CENOZOIC EVIDENCE OF DISPLACEMENTS ALONG THE MEERS FAULT, SOUTHWESTERN OKLAHOMA

A Thesis

by

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ABSTRACT

Cenozoic Evidence of Displacements along the
Meers Fault, Southwestern Oklahoma. (May 1988)

Gregory Allen Kientop, B.S., University of Wisconsin - Oshkosh
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A region within a 40-kilometer radius of the Meers Fault Scarp, southwestern Oklahoma was the site of this paleoseismological investigation. Four sites were described and sampled for analysis. X-ray diffraction, soil composition and structure, petrographic, and provenance studies were conducted defining the surficial geology present along the fault.

Sedimentary records indicate at least four movements along the Meers Fault. At least one left-lateral movement (and possibly as many as four) was established near the Bedrock Pit Site. In addition, small (young) drainages are offset vertically due to the later Holocene displacements. Brittle deformation was associated with this earlier displacement(s) indicating the possibility of an associated earthquake(s).

The three remaining movements are observed in the Pointer Excavation and are Holocene in age. The dominant sense of movement during these events resulted in a down to the south vertical displacement in a 7-centimeters wide portion of a 2-meter wide older fault zone. These Holocene displacements may be the result of

isostatic compensations associated with the enormous erosion rates prevalent throughout the region during Pleistocene and Holocene time.

Evidence of at least one *former Tertiary erosional* surface in the study area was described from lab and field investigations. Climate changes associated with Pleistocene glaciations resultd in partial erosion of the Neogene Ogallalla Formation which had been deposited over this Tertiary surface. The remnant pediment surfaces in the Wichita Mountains may then be used as a relative datum horizon in interpreting Tertiary and younger displacements within the region.

ACKNOWLEDGEMENTS

I would like to thank the members of my thesis committee, Dean Melvin Friedman, and Dr. Michael Waters for their constructive advice and guidance throughout this research project. I am particularly indebted to my thesis committee chairman, Norman R. Tilford, for his constant inspiration through his priceless insight. These people have made enormous contributions to both my thesis topic and my enjoyment of life through betterment of my education.

This research project was funded and supported by the Army Corps of Engineers through the Center for Engineering Geosiences and the Department of Geology at Texas A&M University. The generous support of these organizations resulted in, to a large degree, the success of the investigations. Special thanks goes to Dr. Ellis Krinitsky for his support and inspiration. My thanks to Wanda Henshaw for her statistical advice and know-how.

I hope to always know my friends in Oklahoma who helped make this past year the most memorable of my life. This includes Charlie Bob and Dixie Oliver, Julie and Rueben Pointer and their family and all the other landowners who opened their lives to me. The greatest of these honors was given to me and my family by the Pointers who opened their home to me as though I were a son and allowed me to stay on their ranch for the duration of the field investigation of which a large part was conducted on their land.

I owe all the attributes from the compilation of this text to my ever-loving wife, Margaret, who saw to the last line the satisfactory completion of this thesis.

DEDICATION

Since the time when I licked my first agate with my grandfather, picked up my first fossil in Illinois, and went on field trips with new-found friends, I have remembered with heart-warming appreciation the support that has dogged my every footstep from my parents, teachers, relatives, friends too numerous to mention, and not least of all my wife, Margaret. I realize that I may never fully appreciate the multitude of gifts that are mine today because these gifts of time, effort, and love that have all opened doors for me, have taught me that they will follow me forever -- their depths ever increasing until I lose sight of them amongst themselves. It is to these patrons of my life that I dedicate this token of appreciation -- may it follow them as graciously and as eternally. I would also like to dedicate this work to the memory of my Grandmother Gordhamer, and my friends in geology; Todd Ostrom, Pat Ragen, and Dan Mierswa who have all shared their support with me for the last time.

> "We may enter the infinite through the *minute no*
> less than through contemplation of the vast."
>
> George William Russull

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INTRODUCTION

Statement of Problem

Former paleoseismological studies of the Meers Fault have resulted in many conflicting interpretations of deposits as young as Holocene in age. More studies of this region are necessary in order to relate the seemingly conflicting data that exists today.

Since Taff (1904) utilized the geology along the Blue Creek Canyon Fault during his regional geological survey of the Arbuckle and Wichita Mountains, the Frontal Fault Zone has been defined and characterized in sporadic efforts until a period of intense study began on the Meers Fault in 1983. These efforts include Harlton (1951; 1963; 1972), Chase (1954), Moody and Hill (1956). With the work of Gilbert (1983a; 1983b) regional studies increased dramatically. Identification of the Meers Fault as active in Quaternary time was first mentioned by Moody and Hill (1956, p. 1225) as they described the fault as exhibiting a recent scarp developed in Quaternary alluvium." The possibility of recent of movement along the Meers Fault was not discussed further until 27 years later (Gilbert, 1983a).

With the Meers Fault re-identified and accepted as a fault active in Quaternary time, more intense and detailed studies began to characterize the sense of movement and the recency of this enigmatic structural element (Kerr, 1985; Weisburd, 1985). Subsequently, geomorphic studies of the scarp and the vicinity were completed by Westen (1985), Tilford and Westen (1985), and Ramelli and Slemmons

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This thesis follows the style of the Bulletin of the Association of Engineering Geologists.

(1986) with the regional Quaternary stratigraphy first extensively studied by Madole (1986). In 1985, Madole constrained the latest movements along the Meers Fault as Holocene age (1,280 ± 140 years ago, DIC -3,167) (Madole and Meyer, 1985; Madole, 1988). Some work concerning the number, timing, and sense of Holocene movements was undertaken by Westen (1985), Madole (1986, 1988), and Crone and Luza (1986) as a result there is more evidence of the latest movement but no clear indicators as to the timing or number of earlier events needed to accurately delineate a recurrence interval for the fault. Moreover, no accepted interpretations as to the tectonic style of the Meers Fault were generated. Much of the tectonic history of this fault could be improved if the behavior of the fault was better understood through stratigraphic field evidence than with semi-analogous extrapolations of scarp length-height studies (Ramelli and Slemmons, 1986).

Evidence for Holocene movements associated with the Meers Fault does not include records of significant historical seismicity (Lawson, 1985; Luza and Lawson, 1985) even though there are seismic records for *mid-continent regions* (Figure 1). Reactivation of a fault last believed to have moved during a Permian orogeny poses many intriguing questions about tectonics in the mid-continent which are to date unanswered. The inadequacies of presently accepted plate tectonics models to explain intracontinental tectonic activity simply requires additional relevant information.

From an engineering viewpoint, the determination of whether or not the Meers Fault is truly capable of generating earthquakes is of

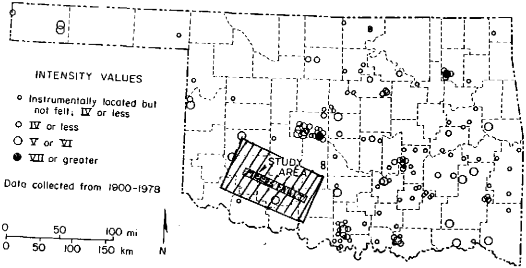


Figure 1. Earthquake map of Oklahoma illustrating seismicity with respect to the Meers Fault study area (modified after Luza and Lawson, 1983).

vital concern to the communities of both Lawton and Fort Sill (a combined population of over 100,000 people). Fort Sill, a major military base, and two large dams (Lakes Lawtonka and Ellsworth) are among the critical facilities in the region potentially threatened by possible earthquakes generated along the Meers Fault and the Frontal Fault Zone (Tilford, 1987).

Significance of the Proposed Study

The primary purpose of this study is to gather paleoseismological data on the Meers Fault likely to be relevant to neotectonic interpretations. Having already discussed the need for more paleoseismic studies along the Meers Fault Scarp, it follows that the presently accepted quiescent period, from Permian time to 1,280±140 years before present, should be further investigated and tested. In areas that lack adequate historical seismicity records, paleoseismological data may prove to be the only means available to characterize a fault. Innovations of both siting methods and excavation techniques will at least give direction to future studies (Sieh, 1984). Future tectonic models will result largely from paleoseismological studies due to the apparent long-term stress generating processes involved (Allen, 1986) because these processes are complex and by no means smoothly continuous (Aki, 1979; Hartzell and Heaton, 1983). Techniques which can infer the presence or absence of earthquakes in an area are both invaluable in characterizing the potential hazards of a fault zone. The use of caves to indicate the presence of earthquakes is an approach proposed in my study.

From Permian times through to the present day, there is a conspicuous absence of well understood regional geologic history for southwestern Oklahoma. A comprehensive literature search compiling many of the past works on the region would serve as an important data base for imminent future studies due to the sporadic nature of past scientific interests in the area. Such data would be useful in describing the regional Cenozoic geology. Much archaeological work has described the recent geology of the area but has only started to be compiled (Ferring, 1987; Gould, 1929).

Geologic Setting

The Wichita Mountains of southwestern Oklahoma lie between the Appalachian and Rocky Mountain Ranges. Located approximately 65 miles west of the Arbuckle Mountains in Oklahoma, the Wichita Mountains border the world renowned Anadarko Basin on its steepened southern extent (Oklahoma City Geological Society, 1971) (Figure 2). Between the Wichita Mountains and the Anadarko Basin lies the Frontal Fault Zone (Harlton, 1951; 1963; 1972). The southern-most boundary fault of the Frontal Fault Zone north of the Wichita Mountains is the Meers Fault (formerly known as the Thomas Fault) (Chase et al., 1956; Decker, 1939; Harlton, 1951; 1963; 1972; Miser, 1954). The Wichita Mountains are composed of Proterozoic to Cambrian igneous rocks (Ham et al., 1964; Hoffman, 1930; Taff, 1904) and then Cambrian to Ordovician limestones in the Slick Hills of the northeastern portion of the mountains (Donovan, 1986; Gilbert and Donovan, 1984).

The igneous core of the Wichita Mountains is believed to have been uplifted twice during Paleozoic time. From 550 to 525 million

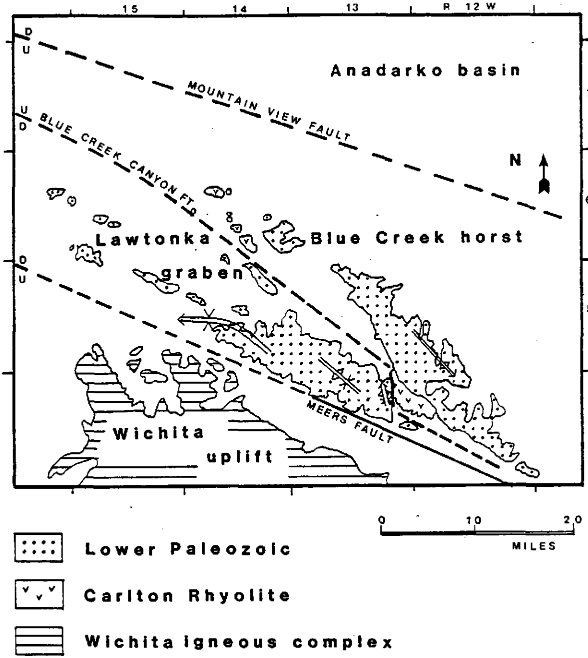


Figure 2. Principal tectonic elements northeast of the Wichita Mountains (from Gilbert and Donovan, 1982).

years ago, an aulacogen is thought to have formed in the region as is evidenced by intrusion of diabase dikes and normal faulting (Brewer et al., 1983; Hoffman et al., 1974; Larson et al., 1985). The region saw the later emplacement of rhyolitic extrusions in Cambrian time (Powell et al., 1980).

From Late Cambrian to Mississippian time the region underwent subsidence during the creation of the Anadarko Basin in which the igneous substrate of the Wichita Mountains were buried under 4 to 60 kilometers of carbonate muds (Amsden, 1975; 1983). The Wichita Province began to be uplifted again during Late Mississippian and Earliest Pennsylvanian time developing many structural features seen today, including the Meers Fault, and contributed sediment to the Hollis Basin (to the south) and the Anadarko Basin to the north (Gilbert and Donovan, 1982). From 3 to 6 kilometers of "granite wash" was deposited in the Anadarko Basin during Pennsylvanian time (Gilbert and Donovan, 1982). It is evidenced that a major compressional phase in the uplift resulted in large-scale overthrusting of the Wichita Province out over the Anadarko Basin (Brewer et al., 1983; Riggs, 1958). Uplift in the Ouachita Belt to the east continued after the thrusting in the Wichita Province ceased. It is thought that the continued thrusting in the Ouachita Belt resulted in the development of a left-lateral wrench fault system in the Arbuckles and the Wichitas (Arbentz, 1956; Booth, 1981; Carter, 1979; Donovan, 1982; Palladino, 1984; Tanner, 1967).

Permian sediments accumulated from 2 to 4 kilometers in thickness burying the exposed igneous core of the Wichita Mountains.

Regionally, the Permian deposits are represented by the allogenic Hennessey Shale which is believed to be partly of fluvial in origin, the Post Oak Conglomerate which is a boulder-cobble conglomerate exhibiting facies from local rhyolite, granite, gabbro, and limestone outcrops (Al-Shaieb et al., 1980; Bridges, 1985; Chase, 1954; Olson, 1967).

There are no known geologic records from the Permian in the region until the Quaternary, though some believe that Cretaceous units once covered the region (Gilbert and Donovan, 1982). No movements between the Anadarko Basin and the axis of the Wichita Uplift have been recognized since the Late Pennsylvanian (possibly Earlier Permian) except for the Holocene movement on the Meers Fault (Crone and Luza, 1986; Donovan et al., 1983; Gilbert, 1983a; Madole, 1986; Moody and Hill, 1956; Ramelli and Slemmons, 1986; Westen, 1985). This 240 million year gap in the geologic record for southwestern Oklahoma indicates that much can be yet contributed to the regional geology of the study area.

The Meers Fault exhibits a 26 kilometer long fault scarp in which the net displacement is down to the south with a maximum relief of 5 meters (Donovan et al., 1983; Ramelli and Slemmons, 1986; Westen, 1985). The fault scarp is nearly linear and strikes N60°W throughout its exposure (Donovan et al., 1983). Approximately 760 meters of throw along the length of the Meers Fault resulted from post-Mississippian movements (Harlton, 1951).

