THE RELATIONSHIP OF HYDROCARBON PRODUCTION TO FRACTURING IN THE WOODFORD FORMATION OF SOUTHERN OKLAHOMA

By

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PREFACE

This thesis deals primarily with petroleum production from the Mississippian-Devonian Woodford Formation. Production is fracture-controlled and the fracturing is likely related to the faulting and folding which occurred during the Pennsylvanian. Both surface and subsurface data were utilized in this study.

I wish to thank Professor Stephen P. Phipps for guidance throughout this study and for editing of the original drafts. Although Dr. Gary F. Stewart is shown herein as thesis adviser, this is a matter of technicality and necessity due to rules that exist at Oklahoma State University. Professor Phipps, in fact was the thesis adviser. However, many thanks are due Dr. Stewart for his suggestions and guidance during the thesis and throughout my scholastic career at Oklahoma State University. Thanks is also given to Dr. R. Nowell Donovan for helpful suggestions and criticism. Many thanks are due Lawrence S. Morrison, who suggested the topic and made suggestions throughout the study. Dr. Thomas Thompson of the University of Oklahoma made helpful suggestions and provided leadership during the study. The information for the Northeast Alden Field provided by Westheimer-Neustadt and Jones and Pellow was much appreciated. Thanks are also due Bob Allen of the Ardmore Log Library, the Oklahoma City Well Log Library, the Ardmore Sample Cut and the Oklahoma Geological Survey's Core Library for information they provided during the study.

I also wish to thank my parents, Jim and Janie Bramlett, for support throughout my scholastic career. Finally, I wish to thank my wife Marie, son Eric and daughter Kristin for love and understanding through the difficult times of school.

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CHAPTER I

INTRODUCTION

The area of investigation covers much of southern Oklahoma from T7N - R5E in Caddo County to T6S - R6E in Marshall County (Figure 1). The part of the stratigraphic section of primary interest is the Woodford Formation of Late Devonian and Early Mississippian age.

The Woodford Formation had been recognized as a possible primary source of petroleum for many reservoirs. However, very little has been known about potential reservoirs that occur within the Woodford itself. Many goelogists believe the Woodford Formation is composed mostly of shale, but in fact chert beds are found in abundance. It is from these chert beds, when enough fracture porosity and permeability are present, that petroleum is produced.

Purpose and Methodology

This study was undertaken to understand what structural situation is required to fracture the Woodford Formation to the degree that petroleum production is possible, and to better understand the parameters that govern the degree of fracturing.

First, a study of the depositional environments of cherts was undertaken. With this knowledge, it was possible to attempt to define the depositional environment of the Woodford Formation as it relates to the depositional history of southern Oklahoma. Next, the structural

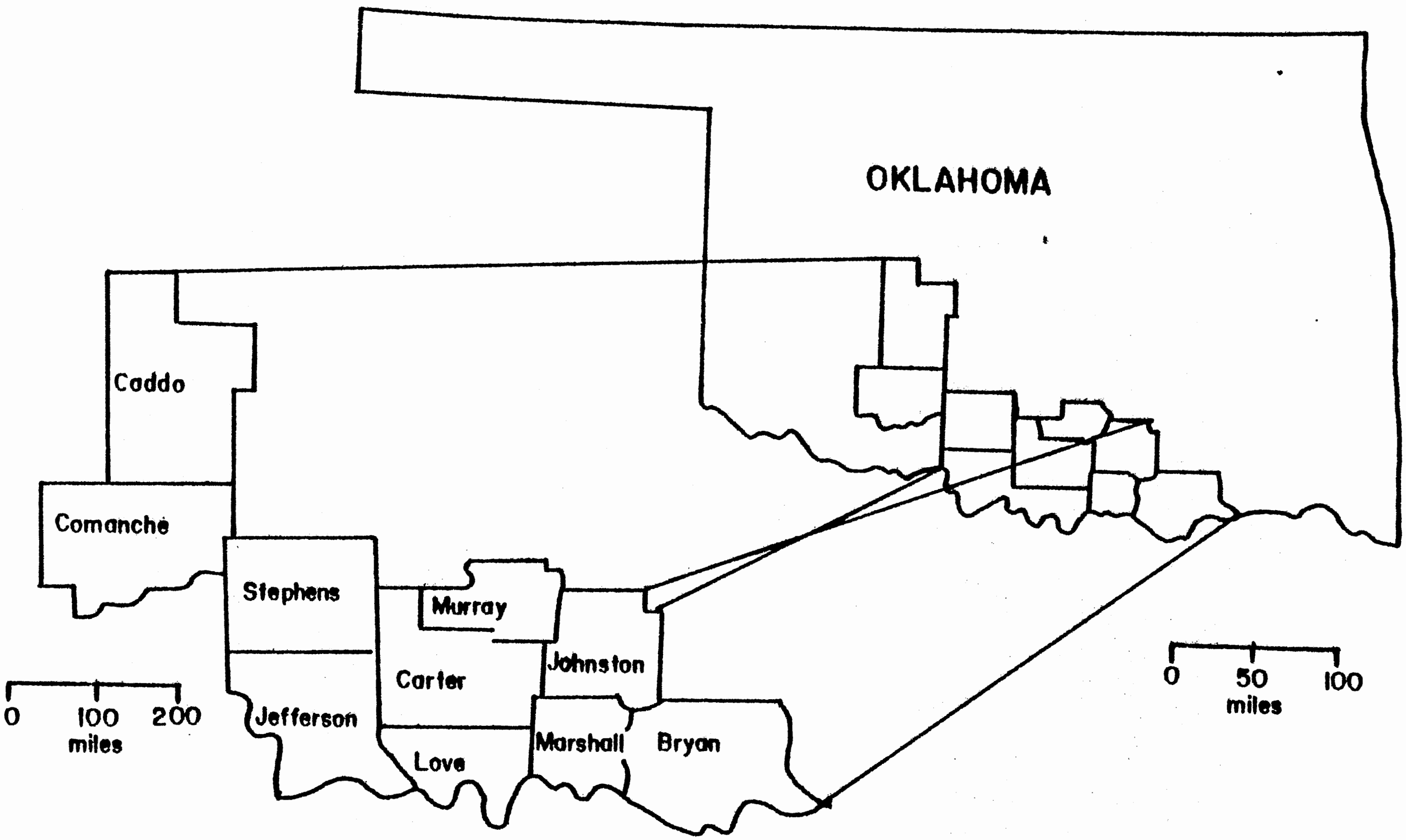


Figure 1. Aerial Map of the Study Area

framework of southern Oklahoma was explored in an attempt to better understand the types of folds and faults encountered in the study area. The parameters most important to fracturing in a zone of interbedded competent and incompetent rocks were then outlined.

With these basic concepts in mind it was then possible to study the Woodford Formation on the surface and in the subsurface. Surface studies were performed on the Woodford in known structural positions in the Arbuckle Mountains. Fracture density measurements were made on chert beds of varying thickness within zones of varying shale-to-chert ratios. This data was then interpreted to determine what effects the thickness and/or the shale-to-chert ratio had on fracture density.

The next step was to examine three fields from which the Woodford Formation has produced. A structural contour map and at least one cross section were made of each field in an attempt to understand the intensity of folding and faulting necessary to create porosity and permeability for production of hydrocarbons. Well cuttings were examined and were combined with well logs to produce a type log of the Woodford in each field. All available cores in the producing fields were examined in an attempt to better understand the intensity of fracturing in the Woodford Formation in producing areas.

Finally, another field which produces from rock types similar to the Woodford was studied using the same methods. The goal was to possibly develop a hypothesis for increased production from the Woodford Formation.

CHAPTER II

LITHOLOGY

Very little has been published on the rock types encountered in the Woodford Formation. Many geologists have described the lithologies found in the Woodford as siliceous shales and black cherts, but this is not a fair representation of the entire formation. One factor inhibiting lithologic studies is that the only measurable outcrops in the Woodford are in the upper 100 feet and lower 50 feet. To remedy this the entire formation will be described using the surface outcrops, well logs, cores and cuttings.

Description of the Woodford

Generally, the part of the Woodford seen in the field was at the top contact with the overlying Sycamore Formation. For this reason, most of the description will come from well data. The Woodford Formation can be dissected into five separate zones (top to bottom): (1) Chert Zone, (2) Shale Zone, (3) Laminated Zone, (4) Emerald Green Shale Zone and (5) Detrital Zone. Each zone will now be described and its unique features mentioned.

Woodford Chert Zone

This zone makes up the majority of outcrops studied here. It ranges from 100 feet thick at the outcrop on the south flank of the

Arbuckle Mountains on Interstate 35 to 75 feet thick in the subsurface at the Caddo Field (Figure 2). The name is somewhat misleading because there are many shale interbeds present, but chert is more abundant here than in any other zone. The cherts are dark brown to black and generally exhibit dense fracturing. They are also extremely hard. In thin section the cherts are obviously rich in sponge spicules and are comprised of five to ten percent radiolarian tests. Small fractures are filled with calcite. All cores described in the Woodford were taken in this zone; they exhibit intense fracturing with many tar seeps and large amounts of sulphur apparently bleeding from the fractures. The shales are also quite silty. Many times distinguishing between the shales and cherts was difficult. This could be due to varying amounts of silica in the shales or clay in the cherts. X-ray diffraction was performed on 40 samples of shales and cherts from this zone. The shales and cherts were remarkably similar. They both are composed primarily of silica, but the cherts showed a relative abundance of dolomite. The presence of dolomite is substantiated by the high birefringence observed in two of the thin sections made from chert samples taken at one locality. However, some of the birefringence can be related to the mixed-layered clays found in the cherts. In one of the two samples silica was almost absent, the rock being principally dolomite. However, this dolomite is most likely secondary (evidenced by dolomite replacing radiolarian tests in thin section). The mixed-layered clays found in both shales and cherts included illite and smectite. The shales were composed primarily of silica with relatively abundant mixed-layer clays and relatively little carbonate. Individual shale and chert layers in this zone almost always exhibited constant lateral thickness. Only one zone

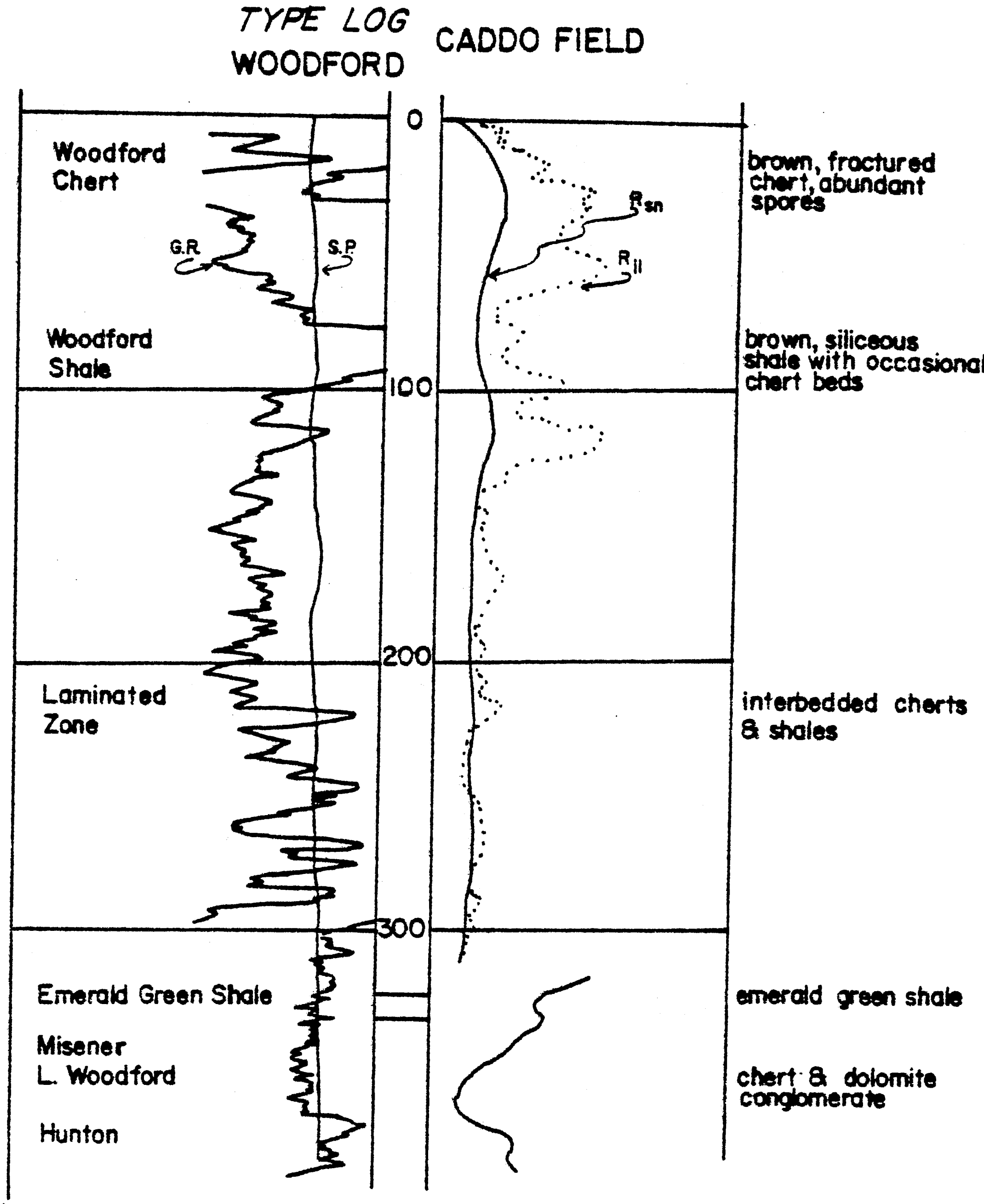


Figure 2. Type Log of the Woodford Formation in the Caddo Field of Carter County, Oklahoma

approximately 50 feet from the top contact exhibited abrupt contacts between shale and chert. Phosphate nodules are abundant throughout the upper 100 feet.

Woodford Shale Zone

For the remainder of the Woodford, subsurface data must be used to describe the zones. The most useful tool for delineating shales and cherts in the Woodford Formation is the gamma-ray log; this log measures the natual radioactivity of the rock. The Woodford shales are extremely rich in uranium, while the cherts are not. The type logs for the three producing fields will be used for measurements of the four remaining zones (Figures 2, 3 and 4). The Woodford Shale Zone ranges from 150 feet at the Northeast Alden Field to 130 feet at the Northeast Aylesworth Field to 120 feet at the Caddo Field. The shales seen in well cuttings are no different from those described in the Woodford Chert Zone. Occasional chert beds can be seen in the samples and on the gamma-ray log. These cherts are also the same as those seen in the upper zone. In an outcrop on the Washita River southwestof Dougherty, Oklahoma, a fossil tree can be found resting on its side. Because this outcrop obviously has been faulted (evidenced by shearing of shales and fossil trees) and because no upper or lower contact can be found, it was not used for measurements.

Laminated Zone

This third zone of the Woodford is made up of interbedded shales and cherts. Because the cherts are more abundant than in the Woodford Shale Zone this zone will be called the Laminated Zone. The total

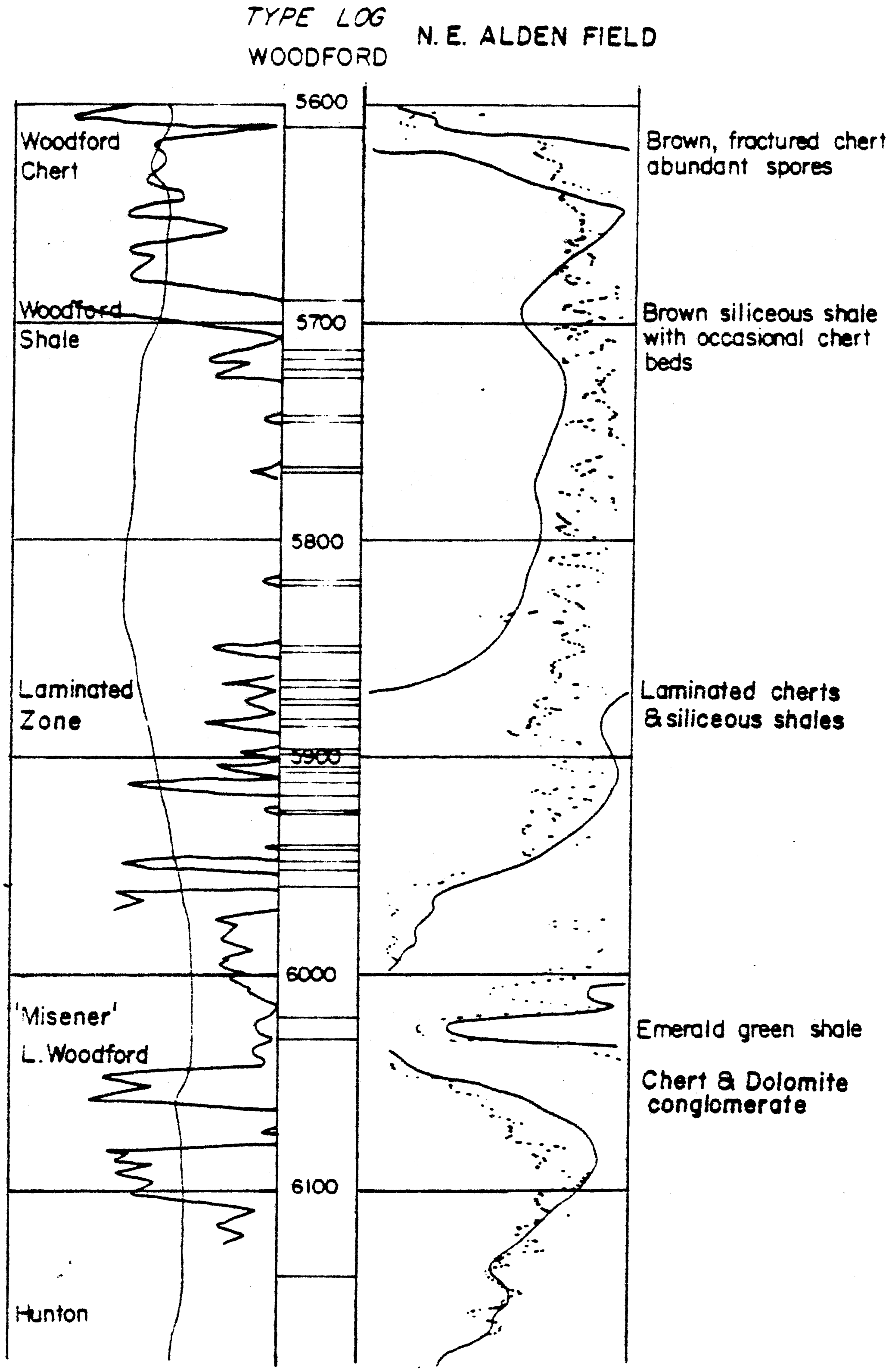


Figure 3. Type Log of the Woodford Formation in the Northeast Alden of Caddo County, Oklahoma

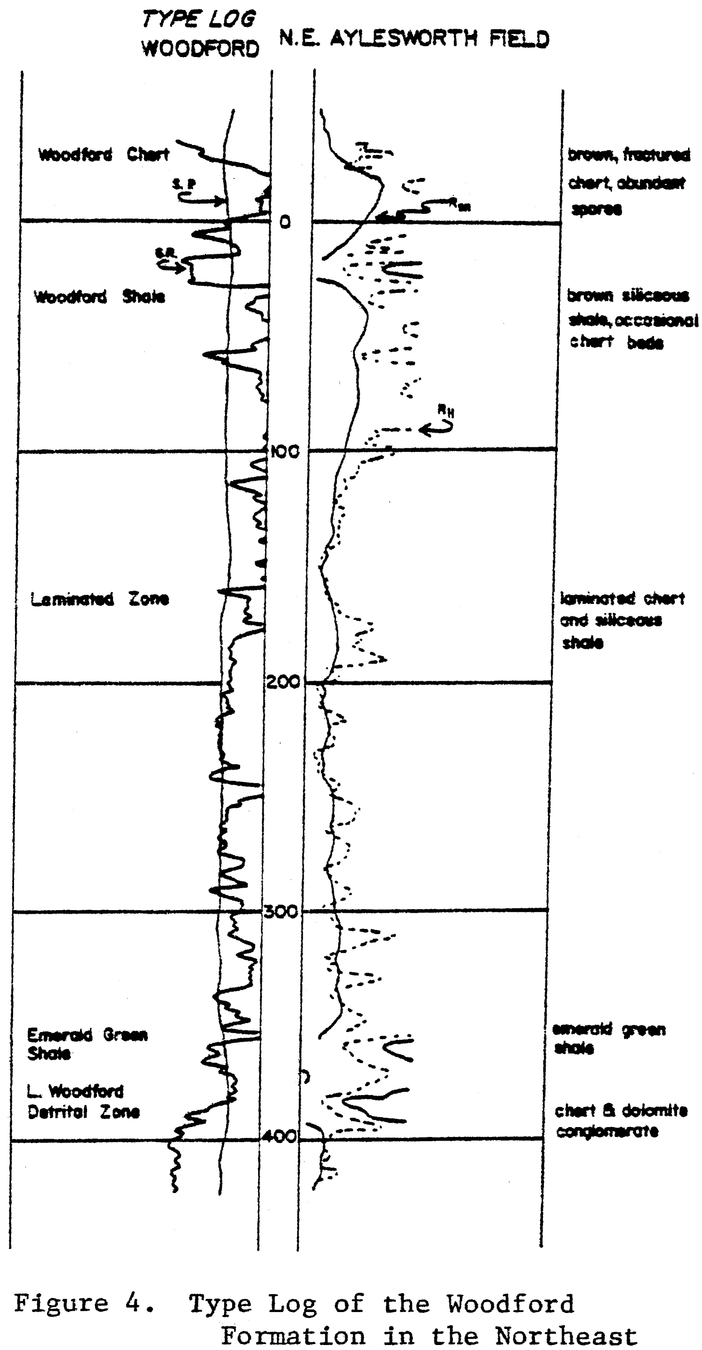


Figure 4. Type Log of the Woodford Formation in the Northeast Aylesworth Field of Marshall County, Oklahoma

thickness of the zone ranges from 175 feet at Northeast Alden to 150 feet at Northeast Aylesworth to 110 feet at Caddo (Figures 2, 3 and 4). The shales and cherts of this zone are the same in appearance as those in the Chert Zone and Shale Zone. Oil shows are seen on fracture faces in the cherts, but no tests have been reported.

Emerald Green Shale Zone

This zone is very uniform in thickness, being 10 feet at Northeast Alden, Northeast Aylesworth and Caddo (Figures 2, 3 and 4). At Aylesworth the very top of this zone is pale green, it grades to a deep emerald green. This pale green color is absent in the other two fields. The shale is as already stated soft and fissile.

Detrital Zone

The Detrital Zone in the Woodford is composed of reworked chert and dolomite and ranges in thickness from 100 feet at Northeast Alden to 48 feet at Northeast Aylesworth to 40 feet at Caddo (Figures 2, 3 and 4). The cherts are glassy in appearance, almost resembling hackly-fractured quartz. The color ranges from light brown to colorless. The dolomites are light brown in color and are very fine grained. Fragments of both types are angular. Oil shows occur in this zone and it has produced at the Northeast Aylesworth Field.

There is some question as to whether this zone actually belongs in the Woodford Formation. Because it rests unconformably on the Hunton Formation, it will be included within the Woodford in this study.

Shales as a Source Rock

The shales of the Woodford Formation have been considered by geologists to be the source beds of petroleum for many reservoirs in Oklahoma. Brenneman and Smith (1955) published a study of oil properties of reservoirs and their possible source beds. In this study, Woodford shales were examined as source rocks for the Misener Sandstone reservoirs in Grant and Garfield Counties of Oklahoma. The study ascertained that the Misener oil most likely did originate in the Woodford. More importantly it pointed out that the Woodford contained 5.45 percent organic carbon, the highest of any formation studied. Brenneman and Smith (1955) also ascertained that 13.2 percent of the total organic carbon ws extractable. If the shales of the Woodford in southern Oklahoma are basically the same in organic carbon content as those in northern Oklahoma, it can be concluded that they are prolific source rocks.

CHAPTER III

DEPOSITIONAL MODEL

In this chapter the depositional history of Cambrian to Pennsylvanian age rocks will be discussed with particular attention being given to the Woodford Formation. However, because chert is seldom dealt with in the literature (compared to other sedimentary rock types) a review of depositional models will be made first.

Deposition of Chert

A wide variety of thought concerning the origin of cherts can be found in the literature beginning in approximately 1860. Owen (1860) and Miser and Purdue (1929) hypothesized that cherts were merely metamorphosed sandstone. Griswold (1892) believed they were deposited as very fine grained sandstones. Honess (1923) countered with the concepts that the cherts were either a product of altered volcanic ash or were totally chemical precipitates (non-biogenic). In 1946, Bramlette suggested a totally biogenic origin for the Monterey Formation of California.

