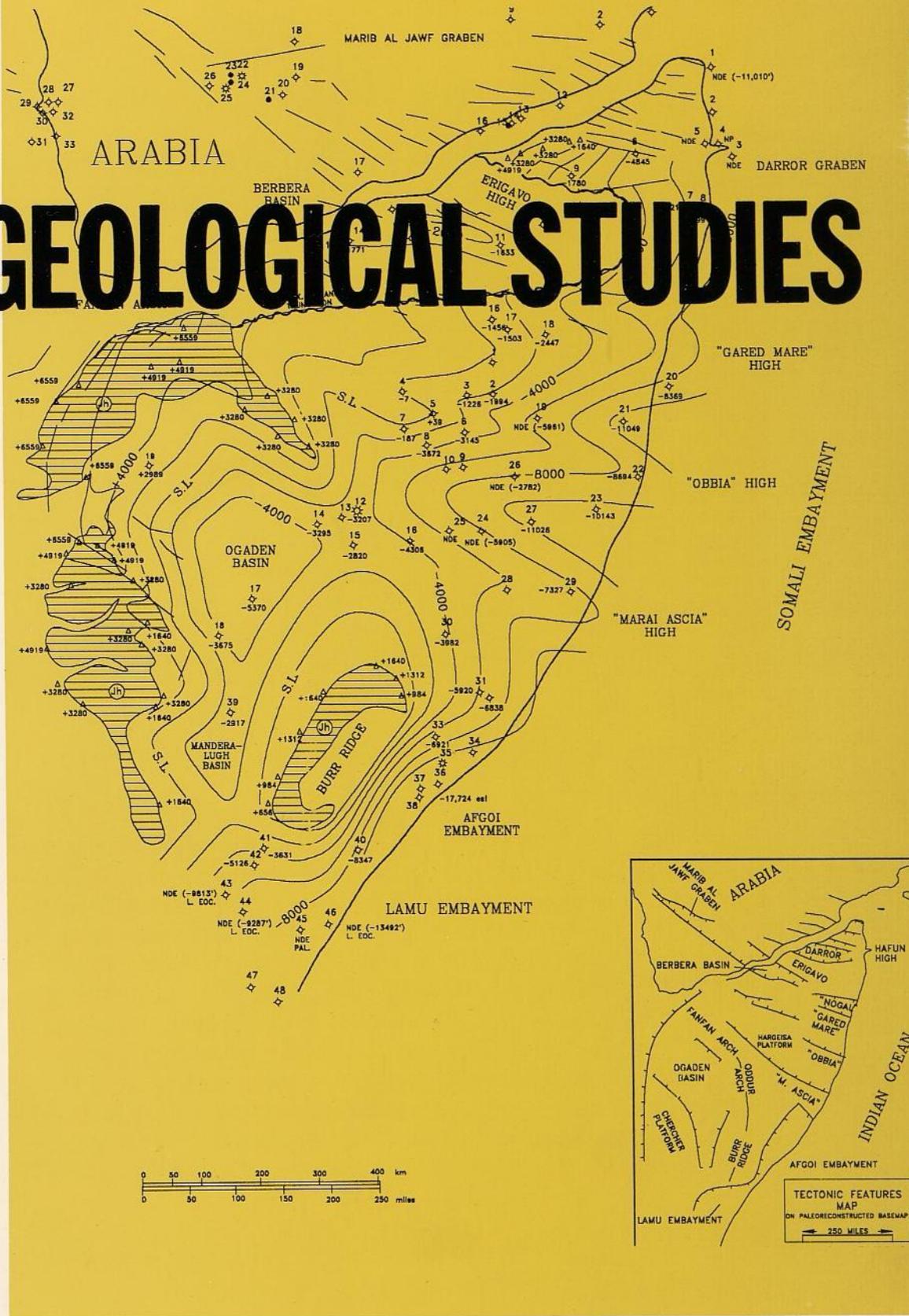
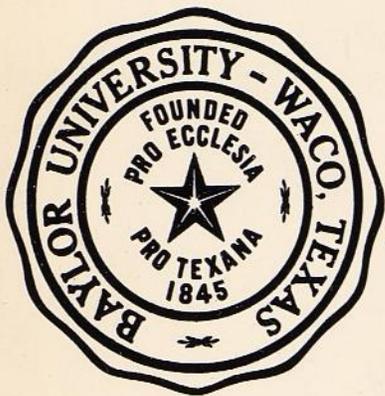


BAYLOR GEOLOGICAL STUDIES

FALL 1989

Bulletin No. 48



Thesis Abstracts

*"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: Generalized structure contour map depicting regional tectonic features in the Horn of Africa.

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THESIS ABSTRACTS

These abstracts are taken from theses written in partial fulfillment of degree requirements at Baylor University. The original, unpublished versions of the theses, complete with appendices and bibliographies, can be found in the Ferdinand Roemer Library, Department of Geology, Baylor University, Waco, Texas.

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Fall 1989

Baylor Geological Studies

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Structural Analysis of the Sheep Mountain-Beaver Creek Thrust Area, Fremont County, Wyoming

Sally Abercrombie

The Sheep Mountain-Beaver Creek area of Fremont County, in western Wyoming, is located in the southwestern Wind River Basin and is a part of the first line of folding down the northeast flank of the Wind River Mountains. The complexity of structural deformation has made the identification of structural style difficult within this region. This study describes and interprets the structure in an attempt to better define structural styles that may be used in mineral exploration and future geological investigations. The Sheep Mountain Anticline lies at the southern, up-plunge end of the line of en echelon folds, which are commonly referred to as the Dallas-Derby trend (Fig. 1). Structures in the trend display a southwest asymmetry which indicates the presence of a southwest-vergent, controlling thrust.

The Beaver Creek Thrust, located in the southern portion of the study area (Fig. 1), is southwest vergent and is interpreted by this author as the up-plunge exposure of the controlling thrust for the entire trend. At the surface, the Beaver Creek Thrust places Mississippian over Cretaceous age rocks. Horizontal displacement on the Beaver Creek Thrust is at least 5000 feet; vertical displacement is about 4000 feet. The Beaver Creek Thrust exhibits a ramping nature rather than having a fault plane with a constant rate of dip. Sweetwater Crossing Anticline, which lies on the hanging wall of the Beaver Creek Thrust and trends east-west, appears to be a ramp anticline, which formed as a result of fault plane geometry rather than north-south directed compression.

Transecting the Beaver Creek Thrust to the north, the east-west trending Clear Creek Fault is oriented parallel to the direction of tectonic transport. The high-angle Clear Creek Fault acts as a compartmental fault, separating differential movement along the southwest-vergent controlling thrust. The surface expression of the Clear Creek Fault shows apparent left-lateral offset. A major change in the trend of the crestal line between Sheep Mountain and South Sheep Mountain suggests the development of separate left-stepping en echelon closures at depth. The northwest end of Sheep Mountain also forms a left-stepping en echelon pattern with Derby Dome. Compartmental faults at basement level below

the en echelon closures have been interpreted by this author to accommodate differential movement of the controlling thrust.

Local northeast-directed thrusts on Sheep and South Sheep Mountain Anticlines place Pennsylvanian over Permian age rocks at the surface (Fig. 2). Because of the overall southwest asymmetry of Sheep Mountain, a deeper, southwest-vergent controlling thrust (SVT-1) is also shown. To the east of Sheep Mountain, SVT-1 is interpreted to have cut up through the basement and Cambrian Flathead Sandstone, and run parallel to bedding in the Cambrian Gros Ventre Shale until it went "blind" and displacement was transferred to the overlying NVT-1, as shown in Fig. 2.

An abrupt plunge at the very northern end of Sheep Mountain gives that end of the anticline a blunt shape, which suggests the presence of a compartmental fault at basement level that accommodates the north plunge of Sheep Mountain and the south plunge of Derby Anticline. North of Sheep Mountain Anticline, a south-vergent thrust, up the north plunge of Sheep Mountain, formed in response to the abrupt north plunge of the Paleozoic rocks. Numerous other thrusts occur within the Mesozoic section as volume adjustments to the en echelon bypass of the anticlines

The Wind River Thrust and associated lines of folding, including the Dallas-Derby trend, developed in a stress field with maximum stress directed N 40° E. COCORP data have shown the Wind River Thrust to have a minimum horizontal displacement of 13 miles. COCORP data also show that the southwest-vergent thrust (SVT) in the Dallas-Derby trend is a small-scale feature relative to the Wind River Thrust, and does not approach the great depth of the Wind River Thrust. The SVT appears to have been carried "piggy-back" on the hanging wall of the Wind River Thrust, becoming active some time after its development.

Erosional forces began to work on the Sheep Mountain-Beaver Creek area from the time uplift began. By Tertiary time, the Sheep Mountain complex was nearly buried in its own debris. Later, renewed uplift resulted in the exhumation of Sheep Mountain to its present state of exposure.

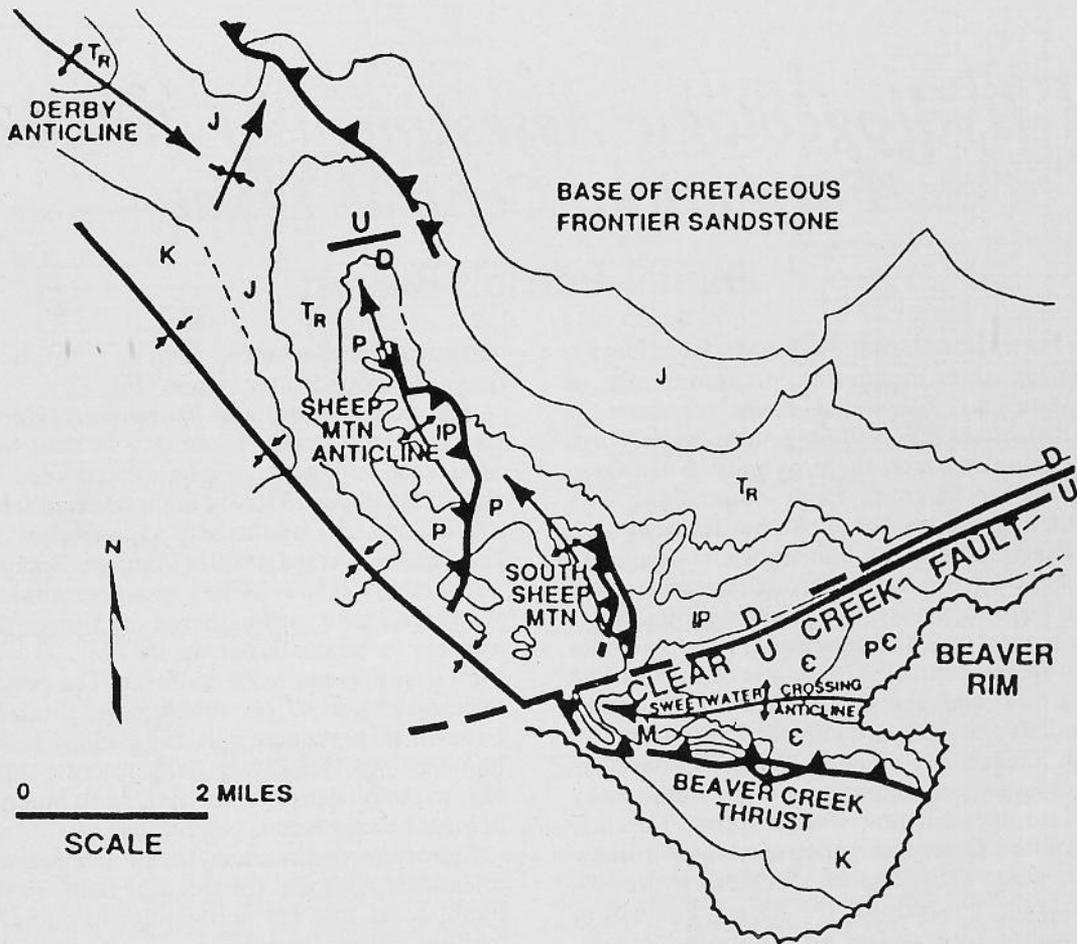


Figure 1. General index map of the study area. Borders include: Derby Anticline to the north, the base of the Cretaceous Frontier Sandstone to the east, and the Tertiary overlap at Beaver Rim to the south. Bounding the study area to the west is the syncline separating the southwest flank of Sheep Mountain from the regional, northeast dip off the flank of the Wind River Mountains. Principal structural features in the study area include, from north to south: the south plunge of Derby Anticline, Sheep Mountain and South Sheep Mountain anticlines, the Clear Creek Fault, Sweetwater Crossing Anticline, and the Beaver Creek Thrust.

