THE PETROLOGY, DIAGENESIS, STRATIGRAPHY, DEPOSITIONAL ENVIRONMENT, AND CLAY MINERALOGY OF THE RED FORK SANDSTONE IN NORTH-CENTRAL OKLAHOMA

By

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CHAPTER I

INTRODUCTION

The Middle Pennsylvanian Red Fork Sandstone is one of the most significant yet elusive producers of oil and gas throughout much of Oklahoma. It was one of the first producing reservoirs in the state, having been discovered near Tulsa in 1908. It is now the objective of widespread exploration in northern Oklahoma and into the Anadarko Basin.

The study area of this thesis is in north-central Oklahoma, on the Oklahoma Platform. It encompasses approximately 324 square miles and consists of nine townships (T3N through T5N, R21E through R23E), in portions of Noble and Pawnee Counties, Oklahoma (Figure 1).

Objectives

The focus of this study is the Red Fork sandstone which is included in the Red Fork interval, Krebs Subgroup, Cherokee Group, Desmoinesian Series, Pennsylvanian System. The Red Fork interval is delineated as the interval below the Pink Limestone and above the Inola Limestone (Figure 2).

The primary objectives of this investigation were as follows:

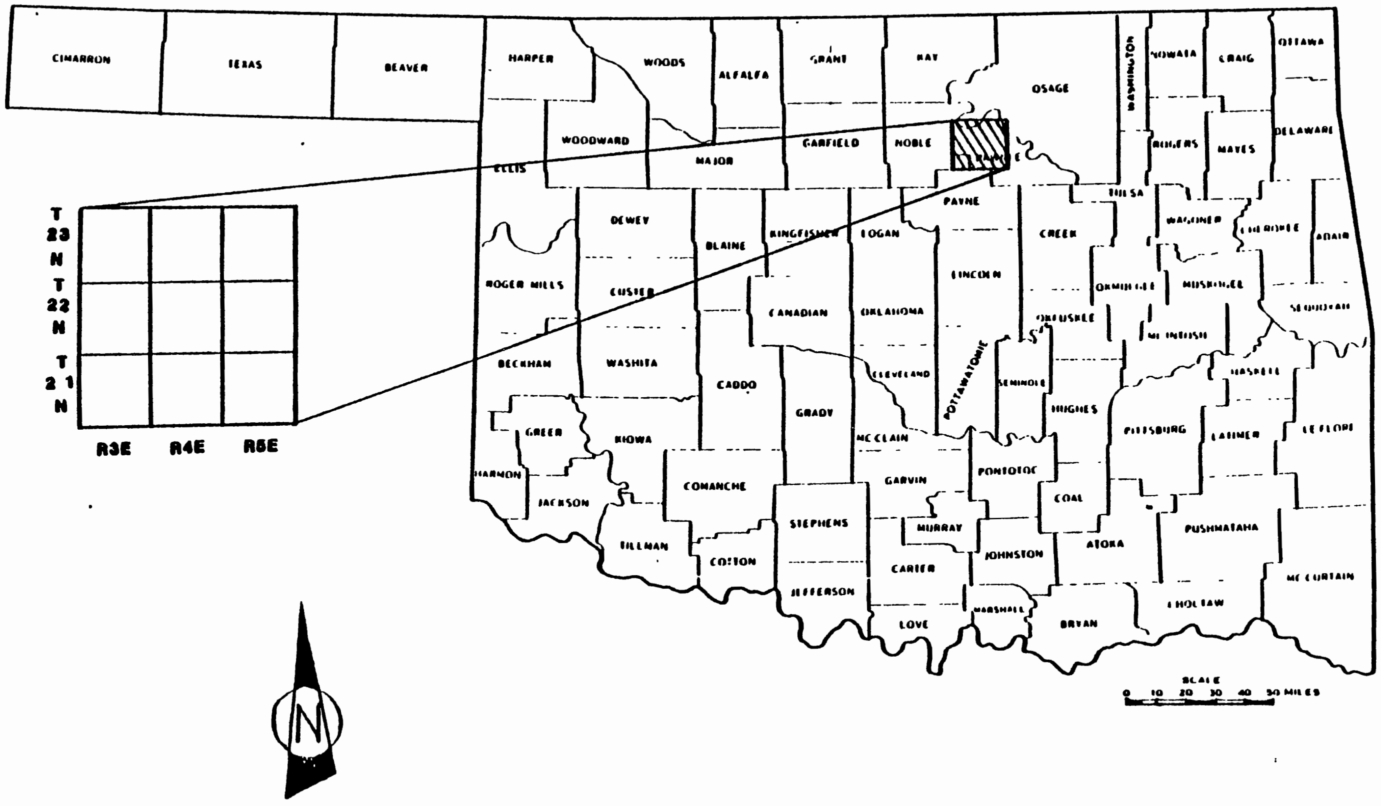


Figure 1. Location Map of Study Area

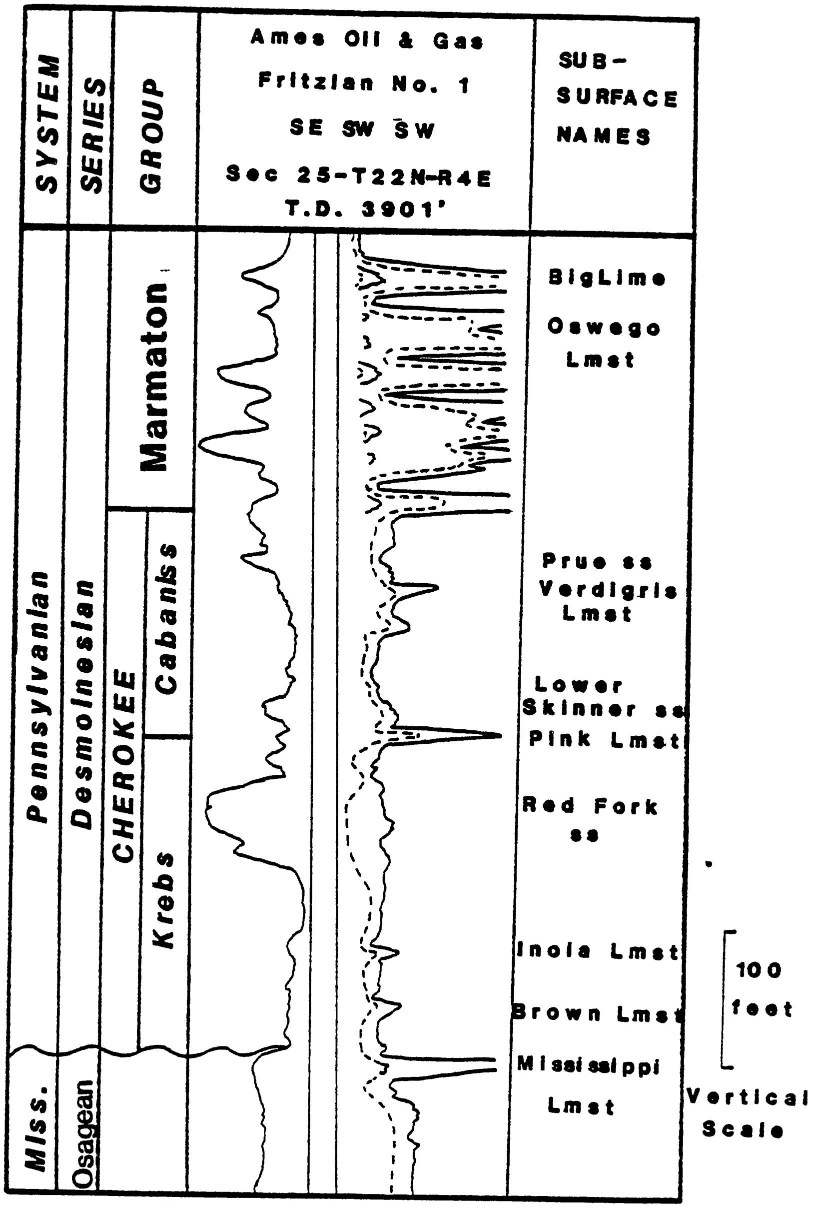


Figure 2. Type Log and Stratigraphic Sequence

1. To develop interpretations of the depositional environment(s) of the Red Fork sandstone based upon core analysis, log signatures and subsurface mapping;

2. To define petrologic characteristics and how diagenetic modifications have affected the Red Fork sandstone; and

3. To interpret types of clays and what effect they have on the permeability and porosity of the sandstone.

Methods of Study

Data for subsurface mapping in this study were compiled primarily from examination of 685 electric logs and analysis of five cores. Pertinent information from these logs was compiled on data sheets which was stored on a computer disk for future analysis. Special attention was given to sand thickness and log signatures of the Red Fork sandstone.

Structural contour maps of the Mississippi Limestone, Pink Limestone and Red Fork interval were prepared to obtain a greater understanding of how each formation was deposited. An isopachous map of the Red Fork sandstone also was constructed in order to obtain insight of the influences of paleotopography on sandstone deposition. A 20 millivolt cutoff from the shale baseline was used on the Spontaneous Potential Curve to delineate the presence of sand.

Six stratigraphic cross sections were constructed to show lateral and vertical facies relationships of the Red Fork sandstone. Three cross sections were parallel to strike and three were parallel to dip of the sandstone.

Five cores of the Red Fork sandstone were examined and described in detail as to their sedimentary structures, mineral constituents, and depositional environments. Sixty-five thin sections were examined to determine petrologic characteristics, diagenetic cements, authigenic clays, and porosity (primary and secondary). Photomicrographs illustrate these characteristics of the core. X-ray diffraction of powdered bulk and clay extracted samples were used to determine general composition and percentage of constituents.

Scanning Electron Microscopy (SEM), with an Energy Dispersive X-ray Analyzer (EDXA), were utilized to identify diagenetic minerals, creation of secondary porosity, and authigenic clays.

Previous Work

The Red Fork sandstone has been a topic of investigation for numerous years because of its vast potential for oil and gas. The Red Fork is part of the Cherokee Group first described by Haworth and Kirk (1894) a sequence of black shale between the Pennsylvanian Fort Scott Limestone (Oswego Limestone) and Mississippian rocks in Cherokee County, Kansas (Withrow, 1968). Oakes (1953) divided the Cherokee Group of east-central and northeastern Oklahoma into the Krebs Group and Cabaniss Group. Branson (1954) of the Oklahoma Geological Survey dropped the term

"Cherokee" from stratigraphic nomenclature and replaced with the two groups devised by Oakes. The term "Cherokee" was readopted in 1956 and the Krebs and Cabaniss Groups were reduced to subgroups.

The stratigraphic position of the Red Fork was specified by Jordan (1957) to be that unit which lies below the Pink limestone and above the Inola limestone. The surface equivalent of the Red Fork sandstone is the Taft Sandstone.

The Red Fork formation was named by Hutchinson in 1911 from a shallow producing sandstone in the formation near the town of Red Fork, Oklahoma (Jordan, 1957). Since that time, numerous studies have been done on the Red Fork by Bass (1934, 1936), Bass et al. (1937), Leatherock (1937), and Howe (1956). Bass (1934) found that in parts of Oklahoma and Kansas, the Burbank sands (equivalent to the Red Fork sandstone in Oklahoma) occurred in trends supposedly parallel to the shoreline of the Cherokee sea. These lenses of sand were separated by gaps which contained no sand. Bass (1934) concluded that the Red Fork sand bodies were deposited as offshore bars separated by tidal inlets. He compared this type of depositional environment to the coastline of New Jersey.

Leatherock (1937) reported that the Red Fork sand was similar to Bartlesville sand in both composition and physical characteristics. Both sandstones are composed mainly of quartz, feldspar, and rock fragments that primarily are cemented by carbonates. Chlorite, magnetite, glauconite, pyrite, and other minerals are noted in both formations (Mason, 1982).

Additional investigations were made by Markham (1937), Wright (1941), Howe (1951), Weirich (1953), Graves (1955), Benoit (1957), Stringer (1957), and Branson (1954) near the area of study. These geologists concluded that the Red Fork sandstone was deposited along the shoreline of the Cherokee sea while it was advancing westward. The sand was covered by advancing marine clayey and carbonate muds. Between bars of well sorted sand, muds and relatively unsorted sand were deposited.

Recent studies have refined interpretations oɪ the depositional environment of the Red Fork. Clayton (1965), Hawissa (1965), Cole (1969), Scott (1970), and Shipley (1975) concluded that the Cherokee sands in north-central Oklahoma were deposited in distributary channels of a deltaic environment. Shipley (1975) concluded that thick accumulations of Red Fork sand represented deposition in channels that were major and minor distributaries of a deltaic system. Chandler (1976) concluded that the Red Fork sand was of lower deltaic facies with both interdistributary fine-grained sand and crevasse splay deposits.

Studies by Dogan (1970), Astarita (1975), Krumme (1975), Glass (1980) and Robertson (1983) include subsurface mapping and correlation of Cherokee sediments nearby the present area of investigation.

Regional investigations by McElroy (1961), Visher et al. (1968), Cole (1969), and Berg (1969) have dealt with the greater framework of Pennsylvanian geology of northeastern Oklahoma.

CHAPTER II

GEOLOGIC HISTORY

Tectonic Setting

The area under investigation is located on the Oklahoma or "Cherokee" Platform (Figure 3). The localized study area is located within an area bounded to the west by the Nemaha Ridge, to the east by the Ozark Dome, to the north by the Cherokee Basin, and to the south by the Arbuckle Uplift and Arkoma Basin.

The Central Oklahoma Platform was relatively stable throughout the Paleozoic. Here, strata dip southwesterly at 25 to 80 feet per mile (Dalton, 1960; Hanke, 1967; Visher, Saitta, Sandro, and Phares, 1971). Numerous local folds and faults interrupt this homoclinal dip.