Most writers now agree that most chert deposits (other than nodular chert) are biogenic, but do not agree on the depth of deposition. Folk in 1973 hypothesized a shallow water origin for chert. McBride has since contended that the cherts were deposited in deep quiet waters.

In this chapter theories of totally non-biogenic origin will be discussed briefly. However, the majority of this portion will be spent on theories of biogenic deposition. Some arguments for the depth of deposition will be presented. Cherts which are clearly lacustrine will not be discussed, since the Woodford is known to be marine.

Inorganic Origin

There are two basic theories of primary inorganic deposition of chert: (1) that involving silica enrichment of seawater by volcanic activity and (2) that involving silica enrichment due to influx of silica-rich terrestrial waters. Both of these ideas consider the presence of radiolarian tests in the cherts to be a consequence of the abundance of silica and do not believe that the radiolarians were the direct cause of silica enrichment.

Bailey, Irwin and Jones (1964) elaborated on the concept that the Franciscan cherts of California were volcanic in origin. The basic evidence is the common occurrence of chert directly overlying pillow basalts. They believed that magma erupted on the seafloor, causing an increase in dissolved silica and an increase in temperature. With cooling of the seawater, supersaturation occurred and silica precipitated. However, a 221 foot thick lens of chert ranging in age from Late Jurassic to Late Cretaceous (40 million years) (McKaughlin, 1977) is convincing evidence that volcanism has little effect on some chert deposition. In this time span the oceanic crust beneath the chert lens, travelling at a conservative seafloor spreading rate of .2 cm per year, would have travelled 800 Km from the mid-ocean ridge where it formed. At this distance, basalt eruptions at the mid-ocean ridge would have had no effect on the deposition of the chert.

Davis (1918) believed cherts to be due to the influx of silica-rich terrestrial waters. He believed that because of seasonal variations in rainfall and flooding, there would be a periodic large influx of silica waters accounting for the rhythmically bedded cherts. Normal seawater has approximately 3ppm silica: this must be raised to over 120ppm to precipitate inorganic silica (Thurston, 1981). It seems unlikely that concentrations of silica could be carried undiluted any great distance into the ocean.

Organic Origin

The most widely accepted view of the origin of cherts is that they result from organic processes, principally radiolarian and sponge spicule accumulations in Paleozoic strata and diatom accumulations in younger sediments. However, the depth at which the cherts were deposited has been the subject of some dispute. Therefore, evidence for both shallow-water and deep-water deposition will be presented.

Shallow Water Deposition. Folk (1973) presented evidence that many cherts around the world could have been deposited in shallow water. He cited sedimentary features and the absence of a Calcite Compensation Depth (CCD) in pre-Mesozoic strata. Jones and Knauth (1979) presented oxygen-isotope data which set part of the Arkansas Novaculite in shallow water.

Folk (1973) quoted others' observations of ripple marks in some chert beds. He also stated that some had seen hummocky bedding surfaces and volcano-shaped mounds like those found in carbonate mudflats. In McBride and Folk (1977), on the Caballos Novaculite of Texas, Folk described: (1) mounds of possible algal origin; (2) fenestral, "birdseye" and Stromatoactis-like structures; (3) quartz pseudomorphs which look like evaporite crystals and (4) pockets filled with pure, well-rounded and sorted quartz sand. He felt that these all pointed to a tidal mudflat deposit, which was at some time subaerially exposed.

The absence of a CCD in pre-Mesozoic strata arises because of the absence of pelagic carbonate fauna (which when present dominate the siliceous fauna). Thus siliceous fauna would dominate deposition even in shallow water. Folk cites this as evidence for a shallow origin.

Jones and Knauth (1979), in their study of the Arkansas Novaculite in the western part of Arkansas, published oxygen-isotope data that indicated shallow water depths. However, oxygen-isotope ratios can be affected by metamorphism. This area has been intensely folded because of the Ouachita orogeny and low-grade metamorphism has taken place. The oxygen-isotope data may then be invalid.

Deep-Water Deposition. Garrison (1974) and McBride in McBride and Folk (1977 and 1979) and in Folk and McBride (1976, 1978a and 1978b) have presented evidence for a deep water origin of many of the world's chert deposits. Their evidence includes: (1) spatial relationship with pillow basalts, (2) interbedding with dark shales, (3) faunal evidence and (4) presence of a CCD. McBride and Folk (1979) have also described possible turbidity current flows in cherts.

Many formations that have abundant chert beds overlie pillow basalts (e.g., Franciscan cherts of California, Radiolarites of Italy and Radiolarites of Greece). These pillow basalts presumably were extruded on the seafloor at the mid-ocean ridge (at considerable depth). The cherts many times are deposited directly on top of the basalts. For these to be shallow marine in origin, deposition would have to be shut off until the basalt could somehow arrive in shallow waters.

Many of these same chert beds are found interbedded with dark brown to black shales. These same types of shales are seen being deposited in deep quiet waters at the present.

Radiolaria live in a wide variety of depths, from surface waters to abyssal depths. Those residing in surface waters have more delicate and slender parts (Berger, 1978). However, the only species of radiolaria generally preserved are the polycystins, because of the rapid dissolution of other species (Berger, 1978). These polycystins are generally found in deep marine waters.

At present, radiolaria are being deposited at depths below the CCD, which ranges from 2.1 to 3.3 miles below sea level. This depth depends on the position relative to the equator. At the equator it is at its maximum of 3.3 miles, probably because of the abundance of carbonate organisms. If the CCD was this deep in ancient seas the radiolarian cherts would have been deposited in quite deep water.

Other hypotheses invoke changes in the chert-shale relationship during or after deposition to explain the interbedding. Davis (1918) hypothesized that silica and clay would be deposited simultaneously and that diagenetic segregation would then form the interbedded deposits he encountered in the Franciscan rocks of California. The segregation of silica and clay has not been recognized in any Recent sediments. In 1977 Fischer called on episodic deposition of chert and clay to account for the interbedding. This concept called for rapid episodic deposition of radiolaria and slow continuous deposition of clay. In this type of deposit contacts should be gradational, because some clay would be present in the cherts as clay deposition is never shut off. Episodic deposition of radiolaria would most likely be caused by a change in nutrient levels and/or temperature. McBride and Folk (1979) hypothesized that the clays were probably deposited slowly and continuously and that the radiolaria were deposited by turbidity flows. Abrupt contacts between shale and chert should be expected because the deposition of the turbidity flow is many times faster than the deposition of the clay. These turbidites could show graded bedding. They might also explain scour features and fining-upward sequences that have been described in some chert deposits.

Deposition and Structural Evolution

It is now possible to attempt to apply some of the basic concepts of chert sedimentation to the Woodford Formation. As seen in the cross-section of southern Oklahoma there is an extreme thickening of all formations deposited prior to the Woodford, indicating the presence of a depositional basin (Figure 5). In 1946 Shatsky recognized the presence of very narrow troughs that extended into continents from folded mountain belts. He termed these features aulacogens and in fact was the first to recognize that an aulacogen was present in southern Oklahoma (Burke and Wilson, 1976). Shatsky's definition of an aulacogen was strictly descriptive, but Burke and Dewey in 1973 and Hoffman, Dewey and Burke in 1974 extended the aulacogen concept and related these features to plate tectonics (Wickham, Pruatt and Thompson, 1975). They believed that an aulacogen represents an arm of a ridge-ridge-ridge triple junction which for some reason ceased to rift apart. Wickham, Pruatt and Thompson (1975) believe that a possible explanation for the failure of

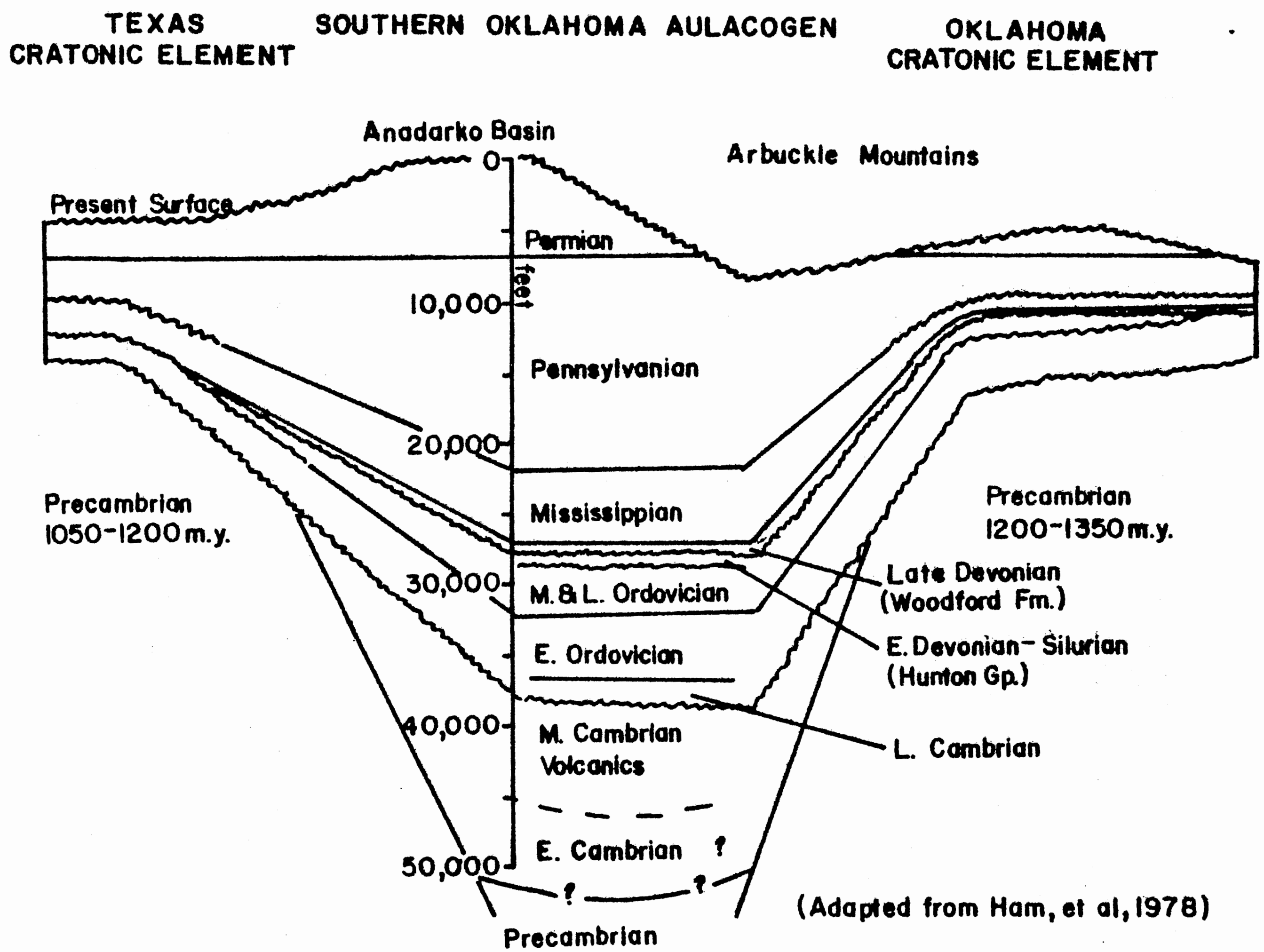


Figure 5. Cross Section of the Southern Oklahoma Aulacogen and Bounding Cratonic Elements

the rifting is that the rift parallels the direction of spreading (Figure 6). It is in this failed rift that a subsiding basin develops: within this basin extremely thick sequences of sediments are deposited. An understanding of the detailed geometry of the basin and of its tectonic causes is of great help in understanding the depositional history of southern Oklahoma. Therefore, the evolution of aulacogens, the depositional history of the southern Oklahoma aulacogen and the closing and deformation stage of the southern Oklahoma aulacogen will be discussed.

Evolution of Aulacogens

The beginning stage of rifting is characterized by the formation of a large dome due to mantle upwelling. Over the center of the dome, fractures occur generally in a radial three-armed pattern with angles of 120° between the arms (Burke and Wilson, 1976) (Figure 6). Grabens form due to extension as the crust stretches over the upwelling. Associated with the rifting is igneous activity, first of the alkalic type and then of the basic type. Gabbros and rhyolites in the Wichita Mountains have been radiometrically dated to be predominantly Middle Cambrian in age which would indicate the beginning of the aulacogen was possibly at about this time. After rifting ceases along the failed arm, the rift zone becomes a rapidly subsiding basin, probably due to weakness of the lithosphere. This subsidence proceeds at a much faster rate in the center of the basin than near the continental margin. This is evidenced by the extreme thickness of sediments within the basin compared with the thinner sequence on the margin (i.e., the Anadarko Basin of Oklahoma).

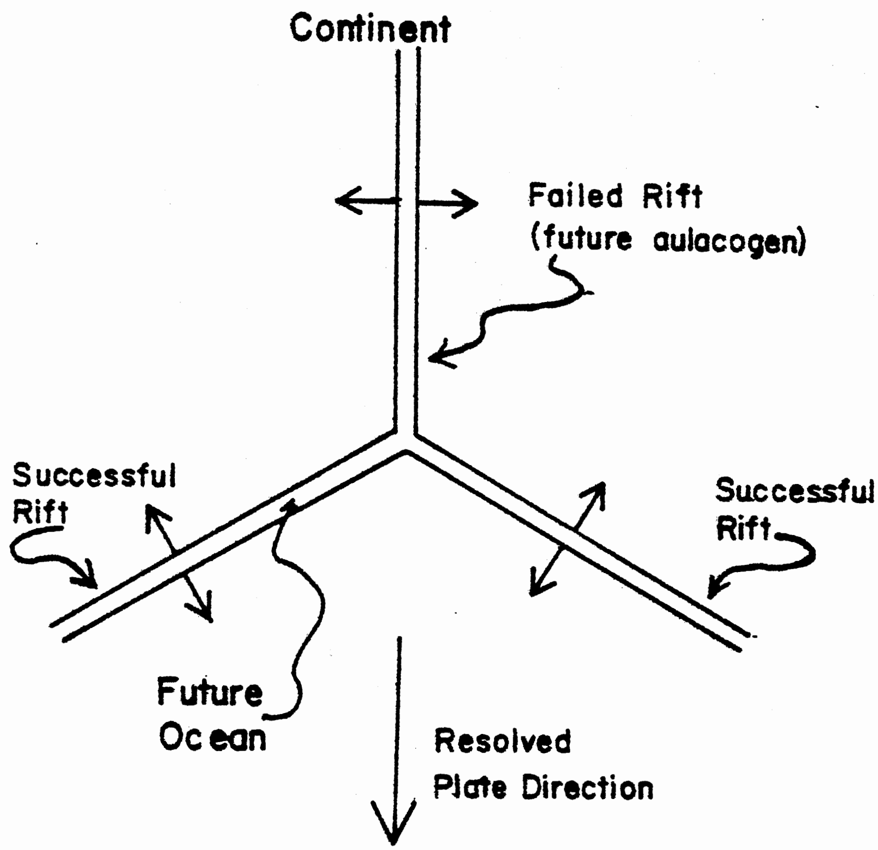


Figure 6. Geometry of a Hypothetical
Triple Junction

Pre-Pennsylvanian Sedimentation in the Basin

Cambrian Through Early Devonian Sedimentation. The first sediment deposited after the formation of the southern Oklahom aulacogen was the Reagàn Sandstone of Late Cambrian age. The Reagan ws probably deposited in a shallow environment as evidenced by abundant glauconite. The Reagan's thickness is very constant throughout Oklahoma except where granite hills protruded above the Cambrian seas (Ham et al., 1978). This constance is due to the fact that the basin had yet to develop. The Reagan marks the beginning of a marine transgression (Ham et al., 1978). The next formation to be deposited was the Honey Creek Formation which is also shallow marine as it has abundant remains of the fossil Trilobite (Ham et al., 1978). The overlying Arbuckle Group spans Late Cambrian and Early Ordovician. The water was shallow as evidenced by trilobites, mollusks, sponges and conspicuous stromatolites (Ham et al., 1978). The only indication of an increase in the depth of deposition is the presence of graptolites at the top of the Arbuckle Group in the West Spring Creek Formation (Ham et al., 1978). The Simpson Group of Middle Ordovician age marks the first real change in rock types. The Joins Limestone, at the base of the Simpson, is basically the same as the underlying Arbuckle Group in depth of deposition, but each of the overlying four formations (Oil Creek, McLish, Tulip Creek and Bromide) is composed of a basal sandstone with green shale and limestone above. This possibly indicates that the depth of deposition varied significantly during most of the Simpson. The basal sandstone of each formation probably marks a time of shallow water, followed by an overall deepening or transgression up to the next basal sandstone. This fluctuation of water depth may have been brought on by either a change in sea level or sedimentation rate. The Viola Formation is of Middle and Late Ordovician age and rests unconformably on the Simpson Group. From faunal investigations and an observed lithologic change from thin laminated beds at the base grading to coarse calcarenites at the top, the depth of deposition appears to have become progressively shallower (Ham et al., 1978). This regression could have been caused either by a slight tectonic uplift, a decrease in subsidence rate or an increase in deposition rate. The Sylvan Shale rests disconformably on the Viola Formation. The Sylvan is green in color with numerous graptolites occurring on the bedding surfaces (Ham et al., 1978). The Sylvan is Late Ordovician in age. Its green color indicates a reducing environment, which places the depth of deposition below wave base. The color, along with the graptolites, which are planktonic fauna, suggests a deeper depth of deposition than that of any preceding formation. The Hunton Group (predominantly limestones) overlies the Viola and represents a time span from very Late Ordovician through Silurian and Early Devonian (Ham et al., 1978). That the Hunton was deposited in a shallow marine environment is evidenced by the numerous (at least five) unconformities within its 350 feet and the abundance of trilobites and other shallow water marine life (Figure 7). The detrital zone at the top of the Hunton or base of the Woodford marks another possible period of tectonism.

Devonian and Early Mississippian Sedimentation. The deposition of the Woodford represents the end of a period of predominantly limestone deposition in southern Oklahoma. The age of the Woodford has been under debate for many years. Early geologists believed it was entirely Early Mississippian in age, because of the major unconformity at the base of

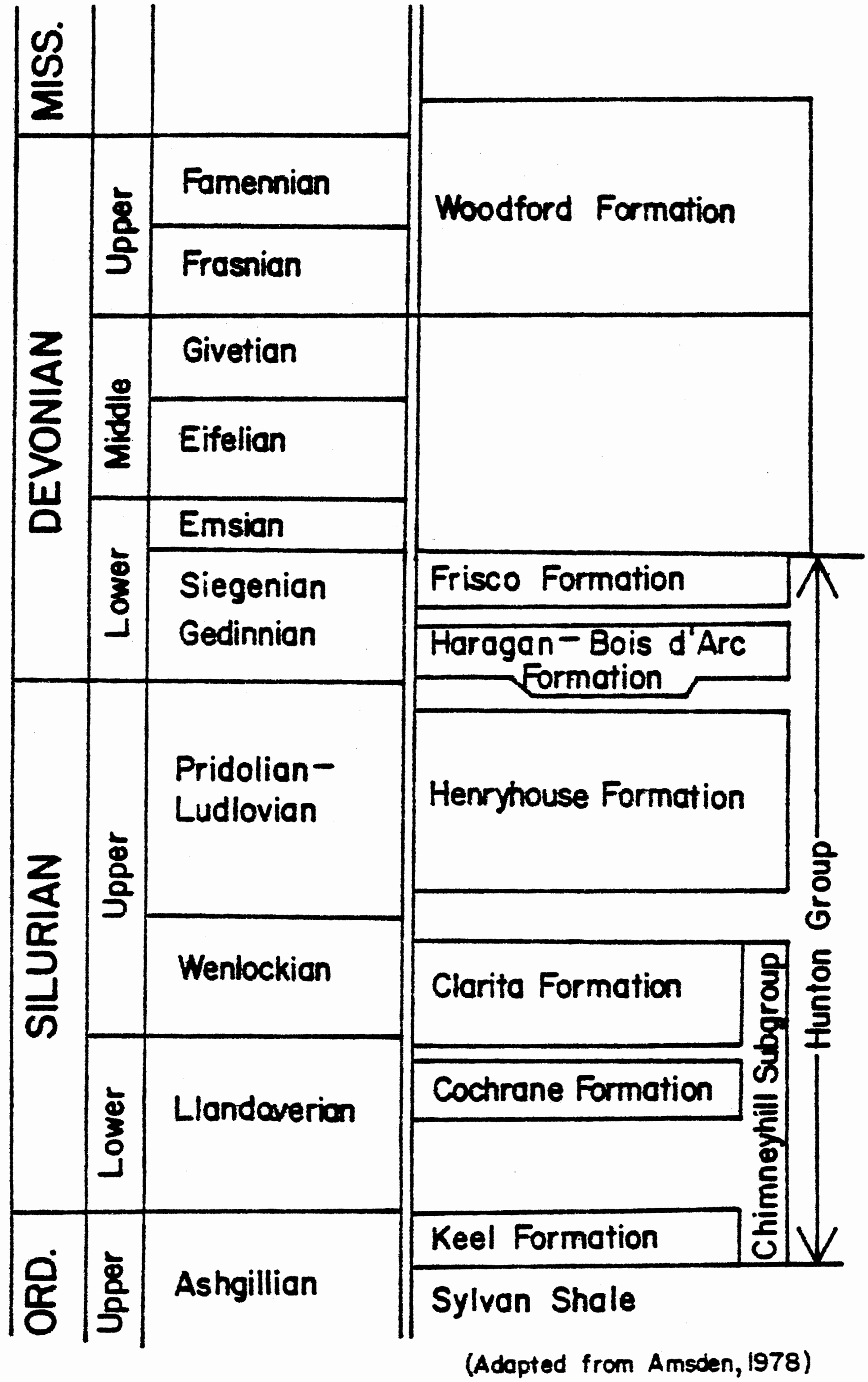


Figure 7. Stratigraphic Section of the Hunton Group and Woodford Formation

the Woodford. In the subsurface at the Northeast Aylesworth Field the Hunton Group is absent and the Woodford Formation lies directly on the Sylvan Shale. However, Haas and Huddle (1965) dated the Woodford Shale using conodonts. They discovered it was predominantly Late Devonian with the upper section being Early Mississippian.

Chert is relatively abundant in southern Oklahoma compared with areas to the north and the south. If chert indicates a deeper environment, then the aulacogen would have been deeper than the cratonic elements during part of the Devonian and Mississippian. As mentioned before, the Woodford Formation is composed primarily of interbedded black cherts and black siliceous shales. The cherts are composed primarily of silica and have abundant radiolarian tests and sponge spicules. They are also relatively free of clays. Overall, the shale and chert beds are quite continuous with very little change in the thickness of individual units. Each of the contacts between shales and cherts is quite abrupt; there are no fining-upward or fining-downward sequences. There are no apparent signs of any sedimentary features such as ripple marks, burrows, cross bedding, etc., that would indicate an origin of current flows. The chert beds do show some evidence of lamination in the form of color variation. The upper 15 feet has shale-to-chert ratios as low as .41:1. There are abundant phosphate nodules in the upper zone of the Woodford. The middle zone of the Woodford is predominantly shale and contains fossil trees. These trees are found lying on their sides and not in the growing position. In the lower part of this zone some chert beds are present, but there are not nearly as many as in the upper zone. The lower zone of the Woodford is made up primarily of chert and dolomite conglomerate. This zone represents reworked material of the Early to Late Devonian unconformity and is separated from the siliceous shales above by a 10 foot layer of emerald green shale.

The evidence (what little is present) points primarily to a depositional model of a progressively deepening basin. The green shale probably indicates the same type of depositional depth as the Sylvan Shale. The green color alone indicates a reducing environment, void of oxygen, that is probably below wave base. However, the shales and cherts in the middle and upper sections probably fit a depositional model of fairly deep, reducing environment. There are some clays within the chert beds, so continuous slow deposition of clays could have taken place with episodic deposition of chert. The episodic oozes could be the result of changes in nutrients or temperature resulting in blooms of radiolaria. The only objection to such a hypothesis was made by McBride and Folk (1979), who believed that burrowing animals would rework the bedding surfaces between episodes of deposition of the radiolarian oozes. This feature is not observed in outcrops of Woodford, but there is also no evidence to support a hypothesis of current deposition. The presence of radiolaria and conodonts, both pelagic organisms, helps to substantiate this claim of deep-water deposition of the Woodford. McBride (Folk and McBride, 1978b) believes this type of deposit occurs at depths greater than 3,000 meters. He arrived at this depth by considering that since calcite is totally absent in the Jurassic Radiolarites of Italy the deposition was below the calcite compensation depth. This is possibly the case for the Woodford Formation, but to ascertain the calcite compensation depth, one would have to reconstruct the paleogeography of the Devonian seas in southern Oklahoma. If the Woodford Formation was deposited in deep, quiet waters, then the subsidence rate of the aulacogen must have remained either constant or it increased and for some reason deposition was not able to keep up with subsidence.