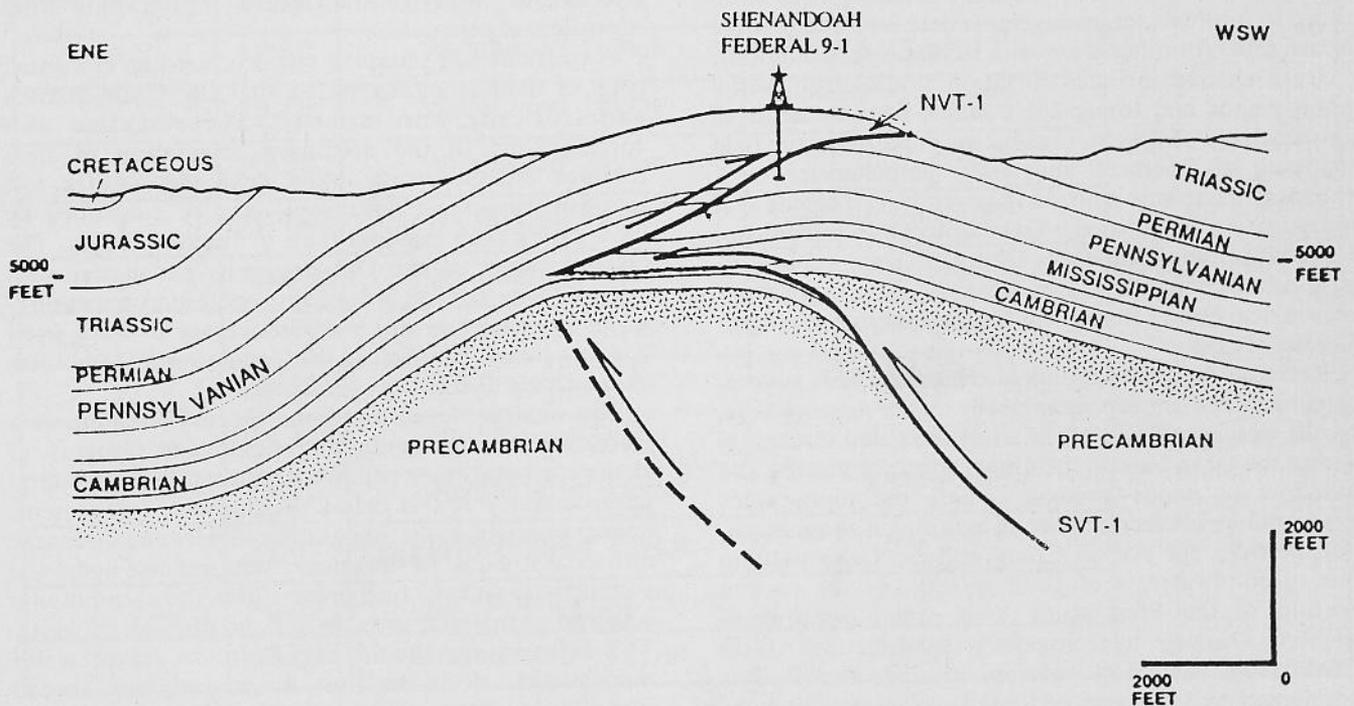


Figure 2. Cross section drawn through the Shenandoah Federal 9-1 well on Sheep Mountain Anticline. The well penetrated Mississippian Madison Limestone on the hanging wall of the overlying thrust, which indicates a pre-Mississippian origin for that thrust. The lower thrust is interpreted as the southwest-vergent thrust, which controls the southwest asymmetry of the entire Dallas-Derby trend of en echelon folds.

A Hydrogeologic Assessment of the Ozan Formation, Central Texas

Daniel Patrick Barrett

The Ozan Formation (Lower Taylor Marl) is a blocky, layered, marine shale composed predominantly of montmorillonite clay. Clays and shales are normally considered hydrologically confining units rather than aquifer materials. However, the proximity of the Ozan outcrop belt to the Balcones Fault Zone, along with surface weathering and release of overburden pressures, results in a weathered horizon that transmits significant amounts of shallow groundwater through interconnected fractures and bedding planes. The shallow groundwater in the Ozan is used by rural landowners and provides baseflow to many central Texas streams including Tehuacana Creek and the Brazos River. The Ozan outcrop parallels the I-35 growth corridor of central Texas, which increases the potential for urban development and subsequent contamination from spills, leaky underground storage tanks, and waste disposal. The clay-rich nature of the Ozan Formation makes it a likely candidate for waste disposal sites. Previous hydrogeologic information concerning the Ozan Formation resulted from laboratory tests for hydraulic conductivity, storage coefficients, and transmissivity values but did not include information regarding flow systems and in situ aquifer parameters.

Therefore, this investigation examined the shallow in situ hydrogeologic characteristics of the Ozan Formation to aid in future water management decisions and provide a case study for other areas with similar clay formations.

Data utilized included lineation studies from aerial photographs and topographic maps, measurements of existing hand-dug wells, installation of piezometers, field mapping of fractures, slug tests, permeameter tests, chemical sampling, and an aquifer test. The area of investigation included the Ozan outcrop in portions of Hill, McLennan, and Falls Counties. Detailed investigations concentrated in two areas: (1) a northern study region near West, Texas; and (2) a southern region near Lorena, Texas.

Recharge to regional and intermediate flow systems originates from the topographically higher Austin Chalk, on the western margin of the study area, and discharges within the Ozan outcrop belt by evapotranspiration and baseflow to major streams. Where the topographic expression provides continuous hydrologic communication between the Austin Chalk and the Ozan outcrop belt, groundwater is of good quality. In the eastern portion of the West study area, where southward-trending drainage hydrologically separates the Austin Chalk from the Ozan outcrop, groundwater flow is dominated by local and regional flow systems and the result is a poor groundwater quality characterized by high total hardness, high sulfate content, and high

electrical conductance, indicative of a sluggish or stagnant groundwater system (Fig. 1).

Effective porosity and hydraulic conductivity values decrease with depth, forming a vertical heterogeneity. Hydraulic conductivity values determined by slug tests within the upper 23 feet of the weathered section average .00182 cm/sec. Conductivity values below 23 feet from the surface average .0000147 cm/sec. Because hydraulic conductivity below 23 feet was determined from both weathered and unweathered sections, the decrease appears to be depth dependant (Fig. 2). Horizontally, the Ozan appears more uniform. The regional density of lineations is .47 per square mile, similar to fracture traces at .45 per square mile, suggesting a regional, lateral homogeneity. However, field fracture measurements vary in lateral density from outcrop to outcrop, resulting in local heterogeneous conditions.

Lineations and fracture traces indicate anisotropy as orientations parallel the trend of faults in the Balcones Fault Zone, and are apparently products of Balcones faulting. Field fracture measurements exhibit varied orientations throughout the Ozan outcrop belt, suggesting that local fracture orientations are not dominated by the regional trend of the Balcones Fault Zone. Water table contours do not show anisotropic effects but slope gently toward topographic lows regardless of orientation.

A constant-rate pumping test produced an elongated cone of depression suggesting that the Ozan behaves anisotropically when stressed. The elongated axis corresponded to the dominant orientation of field fracture measurements taken near the aquifer test location, suggesting anisotropy may be controlled by local rather than regional fault or fracture trends. The layered nature of the Ozan suggests an aquifer with horizontal-to-vertical anisotropy, and outcrop measurements support this idea with an average of three open bedding planes per vertical foot, while vertical fractures average only .7 fractures per linear foot.

The weathered veneer of the Ozan Formation is a fractured medium containing significant amounts of shallow groundwater perched on unweathered material approximately 30 feet below the surface. Flow systems appear to originate on topographic divides and discharge into local streams. In situ aquifer tests indicate hydraulic conductivity values much greater than those commonly accepted as material suitable for land disposal of waste. This information should be helpful in future water management decisions, but more data are needed regarding recharge and the hydrologic relationships between the Ozan and overlying alluvial material along streams.