Little or no lateral displacement is clearly and continuously identified with the Holocene movements (Gilbert, 1983a,b; Tilford and

Westen, 1985) although some investigators have identified what they believe is up to 25 meters of left-lateral displacement (Donovan et al., 1983; Ramelli and Slemmons, 1986). The fault scarp displaces Cambro-Ordovician lower Arbuckle group limestones, Permian Hennessey Shale and Post Oak Conglomerate, and Pleistocene through Holocene stream terrace deposits. Through most of the exposure, the fault scarp offsets Post Oak Conglomerate and Hennessey Shale (Figures 3 and 4). Vertical slickensides (distinctly non-pedogenic) are preserved on clay surfaces above and between lithified, faulted surfaces at Hennessey Shale outcrops (Westen, 1985). Earthquakes have been potentially associated with the Holocene movements of the Meers Fault due to abundant brittle deformation in the Post Oak Conglomerate (Permian) which is believed to have been deformed at low temperature and low effective pressure (Byerlee, 1968; Rutter, 1986). Due to the differing erodabilities of these Permian units, the least eroded portion of the scarp is in the northwest where it displaces resistant Post Oak Conglomerate rather than in the southeast where Hennessey Shale is offset and the scarp is more subdued. The highest portion of the scarp occurs within the Hennessey Shale (Tilford, 1986). The net sense of Holocene displacement (down to the south) is opposite in direction to the displacements that are thought to have formed the Meers Fault and the Frontal Fault Zone (down to the north) (Donovan et al., 1983; Tilford, 1987; Westen, 1985).

The last Holocene movement 1,280±140 years before present DIC-3167) (Madole, 1988) has been studied in various lithologies, and environments via different methods but is still unclear as to the

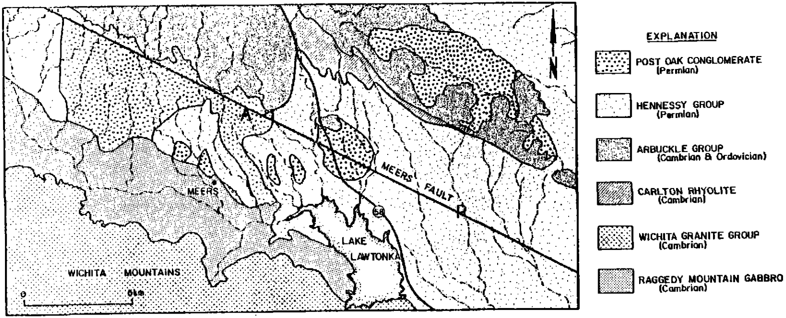


Figure 3. Geologic map of a portion of the study area identifying the locations of the Pointer (P) and alluvial fan (A) sites along the Meers Fault (after Miser, 1954).

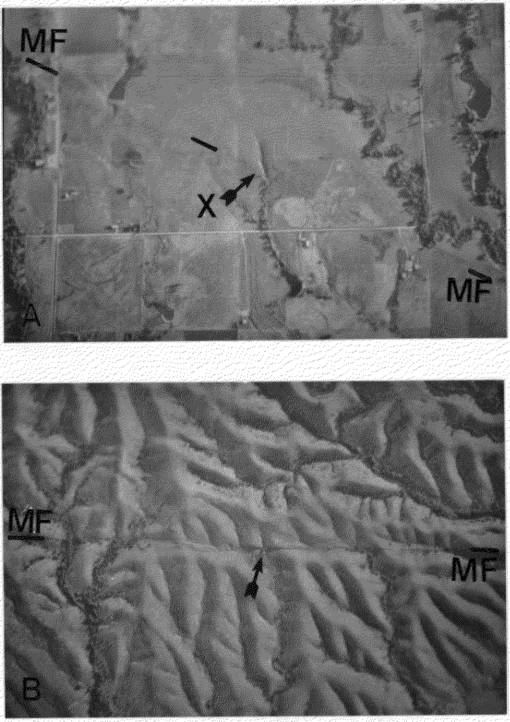


Figure 4. A) Low-sun-angle aerial photograph of the Pointer Site "X" (fault trace between line segments labeled "MF"). B) Low-sun-angle of the alluvial fan site.

sense of movement and the former stress-releasing mechanism(s) (i.e., seismic stick-slip vs. aseismic creep). It is evident that a number of movements have occurred (Ramelli and Slemmons, 1986; Westen, 1985) but the only dated movement is the latest one (Madole, 1986). The Meers Fault is accepted as one of the major faults within the Frontal Fault System (Ham et al., 1964; Harlton, 1972). The Meers Fault has been postulated to be active with the potential for large, damaging earthquakes (Slemmons and Ramelli, 1985). Only about 0.0006% of the 240 million year gap in the geologic record for this region describes the Meers Fault though the fault has existed since Pennsylvanian time.

Physiographic Setting

The eastern Wichita Mountains are part of the south-central Great Plains province (Fenneman, 1931). The study area is in the central lowlands portion of this province approximately 225 kilometers east of the Llano Estacado at the "Break of the Plains" in the panhandle of Texas (Fenneman, 1931). The Wichita Mountains divide the Washita River Valley, 55 kilometers to the north, from the Red River which is about 120 kilometers to the south. Most of the drainage systems in the study area are ephemeral and flow to the southeast representing a tributary system of the Red River. The Meers Fault Scarp intersects 48 ephemeral streams along its 26 kilometer (16.2 miles) length (Westen, 1985).

Erosion dominates the surface processes in the region as continental climatic transitions from moister Pleistocene and Early Holocene times have gradually waned (Ferring and Hall, 1986; Hall, 1982; Hall and Ferring, 1987). The present average annual precipitation rate is 71 centimeters/year (28 inches/year) with a mean annual evapotranspiration rate of 62 centimeters/year (24 inches/year) (Pettyjohn et al., 1983). The present climate is characteristic of the interior continental plains (National Oceanic and Atmospheric Administration, 1977) with warm, moist air moving into the region from the Gulf of Mexico resulting in hot, long and humid summers with moderate winters. This semi-arid climatic region is characterized by alternating periods of flash floods and drought. The mean summer temperature is 107°F with a mean winter temperature of 50°F (Lamar, 1979).

Early records described the vegetation cover for the limestone facies of the Post Oak Conglomerate, before the turn of the century, as tall grasses interspersed with small oaks (Bain, 1900). Natural erosional processes, accelerated by a drying climate and overgrazing in the Slick Hills has resulted in the transportation of much of the soil cover into areas of low relief by sheet wash. Eventually these sediment-filled hollows are emptied during floods by ephemeral drainage systems resulting in a presently sparse vegetative cover consisting of short grasses and progressively more cacti (Mobley and Brinlee, 1957).

The Meers Fault Study Area

The study area for this investigation is slightly larger than regions included in previous studies (Crone and Luza, 1986; Madole, 1986; Ramelli and Slemmons, 1986; Westen, 1985). This is to include areas which might contain karst within the potentially seismically affected area of 40 kilometers (25 miles) radius to the linear surface expression of the Meers Fault Scarp (Tilford, 1987). This designated rectangular region of about 8,566 square kilometers (3,308 square miles) contains elements of the eastern Wichita Mountains, the Slick Hills, many limestone outliers in red bed plains, and some sandstone cuestas near Gotebo. Major cultural elements within the study area include the city of Lawton, the military reservation of Fort Sill, Lakes Lawtonka and Ellsworth (reservoirs), and many smaller communities. The study area is primarily in Caddo, Kiowa and Comanche Counties though parts of Grady, Stephens, Cotton, Tillman, Jackson and Washita Counties are also included in this designated region (Figure 5). The area of investigation is roughly parallel to the axis of the Amarillo-Wichita-Criner Uplift and the alignment of the Frontal Fault Zone (Arbentz, 1956).

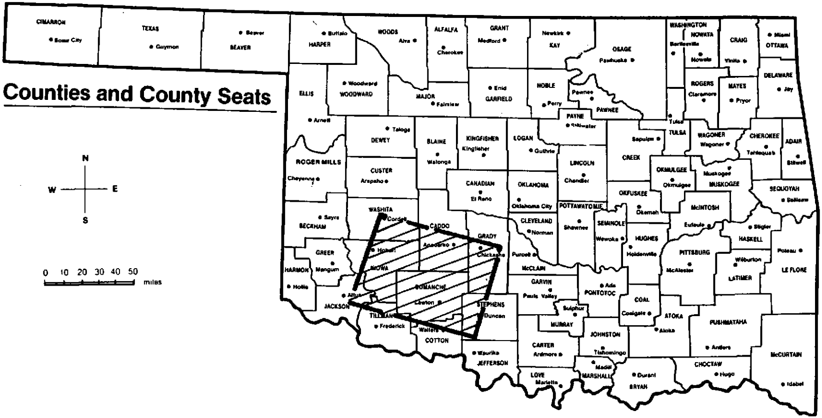


Figure 5. The study area relative to the disposition of counties and county seats in Southwestern Oklahoma.

METHODOLOGY

The Cenozoic sedimentary records within the study area were reviewed for paleoseismological evidence pertaining to fault movements within the Frontal Fault Zone concentration on the Meers Fault Scarp. Information concerning the process or mechanism of fault movement, sense of movement, number of movements, depositional environments as well as related regional geologic history were gathered and interpreted. The qualitative and quantitative documentation of conditions associated with fault movement that were completed in the office, field, and laboratory.

Remote Sensing

A regional imagery analysis of the study area was conducted to identify potential excavation sites and to characterize these sites. Imagery used in describing the study area included stereoscopically viewed low-sun-angle photos, side-looking airborne radar imagery, Skylab imagery, enhanced Landsat 4, MSS bands 2 and 4, a false color composite, as well as some low-altitude photography taken during the investigation of some of the excavation sites. I used 7 1/2 minute quadrangle topographic maps published by the United States Geological Survey to trace overlays of cultural features, drainage, fractures and faults in the pediment study in the Wichita Mountains. Other information gathered from the various imageries included locating areas of shallow bedrock, joints, faults, drainage pattern differences, differing geologic units, variations in deformation, and changes in vegetation cover.

The locations that would later be excavated and studied were primarily established by means of composite analysis of various imageries. I then located the sites in the field, providing the next step in assuring that the site was interpreted correctly and to determine if the site was available for such an investigation from the prospective land owner. I conducted a regional imagery analysis of the eastern Wichita Mountains studying suspected pediment surfaces associated with a possible Tertiary erosional surface in the Wichitas.

Pediment Investigation

A topographical study of the region between the Llano Estacado (High Plains Surface) and Lawton, Oklahoma was directed toward relating levels in the Wichita Mountains to Tertiary erosional surfaces perhaps associated with the deposition of the Ogallala Formation (Neogene). The source of the data were United States Geological Society 7 1/2 minute quadrangles published in 1956. These topographic maps utilize a common contour interval of 10 feet. A pediment in this study is defined as any bedrock surface having a minimum surface area of about 5,810 square meters (62,500 ft^2) and a maximum relief of 6.1 meters (20 feet) vertically. A data point number was arbitrarily assigned to each of the pediment surfaces. Six pieces of information describe each of the 123 data points in the set. The information describing each data point consists of a description of the basic geometry of the feature, the elevation of the pediment, the surface area of the pediment, the township-range location of the pediment surface as well as any well-recognized name for the described surface (see Appendix A).

The basic geometry of the pediment surfaces was described using one of five terms for the purposes of this study. These terms include saddles, flat-topped reliefs, ledges, encircling ledges, and flat-topped ridges. A "saddle" (S) is defined as an area of low relief between two adjacent areas of high relief. A "flat-topped" (F) relief is a topographic feature which has a flat surface or gentle inclination at the point of maximum elevation. A "ledge" (L) is defined as a flat or gently inclined surface adjacent to a singular area of high relief. An "encircling ledge" or "hat" (H) is like a ledge in that it encircles an area of high relief much like the brim of a hat. A "flat-topped ridge" (R) then is a flat or gently inclined linear ridge crest. Judgement is involved in deciding the correct term as there are transitional geometries.

The elevation description for a particular pediment is taken relative to mean sea level. The closest 10-foot contour line to what is taken to be the middle of the pediment area is what is assigned to the feature. In assigning elevations in this manner, it is believed that the pediments are located vertically to within 20 feet (6.1 meters).

The surface area of each of the pediment surfaces was measured using a standardized transparent template and a number varying from 1 to 4 was assigned with "4" representing the largest reference surface area of 371,800 m^2 (4,000,000 ft^2) [a square with sides 610 meters (2,000 feet) long]. Each of the consecutively smaller reference surface areas represent 1/4 of the last reference surface area so that "4" equals from 92,950 to 371,800 m^2 (1,000,000 to 4,000,000 ft^2); "3" equals from 23,238 to 92,950 m^2 (250,000 to 1,000,000 ft^2); "2" equals from 5,810 to 23,238 m^2 (62,500 to 250,000 ft^2); and "1" represents the minimum surface area to define a pediment of about 5,810 m^2 (62,500 ft^2). Again, some decisions must be made as to the number assigned to a pediment as very few of the pediments approximate squares exactly and must be visually approximated. A few pediments filled the "4" range (371,800 m^2 or 4,000,000 ft^2) so that the full range from 5,810 m^2 (62,500 ft^2) is being utilized. Comparatively, these surfaces vary from between 10 and 666 football fields worth of surface area.

The dip direction describes the gentlest peripheral slope beneath the elevation of the pediment and is read as though from a compass in map view (see Appendix A). The readings follow as proceeding from north clockwise; N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW. The readings are approximated visually and were attempted to describe the "leeward face" or the paths gentlest slope down from the pediment. Slope directions were identified to infer former drainage paths and erosional trends. These approximated azimuths are accurate to within 20° ($\pm$20°).

The township-range coordinates were taken for all pediments described. These coordinates are accurate to within 400 meters (1,300 feet). The plan view locations of all 123 of the pediments have been plotted to the same scale as the source maps to show the shapes and sizes of the pediments. The common names of features near pediments was noted to assist in relocating data points. Many of the named features in the Wichita Mountains have pediments associated with them.

Wichita Mountains Study

I performed a field investigation in the eastern portion of the Wichita Mountains attempting to determine if the region had, been subjected to recent earthquakes. The boulder fields and the tor topography (Gilbert, 1979; Twidale, 1982) contained within the main body of the Wichita Mountains were the focus of the study. Descriptions and associations concerning genetic, compositional, and depositional factors which might potentially lead to the generation/concentration of the boulder deposits were made. Viewing "stacked" boulder relationships typical of tor topography as potentially unstable in an earthquake event, I tried to make interpretations as to the likelihood of earthquakes in the eastern Wichita Mountains.