Two factors have been determined to have been the most significant general influences upon deposition of the Red Fork. These are the unconformable surface of the Mississippian Limestone and uplift of the Nemaha Ridge. Plate II is a structural contour map of the Mississippian Limestone, which will aid in inferring the pre-Pennsylvanian drainage pattern. This map shows north to northwest strike with a westerly dip of approximately 50 feet per mile. Closures within the Mississippi Limestone

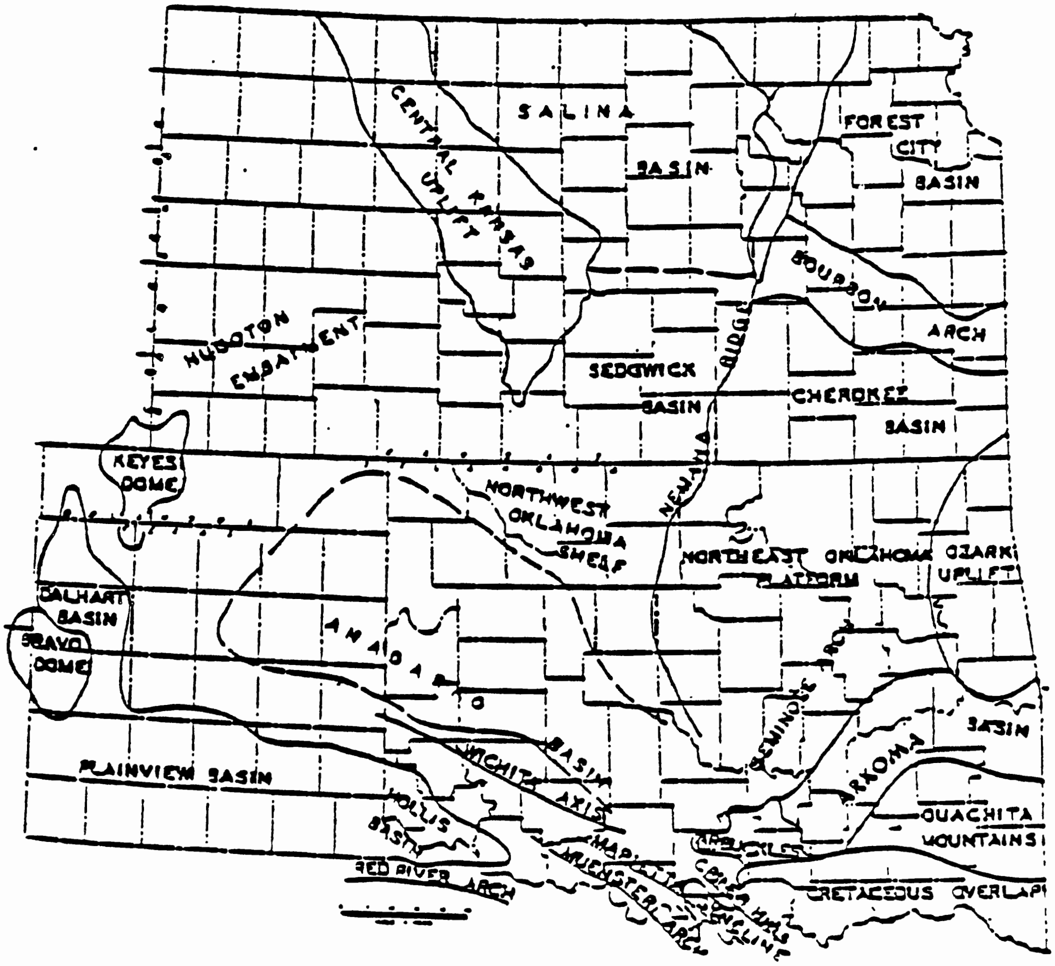


Figure 3. Tectonic Map of Oklahoma and Kansas (after Huffman, 1960)

are structural highs.

Stratigraphic Setting

The Cherokee Group is a 500 to 600 foot thick sequence of predominately clastic rocks. On the Central Oklahoma Platform, sediments of Desmoinesian age lie unconformably upon Mississippian rocks. Cole (1969) recognized a southward thickening of "Cherokee" sediments from the Nemaha Ridge.

The "Cherokee" interval in north-central Oklahoma is defined as including those rocks that overlie Mississippian strata and underlie Oswego strata (Figure 2). The "Cherokee" Group was deposited in a general northward transgression of the Cherokee sea, interrupted by periods of southwestward delta progradation. The source area for most of the sediments of the Desmoinesian age is considered to have been from northeastern Kansas and western Missouri (Weirich, 1953).

The Red Fork interval is defined as the interval between the base of the Pink limestone and the top of the Inola Limestone (Jordan, 1957). The surface equivalent of the Pink limestone is the Tiawah Limestone; the surface equivalent to the Red Fork sandstone is the Taft Sandstone.

Correlations

To illustrate sedimentological and stratigraphic relationships of the Red Fork sandstone, six stratigraphic cross sections were constructed in this study area (Plates 5-10). Three of the cross sections are parallel to strike and three parallel to dip of the Red Fork interval. The Pink limestone is the datum for all the stratigraphic cross sections because it lies directly above the Red Fork interval and is consistent throughout the study area. Locations of wells used for the cross sections are shown in Figure 4 and on the structural contour map of the Red Fork Interval (Plate I).

Seven distinct stratigraphic units were identified within the Cherokee Group on each of the six cross sections. In ascending order these are the Brown limestone, the Inola Limestone, the Red Fork sandstone, the Pink limestone, the Lower Skinner sandstone, the Verdigris Limestone, and the Prue sandstone. The Mississippi limestone, the Oswego limestone, and the Big Lime were also delineated.

Cross sections that are subparallel to strike of the Red Fork show near uniformity of thickness in Cherokee rocks. Thickness varies from approximately 480 feet in the northwest to approximately 620 in the southeast.

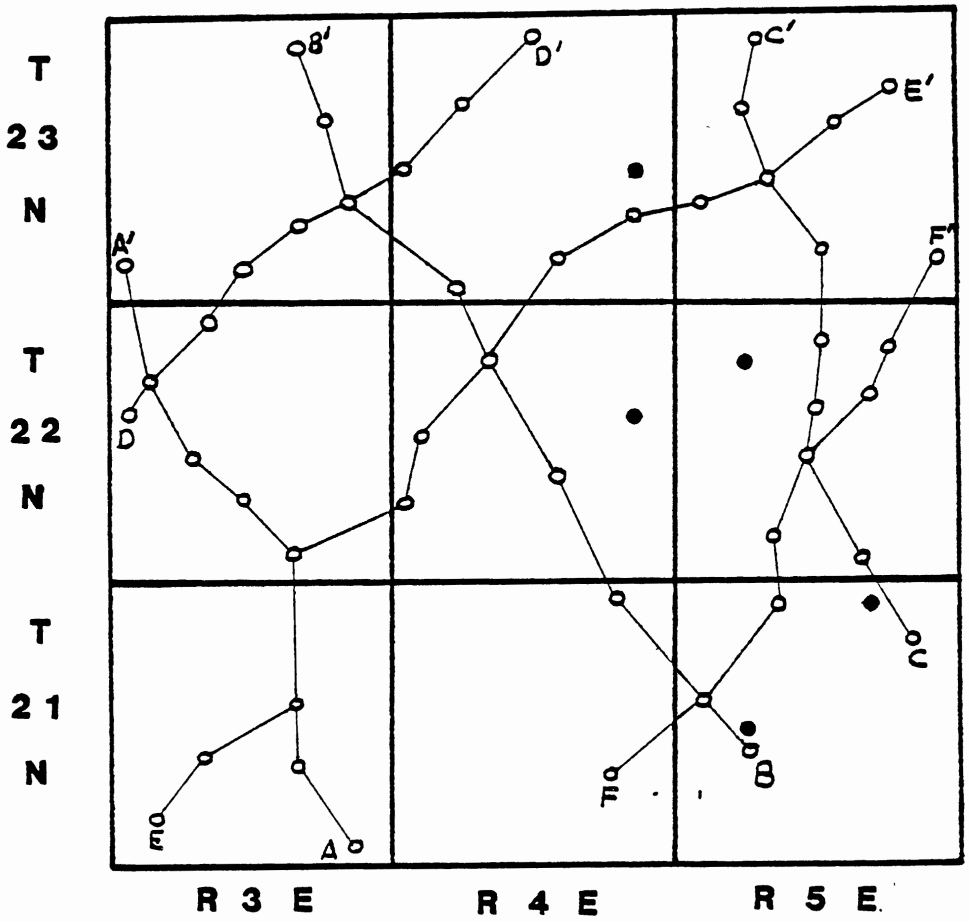


Figure 4. Location of Cross Sections and (●) Represents Location of Cores

CHAPTER III

DEPOSITIONAL ENVIRONMENTS

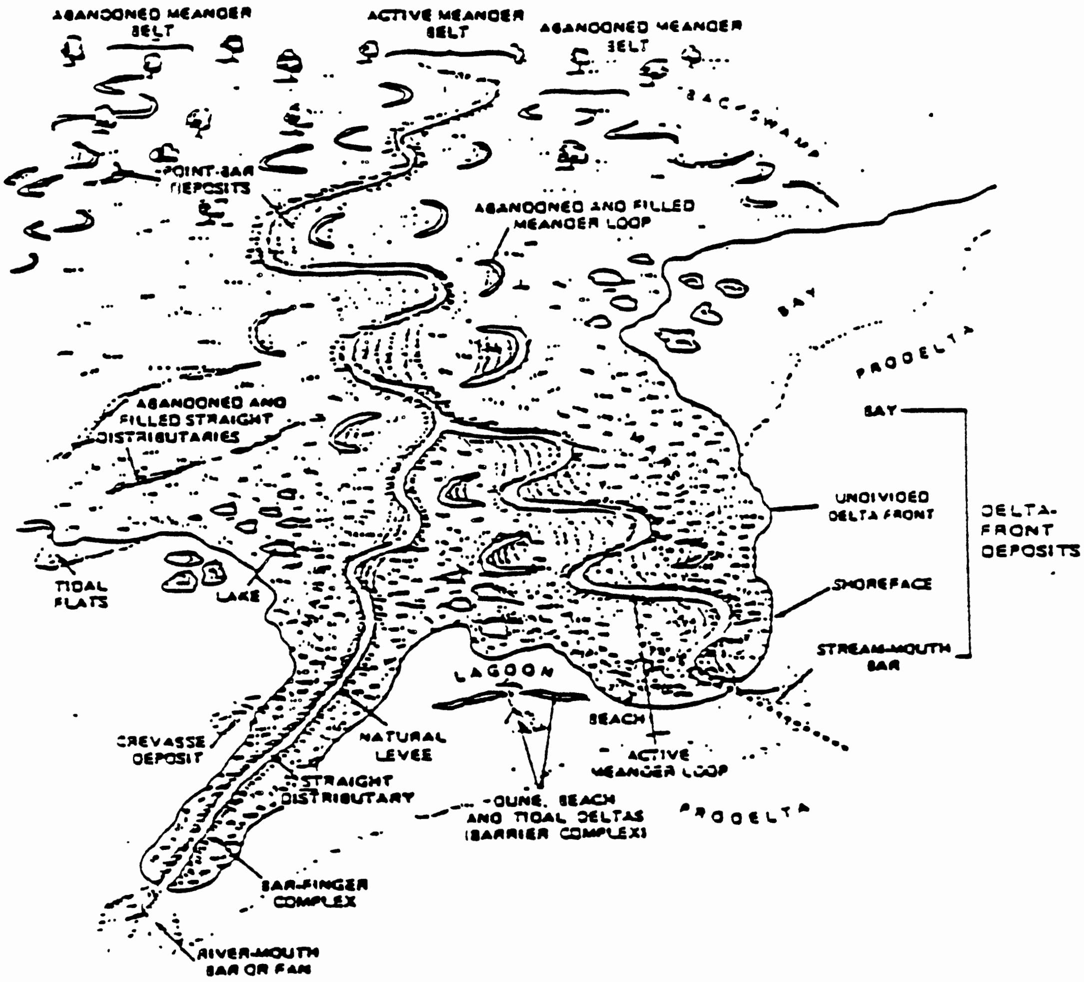
Depositional history of outcropping Pennsylvanian sediments in northeastern Oklahoma was described by Weirich (1953), Visher, Saitta, and Phares (1971), and Brown (1979). Studies of the Cherokee Group in the subsurface are numerous. Work has been done in the subsurface by Berg (1969), Cole (1969), Albano (1973), Astarita (1973), Zeliff (1979), Verish (1979), and Robertson (1983).

The general depositional environment of the Red Fork in this study area is interpreted to have been part of a large fluvial-deltaic system. These conclusions are based upon examination of five cores, four subsurface maps, six stratigraphic cross sections, and evaluation of previous work by other geologists.

Brown (1979) created an idealized sequence of Pennsylvanian fluvial-deltaic facies: (1) Submarine progradation or basinward accretion by suspension deposition (prodelta), bedload channel-mouth deposition and contemporaneous marine reworking (delta front), (2) "vertical", subaerial aggradation of delta-plain facies (deposition of distributary-channel fill, crevasse splays, flood-basin, marsh, and superimposed fluvial channels), (3) abandonment and marine (shoal) destruction of the subsident inactive lobe (deposition of small barrier bars, littoral sheet sandstones and storm berms), and (4) ultimate transgression of marine shale and open marine limestone (Figure 5).

Three main facies are generally observed in fluvial-deltaic sandstone deposits. These are delta-front sandstones, distributary channel-fill sandstones, and point-bar sandstones. Delta-front sandstones are considered to be the most prolific hydrocarbon reservoirs in a deltaic facies. They are commonly described as a coarsening upward sequence of constituents within the sand body. Fisher (1969) concluded that Pennsylvanian delta systems on Mid-continental shelves typically were river dominated and display either elongate or mixed elongate-lobate configurations (Figure 6). Delta-front facies in elongate deltas predominantly are channel-mouth or distributary-mouth bars which commonly form at the mouths of distributary channels on the prodelta front (Figures 7 and 8).

Characteristics of sedimentary structures in channel-mouth bar sediments have been documented by Fisher and Brown (1972) and Shelton (1973). They include (1) horizontal or planar bedding, (2) small- and medium-scale trough cross-beds, (3) oscillation and current ripples, (4) interstratified clay and sand, (5) bioturbation and carbonaceous detritus, (6) glauconite and clayey siderite concretions, and (7) common deformation features due to



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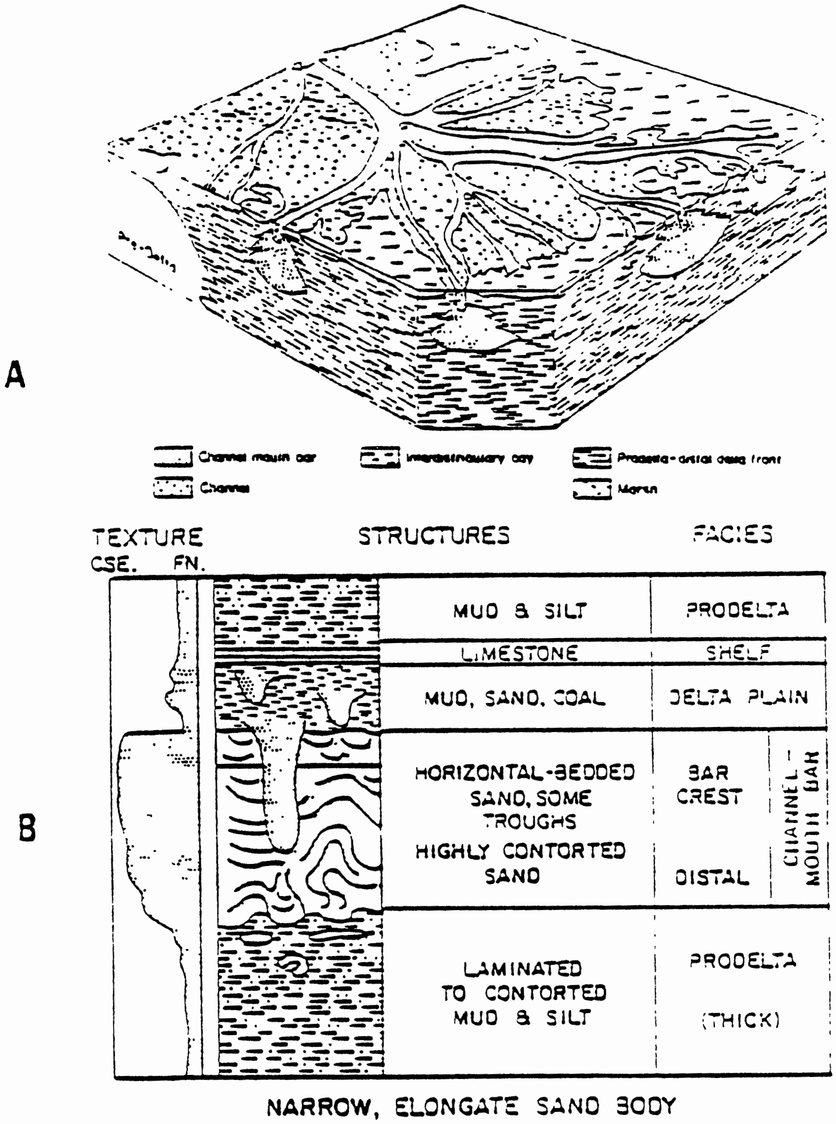