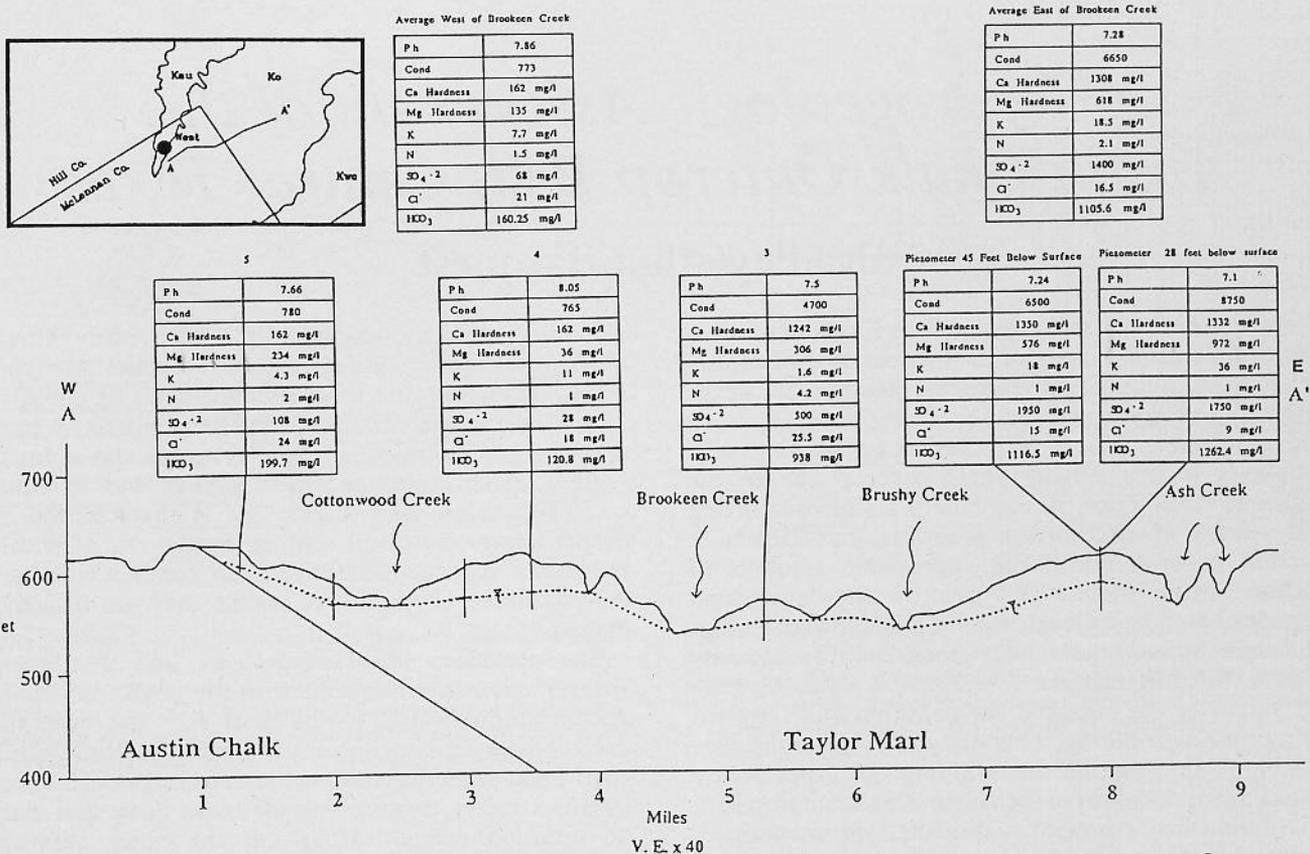


Figure 1. Cross section showing water analysis from five wells along a section extending east-west through the entire northern Ozan outcrop belt. Water quality dramatically decreases east of Brookeen Creek. Topographic dissection by Brookeen Creek creates a discharge point for the intermediate flow system from the Austin Chalk. The decrease in hydrologic communication with the Austin Chalk has therefore resulted in a flow system that is unable to flush the area east of the creek. The result is a groundwater signature high in sulfate, total hardness, and electrical conductance.

Well Number	Depth	Notes	Hydraulic Conductivity (cm/sec)	Average Values cm/sec
6	11.18	Soil	5.80×10^{-3}	1.82×10^{-3}
8	12.50	Weathered Taylor	1.45×10^{-3}	
7	19.70	Weathered Taylor	1.14×10^{-4}	
1	20.38	Weathered Taylor	1.37×10^{-3}	
4	20.50	Weathered Taylor	1.55×10^{-3}	
5	20.75	Weathered Taylor	2.26×10^{-3}	
10	22.76	Weathered Taylor	4.51×10^{-4}	
9	23.32	Weathered Taylor	1.62×10^{-3}	1.47×10^{-5}
12	28.90	Weathered Taylor	3.31×10^{-6}	
2	29.70	Unweathered Taylor	4.90×10^{-6}	
3	38.80	Unweathered Taylor	6.0×10^{-6}	
13	42.00	Bottom Weathered Taylor	3.80×10^{-5}	
11	43.07	Unweathered Taylor	2.14×10^{-5}	

Figure 2. Chart of in situ values showing the relationships between hydraulic conductivity and depth. In general, values are in the .001 cm/sec range within the upper 23 feet, hydraulic conductivity values decrease to about .01 of the shallow values. This suggests that the upper zone is affected most by weathering, creating a fracture network that transmits appreciable amounts of groundwater.

A Hydrogeologic Assessment of the Austin Chalk Outcrop Belt, Central Texas

Bradley Alan Barquest

The Upper Cretaceous Austin Chalk forms an outcrop belt that parallels the major growth corridor of central Texas. This outcrop belt represents less than 3% of the total Texas acreage, yet the corridor is host to approximately 20% of the Texas population. The proximity of the Austin Chalk outcrop belt to the Balcones Fault Zone, in combination with weathering and release of overburden pressures, has created a fracture network containing appreciable amounts of shallow groundwater. This shallow aquifer system provides baseflow to local streams and supplies springs and wells but is poorly understood due to a paucity of data. The urbanization of the Austin Chalk outcrop belt increases the potential for pollution and the need for aquifer remediation. This study attempts to provide hydrologic information that will improve groundwater management decisions in the Austin Chalk outcrop belt.

Groundwater is present within shallow, unconfined, fracture-dominated flow systems. These systems occur predominantly within the weathered section of the formation. Water-table depths below land surface range between 4 feet and 28 feet, with a mean of approximately 11 feet. Typically reflecting a muted expression of the surface topography, maximum water-table depths occur beneath topographic divides, while minimums occur in valleys.

Depths of weathering range from a few feet to greater than 40 feet below land surface. The thinnest weathered sections occur along the crest of the regional divide. Throughout the study area numerous large-diameter wells are present with total depths ranging between 15 and 47 feet below land surface. These depths correspond closely to the weathered section of the formation.

Vertical and horizontal fracture density (fractures per linear foot) vary throughout the outcrop belt. Within the upper 25 feet, fracture densities typically exhibit their greatest variability ranges and highest density concentrations. Below this depth the effects from structural and weathering stresses upon the formation material are reduced. Therefore, groundwater systems exhibit both horizontal and vertical heterogeneity. Locally, moderate to large-scale faulting alters this general scenario. Such faults frequently exhibit orientations coincident with the axial trend of the Balcones Fault Zone and may occur at any depth within the vertical section. Associated with this faulting, particularly within the downdropped blocks, is a significant increase in fracture density and depth of weathering (Fig. 1).

Effective porosity consisting of fault planes, joints, and bedding planes is greatest within 25 feet of land surface, exhibiting a mean of 0.33 percent. At depths greater than 30 feet below land surface, effective porosity decreases by one third, exhibiting a mean value of 0.22 percent.

Groundwater movement within the Austin Chalk outcrop belt occurs within two distinct regimes. An upper regime, which occurs at depths less than or equal to 26 feet below land surface and is characterized by local and shallow intermediate flow systems, and a lower regime, which occurs at depths greater than or equal to 30 feet below land surface and is characterized by deeper intermediate and regional flow systems. Within the upper regime, mean hydraulic conductivities are 0.0036 cm/sec; in the lower regime they are 0.000059 cm/sec.

The combined effect of tectonic and weathering stresses upon the interbedded brittle chalk and more ductile montmorillonitic-rich marl beds has been the development of two distinct fracture systems. Within chalk beds, numerous near-vertical fractures exist. These fractures rarely traverse two or more beds, and only on occasion extend throughout the entire outcrop. Within the marl beds, the dominant fracture style consists of bedding plane separations. Near-vertical fractures are present, but because of the high shrink-swell capability of the marl, these fractures may seal themselves when moist. The net effect of this interbedded lithology has been to develop a fracture flow system in which groundwater movement occurs primarily within the fractured chalk beds. Interbedded marl units act as individual confining beds that impede vertical groundwater flow. Flow within this bedded sequence resembles an assemblage of miniature, areally discontinuous, disjointed and leaky aquifers. As a result, flow systems within the Austin Chalk outcrop belt exhibit strong horizontal-to-vertical, and lateral anisotropy (Fig. 2).

These groundwater flow systems are controlled primarily through topography. Regionally, flow systems are initiated along the crest of the outcrop belt, and groundwater moves down gradient in predominantly southeastwardly or northwestwardly directions discharging into rocks of the Taylor and Eagle Ford Groups. Intermediate and local flow systems initiate at local highs and discharge through evapotranspiration or as baseflow contributions to major streams (Fig. 3).

Chemical analyses indicate a calcium-bicarbonate water suitable for human consumption. However, this quality is not constant through time and exhibits minor seasonal fluctuations. Overall quality appears to be best during the fall, when increased rainfall allows for active flushing. The poorest water quality is encountered during the late summer, when precipitation, water tables, and flow system gradients are at their yearly minimums. The shallow nature of this system makes it extremely susceptible to contamination.

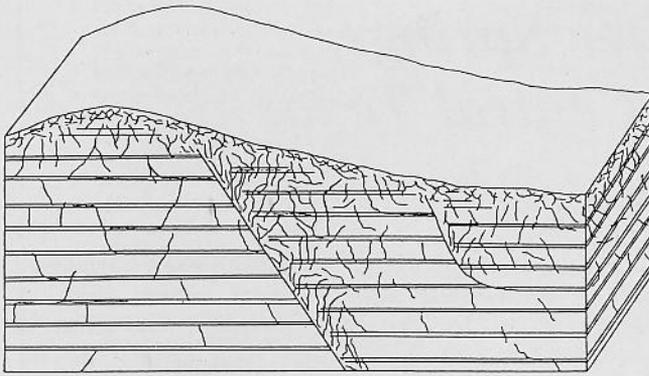


Figure 1. Block diagram illustrating fracture density, distribution, and the effects of faulting. Immediately adjacent to faults, particularly in the downdropped block, fracture densities dramatically increase, often creating enhanced zones of horizontal and vertical permeabilities. Within such areas the increased groundwater movement accelerates the weathering process, which further enhances permeabilities.

Well No.	Well Depth Below L.S. in Feet	Horizontal Hydraulic Conductivity (Kh) (cm/sec)	Vertical Hydraulic Conductivity (Kv) (cm/sec)	Ratio of Anisotropy (Kh/Kv)
51	15	7.0×10^{-4}	8.8×10^{-6}	80
43	18	1.1×10^{-3}	4.9×10^{-6}	225
35	18	1.8×10^{-3}	4.5×10^{-6}	400
32	21	1.1×10^{-3}	4.4×10^{-5}	25
20	21	1.7×10^{-2}	8.5×10^{-5}	200
5	22	6.5×10^{-3}	1.3×10^{-4}	50
12	25	5.0×10^{-4}	1.3×10^{-6}	375
3	47	2.0×10^{-4}	3.2×10^{-7}	630

L.S. Land Surface

Figure 2. Chart depicting the range of horizontal-to-vertical anisotropy determined from aquifer recovery tests. Horizontal-to-vertical anisotropy is common within layered sedimentary systems such as the Austin Chalk. The wide range of anisotropy values suggests a significant variability in the presence of interconnected vertical fractures throughout the outcrop belt.

