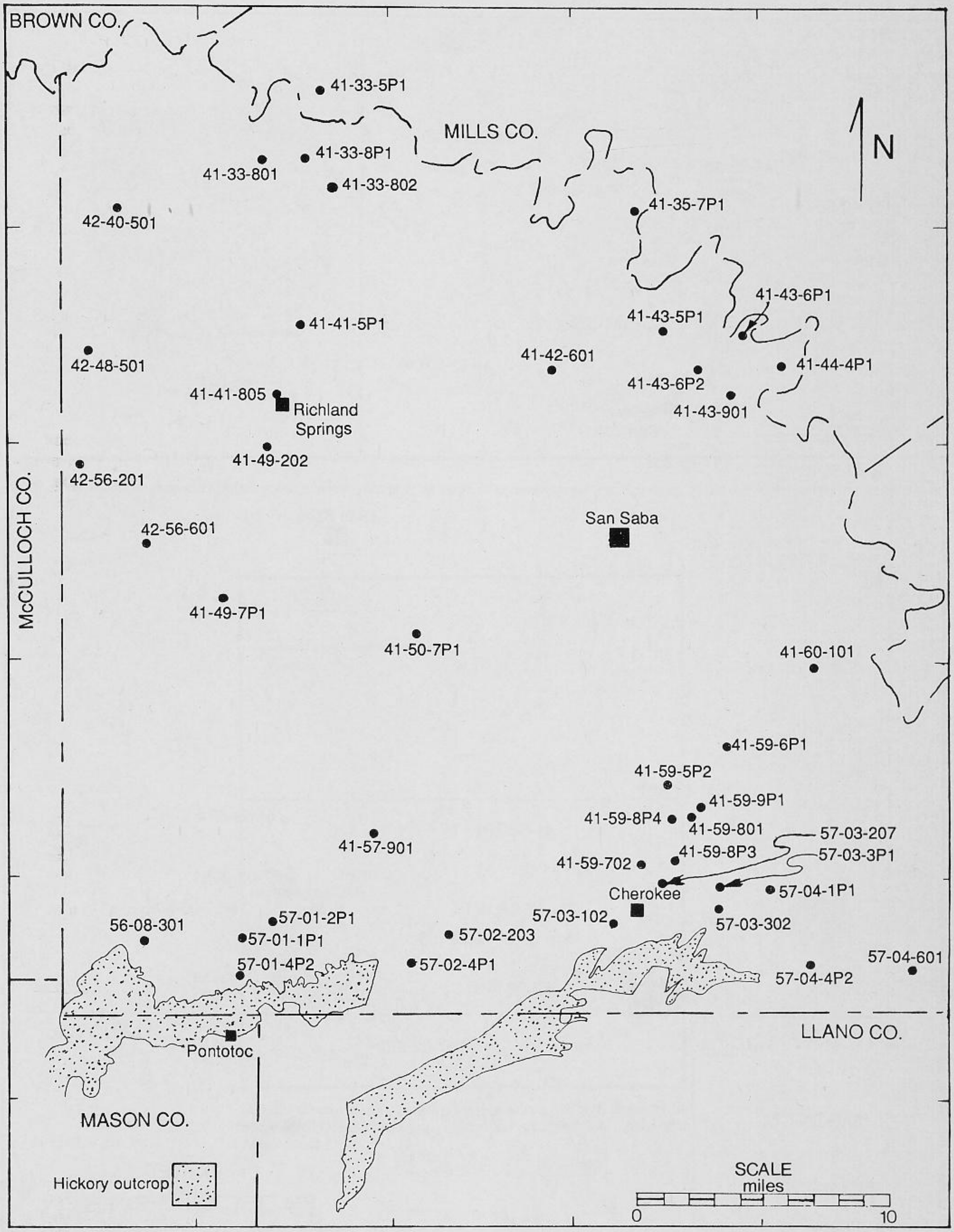


Fig. 36. Regional well number map for Figure 23 (structural contour). Well numbers correspond to well log data in Appendix I.

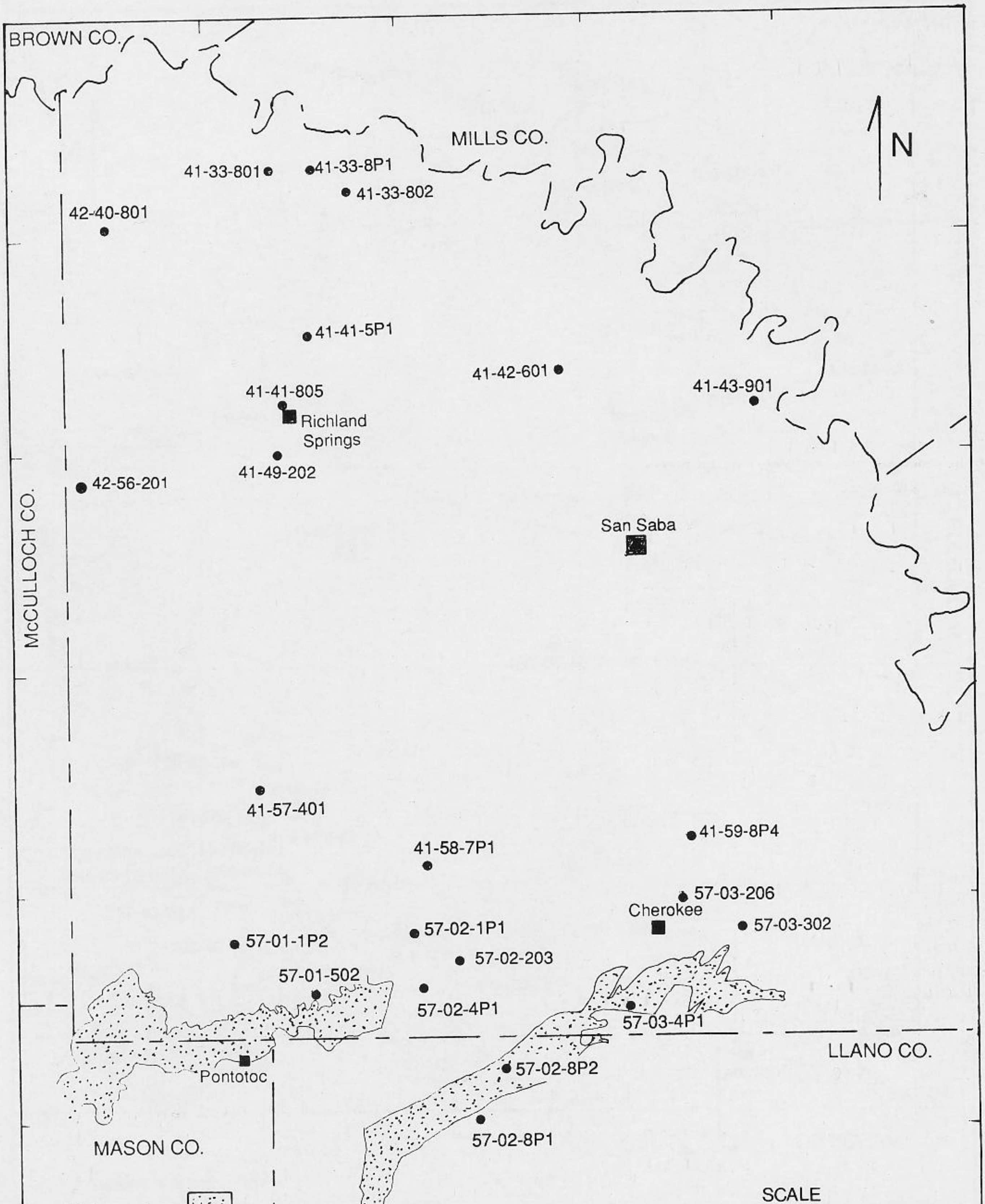


Fig. 37. Regional map showing locations and well numbers for water level measurements in Appendix F and chemical analyses in Appendix G.

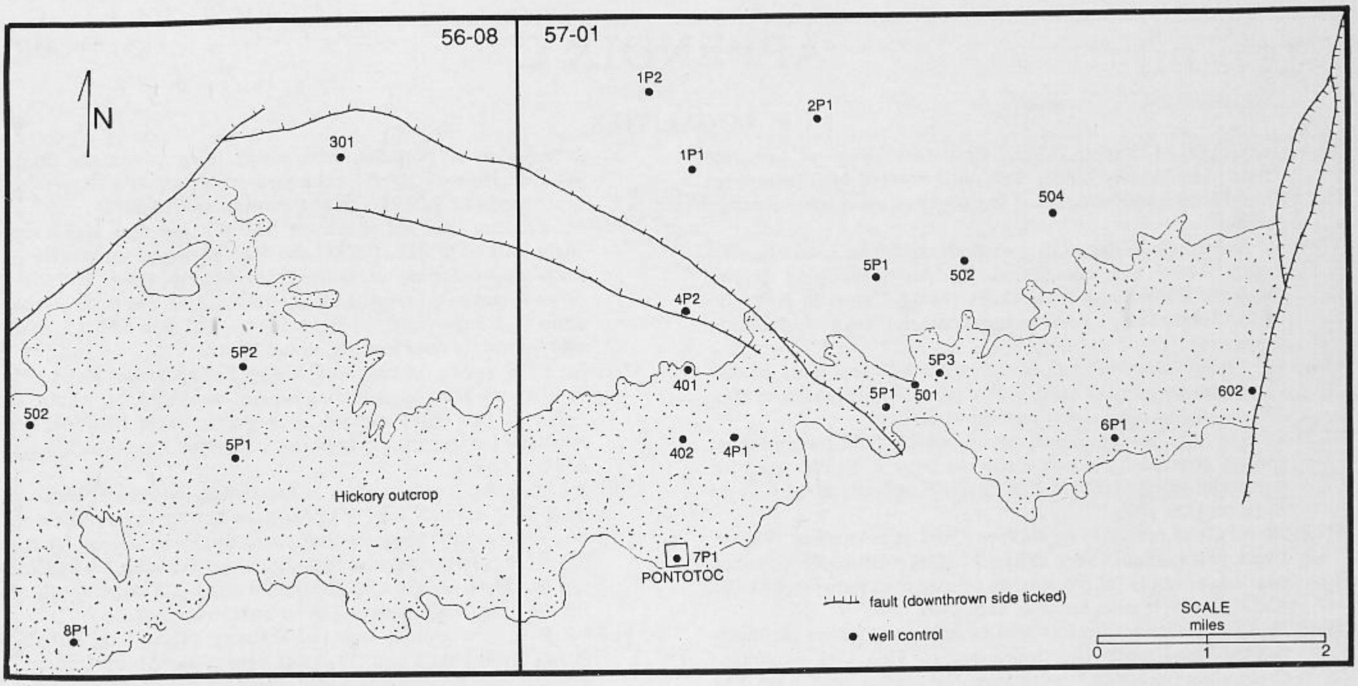


Fig. 38. Pontotoc area map showing locations and well numbers for water level measurements in Appendix F and chemical analyses in Appendix G.