I searched for fine-grained sediments in the region to locate potentially liquefied sediments. Studies of Tertiary to Holocene drainage patterns in and around the Wichita Mountains were made in attempt to piece together a sedimentary record for the region. A survey of the probable surficial processes which had contributed to erosion and the coarse sediments in the area was conducted. This summary of surficial erosional processes operating in the area from at least Pleistocene time to the present should offer an explanation for the generation of the boulders in the region which are by themselves difficult at best to date.

Alluvial Fan Excavation

I distinguished two lobes of fan alluvium by differing vegetative covers along the northwest portion of the Meers Fault Scarp during the regional imagery analysis portion of the investigation. The alluvial fan is situated on the down-block (south) relative to the Meers Fault Scarp. My proposal was to excavate the upper lobe of fan alluvium in hopes of exposing sedimentary responses from two displacements of the fault. The proximity of the fault scarp to the alluvial fan (36 meters) and the incised nature of the scarp by the arroyo drainage supported my hypothesis. This chosen arroyo had less than 400 meters of upstream drainage which allowed the deposition of fine-grained sediments on the alluvial fan due to the limited volume of flow.

A pilot excavation was dug to a depth of about 1.5 meters to gain insight into the nature of the deposit in order to optomize the siting of the main excavation on the top-most lobe of sediment. The excavations were sited on the top-most lobe of the fan in order to maximize the sedimentary record to be exposed in the main excavation. I sited the main excavation off the axis of the alluvial fan in hopes of avoiding most of the coarsest sediment on the fan. Coarse sediment such as boulders and thick gravels would not allow the resolution of the possible movements and would also make the excavating difficult. Due to the desires of the landowner, the main excavation was completed by hand which also allowed for more complete descriptions of the materials exposed as well as control of the degree of disturbance.

I sampled the main excavation at 60 centimeter intervals vertically for the purposes of later conducting x-ray diffraction studies to describe the soil development. The excavation was then mapped in cross-section to within one centimeter indicating changes in the grain size of exposed sediments, thicknesses of units, attitude of the units, and composition of the sediments. I then surveyed the site with respect to the fault zone and the geometry of the alluvial fan using a 30 meter measuring tape.

Pointer Site Excavation

This site was chosen along a spring-fed stream in the southeast portion of the Meers Fault Scarp. The stream is a tributary of Browns Creek (informal name) which in turn is a tributary of East Cache Creek. The area containing this site was studied by Diane Westen during her masters thesis work on the interesting tectonic geomorphology displayed there (Westen, 1985). The stream at this location has less than 400 meters of upstream drainage similar to the Alluvial Fan Site in length and contains conspicuous gully erosion above where the fault scarp crosses it. My excavation site was located on the west bank of the stream-cut at the point where the Meers Fault Zone obliquely crosses the stream.

I excavated the site by hand and mapped it in detail using a vertical grid system superimposed over the exposure. A reference line was established along the length of the excavation in order to locate separate vertical profiles and to document sample locations. The individual deposits in the exposure were described as to grain size, color, internal structures, cementation (if any), geometry of the deposit, and content of datable organic materials. I gathered samples from each of the units described in order to conduct x-ray diffraction studies describe clay mineralogies and in some cases solid development and clay mineral alterations. We then surveyed the site using a 30 meter measuring tape and a plane table alidade. The up- and down-block gradients of the stream were measured to determine if the stream has had enough time to equilibrate with respect to the increased gradient induced by the fault movement(s).

Bedrock Pit Site

Beginning in March of 1987, I studied some vertical sandstone dikes in an excavation that was dug into the fault zone in the northwest portion of the fault scarp by Anthony J. Crone of the United States Geological Survey (Ferring, 1987). The excavation was to remain open and further study of these phenomenon was possible during the course of my field work in the area. No conclusions as to what these sandstone dikes represented were made or have been subsequently published.

The anomalous sandstone in the excavation was described as to grain size, cementation, composition, geometry and alignment of the dikes, and the nature of the host rock in hopes of identifying the sandstone and describing its depositional history. I performed petrographic studies on thin sections made from the sandstone found in-situ in the excavation to compare component mineralogies of the sandstone to the nearby source rocks.

Cave Investigations

I knew from conversations with people who have studied the geology of the region previously, and from speaking with landowners, that caves were known to exist especially in the limestones of the Slick Hills (Donovan, 1987; Oliver, 1986; Pointer, 1987). I visited one cave before the initiation of the investigation, at the invitation of the landowner, to appraise the potential of the region as a karstic study area. Some paleontologic and petrographic (petroleum-related) studies had been completed in karstic settings in the region (Donovan, 1982; 1986; Ham, et al., 1957; Olson, 1967).

I began the investigation with a reconnaissance of the study area in order to identify caves. Fifty-three leads were investigated in the study area in which 32 of these caves were thought to be previously unexplored (Bozeman, 1987; Oliver, 1987). Members of the local chapter of the National Speleological Society (Central Oklahoma Grotto) assisted in surveying, describing, and exploring some of the leads during the investigation (Central Oklahoma Grotto Newsletter, 1987). Only 3 of the 53 leads seemed to contain sedimentary records sufficient to contain information relating to the investigation. Only two of these three leads were accessible for the purposes of this study due to the water level conditions and the extremely difficult descent (30 meter vertical drop) into one of the caves (Bat Cave). One of these caves, Caddo-Moonshine Cave, had been known about for many years and was also known to have been influenced by humans (Oliver, 1987). Caddo-Moonshine Cave still was described in the study because it was the only lead which had a significant detrital sedimentary record contained within it. The remaining lead, which was previously undiscovered, was named Gelfling Cave and contained deformed chemical sediments (cave formations) which were described and interpreted during the investigation in attempts to determine the cause of the deformation.

The study of Caddo-Moonshine Cave began with a survey conducted with a tape measure and a brunton compass (Bozeman, 1987). Information such as fauna, flora, and air temperature was gathered during this survey. The alignment of the cave was described in reference to joint sets, bedding planes, and surficial drainage (arroyo) alignments. A site within the fine-grained sediments within the floor of the cave was chosen and excavated by hand to search for potentially liquifiable sediments. The excavation extended to the bedrock floor of the cave. The sediments at the site were then sampled for bulk density determinations, grain size analysis and x-ray diffraction studies to interpret their relative liquifaction potentials and depositional histories.

Gelfling Cave was surveyed roughly using a brunton compass and measuring tape. I made measurements and descriptions of structures and cave formations that were encountered in this cave. The observations made in Gelfling Cave were particularly useful in interpreting the origin for many of the karst features.

Provenance Studies

In the course of sampling sandstone dikes displayed in the Bedrock Pit Site and in describing the sedimentary environment of the Pointer Site, it became necessary to use a polarizing-petrographic microscope (to analyze thin sections from the indurated samples) and a binocular microscope (for the unconsolidated Pointer Site samples). I typically studied included composition-similarities, component-size, and mode of deposition estimations to compare the samples to known source rocks.

I had oriented thin sections of the vertical sandstone dikes and from two horizontal thin beds of a similar sandstone found above the dikes at the Bedrock Pit Site. Laminations were studied under plain transmitted and polarized light between each of the dikes and included the horizontal beds. I studied the compositions sizes, and degree of rounding of the grains to quantitatively compare the samples to regional lithologies in attempts to relatively date the dikes.

I compared the samples from the Bedrock Pit Site with samples of similar lithology collected from sandstone-capped cuestas a few miles west of Gotebo, Oklahoma. These sandstones were selected as the likliest candidate as the surface analog to the sandstones in the Bedrock Pit Site due to their general appearance, age, and stratigraphic relationships. Extinction angle comparisons were made from plagioclase and potassic feldspar grains to determine potential similarities of the respective source rock materials. I approximated anorthite content of plagioclase grains using the Michel-Levy Method (Jones and Bloss, 1980). Characteristics of cementation were also noted from the respective sandstones. Thin sections of granite samples collected from the eastern Wichita Mountains were similarly studied as the potential source rocks of these sandstone units. Comparative data was referenced from previous petrographic studies of materials in the study area (Al-Shaieb et al., 1980; Gilbert and Donovan, 1982; Ham et al., 1964).

Provenance studies of deposits sampled and analyzed from the Pointer Site were conducted using a binocular microscope. Granule sized fractions of the up-block channel deposit and the down-block orange deposits were compared as to composition, grain shape, and possible provenance relationships. I compared the sand-sized lithic fragments in the granule-sized fractions from the Pointer Site deposits with the sandstones studied at Gotebo and the Bedrock Pit Site to investigate the possibility of the lithologies being the same and therefore forming a relative time horizon between the various sites. The data gathered during the previously described microscopic examinations was then compared with sub-microscopic data gathered via x-ray diffraction studies to provide a broader basis for comparisons between the various sites.

X-Ray Diffraction Studies

X-ray diffraction analysis can yield valuable data about fine-grained deposits. A series of 12 samples gathered from the Pointer Site, the Alluvial Fan Site, and from Caddo-Moonshine Cave were analyzed on a Phillips XRG-3000 x-ray diffractometer. I ran a suite of three variations on each sample collected as Mg-saturated, heat treated (300°C), and untreated to identify and characterize the clay mineralic (<2 micron) fraction. The three variations were necessary to be capable of confidently differentiating various clay mineral components (Walker, 1958).

Much of the recent history of soil deposits is recorded in the sub-microscope fractions represented by various states of clay minerals (Millot, 1970). The relative proximity of the deposit to the surface can be determined by the relative expansion of the layered clay minerals structure (i.e., vertical displacements). The clay mineral components of a deposit can reflect such things as source materials, depositional history, climatic changes, and various oxidation-reduction environments possible for soil deposits. Even the level of ionic substitution in the layered clay mineral structure can be approximated in some cases (Drees, 1987). All of these descriptions are valuable in paleoseismological investigations as the investigator is trying to recreate pre-faulting conditions in order to interpret such information as number of displacements, weathering surfaces, and climatic variables.

PRESENTATION OF RESULTS

Alluvial Fan Excavation

Description

The alluvial fan I sited for excavation on the down-block was deposited from an ephemeral drainage system perpendicularly crossing the Meers Fault Scarp in the western 1/2 of the southwest 1/4 of section 15, township 4 north, range 13 west on the Kimball Ranch in Comanche County. This alluvial fan was thickly vegetated with grasses and sumac and had less then 400 meters of drainage upstream from the fault scarp on the up-block. The excavation was completed by hand and was located 36.5 meters south of the fault scarp on the down-block. It was 10 meters west of the right margin of the fan as you look upstream and had an east-west profile with the dimensions of 2 meters long by 1/2 meter wide (Figure 6A).

Bedrock was encountered in the excavation at a depth of 2.52 meters in which the limestone facies of the Post Oak Conglomerate (Permian) was exposed as a relatively unweathered surface (Figure 6B). The first unit I encountered in the site was a 10 centimeter thick, dark brown organic soil with a few limestone pebbles and cobbles in a matrix of loam. Beneath this horizon was an eight centimeter thick layer of limestone pebbles and cobbles with little fine-grained materials. I next exposed a layer of brown organic-rich soil with a thickness of 8 centimeters which was underlain by 32 centimeters of limestone pebbles with a few cobbles in a small amount of fine-grained brown matrix. The 10 centimeters below this horizon consisted of fractured and re-cemented limestone cobbles, fragments of sheared

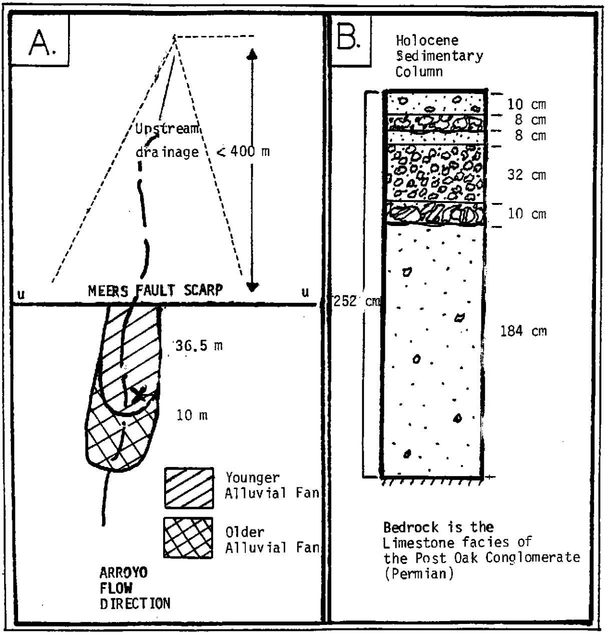


Figure 6. A) Schematic diagram of the Alluvial Fan Site. B) Stratigraphic section of the Holocene sediments exposed at the Alluvial Fan Site.

limestone fault breccia and a few undeformed limestone cobbles (Figure 7). The base of this unit forms a sharp contact with the deposit beneath it. I found the next 184 centimeters to the bedrock surface was composed of a brown, organic-rich, clay loam soil which contained a few pebbles scattered within it but no cobbles. This unit displayed numerous pedologic slickensides (up to two centimeters long) especially in its lower portion, evidencing the abundance of expansive clays. The gravel deposits thinned to the sides of the alluvial fan. This sedimentary column contained numerous grass and sumac roots through to the bedrock surface.

X-ray diffraction tests were conducted on four samples collected from the basal buried soil body at various depths. The clay fractions of samples collected at depths of 68, 145, 186, and 252 centimeters from the surface were analyzed. The most abundant clay mineral was montmorillonite and these <2 micron sample fractions also included quartz and kaolinite with traces of calcite, feldspar, and mica. Generally, the montmorillonite present contained little to no secondary silicate substitutions within their crystal structures and exhibited the effects of weathering uniformly throughout the vertical profile. This uniform degree of weathering evidences that this anomalous 1.8 meter thick A-horizon was transported soil material and not developed in place.