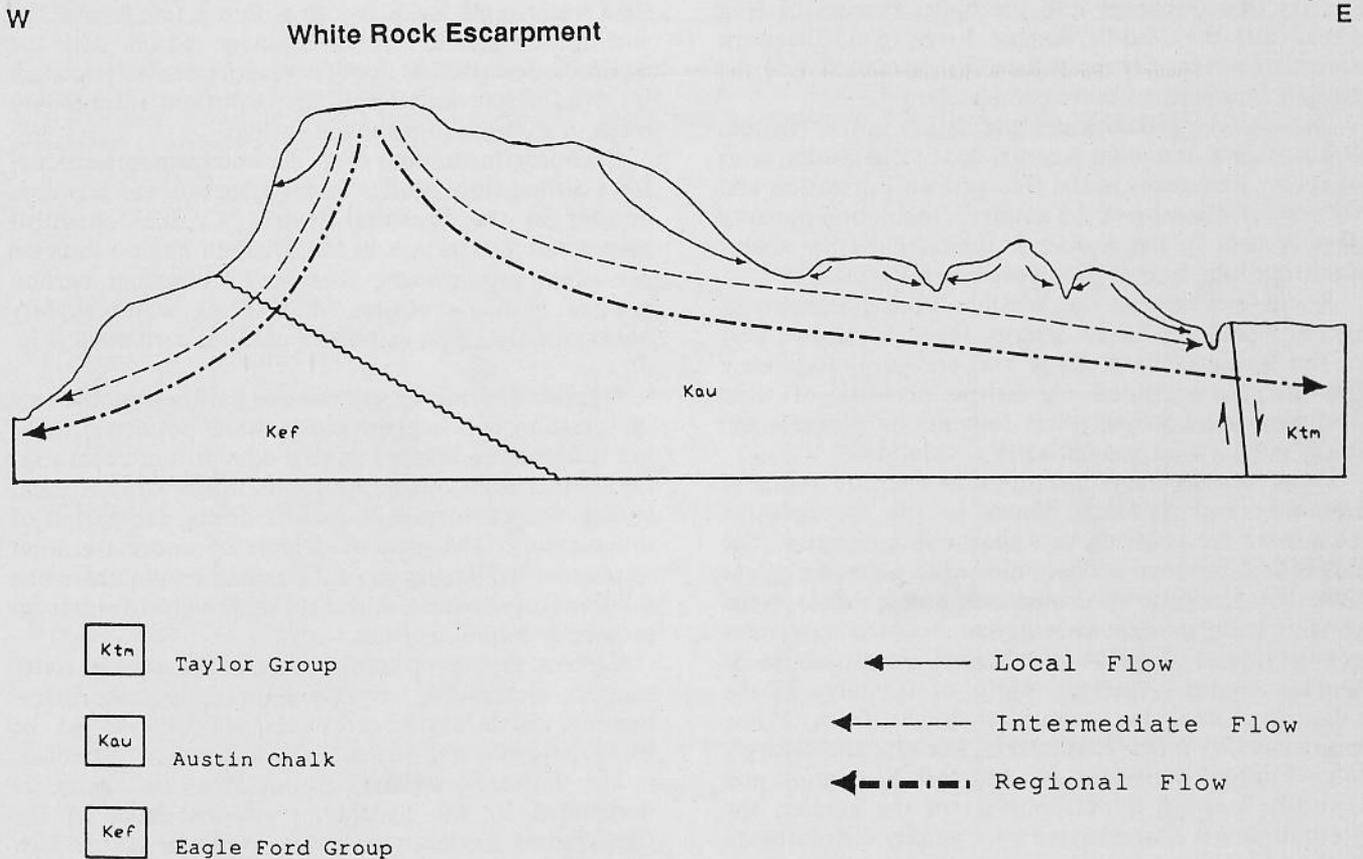


Figure 3. Diagrammatic cross section depicting idealized flow systems within the southern study region. Regional and intermediate flow systems are initiated along the crest of the outcrop belt (White Rock Escarpment) and proceed toward the east or west discharging into rocks of the adjacent Eagle Ford and Taylor Groups. Local flow systems exhibit a greater diversity of flow directions, discharging to augment the baseflow of streams or as evapotranspiration.

Geochemistry and Flow Characteristics of Edwards Aquifer Springs: Washita Prairie, Central Texas

Andrew David Collins

The Edwards aquifer in the Washita Prairie of central Texas is a shallow unconfined aquifer formed in gently eastward dipping limestones of the Edwards and Georgetown Formations. It is quite different from the more prolific Edwards aquifer sections found along the Balcones Fault Zone and in the Edwards Plateau. Because the communities in the Washita Prairie area ceased using the aquifer for their municipal supply around the turn of the century, it has been studied only sparingly.

The aquifer is characterized by intermediate groundwater flow systems developed in tributary basins that discharge into stream channels from springs and seeps. Although numerous hand-dug wells abound, the natural springs provide data regarding flow systems that cannot be obtained from wells. This study investigated five springs that discharge into the upper reaches of Hog Creek and the Middle Bosque River in northeastern Coryell County, Texas, in an effort to understand the aquifer flow systems more completely.

Diffuse-flow groundwater circulation in the Washita Prairie Edwards aquifer is controlled by dissolution rates of shaley limestones in the Georgetown Formation and the fractured nature of the aquifer. Dissolution porosity development in the aquifer is inhibited by the shaley limestone sequence of the Georgetown Formation.

Rocks constituting the Washita Prairie segment of the Edwards aquifer in central Texas lie to the west of the Balcones Fault Zone and are only moderately fractured and jointed. A diffuse network of tight fractures and bedding plane separations provides the initial conduits for groundwater circulation.

Field measurements indicate that aperture width of fractures and bedding planes in the Georgetown Limestone are generally less than one millimeter. The Edwards Limestone is dissolutioned to a greater extent than the Georgetown Limestone and exhibits some conduit features such as honeycombed and cavernous porosity, and dissolution channel development at shallow depths. Aperture width of fractures in the Edwards Limestone generally ranges from a few millimeters to a few centimeters. Because the Georgetown Formation overlies the Edwards Formation and typically forms a thicker portion of the aquifer, the groundwater is characterized by a weakly dissolutioned flow system.

Physical characteristics of groundwater flow systems

in spring drainage basins are most closely associated with a diffuse-flow aquifer feeder system (Fig. 1). Recharge occurs principally from infiltration of precipitation through the thin soils formed on the Georgetown Formation. Groundwater flow directions are controlled by topography. Gentle water-table gradients, ranging from 0.001 to 0.009, and the nature of aquifer dissolution result in slow groundwater circulation and moderate to long residence times.

Throughout most of the year, water-table depths average 20 to 40 feet beneath basin divides and 5 to 10 feet near tributary channels. Aquifer discharge is fairly constant and primarily from perennial springs. During the late spring months, the aquifer is characterized by high-amplitude water-table fluctuations following high-intensity, short-duration precipitation events. At this time water-table levels rise to within a few feet of the surface throughout spring drainage basins and the aquifer is described as flooded. Aquifer discharge occurs from numerous small episodic, overflow springs and seeps in addition to perennial springs.

Chemical fluctuations of spring water support a model for a diffuse-flow aquifer feeder system in the Edwards aquifer in the Washita Prairie. Critical chemical parameters for springs in the Washita Prairie indicate consistent groundwater chemistry, consistent carbon dioxide partial pressures, and spring water slightly undersaturated with respect to calcium carbonate (Fig. 2).

Washita Prairie springs exhibited hardness coefficients of variation that suggest groundwater residence times are sufficient to insure regional equilibrium chemistry. Geometric mean calcite saturation ratios for individual springs ranged from 0.78 to 1.02 during the period of investigation. The greatest degrees of undersaturation were recorded during aquifer flooding conditions when dilution from undersaturated recharge would result from recent precipitation events.

Carbon dioxide partial pressures of spring water samples were highly consistent throughout the investigation. High partial pressures are believed to be generated in the soil, vadose, and shallow phreatic zones.

The Edwards aquifer in the Washita Prairie is dominated by the hydrologic characteristics of the Georgetown Formation, which results in diffuse-flow groundwater circulation and consistent groundwater chemistry.

Washita Prairie spring flow systems	Diffuse-flow feeder systems	Conduit feeder systems
<ol style="list-style-type: none"> 1. Recharge from areal precipitation on shallow clayey soils formed on the Georgetown Formation. 2. Well defined shallow water table. 3. Gentle water table gradients ranging from 0.001 to 0.009. 4. Apertures in Georgetown Formation measured in millimeters; apertures in Edwards Formation measured in millimeters to centimeters. 5. Laminar groundwater flow through tight fracture flow system. 6. Groundwater approaches darcy flow. 7. Moderate to long residence times in lower flow zone; moderate residence times in the upper flow zone. 8. Aquifer discharge through numerous small springs and seeps. 9. Upper flow zone formed predominately in shaley limestones of the Georgetown Formation; lower flow zone development occurs predominately in pure limestones of the Edwards Formation. 10. Constant groundwater hardness; hardness coefficients of variation for individual springs from 6.96 to 10.22. 11. Spring water typically slightly undersaturated; calcite saturation ratios for individual springs from 0.79 to 1.02. 12. Constant carbon dioxide partial pressures (aqueous). 	<ol style="list-style-type: none"> 1. Recharge from slow percolation input of meteoric water. 2. Well defined water table. 3. Gentle water table gradients. 4. Porous voids measured in centimeters or less. 5. Laminar groundwater flow regimes. 6. Groundwater approaches darcy flow. 7. Moderate to long groundwater residence times. 8. Aquifer discharge through numerous small springs and seeps. 9. Typically formed in shaley limestones and dolomites. 10. Constant groundwater hardness. 11. Groundwater near saturation with respect to calcite. 12. Constant carbon dioxide partial pressures (aqueous). 	<ol style="list-style-type: none"> 1. Rapid recharge through distinct sink points. 2. Highly variable water table. 3. Steep water table gradients. 4. Porous voids measured in centimeters to meters. 5. Laminar to turbulent groundwater flow regimes. 6. Groundwater approaches flow through system of pipes. 7. Moderate to long groundwater residence times. 8. Aquifer discharge through large springs. 9. Typically formed in pure limestones. 10. Variable groundwater hardness. 11. Groundwater often undersaturated with respect to calcite. 12. Variable carbon dioxide partial pressure (aqueous).

Figure 1. Flow system characteristics in the Washita Prairie Edwards aquifer. Characteristics of two end-member carbonate flow systems are compared to flow system characteristics of the Edwards aquifer in the Washita Prairie. Physical and chemical characteristics of perennial springs discharging from the Washita Prairie segment of the aquifer suggest a dominantly diffuse-flow aquifer feeder system with only minor development of conduit flow features.