Early to Late Mississippian Sedimentation. Overlying the Woodford is the Sycamore Formation: the contact is gradational. The absence of fauna prevents direct dating of the Sycamore, but it is thought to be Early Mississippian (Ham et al., 1978). The Sycamore Formation is predominantly silty to sandy limestone and shale. Sedimentary structures, currently being studied by B. Gouger and R. N. Donovan at Oklahoma State University, point to deposition by density flows. A deep-water, turbidite environment for the Sycamore meshes well with a deep-water depositional model for the underlying Woodford Formation.

Directly above the Sycamore Formation lies the Caney Formation and directly above the Caney is the Springer Formation. These two formations will be discussed together because they are composed predominantly of shales. The Caney Formation, in outcrop in the Arbuckle Mountains, is a tan to gray siliceous shale with abundant calcareous septarian concretions. The contact between the Caney and the Springer Formations is characterized by abundant siderite beds (Ham et al., 1978). The Springer shales are dark gray non-calcareous, fissile shales. The depositional environment of both the Caney Formation and the Springer Formation was probably quiet and deep water, like that for the Woodford Formation. The relative abundance of silica and the absence of primary calcite is also evidence for a deep-water deposition. However, the Springer Formation contains abundant sandstone beds that could either indicate a depth change to shallower water or could be the result of density flows.

Aulacogen Subsidence and Pre-Pennsylvania Water Depth

Before discussing Pennsylvanian strata in southern Oklahoma, some points about the aulacogen must be made. As was stated, when rifting occurred normal faults developed due to tensional stresses across the aulcogen. These faults extended well into basement rocks and presumably were active during sedimentation in the aulacogen as evidenced by possible growth faults. However, since strike-slip faulting of great magnitude has occurred since deposition, it is difficult to establish whether growth faulting occurred and, if so, to what extent. Theoretically, the subsidence rate of an aulacogen should be quite rapid because it is a thin and weak point in the lithosphere. Thompson (1981) has found that the subsidence rate of the southern Oklahoma aulacogen was very high. If this is the case, then in general the sedimentation rate must have been equally rapid. Evidence is that most of the Paleozoic strata were deposited in shallow water.

Deformation of the Aulacogen and Pennsylvanian Sedimentation

The reason for separating the Pennsylvanian from the pre-Pennsylvanian section is that the Pennsylvanian marks the period of deformation in the Arbuckle Mountains. Isopach maps by Wickham, Pruatt and Thompson (1975) indicate that new basins were beginning to form in Early Pennsylvanian. This probably marks the first deformational period. Ham et al. (1978) have described four principal conglomerates which are a direct result of the deformation of the aulacogen and resulting uplift and erosion: (1) "Franks", (2) Deese, (3) Collings

Ranch and (4) Vanoss. The "Franks" and Deese Conglomerates are principally time equivalent, ranging from Desmoinesian to Missourian in age (Ham et al., 1978). These conglomerates consist of pebble to cobble size material derived from formations as old as the uppermost Arbuckle Group (Ham et al., 1978). This span of time was marked by broad gentle deformation. The Collings Ranch Conglomerate was deposited in mid-Virgilian time and is composed primarily of Arbuckle Group clasts (Ham et al., 1978). The late Virgilian Vanoss Conglomerate is the youngest conglomerate and the only one of the four that contains pre-Cambrian clasts (Ham et al., 1978).

In addition to conglomerates of the Pennsylvanian rocks of southern Oklahoma, the formation also includes shale, limestone and sandstones of varying depositional environments. This variety is due to the active tectonics of this period.

CHAPTER IV

STRUCTURAL STYLES OF WRENCH SYSTEMS

An understanding of the structural style of the area under investigation is critical in attempting to predict hydrocarbon accumulations in fractured reservoirs. The nature of faulting in the Arbuckle-Wichita Mountain area has been debated since the early 1900's. Taff (1904), the earliest investigator, interpreted the various faults in the Arbuckle-Wichita area as being gravity or dip-slip faults. He believed the Arbuckle Mountains were one large fold with many minor folds and attributed all of the structures to horizontal compressive stresses directed toward the northeast. In 1910 Reed described the assymetry of the folds and called the faults normal faults (Carter, 1979). Ham (1956) was the first person to recognize major strike-slip movement in southern Oklahoma. He attributed these strike-slip faults to stresses oriented in a northwestward direction and related in some way to compressive stresses in the Ouachita Mountains. Tomlinson (1952) believed the faults to be "propeller faults", which he described as being faults that dip in different directions on either side of a hinge point along the fault. Haas (1978) described the Reagan Fault Zone as a wrench fault with as much as 15 miles of left-lateral displacement. He cited as evidence <u>en echelon</u> folds, thrust faults and thickness differences across the fault. Carter (1979) used thickness variations in the Hunton Group as evidence for strike-slip movement on the Washita Valley Fault. He found that this fault was also a left-lateral wrench fault with a minimum of 20 miles of horizontal displacement. All writers agree that the major movement occurred in the Pennsylvanian. The Collings Ranch and Vanoss Conglomerates are products of uplift related to this deformation.

Wrench Tectonics

Moody and Hill (1956) and Wilcox, Harding and Seely (1973) have explained wrench tectonics and the geometries of folds and faults that occur with them. Wrench faults are ruptures in the earth's crust in which the dominant movement is in the horizontal plane (Moody and Hill, 1956). The greatest principal stress and the least principal stress will both be oriented horizontally and the intermediate principal stress will be oriented vertically (Moody and Hill, 1956). In the case of a left-wrenching system a primary left-slip fault and a secondary right-slip fault will occur in a shear pattern (Figure 8). Associated with the wrench faults are *en echelon* folds which are the primary folds seen in Figure 8. Along with these folds, thrust faults will often occur. Normal faults are not predicted by Figure 8, but are known to occur in wrench systems. Wilcox, Harding and Seely (1973) state that these normal faults are tension fractures and believe they will most likely occur on the *en echelon* folds, perpendicular to the fold axes.

Structures in Southern Oklahoma

In the Arbuckle-Wichita area, strike-slip faults are predominant. The major strike-slip faults in the area are aligned in a direction between N50E to N80E, with dips generally greater than 70°. Examples

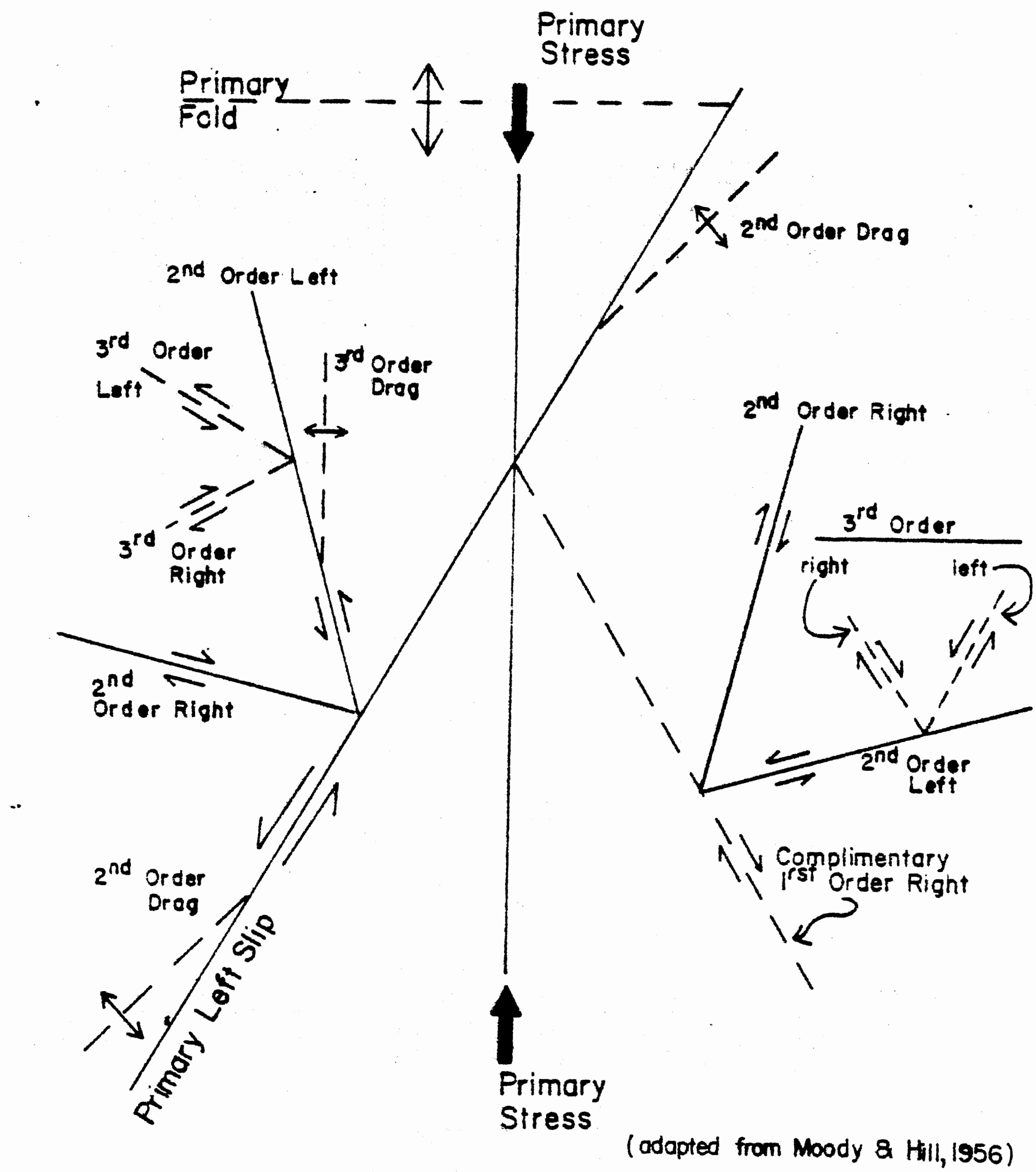


Figure 8. Geometry of Faults and Folds in a Left Lateral Wrench System

are the Mountain View Fault, the Washita Valley Fault and the Nellie Fault (Plate 1). Also conspicuous are folds with axial trends diverging at approximately 55° from the strike-slip faults. They are often extremely tight folds with several hundred feet or more of closure (Figure 9). Many of these folds are bounded on the east by thrust faults. These are the en echelon folds predicted by models set forth by Moody and Hill (1956). En echelon folds are primary traps for hydrocarbons and, due to their close proximity to faults, extreme fracturing is common. This fracturing enhances porosity and permeability and can make a reservoir of a formation that is otherwise too impermeable to produce. The Stonewall Fault seen in T2N and T3N - R6E and R10E is predicted by the model for left-slip systems and should be a first-order right-lateral fault (Figure 8). As seen in Figure 10, the fault appears to be nearly vertical and could very well be right-lateral. In the Caddo anticline (Plate 1) the "S" shape of the fold axis is easily recognizable. This feature is seen in several of the folds in southern Oklahoma and is most likely caused by torsional stresses due to motion on the faults. There is another type of fold present which has a fold axis that parallels the strike-slip faults. These will not be discussed at this point because they may be related to an earlier tectonic episode.

The dominant motion on the fault is left-slip (Carter, 1979 and Haas, 1978). These workers did not discuss the stress orientation which caused such a geometry. There are two possible directions of greatest compressive stress (σ_1) which could cause left-slip movement: (1) northwest-southeast, parallel with the faults and (2) east-west to northeast-southwest. It is extremely difficult to explain the left-slip

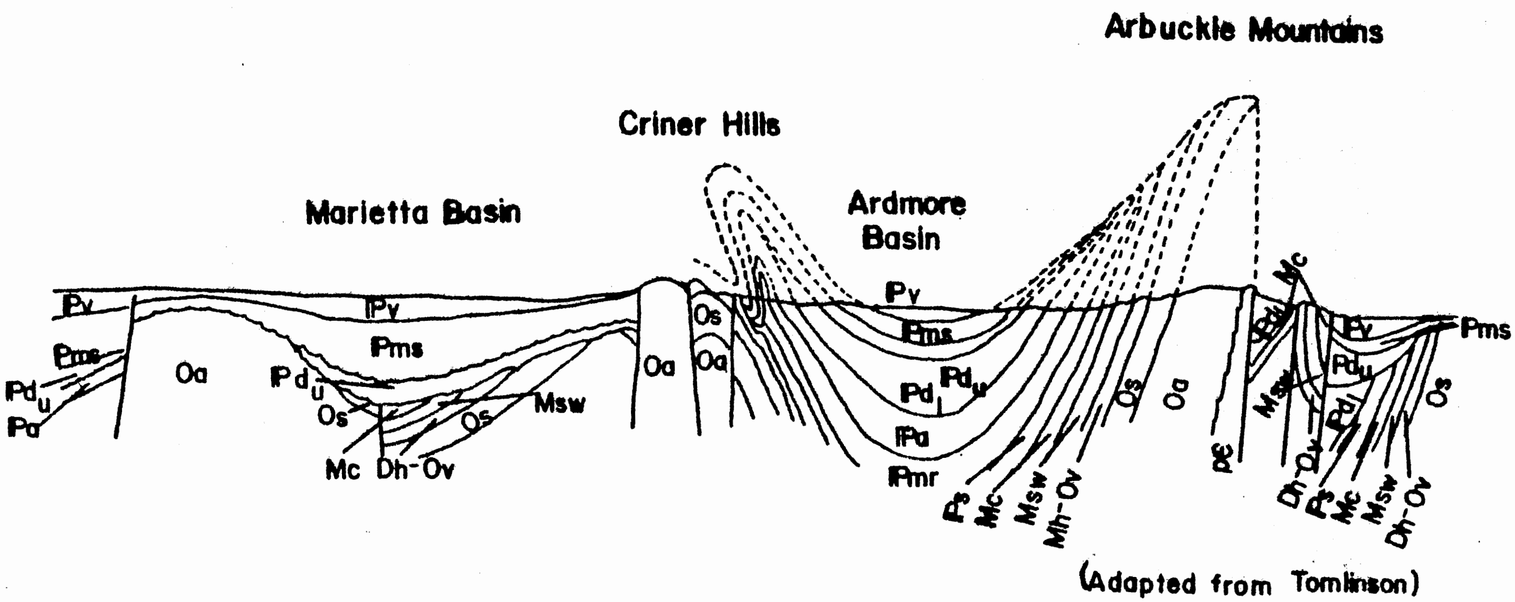


Figure 9. Diagrammatic Cross Section of the Arbuckle Mountains Showing Extremely Tight Folds

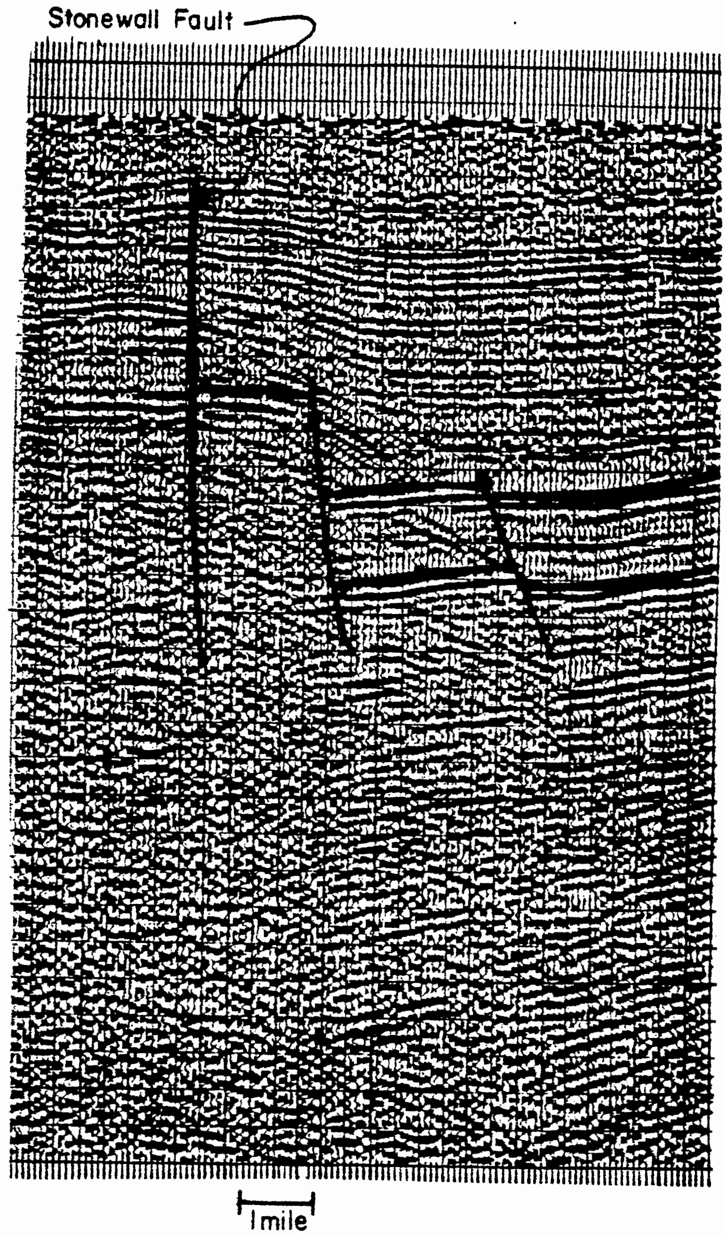


Figure 10. Seismic Profile of the
Stonewall Fault

configuration with the first. If a fault block is driven into the area by westward compression and if this block is moving at a faster rate than the two bounding blocks (which are also moving in the same direction, but at a slower rate), the configuration would not be purely left-slip or right-slip. The fault on the south side of the indriven block would be a left-slip fault. The fault on the north side of the driven block would be a right-slip fault. Right-slip faults that parallel left-slip faults have yet to be described in southern Oklahoma. Furthermore, clay models prepared by Wilcox, Harding and Seely (1973) show that faults parallel to σ_1 do not normally occur. The second explanation, east-west to southeast-northwest, appears to be more likely. This orientation of σ_1 will generate the observed structures under the ideal model of wrench tectonics set forth by Moody and Hill (1956) and Wilcox, Harding and Seely (1973).

Ham (1956) first suggested that the Ouachita Mountains play an important role in the faulting and folding in the Arbuckle-Wichita Mountains. In plate tectonic terms, it is now thought that the Ouachita overthrust belt represents a collision of two plates. The compressional stresses related to this collision may have generated the faults and folds in the Arbuckle-Wichita Mountains.

Thompson (1981) believes the strike-slip faults may have been activated by the collision of the African plate and the North American plate which formed the Appalachian fold belt. Transmission of energy across the North American continent would have formed the strike-slip faults. If old normal faults related to the aulacogen were present, either of the mentioned collisions could have rectivated these faults and resulted in strike-slip movement.

Another feature that warrants consideration is the apparent tilting of blocks from the southeast to the northwest. The best example of this feature is the Tishomingo block. Here the Tishomingo Granite outcrops in the southeast with the sedimentary section through the Caney Shale dipping off it to the northwest. This entire block is bounded by the Washita Valley Fault to the south and the Sulphur Fault to the north. The geometry could be explained by movement of the block in a horizontal direction due to σ_1. These compressional stresses most likely formed a very gently dipping fold which would dip to the west off the Tishomingo Granite. These blocks were also faulted: the result is this odd geometry. This has been termed "scissor" faulting and could account for the vertical diplacement encountered on the largely strike-slip faults. Another possible explanation could be an uplift of the Tishomingo Granite during the rifting stage of the southern Oklahoma aulacogen (Thompson, 1981). Thompson explained that the Arbuckle Group appears to onlap onto the Tishomingo block and explained the tilting phenomena as being merely a pre-existing positive structure with sediment onlapping onto it.

The final major features encountered in the study area are the large folds whose axes parellel the strike-slip faults. If they are not related to the strike-slip faulting, another major tectonic event may have formed these folds. Many of these folds are bounded by faults to the north and south as can be seen in Plate 1. One fold of this type is the Cumberland anticline which is bounded on the north side by a paralleling fault, the Washita Valley Fault. The Madill-Aylesworth anticline is another excellent example of this type of fold. It is linear and parallels the Nellie Fault. The Madill-Aylesworth anticline lacks the contortion seen in the Caddo anticline. These folds that parallel strike-slip faults may be related to compression orientated approximately northeast-southwest. Thus they may be related in some way to a different tectonic event than the collision of North America and Africa. Thompson (1981) stated that two other periods of deformation were possibly present in southern Oklahoma, the first Ordovician and the second Devonian. The Devonian deformation is evidenced by a major unconformity at the base of the Woodford Formation throughout Oklahoma. Thompson believes that this deformation was the result of the North American plate converging with the Eurasian plate. The strike-paralleling folds could be related to one of these earlier tectonic episodes. However, as previously mentioned Harding (1973) believes this type of fold may be due to a dip-slip component of movement on the faults.

California as an Analog

The concept that wrench tectonics was the principal cause of faulting and folding in southern Oklahoma is relatively new in the literature. Examination of a similar situation in another part of the world may help in understanding southern Oklahoma. Several regions dominated by wrench tectonics exist around the world, but one of the most studied is western California. This area is cut by several strike-slip fault zones of which the most well known and probably the most important is the San Andreas. The principal reasons so much is known about these fault zones are twofold: (1) they lie in an area where extensive petroleum exploration has taken place and (2) they are still active and cause damage to buildings and property each year. Strike-slip fault zones that approximately parallel the San Andreas include: (1)

Newport-Inglewood, (2) Nacimiento and (3) San Jacinto.

Harding (1973) dealt with the Newport-Inglewood Trend in southern California and believed it an ideal example of wrench tectonics. It should be noted that the Newport-Inglewood Trend is right-lateral and movement in southern Oklahoma is left-lateral. Because of this, all of the geometries of folds and faults should be exactly opposite in California and Oklahoma. Harding (1973) listed seven criteria for the recognition of wrench tectonics:

> . . . 1) laterally offset fold axes and fold flanks; 2) horizontal slickensides; 3) juxtaposed dissimilar stratigraphies; 4) variable nature of fault zone, 5) en echelon fold and fault pattern; 6) indicated strike-slip genesis of secondary associated structures; and 7) parallelism of zones with documented wrench faults (p. 99).

He then proceeded to give examples of these features in the Newport-Inglewood Trend. Harding (1973) described en echelon folds that were offset as Figure 8 would predict for a right-slip system. He also described lithologic differences across faults that could not be explained other than by strike-slip faulting. Harding (1973) described very low-angle slickensides in well cores. He also described folds that parallel the strike-slip faults (like those seen in southern Oklahoma) and related these folds to a dip-slip component of movement on the faults. The folds that parallel strike-slip faults may be related to fault drag or drape (Harding, 1973).

That the faulting in California is predominantly strike-slip cannot be denied because many of the faults are still active. From an area with active faulting, ideas can be formulated to explain an area with faults which long ago became inactive.

CHAPTER V

FRACTURING

The term "fracture" has thus far been used very loosely in the context of this paper. A fracture can be defined as a break in a material (Whitten and Brooks, 1972). Thus the term "fracture" does not imply that any displacement has taken place. Faults are fractures in which displacement has occurred parallel to the fracture plane (Billings, 1972). Joints, on the other hand, are fractures in which any displacement has taken place only perpendicular to the fracture plane (Billings, 1972). In the purest sense, a fault is a shear failure plane and a joint is a tensional failure plane.

Application of Mohr's Circles and Envelopes

Mohr's circle is a means by which the state of stress at a point (i.e., the relationship between shear and normal stress) can be graphically displayed. A Mohr's circle describes a particular state of stress independent of any specific material. The horizontal axis represents normal stress (compressional when positive, tensional when negative) and the vertical axis represents shearing stress (Figure 11). A Mohr envelope describes the failure behavior of a specific material and exists independently of any specific state of stress. Fractures in a material are represented by points at which Mohr's circles, growing as stresses increase, become tangent to the Mohr envelope for that material.