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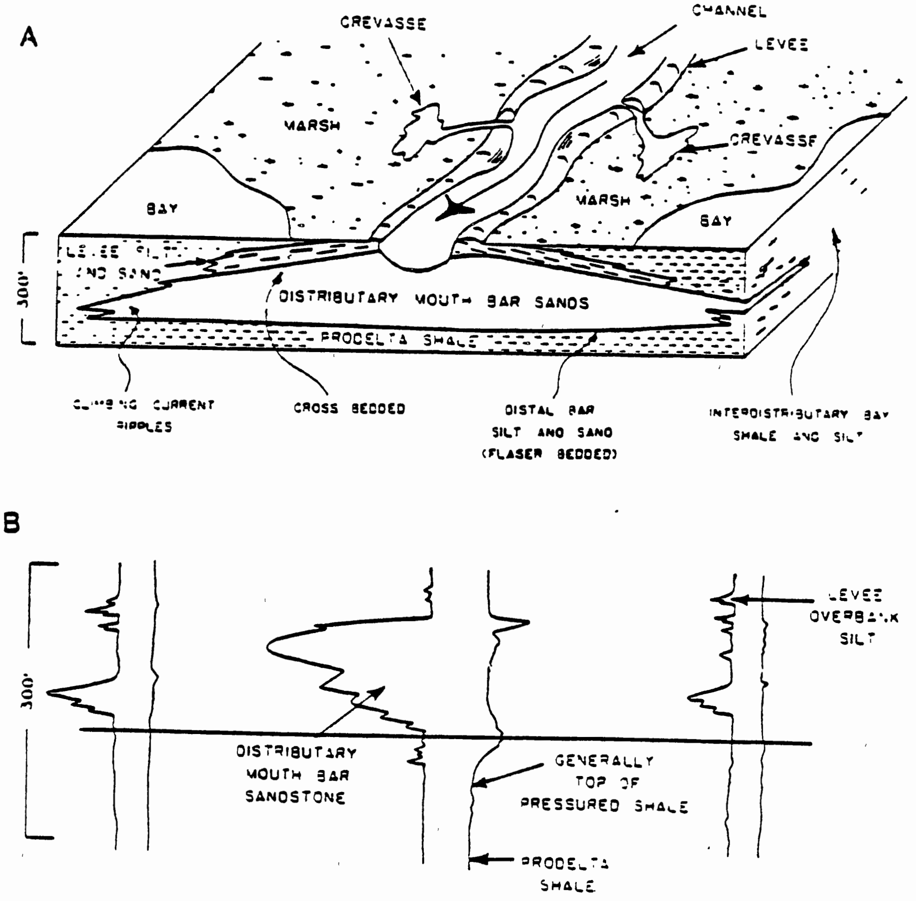

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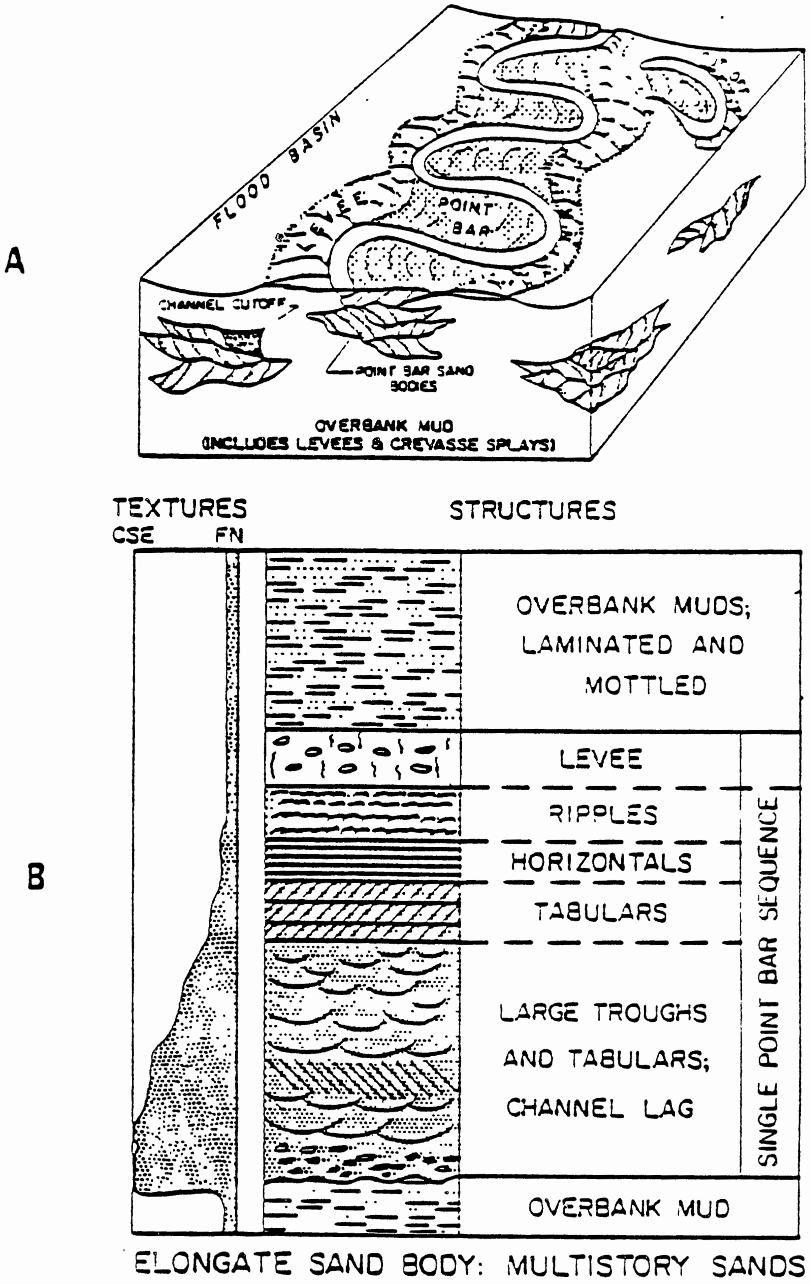


Figure 8. Model of Point-bar Deposition (A) Model of Fluvial Meander-belt Showing Point-bar Depositional Setting; (B) Idealized Vertical Sequence of Point-bar Sediments in Intercratonic Basins (after Brown et al., 1973)

load, slump, flowage and diapirism effects. The channel-mouth bar facies exibits a coarsening upward sequence which can be commonly viewed on the spontaneous potential electric log as an inverted "christmas tree" signature (Figure 6).

Distributary channel-fill will deposit sediment on the mid-deltaic plain (Figure 7). Channel-fill sedimentary structures were also characterized by Fisher and Brown (1972) as (1) massive to highly distorted sand, (2) small- to medium-scale trough cross beds, (3) horizontal or planar beds, (4) climbing ripple co-sets, and (5) overlying laminated abandoned channel-fill muds. Siderite concretions and fossil wood fragments may also be abundant. Brown (1979) concluded that sandstones from different deltaic facies may be superimposed upon each other making identification of individual deltaic facies almost impossible.

Point-bar sediments are deposited on the upper deltaic plain and are associated with fluvial meanderbelt systems (Figure 8). They show a fining upward sequence which also corresponds with a decrease in porosity as grain size decreases. The following sedimentary structure characteristics for point-bar sediments are by Fisher and Brown (1972) in ascending order: (1) basal conglomerate or channel-lag, (2) medium- to large-scale trough cross-bedding, (3) horizontal or planar beds, (4) small-scale cross-beds, (5) current ripples, and (6) overlying laminated muds of swale fill or levee deposits. Brown (1979) concluded that point-bar sediments have sharp basal contacts which generally represent scoured surfaces cut as meandering channels eroded into delta-plain, delta-front, and prodelta deposits.

To fully document the delta-plain depositional environment, five cores were examined. Petrologic logs and photographs of cores are found in Appendix A. Description of the Ames Oil and Gas Company, Rogers No. 2 core, (SE NE NW Sec 13-T22N-R4E) is by Robertson (1983).

Depositional Environment and Thickness

In this study, the Red Fork sandstone was defined as those sediments with negative Spontaneous Potential curve deflection from the shale baseline greater than 20 millivolts on the spontaneous potential curve. The total thickness of the sandstone was recorded and utilized to construct an isopachous map (Plate IV).

The Red Fork sandstone is a multistoried, biofurcated, fluvial-deltaic channel facies. Trend of the major distributary channel predominatly was northwest to southeast levees, splays, and point-bar facies are associated (Figure 9).

Portions of the isopach map of the Red Fork revealed areas in which no sandstone is present. At some localities sandstone is thicker than 130 feet. This type of deposition of sand is characteristic of deltaic facies. Areas of poorly developed sandstone probably were interdistributary terrain.

Sedimentary Features

Seven major sedimentary features were found in each of the five cores. Each of these features can be shown as additional evidence in fully understanding the fluvial-deltaic environment of Red Fork deposition. These seven features are (1) horizontal or planar bedding (Figure 10), (2) massive bedding, (3) interstratification, (4) small- to medium-scale cross-bedding (Figure 11), (5) depositional dip/slope (Figure 12), (6) evidence of deformation (Figure 13), and (7) organic sediments.

Brachiopods, parts of other marine fossils, and fragments of coral also were identified in the black shale located at the base of the Red Fork (Figure 14). In the Martin 1-8 core red colored shales were present which represented the presence of iron oxidized to hematite causing the red color in the shale.

Spontaneous Potential Log Patterns and Environments

The spontaneous potential log (hereafter referred to as "S.P.") pattern can be a useful tool to interprete depositional facies. The S.P. signature responds to lithology and grain size, and the response can be used to make interpretations concerning sedimentary environments (Coleman and Prior, 1980).

The upper-deltaic-plain environment is associated with a fining upward sequence of point-bar deposits. This type

Figure 10. Horizontal or Planar Bedding, Thompson-Tye Drilling, No. 3 Shields, Depth 2655 feet, Sec. 2-T21N-R5E

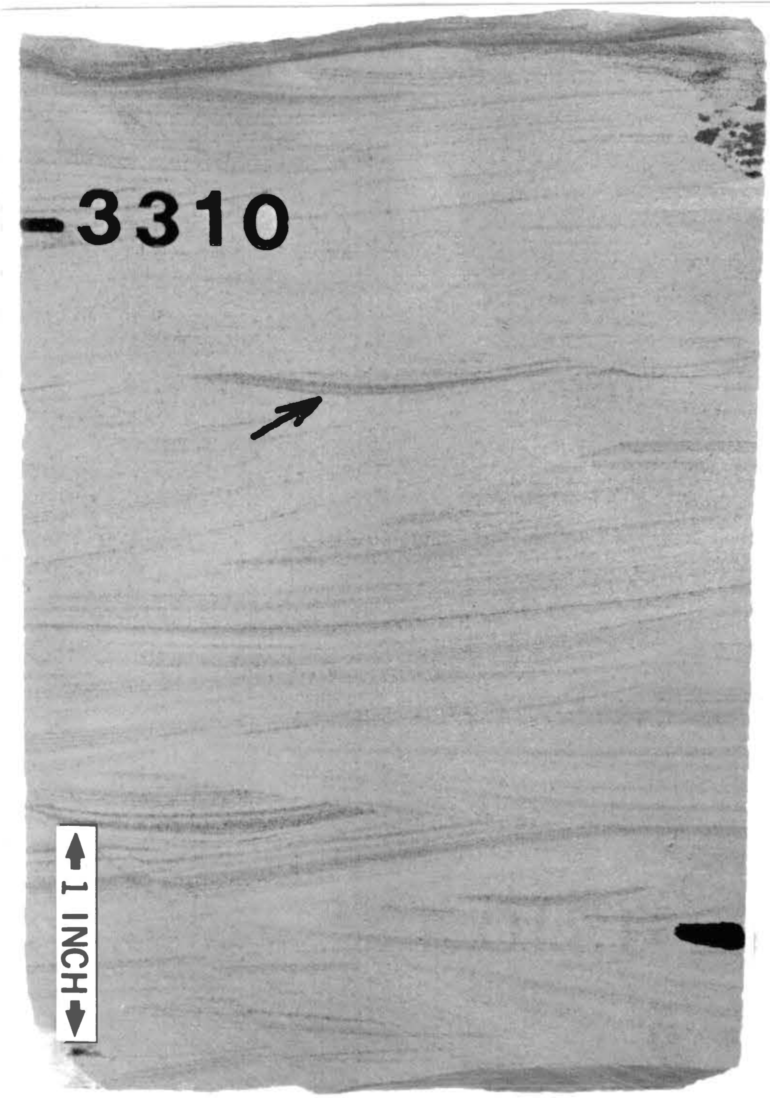


Figure 11. Small- to Medium-Scale Cross Bedding, Perkins Production Company, No. 1, Depth 3310 feet, Sec. 20-T21N-R5E

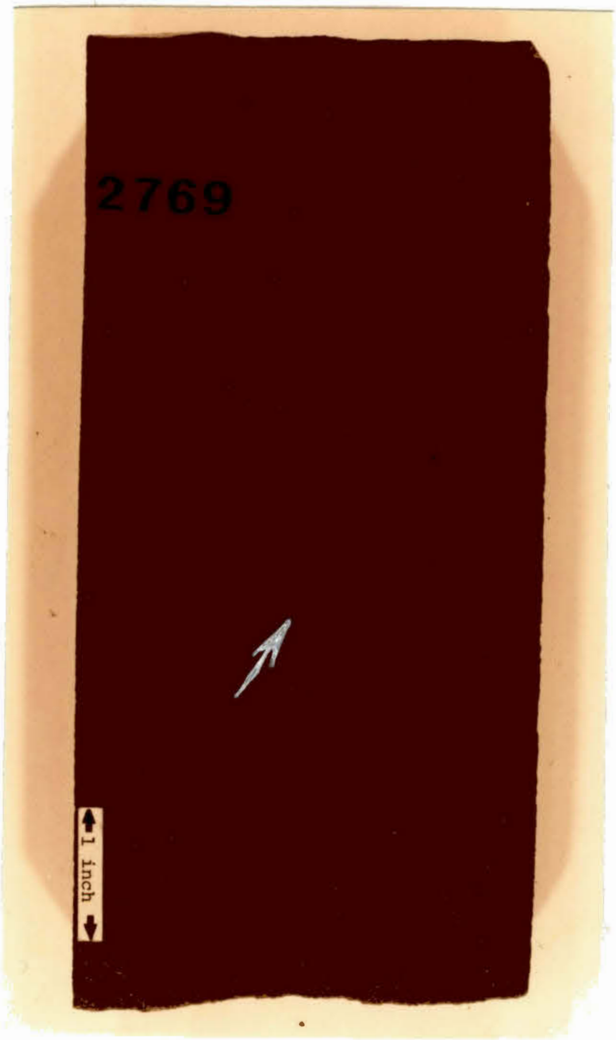


Figure 12. Depositional Dip, Thompson-Tye Drilling, No. 3 Shields, Depth 2769 feet

Figure 13. Evidence of Deformation, Thompson-Tye Drilling Company, No. 3, Shields, Depth 2770 feet, Sec. 2-T21N-R5E

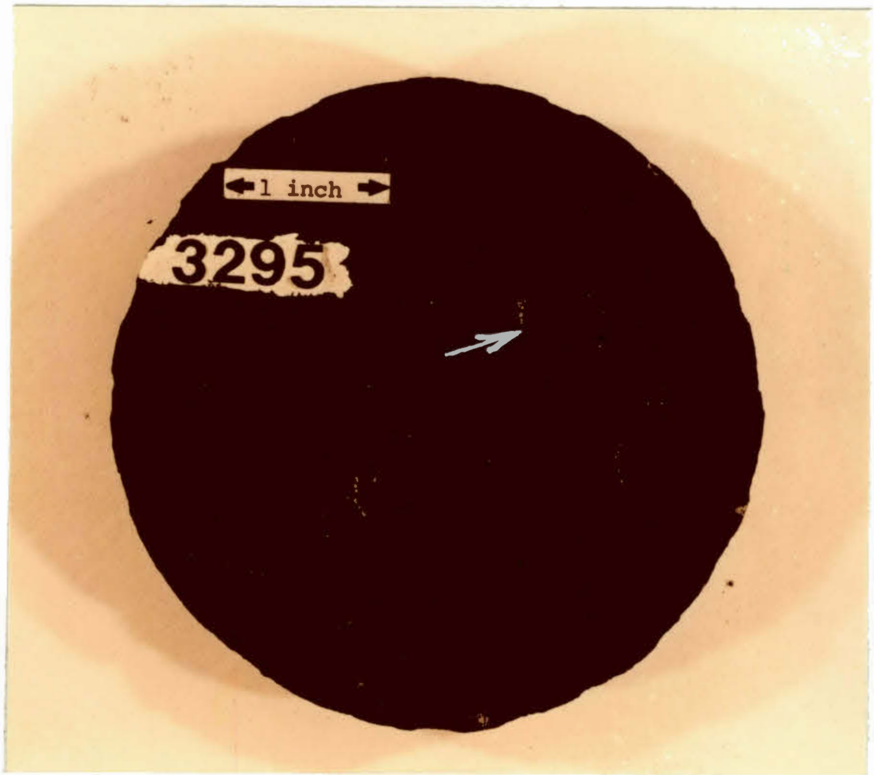


Figure 14. Fragments of Fossils in Black Shale. Brachiopod Shell in Upper Right-hand Part of Photograph. Bandera Energy Company, No. 1-8 Martin, Depth 3295 feet, Sec. 8-T22N-R5E

of facies has a "christmas-tree" log signature because the sand is more porous at the lower part of the rock. Thus, the signature of the S.P. will be suppressed at the upper part of the sand where it is less porous and shift to the left generally with increasing porosity.