Interpretation and Discussion

The interpretations of the deposits at the alluvial fan site are based primarily on the assumption that a soil deposit represents a period of erosional quiescence and likewise records periods of no

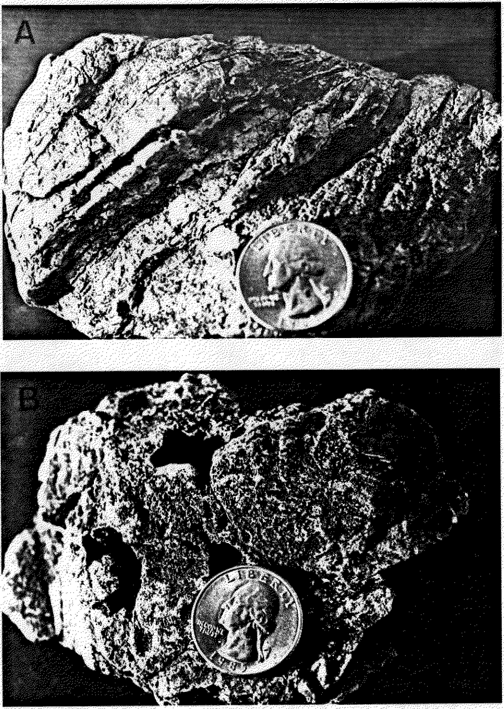


Figure 7. Tectonically deformed Post Oak Conglomerate detritus at the alluvial fan site A) limestone cobble and B) carbonate fault breccia.

vertical movement along the scarp of the Meers Fault. The pebbly and cobbly deposits would then represent periods of increased gradient for the drainage system created by vertical movements along the Meers Fault. These movements generated transgressive deposits on the alluvial fan as the drainage system re-established the gradient on the up-block. Evidence which lends confidence to these interpretations includes the frequency of material that can be traced directly to within the fault zone (i.e., fractured-leveled cobbles and breccia) within the lower-most cobble deposit, the extreme thickness of the basal buried soil horizon, the sharp soil-cobble contacts, all combined with the proximity of the fault scarp and limited upstream drainage area.

The characteristics of the basal soil deposit would associate this deposit with a Mid-Holocene age as an analog of the Browns Creek alluvium with the subsequent deposits representing the Late Holocene age East Cache alluvium (Figure 8) (Madole, 1987). My interpretations are then supported by evidence for two movements of the Meers Fault with at least significant vertical components in the Late Holocene. The latest movement is evidenced by a thinner pebble-cobble deposit because either there was little easily erodable material available at that time or possibly the vertical displacement was of a lesser magnitude than the previous movement. Accurate radiocarbon dating within the deposit was ruled out due to the presence of roots extending to bedrock and x-ray diffraction results evidencing it as a transported soil (Blong and Gillespie, 1978).

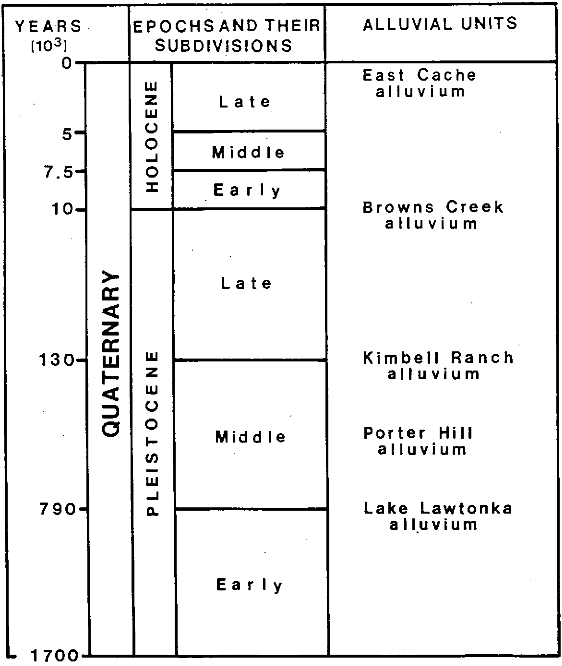


Figure 8. Time-stratigraphic relations and estimated ages of Quaternary alluvial units along the Meers Fault (after Madole, 1986).

The basal soil unit is interpreted as a transported soil due to the sharp contact that exists between the bedrock surface and the base of the soil which is uncharacteristic of a parent material-solum transition (Brady, 1974). Many other similarly transported soil deposits have been identified in the region during this geologic period (Donovan, 1986; Ferring, 1987).

Pointer Site Excavation

Description

The Pointer Site is located on land leased to Mr. Rueben Pointer where the Meers Fault Scarp obliquely crosses a spring-fed tributary of East Cache Creek in the southwest 1/4 of the southeast 1/4 of section 34, township 4 north, range 12 west in eastern Comanche County. The site is located in the Hennessey Shale (Permian) near the southeastern terminus of the Meers Fault Scarp. The fault has, as with the Alluvial Fan site, uplifted the headward drainage area of this stream and deposited Holocene sediments south of the fault scarp onto the down-block (Figure 4B). I completed the excavation by hand along the west bank of the stream-cut where the fault scarp intersects the stream. Exposures of the fault zones, the materials composing the up-block, and the sediments that have been deposited on the down-block can be seen along this 26 meter long excavation (Figure 9). The exposure has a maximum vertical height of 2.8 meters at the fault zone with the potential vertical expression of the excavation being limited by the shallow water table. I measured the total upstream channel length of this drainage at less than 145 meters. The Pointer Site contains a recognized total of 13 different deposits displaying marked

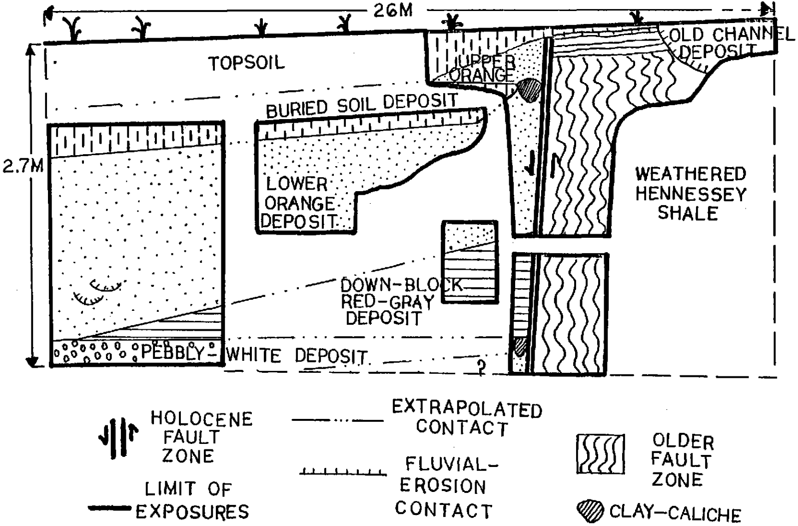


Figure 9. Schematic diagram of the Pointer Site Excavations.

changes in; degree of induration, geometry of the deposit, grain size, color, sedimentary and tectonic structures, composition, geologic age, and attitudes (Figure 9).

I classified the topsoil covering the excavation as a sandy clay loam texturally having a natural bulk density of 1.76 grams/ centimeters^3 and a total porosity of 32%. The clay mineral that predominates the clay fraction is montmorillonite with some kaolinite. Underneath the topsoil on the down-block near the fault zone is a small lenticular deposit of oxidized-dehydrated clay and granules. I named this unit the "upper-orange" deposit (Figure 9). The unit has a maximum thickness of 61 centimeters near the Holocene fault zone. This deposit pinches out southward away from the Holocene fault zone in only 2.8 meters over a buried soil horizon.

The buried soil I mentioned above is the basal portion of the previously described topsoil deposit in which is contained the "upper-orange" unit. This wedge of buried soil is texturally a clay loam as it contains a higher percentage of clay than does the later developed soil or topsoil unit. The buried soil unit has a lower bulk density relative to the topsoil of 1.61 grams/centimeters^3 and a greater porosity of 38.1%. Both soils represent A-horizons though the buried soil appears higher in organic matter (darker brown) and has better developed soil structure. From x-ray diffraction studies, both soils display a weathered layered silicate structure though the buried soil appears more weathered than the present day surface soil.

At the Holocene fault zone, on the down-block, I found an accumulation of gray clay and caliche nodules at the same horizon as

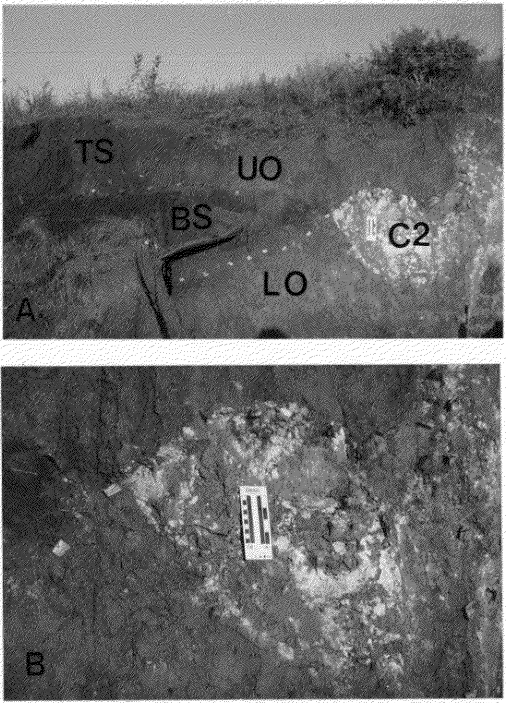


Figure 10. A) The buried soil and caliche-clay deposits exhibiting plane of compaction between the upper- and lower-orange deposits (scale card is 6 inches long). B) Close-up of caliche-clay deposit (Holocene fault zone indicated by pink flagging).

the buried soil (Figure 9). This deposit of clay and caliche has a vertical cross-sectional area of 3,390 centimeters^2 and displays the effects of compaction by burial as the upper-orange unit was deposited over it and the buried soil at the same point in time due to the preserved plane of compaction as is indicated by the top of the buried soil (Figure 10). From x-ray diffraction studies, I found that the gray clay material is composed of montmorillonite with some vermiculite substitutions in the layered silicate structure indicating intense weathering. The gray clay also has not been at the surface as long as the buried soil has as is shown by the well-preserved structure of the clay mineralogy (Drees, 1987; Millot, 1970).

Beneath the buried soil and the gray clay-caliche horizon on the down-block, I encountered a sandy, orange-colored deposit similar to the upper-orange unit except in extent (Figure 9). This lower-orange unit is roughly three times the thickness of the upper-orange deposit at the Holocene fault zone. The lower-orange unit is in part a transported deposit as it includes fluvial cross-bedding. The lower-orange unit has sharp upper and lower contacts, and slopes away from the fault scarp on the down-block thinning 0.61 meters in 9.75 meters distance. When projected away from the Holocene fault zone, the lower-orange unit is likely to extend a total distance of 35 meters to the southwest. It also overlies a deposit which thins away from the fault zone on the down-block (down-block red deposit). The lower-orange unit contains, at the base, inclusions of gray clay and weathered Hennessey Shale derived from the fault zone and the up-block respectively. I described the lower-orange unit as having columnar structure developed within it and the upper-orange unit as massive (Figure 11).

Under the lower-orange unit I found a deposit of dark red, clayey material with an angular-blocky structure (Figure 9). This down-block red deposit is identical in nature to the up-block red unit in the older fault zone except for the deformed appearance of the material contained within the older fault zone. These two similar deposits are separated by the Holocene fault zone. I described the geometry of the down-block red deposit as wedge-shaped with it terminating to the southwest within 11.7 meters. I found the deposit exposed only in the excavations near the Holocene fault zone and in the southern-most excavation where it is seen to terminate as a laminated gray clay (Figure 12). I calculated a slope of 3° to the top of the down-block red deposit from the maximum 0.6 meter thickness of the unit at the Holocene fault zone. The down-block red unit does contain pebble-sized chunks of gray clay material eroded from the gray clay material displayed in the nearly vertical Holocene fault zone.

I found that the down-block red unit was deposited on a horizon consisting primarily of pebble-sized caliche nodules (Figure 9). This pebbly-white unit contains primarily vermiculite in the clay fraction studied via x-ray diffraction analysis which sets it apart from all the montmorillonite-rich units exposed in this excavation. This unit also contains an accumulation of gray and red clay with caliche nodules at the point where this white horizon comes against the Holocene fault zone similar to the accumulation present alongside the buried soil above (Figure 13A). This accumulation of clay and caliche

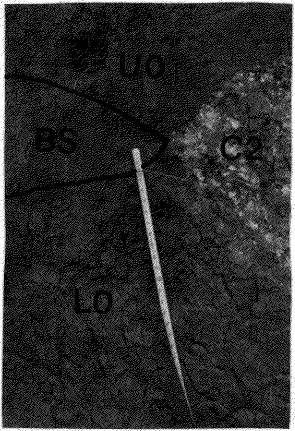


Figure 11. Photograph comparing the massive upper-orange unit with the columnar structure contained within the lower-orange unit at the Pointer Site.

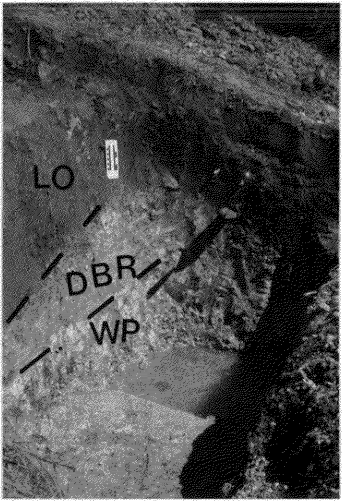


Figure 12. Photograph showing the discontinuous nature of the down-block red deposit (gray unit) as it pinches out away from the fault zone at the Pointer Site (scale is 6 inches long).

Figure 13. A) The upper and lower caliche-clay accumulations near the fault zone at the Pointer Site marking former positions of erosional equilibrium between events. B) Close-up of the lower (earlier) accumulation showing the sheared right margin of the deposit.

is sheared-off where it is in contact with the Holocene fault zone (Figure 13B) attributing to the existence of a later movement along this zone. The base level of the stream lies upon this pebbly surface on the down-block attesting to the relative stability of this horizon at the surface. The thickness of this unit varies from 7.5 centimeters at the Holocene fault zone to an undetermined thickness of at least 40.5 centimeters at the southern-most end of the excavation (Figure 14). Using the pebbly-white unit as a relative time-marker horizon, a total thickness of 1.8 meters of detritus was deposited on the down-block from the later two of the three movements.

Little is known about what underlies the pebbly, white layer other than near the Holocene fault zone there is at least 15 centimeters of a sandy red-orange material on the down-block (Figure 14). The nature of the material resembles the indurated, fluvial deposit in composition though it is more oxidized and not indurated. The base of the Pointer Site excavation was controlled by the ground water depth in the spring-fed drainage.