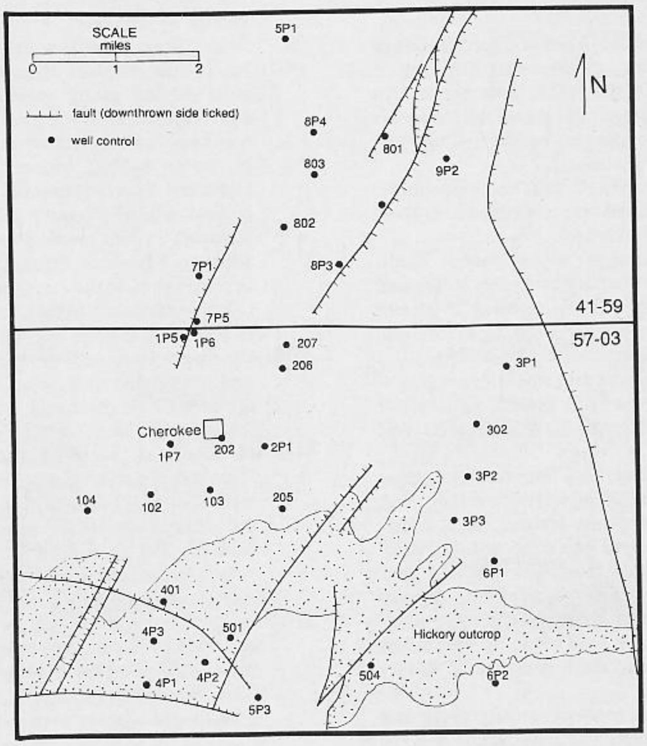


Fig. 39. Cherokee area map showing locations and well numbers for water level measurements in Appendix F and chemical analyses in Appendix G.

APPENDIX C

LOCALITIES

41-41-7a: Richland Spring, slight flow from base of concrete foundation for city supply well, area covered by alluvium (in city of Richland Springs, 250 feet north of main street through town).

41-43-6a: Blue Bluff, 30 feet of Strawn shales with thin sand stringers, highly folded and convoluted, represents slumping of soft sediment from Shaw Bend faults (along Colorado River on Mills County side, 1.5 airline miles east-northeast of McMillan Cemetery).

41-49-1a: Linear sink holes in Ellenburger, 5-10 feet wide, shows cavernous porosity of the Ellenburger (2.9 miles south of U.S. 190 on county road, 0.4 miles west in pasture).

41-51-4a: San Saba Springs, discharge in Marble Falls outcrop area, springs covered by pond, discharge around 10 cfs, used for municipal supply (east end of city of San Saba at Mill Pond Park off U.S. 190).

41-58-7a: 1-2 cfs of baseflow on Wallace Creek at junction of Wallace Creek and Latham Creek at upper end of Wallace Creek valley near major faults (at crossing on county road between FM 501 and U.S. 190, 9 miles south of U.S. 190).

41-58-7b: 5 feet of Cretaceous Edwards Limestone in borrow pit, thinly bedded, hard white limestone, part of Shin Oak Mountain Cretaceous outlier (2.7 miles north on county road from FM 501).

41-59-8a: 6 feet of Point Peak shale in borrow pit, by county road at edge of Cherokee Creek alluvium, interbedded shale and limestone probably near top of member, broad floodplain of Cherokee Creek result of weathering of Point Peak (2.5 miles northeast on county road from Highway 16, turn off near Cherokee Home).

41-59-8b: Lion Mountain Sandstone exposed in bed of Cherokee Creek below low water dam, glauconitic, medium- to fine-grained sandstone; 1-2 cfs of baseflow in the creek, flow appears to decrease downstream (low water dam 1.7 miles northeast on county road from Highway 16 at exit just north of Cherokee, two crossings within 1.5 miles downstream).

41-59-8c: Welge Sandstone in bed of Cherokee Creek, non-glauconitic, coarse grained (2.2 miles northeast on county road from Highway 16 at exit just north of Cherokee).

41-59-9a: Steeply dipping beds of Ellenburger along Darnoc Fault, beds become horizontal and unfaulted about 20 feet to the east (1.6 miles, northeast on county road from Highway 16 at exit just north of Cherokee, west on pasture road to creek, and north in creek bed; see George Epperson for permission).

56-08-4a: Beds dipping eastward 30-40 degrees with small-throw, down-to-the-west faults, part of Fredonia fault system, calichefied, probably Point Peak (in roadcut on U.S. 71, 0.2 miles east of Fredonia.

56-08-8a: Hickory Hollow section; 0-50 feet, very fine- to very coarse-grained sandstone, very fine sand is powdery, overlies pink micaceous gneiss; 50-110 feet, very fine-grained sand, cross-bedded, average 4-inch thick bed, some hematitic nodules, wavy silty laminations; 110-140 feet, shaly sandstone; 140-180 feet, slightly to moderately hematitic sandstone, very fine to very coarse sandstone (1.5 miles south of U.S. 71 on county road, gate at westward turn in road, pasture road to escarpment down ravine west of cabin with spring and dam, property of Randy Baker of Brady).

57-01-3a: 20 feet of Point Peak shale in roadcut, mostly shale and silt with interbedded thin limestones (on FM 501, 1.8 miles from eastward turn north of Pontotoc escarpment).

57-01-3b: San Saba Limestone exposed in shallow swale, in Potter Flats, beds have rectangular fracture pattern, and 5-10 degree dip indicating nearby fault, San Saba outcrop normally rugged, so extremely flat terrain indicates pedimented surface extending from base of Shin Oak Mountain Cretaceous outlier to Cherokee Creek, topographic map suggests two levels are present with a break on the Kuykendall Ranch (0.2 miles north of FM 501, on county road to San Saba, east of county road).

57-01-4a: Upper facies of Hickory and lower Cap Mountain Limestone in roadcut at Pontotoc escarpment, Cap Mountain thinly bedded, Hickory tightly cemented with hematite decreasing downward (1.7 miles north of Pontotoc on FM 501).

57-01-4b: Crossing of Field Creek on FM 501, standing water and slight flow on 9/5/88, 1/6/88, and 5/25/88 appears to discharge from upper facies; at crossing of county road 3500 feet downstream in outcrop of middle facies creek bed dry on same dates (1.7 miles north of Pontotoc on FM 501 and 0.5 miles east on county road just past county line).

57-01-5a: Bush Spring in fractured Valley Spring gneiss just south of Hickory outcrop, standing water, no discharge, photo in figure 12 (2.2 miles west on county road from FM 501, 0.1 miles south of road in dry tributary to Panther Creek, a tributary of Field Creek).

57-01-5b: Standing water in deep ravine in Cap Mountain outcrop on 9/6/88, 4/23/88, and 5/25/88, does not appear to be result of recent runoff, suggests that some discharge occurs on the Pontotoc escarpment, also indicates water available for leakage can be stored by the Cap Mountain itself (1.5 miles south of FM 501 on county road, 0.2 miles west to ravine).

57-01-6a: 40 feet of middle facies of Hickory exposed on hillside, thinly bedded sand and silty sand capped by 2-foot, medium-grained, case-hardened massive sandstone apparently supporting hillslope (3.3 miles northeast on county road from Field Creek on U.S. 71, first intersection veer right, second turn left; outside entrance to 7 PE Ranch owned by Betty Low).

57-01-6b: Estimated 0.5 cfs of flow on Cold Creek at culvert just south of the Hickory outcrop fall of 1987 and spring of 1988, vegetation downstream indicates perennial flow, area covered mostly by alluvium, Precambrian rocks exposed downstream from culvert (4 miles south of FM 501 on county road).

57-01-7a: 20 feet of basal Hickory overlying Precambrian gneiss in road ditches along county road south of Pontotoc, partly covered; Precambrian gneiss fine grained, pink and micaceous; 5 feet above Precambrian, coarse- to medium-grained sandstone, brown to reddish brown, reddish tint due to pink feldspar, estimated 5 percent granule size quartz and feldspar, calcareous cement, visible porosity appears to be result of dissolution of feldspar; 15 feet above Precambrian, medium- to fine-grained white to brown sandstone, 1 percent granule size quartz, with occasional ⅛-inch coarse-grained layers, case hardened with calcareous cement (road ditch along county road, 0.2 miles south of Pontotoc at edge of Pontotoc Creek valley).

57-01-7b: Slight flow on Pontotoc Creek, ponded water in channel and vegetation suggesting water ponded there perennially, appears to be discharge from lower facies (0.4 miles east of junction of FM 501 and U.S. 71).