Conclusion Concerning Deposition of the Red Fork Sandstone

1. Both the Inola and Pink Limestones represent marine transgressions of the Cherokee sea. The Red Fork sandstone represent a regressive phase of "Cherokee" cyclic deposition.

2. The Red Fork was deposited in a deltaic environment with an assortment of major and minor distributary channels to crevasse splays similar to that of the present Mississippi River Delta.

3. The source of sediment for the Red Fork was from the north to northwest.

4. Southeasterly thickening of the entire Cherokee Group toward the Arkoma Basin indicates that onlapping conditions and cyclic sedimentation were predominate during deposition of the Cherokee Group.

CHAPTER IV

PETROLOGY

Introduction

To obtain a greater understanding of the Red Fork, analysis of detrital and authigenic constituents must be undertaken. Several methods were used to determine the mineralogy including thin-section analysis, X-ray diffraction of powdered bulk and clay extracted samples, and use of the scanning electron microscope (SEM).

Petrologic analysis of the Red Fork sandstone included examination of five cores (Figure 5): (1) A & W Production Company, Brien No. 3, (Sec. 26, T23N, R4E) from which 15 thin sections were examined, (2) Bandera Energy Company, Martin 1-8, (Sec. 8, T22N, R5E) from which 14 thin sections were examined, (3) Ames Oil and Gas Company, Rogers No. 2, (Sec. 13, T22N, R4E) information from 21 thin-sections was obtained from Robertson, (1983), (4) Thompson-Tye Drilling Company, #3 Shields, (Sec. 2, T21, R5E), from which eight thin-sections were examined, and (5) Perkins Production Company, Buchanan #1, (Sec. 20, T21N, R5E) from which five thin-sections were examined. Bulk and clay-extracted samples were taken from the thin-section sample locations in the cores and analyzed X-ray diffraction techniques. The scanning electron microscope was utilized to illustrate textural relationships, identify authigenic minerals, and view pore spaces.

Data from the thin-sections were plotted according to Folk's (1968) sandstone classification (Appendix B). This classification accounts for grains of quartz, rock-fragments, and grains of feldspar. The Red Fork sand in all five of the cores plotted as sublitharenite (Figure 15).

Detrital Constituents

Thin-sections varied from silt to coarse grained sand. However, the grains were predominately very fine to fine grained. The major detrital constituent is quartz, which averages between 45 to 65 percent of all the samples. Quartz grains are mainly monocrystalline; polycrystalline quartz is rare.

Rock fragments were abundant in the majority of the samples analyzed. Fragments of metamorphic rock were most common; they constituted approximately 20 to 32 percent of the sand. Sedimentary rock fragments were also present, however, to a lesser extent. They were found to only account for about three to 10 percent in the thin-sections. Sedimentary rock fragments commonly were composed of siltstones and shale clasts. Illite was always present lining the edges of the sedimentary fragments.

Feldspar grains are a common mineral assemblage in sandstones. However, feldspar grains accounted for only 10

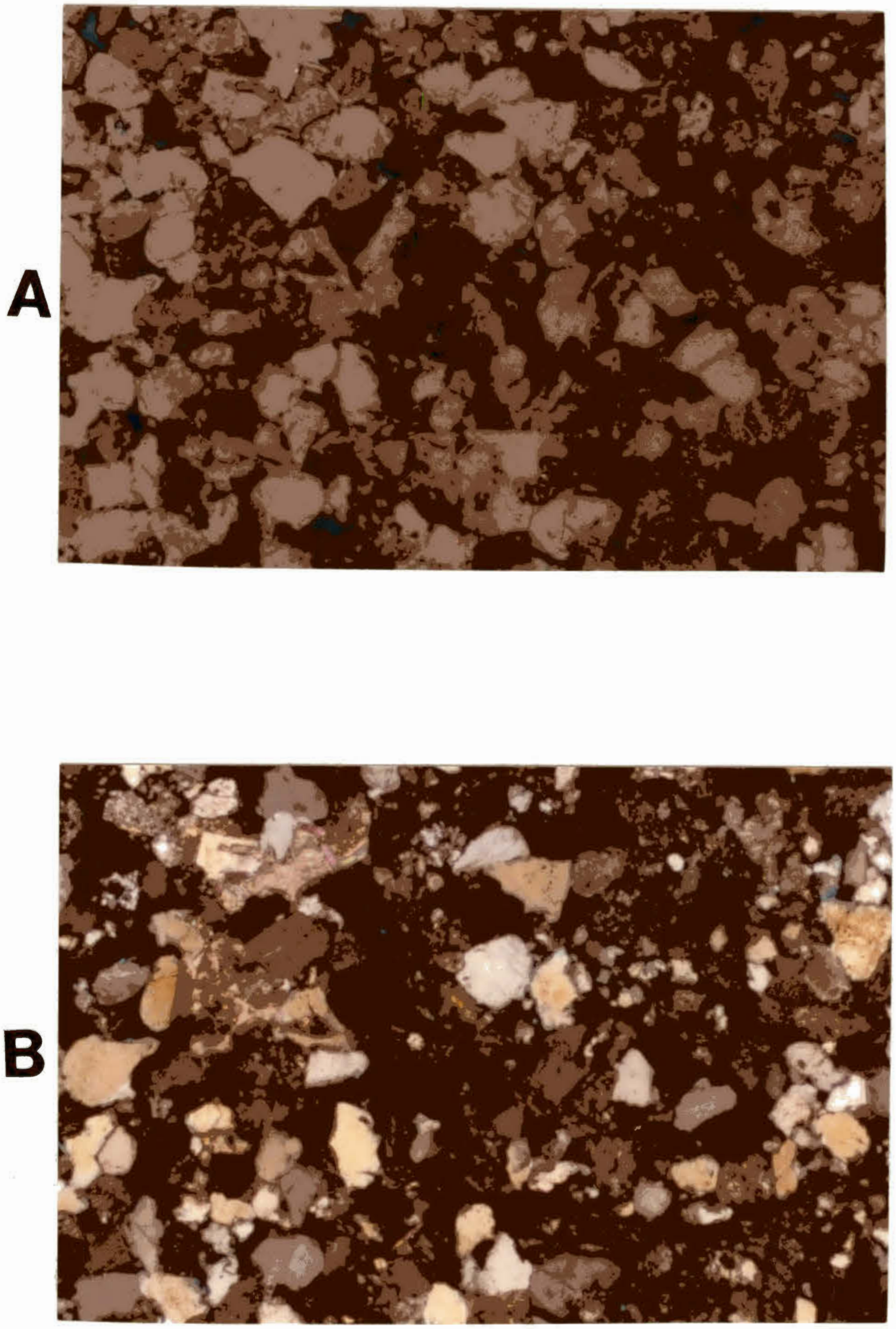


Figure 15. The Red Fork Sand was Concluded to be a Sublitharenite. (A) Displays the Presence of Feldspars, Quartz, and Rock Fragments. Plane Polarized Light, 40X, (B) Same Sample But Crossed Nichols, 40X

to 22 percent in the Red Fork sand. This was due in part to diagenetic dissolution of feldspar grains which will be discussed in more detail in Chapter V. The primary types of feldspars grain observed were potassium feldspar and plagioclase (possible sodium rich). The potassium feldspar grains showed no twinning, however, the plagioclase grains various degrees of extinction (Figure 16). In the majority of the thin-sections, carlsbad and albite twinning were observed which indicates the possiblity of the presence of oligoclase and andesine.

Other detrital constituents observed in the cores was the presence of muscovite, pyrite, sphene, zircon, oil stain, carbonaceous material, and glauconite. However, these constituents were not abundant and varied between a trace and eight percent of the entire sample that was analyzed. Pyrite, sphene, zircon, and glauconite occurred as silt-sized grains. Muscovite occurred as fine-sized grains that often showed ductile deformation around other surrounding grains (Figure 17).

Detrital clays constituted from trace amounts to 12 percent of the rock. Detrital clay was mechanically injected in between the grains of the sandstone which is not easily identified in thin-sections. This detrital matrix characteristically reduced both the porosity and permeability of the sandstone.

Figure 18 shows the average composition of detrital constituents found in the cores studied. Quartz, feldspar,

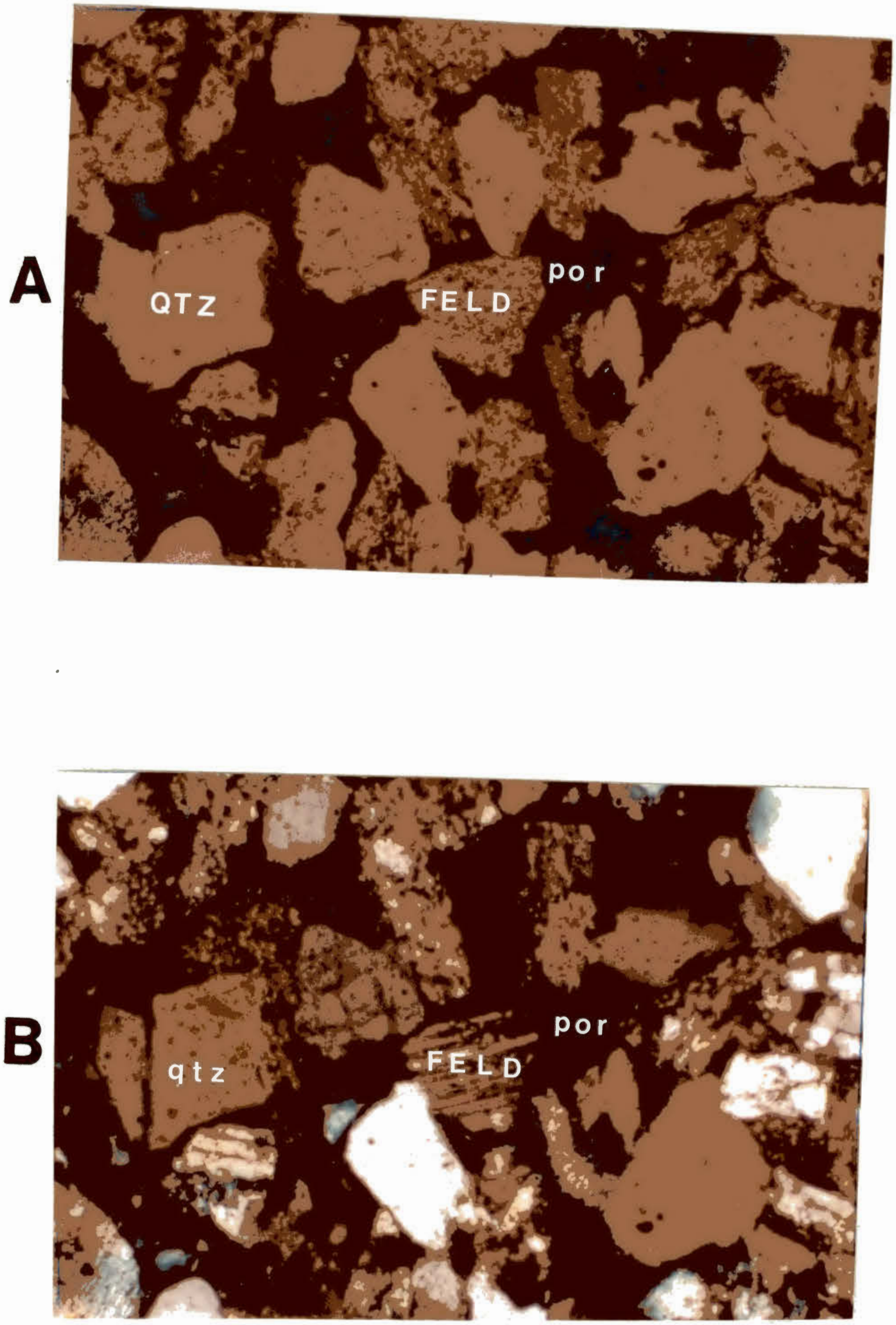


Figure 16. Evidence of Feldspar Grains (A) Shows Twinning of Feldspar Grain and Presence of Quartz Grain, Plane Polarized Light, 200X. (B) Same Sample But in Crossed Nicols, 200X