On the up-block, the exposed units include the up-block red, the fluvial channel deposits, and the deformed Hennessey Shale in the pre-Holocene fault zone (Figure 9). The up-block red unit is the relatively undeformed portions of the Hennessey Shale which although heavily weathered in the excavation form resistant outcrops further upstream on the drainage. The up-block red unit displays a heavily mottled red, yellow, orange, and white (caliche) appearance and is composed of both clayey and indurated blocks. This unit is generally

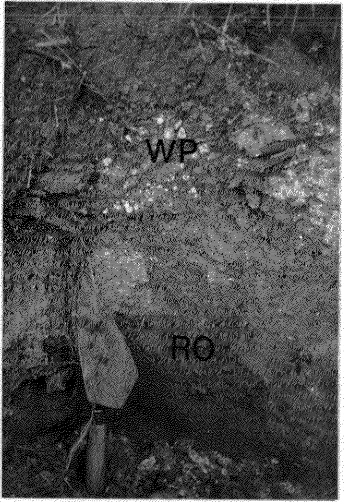


Figure 14. Photograph displaying the white-pebbly deposit and the red-orange deposit at the base of the Pointer Site excavation near the fault zone on the down-block (blade of trowel is 6 inches long).

overlain by the gray to tan, partly indurated, fluvial channel deposits.

The channel deposits cover 12 meters of the exposed 14 meters of the up-block in the excavation and are composed of granule- to sand-sized lithic fragments of granitic rocks and of a quartz arenite with well-rounded grains and silica cementation. The arenitic, lithic fragments make up the most material in these channel deposits (70%) even though there is no source rock present for this detritus locally. The channel deposits have an average thickness of about 1.8 meters and contain a joint set which trends approximately N57°W probably associated with the Holocene deformations in the excavation.

I found the fault zone exposed in the excavation to be a broad (at least 2.3 meters wide), deformed, and altered zone with a more recent Holocene deformational zone superimposed over it. The older deformational zone contains mostly altered and sheared Hennessey Shale with vertical and horizontal alignments of caliche and blocks of indurated arenitic sandstone (Figure 15). The Holocene deformational zone is displayed along the southwestern-most extent of the pre-Holocene fault zone as a 7-centimeters wide and very uniform, gray clay seam with caliche modules. This clay seam contains poorly preserved vertical slickensides (Westen, 1985) and exhibits an unusual bilateral color symmetry presumed to be caused by the mixing and alterations of the respective up- and down-block materials by tectonic movements and weathering (Figure 16). Some shear zones in the pre-Holocene fault zone appear to have been partly utilized by splaying of shear zones near the surface or from pre-Holocene

Figure 15. The deformed nature of the pre-Holocene fault zone at the Pointer Site.

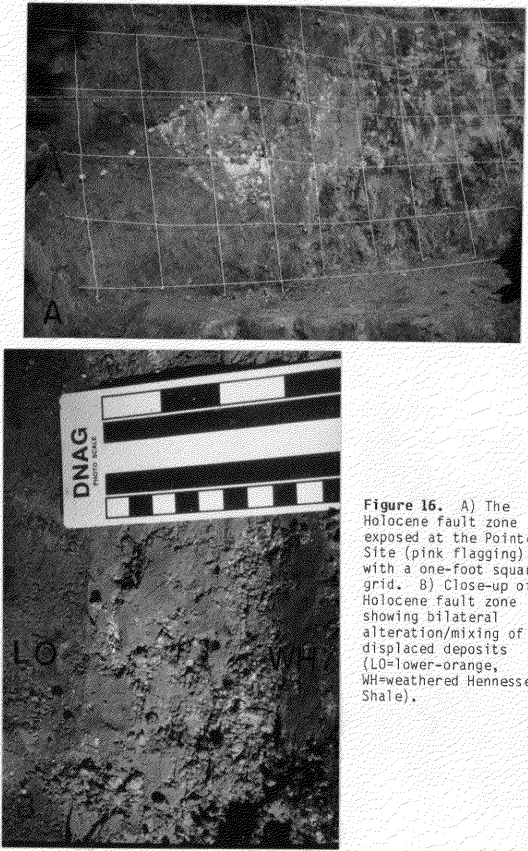


Figure 16. A) The Holocene fault zone exposed at the Pointer Site (pink flagging) with a one-foot square grid. B) Close-up of Holocene fault zone showing bilateral alteration/mixing of displaced deposits (LO=lower-orange, WH=weathered Hennessey Shale).

movements. The Holocene fault zone is vertically continuous in the outcrop to within 15 centimeters of the surface dipping 86° to the southwest and striking N61°W. I measured gradients of Pointer Site drainage on both of the faulted segments of the stream at 1.5 ± 0.25 feet per 100 feet distance indicating the fluvial system is equilibrated.

Interpretation and Discussion

The proximity of the buried soil deposit to the Holocene fault plane implicates that it is unlikely to be transported soil as indicated by the fine texture, preserved structure, and because the deposit thins as it approaches the fault zone. I think the thinning of the buried soil deposit as it nears the Holocene fault zone is likely due to the preferential use of the weathered down-block detrital sediments as a growth medium by vegetation and soil forming organisms than the relatively indurated Hennessey Shale and fluvial sediments present at the surface on the up-block. This tendency of vegetation growth to prefer the down-block is visible all along the scarp of the Meers Fault yet today (Figure 17).

I interpret the presence of a poorly developed A-horizon material on the up-block as an indicator that the faulting is very recent and that the up-block has been undergoing erosion and not stable soil development. The A-horizon material above the buried unit is then likely to have been reworked and transported by slopewash (Madole, 1988) from the up-block as it exhibits a coarser texture due to the incorporation of sand-sized particles which can be traced from the partly indurated fluvial sediments on the up-block. The present

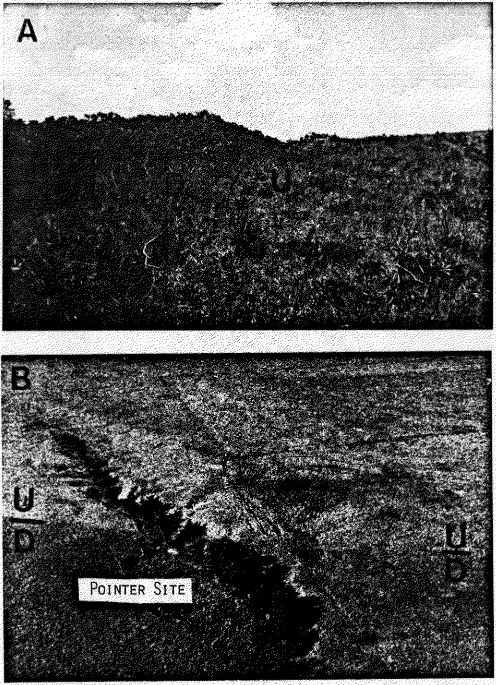


Figure 17. Vegetational differences between the up- (U) and down-blocks (D) at the A) alluvial fan site and B) Pointer Site.

A-horizon material tends to thicken as it becomes more distant to the fault scarp. The upper-orange deposit and the reworked A-horizon material began deposition on the down-block at the same time as indicated by the sharp buried soil to upper-orange contact, the lense-shaped geometry of the upper-orange unit with the present day soil, and the vertically gradational nature of the upper-orange material with the present day soil near the Holocene fault zone.

I interpret the deformed Hennessey Shale in the older fault zone as having been further altered along the weathering zone the Holocene fault zone represents by a combination of mixing of the materials near the Holocene fault zone during movements and the effects of percolating water in this zone of weakness afterward. My x-ray diffraction data attested to the similarities in the composition of the gray clay materials throughout the excavation as well as to their proposed origins. The fact that the buried soil unit pre-dates the accumulation of gray clay material allowed me to associate the deposition of the upper-orange unit with the latest Holocene movement displayed in this outcrop.

The coarser textures of the orange units compared with the respective A-horizon material is atypical of solely-pedologically derived subsoils (Brady, 1974). Interpretations of the orange deposits as B- or C-horizons could only be possible if you first described the erosional, non-pedologic processes that generated them and then the development of A-horizon material and the subsequent use of the orange deposits as subsoils.

The greater extent of the lower-orange deposit compared with the upper-orange unit possibly indicates a relatively greater vertical component of movement along the Holocene fault zone. The more distal nature of the lower unit to the fault scarp, combined with the fact that the lower unit is also thicker, implies greater relief and not simply a longer period of erosion.

The down-block red deposit represents the debris that first eroded from the then newly-formed fault scarp resulting from the earlier of the two most recent movements revealed in this excavation. I intrerpreted the gray clay as reworked material from within the Holocene fault zone and the red material was reworked from the weathered Hennessey Shale in the older fault zone.

The fact that gray clay from the Holocene fault zone had to have existed prior to the earlier movement indicates that there was very likely at least one movement along this zone prior to the time of the earlier movement displayed at this site. The pebbly-white deposit then represents a unit that had existed at the surface as is evidenced by the caliche present either as an in-situ deposit or as a surface lag deposit.

A possible source of the abundant, arenitic fragments within deposits throughout the Pointer Site may have been, in the recent geologic past, the Neogene Ogallala Formation (Bollinger, 1925; Fenneman, 1931; Menzer and Slaughter, 1971). The source of these arenitic fragments at the Pointer Site was the fluvial channel deposits. The overall color, lack of conspicuous deformation in the fluvial channel deposits, along with the superimposed stratigraphic relationship displayed in outcrops along the drainage indicated to me that this unit pre-dated the Holocene faulting described yet post-dated the deposition of the Permian Hennessey Shale (Madole, 1988).

Vegetative growth along the drainage has rendered radiocarbon dating within the Pointer Site unfeasible due to the deep root penetrations/contaminations and the nearness of the buried soil to the present day surface. Of the three Holocene displacements evidenced at the Pointer Site, the two most recent movements are likely duplications of the displacement recorded the Alluvial Fan Site.

Bedrock Pit Site

Description

In March of 1987, Anthony Crone of the United States Geological Survey excavated an open-cut into the limestone facies of the Post Oak Conglomerate (Permian) on the Kimball Ranch in the northwest portion of the Meers Fault Scarp (Ferring, 1987). I described the green sandstone that formed four vertical dikes and two thin horizontal laminations (Figure 18) in the open-cut as well in thin sections.

The thin sections revealed the sandstone to be a quartz arenite with grain size variations between a very fine (0.08 millimeter) and medium (0.48 millimeter) sand-sized particles (Figure 19A). The sandstone contains primarily angular to well-rounded quartz grains with quartz overgrowths in a sparry calcite cement. I found minor grain components to include potassic feldspar, plagioclase, weathered sodic and potassic, plutonic, lithic fragments, and micritic, carbonate fragments (Figure 19B). The carbonate fragments are generally the largest grains in the sandstone with length to width

Figure 18. A) The vertical sandstone dikes (arrows) in the bedrock pit site (parallel to hammer handle). B) One of the two thin horizontal sandstone laminations seen on the up-block (arrows) in the bedrock pit site.

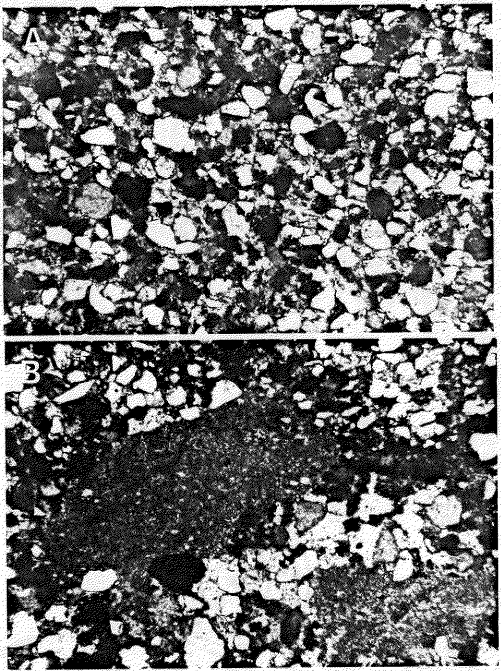


Figure 19. Thin sections (under polarized light) from the vertical sandstone dikes at the bedrock pit site showing: A) typical grain characteristics and B) carbonate lithic fragments.

ratios as great as 6.6 to 1, of similar micritic compositions, poor sorting, and evidence of brittle fracturing such as a "sliver-like" appearance and fractures. The origins of the arenitic sandstone were not as obvious as the minor components it contains as no similar lithologic unit is encountered until approximately 130 kilometers to the northwest where Quaternary sandstones reworked from the Ogallala Formation crop out near Gotebo (Miser, 1954).

Thin sections of green calcite-cemented, quartz arenite samples collected from sandstone-capped cuestas west and north of Gotebo, Oklahoma were compared with the sandstones studied in the Bedrock Pit Site. With the exceptions of no lithic or limestone fragments present in the Gotebo samples, these green sandstones proved nearly identical. The Gotebo samples contained plagioclase, potassic feldspar, and predominantly quartz grains varying from angular to sub-rounded, medium silt (0.02 millimeters) to fine sand-size particles (0.1 millimeter) in a very sparry calcite cement (4 millimeters diameter patches) (Figure 20). The samples from the Bedrock Pit Site often displayed grains that were pitted whereas the Gotebo samples indicated no signs of pitting. The Gotebo sample exhibited about 1.0 millimeter laminations similar to the Bedrock Pit samples. The smaller grain size and omission of lithic, plutonic fragments in the Gotebo samples is likely due to the more distal location of Gotebo relative to the well-exposed Wichita Mountains than the more proximal Bedrock Pit Site. This study revealed that the plagioclase and potassic feldspars are similar to those of the Wichita Mountains and that the quartz grains of the Gotebo and Bedrock Pit samples did not compare directly

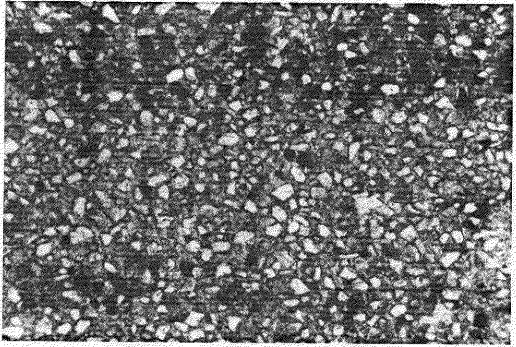


Figure 20. Thin section (transmitted light) of the green sandstone collected west of Gotebo, Oklahoma, displaying similar characteristics to the samples collected at the bedrock pit site (see Figures 19 and 21).

with those of the granites sampled inferring that it was probably derived from a more distal source. The anorthite-content of the plagioclase incorporated into these samples varied between An_{80}-An_{100} indicating that the gabbros and ultramafics exposed in the Wichita Mountains Igneous Complex were most likely the source of this detritus (Ham et al., 1964).