57-01-8a: Gneiss at top of Panther Rock ridge, no visible difference from rest of gneiss in area, weathering of gneiss produced rugged terrain of 10-20 foot high columns and boulders at top of ridge only, may be related to fault which cuts through the Cambrian rocks to the north and whose trace lines up with the divide between Panther Rock ridge and adjacent High Rock ridge (on county road 1 mile northeast of Field Creek at U.S. 71).

57-01-9a: 20 feet of upper hematitic facies of Hickory Sandstone, dusky red, well rounded, very coarse to coarse, massive beds 1-2 feet thick, strongly cemented with hematite overlain by 3 feet of Cap Mountain Limestone, sandy gray to brown limestone, gradational contact between two members, photo in figure 14 (roadcut on U.S. 71, 5 miles east of Valley Spring).

57-02-3a: Hext Spring issues approximately 1 cfs from solution cavity in San Saba Limestone in fall of 1987 (on property just west of FM 501 crossing of Cherokee Creek; see Tom Dean for access).

57-02-8a: Sand Spring issues out of fracture in lower facies of Hickory, located in incised dry tributary to Sand Spring Creek, estimated discharge on 10/27/88 approximately 1 cfs, discharge soaks into soil downsteam, suggests complex flow paths in the outcrop area as a result of faulting (on T-Stripe Ranch, 1 mile north of Valley Spring; see W. C. Buntyn for access).

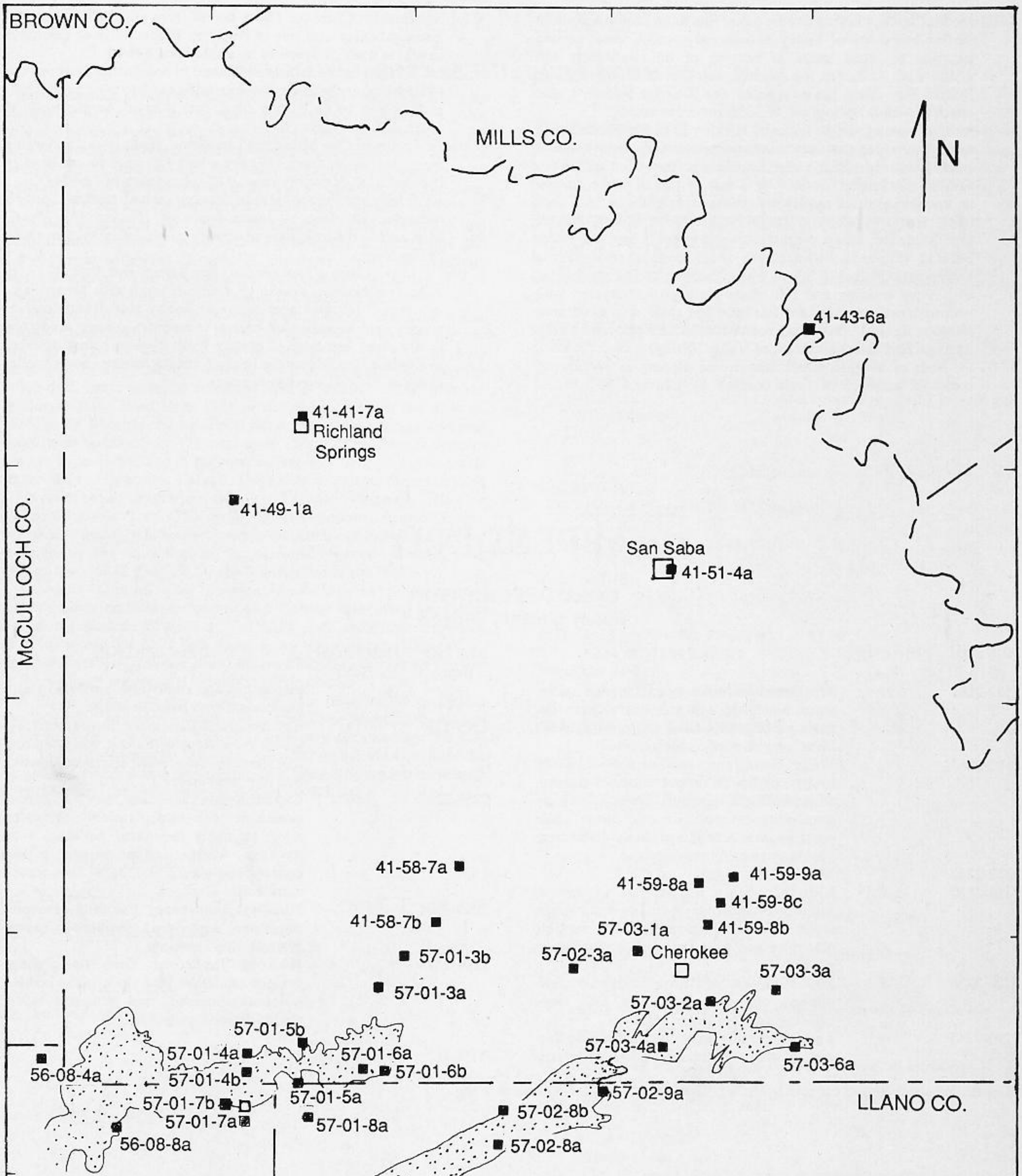


Fig. 40. Locality map. Localities are numbered by the state well numbering system in Figure 35 with the exception that a letter is used in place of the last two digits.

57-02-8b: McClatchey Spring issuing out of San Saba Limestone about 20 feet below top of Valley Springs escarpment, water carried by pipe to stock tanks at bottom of hill, extremely flat pedimented surface at top of escarpment, several other springs located high along the escarpment (on T-Stripe Ranch, 1 mile north of Valley Spring; see W. C. Buntyn for access).

57-02-9a: Outcrops of middle facies of Hickory in bed of Pecan Creek near county road crossing; tributary upstream adjacent to county road, 2 feet of reddish brown, medium-grained sand with wavy bedded silt lenses, overlain by 3 feet of tan to white coarse- to medium-grained sand with tabular crossbeds up to 1 foot thick, scattered albite grains in well-rounded quartz, surface case hardened, sharp contact between upper 3 feet and lower 2 feet; 15 yards downstream from county road facing downstream, 4 feet of tan to white, medium to fine sandstone, with wavy bedding and thin shale partings; interlayered with yellowish tan, wavy bedded fine sand and shale, sharp contacts, photo in figure 13 (at county road between Cherokee and Valley Springs, 6.85 miles northeast of Valley Spring).

57-03-1a: Beds of Morgan Creek Limestone, dipping at 30 degrees, indicates presence of fault covered by alluvium, 1-2 cfs of baseflow on Cherokee Creek across fence (on L. D. Boultinghouse property west side of Highway 16 just north of Cherokee Creek, at back of property by abandoned house).

57-03-2a: 3-5 foot red hematitic sandstone in road ditch marking top of Hickory, underlain by nonhematitic sandstone (1.5 miles east of Highway 16 on county road, first turn-off on Highway 16 south of Cherokee).

57-03-3a: Spring in Cap Mountain Limestone, slight flow discharging through fracture from Hickory which has an artesian head in the area (east of county road, 0.65 miles south of FM 501).

57-03-4a: Gently rolling topography lacking incised stream channels indicates underlain by lower facies of Hickory (on W. C. McKneely property, west of county road, 2.4 miles due south of Cherokee).

57-03-6a: Little Llano River section, see Barnes and Bell (1977, p. 132); crossbedded, coarse to medium sand with granule-size quartz and feldspar near house at Bobby Hall Ranch east of county road; crossbedded coarse- to medium-grained sandstone in dry creek bed west of county road; 10-foot hematitic layer just below Cap Mountain in road cut on county road (2 miles south of FM 501 on county road).

APPENDIX D

CORE DESCRIPTION
Bobby Griffith, Softge # 1

DEPTH* (feet)	THICKNESS (feet)	DESCRIPTION
2122-2161	39	Morgan Creek limestone, calcareous wackestone, bioclastic, light gray with reddish tint, shale partings, styolites, one laminated silt layer, one hematitic sandy layer.
2161-2203	42	Welge Sandstone, sandstone with shale, lower coarse- to upper medium-grained, white to light gray to green, sparingly glauconitic except for one zone; shale partings, wavy bedding, thinly laminated; visible dissolution porosity.
2203-2210	7	Missing
2210-2220	10	Lion Mountain Sandstone, calcareous cemented sandstone with bioclastic limestone streaks, medium-grained, variable glaconite and hematite, visible dissolution porosity.
2220-2226	6	Lion Mountain Sandstone, medium- to fine-grained sandstone and shale with wavy bedding and thin flaser bedding.
2226-2245	19	Lion Mountain Sandstone, medium- to fine-grained sandstone interbedded with bioclastic packestone and some shale partings, mostly glauconitic with some hematite.
2245-2259	14	Cap Mountain Limestone, medium- to fine-grained sandstone with shale, wavy bedding, thin flaser bedding, some calcareous streaks, one thin wackestone.
2259-2295	36	Cap Mountain Limestone, very fine-grained sandstone with shale, variably cemented, wavy to finely laminated bedding, shale partings, white to light brown, almost entirely non-glauconitic, some thin wackestone beds.
2295-2304	9	Hickory Sandstone, hematite-cemented sandstone, dusky red, medium- to coarse-grained, shale partings.
2304-2311	7	Hickory Sandstone, fine- to medium-grained sandstone with shale, wavy bedded, dolomite-cemented, thin hematitic layers, visible dissolution porosity.
TOTAL	189	

*Depths are those logged on core by driller. They are at variance with electric log.