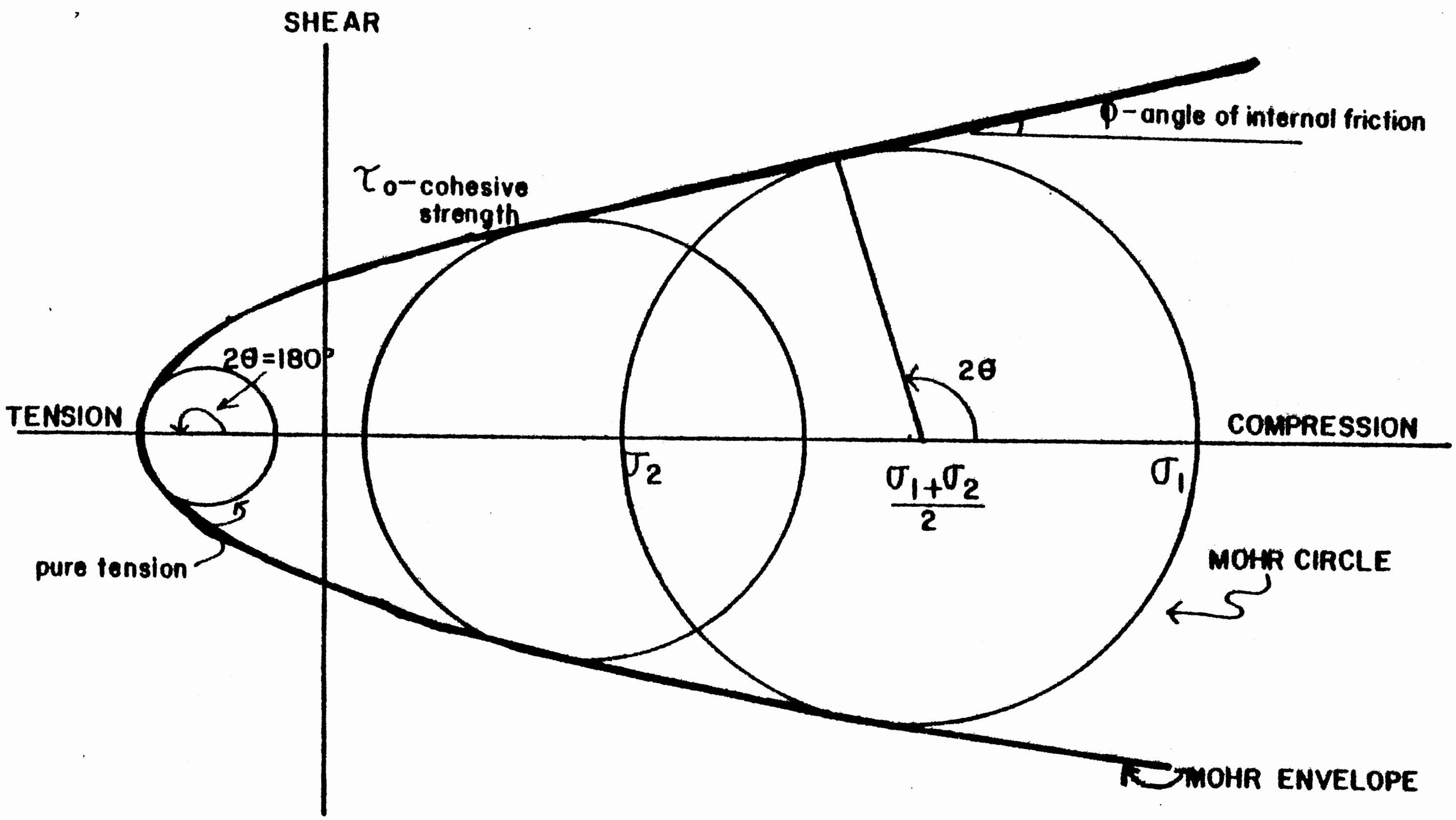


Figure 11. Hypothetical Mohr Circles and Envelope

For each Mohr envelope there exists a circle which is tangent to the envelope at the horizontal axis. In this circle the least principal stress is perpendicular to the failure plane. If this point of tangency is to the left of the vertical axis, the point represents a least principal stress which is truly tensional and the failure is a tensional failure (i.e., a joint).

Any circle tangent to the envelope can be represented by specifying the location of its center (equivalent to giving the mean stress) and by specifying its radius (equivalent to giving the deviatoric stress). The least principal stress will always plot to the left of the center and so its deviatoric stress is always negative or "tensional". However, these deviatoric "tensions" only represent true tensions if to the left of the vertical axis (this can only occur if the center of the circle is not too far to the right of the horizontal axis [i.e., if the mean stress is relatively low]). Geologically, this corresponds to low confining pressure (low overburden or shallow depth). The points of tangency of all of these circles with the Mohr envelope, no matter whether the least principal stress is positive or negative, are off the horizontal axis and hence have non-zero Y values. This means that the shear stresses along the failure plane are non-zero, and that the fractures are therefore shear failures or faults.

Substantial overburden increases the confining pressure, or mean stress, which shifts the circle to the right. When the circle is far enough to the right the first point of tangency with the envelope (i.e., the first failure as the stresses increase) will be on the limb of the envelope and not at its nose. Hence, deep burial prevents the development of true tensional fractures, or joints (all fractures at depth are faults).

Interbedded Competent and Incompetent Units

Harris, Taylor and Walper (1960), Price (1966) and McQuillan (1973) have all treated the effects of bed thickness on the density of fracturing. Price (1966) arrived at a simple equation that expresses this relationship:

$$F = \sigma_T \cdot z \text{ (acting over a distance L)}$$

where F is the force per unit layer width required to fracture the bed, $_T$ is the sum of all stresses acting on the layer and z is the thickness of the layer (Figure 12). It is evident that with a smaller value of z, less force would be required to fracture the unit. This equation assumes that a brittle, competent layer is bounded by incompetent layers (Price, 1966). Price (1966) also assumes that the competent layer has a tensile stress acting on it and is at the point of failure throughout. This total stress causes the first fracture to develop. The fracture would continue to widen if it were free to do so, but friction between the competent and incompetent layers (frictional shearing stress) opposes further widening (Price, 1966). Therefore, rather than existing fractures widening, more fractures will form (Price, 1966). He noted that the most important feature of this concept was that frictional traction resisting bedding plane slippage had to balance the total force F acting along the competent bed. Price (1966) also stated that:

> This simple and approximate mechanism, in which it has been assumed that the cohesion between adjacent beds is non-existent and that the coefficient of friction, the stress acting normal to the bed and the total stress are all constant

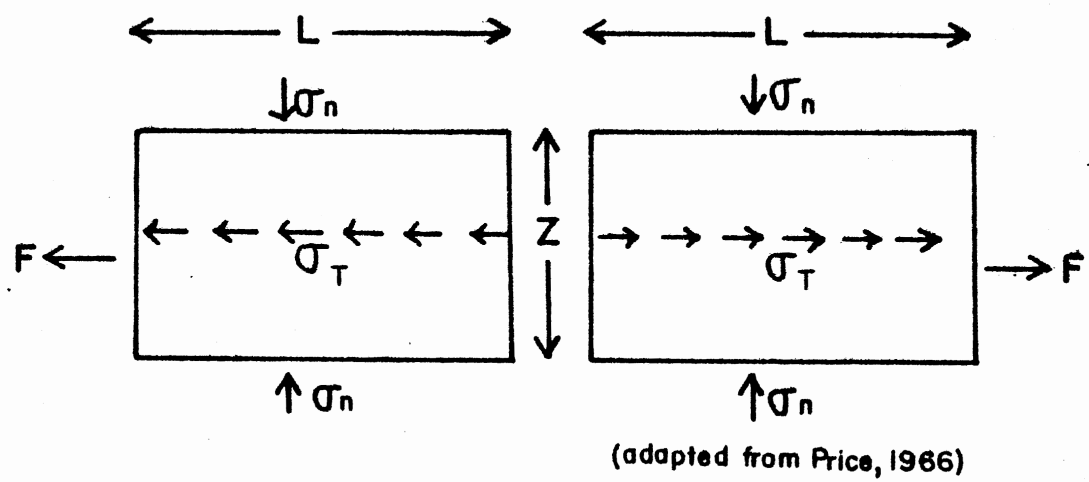


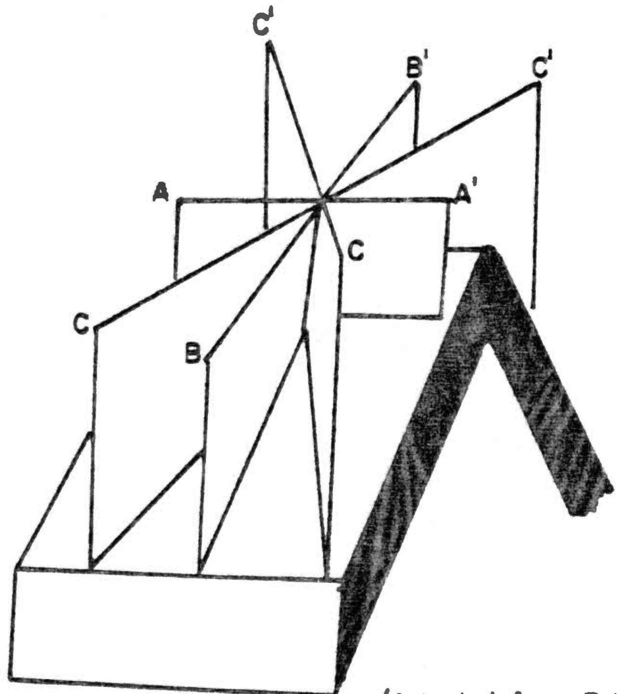
Figure 12. Diagrammatic Representation of Total Stress in a Section of a Competent Bed

> gives rise to an exact relationship between joint separation and bed thickness (p. 147).

These factors will vary between localities, but in one particular locality, such as those in the study area, the rock types are fairly consistent. Therefore, only small variations in the equation should result (Price, 1966).

Joint Geometries on Folds

Basically, three joint patterns can be recognized: (1) release joints, parallel to the fold axis, (2) extension joints, perpendicular to the fold axis and (3) the conjugate or shear set at some non-zero angle less than 90 degrees from the fold axis (Figure 13). Release joints are believed to be caused by the release of the load (the stress that formed the fold) after the folding phase (Billings, 1972). Billings (1972) also states that these joints result from extension on the crest of the fold. However, Price (1966) does not think these "release joints" caused by flexure of a bed during the folding stage should be referred to as joints. These fractures would have an orientation approximately parallel to the axis of the fold. They would be directly related to tectonism responsible for the fold. Price stated that these fractures were open, or more often filled with quartz or carbonate material, and the fracture surfaces are often rough and irregular. He terms these features tension "gashes". Price (1966) believes that true joints parallel to the fold axis would only form due to stored or residual confining stresses and the release of these during the stripping of overburden (discussed later). Therefore, these tensional "gashes" would take on a genetic connotation. Extension joints (Figure 13) are believed to be caused by elongation of the fold axis parallel to



(Adapted from Price, 1966)

Figure 13. Block Diagram Showing the Geometries of Joints as Related to a Fold

its axis (Billings, 1972). The conjugate joint set many times has an orientation which closely resembles that of the wrench faults which develop under the same stress field as the fold (Price, 1966). Because these joints' geometry closely resembles the resulting shear pattern they will be termed shear joints.

CHAPTER VI

SURFACE FRACTURE DATA

Since very little production has been established or attempted in the Woodford Formation, very few cores through the Woodford have been taken. Cores are essential to a quantitative analysis of a fractured reservoir in the subsurface. The purpose of the field work was to better understand the factors that are important in the fracturing of the Woodford cherts.

Methodology

The surface study areas were chosen in known structural positions away from known major faults. Such areas were assumed to be less complex than those nearer major faults. Once the general areas were chosen outcrops were selected which would lend themselves to the type of study in mind. This was the most difficult step because in order to measure fracture densities either the upper or the lower surface of the bed must be exposed. There must also be enough surface exposed to get a statistically sound measurement. It became evident after several trips to the field that outcrops which were cut by streams and had dips in the range of 20 to 30 degrees were the easiest from which to obtain data.

Once a good outcrop was chosen the next step was to locate the section in the stratigraphic column. Because the lower part of the Woodford is predominantly shale it rarely outcrops. Indeed, generally only the upper contact of the Woodford Formation with the Sycamore Formation can be seen. This was true of every outcrop studied except one at Camp Classen.

When the actual data gathering began the first step was to locate a section of chert and shale that offered several good surfaces for the measurement of fracture densities. The thickness of each individual bed over a four-foot section was measured. This was done to arrive at a shale-to-chert ratio for the four-foot section.

After the shale-to-chert ratio was calculated the next step was to take strike and dip measurements. This was followed by the actual fracture density measurements. When possible, one foot was marked off normal to the fractures and the number of fractures occurring within that distance were counted. Generally, two fracture sets were present, usually intersecting at an angle of eighty to ninety degrees. The number of fractures within each set was counted, and the numbers were added together for later representation in graph form. However, in some cases three fracture sets were present: in this case, a one-foot square with sides approximately normal to two of the fracture sets was drawn and the number of fractures inside the square was tallied. In all cases the thickness of the bed was reported, as was the orientation of each fracture set.

In general, many of the fracture sets had one set paralleling the dip and another paralleling the strike. In a few instances the fracture was at some angle to strike or dip. However, if strike and dip sets were present, the fractures showed no other orientation in that location. The fractures were usually laterally continuous without bifurcation and in some cases showed vertical continuity through several chert layers. Even though the fractures were continuous through several chert beds, fractures were conspicuously absent in shale beds. The fractures were generally oriented perpendicular to the bedding surface.

The final step was to display the data graphically. Because the fractures were essentially perpendicular to bedding, the best means of representing the fracture orientations was the rose diagram. In plotting the fracture orientations on the rose diagrams, class intervals of ten degree ranges were used. Another means of displaying the fracture data was graphing thickness versus fracture density. This was done for each individual location as well as for the total data set.

Field Localities

Fitzgerald Ranch

This outcrop is on the Fitzgerald Ranch in the SW/4 of the SW/4 of section 29, the SE/4 of the SE/4 of section 30 and N/2 of the N/2 of the NE/4 of section 31, all in T2S - R1E (Springer 7.5-minute quandrangle) (Figure 14). This outcrop is on the south flank of the major Arbuckle anticline. There are only very minor local faults in this outcrop and no measurements were taken close to any of these faults. This is one area where a limited exposure of the lower as well as upper section of the Woodford Formation can be seen.

Measurements at sections 3a and 3e as seen in the Appendix were taken toward the upper part of the Woodford Formation and have shale-to-chert ratios of 1.41:1 and 1.03:1, respectively. Both of these sections had only limited exposures of surfaces that allowed measurements of fracture densities. However, the information taken from both of these localities correlated together quite well, as will be seen later

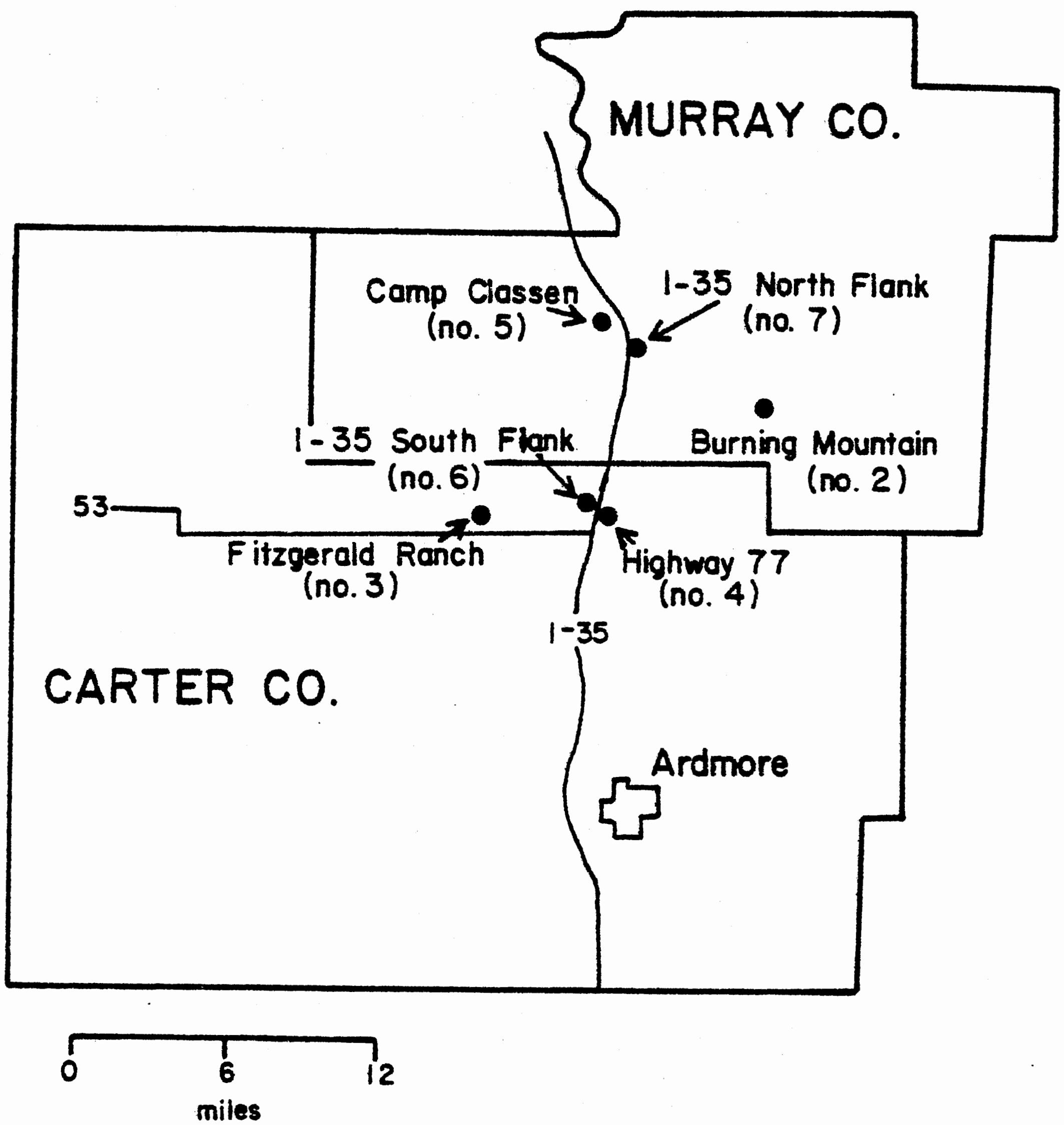


Figure 14. Aerial Map of Localities at Which Surface Data was Collected

in the evaluation of data. Both stations were exposed by stream dissection.

Measurements of section 3b were taken toward the lower part of the upper section. The shale-to-chert ratio taken at 3b was 2.43:1. This location was at a sheer cliff with its walls parallelling strike: only one reliable density measurement could be taken. This exposure is along the same creek that exposed locality 3a.

Sections 3c and 3d were both measured in the middle section of the Woodford Formation. They had extremely different shale-to-chert ratios of .82:1 and 2.38:1, respectively (good fracture density measurements could be taken, but because of the rocks attitude, mesurements of thickness were extremely difficult). However, most of the beds were in the range of 1/4 to 1 inches thick and had fracture densities that were consistent with their thickness.

The strike of the Woodford Formation in this area ranges from N70E to N85E; dips range from 23° SE to 26° SE. Examination of the fracture density versus thickness for this locality shows that there is no curve which adequately fits the data (Figure 15). This means that the density of fracturing must relate to something other than thickness alone. The most likely explanation for this is the shale-to-chert ratio (evidence will be presented in a later section). The rose diagram for the fracture orientations can be seen in Figure 16. From the wrench-tectonic model, a greatest principal stress oriented approximately N90E (E-W) can be inferred.

Burning Mountain

The Burning Mountain is located in the SE/4 of the SE/4 of section

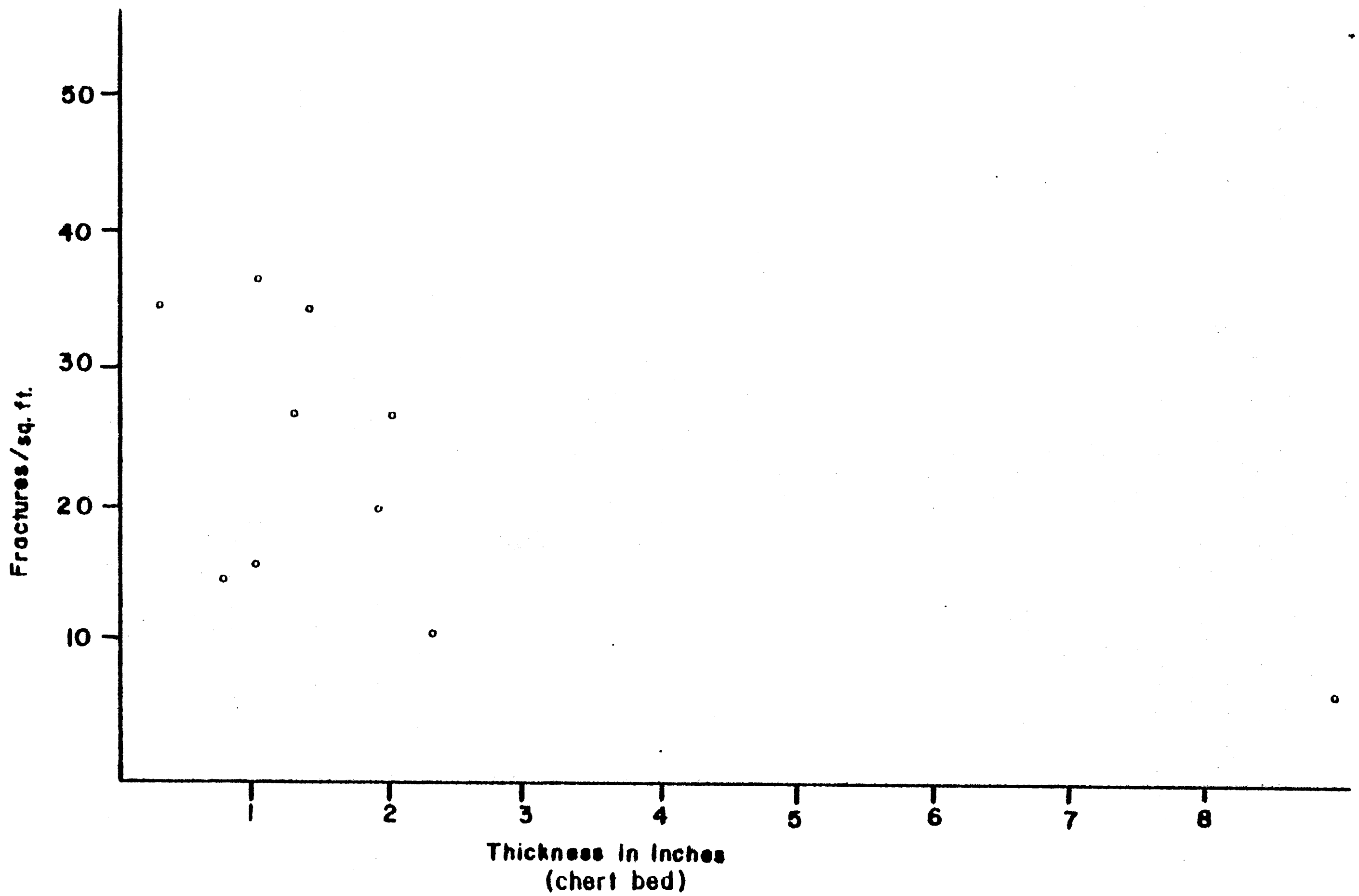


Figure 15. Density-Thickness Plot for the Fitzgerald Ranch Exposure

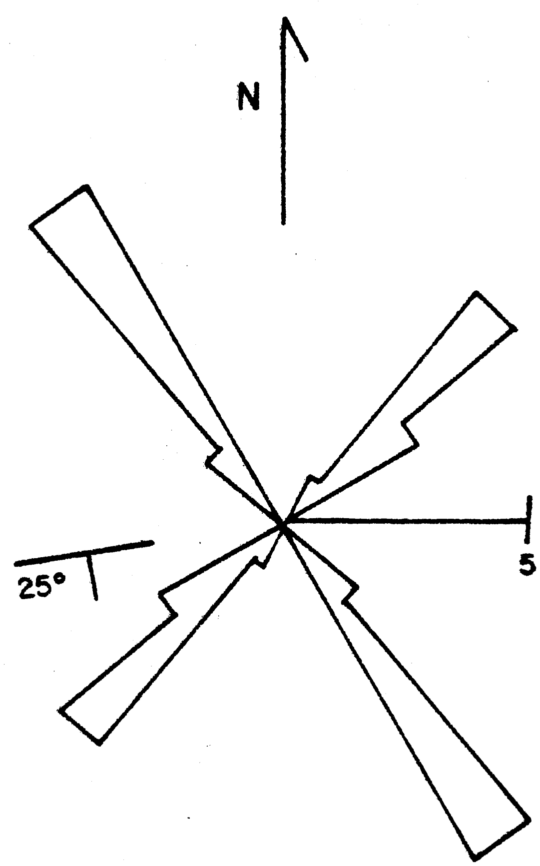


Figure 16. Rose Diagram of the Fracture Orientations for the Fitzgerald Ranch Surface Locality

18 in T2S - R3E (Dougherty 7.5-minute quadrangle) (Figure 14). According to the natives of the area, at some time in the past, lightning or some other source of fire ignited petroleum seeping from the side of the mountain; hence the name. This location is on the gently dipping (20° SW) southwest limb of an anticline with a strike-slip fault located approximately one mile south of the location. The Burning Mountain offers an excellent exposure of the upper part of the Woodford Formation because of the gentle dip and because of its dissection by a running stream.