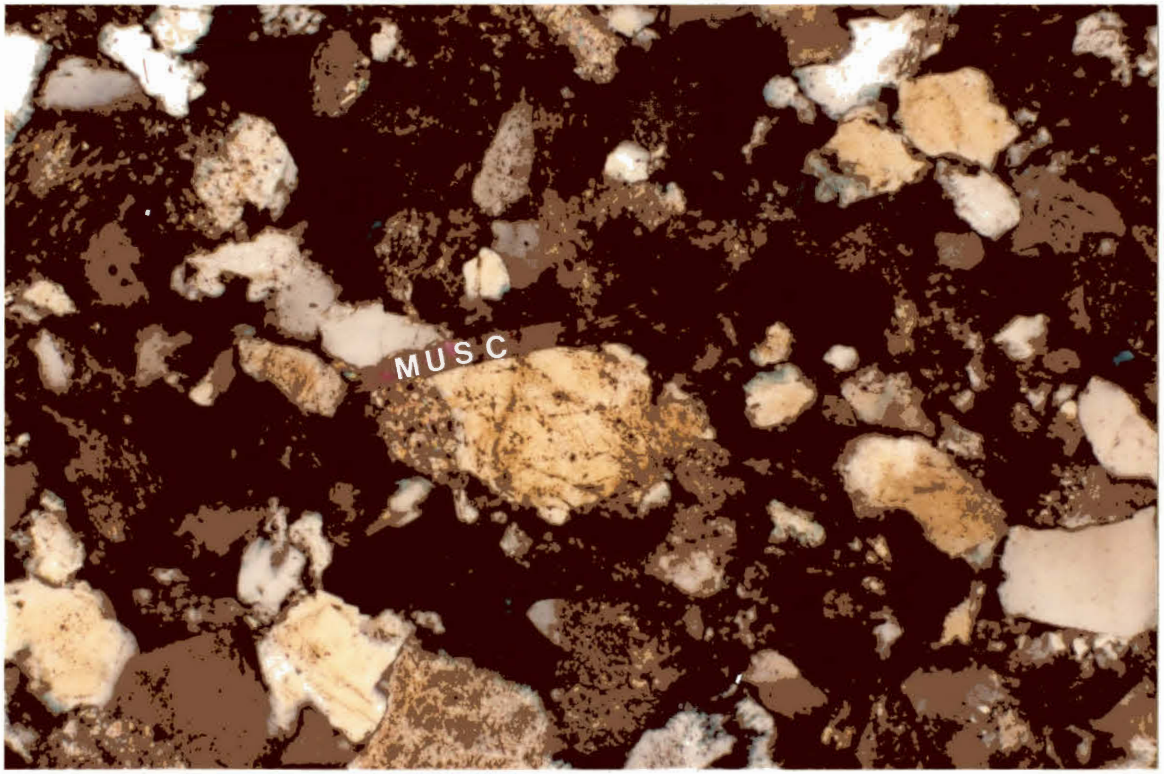


Figure 17. Muscovite Grain, Crossed Nicols, 100X

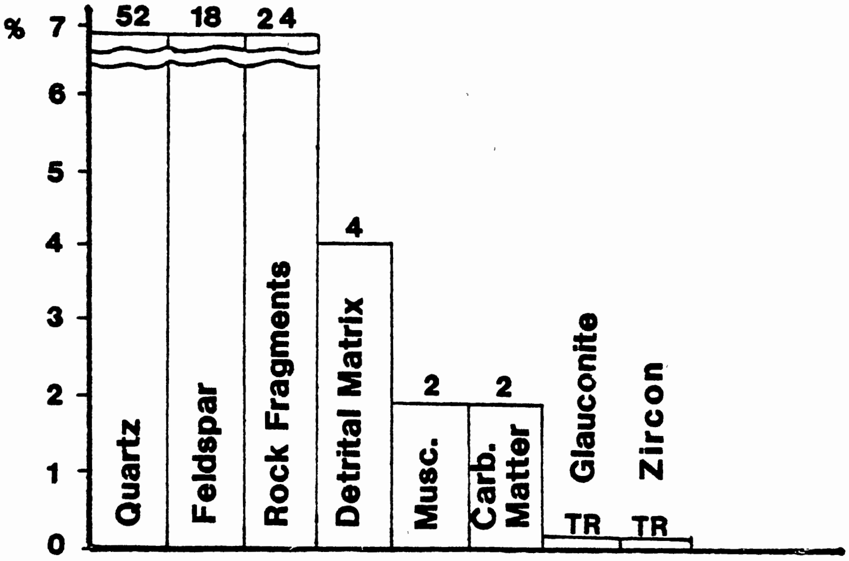


Figure 18. Detriatal Constituents

and rock fragments accounted for the majority of the Red Fork sand's constituents. This is a common characteristic of the Cherokee sands throughout much of north-central Oklahoma (Mason, 1982, Robertson, 1983, Lojek, 1983, and Balke, 1983).

Authigenic Constituents

Authigenic constituents consisted of mainly calcite, syntaxial quartz overgrowths, kaolinite, illite, chlorite, and pyrite. These materials served to reduce the effective porosity and permeability of the sandstone. Their formation was caused by later diagenetic events in which chemically rich solutions passed through the sandstone grains and these authigenic constituents precipitated. Figure 19 shows the average composition of authigenic material found in the samples that were analyzed.

Syntaxial quartz overgrowths were very apparent in that they were readily apparent by the presence of their "dust rims". These dust rims are made up of detrital clay which surrounded the original quartz grain (Figure 20). Quartz overgrowths ranged from one to nine percent. Possible sources for silica were pressure solution of quartz grains, dissolution of feldspar grains, and dissolution of clay minerals. The precipitation of quartz overgrowths is strongly dependent upon the chemistry of the pore fluids which pass through the sandstone. If the solution is acidic or has a high pH, then silica will precipitate. If the mineral rich solution is basic or has a low pH, then calcite cement will precipitate.

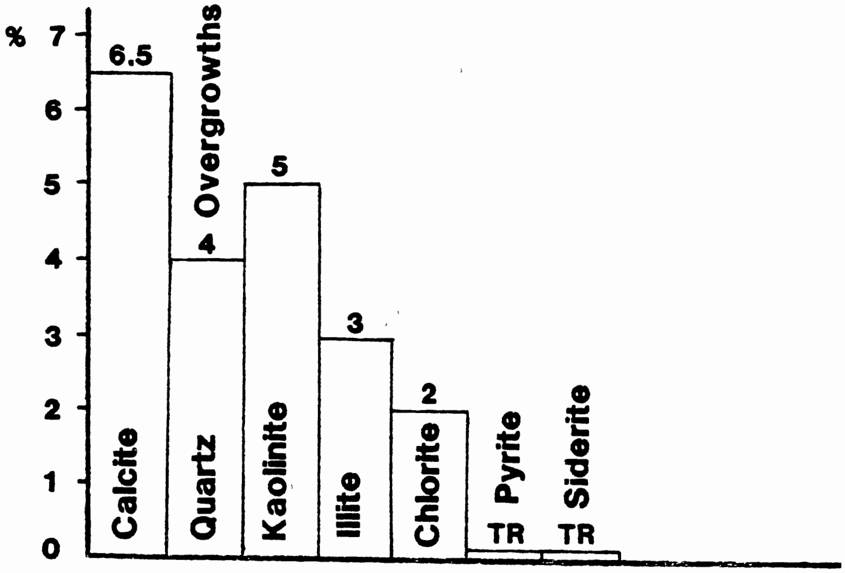


Figure 19. Authigenic Constituents

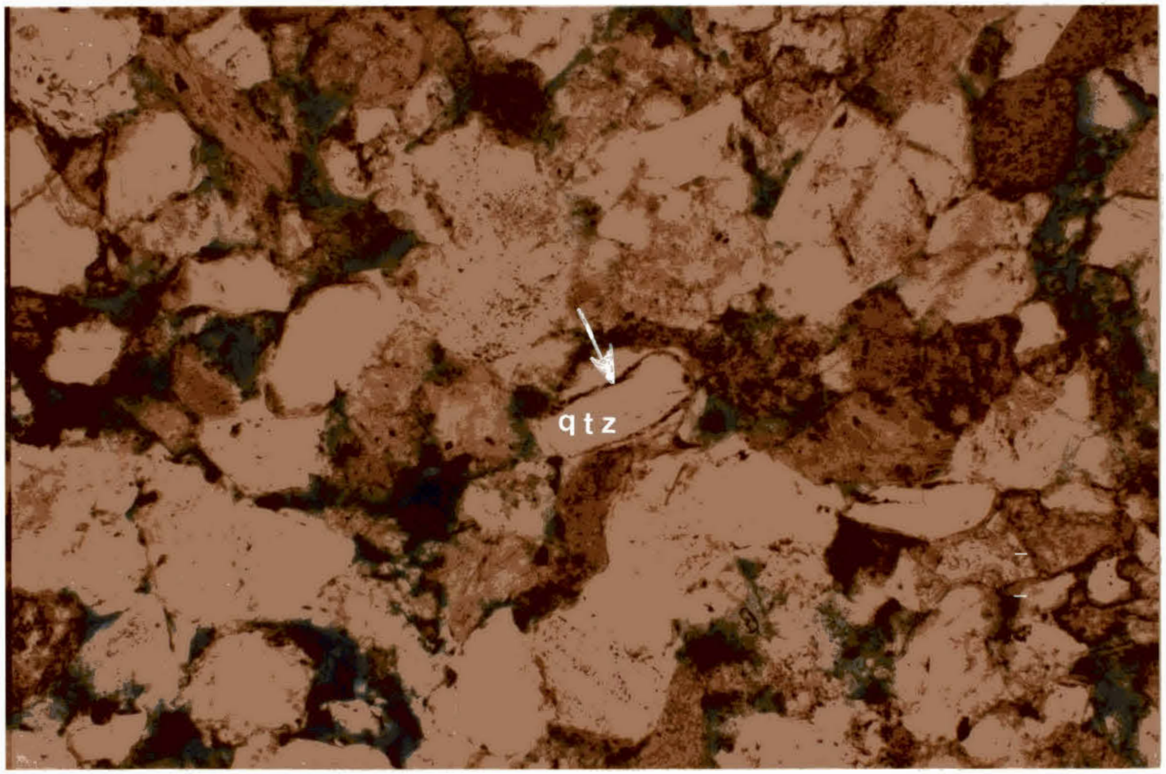


Figure 20. Quartz Overgrowths Evident By Presence of "Dust Rims", Plane Polarized Light, 100X

Authigenic calcite cement was identified in the majority of the thin-sections analyzed (Figure 21). It ranged from three to eight percent of total composition and averaged approximately 6.5 percent. Dissolution of the calcite cement was documented and created secondary porosity within the sandstone.

Authigenic Clays

Authigenic kaolinite, illite, and chlorite were present in the Red Fork sand. The presence of these clays was confirmed by X-ray analysis (Figure 22) and thin-section petrology. The X-ray diffraction angle in angstroms for kaolinite or chlorite occurs between 12.3 and 12.5, illite occurs at 8.8, and chlorite occurs at 6.2. The peak reduction after the sample was heated or dewatered proved the presence of kaolinite and not chlorite at the kaolinite peak position in the samples. The SEM demonstrated how kaolinite filled the pore spaces between the grains while illite and chlorite were found as pore linings.

Authigenic clays were identified by thin-section petrology and SEM. Kaolinite was readily documented by its distinctive morphology which is stacked pseudo-hexagonal plates or "books" which was commonly found in pore spaces. This type of stacking in a "snake-like" manner is called vermicular kaolinite. Kaolinite appeared brown under plane-polarized light and exhibited low birefringence (Figure 23). Through the aid of the scanning electron

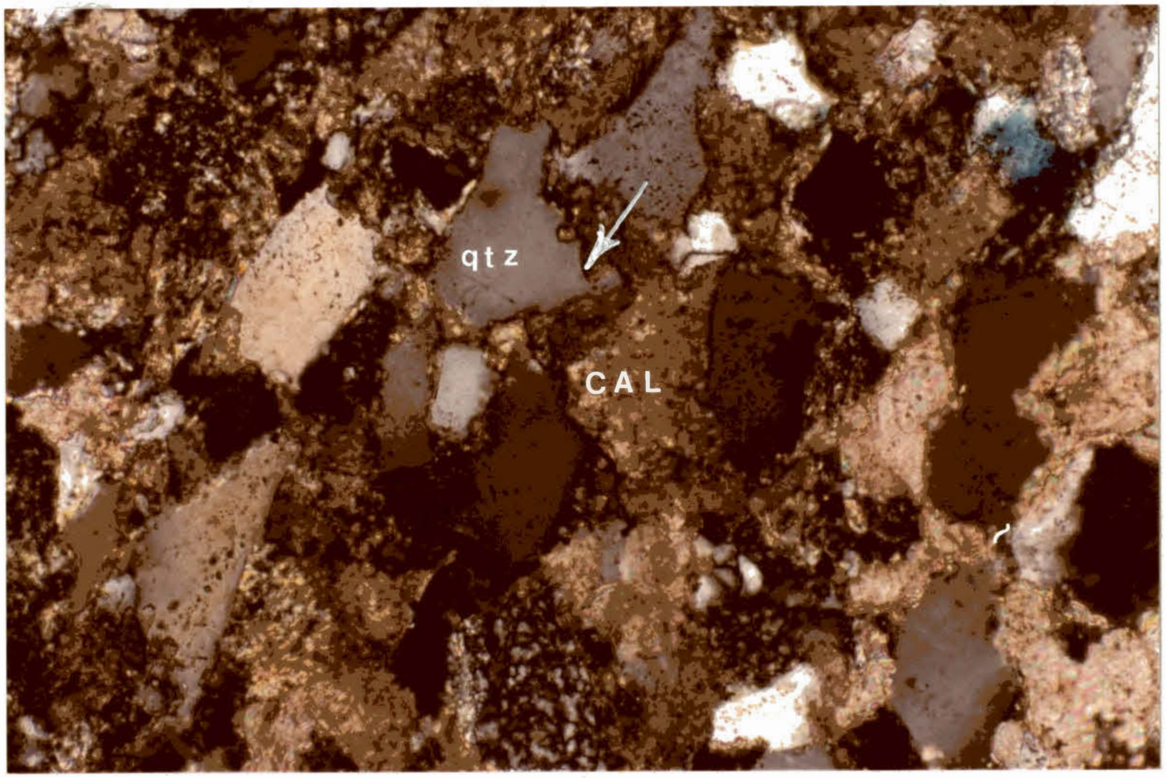


Figure 21. Calcite Cement With Evidence of Quartz Grain Dissolution, Crossed Nicols, 200X