APPENDIX E

ESTIMATION OF TRANSMISSIVITY FROM WELL DATA

Data recorded on driller's logs for three wells in the Cherokee area completed in the middle and lower facies of the Hickory are given below. The wells were pumped at different rates, increasing through time. Although an exact transmissivity cannot be calculated from these data, an approximation can be made. Equation (1) is described by Logan (1964, p. 36) and, based on the Thiem equation, approximates T when Q, s, ro, and rw are known. Because ro is usually not known, equations (2) and (3) were developed assuming average confined and unconfined conditions, respectively. By using the pumping rate and drawdown in equations (2) and (3), the approximate transmissivity was calculated. The permeability (hydraulic conductivity) was calculated by dividing by the saturated thickness (equation 4).

In 1973, well 41-42-601 was drilled for the North San Saba Water Supply Corporation by J. L. Myers. The well was pumped for one week at a rate of 82.5 gpm and the initial and static heads were measured. In addition, the well has been in use since 1974 and the volume of water pumped from the well is known, along with the decline in static head from 1973 to the present (Jacob and Martin, 1986, p. 8). Because the aquifer is deeper than the average confined conditions assumed in (2), equation (5), the distance-drawdown modification of the Jacob approximation, was used to approximate ro based on a reasonable T and S. T was then calculated using equation (1) in order to improve the estimation of T from equation (2). Equation (2) would give a T of 4500 gpd/ft, while equations (1) and (5) give a T of 5270 gpd/ft, which is believed to be a better estimation. Dividing through by the thickness of the screened interval would give a permeability of 42 gpd/ft/ft for the lower facies of the Hickory.

The main assumption for this approximation is that the drawdown approximates equilibrium conditions. Calculations using the Theis equation (equation 6) with a T of 5270 gp/ft show that the value of W(u) would be 20.7. This value is on the asymptotic portion of the Theis curve, which indicates that drawdown is occurring very slowly in the well and approaches equilibrium conditions.

A further check for the T and S values is obtained by predicting the long-term drawdown since 1973. The Theis equation (equation 6) gives a drawdown of 21 feet at an arbitrary distance near the well of 1 foot. This compares favorably with the actual drawdown in the well of 24.6 feet. Because pumpage has not been constant but increasing over the years, the comparison is limited in validity.

Equations

$$(1)\quad T = \frac{528 \cdot Q \cdot \log(ro/rw)}{s}$$

$$(2)\quad T = \frac{2000 \cdot Q}{s}\ \text{(confined)}$$

$$(3)\quad T = \frac{1500 \cdot Q}{s}\ \text{(unconfined)}$$

$$(4)\quad K = T/b$$

$$(5)\quad ro = \sqrt{\frac{T \cdot t}{4790 \cdot S}}$$

$$(6)\quad S = \frac{T \cdot t \cdot u}{2693 \cdot r^2}$$

$$(7)\quad s = \frac{114 \cdot Q \cdot W(u)}{T}$$

where Q - pump rate (gpm)
ro - radius of cone of depression (ft)
rw - radius of well (ft)
r - radius from well (ft)
s - drawdown (ft)
K - permeability (gpd/ft/ft)
T - transmissivity (gpd/ft)
b - saturated thickness (ft)
W(u) - non-equilibrium well function for variable u
t time (min)
S - -storage coefficient

Data

Shallow outcrop wells

Well no.	depth (ft)	max pump rate (gpm)	drawdown (ft)	saturated thickness (ft)	confined or unconfined
57-03-501	186	125	60	120	unconfined
57-03-103	270	175	250	210	confined
57-03-1P6	444	200	105	155	confined

Deep confined well (41-42-601)

Flow test - 1973
s - 37 ft
Q - 82.5 gpm
t - 10020 min
S - .00005 (assumed)
b - 126 ft

Long term drawdown 1973-1988
s - 24.6 ft
t - $7.36\text{x}10^6$ min (14 years)
total volume pumped - $2.7\text{x}10^8$ gal
average Q - 37 gpm

Calculations

Well 57-03-501:

$$(3)\quad \frac{1500 \cdot 125\ \text{gpm}}{60\ \text{ft}} = T = 3125\ \text{gpd/ft}$$

$$(4)\quad \frac{3125\ \text{gpd/ft}}{120\ \text{ft}} = K = 26\ \text{gpd/ft/ft}$$

Well 57-03-103:

$$(3)\quad \frac{2000 \cdot 175\ \text{gpm}}{250\ \text{ft}} = T = 1420\ \text{gpd/ft}$$

$$(4)\quad \frac{1420\ \text{gpd/ft}}{210\ \text{ft}} = K = 7\ \text{gpd/ft/ft}$$

Well 57-03-1P6:

$$(3)\quad \frac{2000 \cdot 200\ \text{gpm}}{155\ \text{ft}} = T = 2580\ \text{gpd/ft}$$

$$(4)\quad \frac{3810\ \text{gpd/ft}}{105\ \text{ft}} = K = 25\ \text{gpd/ft/ft}$$

Well 41-42-601

Approximate ro to calculate T

$$(2)\quad \frac{(2000) \cdot (82.5\ \text{gpm})}{37} = T = 4500\ \text{gpd/ft}$$

$$(5)\quad \sqrt{\frac{(4500\ \text{gpd/ft}) \cdot (10{,}020\ \text{min})}{4790 \cdot (.00005)}} = ro = 13{,}370\ \text{ft}$$

Calculate T by Logan's method

$$(1)\quad \frac{528 \cdot 82.5\ \text{gpm} \cdot \log(13{,}372\ \text{ft}/\ .45\ \text{ft})}{37\ \text{ft}} = T = 5270$$

Divide by saturated thickness to obtain permeability

$$(4)\quad \frac{5270\ \text{gpd/ft}}{126\ \text{ft}} = 42\ \text{gpd/ft/ft}$$

Calculate W(u) to show changes in drawdown will be small

$$(7)\quad \frac{114 \cdot (82.5\ \text{gpm}) \cdot W(u)}{5270} = 37\ \text{ft} \qquad W(u) = 20.7$$

Calculate long-term drawdown 1973-1974 based on estimated T and S

$$(6)\quad \frac{5270\ \text{gpd/ft} \cdot (7.36\text{x}10^6\ \text{min}) \cdot u}{2693 \cdot 1^2} = .00005$$

$$u = 3.56\text{x}10^{-12}$$

$$W(u) = 25.82$$

$$(7)\quad \frac{114 \cdot (37\ \text{gpm}) \cdot 25.82}{5270} = 21.0\ \text{ft}$$ drawdown close to actual drawdown of 24.6 ft.

APPENDIX F

WELL MEASUREMENTS AND RAINFALL DATA

WELL MEASUREMENTS

Well No.	AQ	Land Elev.	MP	Measured	Date	Measured	Date
41-33-801	hwe	1318	4.0	60 gpm	9/14/87		
41-33-802	hwe	1370	?	flows	7/10/73		
41-33-8P1	hwe	1382	2.0	8 gpm	10/3/87		
41-41-401	e	1416	?	918 gpm	1947	318	7/13/61
41-41-5P1	h	1500	2.0	46.8 ft	1/5/88		
41-41-805	e	1362	10	12.2 ft	1/5/88		
41-42-601	h	1370	3.0	+101.6 ft	8/6/73	+78.0 ft	9/15/87
41-43-901	hwe	1255	4.0	75 gpm	9/15/88		
41-49-202	hwe	1445	?	flows	8/14/73		
41-57-401	e	1530	0.5	189.5 ft	9/19/84		
41-58-7P1	we	1830	1.3	288.1 ft	1/5/88	314.1 ft	5/24/88
41-59-5P2	hwe	1425	0.5	20 gpm	1/6/88		
41-59-7P1	w	1495	0.8	36.1 ft	9/15/87		
41-59-7P5	w	1470	1.1	34.9 ft	5/26/88		
41-59-801	hw	1402	1.0	flows	10/4/88	0.2 gpm	4/24/88
41-59-802	w	1450	0.2	8.52 ft	9/15/87	21.9 ft	5/26/88
41-59-803	hw	1410	0.0	flows	9/15/88		
41-59-8P3	hw	1452	0.5	17.1 ft	10/4/87	20.9 ft	5/26/88
41-59-8P4	hw	1412	3.0	+25.4 ft	5/24/88		
41-59-8P6	hw	1440	0.9	flows	9/15/88		
41-59-9P2	e	1445	1.0	113.4 ft	5/26/88		
42-40-801	hwe	1531	?	near top	1949		
42-56-201	hwe	1625	0.8	138.8 ft	7/12/73		
56-08-301	h	1800	0.0	75 ft	1972		
56-08-502	h	1720	1.0	55.4 ft	1/6/88	55.9 ft	5/25/88
56-08-5P1	h	1745	0.2	153.0 ft	9/6/87	151.2 ft	1/6/88
				150.6 ft	5/24/88		
56-08-5P2	h	1710	0.1	113.7 ft	1/6/88	112.5 ft	5/24/88
56-08-8P1	h	1800	1.2	25.2 ft	5/24/88		
57-01-1P1	w	1865	1.5	119.8 ft	9/6/88	127.2 ft	5/25/88
57-01-1P2	hw	1775	0.5	125.0 ft	9/6/88		
57-01-401	h	1717	1.1	65.0 ft	5/24/88		
57-01-4P1	h	1565	0.2	27.3 ft	9/5/88	28.3 ft	1/6/88
				29.3 ft	5/25/88		
57-01-4P2	h	1890	1.6	237.8 ft	4/23/88	248.3 ft	5/25/88
57-01-501	h	1658	0.5	41.0 ft	7/23/73		
57-01-502	h	1752	1.3	63.0 ft	9/6/87	78.4 ft	4/23/88
				80.0	5/25/88		
57-01-5P1	h	1971	?	371	10/4/76		
57-01-5P2	h	1615	0.4	36.3	9/6/87	34.1	5/25/88
57-01-5P3	h	1635	0.0	23.3	9/6/87	23.6	5/25/88
57-01-6P1	h	1620	0.4	71.8	10/27/87	67.9	5/25/88
57-01-7P1	h	1562	3.0	26.3	9/6/87	26.5	1/6/88
				22.9	5/25/88		
57-02-1P1	e	1805	1.0	169.8 ft	9/5/87	171.8 ft	1/5/88
				171.7 ft	5/25/88		
57-02-301	w	1570	1.0	71.9 ft	10/31/86		
57-02-4P1	hw	1750	0.0	222.6 ft	10/27/87	223.6 ft	5/26/88
57-02-8P1	p	1400	0.8	13.4 ft	10/27/87	35.6 ft	5/24/88
57-02-8P2	h	1530	0.0	92.6 ft	10/27/87	93.8	5/24/88
57-03-102	h	1550	1.0	67.4 ft	5/26/88		
57-03-103	h	1508	1.2	21.6 ft	1/4/88	24.7 ft	5/26/88
57-03-104	h	1570	0.0	80.7 ft	7/26/73		
57-03-1P5	w	1481	1.0	17.2 ft	1/4/88	18.1 ft	5/25/88
57-03-1P6	h	1476	0.5	12.9 ft	5/26/88		
57-03-1P7	h	1515	1.0	43.4 ft	5/26/88		
57-03-202	h	1503	1.0	45.7 ft	1/4/88	46.9 ft	5/26/88
57-03-205	h	1530	0.7	43.9 ft	5/27/88		
57-03-206	H	1463	?	flows	winter		
57-03-207	h	1450	1.5	flows	1/4/88	flows	4/23/88
57-03-2P1	h	1470	0.3	flows	1950's	8.77 ft	10/4/88
				10.5 ft	5/25/88		
57-03-302	h	1400	1.5	flows	1/4/88	flows	5/27/88
57-03-303	h	1385	1.8	+11.6 ft	8/8/73		