Interpretation and Discussion

I interpreted the source of the potassic and sodic feldspars, along with their perspective lithic fragments to likely be the nearby Wichita Mountains Igneous complex. The angular carbonate fragments were probably generated by the fracturing of the host rock (limestone facies of the Post Oak Conglomerate) during the fault movements and were transported only a very short distance from where they were sampled prior to lithification.

Horizontal bedding is visible in all of the samples including the vertical dikes indicating that the sand was deposited into a fissure in the lithified cobble conglomerate and not injected from below (Figure 21). This information also evidences the sandstone as a younger deposit compared to the Permian conglomerate in which it is contained. The horizontal laminations are a problem in that they are contained in what is recognized as lithified Post Oak Conglomerate and yet they resemble no known sandstone facies of this Permian unit (Al-Shaieb et al., 1980; Chase, 1954). The identical natures of the horizontal laminations and the vertical dikes indicates that they are similar source and yet the green sandstone is younger than the conglomerate and is contained as horizontal laminations within this

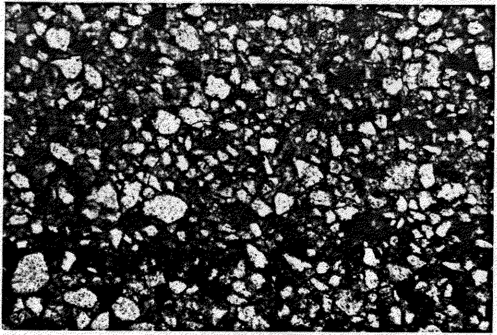


Figure 21. Thin section (transmitted light) displaying the horizontal laminations found in the vertical sandstone dikes at the bedrock pit site (2 millimeters thick).

indurated conglomerate. It was noted that these two horizontal laminations of quartz arenite are contained within a weathered, clay-rich zone of the conglomerate on the up-block and are capped by up to 0.6 meters of well indurated limestone cobble conglomerate of different appearance than the conglomerate that contains the sandstone as vertical dikes (Figure 22). Perhaps these upper layers of what was thought to be Permian conglomerate is then even younger than this arenitic sandstone. Past researchers in the region have also wondered if a part of the Post Oak Conglomerate was significantly younger and perhaps deposited during Pleistocene times (Bridges, 1985; Taff, 1904).

The descriptions of the detritus making up the Ogallala Formation deposited in Late Miocene through to Late Pliocene times (Gustavson and Finley, 1985; Seni, 1980; Van Houten, 1961) on the Middle Tertiary erosional surface existing in this region before this period (Menzer and Slaughter, 1971) compare favorably with the descriptions of the sandstones in the Bedrock Pit Site (Frye and Swineford, 1946). If a Late Tertiary age is assigned to the green sandstones, then from at least one to possibly four movements have occurred along the Meers Fault in a time span prior to the lithification of the sandstone (Late Pliocene). The horizontal slickensides preserved very near the surface on the limestone conglomerate walls containing the sandstone dikes in the Bedrock Pit Site (Crone, 1987) would then record lateral Tertiary movements (Figure 23). The brittle deformation abundantly displayed within the Late Tertiary-Pleistocene fault zone indicates the possibility of significant ground accelerations accompanying these

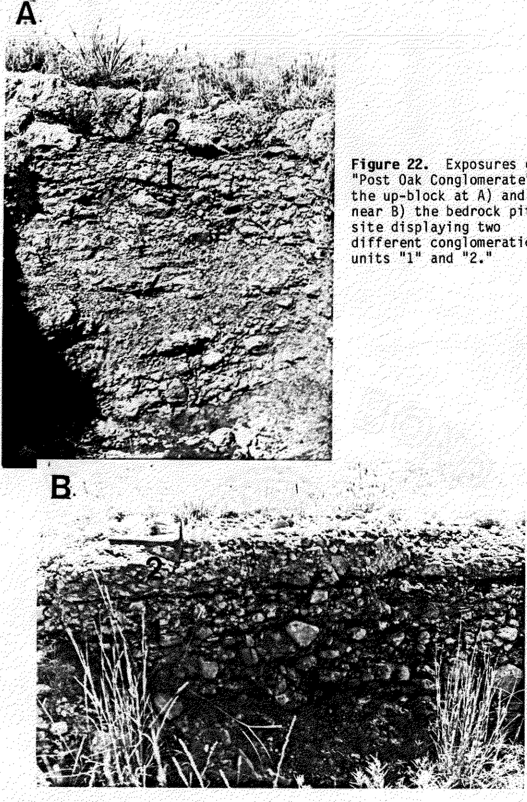


Figure 22. Exposures of "Post Oak Conglomerate" on the up-block at A) and near B) the bedrock pit site displaying two different conglomeratic units "1" and "2."

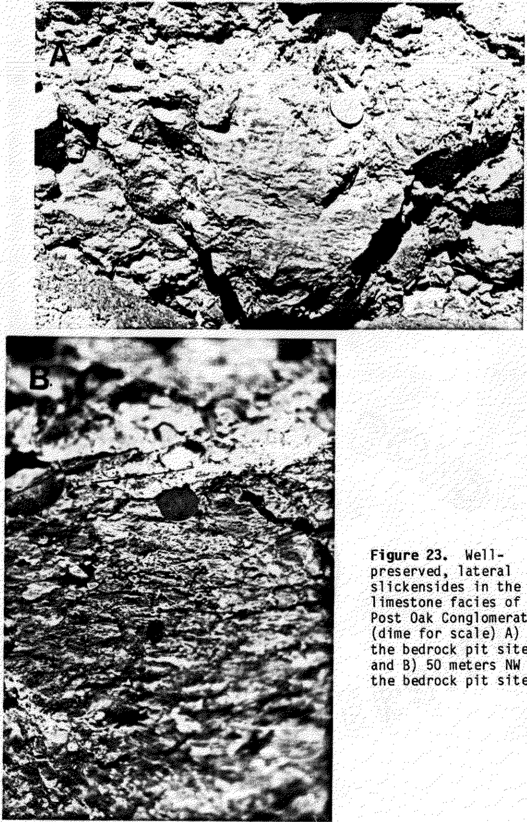


Figure 23. Well-preserved, lateral slickensides in the limestone facies of the Post Oak Conglomerate (dime for scale) A) at the bedrock pit site and B) 50 meters NW of the bedrock pit site.

events (Figure 18A). Remnant topography and superimposed drainage systems from the Tertiary might help to remove much of the confusion involved in determining the sense of movement(s) of later Holocene faulting along the Meers Fault (Ramelli and Slemmons, 1986; Westen, 1985) as the sense of motion in the Late Tertiary was likely left-lateral.

Cave Investigations

Description

During the cave investigation portion of the field work in the study area, we examined a total of 53 caves, many of them previously not mapped. Many of the caves are located within Cambro-Ordovician limestones of the Slick Hills north of the Meers Fault Scarp. Subsequent investigations took place in Caddo-Moonshine Cave and Gelfling Cave (see Appendix B).

Interpretation and Discussion

The data gathered during this study had no direct association with displacement along the Meers Fault.

Wichita Mountains Study

Description

The field investigation I performed in the eastern segment of the Wichita Mountains began with efforts to locate boulder accumulations and describe their genetic relationships to local landforms. Some examples of significant boulder deposits exist on the slopes of Mount Scott (SE 1/4 section 11 T3N R13W) and in a relatively minor drainage west of Elk Mountain (E 1/2, NW 1/4 section 24 T3N R15W), both in Comanche County (see Appendix C).

Interpretation and Discussion

No evidence directly related to displacements along the Meers Fault was located during this study. Evidence of the genesis of these boulder deposits indicates that there was likely a pre-Pleistocene mantle-controlled erosional stand in the study area. The deposits represent corestones which were concentrated vertically due to erosion to a greater extent than they have been transported laterally resulting in the typically "stacked" deposits (Figure 24).

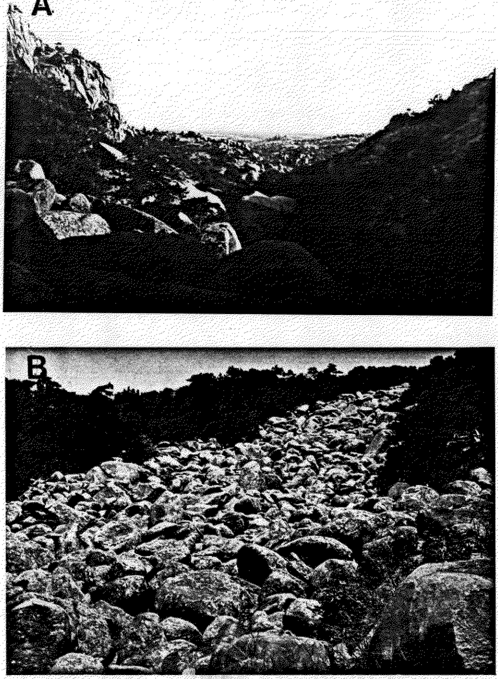


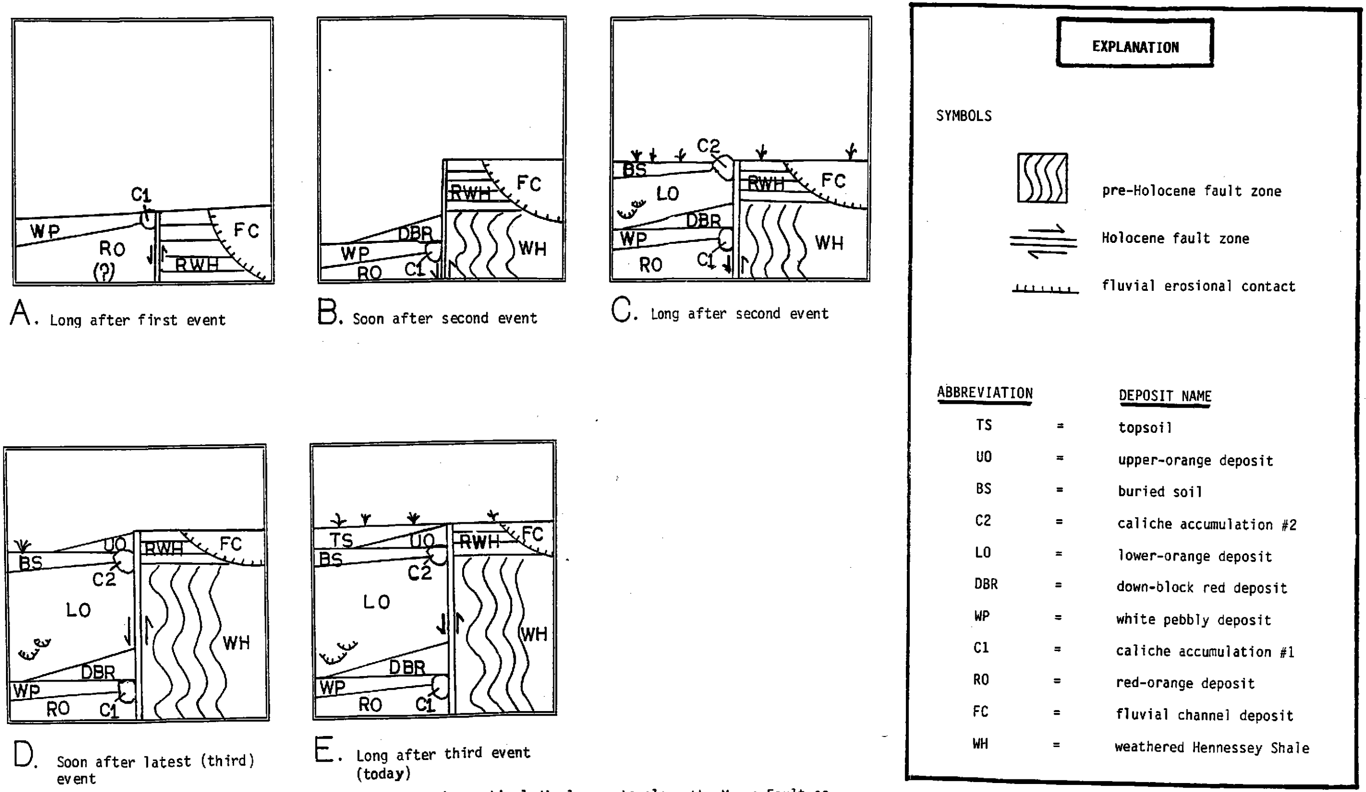
Figure 24. The accumulations of stacked boulders at A) Elk Mountain and B) Mount Scott.

CONCLUSIONS

Summary of the Studies Along the Meers Fault

This investigation describes evidence for at least four movements along the Meers Fault. Three of these movements have been in Holocene time and have been described at the Pointer Site (Figure 25) and Alluvial Fan excavations. The remaining known movement probably occurred during the Late Miocene to Early Pleistocene time (11 to 1 million years ago) and is described from the Bedrock Pit Site. From the multiple sandstone dikes present at this site, as many as four movements may have occurred during this period though these multiple fractures may represent just one or a few events. I think it is likely that multiple movements occurred during this period judging from the relative amount of left-lateral offset I believe attributed to this period of faulting. The approximate date(s) assigned to the Miocene-Pleistocene movement(s) relies on the correct identification of the rock unit incorporated within the fault zone during the movement(s) as associated with deposition and/or erosion of the Neogene Ogallala Formation from the study area. It is conceivable that this sandstone could be an older Tertiary unit. Investigations within the Wichita Mountains concerning possible Tertiary, soil-mantled erosional stands yielded evidence that the region did in fact exhibit a Tertiary erosional surface which was later reworked during Late Pliocene-Pleistocene time after and/or perhaps during the local deposition of the Ogallala Formation.

The sense of movement of at least one (to as many as four) older event(s) is suspected to have been largely left-lateral as is



A. Long after first event

B. Soon after second event

C. Long after second event

D. Soon after latest (third) event

E. Long after third event (today)

EXPLANATION

SYMBOLS

pre-Holocene fault zone

Holocene fault zone

fluvial erosional contact

ABBREVIATION		DEPOSIT NAME
TS	=	topsoil
UO	=	upper-orange deposit
BS	=	buried soil
C2	=	caliche accumulation #2
LO	=	lower-orange deposit
DBR	=	down-block red deposit
WP	=	white pebbly deposit
C1	=	caliche accumulation #1
RO	=	red-orange deposit
FC	=	fluvial channel deposit
WH	=	weathered Hennessey Shale

Figure 25. Sequence of Holocene erosional responses to vertical displacements along the Meers Fault as evidenced at the Pointer Site.

evidenced by well-preserved slickensides and drainages displaying lateral offset. No clear evidence as to whether these movements were accompanied by earthquakes was found though much brittle deformation occurred in the fault zone during this (these) event(s). Evidence recording this (these) movement(s) has been dramatically altered by erosion during Pleistocene to Holocene times.