Spring	Aver. Total Hardness as (ppm) CaCO ₃	Hardness Coefficient Variation (%)	Geometric Mean Calcite Saturation Ratio	Geometric Mean log P(CO ₂) (10 ⁻³)	Average Ionic Strength (10 ⁻³)	Range of observed Discharge (cfs)
Hurst	274	10.22	0.86	-2.44	8.53	0 - 1.241
Turnersville	258	7.10	0.78	-2.45	8.40	0 - 0.998
Tharp	257	9.22	0.78	-2.45	8.44	0 - 0.575
Picken's Pool	250	7.49	1.02	-2.46	8.37	0.022 - 0.815
Osage	245	6.96	0.83	-2.48	7.67	0.090 - 1.510
Average	257	8.20	0.85	-2.46	8.28	-----

Figure 2. Critical spring water chemical parameters. Fluctuations of these derived chemical parameters are regarded as the most significant basis for hydrochemical interpretation of aquifer flow mechanics in spring drainage basins. Washita Prairie springs exhibit low coefficients of variation of groundwater hardness, slightly undersaturated groundwater, and consistent carbon dioxide partial pressures. Spring water critical parameters suggest that spring discharge is fed predominantly by a diffuse-flow aquifer feeder system.

Hydrocarbon Potential of the Triassic-Jurassic Interval, Horn of Africa

Andrew D. Elifritz

The Horn of Africa is located in central East Africa and for 35 years has been an unrewarding hydrocarbon exploration target despite its many similarities and close proximity to the most prolific hydrocarbon producing region in the world, the Middle East. Recent oil discoveries in North Yemen have renewed exploration interests in the Horn of Africa.

Oil exploration potential for Middle and Upper Jurassic carbonate grainstones is excellent. In the Middle East, similar Jurassic carbonate reservoirs contain 177 BBOE (billion barrels of oil equivalent) ultimate recoverable reserves. Ghawar Field in Saudi Arabia is a viable exploration model for the Jurassic reservoirs in the Horn of Africa. Basal, basin-fill Triassic-Jurassic continental clastics are also exploitable, but mainly for gas reserves on and around horst block structures such as the Yemen Alif and Lam Fields, Sudan Unity and Heglig Fields, and the Tenneco No. 1 Calub non-economic discovery (eastern Ethiopia).

The Horn of Africa structural setting is a key feature in the assessment of exploration potential and is a result of three phases of tectonism that include: (1) WNW-ESE extension during the Triassic-Early Jurassic (Liassic) breakup of Pangea; (2) Cretaceous to Early Tertiary NNE-SSW extension during widening of the Indian Ocean; and (3) Tertiary to Holocene NNE-SSW extension and formation of the Gulf of Aden.

Continental rifts and uplifts dominate the Horn of Africa structural setting. NNE trending structural features, such as the Burr Uplift, Mandera-Lugh Basin, and Ogaden Basin (Fig. 1), formed during Triassic to Early Jurassic extension and the breakup of Pangea. During this period all of East Africa was extended roughly east-west, and north-south trending Karroo continental basins developed from South Africa to Kenya. NNE structural grain was probably obsequious during the breakup but only remnants remain due to strong Cretaceous and Tertiary overprinting.

Cretaceous to Tertiary WNW trending structural features formed during north-south widening of the Indian Ocean and Gulf of Aden. These include the Hafun High, Darror Graben, Erigavo High, Berbera Basin, "Nogal" Graben, "Gared Mare" High, "Obbia" High, Fanfan Arch, and "Marai Ascia" High (Fig. 1). Distant but possibly related structural features of this trend are the Muglad and Melet grabens of interior Sudan, the Anza Graben of northern Kenya, and the Marib al Jawf Graben of North Yemen.

The primary structural style in the Horn of Africa is basement-involved normal faulting. The rifts and uplifts, at the time of formation, trended perpendicular to the direction of minimal principle stress. Faults within the rifts tend to parallel the rift margins and display complex bifurcating, en echelon, and dogleg patterns. Intrarift, basement highs with rotated fault blocks, reverse drag folds, and drape folds are viable petroleum prospects.

Tenneco well and seismic control indicate thick sequences (+15,000 feet) of nonmarine Triassic Karroo and Jurassic Adigrat deposits in the deep Ogaden Basin of eastern Ethiopia. Faulting and uplift contemporaneous with deposition of these units is indicated by significant thickening across many faults and gradual thinning over positive areas. The deposits record rifting and graben filling prior to the breakup of Pangea and the creation of the incipient Indian Ocean-Somali Basin.

Well cores within the continental Triassic-Jurassic interval in the Ogaden Basin display facies indicative of subaerial, transitional, and marine deposition. The cored intervals reveal an upward progression from early gravelly braided stream deposits, to late sandy braided stream-meandering stream deposits, to transitional and basal transgressive deposits. Coarser grained, higher energy deposits occur along the margins of the basins and near structurally high features within the basins.

Nineteen giant oil fields produce from Jurassic carbonates in the Middle East. Hamanlei Formation well cores from the Ogaden Basin display many sedimentological similarities to the Arab Jurassic carbonates. Porous intervals and hydrocarbon shows are common in the skeletal-oolitic grainstone facies and sucrosic dolomite facies, although no economic zones have yet been encountered.

Geochemical data have revealed three possible source rocks in the Triassic-Jurassic interval. The source rock having the best potential appears to be the Urandab shale, although potential source rocks also exist in middle Hamanlei tidal-flat deposits. Potential seals include middle Jurassic Hamanlei anhydrites, Upper Jurassic Urandab shales and micritic carbonates, and Lower Cretaceous evaporites.

Although the Horn of Africa has been an unrewarding area for hydrocarbon exploration to date, the geology indicates that sufficient potential exists for additional exploration efforts.

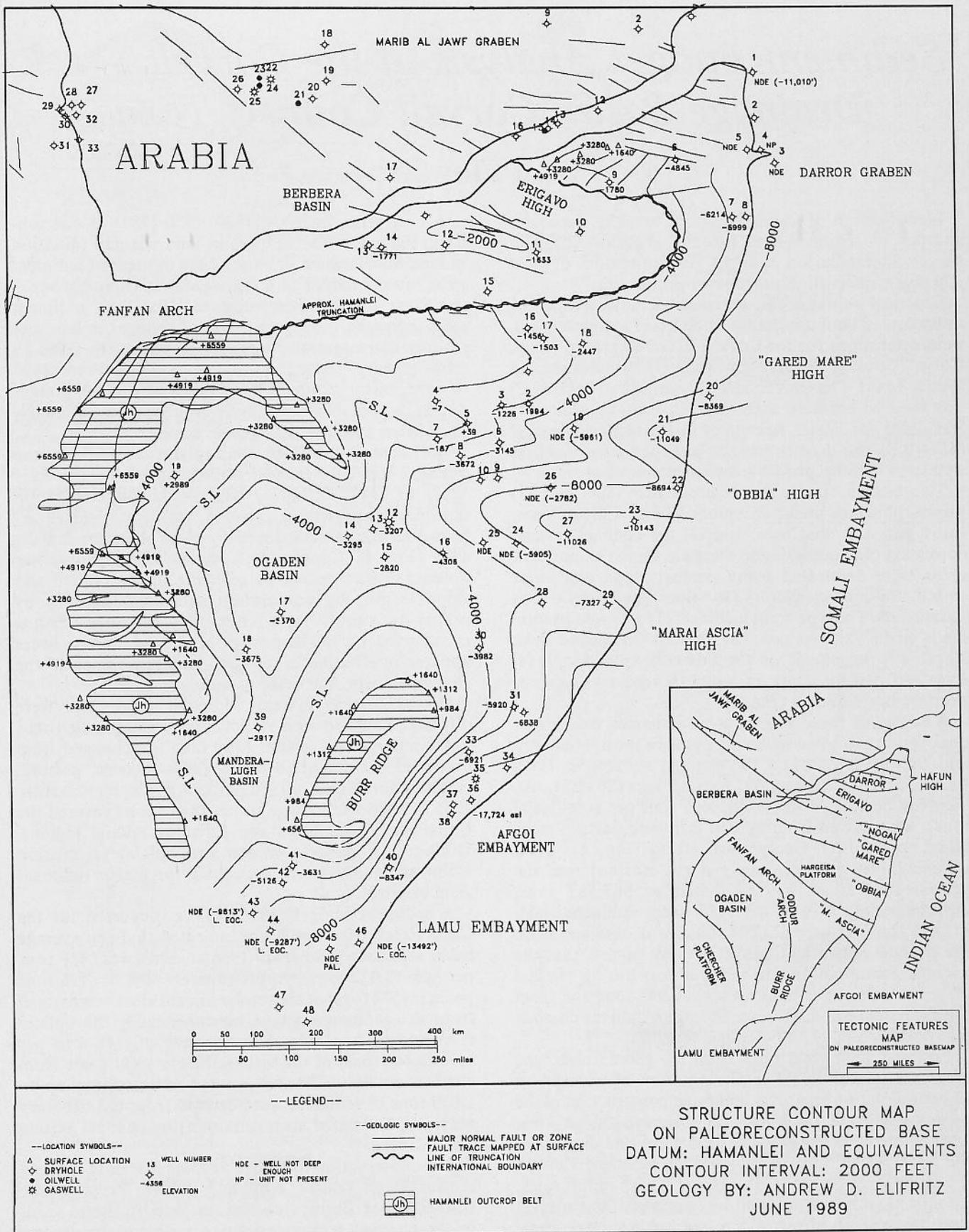


Figure 1. Generalized structure contour map depicting regional tectonic features in the Horn of Africa. Constructed on the top of the Middle Jurassic Hamanlei Formation and equivalents, the map clearly depicts NNE and WNW trends of structures. In northern Somalia, the unit is truncated across regional highs and preserved in regional lows. Informal names assigned by the author are in quotes.

Sediment Budget Analysis of the Coryell Creek Drainage Basin, Coryell County, Texas

Beth Flowers

Identification of sediment source areas is critical to analysis of sediment loss through erosion. Sediment source identification aids in determination of cost effective conservation practices within basins.

Sediment source areas, sediment yield, as well as the influences of land use change upon basin sediment yield, were determined for the Coryell Creek Drainage Basin, Coryell County, Texas, approximately 30 miles west of Waco, Texas. The Universal Soil Loss Equation (USLE) was used to estimate sheet and rill erosion, while the Simulator for Water Resources in Rural Basins model (SWRRB) was used to predict basin sediment yield, as well as to identify probable sediment source areas.

Two basic sediment source areas were identified: (1) geomorphic type areas, or regions having similar slopes, soil types, and land uses; and (2) the channel system, consisting of tributaries and the main stem. Geomorphic areas were delineated using percent slope and slope length, soil erosion factors (K values), and land use as parameters. The type areas included: (1) crop and pasture lands in the valley region; (2) forested Comanche Peak slopes; (3) rangelands on the Edwards upland; and (4) crop and pasture lands on lower Georgetown deposits near the basin divides (Fig. 1).

Analysis of these source areas indicates that major contributors to basin sediment yield are the upland crop and pasture region and the channel system. In 1983, total sediment yield was .491 tons per acre (26,805 tons). Thirteen percent of this yield, .066 tons per acre (3,603 tons), was derived from upland crop and pasture areas lying upon lower Georgetown strata (Fig. 2). Total sediment loss due to sheet and rill erosion from the geomorphic areas was estimated at 363,583 tons. Approximately 87% of the 1983 basin sediment yield, or .425 tons per acre (23,202 tons), was obtained from the channel network. Channel surveys suggest that the average annual volume of material lost during the last 50 years from the tributaries was 40,943 tons and from the main stem was 6,809 tons. Storage within the channel was estimated at 24,550 tons per year.