Well No	AQ	Land Elev.	MP	Measured	Date	Measured	Date
57-03-3P2	h	1435	3.0	3.0 ft	5/27/88		
57-03-3P3	h	1447	1.0	16.4 ft	5/27/88		
57-03-401	h	1530	0.0	47.4 ft	1/4/88	50.6 ft	5/26/88
57-03-4P1	h	1518	0.5	21.4 ft	1/4/88	22.6 ft	5/26/88
57-03-4P2	h	1515	0.5	12.4 ft	1/4/88	15.3 ft	5/25/88
57-03-4P3	h	1521	0.7	21.9 ft	1/4/88	22.8 ft	5/26/88
57-03-501	h	1535	0.0	58.9 ft	4/23/88		
57-03-5P3	p	1512	2.5	31.9 ft	5/27/88		
57-03-6P1	h	1500	0.0	68.8 ft	5/27/88		
57-03-6P2	p	1398	1.0	38.7 ft	5/27/88		

AQ - aquifers open to: h-Hickory, w-Welge, e-Ellenburger, p-Precambrian.
MP - height in feet of measuring point above land surface.
MEASURED - discharge or depth below MP, + indicates height above MP.

RAINFALL AND EVAPORATION DATA

(all data in inches)

	Monthly Average Rainfall at San Saba for 1963-76 (1)	Monthly Average Pan Evaporation at San Saba for 1919-50 (2)	Monthly Total Rainfall at San Saba for 1987-88 (3)	Monthly Total Rainfall at Taylor Ranch for 1987-88 (4)
June	1.62	7.75	3.00	4.13
July	2.08	9.88	1.51	0.98
August	2.78	10.00	2.37	3.42
September	3.57	7.67	1.39	3.57
October	3.50	6.38	1.09	0.34
November	1.56	4.38	2.82	2.07
December	1.09	3.25	1.10	1.29
January	1.28	2.75	0.22	0.23
February	1.53	2.88	1.28	0.45
March	1.37	4.25	1.44	1.25
April	3.21	5.00	0.28	0.69
May	3.96	5.75	1.85	3.31

(1) recorded at gauge at City of San Saba municipal works, data from Bynum (1982)
(2) from maps in Larkin and Bomar (1983)
(3) recorded at gauge at City of San Saba municipal works
(4) recorded at Taylor Ranch, on FM 501, 5 miles from Pontotoc

APPENDIX G

CHEMICAL ANALYSES AND DATA FOR PIPER DIAGRAM

CHEMICAL ANALYSES

(data in mg/l)

Hickory aquifer—Northern San Saba County

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	TDS
a 41-33-801	7/10/73	11	14	740	437	15	920	1940
a 41-33-802	2/16/59	4	12	896	428	8	1100	2216
41-41-5P1	11/2/82	1	2	324	666	0	101	1095
41-42-601	8/6/73	1	1	225	438	24	76	568
b 41-42-601	6/13/79	1	4	275	463	24	146	707
b 41-42-601	7/23/87	1	5	348	421	26	283	893
a 41-43-901	2/12/59	11	30	1130	456	26	1550	2989
a 41-49-202	6/24/79	5	34	310	274	124	277	902
a 42-48-501	8/9/73	12	53	318	267	115	349	1014

Ellenburger aquifer—Northern San Saba County

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	TDS
41-41-401	7/10/73	26	105	13	412	12	17	399
41-50-501	7/12/73	57	121	2360	316	20	3760	6486

Hickory aquifer—Pontotoc area

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	TDS
a 56-08-301	7/24/73	23	116	25	401	21	41	478
57-01-401	1/14/59	51	54	24	386	14	44	396
57-01-402	7/24/73	17	86	23	293	22	46	351
57-01-402	6/13/79	19	105	49	357	21	77	474
57-01-4P2	4/23/88	61	43	13	425	8	26	375
57-01-4P3	4/23/88	48	113	78	425	77	134	696
57-01-501	7/23/73	5	67	7	201	7	16	228
57-01-503	7/23/73	10	85	22	279	10	39	323
57-01-6P2	4/23/88	10	38	44	104	25	61	288
57-01-7P2	4/23/88	16	78	49	257	46	51	424

Welge aquifer—Pontotoc area

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	TDS
57-01-1P1	4/23/88	9	152	33	472	27	41	533

Hickory aquifer—Cherokee area

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	TDS
a 41-59-5P1	4/23/88	29	62	24	340	21	12	328
a 41-59-801	7/13/73	21	69	21	326	17	19	320
a 41-59-801	4/24/88	20	68	29	321	18	18	323
a 41-59-803	1/14/59	22	67	28	318	19	18	322
a 41-59-803	7/13/73	23	69	19	316	17	19	315
c 57-03-103	9/27/72	16	105	32	351	11	64	421
c 57-02-202	6/28/72	17	80	27	275	11	59	342
57-03-207	4/24/88	16	75	27	321	18	17	329
57-03-302	7/26/73	17	64	14	276	24	13	282
57-03-302	6/12/79	17	81	14	324	25	14	323
c 57-03-401	7/27/73	24	141	75	397	127	115	375
c 57-03-4P2	4/23/88	110	30	360	265	213	522	1404
c 57-03-501	7/23/73	19	86	76	307	29	119	514
c 57-03-501	6/12/79	17	108	124	332	32	206	680

a - completed in both Hickory and overlying aquifers
b - represents mixed water from region around well due to cone of depression
c - appears affected by contaminants

Sample for well 41-41-5P1 was taken by the driller and run by Pope Testing Laboratories, Dallas. Samples from 1988 were taken by the author and run by the Texas Health Department. All other samples were taken by the Texas Water Development Board and run by the Texas Health Department.

DATA FOR PIPER TRILINEAR DIAGRAM

(data in percentage of total anions or cations)

Hickory aquifer—Northern San Saba County

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	Ion Balance
41-33-801	7/10/73	3	2	95	21	1	78	98
41-41-5P1	11/2/82	1	1	98	79	0	21	96
41-42-601	8/6/73	1	1	98	73	5	22	99
41-43-901	2/12/59	2	3	95	14	1	85	99
41-49-202	6/24/79	3	11	86	30	17	53	99
42-48-501	8/9/73	6	15	79	26	14	59	95

Hickory aquifer—Pontotoc area

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	Ion Balance
57-01-401	1/14/59	53	34	13	80	4	16	99
57-01-402	7/24/73	21	64	15	73	7	20	98
57-01-501	7/23/73	10	82	8	85	4	11	95
57-01-503	7/23/73	14	70	16	78	4	19	97

Hickory aquifer—Cherokee area

Well No.	Date	Mg	Ca	Na	HCO3	SO4	Cl	Ion Balance
41-59-803	7/13/73	32	56	13	85	6	9	98
57-03-103	9/27/72	17	66	17	74	3	23	97
57-02-202	6/28/72	21	61	18	70	4	26	97
57-03-302	7/26/73	27	61	12	84	9	7	96
57-03-401	7/27/73	16	57	27	53	21	26	99
57-03-501	7/23/73	17	47	36	56	7	37	98

APPENDIX H

NUMERICAL MODEL FOR CROSS-SECTIONAL FLOW NET IN PONTOTOC AREA

In order to approximate a vertical flow net for the cross section in Figure 25, a numerical model was created with an IBM BASIC computer program written by the author. A listing of the program is included below. The model is based on a modification of a finite difference iterative technique described by Freeze and Witherspoon (1966).