The three Holocene events are thought to have generated mainly vertical offset as is indicated by vertical slickensides in clay deposits within Holocene fault zone. Since multiple Holocene movements are known to have occurred, the clay slickensides may reflect only the latest movement. In concluding that these three movements were mainly vertical displacements, it is assumed that a continuous series of displacements along a fault will reflect the long-term stress generating processes and display similar senses of movement. The latest movement demonstrates a total vertical displacement of about one meter. The preceding movement displaced 1.8 meters of sediment onto the down-block. The presence of altered gray clay along a time-marker horizon at the base of the Pointer Site indicates that a detrital wedge of sediments recording an earlier Holocene displacement exists unexposed beneath the water table at this site. Aside from the knowledge of the existence of this third and oldest-known Holocene event nothing is known about it due to the limited exposure of the sediments recording this movement. The widely deformed and altered fault zone at the Pointer Site was utilized during the pre-Holocene movements as is evidenced by lithified blocks of (Ogallala) sandstone in the deformed zone. This wider zone of alteration associated with the older event may indicate a differing sense of movement and/or stress relieving mechanisms during this period of time along the Meers Fault. A significant component of compressive stress accompanied the Holocene displacements as is indicated by folded sediments.

The lack of significant historical seismicity along the Meers Fault allows no clear indication whether earthquakes accompanied these Holocene displacements. All that can be conclusively said about the rate of movements along the Meers Fault is that the average rate is significantly greater than the rate of surface erosion and deposition. The fractured cave formation described in Gelfling Cave may indicate strong ground motions in the vicinity of the Frontal Fault zone during Holocene time although the controls on the history of this sedimentary deposit are only beginning to be understood rendering this piece of evidence inconclusive by itself. Paleoseismological studies concerning this topic of strong ground motions were unable to disclose evidence due to the lack of continuous fine-grained sedimentation and a predominantly erosional geologic history of the region. Much more work needs to be completed in the study area to more consistently define the regional geology and investigate this complex and long-lived structural element in the mid-continent.

Future Work

As with many regional geologic investigations, this study has generated at least as many questions as it has addressed. Many of the questions which arose during the study could not be fully investigated as they included topics not directly relevant to this thesis.

In testing the hypothesis that the sandstone dikes in the Bedrock Pit Site are Tertiary in age, a search for evidence within the Wichita Mountains of a Tertiary erosional surface was conducted. The results of my study are preliminary in nature but might provide a window into the Tertiary geological history for much of the region. It is vital to realize that these investigations were performed with a minimum of actual field work during this thesis study as the scope of such a topic exceeded the amount of time and efforts available to complete the various topics of this investigation. More work is needed to identify the hypothesized pediment surfaces as well as the previously described Pleistocene drainage systems, gravel stand elevations relative to the pediment surfaces, and the water-polished surfaces in the Wichita Mountains.

The Bedrock Pit Site can be further described and excavated to better determine the nature of the Miocene-Pleistocene events as well as further detailed petrographic studies of the green sandstone preserved there. Better descriptions of the sandstone dikes may extend the faulting history of the Meers Fault as well as better describe the long-term stress field for this enigmatic fault zone.

Work at the Pointer Site has revealed much about the last two events along the Meers Fault. More important perhaps, was the evidence of a third older event but unmistakenly Holocene. These new data should stimulate further study of this third movement and possibly for earlier events. The existing exposure could be developed further into the cut-bank to better describe its three-dimensional character and the magnitude of possible lateral movements associated with earlier events. Developments of paleoseismological excavations requires both care and time to insure accurate and complete collection of data. Sites such as the Bedrock Pit and Brown's Bluff, and Pointer locations inevitably will prove invaluable.

During the cave investigations portion of this study, it became increasingly obvious that no comprehensive attempt had been made to describe the regional geologic history of the karst exposed in the vicinity of the Wichita Mountains. Many caves in this area are yet to be located, explored, and described. Cave deposits hiatuses can record geological information such as uplift, climate, topography, erosional processes as well as periods of sustained erosion. In that karst features in the area have been dated as ranging from Permian to Recent times, a large potential exists to add to the geologic history of the region through such studies.

In summary, nearly every aspect of study included in this investigation indicated potential for further interpretation and development. The areas in which additional efforts could easily improve the geological history of southwestern Oklahoma include:

1) To complete field work describing evidence for past erosional stands in and around the Wichita Mountains.

2) To develop further the Bedrock Pit and Pointer sites.

3) To collect and compile geologic data from caves in the region.

4) To locate, excavate, and describe other sites along the Fault and the Frontal Fault Zone for paleoseismological data.

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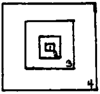
APPENDIX A

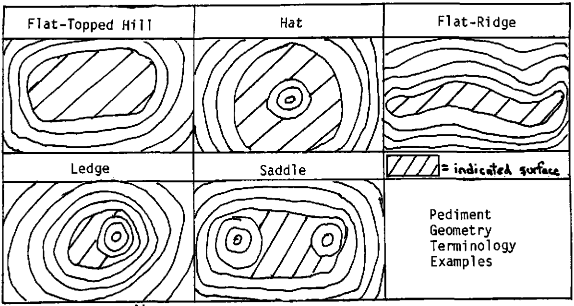
Pediment Study Terminology

Pediment Size

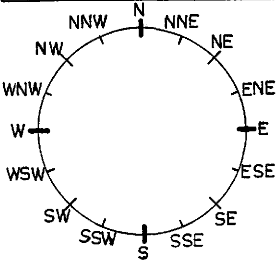


Size	Square Footage	Square Dimension (along one side)	Unit Ratio
4	4,000,000	2,000 feet	64
3	1,000,000	1,000 feet	16
2	250,000	500 feet	4
1	62,500	250 feet	1

(drawn to scale used)



Pediment Geometry Terminology Examples



Pediment Dip Azimuth Scale

United States Geological Survey 7 1/2 minute quadrangles used: (1956 editions)

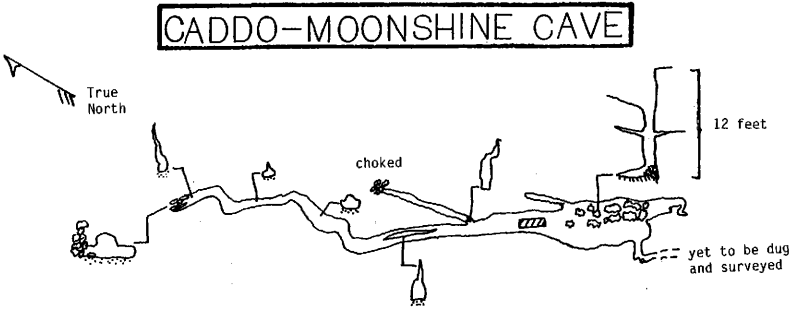
Odetta
Quanah Mountain
Mt. Scott
Fort Sill
Meers
Saddle Mountain
Cooperton
Blair

APPENDIX B

During the cave investigation portion of the field work in the study area, we examined a total of 53 caves, many of them previously not mapped. Many of the caves are located within Cambro-Ordovician limestones of the Slick Hills north of the Meers Fault Scarp. Subsequent investigations took place in Caddo-Moonshine Cave and Gelfling Cave.

The data gathered during this study had no direct association with displacement along the Meers Fault.

Caddo-Moonshine Cave is located in the Lower Arbuckle Group carbonates in Caddo County (NE 1/4, NE 1/4, section 35T 5N R13W). This cave was chosen as an investigation site because it was the only cave known in the area to contain abundant fine-grained sediments (Figure 26). I excavated a 2.3 meter long, 55 centimeters wide trench into the sediments to a depth of 122 centimeters whereupon limestone bedrock was contacted. I encountered a contact between two units at approximately 61 centimeters depth with the uppermost deposit consisting of an organic-rich, transported A-horizon material which contained evidence of human disturbance (bricks and spoon found). This horizon contained abundant charcoal and wood fragments though could not be used in the study being that it had been thoroughly disturbed and was likely of recent origin. The deposit in the floor of the cave consisted of an orange, massive, montmorillonitic clay which contained some charcoal within it. I tested the clay with a hand-held consolidometer to measure the relative cohesiveness of the clay. An average of 1.15 tons per square foot was measured describing



Surveyed Length: 144.9 feet
Surveyed on 6 June 1987
By Sue Bozeman,
Becky Jagnow, and
Kevin Thomas

Cave Life: Tiger salamander, Western long-eared bat cave crickets, butternut hickory

▨ = Excavation Site Location

Figure 26. Surveyed, schematic map of Caddo-Moonshine Cave.

the clay as an extremely cohesive deposit (moisture content 17% by weight) and an unsuitable medium for paleoseismological studies (Morris, 1987). This orange clay was thoroughly bioturbated by tree roots. Information concerning the genesis of karstic features in the region was gained from the study of this cave as well as Gelfling Cave.

Gelfling Cave is situated along an arroyo on the Kimball Ranch in Lower Arbuckle Group carbonates in section 36 T5N R13W in Caddo County. The cave is solutioned along bedding plane surfaces which dip 24° to the northeast, and two joint alignments, N66°W and N36°W respectively (Figure 27A). The most prominent feature of Gelfling Cave is the bedding plane which has collapsed to the floor of the cave entrapping coarse cobbly sediment beneath it (Figure 27B). After the collapse, the fallen bedding plane was cemented to the sediments trapped in the floor of the cave stabilizing itself (Figure 28). Following the collapse of the bedding plane, the cave saw the initiation of growth of cave formations from this "new ceiling" down to the "former ceiling" and eventually connecting the two together rigidly. At some point after this, the connected cave formation was fractured and displaced about 5 millimeters down-dip as the collapsed bedding plane stabilized itself once again. In light of the size of this collapsed and yet intact block of limestone which is approximately 144 square meters surface area and from 0.6 to 1.2 meters thick, I find it surprising to realize that it has moved at all and yet it has moved 5 millimeters probably in the last few thousand years. The evidence that this movement occurred within the last few

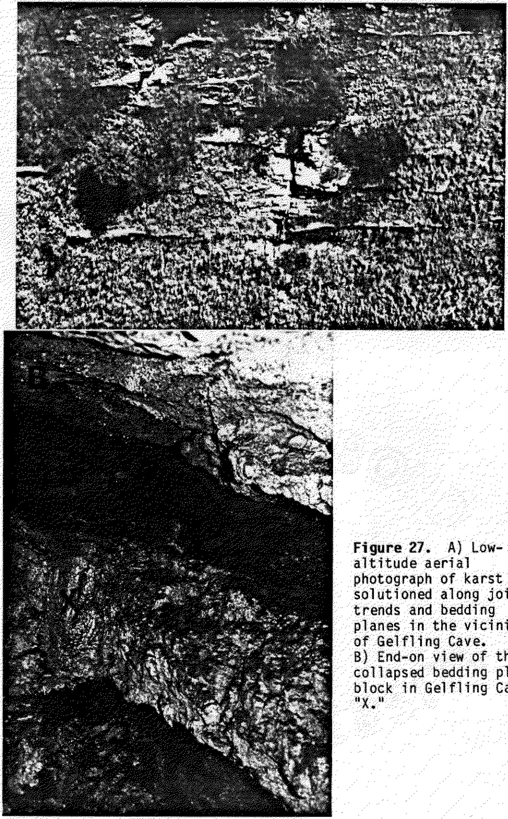


Figure 27. A) Low-altitude aerial photograph of karst solutioned along joint trends and bedding planes in the vicinity of Gelfling Cave.
B) End-on view of the collapsed bedding plane block in Gelfling Cave "X."

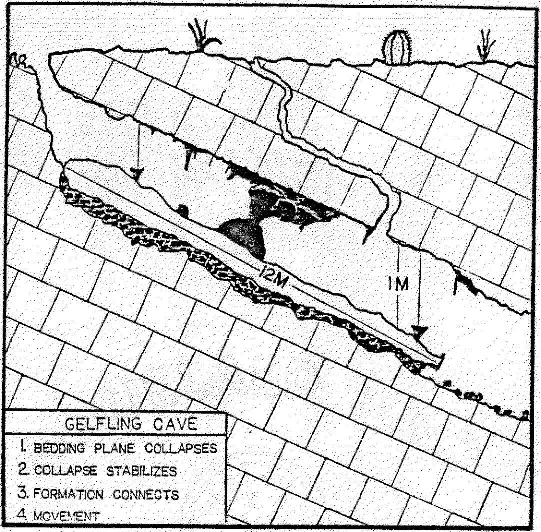


Figure 28. Schematic diagram of Gelfling Cave illustrating the sequence of events leading to the eventual fracturing of the cave formation.

thousand years is based upon the fact that the fractured cave formation is yet growing and that if this deposit grows at the minimum rate for a similar climate at this same latitude of 1/10 of an inch in 100 years this fracture would have been mostly obscured where it is not today (Figure 29) (Jackson, 1982). Gelfling Cave is located between arroyos about half way to the crest of a ridge so that it is not expected to experience the catastrophic flooding there would occur further down the ridge in the drainage path. The collapsed bedding plane is located in the shallowest portion of Gelfling Cave so that there is a minimum amount of feeder channels funneling water through the cave at this point than deeper in the cave system.