Low sediment yield rates from the geomorphic type areas are related to (1) implementation of widespread soil conservation measures and pond construction in the upland region of the basin; (2) a forested slope area; and (3) a low slope gradient (less than one degree) in the lower valley area. High rates of sediment yield in the channel region are attributed to (1) high runoff rates, associated with land use and low permeability soils; (2) steep channel gradient; (3) a bedrock channel floor, instrumental in causing lateral rather than downward scour; and (4) availability of highly erosive clay loam material in channel walls.

A time series analysis (1830, 1936-1983) of one sub-basin indicated that changes in land use and initiation of land management practices have influenced sediment yield rates. Analysis of a representative tributary basin, the Clear Creek Basin, suggested that total sediment yield increased 250% as a result of changes in land use from a native grassland prairie of the early 1800s to crop, pasture, range, and forest by 1936. From 1936 to 1983, basin sediment yield rates were much greater during periods in which range was present on Comanche Peak slope and Edwards upland areas (Fig. 3).

Sediment yield from the upland areas near the drainage divides increased dramatically from the early 1800s to 1941. Following widespread implementation of contour and terrace farming, sediment yield values from this area were reduced by more than one-half by 1951 (Fig. 4). Contour and terrace farming practices lowered erosion values by reducing slope gradient and slope length, by conserving soil moisture, and by removing runoff in a controlled manner. Ponds constructed on drainageways in upland regions were apparently effective in reducing runoff to much of the channel system, and acted as sediment traps.

In the channel system, sediment yield rates were directly related to stream discharge and indicated that this discharge was greater after land use changed from grassland prairies of the early 1800s to crop, pasture, range, or forest uses in 1936. Discharge was highest from 1965 to 1978 when range rather than forest covered the Comanche Peak slopes and Edwards upland regions. During such periods, greater rates of lateral erosion within the channel area accounted for higher sediment yield values (Fig. 4).

A sediment budget (1936-1983) constructed for the Clear Creek tributary basin indicated that the average basin sediment yield from 1936 to 1983 was .486 tons per acre (2,022 tons). Approximately 40% or .138 tons per acre (574 tons) of the total sediment yield was derived from the geomorphic type area, primarily the upland crop and pasture area. Sixty percent of .348 tons per acre (1,448 tons) of the total sediment yield came from channel erosion. Channel surveys indicate that up to 1,630 tons of sediment were derived from the tributary network. Estimated storage within the channel system was 182 tons.

Soil conservation measures have significantly reduced erosion from upland crop and pasture areas in the Coryell Creek Basin. However, erosion by lateral scour in the channel region remains a problem. Implementation of a good vegetative cover appears to reduce surface runoff and discharge through the channel system.

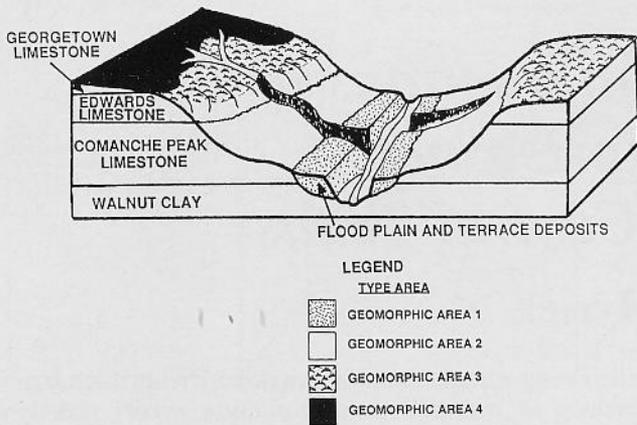


Figure 1. Geomorphic type areas (1983) were delineated according to gradient of slope, soil erosion values or K factors, and land use. Geomorphic area one was characterized by nearly level slopes, a .28 K value, and crop and pasture land use in the flood plain and terrace regions. Area two rested on slopes averaging 15 percent, had a soil erosion value of .10, and was used predominantly as forestland. Type area three consisted primarily of upland areas lying on the Edwards limestone. Characteristics of this region included two percent slopes, a .15 K factor, and rangeland usage. Area four was assigned to upland areas resting on lower Georgetown strata and consisted of two percent slopes, soils with an averaged K factor of .26, and a predominant land usage of crop and pasture. These characteristics were useful for estimation of sediment loss and yield, utilizing the Universal Soil Loss Equation and the SWRRB model.

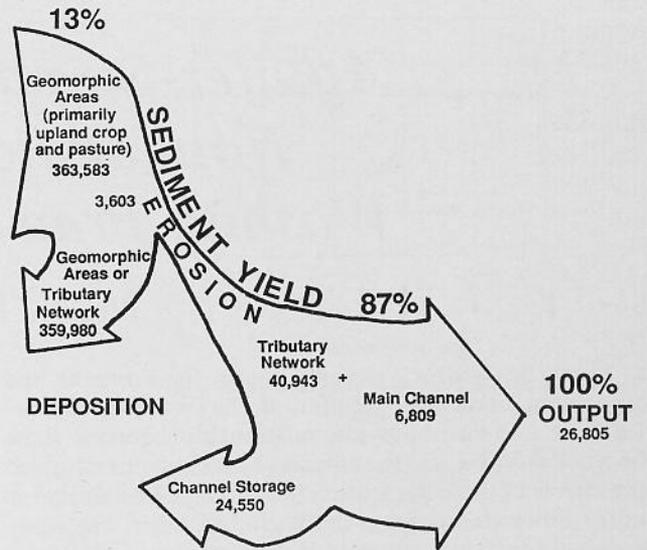


Figure 2. A 1983 sediment budget for the Coryell Creek Drainage Basin was determined using field reconnaissance and sediment yield values (in tons) generated by the SWRRB model.

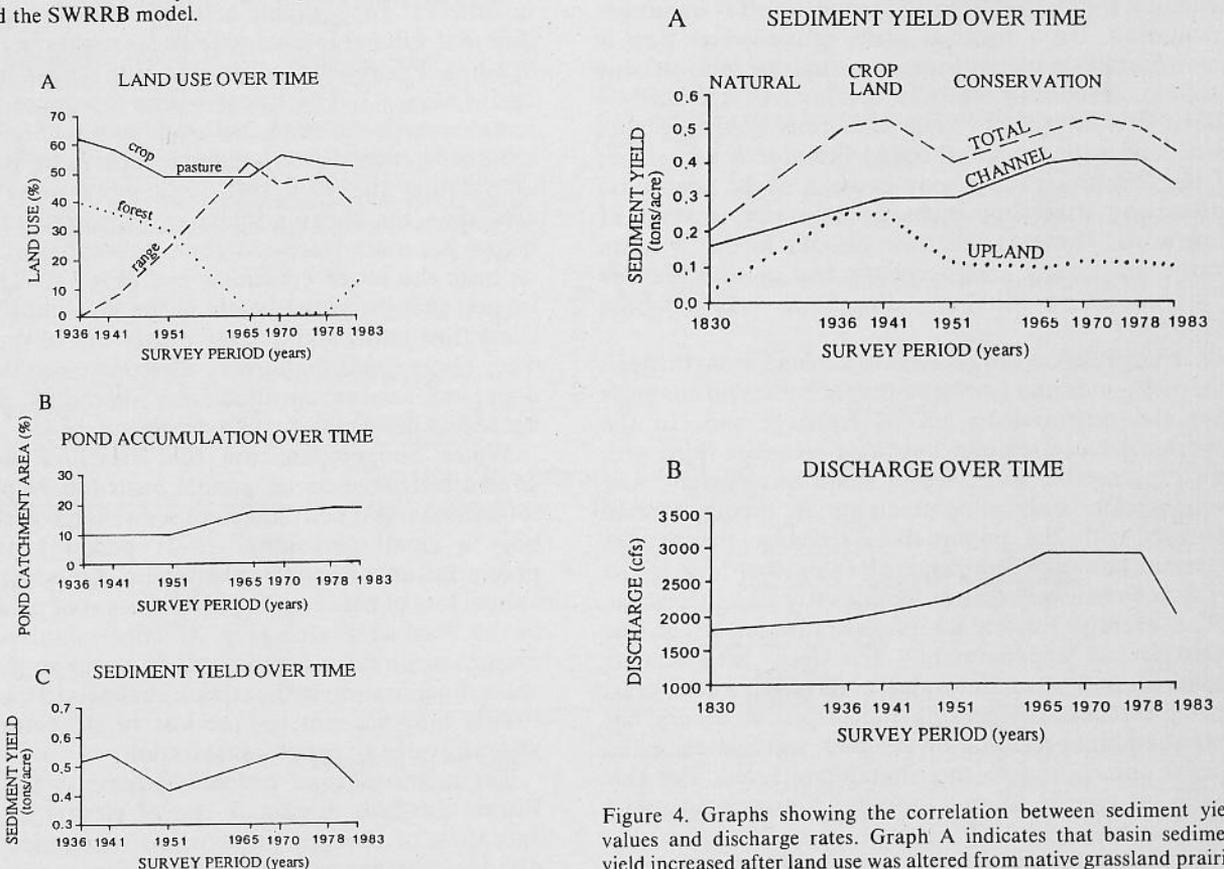
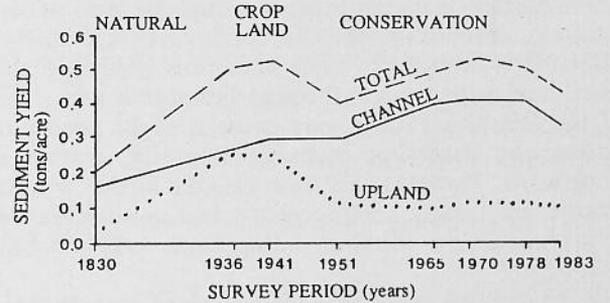


Figure 3. Graphs showing how land use and land management practices influenced sediment yield from 1936 to 1983 in a representative sub-basin in the Coryell Creek area. Graph A shows land use trends during the survey period. Graph B indicates that from 1936 to 1983, catchment area for stock ponds increased by eight percent. Values plotted on Graph C suggest that sediment yield decreased until 1951, increased until 1970, and lowered after 1978. Comparison of graphs A, B, and C suggest that despite increases in stock pond catchment area, sediment yield was relatively high when percentage of forestland was reduced.

A SEDIMENT YIELD OVER TIME



B DISCHARGE OVER TIME

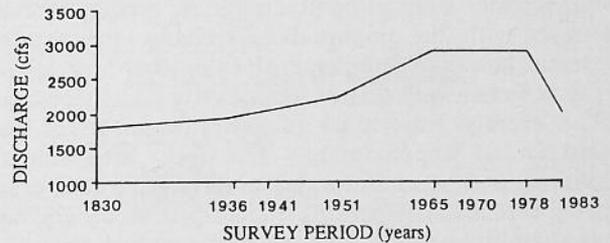


Figure 4. Graphs showing the correlation between sediment yield values and discharge rates. Graph A indicates that basin sediment yield increased after land use was altered from native grassland prairies of the early 1800s to crop, pasture, range, and forest of 1936. Sediment yield from the upland area also increased after land use in that area was changed from grassland to cropland. Following widespread implementation of soil conservation measures and construction of ponds by 1951, sediment yield from the upland areas was reduced. Channel sediment yield rose slightly from 1830 to 1951. After 1951, this rate increased greatly. Graph B shows stream discharge simulated for 1830 to 1983. Dramatic increases in discharge occurred after 1951. Comparison of graphs A and B indicate that channel sediment yield rates are highly dependent upon stream discharge.