This location was divided into three stations, 2a, 2b and 2c, from the bottom to the top of the Woodford Formation, respectively. The lowest station, 2a, has a shale-to-chert ratio of 1.87:1; it strikes N76W and dips 20° SW. The middle station, 2b, has a shale-to-chert ratio of 2.27:1 with a strike of N73W and a dip of 20° SW. The upper section, 2c, has a shale-to-chert ratio of .766:1, strikes N70W and dips 18° SW. Data for Burning Mountain can be seen in the Appendix.

The plot of thickness versus fracture density for Burning Mountain reveals no noticeable trends for the data as a whole (Figure 17). The points are scattered over the graph with no recognizable pattern. From the rose diagram of the fracture orientations a greatest principal stress in a N65E direction could possibly be inferred (Figure 18).

The rocks in this location are well exposed and excellent data can be collected. Before the summer months, when the algae were not as prolific, some measurements of the fracture densities were taken on partially submerged units where the fractures had been cleaned by running water.

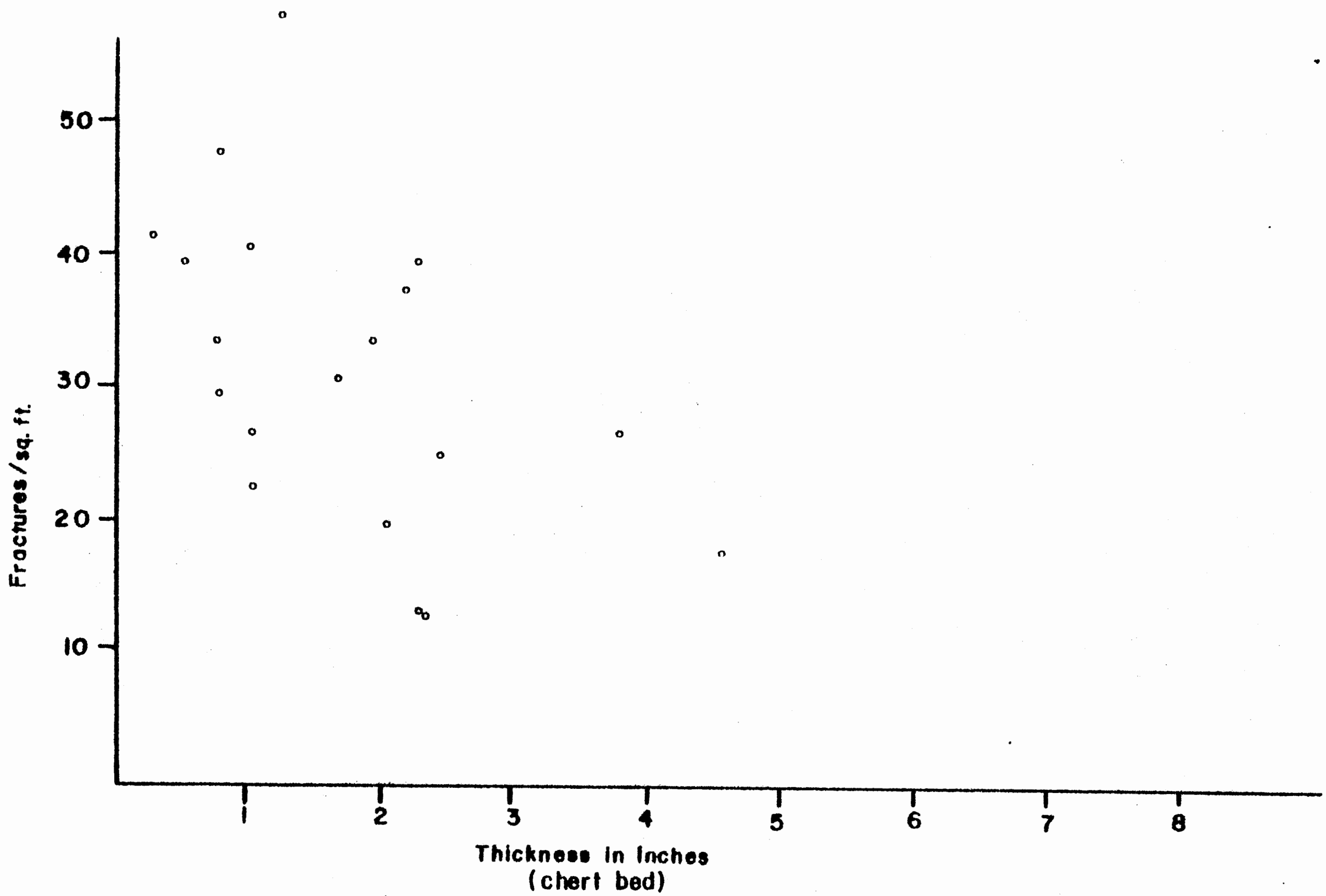


Figure 17. Density-Thickness Plot for the Burning Mountain Exposure

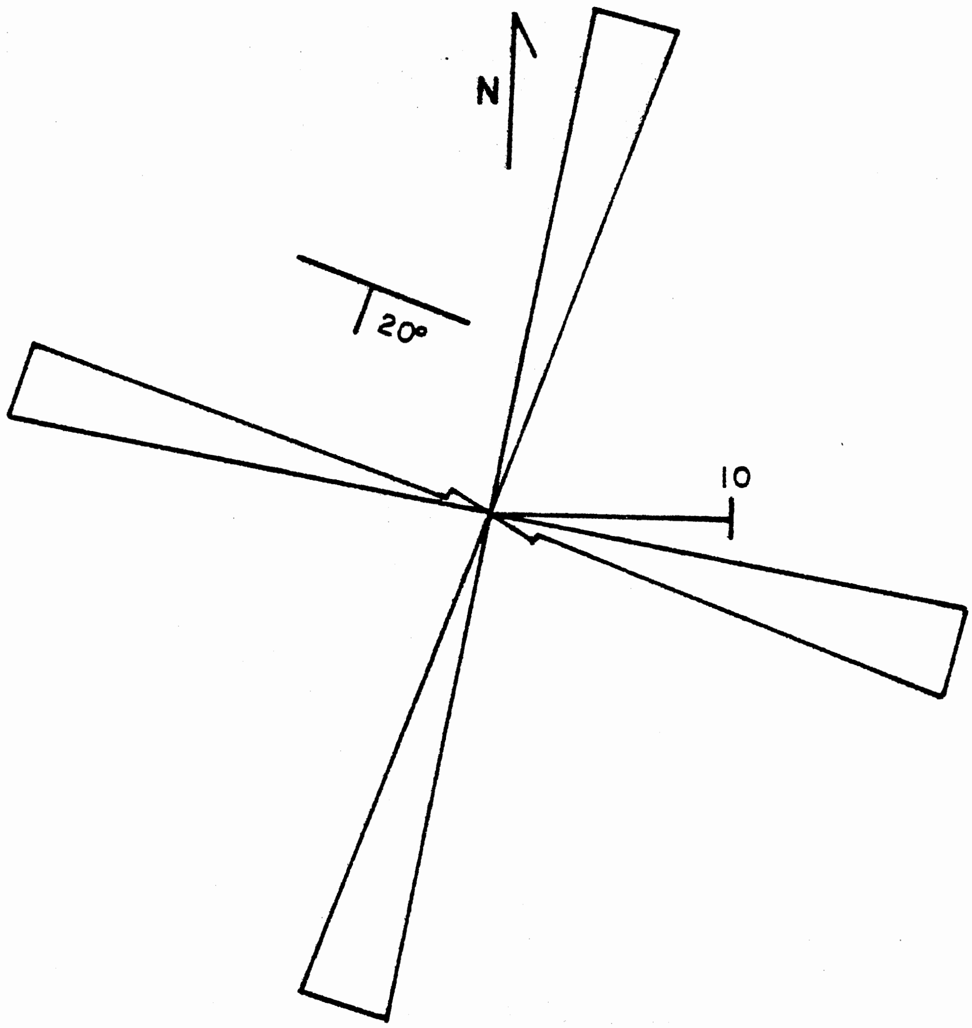


Figure 18. Rose Diagram of the Fracture Orientations for the Burning Mountain Surface Locality

Interstate 35 (South Flank) and Highway 77

An excellent outcrop of the Woodford Formation occurs in the SE/4 of the NW/4 of the SE/4 (Interstate 35) and in the NW/4 of the SE/4 of the SE/4 (Highway 77) of section 25 in T2S - R1E (Springer 7.5-minute quadrangle) (Figure 14). Because these outcrops are very near each other they will be considered together and their data can be seen in the Appendix. At Interstate 35 (south flank) the beds strike approximately N50W and dip approximately 65° SW. At Highway 77 the strike is N75W and the dip is 43° SW.

These two localities, like that on the Fitzgerald Ranch, are located on the south flank of the major Arbuckle anticline. There are no major faults in the immediate vicinity, but at Highway 77 the measurements were taken next to a small fold. The crest of this fold had intense fracture development. This type of shattering might be expected where the fold becomes very tight.

Stratigraphically, the upper 100 feet of the Woodford, including its contact with the Sycamore, and the lower 10 feet including its contact with the Hunton Group are exposed at the location on Interstate 35 (south flank). At Highway 77, the section exposed is toward the top of the Woodford. The one section measured at Highway 77 had a shale-to-chert ratio of .41:1. This was the lowest amount of shale found at any locality: the fracture densities were very low (it must be noted that the fracture densities might have been lower had they not been measured so near a local fold). The first section measured on Interstate 35 (south flank), 6a, also showed a very low shale-to-chert ratio of .42:1. Stations 6b and 6c had shale-to-chert ratios of .91:1 and 1.37:1, respectively.

The graph of bed thickness versus fracture density for Interstate 35 (south flank) and Highway 77 is in Figure 19. Interpretation of this graph is extremely difficult because there does not appear to be a simple linear relationship between the variables. Obviously, if the data are valid, there must be another factor which accounts for the fracture density variations. The rose diagram of the fracture orientations indicates a greatest principal stress orientation in a N85E direction, which again correlate very well with the wrench-tectonic interpretation of the region (Figure 20).

Although the upper section is typically well exposed here, the lower section, which is predominantly shale, forms slopes and is covered by soils. The bottom ten feet of the Woodford Formation exposed here contain very few chert beds; because of difficulty in measuring any fracture densities, this section was not studied in detail.

Interstate 35 (North Flank)

This outcrop is on Interstate 35 on the north side of the Arbuckle Mountains in the SW/4 of the NE/4 of the NE/4 in section 30 of T1S - 62E (Turner Falls 7.5-minute quadrangle) (Figure 14). The beds in this location are overturned and exposed in such a manner as to make measurement of thicknesses of individual units very difficult. The data for this location can be seen in the Appendix. Although the manner in which the beds outcrop allows very easy measurement of fracture densities, because of the difficulty of measuring a four foot-section, only one zone of four feet was studied. If, as seems likely, the shale-to-chert ratio plays an important role in fracturing, randomly measuring fracture densities would not be useful. The strike at this station is N62W and dip

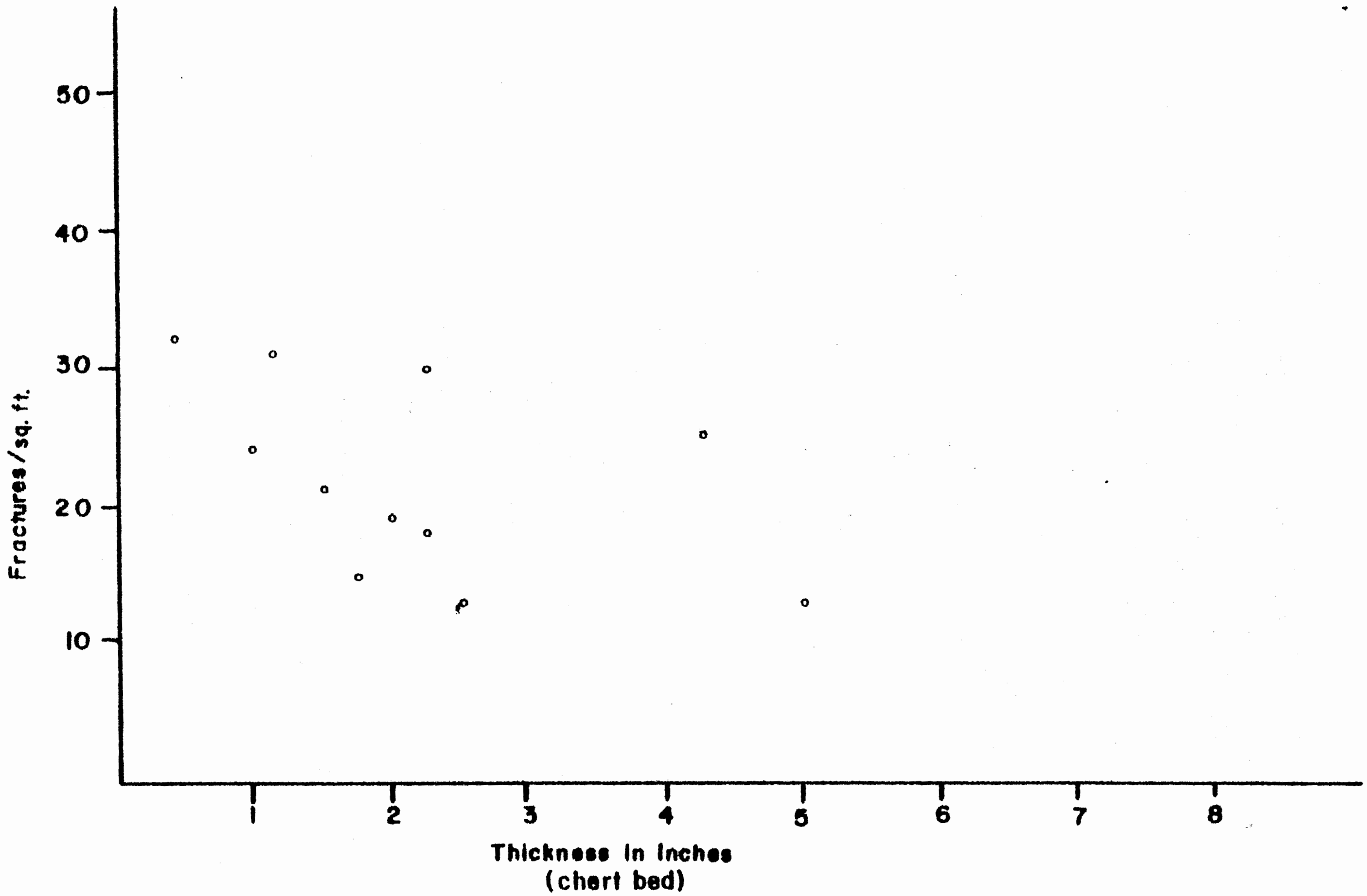


Figure 19. Density-Thickness Plot for the Highway 77 and Interstate 35 (South Flank) Exposures

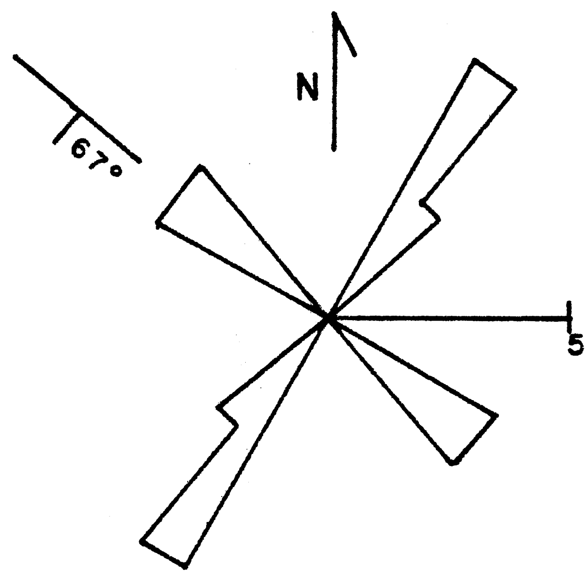


Figure 20. Rose Diagram of the Fracture Orientations for the Interstate 35 South Flank and Highway 77 Surface Localities

is overturned to 73° SW.

Structurally, this station is on the north-dipping flank of the major Arbuckle anticline. The beds are overturned and it is a possibility that the fracture density measurements could be anamolously high because of the higher degree of rotation.

Stratigraphically, the section measured at this location was again in the upper Woodford Formation, but was closer to the bottom of the upper section than other localities. The shale-to-chert ratio at this location was 2.64:1. The graph of bed thickness versus fracture densities for this station is a straight line, which would be expected since only one section with one shale-to-chert ratio was measured (Figure 21). The rose diagram for the location again points to a greatest principal stress at a N75E orientation (Figure 22).

Camp Classen

This outcrop was on the Classen Creek east of Lake Classen in the NE/4 of the NW/4 of the NE/4 of section 24 in T1S - R1E (Turner Falls 7.5-minute quadrangle) (Figure 14). This exposure of the Woodford Formation was very poor, but it is important because it is in the lower section of the formation. The data for this location can be seen in the Appendix. The shale-to-chert ratio at this station is 3.02:1. The strike of the beds is N28W and the dip is vertical.

Only two densities were measured at this station; hence any attempt to determine the greatest principal stress orientation or to plot fracture densities would be useless. However, the data can be used in the overall interpretation of the fracturing in the Woodford Formation.

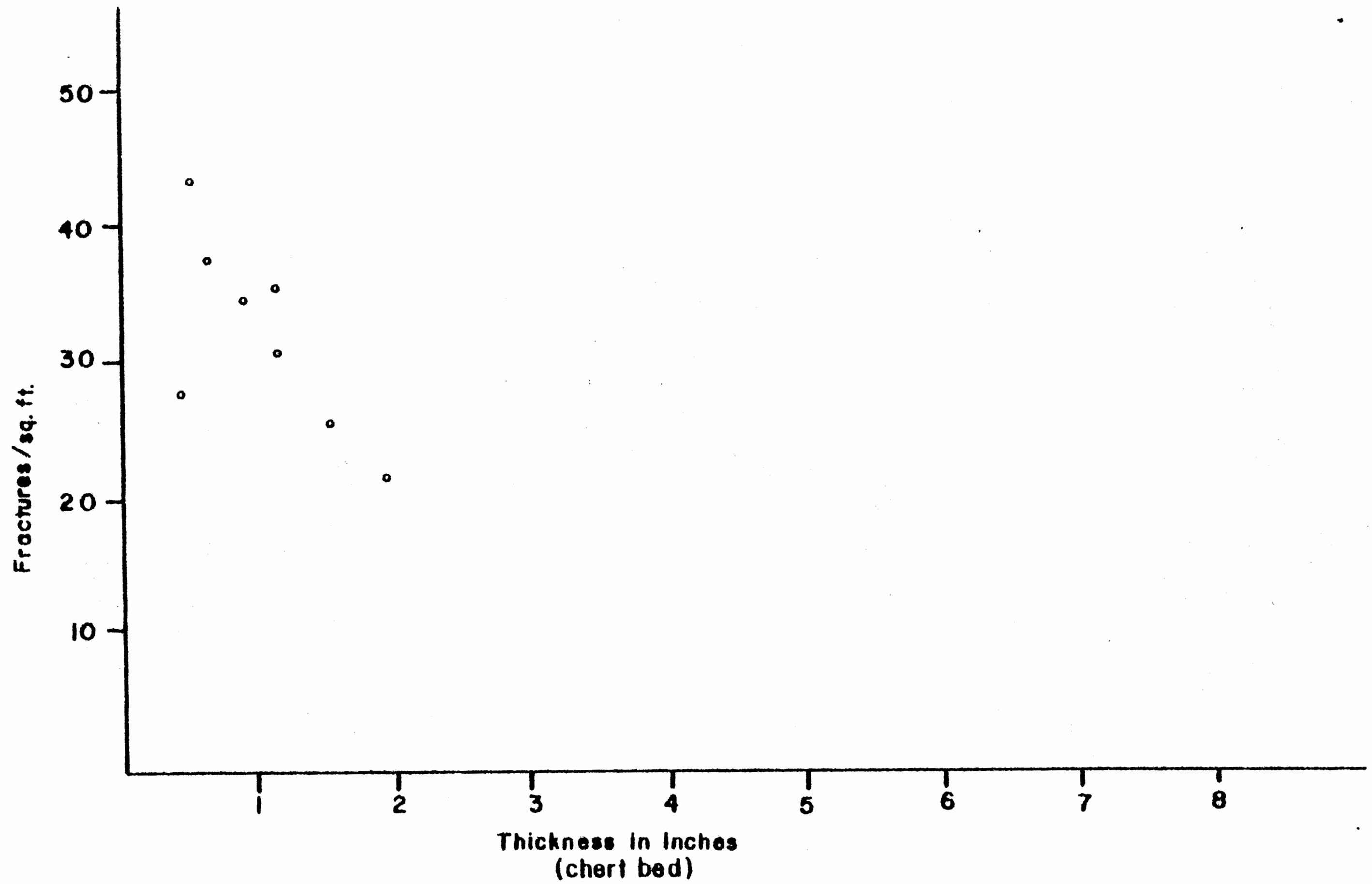


Figure 21. Density-Thickness Plot for the Interstate 35
(North Flank) Exposure

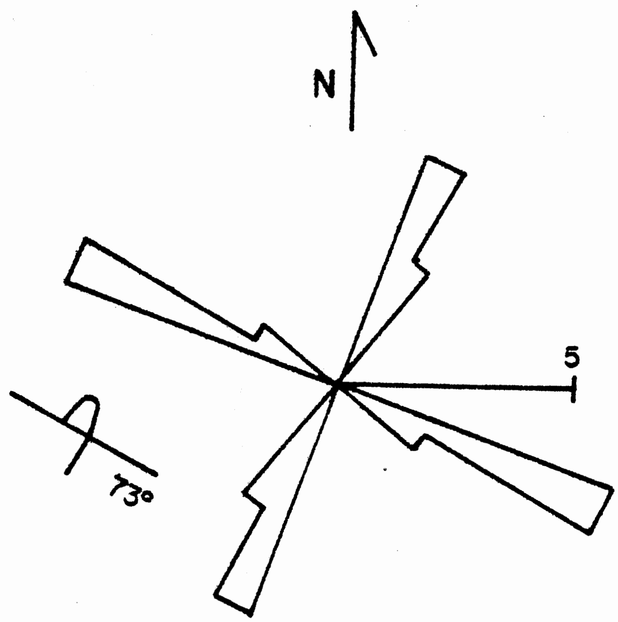


Figure 22. Rose Diagram of Fracture Orientations for the Interstate 35 North Flank Surface Locality

Interpretation of Fracture Orientations

All of the data collected in the field are very much alike in orientation of fractures. At the Fitzgerald Ranch and Camp Classen localities the fractures were not oriented parallel to the strike or dip. These fracture orientations were stereographically rotated to remove influence of dip. After rotation they were plotted on an rose diagram. All of the fractures fall within a 40° orientation range (Figure 23). This is quite consistent considering the range in the strike and dip from location to location.

With the data in hand, a possible cause of the fracturing can be hypothesized. Many ideas have been put forth to explain joint patterns. In 1933, Kendall and Briggs postulated that joints were related to alternating torsional stresses due to semi-diurnal tidal action caused by the gravitational attraction of the moon (Price, 1966). Another concept explains jointing by unloading during uplift and erosion. Another theory claims that the joints are caused directly by tectonics.

Kendall and Briggs believed that tidal action would cause minor, rhythmic movement of underlying recently consolidated material. They postulated that overlying unconsolidated material would eventually fail due to energy propogated up through pre-existing fractures in the underlying newly consolidated material (Price, 1966). However, Price (1966) does not believe that these joints would survive burial, but would heal with increasing overburden. Furthermore, if tidal action were the cause of fracturing in the study ares, the shales should exhibit jointing. This is not the case in southern Oklahoma in the Woodford Formation.