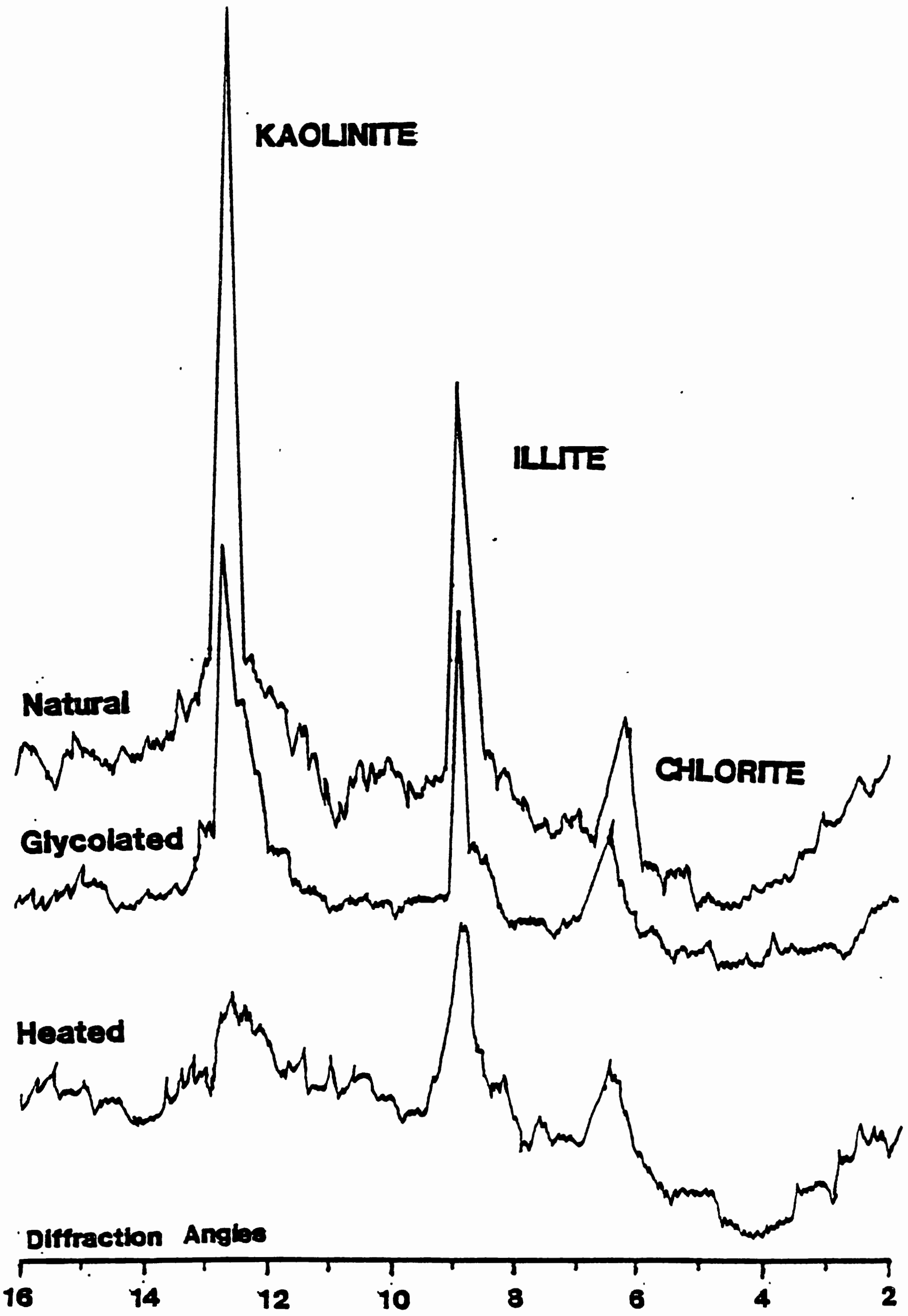


Figure 22. Type X-ray Peaks of Authigenic Clays

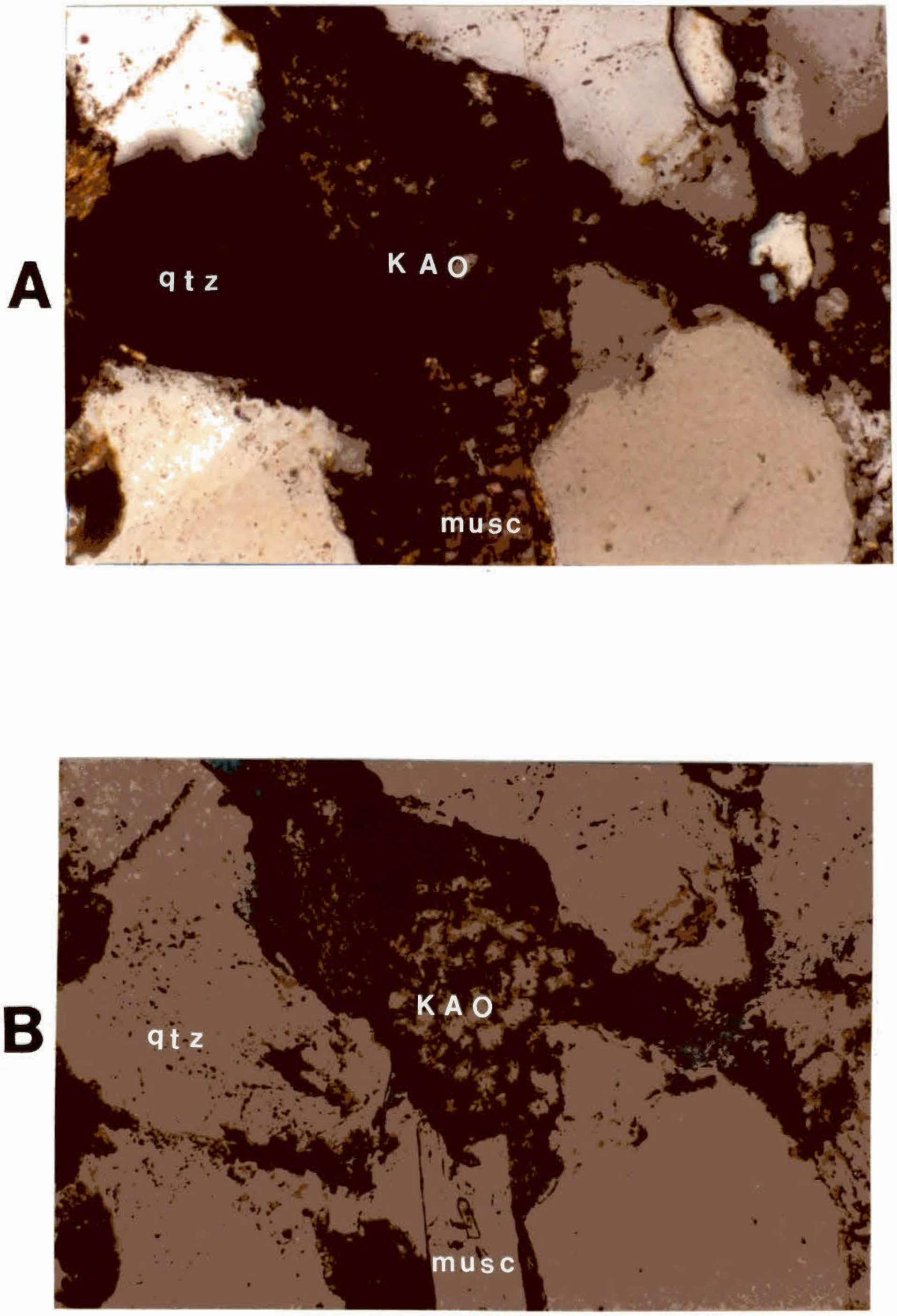


Figure 23. Pore-filling Vermicular Kaolinite, (A) Crossed Nichols, 200X, (B) Plane Polarized Light, 200X

microscope, kaolinite was found precipitated in oversized pore spaces which resulted in microporosity (Figure 24).

Authigenic illite was found to occur lining grains or bridging pore spaces between grains. Illite was identified by SEM as delicate "lath-like" structures which had the effect of decreasing both permeability and porosity (Figure 25). Illite in thin-section has high birefringence and was brown in color in plane-polarized light (Figure 26).

Authigenic chlorite appeared in SEM in its common end to face morphology. It was commonly found in the pore lining of grains which also reduces the sandstone's porosity and permeability (Figure 27). In thin-section, chlorite was olive-green in color under plane-polarized light and had an isopachous texture around many of the grains (Figure 28).

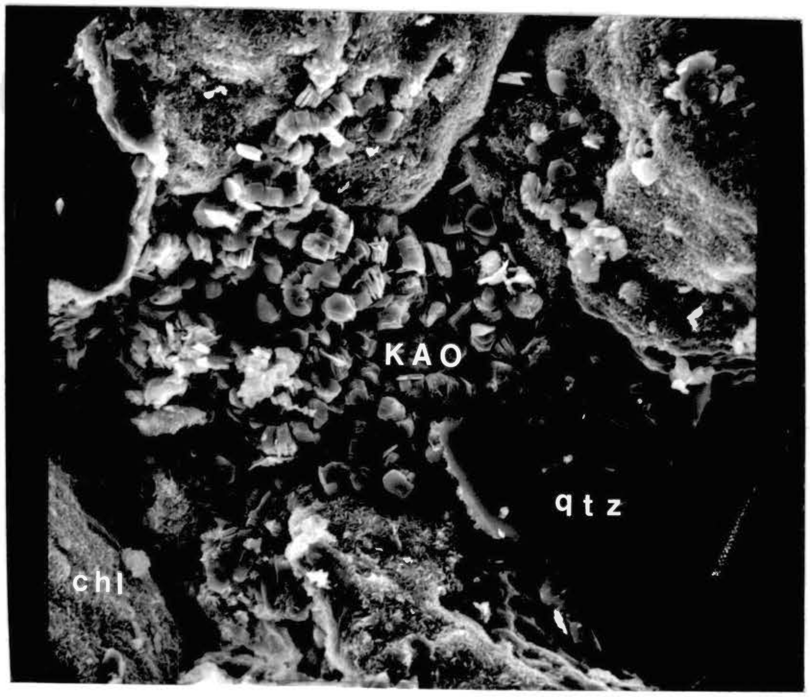


Figure 24. Kaolinite Found in Pore Spaces (SEM), 1500X

Figure 25. "Lath-like" Structures of Illite (SEM), 3000X

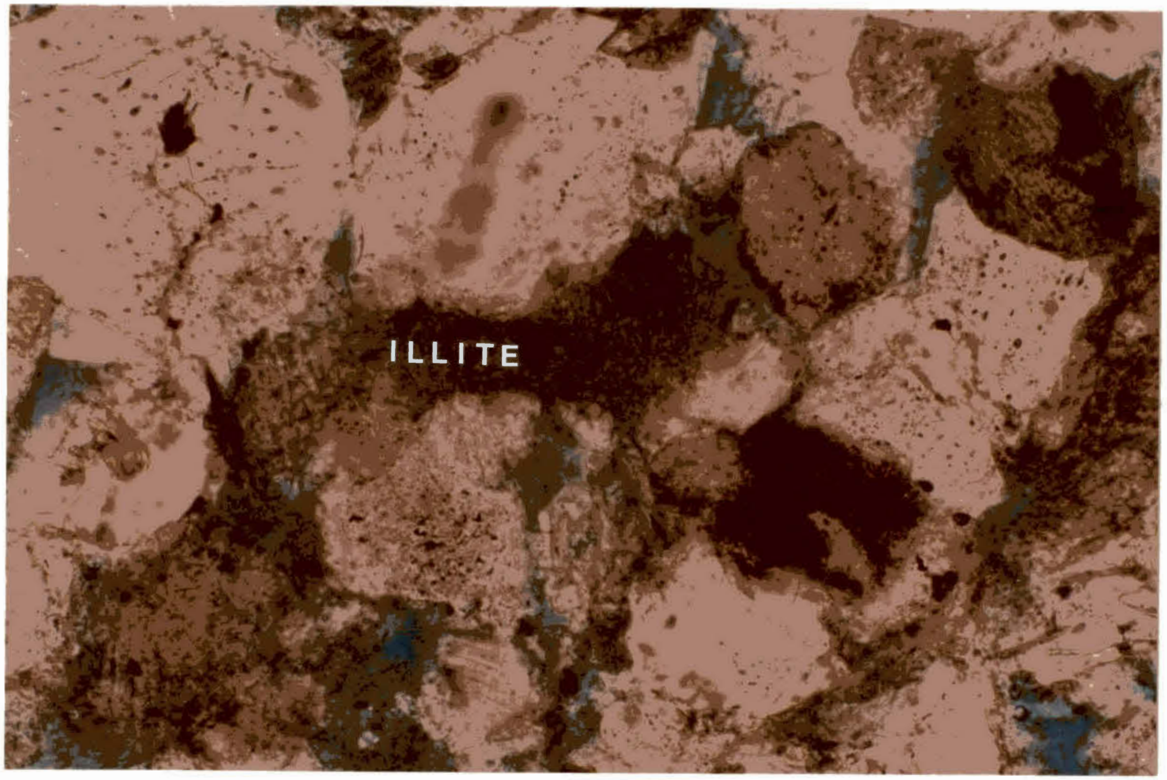


Figure 26. Illite Deposited in Pore Spaces, Plane Polarized Light, 200X

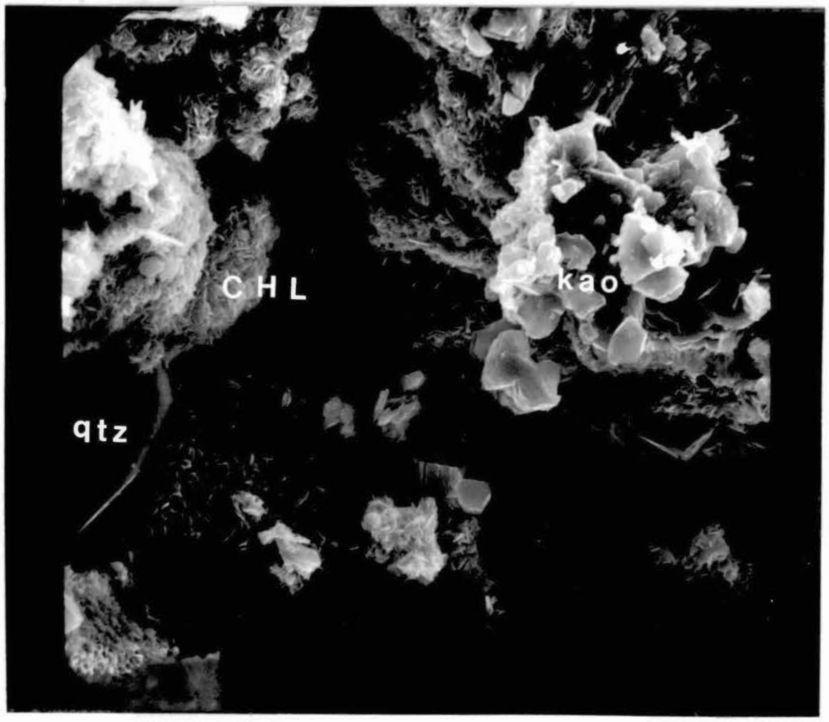


Figure 27. Chlorite Formed Around Grains (SEM), 1500X

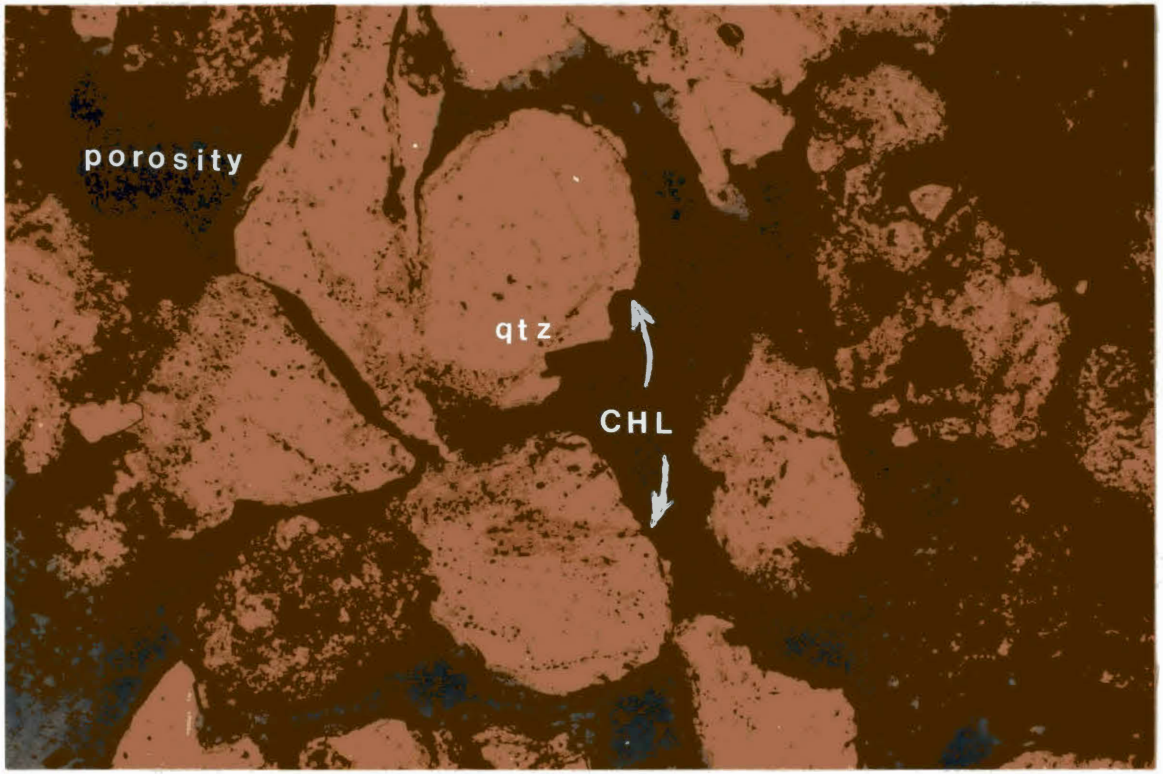


Figure 28. Isopachous Chlorite Surrounding Quartz Grains, Plane Polarized Light, 200X

CHAPTER V

DIAGENESIS

Introduction

A general term for diagenesis includes all physical and chemical alterations to which sediments are subjected to from the time of their deposition until they become slightly metamorphosed. These diagenetic events have been found to significantly influence reservoir quality of the Red Fork sandstone. Understanding of the units complex diagenetic history will aid in realizing what controls permeablity and porosity in the sand and how to preserve them both for maximum productivity of the formation.