Aquifer-Stream Interactions in Nonkarstic Limestones: Washita Prairie, Central Texas

Mark K. Myrick

Numerous bedrock streams dissect the Edwards and associated limestones aquifer of the Washita Prairie. Little is known about the relationship between these bedrock streams and the aquifer. This study investigated the effects of these streams on the recharge and discharge of the Edwards aquifer in the Washita Prairie. The study area concentrated on the drainage basins of Childress Creek and the Middle Bosque River, northwest of Waco, in central Texas. Groundwater in the Washita Prairie moves through nonkarstic limestones along an integrated network of fractures and bedding planes causing diffuse groundwater flow. Lineations observed on remote imagery exhibit orientations slightly related to regional structural trends, but lineations show no clear dominant orientation. On a regional scale, groundwater flow is homogeneous and isotropic due to the lack of one dominant fracture system. The dominant control on flow direction is topography. The numerous bedding planes associated with the interbedded limestones and shales of the Washita Prairie may cause a slight horizontal anisotropy directing recharge laterally instead of downward. However, all flow systems in the Washita Prairie are locally heterogeneous and anisotropic due to variations in lithology, diagenesis, and localized fractures.

Recharge appears to occur in the upland areas through thin rocky soils and fractured bedrock. Stream channels have the potential to act as recharge sites in the uppermost basin regions, but these areas are lined with slowly permeable soils, are of small areal extent, and contain water only after precipitation events. Stream channels with the potential to recharge the aquifer represent less than one percent of the total area of the Washita Prairie and do not significantly affect recharge.

The average fluctuation of groundwater levels was found to be approximately five feet, with similar maximum and minimum water levels reached each year. During extended dry periods some depletion occurs, but after abundant precipitation resumes, water levels in the aquifer quickly rise to their maximum levels. For this reason, change in annual storage is considered to be approximately zero.

The aquifer has an effective porosity of approximately 1-2 percent which allows for large groundwater rises after precipitation events. Corresponding with ground-

water rises are increases in stream flow. Stream discharge increases in response to precipitation events shortly before the groundwater responds, but in most areas groundwater maintains a higher head than the stream, and channels continue to act as discharge points.

Stream discharge per square mile of contributing basin area in similar topographic areas does not vary greatly even in areas of high lineament density. This finding suggests that groundwater flow to streams is homogeneous. Supporting this finding is the fact that the meandering nature of the streams of the Washita Prairie causes all orientations of water-bearing fractures to discharge into the stream channels. However, streams in different topographic settings were found to have different discharge characteristics, suggesting that the Washita Prairie can be divided into upper and lower basins (Fig. 1). The upper basins are more fractured and dissolutioned than the lower basins. Streams with minimal vertical dissection, but located in the upper zone of fractures (upper basin), yield more water per unit area than the streams that have dissected the aquifer below the more fractured zone (lower basin) and into or near the lower confining bed (Fig. 2). These data suggest that the groundwater in the Washita Prairie has short flow paths and quickly moves out of the aquifer. They also suggest that deeper dissection into the aquifer does not increase groundwater discharge due to a decreased permeability with depth.

Water budgets indicate that baseflow dominates stream discharge on an annual basis (36-79 percent of total discharge), but total stream discharge accounts for only a small percentage (8-21 percent) of annual precipitation. Evapotranspiration accounts for an annual loss of between 79 and 92 percent of precipitation in the Washita Prairie (Fig. 3). Ninety-four percent of evapotranspiration is estimated to occur in the upland areas. Evaporation in the stream channels in the Washita Prairie may account for the loss of six percent of all water lost due to evapotranspiration.

The relationship of bedrock streams to the Washita Prairie Edwards aquifer is one of discharge, with the exception of perhaps the smallest tributaries near the divides. Recharge occurs primarily through areal infiltration of precipitation on the uplands.

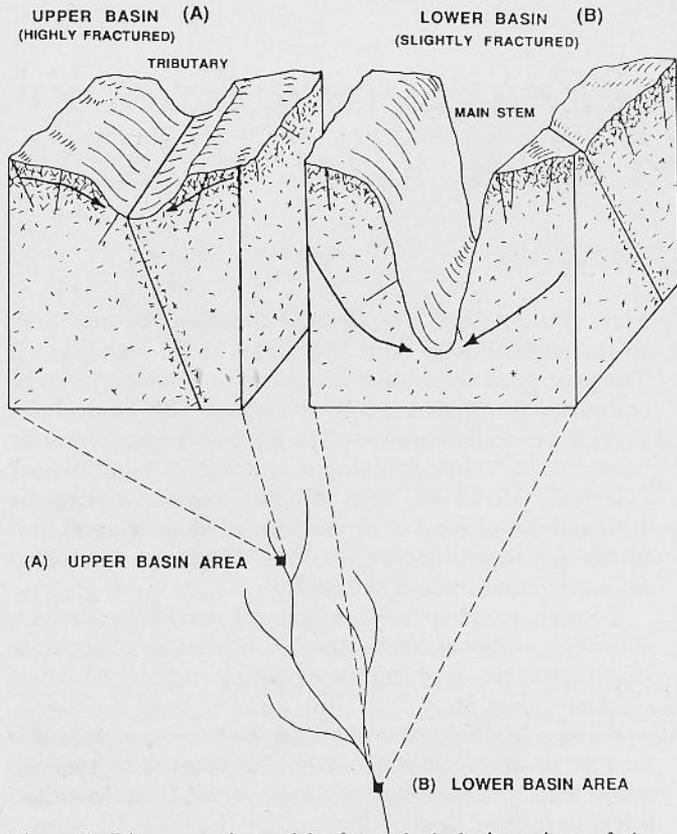


Figure 1. Diagrammatic model of two hydrologic regions of the Washita Prairie. The upper basin is drained by tributaries that receive baseflow discharge from a highly fractured and slightly dissolved region. Regions of the basin that are more deeply dissected (lower basin) are drained by trunk streams. These streams receive some baseflow discharge from highly fractured and slightly dissolved areas, but most water comes from an intermediate flow system where water moves through a less fractured and less dissolved zone.

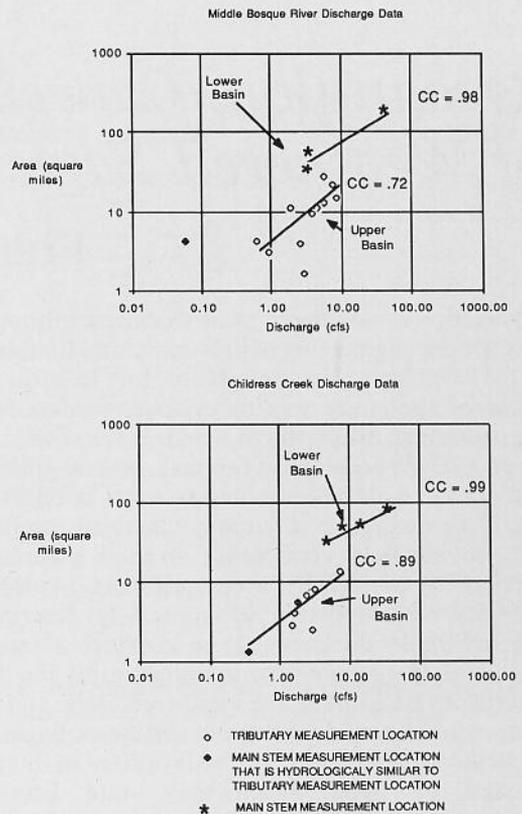


Figure 2. Baseflow discharge plotted against contributing basin area. The upper basin areas, which are dominantly drained by tributaries, discharge more water per unit area than the main stem areas (lower basin).

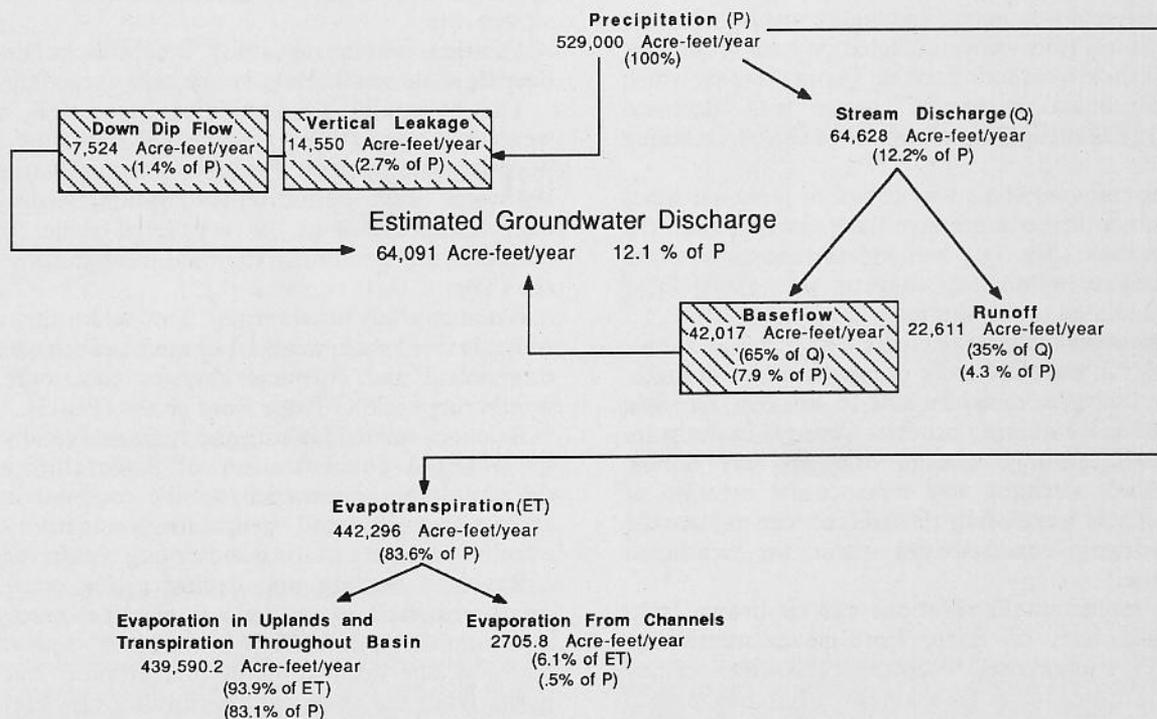


Figure 3. Water budget results. Water budget calculations (Middle Bosque River and Hog Creek) for the water year 1985 showed that a majority (83.6 percent) of annual precipitation is lost due to evapotranspiration. Direct runoff accounted for only 4.27 percent of estimated annual precipitation. Of the total stream discharge, baseflow accounted for a majority of the water seen in the stream channels (65 percent). Total groundwater discharge was estimated to be 64,091 acre-feet or 12.1 percent of annual precipitation.