Joints occur in areas where no tectonic deformation had taken place. Price (1966) dealt with this matter and concluded that these

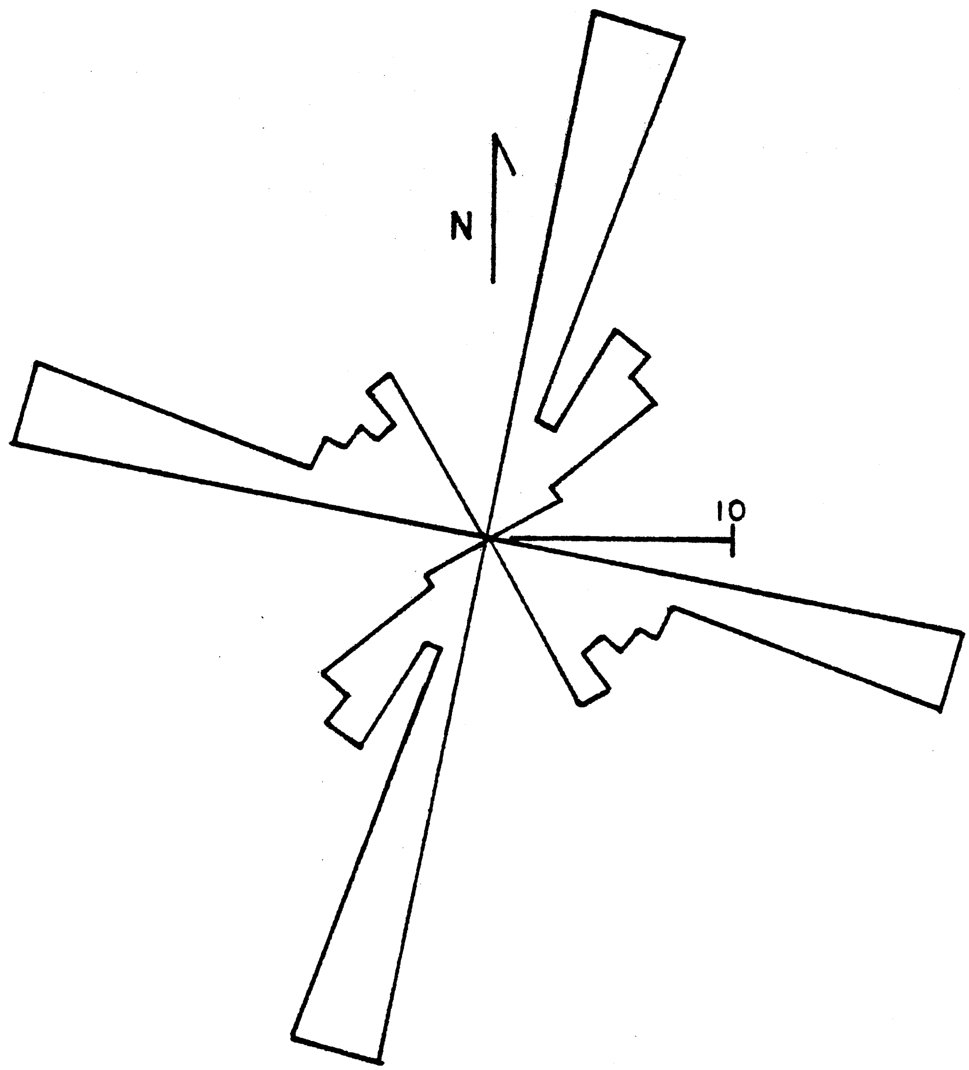


Figure 23. Rose Diagram of the Fracture Orientations for All Data Collected at the Surface

joints must be the direct result of unloading. He believes this is because the initial stresses only approximated the hydrostatic state. The greatest principal stress is oriented vertically. If so, one horizontal stress will be the minimum stress, and a tensional joint will develop normal to this direction (Price, 1966). After this stress is relieved (by rupture) the intermediate stress direction (also in the horizontal plane) becomes the minimum stress and another tensional joint will result, thus forming the two perpendicular joint sets commonly observed in flat-lying rocks (Price, 1966).

These two causes of jointing are not directly related to tectonics, but two very important possible causes of jointing are. The first is not formed until sometime after the folding and faulting stages. Residual tectonic stresses are stored in the rocks after folding and faulting is complete (Price, 1966). Again, unloading begins the process of jointing. The first step is for the least principal stress to increase and become the intermediate principal stress and the intermediate principal stress to become the least principal stress (due to the removal of overburden) (Price, 1966). The greatest principal stress is horizontal and the intermediate principal stress is vertical (Price, 1966). At this point a shear joint set will develop. This development would reduce the greatest principal stress to the point where the vertical stress could become the greatest principal stress (Price, 1966). If the vertical becomes the greatest principal stress, tensional joints will develop as previously outlined (Price, 1966).

The most satisfactory explanations for tensional joints are those involving residual stresses: in the first case burial or confining stress; in the second, tectonic stresses. In the discussion of Mohr circles and envelopes it was shown that true tension is restricted to relatively shallow depths. If this is the case, then joints formed at great depth could not be purely tensional. However, joints at depth could be generated by compression and therefore should be termed shear joints. These shear joints should show some preferred orientation to the greatest principal stress direction responsible for the faulting and folding observed in the study area. In the truest sense these shear joints may not be joints at all, but may be strike-slip faults with microscopic offset.

This author hypothesizes that the fractures seen in the study area are most likely related to compression and therefore are shear joints. Price (1966) states that:

> Shear joints are usually markedly planar fractures which are not affected by local changes in lithology. For example, they tend to cut across pebbles in conglomerates, mud pellets, etc., without change of direction of the joint plane. Tension joints in some areas are more irregular surfaces which tend to be deflected by, and follow the outline of, the type of minor variation in lithology noted above (p. 121).

In the Woodford Formation of southern Oklahoma, many of the fractures cut directly through the phosphate nodules that occur in some chert beds. Also, this area has been highly tectonized; any hypothesis for the origin of fractures unrelated to tectonics seems unlikely. Therefore, the two principal hypothesis for the origin of the joints would be: (1) joints caused by the release of principal stresses due to the stripping of overburden as outlined above, where the stresses are derived from stored tectonic energy, and (2) compressional shear joints caused directly by tectonics. The joints resulting from the release of overburden and interchanging of greatest, intermediate and least principal stresses would be oriented in relation to the original stresses. If, for instance, the stresses were stored in a fold, the greatest principal stress would be approximately perpendicular to the axis of the fold. Therefore, the resulting shear joints should be oriented about the greatest principal stress as Moody and Hill predicted for the primary left-slip and secondary right slip (Figure 9). The joints should then change orientation from location to location with a changing stored principal stress.

However, the fracture orientations are quite constant throughout the study area between localities. This can be seen by superimposing rose diagrams of fracture orientations (Figure 23). The fractures become more closely aligned even after the effects of folding are removed by stereographic rotation. This suggests that the fractures formed independently of the folds and that they may predate the folding. This may indicate that the fractures are not due to local variations in stress orientations, but may be related directly to the greatest principal stress direction that formed the strike-slip faults. If this is true then the fractures may have formed very early in the tectonic history (possibly simultaneously with the strike-slips faults) and not after folding and subsequent unloading of sediment.

Interpretation of Densities, Thicknesses and Ratios

It is known that the thickness of a unit has a direct effect on the degree to which a unit will fracture (Price, 1966) and (McQuilan, 1973). Investigation of the data shows that this applies to the Woodford. This is seen in the data collected at Interstate 35 (north flank) (Figure 21). However, the ratio of incompetent (shale) beds to competent (chert) beds is another possible controlling variable.

As seen in Figure 24, there is a wide scatter of data on the graph with no recognizable pattern present. This was also seen at specific localities (for example, Fitzgerald Ranch, Figure 15). If thickness were the main variable, each locality should show a straight line or simple curve. Since this is not the case, the effects of the varying shale-to-chert ratios will be examined.

Shale-to-Chert Ratio of 0:1 to .5:1

Figure 25 is the graph for the shale-to-chert ratio between 0:1 to .5:1. It shows a linear relationship between thickness and fracture density. However, with only four points on the graph this may not be significant. It could be said that if this line is representative of the relationship of thickness to fracturing for this particular range, then it would have a slope of .76 $\left(\frac{\text{frac. per sq. ft.}}{\text{bed thickness}}\right)$. There are two reasons why there are only four data points here: (1) this range of shale-to-chert ratio is seldom encountered in the Woodford Formation and (2) when encountered the chert generally protects the shale from eroding. Hence, the outcrop will generally have a sheer face which does not facilitate measurements of fracture densities.

Shale-to-Chert Ratio of .6:1 to 1:1

In Figure 26, the graph of thickness versus fracture density for the shale-to-chert ratio in the range of .6:1 to 1:1, a straight line best fits the data. This line has an approximate slope of .58 $\left(\frac{\text{frac. per sq. ft.}}{\text{bed thickness}}\right)$. The point plotted at 8 7/8 inches indicates a possible flattening of the curve with greatly increased bed thickness.

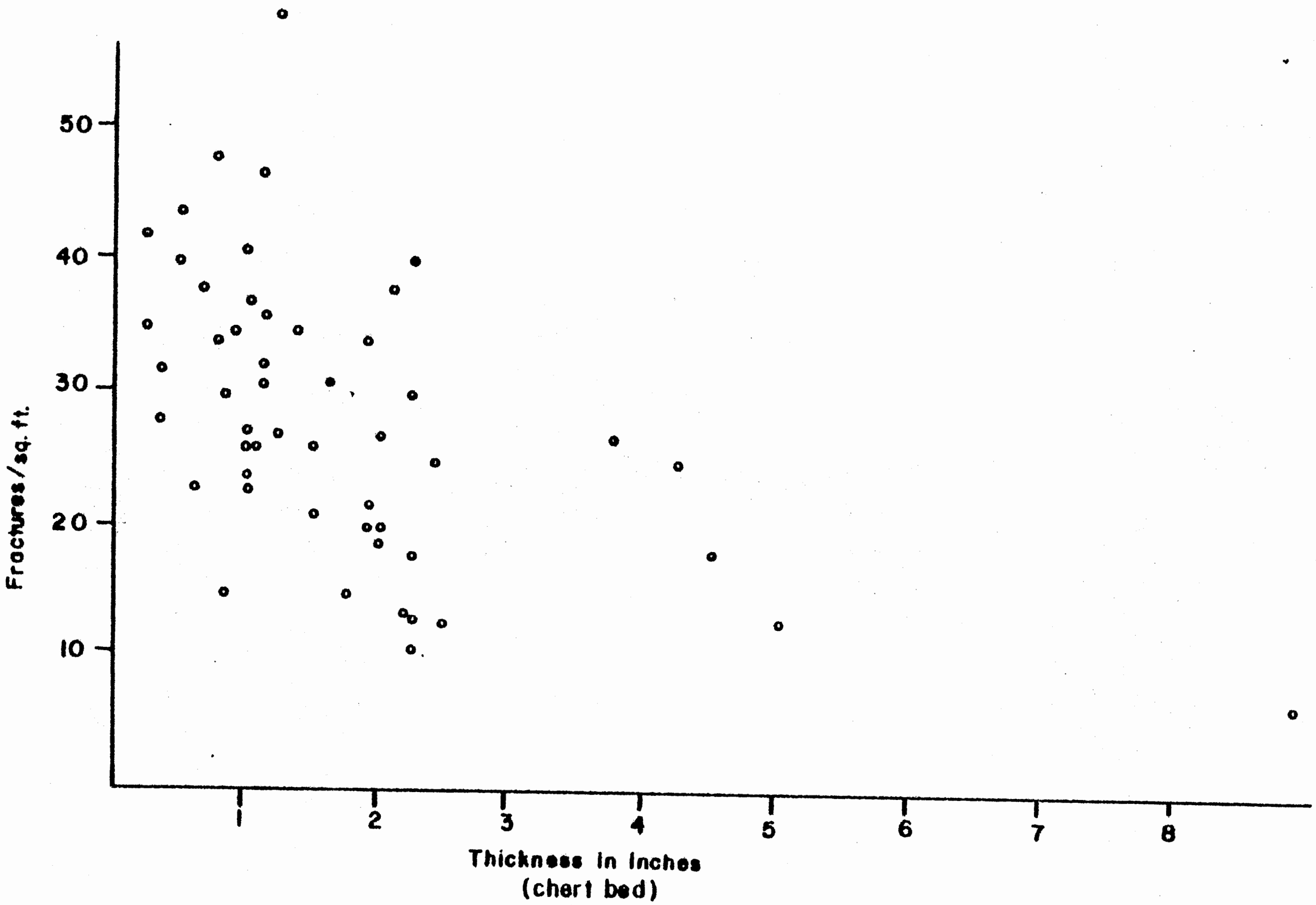


Figure 24. Density-Thickness Plot for All Surface Data

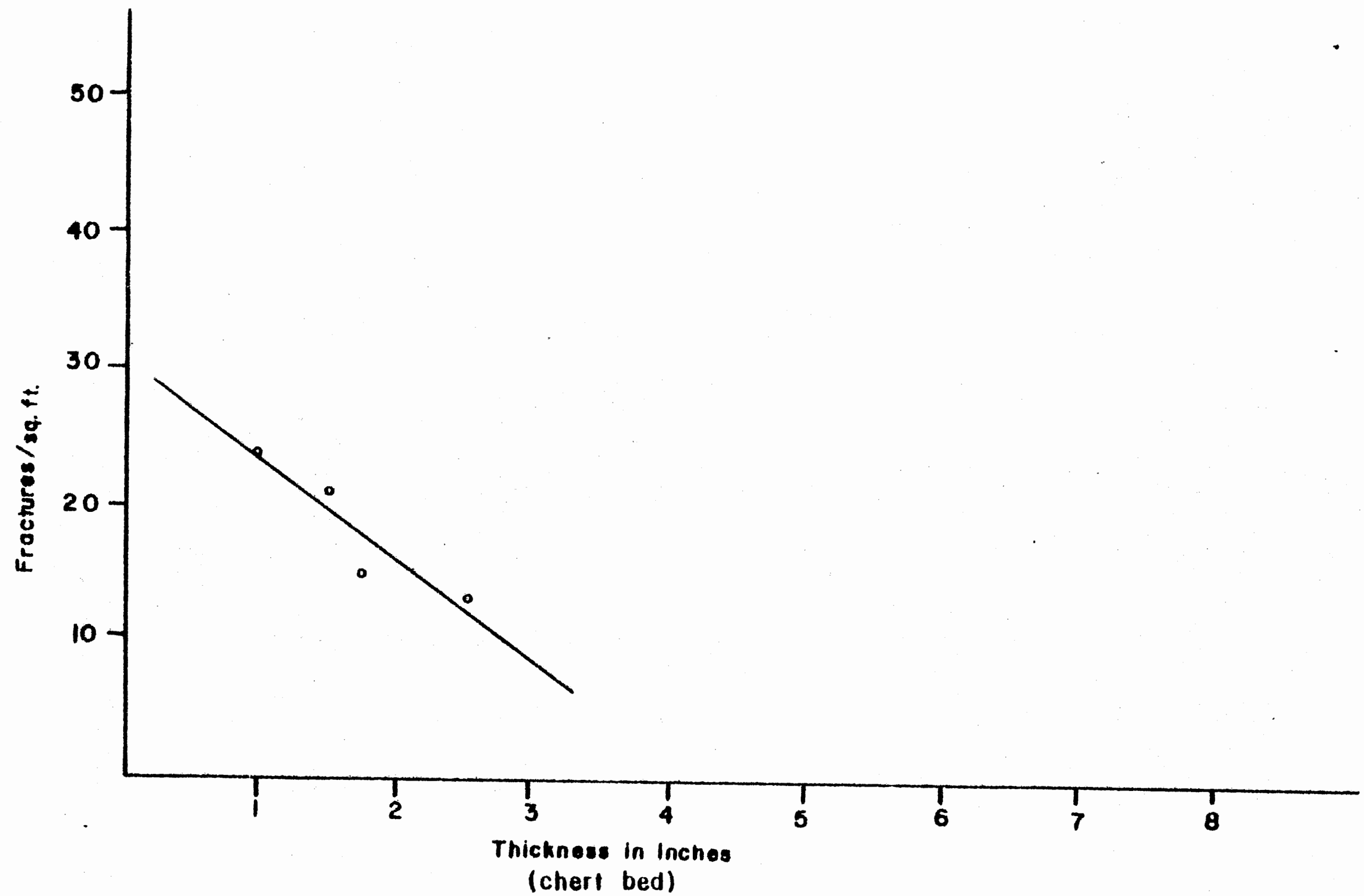


Figure 25. Density-Thickness Plot for Beds in a Zone
With a 0:1 to .5:1 Ratio Range

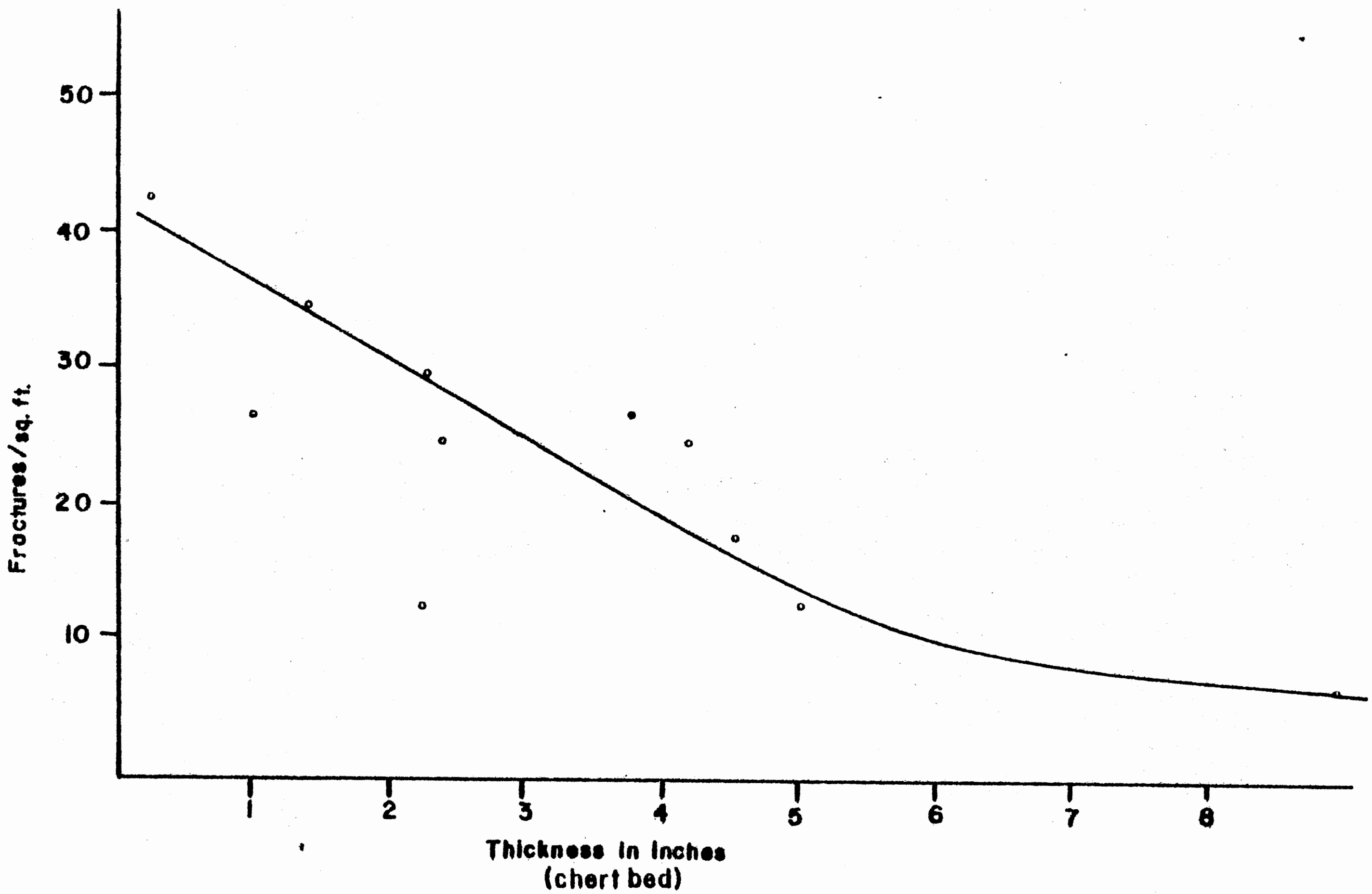


Figure 26. Density-Thickness Plot for Beds in a Zone
With a .6:1 to 1:1 Ratio Range

Because beds over five inches are very uncommon, no more data could be obtained that would prove or disprove this flattening. However, the possible flattening of the curve is expected because a bed several feet thick would still contain fractures and not be totally unfractured as a straight line would predict.

Shale-to-Chert Ratio of 1:01:1 to 2:1

The third range of ratios, from 1.01:1 to 2:1 shows a curve similar to the previous one (Figure 27). However, the slope of the top half of the curve is approximately 4.3 $\left(\frac{\text{frac. per sq. ft.}}{\text{bed thickness}}\right)$. This steep slope indicates that for beds in the shale-to-chert ratio range of 1.01:1 to 2:1 the fracturing of thin beds will be intense.

Shale-to-Chert Ratio of 2.01:1 and Up

In the final range of shale-to-chert ratios, 2.01:1 and up, the graph shows a broad scattering of points (Figure 28). The line drawn in Figure 28 is a possible interpretation of the data. If this line is representative for this shale-to-chert ratio range, then its slope for the upper half of the curve would be approximately 3.9 $\left(\frac{\text{frac. per sq. ft.}}{\text{bed thickness}}\right)$.

Conclusions

The most important conclusion to be drawn is that there is probably a relationship between density of fracturing and the shale-to-chert ratio. The zones that contained increased amounts of shale showed higher fracture densities at a given bed thicknes than those that were predominantly chert. This point is evidenced by very steep slopes for the ranges of 1.01:1 to 2:1 and 2.01:1 and up, which were 4.3 and 3.9,

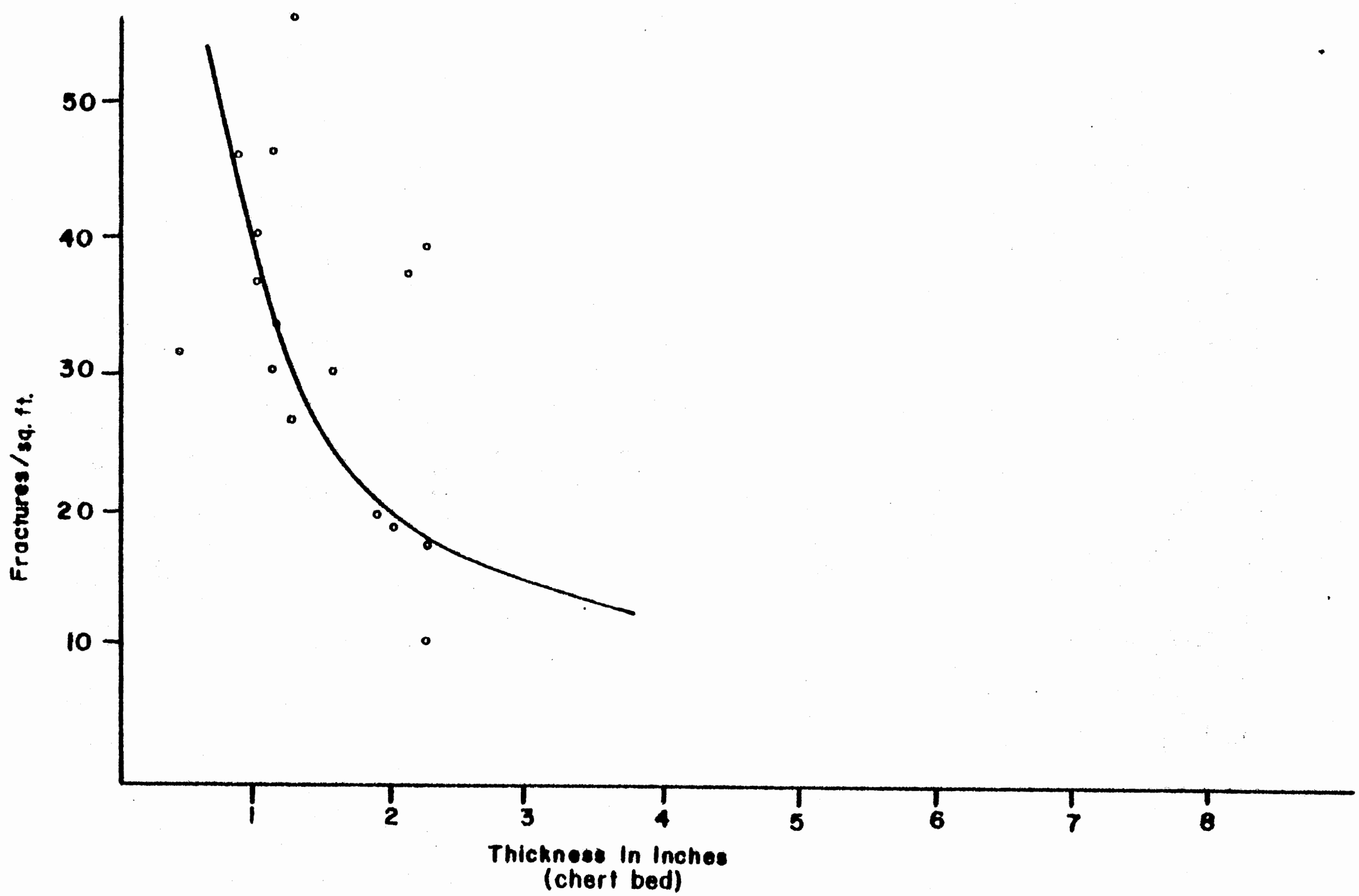


Figure 27. Density-Thickness Plot for Beds in a Zone
With a 1.01:1 to 2:1 Ratio Range