Many features of the limestone cave systems exposed in the Slick Hills are characteristic of caves in old age rather than those being newly formed at their present location geologically (Jackson, 1982). Evidence of Permian paleokarst has been exposed in local quarries and roadcuts within the study area attributing to at least one former period of solutional history prior to the present day (Ham, et al., 1957; Olson, 1967; Donovan, 1982; 1986). In one quarry near Bally Mountain, paleokarstic features are filled with sediments containing varved clays and post-Permian skeletal materials indicating a more recent period of limestone dissolution and exposure to the surface during Tertiary and Holocene time (Steele, 1988). I think The lack of well-developed cave formations in the caves studied near Caddo-Moonshine and Gelfling Caves indicates that the rock units containing these caves have not been long in the vadose zone (Jackson, 1982) and certainly not since Permian time. The large size of the

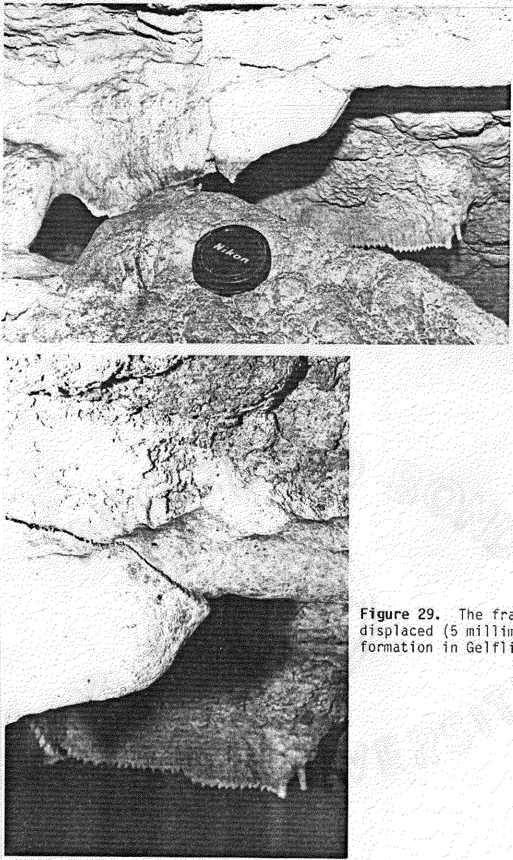


Figure 29. The fractured and displaced (5 millimeters) cave formation in Gelfling Cave.

bedding plane which collapsed intact in Gelfling Cave indicates that this cave was likely filled with water and the bedding plane "buoyed" as it fell to the floor of the cave, thus, keeping it intact. The keyhole-shaped cross-sectional geometry of the passages in Caddo-Moonshine Cave also evidences a lowering of the water table near it since sub-aqueous dissolution tends to uniformly affect the solutioning of carbonate along a fissure since it is under hydraulic pressures while a sub-aerial fluvial-like system, as exists there today, emphasizes lateral and primarily downward solutioning (Davis, 1930; Jackson, 1982; Jones, 1971). The seemingly unrelated attitudes of cave and surface drainage alignments is likely evidence that these karstic features are inherited although probably much younger than Permian in age.

APPENDIX C

The field investigation I performed in the eastern segment of the Wichita Mountains began with efforts to locate boulder accumulations and describe their genetic relationships to local landforms. Some examples of significant boulder deposits exist on the slopes of Mount °Scott (SE 1/4 section 11 T3N R13W) and in a relatively minor drainage west of Elk Mountain (E 1/2, NW 1/4 section 24 T3N R15W), both in Comanche County.

The Mount Scott deposit lies in what also appears to be a minor drainage although the drainage area upstream from this deposit is so dwarfed by the size and scale of the deposit that necessary volume of water required to saturate the boulder deposit is many factors of magnitude greater than the present drainage is capable of generating. A downslope migration hypothesis with mechanisms of transport such as by freezing and thawing actions and/or slow undermining erosion could not have generated this deposit since many of these two meter diameter granitic boulders are stacked many layers thick on top of each other. The actual thickness of this deposit is not accurately known.

The Elk Mountain deposit lies in a minor drainage so insignificant that it was not mapped by the United States Geological Survey as even an ephemeral drainage system though its drainage area is significant. This drainage has been named the "Valley of the Boulders" (Ellenbrook, 1984). This watershed has no surface drainage near its upstream extent because it is lost down in the base of an enormous pile of boulders 3 to 12 meters in diameter. This deposit is piled so high that you can actually climb down between the boulders, due to their substantial size, to depths in which sunlight cannot reach. A "surface drainage" is found at points at depth in this pile of boulders flowing over a floor of saturated grus during the spring.

It is evident that the present drainage has not transported the boulders very far, if at all, and that the previously described mechanisms of freezing and thawing and undercutting erosion could not have resulted in the present configuration of boulders. I also noted that the deposit of boulders extends from the very upstream divide of the drainage to midway down the valley rather than towards the base of the valley where the energy of the drainage is greater. The "window into the Wichitas," as the view from this valley has been named, displays much greater relief across the valley than did the drainage on Mount Scott. It is perhaps feasible to imagine then that the boulders near Elk Mountain had been toppled off the valley walls by some mechanism, as boulders rest there yet today, and tumbled onto the pile in a "stacked" manner due to the momentum of their fall (Figure 30A). A few of the boulders are split into fragments where present in the deposit perhaps attributing to this process of accumulation. I believe this mechanism could not have formed the Mount Scott deposit as there is inadequate relief present. Another boulder deposit similar to the "Valley of the Boulders" is located near Elk Mountain and is named the "Rock Rooms" (Ellenbrook, 1984).

Approximately 20% of the observable boulders in the deposit at Elk Mountain display a flat side with rounded corners attributing a relatively early tor-block erosional weathering stage to it (Ruxton and Berry, 1957; Twidale, 1982) (see Figures 30B and 31). It is a

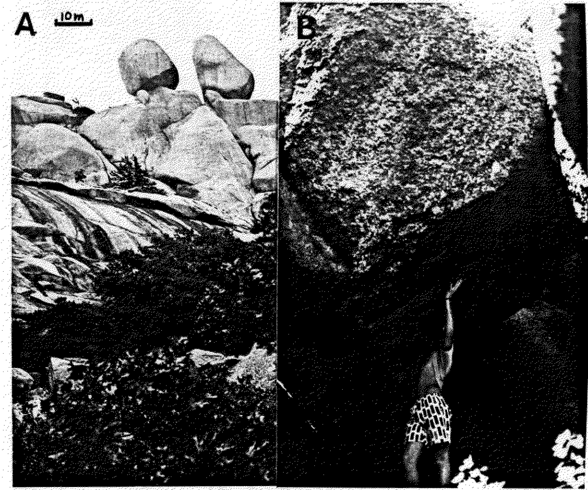


Figure 30. A) Perched boulders known as the "Apple" and the "Pear" on a ridgecrest west of Elk Mountain in the Eastern Wichita Mountains. B) A boulder in the deposit at the base of the ridge displaying a flat side.

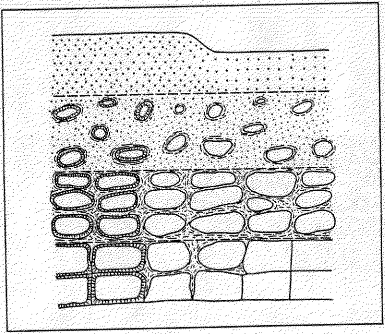


Figure 31. Zones developed in a mature weathering profile on granite (from Ruxton and Berry, 1957).

seemingly logical step then to assume that these boulders initially rested on or against some stable, unweathered surface with their surface isolated from most of the intense weathering. The problem rests then with the mechanism of transport. How do boulders with a flat side get stacked onto the deposit? A possible solution is that this may result from a combination of the effects of freezing and thawing on an unstable slope, such as along a sheeting joint, resulting in the creep of the boulder downslope and then the eventual instability of the boulder on the steepening slope causing it to tumble catastrophically onto the deposit. The boulders with a flat side may also be added to the deposit by toppling caused by an avalanche of more rounded boulders carrying it with the slide onto the deposit. Subsequent erosion would then transport all but the boulder corestones away regardless whether the dominant transport process was surficial, erosional or tectonic (Pearce and Watson, 1986).

Since I could not resolve the possible mechanism of earthquake induced boulder-toppling from the results of these previously described potential mechanisms, the study was inconclusive as to whether the region had undergone significant ground accelerations. I did succeed in gathering field evidence of a past mantle-controlled erosional stand in the study area (Mabbutt, 1966; Oberlander, 1974; Twidale, 1982).

My next portion of the Wichita Mountains Study included a search for fine-grained unconsolidated deposits which might also record evidence of earthquake-induced ground accelerations (Allen, 1975; Obermeirer et al., 1985; Sieh, 1978; 1984; Shepard, 1985; Thorson et al., 1986; Vanarsdale, 1986). Due to the physical nature of the sediments derived from local source rocks during at least the present erosional environment, no suitably continuous fine-grained deposit could be located in a protected depositional setting. The predominant sediment grain-size range in the region of the eastern Wichita Mountains varies from about two millimeters diameter (very coarse sand) to about 30 centimeters (small boulders). The grain-size requirement for most paleoseismological, liquefaction-slump studies are less than about 1/2 of a millimeter (medium sand) and do not include under-saturated, cohesive or compacted clay deposits (Ishibashi et al., 1982; Morris, 1987). The unusually coarse nature of the sediments around the Wichita Mountains ruled out the likelihood of a successful paleoseismological investigation. No suitable deposits were located in the search which indicated in itself that the region has undergone erosion for a considerable length of the recent geologic history of the area.

APPENDIX D

It has become apparent during the course of this investigation that much evidence describing the Cenozoic Geology of the Wichita Mountains region exists either previously undescribed or in a form which needs compilation with similar data from previous field studies. The oldest Cenozoic remnants thought to exist in the vicinity of the Wichita Mountains consist of the pediments developed on the igneous core materials of the mountains. The pediment surfaces are believed to have been developed by a mantle-controlled Tertiary erosional surface thought to have existed in the region possibly from as early as Mesozoic times through to at least the Late Miocene (Bollinger, 1925; Harrell, 1987; Hunter, 1960; King, 1953; Mabbutt, 1966; Oberlander, 1974; Tuan, 1959; Twidale, 1981; 1982). These morphological surfaces exhibit surface areas as great as 371,000 square meters (4 million square feet) with a total relief of less than 6.1 meters (20 feet) and are present at accordant elevations along an axis dipping generally from west to east. The Tertiary erosional surface thought to have developed the sub-soil weathering front which created the observed pediments is located today beneath the Ogallala Formation about 125 kilometers west of the study area (Frye and Leonard, 1957a; 1959a; 1959b; Gustavson and Finley, 1985; Harbour, 1975; Seni, 1980; Reeves, 1976) in the Texas panhandle and is preserved also in other semi-arid regions of the western U.S. (Oberlander, 1974) and elsewhere around the globe (King, 1953; Mabbutt, 1966; Twidale, 1982). The Neogene Ogallala Formation ceased deposition during Pliocene time (Gustavson and Finley, 1985; Seni, 1980). During Pliocene time (2 to 5 million years ago), the climate became drier -- close to what exists in the region today with the gradual addition of a caliche caprock over the Neogene Ogallala Formation (Frye and Leonard, 1959a; Reeves, 1976; Seni, 1980). This Tertiary weathering surface remained relatively stable until Late Pliocene times.

This Tertiary surface may have existed for as long as 63 million years until about 2 million years ago (Frye and Leonard, 1957a; 1957b; Haynes, 1975; Reeves, 1976; Wendorf, 1961; Wendorf and Hester, 1975). Near the start of the Pleistocene, the region underwent a rapid change in climate with greater precipitation rates and correspondingly enormous erosional rates (Cook, 1927; Frye, 1945; Frye and Leonard, 1957a; 1957b; 1959a; 1959b; Gould, 1929; Hoffman, 1930). In the Wichita Mountains this erosion created steep canyons and extensive gravel deposits in exhuming bedrock surfaces including the pediments (Gould, 1929; Hoffman, 1930). Erosional remnants that are observable within the Wichita Mountains and the surrounding region include pedestals, boulder accumulations, flared boulders and bedrock surfaces and fluvially-polished bedrock surfaces (Twidale, 1982) (Figures 24 and 32). The erosional gravels compose what is known as the Seymour Formation of west, central Texas and elsewhere in the region and are believed to be associated with the Kansan glacial stage (Menzer and Slaughter, 1971). Some gravels transported from the Wichita Mountains southward as part of a fluvial system of the ancestral Red River have been dated as associated with the Aftonian interglacial stage (Cook, 1927; Figgins, 1927; Gould, 1929) about 2 million years ago.

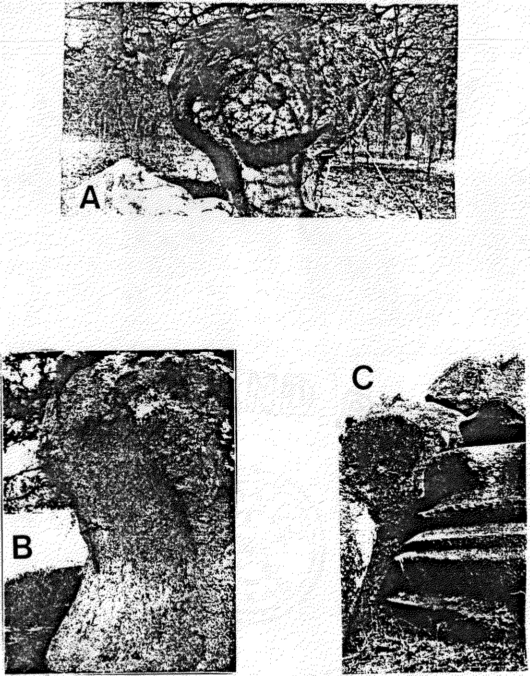


Figure 32. Some examples of mantle-controlled erosional features displaying typical "flared" edges on granites in the Arbuckle Mountains and in the Wichita Mountains. The example from the Wichita Mountains also shows evidence of water polishing probably from eroding stream drainages (photos from: Redfield, 1928; Weidman, 1928. Also see Evans, 1929; Hunter, 1960; Taylor, 1915, for more examples.

After this Pleistocene erosion transported the easily erodable weathered Tertiary mantle materials (principally gravel and grus materials exposing the Tertiary pediment surfaces), the drainage systems of the late Pleistocene and Holocene times assumed positions between gravel-divides in the then oversized drainages as the precipitation rates decreased to levels closer to that of today (Hoffman, 1930). The "Caddo Canyons" located within Caddo County, are prominent geomorphic bedrock features with vertical walls cut down as much as 60 meters into Permian Rush Springs Sandstone prior to 12,000 years before present (Hall and Ferring, 1987).

During early Holocene a similar erosional system as is seen today existed although the climate was slightly wetter during periods (Ferring, 1987). The "Caddo Canyons" were filled with sand during Holocene time indicating a lesser, erosional capability during this period (Hall and Ferring, 1987). Erosion has dominated the regional environment through to the present day as is evidenced by commonly thickened, cumulic A-horizons (Ferring, 1987; Madole, 1987). Many of these regional climatic characteristics were observable and described during the course of this investigation.

VITA

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He is presently employed by Texas A&M University Geology Department as a teaching assistant for a minerals resources class and as such has taught physical geology, engineering geology, environmental geology, mineralogy, lithology, and field methods throughout his academic career. His field experience previous to this investigation included projects in eastern Wisconsin, British Columbia, northern Alberta, Yukon Territory, and in the Cohuilian desert in northern Mexico.

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