Recognition, Genesis, and Engineering Geology of Weathered Eagle Ford Shale, Central Texas

Frank Paniszczyn

Knowledge of weathered shale thickness is important for the proper engineering of light structural foundations and for evaluating its suitability for landfills. The purpose of the study was to evaluate the occurrence and geotechnical properties of a central Texas weathered shale profile. To accomplish this task, several goals were identified: 1) to classify weathering zones in Eagle Ford shale; 2) to determine if visually classified weathering zones provide field verification of shale geotechnical properties; 3) to identify a cost efficient, exploratory geophysical tool capable of accurately determining weathered shale thickness; 4) to conduct a series of surveys with the geophysical tool illustrating the lateral and vertical variability in the weathered shale; and 5) to develop a genetic model for the evolution of Eagle Ford shale weathering patterns. Methods utilized in this study consisted of field, laboratory, and literature investigations.

The study area is located within the city of Woodway, a suburb of Waco, McLennan County, Texas. The site lies within the Eagle Ford Prairie. This study has concentrated on the Eagle Ford Group, which consists of the South Bosque and Lake Waco Shale Formations.

A gradational weathering profile exists in the Eagle Ford shale, consisting of unweathered, slightly weathered, moderately weathered, and highly weathered shale.

Geotechnical tests were conducted on each of the four individual shale weathering zones. The manner by which these geotechnical properties change with increased weathering adds insight into Eagle Ford shale weathering processes.

The unweathered shale was found to have ten times greater unconfined compressive shear strength than the weathered shale (Fig. 1). The increase in shear strength with decreased weathering suggests that shale shear strength is related to weathering.

Shale moisture contents decrease with depth and shale weathering, and are inversely proportional to strength. It is suggested that moisture acts to weaken the shale and aid in the weathering process. Changes in moisture content preferentially weaken oriented clay bonds, decrease shale strength, and enhance the creation of fractures. These weathering-related fractures explain the higher hydraulic conductivities within the weathered shale profile.

Several important implications can be drawn from geotechnical tests of Eagle Ford shale weathering profiles. (1) A visual shale weathering classification may provide simple field assessment of geotechnical properties. (2) Significant strength variation between the weathered and unweathered zones may explain the depths of landslide shear planes which bottom out at the contact between the weathered and unweathered

shale. Foundation piers should therefore be anchored in the unweathered zone for better slope stability. (3) The weathered shale has been shown to possess hydraulic conductivity values to .000001 cm/sec. The Eagle Ford shale is generally considered to have very low hydraulic conductivity values, making it suitable as landfill liner material. However, the .000001 cm/sec hydraulic conductivities found in the weathered shale suggest that in situ hydrogeologic evaluations should be conducted for waste containment suitability.

Comparisons between borings and electrical resistivity soundings substantiate electrical resistivity as an accurate reconnaissance tool for determining weathered shale thickness (Fig. 2).

Using resistivity surveys and bore hole control, a weathered shale isopach map was constructed of the study area. Weathering thickness varied from less than 9 feet to greater than 36 feet.

Weathered shale is absent in channel bottoms and is generally thinner adjacent to drainage channels. Erosion within the ephemeral drainage channels is thought to occur at a rate equal to or greater than weathered shale generation, thus preventing weathered shale accumulation. Deeper weathering occurs on drainage divides where erosion processes occur at a slower rate.

Faulting within the study area has produced the deepest shale weathering, in one case exceeding 36 feet.

The hydraulic conductivities associated with the weathered zone (Fig. 1), combined with low effective porosity values, allow for large seasonal variations in the water table. Periodic precipitation creates wetting and drying cycles in the weathered shale. Repeated shrinking and swelling of the clays mechanically fracture the shale.

Based on study observations, a model for the evolution of Eagle Ford shale weathering can be constructed. Both mechanical and chemical changes contribute to the weathering cycle of Eagle Ford shales (Fig. 3).

Balcones-related faulting and stress relaxation resulted in localized concentration of discontinuities. The discontinuities enhanced hydraulic conductivity of the shale. The enhanced hydraulic conductivity allows effective alternate wetting and drying within the shale.

Repeated wetting and drying cycles occur in the weathered shale in response to seasonal precipitation, inducing the shrink-swell breakup of the shale. In addition, the infiltration of precipitation leaches out pyrite from the shale, which ruptures clay-clay bonds. The oxidation of pyrite also releases additional ions which combine to form gypsum. The growth of gypsum crystals pry the shale apart, thus contributing to the mechanical breakup of the shale.

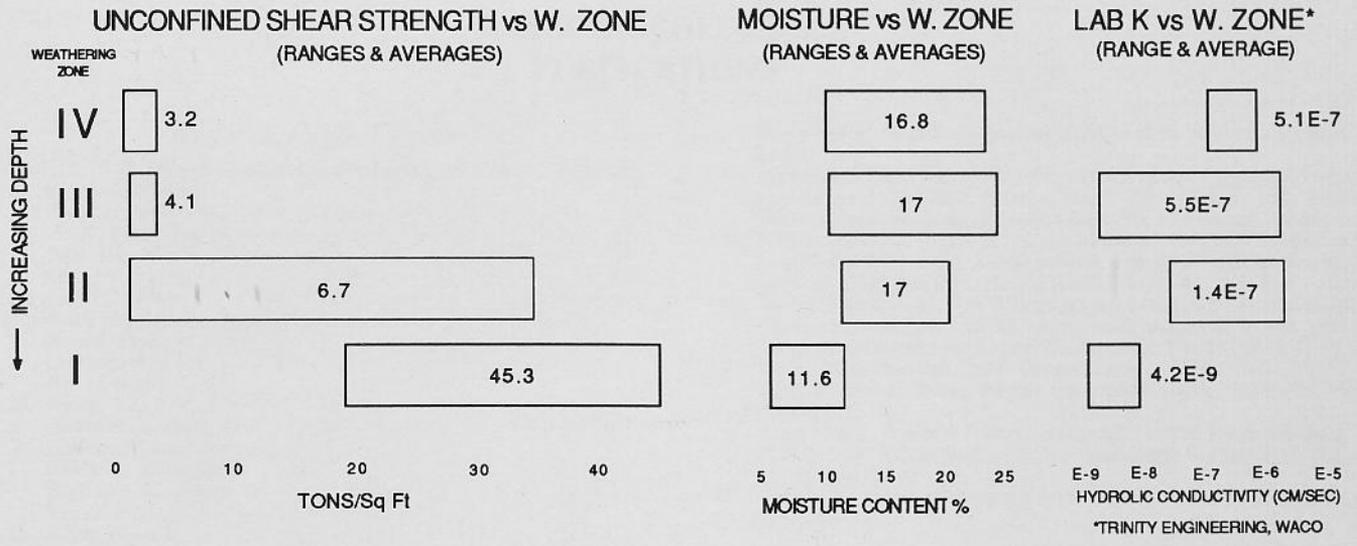


Figure 1. Weathering zones versus shear strengths, moisture contents, and hydraulic conductivities based on 78 tests conducted on weathered profiles of Eagle Ford shales. The boxes indicate the range of values while the numbers inside the boxes indicate the averaged values. Zone I designates unweathered shale, weathering zone II designates the slightly weathered shale, weathering zone III designates moderately weathered shale, and weathering zone IV designates highly weathered shale.

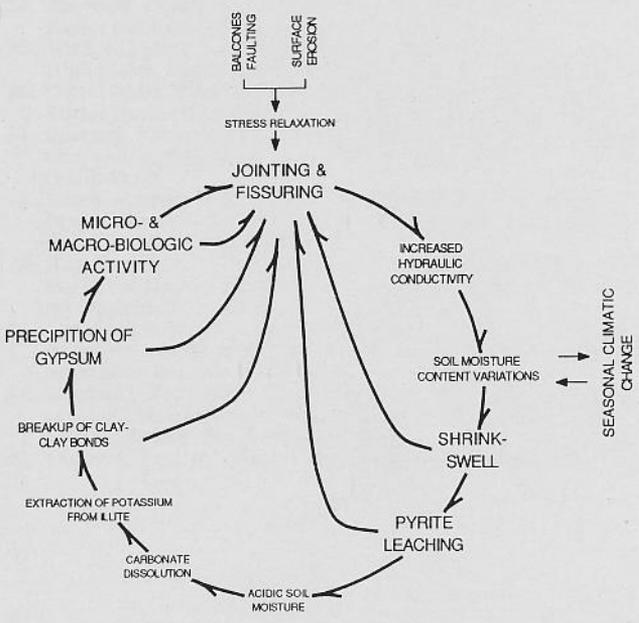


Figure 2. Electrical resistivity versus seismic refraction in determining depth to unweathered shale. Illustrated is just one example of numerous shallow seismic refraction and electrical resistivity surveys conducted to establish the effectiveness of each technique in approximating the depth to unweathered shale. Both survey methods were done in close proximity to a boring, where the depth to unweathered shale was known. The results of the shallow seismic refraction survey indicated a refractor surface at 4.4 feet, which is 17.6 feet in approximating the depth to the weathered/unweathered contact indicated in the boring. Results of this electrical resistivity survey predicted the depth to unweathered shale with 95% accuracy.

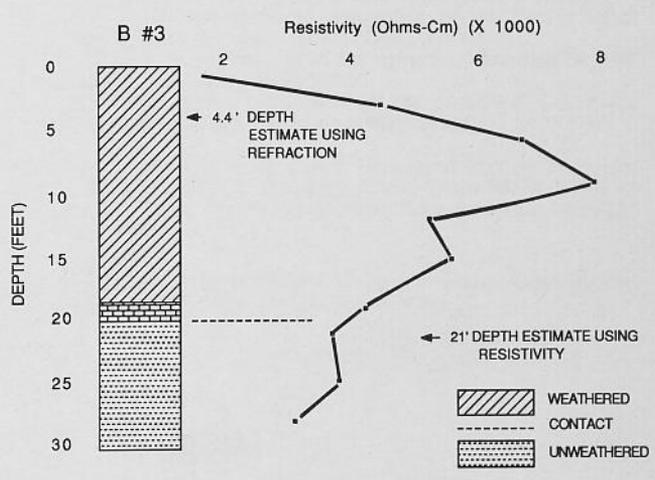


Figure 3. The weathering cycle in the Eagle Ford Group clearly shows that fracturing is a major factor in weathering. The results of Balcones-related faulting and surface erosion have created stress-induced discontinuities as foci of chemical and mechanical weathering. Variations in shrink-swell further fracture the shale. Oxygen within the infiltrated precipitation leaches the pyrite from the shale, ultimately resulting in the breakup of clay-clay bonds, and the precipitation of gypsum. Finally, biologic activity enhances jointing and fissuring.

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