Lines 110-200 of the program contain a data set that defines a set of nodes representing the saturated part of the aquifer. The arrangement of the data represents the geometry of the saturated part of the aquifer and the numbers assign horizontal and vertical permeabilities to the nodes (see lines 110-120 in program listing). The nodes represent points in the aquifer with a horizontal spacing of 500 feet and a vertical spacing of 50 feet. The nodes with odd numbers are part of a constant head boundary representing the water table and are assigned initial head values from the data set in lines 230-250. The zero-numbered nodes are part of a no-flow boundary representing the underlying relatively impermeable Precambrian rocks. During each iteration, the head values along the right boundary are set so that the vertical difference in head between the nodes in the third to last column (column 33) is equal to the vertical difference in head in the last column (column 35). Because the potentiometric surface has a low gradient in the area, horizontal changes in head are not great and the actual conditions are approximated.

The governing equation for the program is in lines 720-750 and is a five-point operator in which the nodes are weighted by their horizontal and vertical permeability in order to account for anisotropy and differences in permeability between different facies of the Hickory. The no-flow boundaries are created by temporarily assigning head and permeability values to the zero-numbered nodes that are equal to that of the node opposite in the five-point operator. A convergence criteria of 0.1 is used and the output is given in the same format as the data set defining the nodes.

```
10 DIM H(35,9)
20 DIM D(35,9)
30 DIM KH(35,9)
40 DIM KV(35,9)
50 REM CRIT=ACCEPTABLE CONVERGANCE VALUE
60 CRIT=.1
70 REM AL=H^2/V^2 (H-HORIZONTAL NODAL SPACING; V-VERTICAL NODAL SPACING)
80 AL=100
90 REM
100 REM DESCRIPTOR ARRAY
110 REM  1,2,3,4,5,6,7,8,9,0,1,2,3,4,5,6,7,8,9,0,1,2,3,4,5,6,7,8,9,0,1,2,3,4,5
120 DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,5,5,5,5,5,5,5,5,5,7,7,7,7,7,7
130 DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,3,3,3,3,4,6,6,6,6,6,6,6,6,6,6,6,6,6,6
140 DATA 1,1,1,1,1,1,1,1,1,1,1,3,3,3,3,3,4,4,4,4,4,4,4,4,4,4,4,4,4,6,6,6,6,6,6
150 DATA 0,0,0,0,2,2,2,2,2,2,2,2,2,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4
160 DATA 0,0,0,0,0,0,0,0,0,0,2,2,2,2,2,2,2,2,2,2,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4
170 DATA 0,0,0,0,0,0,0,0,0,0,0,0,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,4,4,4,4,4,4,4
180 DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2
190 DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,2,2,2,2,2,2,2
200 DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
210 REM
220 REM WATER LEVEL DATA
230 DATA 542,542,541,540,539,537,537,538,539,540,542,540,538,536,537
240 DATA 550,560,570,580,600,625,653,660,655,650,648,647,646,645,643
250 DATA 642,640,638,636,634,632
260 REM
270 REM READ DESCRIPTOR ARRAY
280 FOR J=1 TO 9
290 FOR I=1 TO 35
300 READ D(I,J)
310 NEXT I
320 NEXT J
322 REM
325 REM READ HEAD AND CONDUCTIVITY VALUES
330 FOR I=1 TO 35
340 FOR J=1 TO 9
350 IF D(I,J)=0 THEN 390
360 IF D(I,J)=1 THEN READ H(I,J):GOTO 372
362 IF D(I,J)=3 THEN READ H(I,J):GOTO 372
364 IF D(I,J)=5 THEN READ H(I,J):GOTO 372
366 IF D(I,J)=7 THEN READ H(I,J):GOTO 372
370 H(I,J)=575
372 IF D(I,J)<3 THEN KH(I,J)=40:KV(I,J)=10:GOTO 390
```

```
374 IF D(I,J)<5 THEN KH(I,J)=40:KV(I,J)=1:GOTO 390
376 IF D(I,J)<7 THEN KH(I,J)=20:KV(I,J)=5:GOTO 390
378 IF D(I,J)=7 THEN KH(I,J)=2:KV(I,J)=1
390 NEXT J
400 NEXT I
402 REM ASSIGN CONSTANT HEAD TO LAST COLUMN
403 FOR J=1 TO 8
404 H(35,J)=630
405 NEXT J
410 REM
420 REM **********START LOOP***********
430 NUMIT=NUMIT+1
440 AMAX=0
450 FOR J=1 TO 9
460 FOR I=1 TO 34
465 REM INITIAL FLAGS
480 F1=0
490 F2=0
500 F3=0
510 REM SKIP NODES NOT IN FLOW SYSTEM
520 IF D(I,J)=0 THEN 830
525 IF D(I,J)=3 THEN 830
530 IF D(I,J)=1 THEN 830
540 IF D(I,J)=5 THEN 830
545 IF D(I,J)=7 THEN 830
550 REM
560 REM CHECK FOR NO-FLOW BOUNDARIES, CREATE NO FLOW CONDITION
570 IF D(I-1,J)>0 THEN 610
580 H(I-1,J)=H(I+1,J)
590 KH(I-1,J)=KH(I,J)
600 F1=1
610 IF D(I+1,J)>0 THEN 650
620 H(I+1,J)=H(I-1,J)
630 KH(I+1,J)=KH(I,J)
640 F2=1
650 IF D(I,J+1)>0 THEN 690
660 H(I,J+1)=H(I,J-1)
670 KV(I,J+1)=KV(I,J)
680 F3=1
690 REM
700 REM ERROR AND HEAD AT CENTRAL NODE
710 OLDVAL=H(I,J)
720 NUMH=KH(I-1,J)*H(I-1,J)+KH(I,J)*H(I+1,J)
730 NUMV=AL*KV(I,J-1)*H(I,J-1)+AL*KV(I,J)*H(I,J+1)
740 DEN=KH(I-1,J)+KH(I,J)+AL*KV(I,J-1)+AL*KV(I,J)
750 H(I,J)=(NUMH+NUMV)/DEN
760 ER=ABS(H(I,J)-OLDVAL)
770 IF ER>AMAX THEN AMAX=ER
780 REM
790 REM REASSIGN CORRECT KV,KH,H VALUES
800 IF F1=1 THEN KH(I-1,J)=0:H(I-1,J)=0
810 IF F2=1 THEN KH(I+1,J)=0:H(I+1,J)=0
820 IF F3=1 THEN KV(I,J+1)=0:H(I,J+1)=0
830 NEXT I
840 NEXT J
850 REM ANOTHER ITERATION IF ERROR GREATER THAN CRITERION
855 PRINT AMAX,NUMIT
860 IF AMAX>CRIT THEN GOTO 420
870 REM
880 REM PRINT RESULTS
890 FOR J=1 TO 9
900 LPRINT USING "### ";H(1,J),H(2,J),H(3,J),H(4,J),H(5,J),H(6,J),H(7,J),H(8,J)
H(9,J),H(10,J),H(11,J),H(12,J),H(13,J),H(14,J),H(15,J),H(16,J),H(17,J),H(18,J)
```

```
905 LPRINT
910 NEXT J
920 LPRINT
930 FOR J=1 TO 9
940 LPRINT USING "### ";H(19,J),H(20,J),H(21,J),H(22,J),H(23,J),H(24,J),H(25,J)
H(26,J),H(27,J),H(28,J),H(29,J),H(30,J),H(31,J),H(32,J),H(33,J),H(34,J),H(35,J)
945 LPRINT
950 NEXT J
960 LPRINT USING "###"; NUMIT
970 LPRINT USING "#.#####";CRIT
1000 END
```

APPENDIX I

WELL LOG DATA

DEPTH TO TOPS OF UNITS ON LOGS

Depth to Top (Feet)

Thickness (Feet)

Well No.	Surface Elev.	Ellenburger San Saba	Point Peak	Morgan Creek	Welge - Lion Mtn	Cap Mtn	Hickory	P-C
41-33-801	1325	885	2090	--	--	--	2410e	2755
		1205	--	--	--	--	345	--
41-33-802	1272	720	1990	2060	2180	--	2324	--
		1270	70	120	--	--	--	--
41-33-8P1	1386	--	2100	2180	2280	2380	2420	--
		--	80	100	100	40	280+	--
41-33-5P1	1362	1070	2410	2490	2610	--	2750	3030
		1340	80	120	--	--	280	--
41-35-7P1	1200	1891	--	--	--	--	3826e	--
		--	--	--	--	--	--	--
41-41-5P1	1511	820	2144	2230	2355	--	2460e	--
		1324	86	125	--	--	349+	--
41-41-805	1362	275	--	--	--	--	1915	--
		--	--	--	--	--	--	--
41-42-601	1375	1260	2847	2925	3055	--	3195	--
		1582	78	130	--	--	293+	--
41-43-5P1	1220	990	--	--	--	--	2730e	--
		--	--	--	--	--	--	--
41-43-6P1	1245	1610	3270	3350	3460	--	3600	3872
		1660	80	110	--	--	272	--
41-43-6P2	1293	1210	2850	2930	3050	--	3190e	--
		1640	80	120	--	--	--	--
41-43-901	1210	1030	2694	--	2895	--	3040	3382
		1664	--	--	--	--	342	--
41-43-902	1290	1287	2870	2955	3078	--	3218e	--
		1583	85	123	--	--	--	--
41-44-4P1	1192	1670	3335	3415	3546	--	3680	--
		1665	80	131	--	--	215+	--
41-49-202	1445	--	--	--	--	--	1913e	2223
		--	--	--	--	--	--	
41-49-7P1	1543	--	1220	1290	1400	1490	1610	1920
		--	70	110	90	120	310	--
41-50-7P1	1540	180	1680	1795	1920	--	2130e	--
		1480	115	125	--	--	--	--
41-57-901	1705	--	365	500	620	--	870e	--
		--	135	120	--	--	--	--
41-59-5P1	1465	--	--	--	520	--	830e	--
		--	--	--	--	--	--	--
41-59-5P2	1425	--	--	--	--	640	820	--
		--	--	--	--	180	80+	--
41-59-6P1	1570	--	770	855	990	--	1310	1480
		--	85	135	--	--	170	--
41-59-702	1495	--	--	55	190	260	430	615
		--	--	135	70	170	185	--
41-59-7P1	1495	--	--	86	225	292	435e	--
		--	--	139	67	--	--	--
41-59-801	1402	--	--	0	135	200	340	380
		--	--	135	65	140	40	--