Previous Investigation

Early pioneers in this field discovered the importance of diagenetic alterations in the creation of secondary porosity in reservoir rocks. Notable papers on this subject include Blatt (1979), Hayes (1979), Pittman (1979), and other studies compiled by Scholle and Schluger (1979). Al-Shaieb and Shelton (1981) discuss the role of secondary porosity to the migration of hydrocarbons. Wilson and Pittman (1977) observed authigenic clays in sandstones and discussed their importance and formation by different processes of diagenesis.

Predominant diagenetic events observed in the Red Fork sand were dissolutions, precipitates. and replacement events.

Dissolution Events

Partial or complete dissolution of detrital grains or cements were a common occurence in all of the Red Fork samples analyzed. Detrital quartz, metamorphic and sedimentary rock fragments, detrital matrix, and feldspar are predominately the most common grains active in observed dissolution events. The evidence for dissolution of quartz was observed as either partially corroded syntaxial quartz overgrowths or partially dissolved surfaces of the original grain. The dissolution of quartz could be due to the result of sediment compaction and/or the presence of alkaline solutions. Evidence supporting both hypotheses was observed in all samples.

Dissolution events of metamorphic and sedimentary rock fragments and detrital matrix were observed. This phenomenon was rare and did not account for much of the secondary porosity.

Feldspars were the most commonly dissolved detrital grain in the Red Fork sand. This partial or complete dissolution of feldspar generated much of the secondary porosity in the reservoir. Dissolution of feldspar grains initially began at cleavage planes of the feldspar grains which are the weakest bonds and are most susceptable to ionic substitution. The dissolved feldspar grain is later precipitated and produces the required chemical material to produce the observed authigenic clays.

Dissolved feldspar grains creating secondary porosity are a common characteristic to Cherokee reservoir sands. Pittman (1978) states that dissolution of feldspar grains is common worldwide in sandstones of all ages.

Precipitates

Precipitates of the Red Fork sandstone are classified into three different groups. These groups are precipitation of silica, carbonate, and clay minerals.

Silica

Precipitation of silica was recognized in all samples as syntaxial quartz overgrowths. This precipitation of silica was present early and throughout much of the diagenetic history of the Red Fork sand. This was evident by the presence of quartz overgrowths displaying a stacking pattern of thin layers of quartz upon each other. This created a layered appearance in which each layer of silica represented a different stage of precipitation. In between each of these silica layers, a thin layer of clay dust was deposited which enhanced this layering pattern. Possible sources for this influx of silica include: (1) hydrolysis of feldspar grains, (2) pressure solution of silica rich minerals, (3) precipitation of sea water, and (4) alteration of clay minerals.

Quartz overgrowths can play an important role on the porosity of the sandstone. If not for dissolution of this precipitation of silica, the silica overgrowths would have grown into all available pore spaces. This would have cut off much of the porosity observed in the sand.

Microquartz is also a common precipitate found in the Red Fork sand. These microquartz grains, commonly occurring as euhedral, precipitated in pore spaces that were partially filled with clay.

Carbonate

Carbonate precipitation has an inverse relationship regarding the precipitation of silica. Carbonate minerals form in basic environments while silica forms in acidic conditions. Three types of carbonate minerals were observed in the Red Fork sand. These are carbonate cement, dolomite, and siderite.

Carbonate cement was observed to form in pore spaces in between the grains of sand. This also aided in decreasing the porosity and permeability. Carbonate cement was also found to be precipitated around quartz grains which display pH alterations within the sand body.

Traces of dolomite cement was recognized in thin section and with the aid of the scanning electron microscope. Dolomite was not abundant because it was observed in thin section to be replaced by calcite cement.

Siderite cement ranged from a trace to approximately two percent. Two episodes of siderite cement were concluded by observing siderite deposited on original quartz grains and also on later forming quartz overgrowths.

Authigenic Clays

As mentioned previously, the Red Fork contains three types of clays which are (1) kaolinite, (2) illite, and (3) chlorite. Authigenic kaolinite is the most abundant of the three clays and commonly formed in pseudo-hexagonal plates. These plates stacked upon one another resembling a "snake-like" pattern defined as vermicular kaolinite. Vermicular kaolinite occurred in pore spaces within the sand grains decreasing porosity and permeability (Figure 29). Microporosity is well developed in between these kaolinite booklets, however, the minute size of these pore spaces does not enhance fluid flow (Figure 30). Thus, effective porosity is not increased by the presence of this type of porosity.

Figure 31 illustrates how illite was precipatated in either a pore lining or pore bridging within the sand grains. The scanning electron microscope demonstrated the delicate "lath-like" structure and high surface area of illite. Additional microporosity can form in between illite surfaces, however, this also is not significant in the total amount of Red Fork porosity.

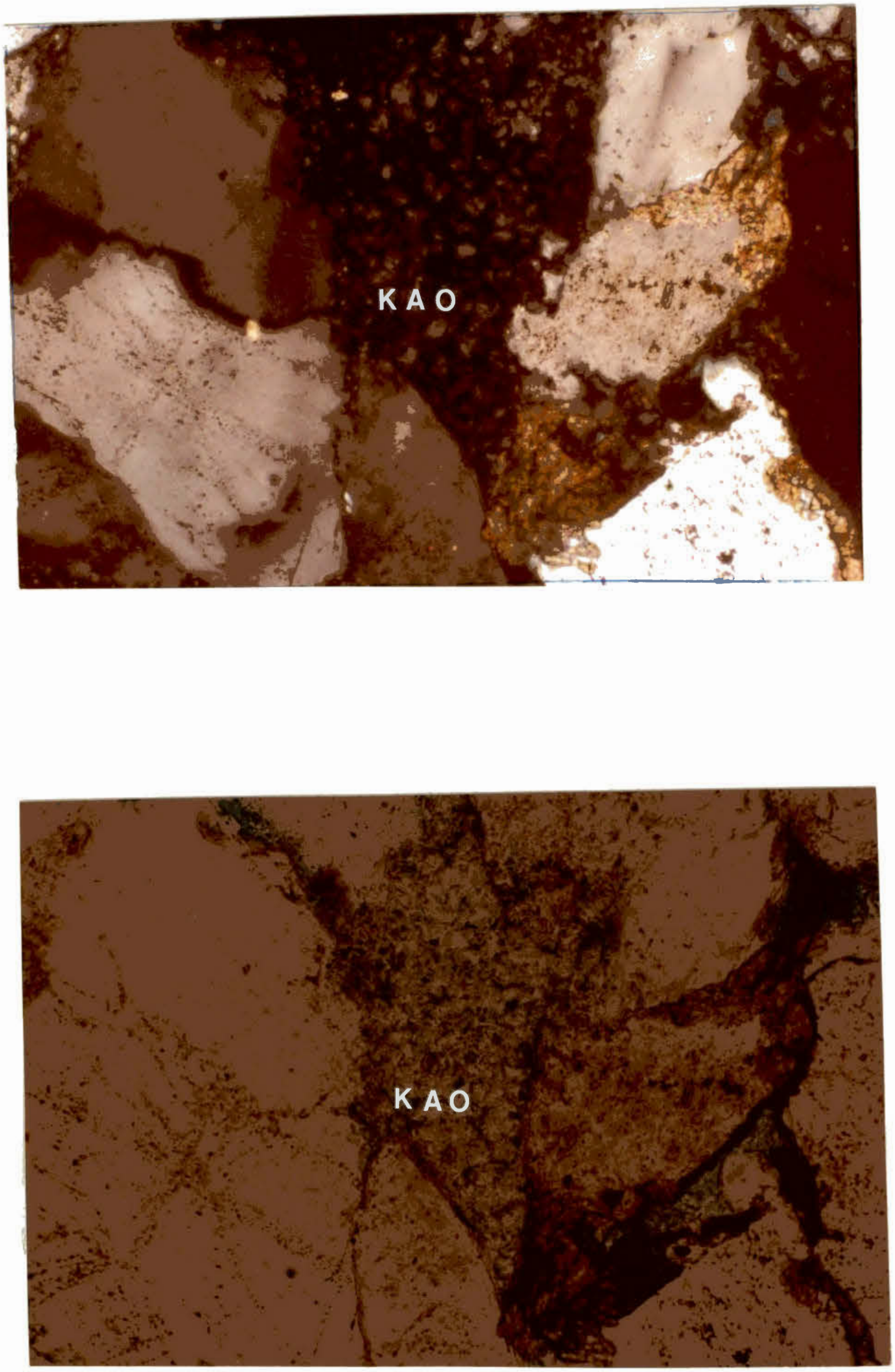


Figure 29. Vermicular Kaolinite in Pore Spaces Decreasing Porosity, (A) Crossed Nichols, 200X, (B) Plane Polarized Light, 200X

Figure 30. Microporosity In Between Kaolinite Booklets (SEM), 2500X

Figure 31. Illite Forming Pore Bridges Between Sand Grains (SEM), 3000X

Chlorite

Chlorite in the Red Fork was found as grain coatings and lining pore spaces in between the grains. Chlorite morphology seen by the scanning electron microscope was thin plates stacked end to end upon each other. This has also been called a two dimensional "house of cards" arrangement (Figure 32).

Geochemical Processes

Geochemical reactions determine the diagenetic events that have been described previously in this text. These reactions can be separated into three groups. They are (1) dissolution and precipitation of quartz and calcite, (2) feldspar hydrolysis reactions, and (3) oxidation of iron.

Quartz and Calcite

The pH of pore fluids is the major factor controlling the precipitation or dissolution of quartz and calcite. As previously stated, at pH greater than 9.0, all forms of quartz will dissolve and calcite will precipitate. At pH of 8.0, the inverse will be apparent. The solubility of calcite will also decrease with increasing depth (greater than 10,000 feet) and temperature under normal pressures (McBride, 1977).

The equilibrium reactions for dissolution of quartz and calcite are:

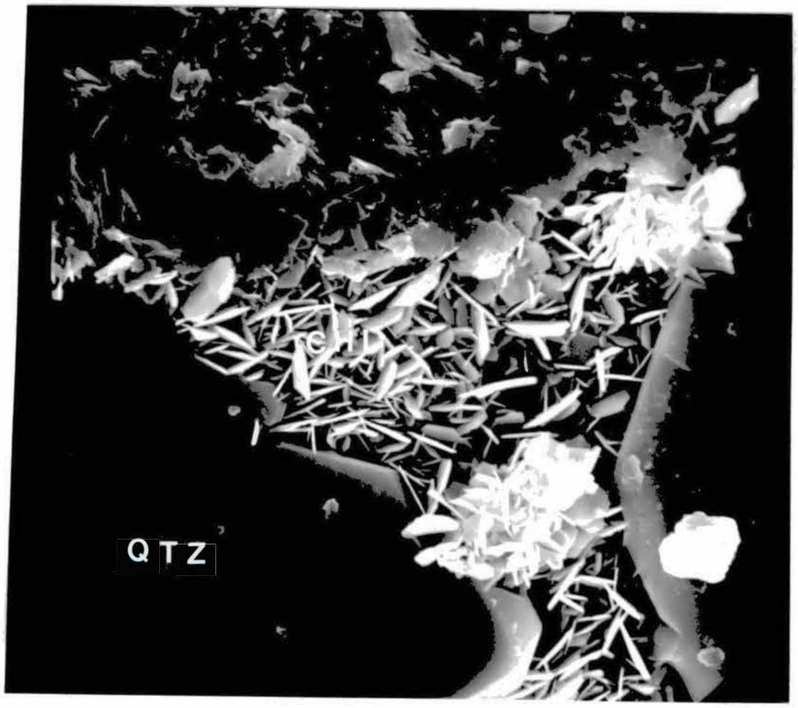


Figure 32. Chlorite Formed "House of Cards" Arrangement (SEM), 2200X

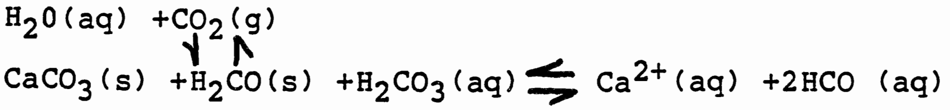
Silica -

$$SiO_2 + 2H_2O(aq) \rightleftharpoons H_4SiO_4(aq)$$

$$H_4SiO_4(aq) \rightleftharpoons H_3SiO_4(aq) + H^+(aq)$$

$$H_3SiO_4(aq) \rightleftharpoons H_2SiO_4(aq) + H^+(aq)$$

Calcite -



$$\begin{array}{l} \qquad\quad H_2O(aq) + CO_2(g) \\ \qquad\qquad\quad \downarrow \; \uparrow \\ CaCO_3(s) + H_2CO(s) + H_2CO_3(aq) \rightleftharpoons Ca^{2+}(aq) + 2HCO\ (aq) \end{array}$$

Al-Shaieb and Shelton (1981) concluded that dissolution of silica may be increased by the following: (1) compaction of hydrogen ions during the dissolution of feldspar grains may increase the pH of pore fluids, (2) the result of the reaction between silicic acid and bicarbonate ions will increase the reaction of silica and water adding to increase the solubility of quartz, and (3) an increase in temperature will increase the dissolution of quartz.