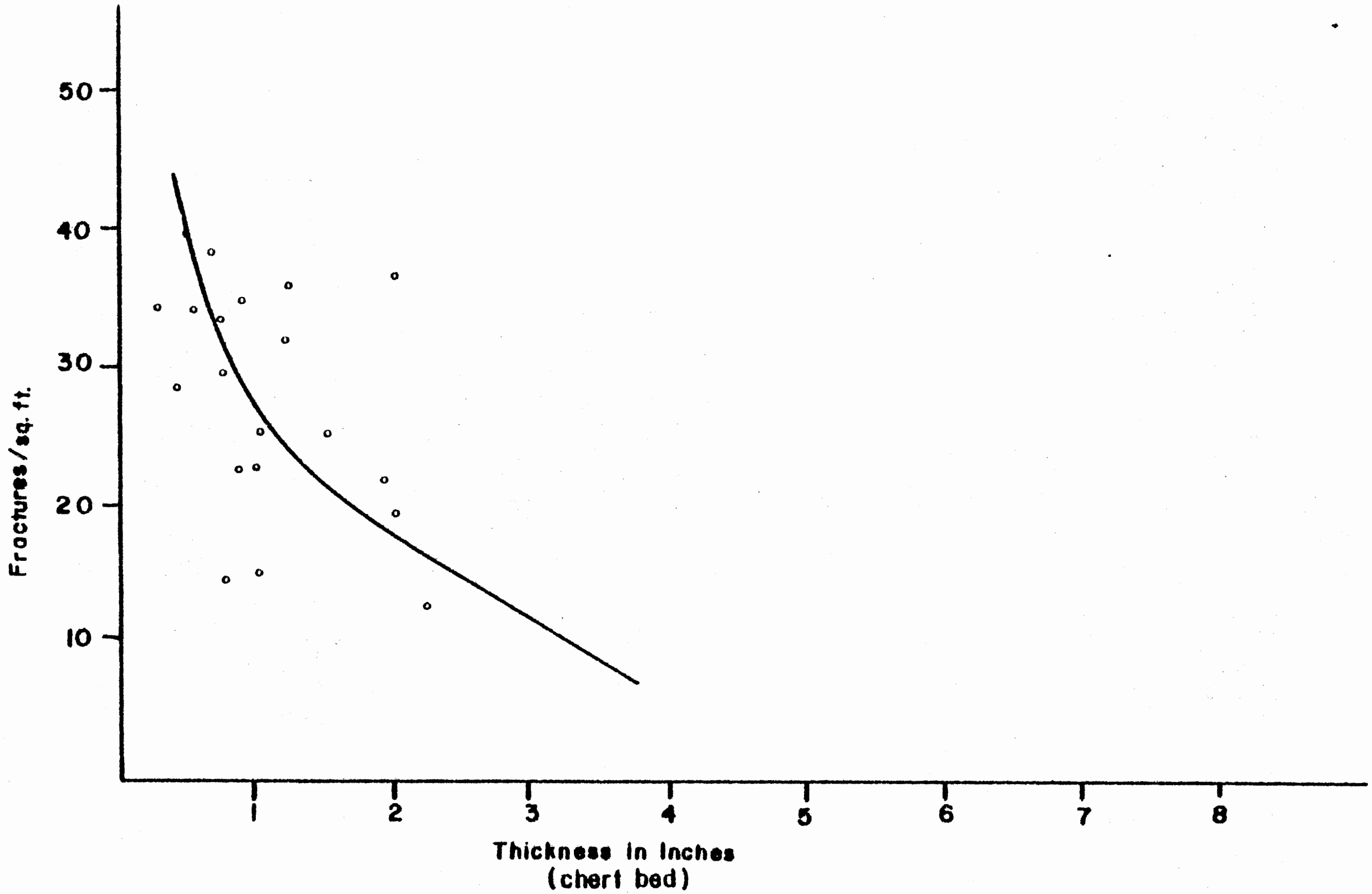


Figure 28. Density-Thickness Plot for Beds in a Zone With a 2.01 and Up Ratio Range

respectively. These steep slopes indicate a rapid increase in fracture density with only a minor decrease in the thickness of a unit. This relationship could be quite significant, because in the Woodford Formation; most of the chert beds are less than one inch thick. Also, the laminated zone toward the base of the Woodford Formation has a relatively high shale-to-chert ratio with many thin beds of chert. This zone, which has yet to be exploited for hydrocarbons, could be extensively fractured and may be the best zone for production within the Woodford Formation.

CHAPTER VII

FIELD PRODUCING FROM FRACTURED CHERTS

Fields Producing from the Woodford Formation

This chapter reviews the fields that produce hydrocarbons from the Woodford. Because of its lack of primary porosity and permeability, the Woodford must be fractured to produce petroleum. Cores and well logs were examined to determine the intensity of fracturing. In most fields in which the Woodford Fromation has produced it has been only a secondary zone of interest. Also, several years ago when coring was more common than today, the Woodford was believed too dense to produce hydrocarbons. For these two reasons very few cores have ever been taken from the Woodford Formation.

In the Northeast Alden Field, where several cores of the Woodford do exist, actual permeability and porosity measurements were performed on the core. From these studies it was determined that logging methods did not give a true value of porosity. Therefore, very little quantitative data can be obtained from logs or from cores. Close attention must then be paid to the structural situation and to the lithologies that exist in each area where the Woodford is productive.

Northeast Alden Field

The Northeast Alden Field has the best available information for an investigation of the potential of the Woodford Formation as a petroleum reservoir. The entire Northeast Alden Field has production from the Woodford, but the principal study area is sections 35 and 36 of T7N - R13W and section 1 of T6N - R13W. The Westheimer-Neustadt Corporation originally drilled the #1 Hall in the SW/4 of the SE/4 of section 36 in T7N - R13W in March of 1967, but because of the structural position and low-gravity oil encountered, the well was abandoned. Jones and Pellow became the operator on a farmout from Westheimer-Neustadt and after successfully offsetting the #1 Hall, re-entered the old hole. The drill bit left the old hole, drifted up-dip, and penetrated the Woodford at a position approximately 300 feet higher structurally than in the original hole. This well initially produced 215 barrels of oil per day (BOPD). The north half of the field has been extensively investigated with several cores taken, a combustion tube test run and in-depth production reports kept. Probably the most advantageous aspect of this field is that the Woodford Formation is the only zone that produces. This results in excellent information being available for this study.

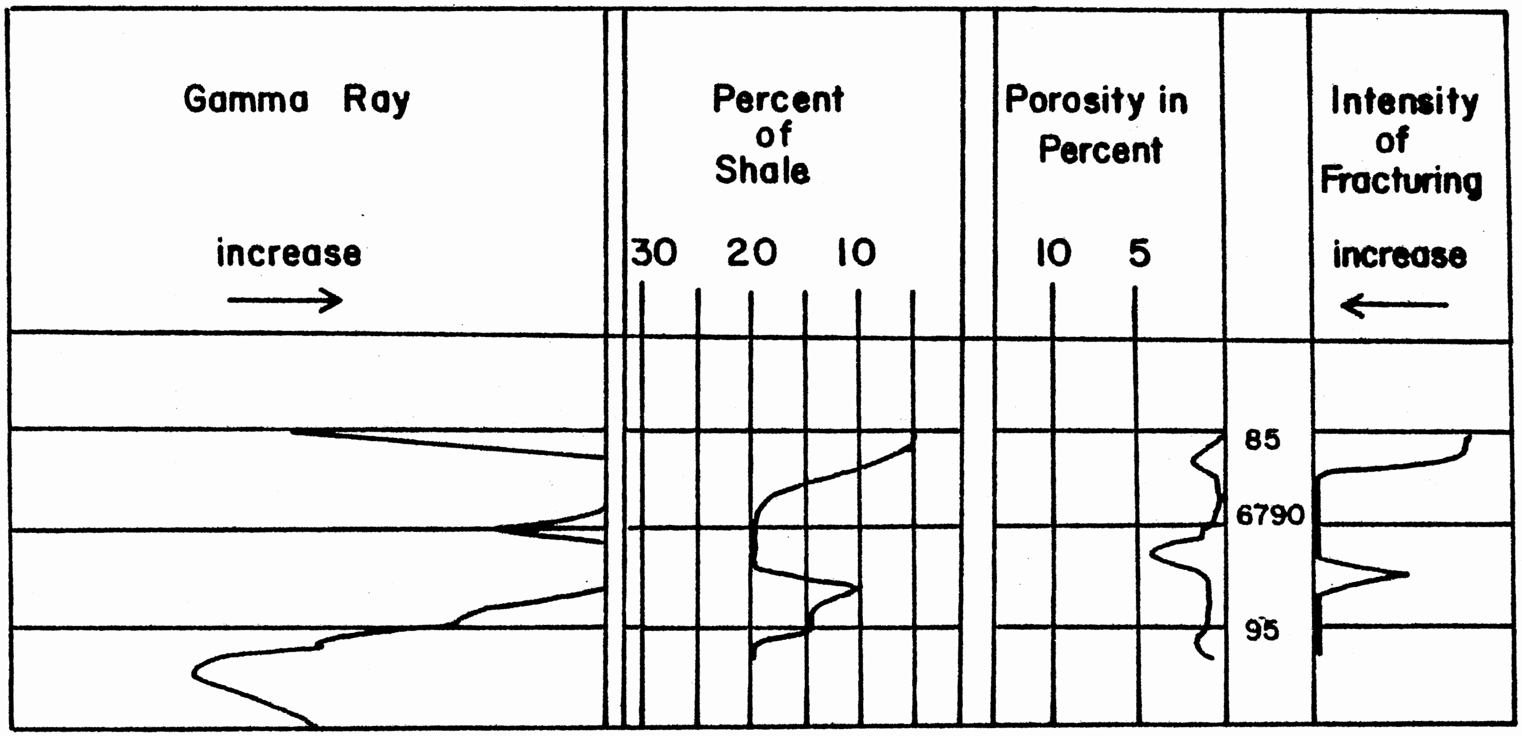
The basic structure present at the Northeast Alden Field is doubly-plunging anticline with a northwest trending axis (Plate 2). The Mountain View Fault, a major left-lateral fault, bounds the field to the north. To the south of the field is another left-lateral fault of lesser magnitude. To the east of the field is a thrust fault which is probably associated with the folding. These features can be seen on the structural contour map, contoured on top of the Woodford Formation (Plate 2). The Mountain View Fault is believed to be a primary left-slip fault (Figure 9). The fault which bounds the field to the south and the fault which intersects the Mountain View Fault at an acute angle in the SE/4 of the NW/4 of section 36 T7N - R13W are probably second-order left-slip faults. The faults alone do not form the trap as the beds are folded into a sharp anticline. From a wrench-tectonic interpretation this fold is most likely a direct result of the strike-slip faulting (Figure 9). As seen in both cross sections, the east side of the fold is steeper with a maximum change in elevation of 800 feet over a distance of only 725 feet horizontally (Plates 3 and 4). The west side of the fold has relief of 1100 feet over a horizontal distance of 1914 feet. The south nose of the fold is more tightly folded than the north nose. There is also a strong possibility that the North Alden fold is an extension of the major fold which includes the Apache fold and the Southwest Richards fold. The Northeast Alden fold has been offset in an left-lateral sense if this is true (Plate 1).

Examination of the type log and well cuttings of the Northeast Alden Field shows that the total thickness of the Woodford Formation in this field is approximately 530 feet (Figure 3). The upper 80 feet of the Woodford is the only zone which has produced at Northeast Alden. As seen on the type log, the upper 80 feet is relatively shale-free on the gamma-ray log with only occasional shale streaks. The next 280 feet of the Woodford is made up of interbedded shales and cherts. Shale is predominant, but in the lower 115 feet of this zone, chert beds are quite abundant as evidenced by the gamma-ray log (Figure 3). This zone is referred to as the laminated zone. The lower 170 feet consists of 95 feet of siliceous cherty shales, followed by 10 feet of emerald-green shale and underlain by 60 feet of chert and dolomite conglomerate. This conglomerate is considered by some geologists to be part of the Woodford. However, it correlates with the Misener Formation to the north, also a detrital zone, which many geologists consider to be part of the Hunton Group. The cherts of the middle and lower zones have not been tested at Northeast Alden.

Three cores were examined in the Northeast Alden Field including the Bromide Unit #1 (Harrison #2), the Hall #2 and the Hall #2-B. All three cores were taken within the upper massive chert of the Woodford Formation. The description of each core, along with permeability and porosity curves, can be seen in Figures 29, 30 and 31. It was hoped that quantitative measurements of the fractures could be made like those in the surface study. This was not done because the cherts are so totally shattered that no measurements of directions or densities of fracturing were possible. Even though no quantitative measurements could be taken, it was evident that where shale was more abundant the cores were more intensely fractured. Conversely, in the #2-B Hall toward the bottom of the cored interval shale is almost totally absent and the chert exhibits almost no fracturing. Large amounts of sulphur are present on the cores and in many places tar has "bled" from fractures in the core. Where fractures are abundant the cherts and shales are black, presumably from hydrocarbons. Where fractures are sparse the cherts are a lighter color. Measurements made on the #2-B Hall core by Core Laboratories, Inc. indicate that the Woodford has a total porosity of approximately 14.4 percent. However, only 9 percent is effective porosity because there is so much immovable oil clogging the pore space. The average permeability for the upper zone of the Woodford in the #2-B Hall is approximately 14 millidarcys.

Again, the Northeast Alden Field is unique in that the Woodford is the only producing zone. This fact allows a performance study to be made to see if it is economical to produce from the Woodford. The

BROMIDE UNIT I c se se sec. 35-T7N-R13W



(Porosity measurements by Core Laboritories, Inc.)

Figure 29. Core Description of the #1 Bromide Unit in the Northeast Alden Field

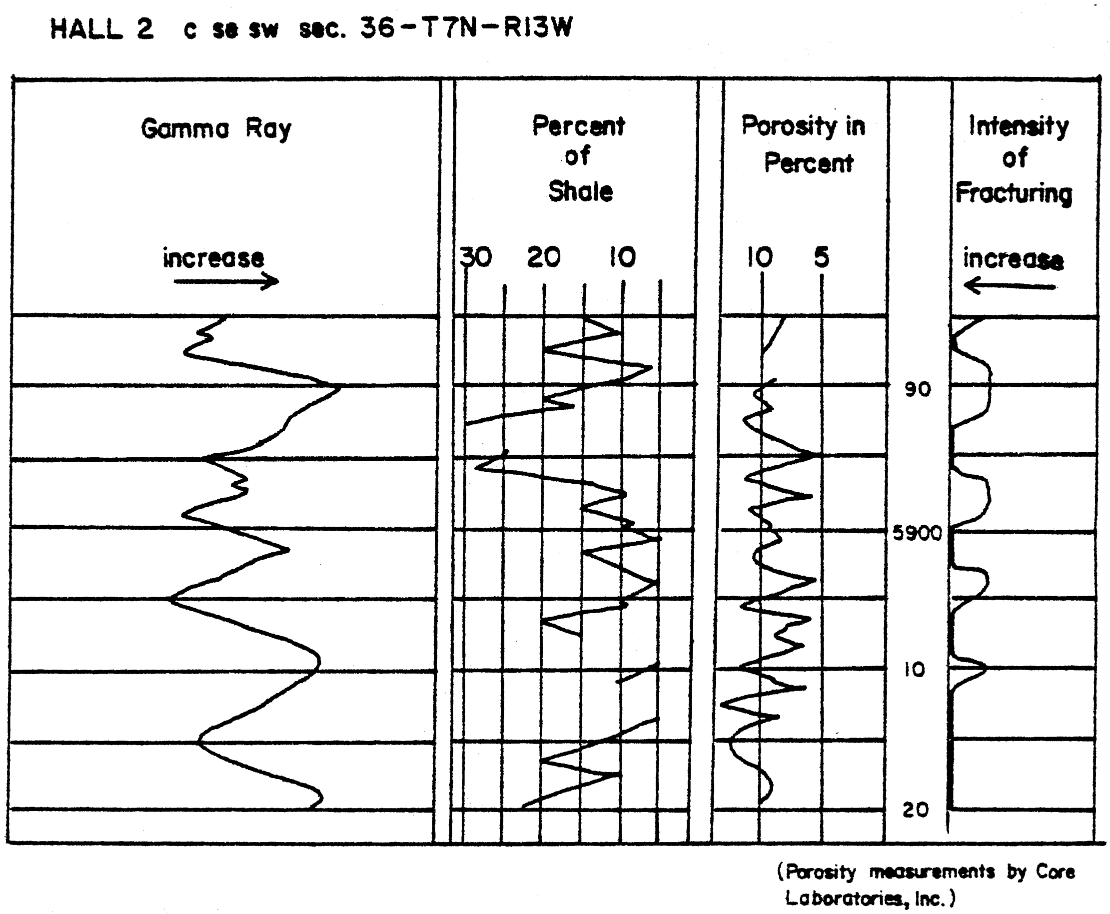


Figure 30. Core Description of the #2 Hall in the Northeast Alden Field

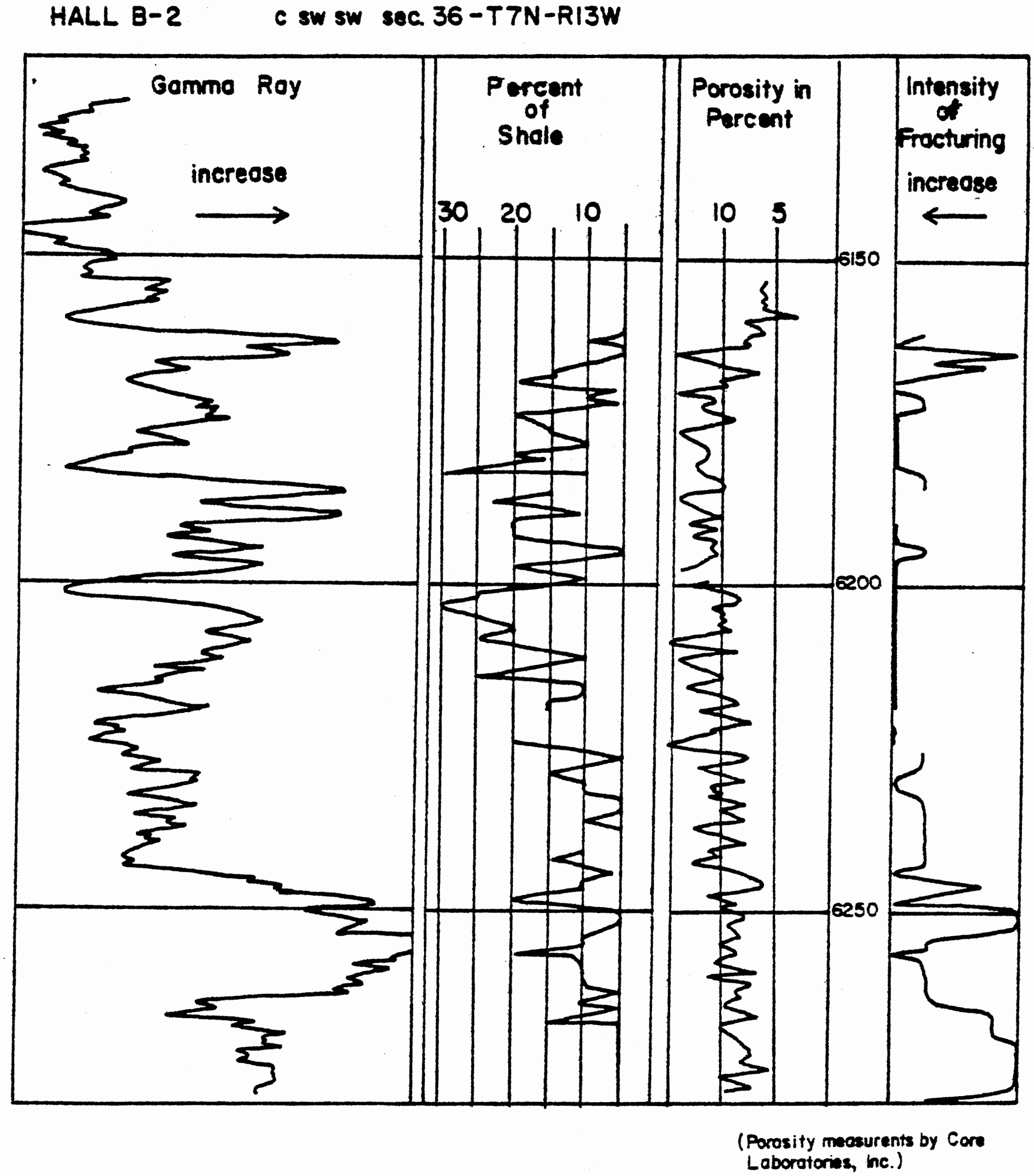


Figure 31. Core Description of the B-#2 Hall in the Northeast Alden Field

initial production of the Woodford Formation in the various wells ranges from 160 BOPD to 215 BOPD with varying amounts of gas. The cumulative production of wells drilled by Jones and Pellow is 991,701 barrels of oil (as of December, 1980). These wells have produced since the late Sixties with average daily production for their lives ranging from 10 BOPD to 45 BOPD. All of these figures are quite high for a formation that has been considered too impermeable to produce.

TOR Developments, Inc. performed combustion tests on several plugs taken from the Woodford cores to determine if in situ retorting would be economical in recovery of immovable hydrocarbons. They determined that the 14 percent porosity was filled by 25.2 percent mobile oil, 57.7 percent residual hydrocarbons and 17.1 percent water. The reported recoverable oil by primary techniques is 281 barrels per acre-foot and 645 barrels per acre-foot of solid non-recoverable hydrocarbons. The report concluded that a retort could be performed in the Woodford if the economics were favorable.

Obviously, from production data, there are abundant recoverable hydrocarbons present in the Woodford Formation. The primary factor involved in production is the amount of fracturing which has taken place to create porosity and permeability. The TOR Developments report stated that immovable hydrocarbons could very well be the only thing holding the core together because the Woodford is so intensely fractured. The intense folding and faulting that occurred in the immediate Northeast Alen area is most likely the direct cause of fracturing, but because of the intensity of fracturing, no conclusions about the orientations of stresses can be made.

Northeast Aylesworth

The Northeast Aylesworth Field was chosen for this study because it offers another look at an area where the Woodford Formation produces. However, the Woodford is by no means the primary producing interval in this area. The primary producing interval is sandstone of the Tulip Creek Formation. Other producing intervals in this field are the "Arbuckle Sand" (Cretaceous), Goddard Sands, Sycamore Formation, Woodford Formation, Hunton Group (where present), Viola Formation and Bromide Sands (Womack, 1955). The first economical well drilled in this field was drilled by Potts (Samedan) in the NE/4 of the NE/4 of the SW/4 of section 13 of T6S - R6E for 100 BOPD from the Bromide Sands. The Aylesworth Field extends further southwest, but because the Woodford produces primarily in the area mapped the rest of the field will be omitted.