DEPTH TO TOPS OF UNITS ON LOGS

Depth to Top (Feet)

Thickness (Feet)

Well No.	Surface Elev.	Ellenburger San Saba	Point Peak	Morgan Creek	Welge - Lion Mtn	Cap Mtn	Hickory	P-C
41-59-803	1410	--	--	--	--	--	445e	675
		--	--	--	--	--	--	--
41-59-8P3	1492	--	--	--	120	180	370	600
		--	--	--	60	190	230	--
41-59-8P4	1412	--	0	154	286	354	530	--
		--	154+	132	68	176	180+	--
41-59-8P7	1475	--	--	--	--	--	183	--
		--	--	--	--	--	--	--
41-59-9P1	1394	--	--	--	--	--	370	600
		--	--	--	--	--	--	--
41-60-101	1440	--	1685	1790	1890	1990	2100	2170
		--	105	100	100	110	70	--
42-40-801	1500	--	--	--	2475	--	2655	2960
		--	--	--	--	--	30	--
42-48-501	1605	--	1920	--	--	--	2200	--
		--	--	--	--	--	--	--
42-56-201	1610	--	1255	1320	1430	1525	1635	--
		--	65	110	95	110	--	--
42-56-601	1690	--	1020	1165	1285	1350	1480	--
		--	145	120	65	130	--	--
56-08-301	1800	--	--	--	--	75	290	639
		--	--	--	--	215	349	--
57-01-1P1	1865	--	--	60	170	230	414e	--
		--	--	110	60	--	--	--
57-01-4P2	1850	--	--	--	--	65	249	--
		--	--	--	--	184	--	--
57-01-2P1	1875	--	0	122	248	300	480	--
		--	122	126	52	--	--	--
57-02-203	1695	--	142	285	396	--	641	--
		--	143	111	64+	--	--	--
57-02-4P1	1750	--	--	87	205	280	450	--
		--	--	118	75	170	--	--
57-03-102	1550	--	--	--	--	--	153	510
		--	--	--	--	--	357	--
57-03-104	1570	--	--	--	--	--	220	--
		--	--	--	--	--	--	--
57-03-1P2	1530	--	--	--	--	--	100	--
		--	--	--	--	--	--	--
57-03-1P4	1560	--	--	--	145	235e	405e	--
		--	--	--	--	--	--	--
57-03-1P6	1475	--	--	--	80	170	325	--
		--	--	--	90	155	115+	--
57-03-207	1455	--	--	--	--	--	107	437
		--	--	--	--	--	--	--
57-03-302	1400	--	--	--	---	--	125	--
		--	--	--	--	--	235+	--
57-03-3P1	1400	--	--	--	--	--	145	--
		--	--	--	--	--	--	--
57-04-1P1	1495	0	1415	1555	1695	1765	1930	2225
		1415+	140	140	70	165	295	--
57-01-4P2	1511	0	360	--	--	--	800	1141
		--	--	--	--	--	341	--
57-04-601	1413	0	510	--	--	--	985	1089
		--	--	--	--	--	104	--

e - estimated depth to top

+ - interval thickness on well log, actual thickness is greater

REFERENCES

Almy, C. C., Lidiak, E. G., and Rodgers, J. W., 1961, Geophysical studies of the Little Llano River valley, Llano and San Saba Counties, Texas: Texas Journal of Science, v. 13, no. 4, p. 460-477.

Barnes, V. E., 1976, Geologic atlas of Texas, Brownwood sheet (1:250,000): Texas Bureau of Economic Geology.

Barnes, V. E., 1981, Geologic atlas of Texas, Llano sheet: (1:250,000): Texas Bureau of Economic Geology.

Barnes, V. E., Cloud, P. E., Dixon, P. L., Folk, R. L., Jones, E. C., Palmer, A. R., and Tynan, E. J., 1959, Stratigraphy of pre-Simpson Paleozoic subsurface rocks of Texas and southeast New Mexico: Texas Bureau of Economic Geology, Publication 5924, p. 1-836.

Barnes, V. E., and Bell, W. C., 1977, The Moore Hollow Group in central Texas: Texas Bureau of Economic Geology. Report of Investigations 88, 169 p.

Barnes, V. E., and Schofield, D. A., 1964, Potential low grade iron ore and hydraulic fracturing sand in Cambrian sandstones, northwestern Llano region, Texas: Texas Bureau of Economic Geology. Report of Investigations 53, 58 p.

Belforte, A., 1971, Structural geology of the southern part of the Fort Worth basin: Unpublished master's thesis, University of Texas, 75 p.

Black, C. W., 1988, Hydrogeology of the Hickory Sandstone aquifer, upper Cambrian Riley Formation, Mason and McCulloch Counties, Texas: Unpublished master's thesis, University of Texas, 195 p.

Bridge, J. and Girty, G. H., 1937, A redescription of Ferdinand Roemer's Paleozoic types from Texas: U. S. Geological Survey Professional Paper 186, p. 237-271.

Chebotarev, I. I., 1955, Metamorphism of natural waters in the crust of weathering: Geochim Cosmochim Acta, v. 8, p. 22-48, 137-170, 198-212.

Cheney, M. G., 1940, Geology of north-central Texas: American Association of Petroleum Geologists Bulletin, v. 24, p. 65-118.

Cloud, P. E., and Barnes, V. E., 1948, The Ellenburger Group of central Texas: University of Texas Publication 4621, 473 p.

Cornish, F. G., 1975, Tidally influenced deposits of the Hickory Sandstone—Cambrian, central Texas: Unpublished master's thesis, University of Texas, 186 p.

Flawn, P. T., 1956, Basement rocks of Texas and southeast New Mexico: University of Texas Publication 5606, 261 p.

Freeze, R. A. and Witherspoon, P. A., 1966, Theoretical analysis of regional groundwater flow: analytical and numerical solutions to the mathematical model: Water Resources Research, v. 2, no. 4, p. 641-656.

Grimshaw, T. L., and Woodruff, C. M., 1986, Structural style in an en echelon fault system, Balcones fault system, central Texas, geomorphic and hydrologic implications, *in* Abbot, P. L., and Woodruff, C. M., eds., The Balcones Escarpment: published for the Geological Society of America meeting in San Antonio, November 9-14, 1986, p. 77-90.

Jacob and Martin Consulting Engineers, 1986, Report on water system study for the North San Saba Water Supply Corporation: Jacob and Martin, Inc., Abilene, Texas 74 p.

El Jard, M. R., 1982, Diagenesis of the Hickory Sandstone (Cambrian), McCulloch and Mason Counties, Texas: Unpublished master's thesis, University of Texas, 179 p.

Johnson, B., 1987, oral communication: Texas A&M University, November 11, 1987.

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

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

Lee, R., and Strickland, D. J., 1988, Geochemistry of groundwater in Tertiary and Cretaceous sediments of the southeastern coastal plain in eastern Georgia, South Carolina, and southeastern North Carolina: Water Resources Research, v. 24, p. 291-303.

Lewis, D. C., Kriz, G. J., and Burgy, R. H., 1966, Tracer dilution sampling technique to determine hydraulic conductivity of fractured rock: Water Resources Research, v. 2, p. 533-542.

Logan, J., 1964, Estimating transmissivity from routine production tests of water wells: Groundwater, v. 2, p. 35-37.

McGehee, R., 1979, Precambrian rocks of the southeast Llano region, Texas: Bureau of Economic Geology, Circular 79-3, 36 p.

Mason, C. C., 1961, Groundwater geology of the Hickory Sandstone member of the Riley Formation, McCulloch County: Texas Water Commission, Bull. 6017, 84 p.

Maxwell, J. C., 1964, Influence of depth, temperature, and geologic age on porosity of quartzose sandstone: American Association of Petroleum Geologists Bulletin, v. 48, p. 697-709.

Mount, J. R., Rayner, F. A., Shamburger, V. M., Jr., Peckham, R. C., and Osborn, F. L., Jr., 1967, Reconnaissance investigation of the groundwater resources of the Colorado River Basin, Texas: Texas Water Development Board, Report no. 1, 107 p.

Orr, H. D., 1962, Structural geology of the San Saba area, San Saba County: Unpublished master's thesis, University of Texas, 70 p.

Paige, S., 1911, Mineral resources of the Llano-Burnet region, Texas with an account of the pre-Cambrian geology: U.S. Geological Survey Bulletin 450, p. 256-268.

Plummer, F. B., 1950, The carboniferous rocks of the Llano region of central Texas: University of Texas Publication 4329, 170 p.

Preston, R., 1974, Unpublished delineation maps of the Hickory aquifer: Texas Water Development Board.

Roemer, F., 1849, Texas, mit besonderer Rucksicht auf deutsche Auswanderung und die physischen Verhaltnisse de Landes, xiv: Adolph Marcus, Bonn (Germany), 464 p.

Sokol, D., 1963, Position and fluctuations of water level in wells perforated in more than one aquifer: Journal of Geophysical Research, v. 68, p. 1079-1080.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 67, p. 4375-4387.

U.S. Environmental Protection Agency, 1986, Primary drinking water regulations: U.S. Government Printing Office, Code of Federal Regulations, Title 40, part 141.15, p. 527.

Walper, J. L., 1982, Plate tectonic evolution of the Fort Worth Basin: Dallas Geological Society, p. 237-251.