The Northeast Aylesworth Field is broken by at least two major strike-slip faults that trend parallel to the axis of the Aylesworth anticline (Plate 5). As can be seen in the seismic line (which is located approximately perpendicular to the fold axis, northeast of the mapped area) (Figure 32) there are two major faults which intersect at depth. This feature has been termed a "flower structure" by some (Thompson, 1981) and a "pop-up feature" by others (Morrison, 1981b). Another feature observable on this seismic line is the obvious thickness changes of Mississippian and post-Mississippian strata across the faults. This may indicate that the faulting is strike-slip in nature (this is one criterion set forth by Harding in 1973). Other evidence described by Carter (1979) and Haas (1981) (previously mentioned in Chapter IV) validates the strike-slip hypothesis. The fact that the

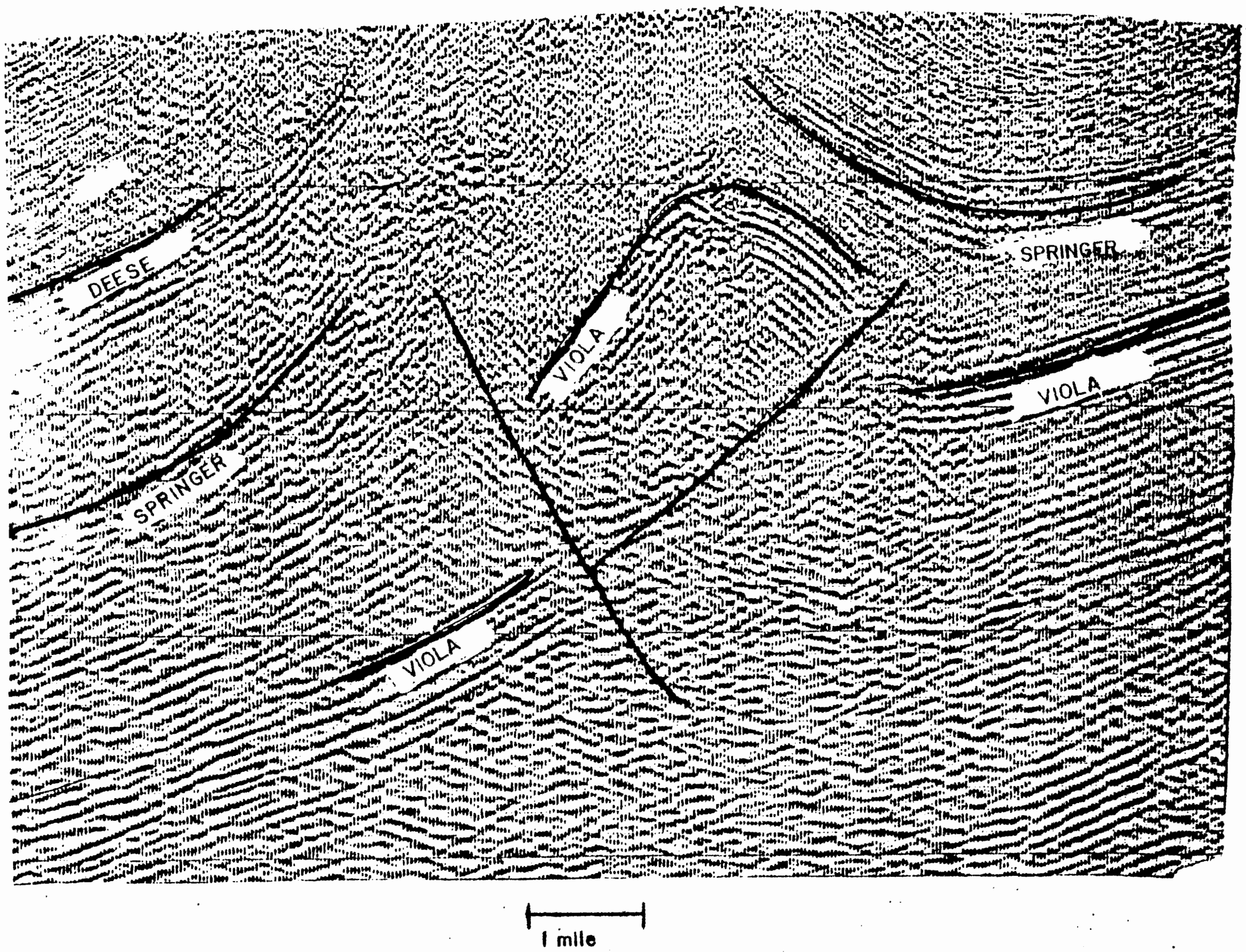


Figure 32. Seismic Profile of the Madill-Aylesworth Anticline

fold axis parallels the strike-slip faults again might possibly indicate that folding began prior to the faulting (caused by a different stress orientation and possible a different deformational period). Other evidence for an earlier tectonic episode is the thinning or total absence of the Hunton Group in the Aylesworth area which may indicate early to late Devonian deformation. However, the parallelism of the fold axis and the faults may also be explained by a compression perpendicular to the faults caused by the dip component of the faults (Harding, 1973).

Like the Northeast Alden anticline, the Northeast Aylesworth anticline is very tight with a change in elevation of 1000 feet with 1155 feet of horizontal change. This field does not have many minor faults as seen in the Northeast Alden Field.

The Woodford Formation in the Northeast Aylesworth Field has a maximum thickness of approximately 380 feet (Figure 4). The Woodford section in this well shows apparent thickening probably because of hole deviation or slight down-dip drilling. It was assumed that each zone was thickened and a multiplier of .86 (normal section/expanded section) was used to convert the thickness to a normal section. The sequence of lithologies is very similar to that at the Northeast Alden Field. The upper 40 feet is again predominantly chert with occasional shale streaks. The next 130 feet is primarily shale, but again has a few interbedded chert layers toward the bottom. The next zone is the laminated chert and shale section of the Woodford; it is approximately 152 feet thick. This zone is followed by 10 feet of emerald-green shale. The bottom 48 feet is made up of chert and dolomite conglomerates which again correlate to the post-Hunton unconformity surface.

Only one well was cored in the Woodford Formation at Northeast

Aylesworth. It was cored in the upper 30 feet of the formation (Figure 33). The upper seven feet of the core showed very few fractures and had relatively few shale beds. Minor faults were abundant in the cherts. The next 21 feet of core were highly fractured with no recognizable patterns of fracture directions. Like the core from Northeast Alden, this core had sulphur on it and had many seeps of tar which occurred near fractures.

The Woodford Formation here has had initial production that ranges from 269 BOPD to 9 BOPD. However, again the Woodford production in all reported cases was commingled with at least one other zone; so no cumulative production can be reported. Unlike Northeast Alden, the Northeast Aylesworth Field has Woodford production from the lower detrital zone. The detrital zone is generally perforated along with the upper chert so the initial production tests are for both zones.

Caddo Field

The Caddo Field is yet another area where the Woodford Formation is commercially productive. As in the Northeast Aylesworth Field the Woodford is by no means the primary productive zone. Producing zones include: (1) Third Bromide Sand, (2) Viola Formation, (3) Hunton Group, (4) Woodford Formation, (5) Sycamore Formation and (6) Springer Sands. The discovery well at the Caddo Field is the Pure Oil Company's #1 Noble in the NE/4 of the SE/4 of section 35 of T3S - R1E. It was drilled in early 1939 and completed for 185 BOPD from the Sycamore Formation (Becker, 1966).

The Caddo Field is located on a tightly folded anticline with its axis trending approximately northwest-southeast (Plate 7). As can be

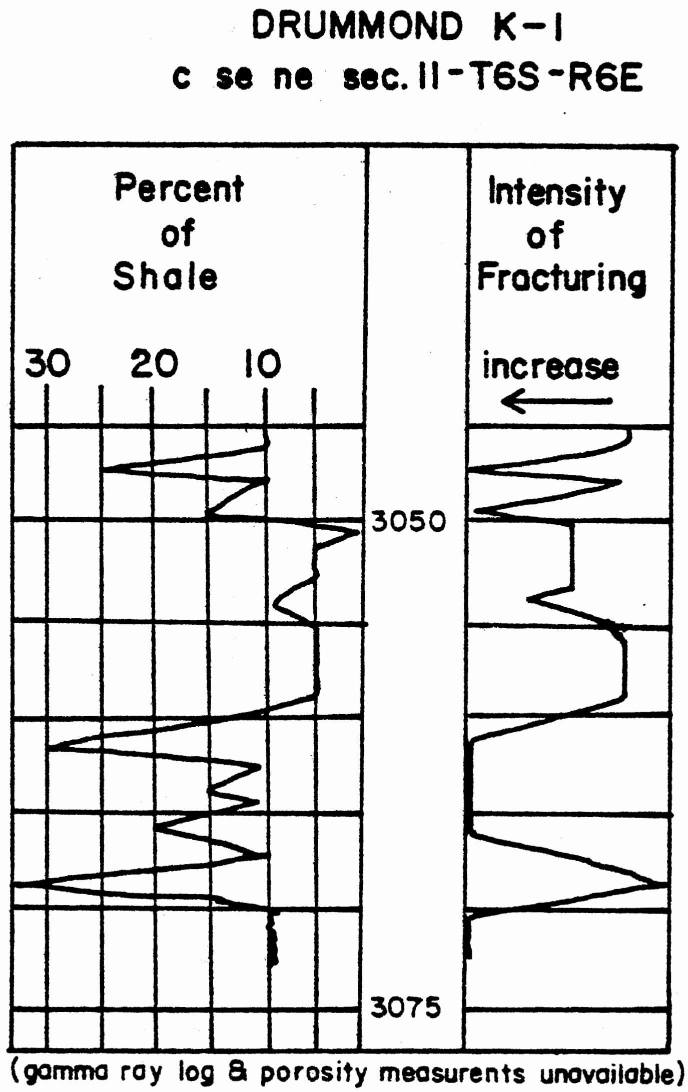


Figure 33. Core Description of the #1-K Drummond in the Northeast Aylesworth Field

seen in Plate 1, at the surface the Caddo anticline has an "S" shaped axial trace. This is most likely due to the wrenching effect of the bounding strike-slip faults. However, at depth the axial trace straightens and the fold becomes a normal doubly-plunging anticline (Plate 7). The east side of the fold terminates against a thrust fault. This along with the angle at which the fold intersects the strike-slip fault in Plate 1 indicates the fold is of the primary type (Figure 9). A seismic line, located perpendicular to the fold axis at the south end of the fold, verifies the thrust fault mapped on the east side of the fold (Figure 34). The cross section also shows a tightly folded anticline terminated by a thrust fault (Plate 8).

As at the Northeast Alden Field, at Caddo the Woodford produces from the upper massive chert section alone. The total thickness of the Woodford Formation at the Caddo Field is approximately 330 feet (Figure 5). The lithologic sequence is similar to that in Northeast Alden and Northeast Aylesworth. The Woodford Formation consists of an upper more massive chert zone that is 75 feet thick. This is underlain by a 120 foot zone of shale with occasional chert beds. The laminated chert and shale zone is approximately 110 feet thick. The emerald green shale is 110 feet thick. Finally, the detrital zone of chert and dolomite conglomerates is only 40 feet thick (Figure 2). There have been no reports of any cores taken in the Woodford Formation at the Caddo Field.

As in the Aylesworth Field the Woodford production is commingled with that of other zones. Because of this, any analysis of production potential is not possible. Initial productions of the Woodford at the Caddo field range from 29 BOPD to 195 BOPD. Gas wells in the Woodford are common and produce between 400,000 and 800,000 cubic feet of gas per day.

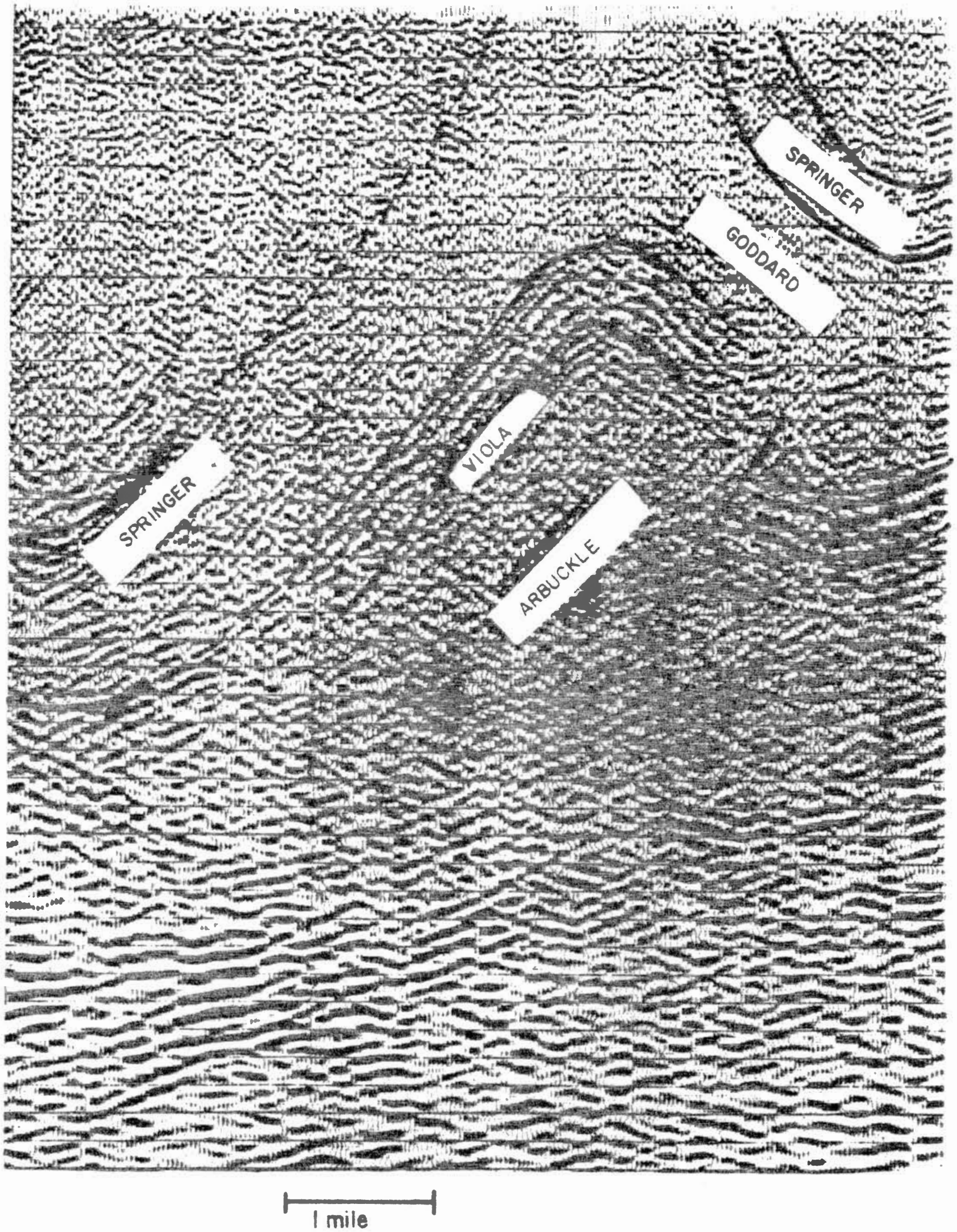


Figure 34. Seismic Profile of the Caddo Anticline

The Woodford Formation has produced and is still producing from fractured cherts in several localities in southern Oklahoma. All of the reported production comes from the upper chert zone or the lower detrital zone. As seen from the surface fracture data interbedded shales and cherts generally are more highly fractured than beds of massive chert with only occasional shale beds. The middle zone of the Woodford Formation (laminated zone) which is made up of interbedded shales and cherts could be a possible reservoir with even more fracturing than is present in the upper of lower zone. Another advantage such a zone would have is the abundance of excellent source rock which would supply the fractured cherts with hydrocarbons. Therefore, it becomes advantageous to investigate a similar reservoir to test the hypothesis that the laminated zone will be the best reservoir.

Production fron the Arkansas Novaculite

The Arkansas Novaculite of southern Oklahoma had not created much interest from a petroleum standpoint until, in 1977, Westheimer-Neustadt drilled the #1 Wallace in the NE/4 of the SW/4 of the NE/4 of section 2 in T8S - R5E. The discovery well of the Isom Springs Field initially flowed 250 BOPD and 159,000 cubic feet of gas per day.

The Arkansas Novaculite in the Isom Springs Field is made up of: (1) upper massive, (2) maroon shale, (3) green and brown siliceous shale, (4) laminated shale and chert and (5) lower massive chert (Morrison, 1981a). The original objective was to produce from the massive cherts, but during drilling the well almost blew out while drilling the laminated zone. It was later determined that the massive cherts contained very little producible hydrocarbons and that the laminated chert and shale zone was the primary producing interval. Since that first well, several wells have been completed in basal Stanley sands. Because the laminated zone of the Arkansas Novaculite resembles the laminated zone of the Woodford Formation, the Isom Springs Field would be an excellent comparative example.

Structually, the Isom Springs area contains a very complex set of faults and folds. The dominant faulting in this area is thrusting. The structural contour map of Isom Springs was contoured on the pre-Stanley unconformity (Plate 9) (because the purpose is to look at general features, the use of an unconformity to contour is acceptablet). This map indicates a tightly folded anticline cut on the west side by a thrust fault. There are several cross-faults intersecting the fold (Plate 9). The orientation of the greatest principle stress (σ_1) which would result in this type of fold is the same as the principle stress involved in the faulting and folding in the Arbuckle Mountains. The cross section shows the imbricate thrusting and intense folding involved in the structure of Isom Springs (Plate 10).

The laminated zone in the Arkansas Novaculite at Isom Springs is approximately 100 feet thick. Estimates of productive potential of Isom Springs have been placed at between 285,000 and 450,000 barrels of oil per well per penetration of the laminated zone (Morrison, 1981a). This production all comes from a zone of thinly laminated shales and cherts. Attempts have been made to core the laminated zone, but apparently due to intense fracturing, the core barrel jams and peices of chert generally 1/2 to 3/4 of an inch thick are recovered. Several pieces in this size range have been recovered with shale contacts on top and bottom. Therefore, it is reasonable to assume that the individual chert beds are no thicker than the fragments.

The discovery of oil in the Arkansas Novaculite at Isom Springs has sparked exploration in this zone in the Ouachita Front Fault Zone south into Texas. This discovery could result in the finding of many new fields.

CHAPTER VIII

CONCLUSIONS

Southern Oklahoma's structural and depositional history both present a challenge. The possiblity that an aulacogen existed in pre-Pennsylvanian time is supported by the presence of thick sequences of sediments in a restricted trough. These were later deformed by some type of tectonism. The primary type of faulting in southern Oklahoma is left-slip transcurrent faulting, with associated normal and thrust faults. Along with these faults are en echelon folds as predicted by Moody and Hill (1956). The stresses that caused these folds and faults must have been tremendous and probably accounted for the intense fracturing encountered in the surface and subsurface study areas.

The surface data indicates a relationship between the intensity of fracturing and the thickness of a particular layer and also to the ratio of competent to incompetent rock present. These same relationships seem to hold true in the subsurface. However, fracturing is so intense in the available cores that quantitative measurement of the fracturing is impossible. In Marshall County, in the Isom Springs Field, the most prolific reservoir is the laminated zone of the Arkansas Novaculite. This zone is composed of thin layers of chert and siliceous green shale. The more massive cherts in the Arkansas Novaculite are not as permeable and produce only minor amounts of oil.

It is quite possible that the best zone in the Woodford Formation has been completely neglected. There is a zone in the Woodford that is similar to the laminated zone of the Arkansas Novaculite. This zone occurs below the massive chert beds of the upper Woodford and consists of thin layers of chert and brown siliceous shale. It is usually approximately 100 feet thick where observed. Fracturing in this zone could be similar to the fracturing of the laminated zone of the Arkansas Novaculite and a tremendous amount of oil may yet be recovered. These interbedded cherts and shales provide a series of beds with fracture porosity in the cherts and source rocks in the shales. This may explain the abundance of oil in the laminated zone of the Arkansas Novaculite and points to the possibilities in the Woodford Formation.

This concept may be much more widely applicable than just to the Woodford Formation. Any reservoir (fractured or unfractured) that is laminated with a source rock (predominantly black shales) has the potential to be productive of large amounts of hydrocarbons. The Mississippi Limestone in the Sooner Trend of northern Oklahoma is productive in a zone that is composed of thinly laminated limestone and shale (Thompson, 1981). The Viola Limestone in southern Oklahoma has some of its best production from a similar zone (Morrison, 1981b). The thickness of each individual layer need not be great, but the porosity and permeability must exist.

From the data gathered in the surface and subsurface in this study it appears that laminated zones consisting of thin layers of fractured competent beds alternating with thin layers of shale (source rock) will be more intensely fractured when folded than more massive competent beds. Consequently, the laminated zones would be the most permeable and provide the best reservoirs. This implies that the laminated zone of the Woodford may be an overlooked reservoir of some importance.

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APPENDIX

SURFACE DATA

SURFACE DATA

Loc.	Set #	Fracture Density (Fractures/Ft^2)*	Restored Orient (Trend)	Shale: Chert Ratio	Strike	Dip	Thickness of Chert Bed
3a'	1	12	N49E N30W	1.42:1	N79E	26°SE	1 1/4"
	2	14 23	N46E N33W	1.42:1	N79E	26°SE	1"
3b	1	14	N51E N34W	2.43:1	N70E	26°SE	2"
3c	1	4 3	N47E N38W	.82:1	N73E	25°SE	8 7/8"
	2	19 16	N48E N37W	.82:1	N73E	25°SE	1 3/8"
3d	1	8 7	N50E N30W	2.38:1	N79E	24°SE	3/4"
	2	10 16	N44E N36W	2.38:1	N79E	24°SE	1"
	3	10 11 14	N55E N33W N88E	2.38:1	N79E	24°SE	1/4"
3e	1	10 10	N40E N48W	1.03:1	N86E	23°SE	1 7/8"
	2	6 5	N40E N43W	1.03:1	N86E	23°SE	2 1/4"
2c	1	23 19	N16E N70W	.766:1	N70W	18°SW	1/4"
	2	15 12	N19E N72W	.766:1	N70W	18°SW	1"
	3	8 5	N20E N69W	.766:1	N70W	18°SW	2 1/4"
	4	14 11	N20E N68W	.766:1	N70W	18°SW	2 3/8"

*See page 48 for explanation of counting technique.

Loc.	Set #	Fracture Density (Fractures / Ft^2)	Restored Orient (Trend)	Shale: Chert Ratio	Strike	Dip	Thickness of Chert Bed
	5	15 12	N17E N71W	.766:1	N70W	18°SW	3 3/4"
	6	9 9	N20E N72W	.766:1	N70W	18°SW	4 1/2"
2b	1	16 14	N14E N74W	2.27:1	N73W	20°SW	3/4"
	2	21 19	N15E N73W	2.27:1	N73W	20°SW	1/2"
	3	12 11	N13E N74W	2.27:1	N73W	20°SW	1"
	4	7 6	N15E N75W	2.27:1	N73W	20°SW	2 1/4"
	5	18 16	N16E N73W	2.27:1	N73W	20°SW	3/4"
	6	10 10	N15E N72W	2.27:1	N73W	20°SW	2"
2a	1	24 14	N14E N77W	1.87:1	N76W	20°SW	2 1/8"
	2	25 15	N13E N74W	1.87:1	N76W	20°SW	2 1/4"
	3	29 18	N15E N75W	1.87:1	N76W	20°SW	1 1/8"
	4	32 27	N13E N76W	1.87:1	N76W	20°SW	1 1/4"
	5	34 14	N14E N73W	1.87:1	N76W	20°SW	3/4"
	6	18 16	N12E N78W	1.87:1	N76W	20°SW	1 7/8"
	7	20 11	N11E N77W	1.87:1	N76W	20°SW	1 5/8"
	8	26 15	N15E N76W	1.87:1	N76W	20°SW	1"

Loc.	Set #	Fracture Density (Fractures / Ft^2)	Restored Orient (Trend)	Shale: Chert Ratio	Strike	Dip	Thickness of Chert Bed
HWY 77	1	7 6	N75W N15E	.41:1	N75W	43°SW	2 1/2"
	2	8 7	N75W N13E	.41:1	N75W	43°SW	1 3/4"
I-35 SOUTH FLANK	1	11 10	N49W N40E	.42:1	N49W	69°SW	1 1/2"
	2	14 10	N50W N35E	.42:1	N49W	69°SW	1"
	3	12 13	N51W N37E	.91:1	N51W	67°SW	4 1/4"
	4	6 7	N52W N38W	.91:1	N51W	67°SW	5"
	5	12 18	N51W N37E	.91:1	N51W	67°SW	2 1/4"
	6	16	N48W	1.37:1	N48W	71°Sw	1 1/8"
	7	17 15	N48W N39E	1.37:1	N48W	71°SW	3/8"
	8	10 8	N49W N38E	1.37:1	N48W	71°SW	2 1/4"
	9	10 9	N50W N41E	1.37:1	N48W	71°SW	2"
						(overturned)	
I-35 NORTH FLANK	1	20 18	N62W N25E	2.64:1	N62W	73°SW	5/8"
	2	12 16	N64W N22E	2.64:1	N62W	73°SW	3/8"
	3	20 15	N59W N28E	2.64:1	N62W	73°SW	7/8"
	4	16 10	N63W N25E	2.64:1	N62W	73°SW	1 1/2"
	5	21 11	N63W N27E	2.64:1	N62W	73°SW	1 1/8"

Loc.	Set #	Fracture Density (Fractures / Ft^2)	Restored Orient (Trend)	Shale: Chert Ratio	Strike	Dip	Thickness of Chert Bed
I-35 NORTH FLANK	6	10 12	N61W N30E	2.64:1	N62W	73°SW	1 7/8"
	7	20 24	N59W N30E	2.64:1	N62W	73°SW	1/2"
	8	16 8 12	N61W N30E N71E	2.64:1	N62W	73°SW	1 1/8"
CAMP CLASSEN	1	14 12	---- ----	3.02:1	N28W	vertical	1"
	2	13 10	---- ----	3.02:1	N28W	vertical	5/8"

VITA

Richard Randall Bramlett

Candidate for the Degree of

Master of Science

Thesis: THE RELATIONSHIP OF HYDROCARBON PRODUCTION TO FRACTURING IN THE WOODFORD FORMATION OF SOUTHERN OKLAHOMA

Major Field: Geology

Biographical:

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