INDEX

BAYLOR GEOLOGICAL PUBLICATIONS*

Baylor Geological Studies

1-8, 12, 16-25, 30: Out of print. For titles see earlier Baylor Geological Studies Bulletins.

†9. Part II: Soils, 1965, Soils and urban development of Waco by W. R. Elder: Baylor Geological Studies Bull. No. 9 (Fall). $5.00.

†10. Part III: Water, 1966, Surface waters of Waco by Jean M. Spencer: Baylor Geological Studies Bull. No. 10 (Spring). $5.00.

†11. Part III: Water, 1976, Subsurface waters of Waco by Siegfried Rupp: Baylor Geological Studies Bull. No. 11 (Fall). $5.00.

15. Boone, Peter A., 1968, Stratigraphy of the basal Trinity (Lower Cretaceous) sands, central Texas: Baylor Geological Studies Bull. No. 15 (Fall). $5.00.

26. Davis, Keith W., 1974, Stratigraphy and depositional environments of the Glen Rose Formation, north-central Texas: Baylor Geological Studies Bull. No. 26 (Spring). $5.00.

27. Baldwin, Ellwood E., 1974, Urban geology of the Interstate Highway 35 growth corridor between Belton and Hillsboro, Texas: Baylor Geological Studies Bull. No. 27 (Fall). $5.00.

28. Allen, Peter M., 1975, Urban geology of the Interstate Highway 35 growth corridor from Hillsboro to Dallas County, Texas: Baylor Geological Studies Bull. No. 28 (Spring). $5.00.

29. Belcher, Robert C., 1975, The geomorphic evolution of the Rio Grande: Baylor Geological Studies Bull. No. 29 (Fall). $5.00.

31. Dolliver, Paul Noble, 1976, The significance of Robert Thomas Hill's contribution to the knowledge of central Texas geology: Baylor Geological Studies Bull. No. 31 (Fall). $5.00.

32. Pool, James Roy, 1977, Morphology and recharge potential of certain playa lakes of the Edwards Plateau of Texas: Baylor Geological Studies Bull. No. 32 (Spring). $5.00.

33. Bishop, Arthur L., 1977, Flood potential of the Bosque basin: Baylor Geological Studies Bull. No. 33 (Fall). $5.00.

34. Hayward, Chris, 1978, Structural evolution of the Waco region: Baylor Geological Studies Bull. No. 34 (Spring). $5.00.

35. Walker, Jimmy R., 1978, Geomorphic evolution of the Southern High Plains: Baylor Geological Studies Bull. No. 35 (Fall). $5.00.

36. Owen, Mark Thomas, 1979, The Paluxy Sand in north-central Texas: Baylor Geological Studies Bull. No. 36 (Spring). $5.00.

37. Bammel, Bobby H., 1979, Stratigraphy of the Simsboro Formation, east-central Texas: Baylor Geological Studies Bull. No. 37 (Fall). $5.00.

38. Leach, Edward Dale, 1980, Probable maximum flood on the Brazos River in the city of Waco: Baylor Geological Studies Bull. No. 38 (Spring). $5.00.

39. Ray, Bradley S., Oklahoma: Baylor Geological Studies Bull. No. 39 (Fall). $5.00.

40. Corwin, Linda Whigham, 1982, Stratigraphy of the Fredericksburg Group north of the Colorado River, Texas: Baylor Geological Studies Bull. No. 40 (Spring). $5.00.

41. Gawloski, Ted, 1983, Stratigraphy and environmental significance of the continental Triassic rocks of Texas: Baylor Geological Studies Bull. No. 41 (Spring). $5.00.

42. Dolliver, Paul N., 1984, Cenozoic evolution of the Canadian River basin: Baylor Geological Studies Bull. No. 42 (Spring). $5.00.

43. McKnight, Cleavy L., 1986, Descriptive geomorphology of the Guadalupe Mountains, South-Central New Mexico and West Texas: Baylor Geological Studies Bull. No. 43 (Spring). $5.00.

44. Matthews, Truitt F., 1986, The petroleum potential of "serpentine plugs" and associated rocks, central and south Texas: Baylor Geological Studies Bull. No. 44 (Fall). $5.00.

45. Surles, Milton A. Jr., 1987, Stratigraphy of the Eagle Ford Group (Upper Cretaceous) and its source-rock potential in the East Texas basin: Baylor Geological Studies Bull. No. 45 (Fall). $5.00.

46. Rapp, Keith Burleigh, 1988, Groundwater recharge in the Trinity Aquifer, central Texas: Baylor Geological Studies Bull. No. 46 (Spring). $5.00.

47. Anderson, L. Marlow, 1989, Stratigraphy of the Fredericksburg Group, East Texas Basin: Baylor Geological Studies Bull. No. 47 (Spring) $5.00.

48. Fall, 1989, Thesis Abstracts: Baylor Geological Studies Bull. No. 48. $5.00

49. Hawthorne, J. Michael, 1990, Dinosaur Track-bearing Strata of the Lampasas Cut Plain and Edwards Plateau, Texas: Baylor Geological Studies Bull. No. 49 (Spring). $5.00.

50. Fall, 1990, Thesis Abstracts: Baylor Geological Studies Bull. No. 50. $5.00.

Baylor Geological Society

101-134, 137, 138, 149: Out of print. For titles see earlier Baylor Geological Studies Bulletins.

139. Urban development along the White Rock Escarpment, Dallas, Texas, 1978. $1.50.

140. Paluxy Watershed. Geology of a river basin in north central Texas, 1979. $1.50.

141. Geomorphic evolution of the Grand Prairie, central Texas, 1979. $1.50.

142. The nature of the Cretaceous-precretaceous contact, Central Texas, 1979. $4.00, a professional level guidebook.

143. The Geology of Urban Growth, 1979. $1.50.

144. A day in the Cretaceous, 1980. $1.50.

145. Landscape and Landuse, 1980. $1.50.

146. Southeastern Llano Country, 1983. $1.50.

147. Early and Late Paleozoic Conodont Faunas of the Llano Uplift Region, Central Texas—Biostratigraphy, Systemic Boundary Relationships, and Stratigraphic Importance, 1987. $12.00.

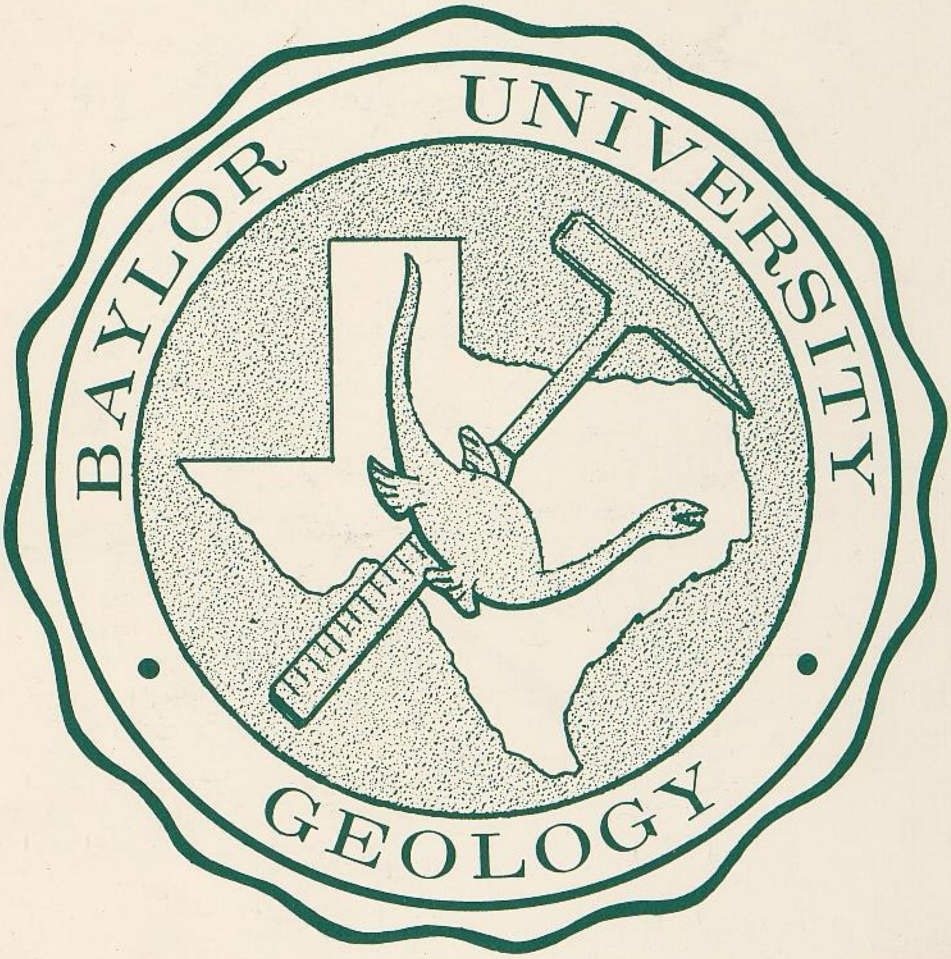
148. Lower Cretaceous Dinosaur Footprints of the Paluxy River Valley, Somervell County, Texas, 1987. $15.00.

150. Pre-Pennsylvanian Geology of the Arbuckle Mountain Region. Southern Oklahoma, 1987. $10.00.

151. Edwards-dominated Landscapes in the Lampasas Cut Plain: Form, Processes, and Evolution, 1987. $13.00.

*Publications available from Baylor Geological Studies or Baylor Geological Society, Baylor University, Waco, Texas 76798. Prices do not include shipping and handling costs; Texas residents add 8¼ percent sales tax.

†Part of **Urban Geology of Greater Waco**, a series on urban geology in cooperation with Cooper Foundation of Waco.


BAYLOR UNIVERSITY
GEOLOGY