Feldspar Hydrolysis

The dissolution of feldspar is also pH dependent and results from hydrolysis reactions. Hydrolysis reactions are those reactions that take place between water and the ion of a weak acid or a weak base. As pH decreases, feldspar will dissolve (or alter to clay) and silica will precipitate. The major equilibrium reactions that take place are:

$$\underset{\text{(K-Feldspar)}}{3KAlSi_3O_8} + 2H_2CO_3(aq) + 12H_2O \rightleftharpoons \underset{\text{(Illite)}}{KAl_3Si_3O_{10}(OH)^2} + 2K^+(aq)$$

$$+\ 6H_4SiO_4(aq) + 2HCO_3^-(aq)$$

(Silicic Acid)

(Al-Shaieb and Shelton, 1981)

$$2KAl_3S_3O_{10}(OH)_2 + 2H_2CO_3(aq) + 3H_2O(aq) \rightleftharpoons 3Al_2Si_2O_5(OH)_4$$

(Illite) (Kaolinite)

$$+\ 2K^+(aq) + 2HCO_3^-(aq)$$

(Al-Shaieb and Shelton, 1981)

Al-Shaieb and Shelton (1981) stated that the dissolution of feldspar may be enhanced by an increased concentration of CO_2 which releases sodium, calcium, potassium, and magnesium ions into the pore fluids. A synthesized feldspar hydrolysis reaction which took place in the Red Fork is:

$$(1/2\ Ca, Na, K)\ Al_3SiO_8(s) + 6H_2O(aq) +$$
$$2H^+(aq) \rightleftharpoons 3H_4SiO_4(aq) + 2(OH)^-(aq) +$$
$$(1/2\ Ca^{2+}, Na^+, K^+)(aq) + 3Al^{3+}(aq)$$

Iron Oxidation

Chlorite forms as an alteration of both kaolinite and illite through the oxidation of iron ions.

$$3.5Fe^{2+} + 3.5Mg^{2+} + 9H_2O + 3Al_2Si_2O_5 \rightleftharpoons$$

(Kaolinite)

$$Fe_{3.5}Mg_{3.5}Al_{6.0}O_{20}(OH)_{16} + 14H^+$$

(Chlorite)

(Boles and Franks, 1979)

$$3KAL_2ALSiO_3O_{10}(OH)_2 + 10(Fe,Mg)^{2+} + 12H_2O \rightleftharpoons$$

(Illite)

$$2AL(Mg,Fe)_5AlSi_3O_{10}(OH)_8 + 5Al^{3+} + 3Si(OH)_4 + 3K^+ + 2H^+$$

(Chlorite)

(Al-Shaieb, 1981)

CHAPTER VI

PARAGENETIC SEQUENCE

Figure 33 shows the paragenetic sequence of diagenetic events that led to the present status of the Red Fork Sandstone. Diagenetic events are plotted on the vertical axis and relative time is plotted on the horizontal axis. Each episode is delineated by either a dashed line (representing an event that may have been sporadic or not conclusively documented) or a solid line (representing a proven or continuous episode).

The diagenetic system was continuously affected by major and minor tectonic changes. The chemistry of the subsurface fluids, which created much of the changes within the Red Fork, is dynamic and quite complex. Minor folding or faulting could introduce different pore fluids which could alter formation temperature, pressure, or pH of the post-depositional environment. Thus, the diagenetic system of the Red Fork sand seldom could be considered in equilibrium. For example, in acidic environments silica will precipitate while calcite will dissolve. Any alterations in the pH of the pore fluids will affect this chemical process.

The different stages of the diagenetic history were

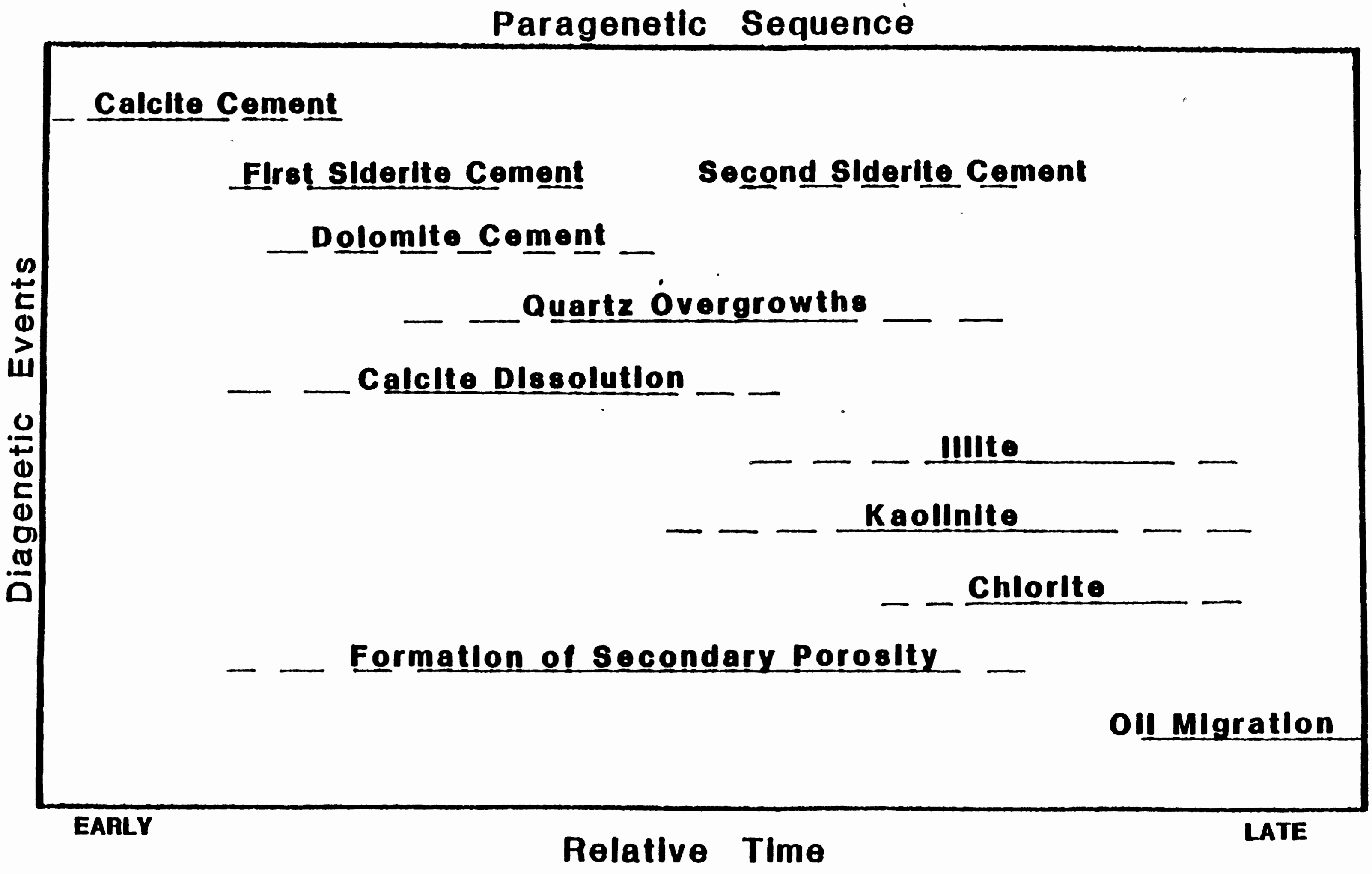


Figure 33. Paragenetic Sequence

determined by emperical observations and based upon possible chemical reactions. The event of oil migration occurring in the later time period of the paragenetic sequence was hypothesized by the presence of oil stain on grains that also formed later in the sand's diagenetic history.

CHAPTER VII

POROSITY

Introduction

Total porosity within a sand body is defined as being the percent ratio of total volume of pore spaces to the total volume of the rock. Identification of porosity types was based upon thin section examination and use of the scanning electron microscope. Thin sections were prepared by impregnating the sample with blue epoxy. This procedure was done in order that the size and geometry of the pore spaces would be preserved for identification. The scanning electron microscope provides examination of the delicate structures of the sand's constituents. Thus, minute details of the evolution of secondary porosity can be observed which has been concluded to play an important role in the resultant effective permeability of the rock.

Two types of porosity were observed in the Red Fork. The first type is primary porosity or intergranular porosity which forms from initial depositional processes. The second type is called secondary porosity which results from shrinkage, fracturing, dissolution, or a combination of all of these methods.

Primary Porosity

Primary porosity, commonly observed to be intergranular, is porosity which developed by original sedimentation processes when the rock was initially deposited. This type of porosity was of minor importance compared with the overall porosity of the sand. An average of three percent primary porosity was recognized in the samples analyzed. This small amount of primary porosity is due to a combination of overburden pressures, time stresses on the rock, and the introduction of cementation. This type of cementation was in the form of quartz overgrowths and injection of detrital matrix.

Petrographic Criteria

Secondary pores of reduced intergranular porosity is documented in many sandstone bodies throughout the world (Scholle and Schluger, 1979). In thin-section analysis, Schmidt and McDonald (1979) recognized eight criteria for identification of secondary porosity. These are: (1) partial dissolution, (2) grain molds, (3) inhomogeneity of packing and "floating" grains, (4) oversized pores, (5) elongated pores, (6) corroded grains, (7) honeycombed grains, and (8) fractured grains.

Secondary Porosity

Secondary porosity is defined as pore space that is created by means other than by primary cementation and compaction. This type of porosity is credited for the majority of the pore spaces in the Red Fork sand in the study area. Petrologic analysis of the sand demonstrated an average of 12 percent secondary porosity which fluctuated between seven and twenty percent.

The major types of secondary porosity observed were oversized pores, grain molds (Figure 34), honeycombed pores (Figure 35), micro-pores (Figure 36), "floating" grains, and corroded grains (Figure 37). The majority of the secondary porosity was created by the dissolution of feldspar grains. Dissolution of calcite and silica, however, also created minor amounts of diagenetic porosity.

Partial or complete dissolution of feldspar grains was paramount in the development of both the total and effective porosity in the Red Fork sand. This also allowed easier access for fluids to pass through the sandstone which promoted additional diagenetic reactions. Secondary porosity was both created and destroyed through these diagenetic processes. Dissolution created pore spaces, however, precipitation of authigenic clays within the pore spaces reduced effective porosity and permeability by filling in and clogging pore throats.

Graphic displays of significant petrologic information taken from thin-section analysis can be found in Appendix C. These graphs show the relationships of different Red Fork constituents to porosity, grain size, and the interval depth. The graphs display how, when the percent of feldspar

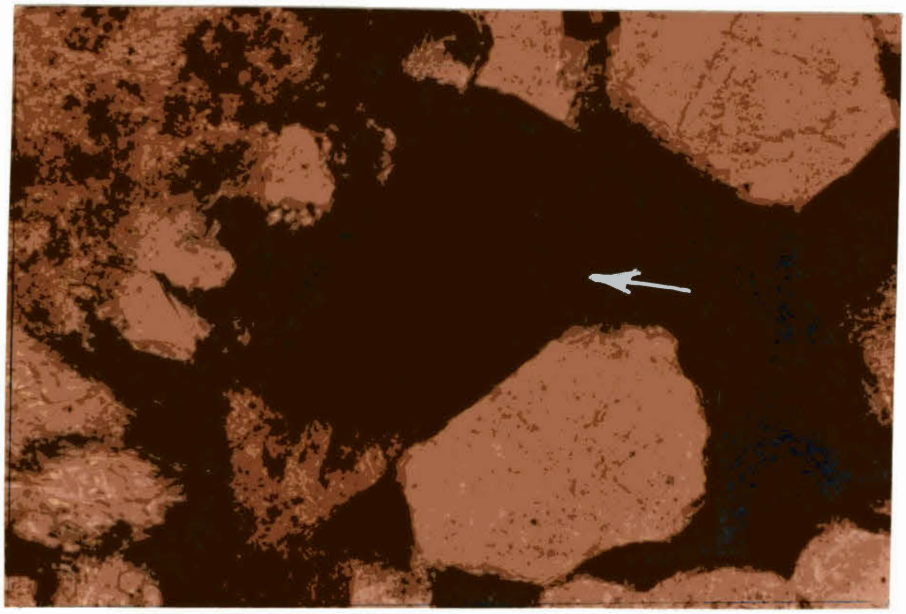


Figure 34. Grain Mold, Ghost of a Dissolved Grain Infilled with Authigenic Illite, 200X

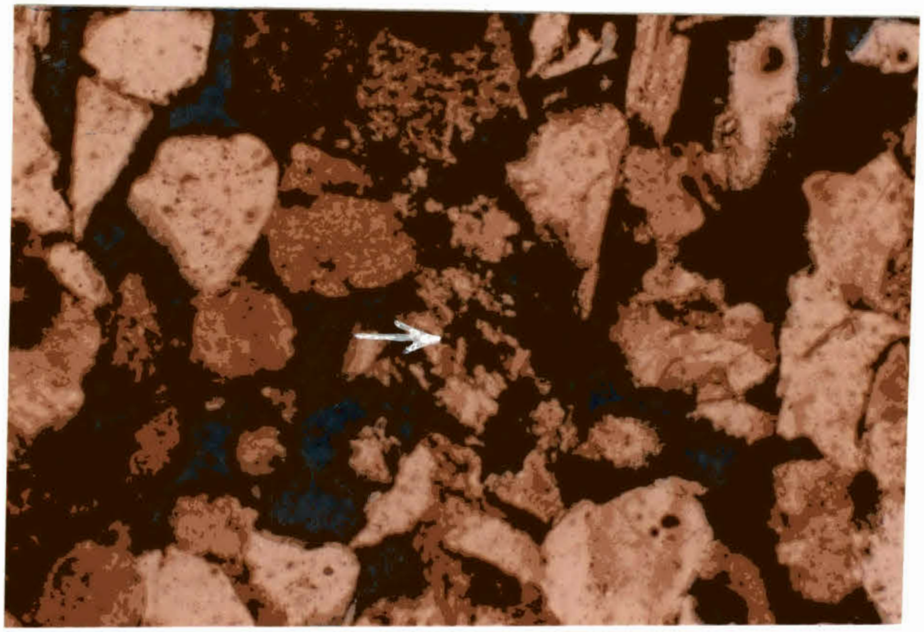


Figure 35. "Honeycombed" Pores, 100X

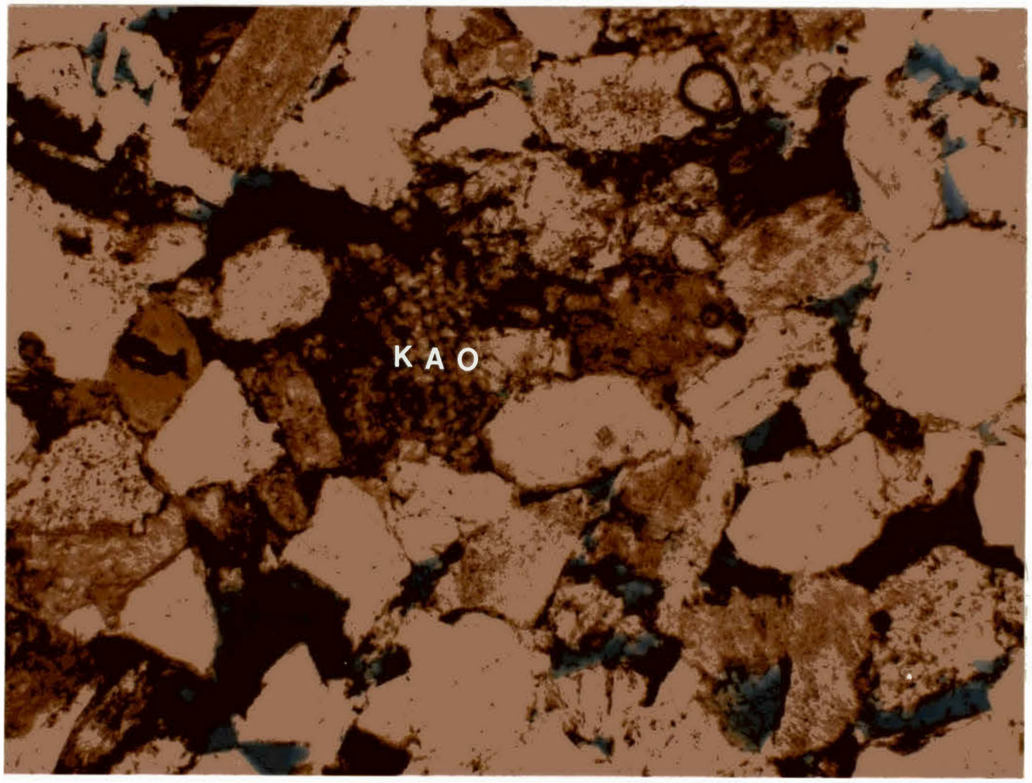


Figure 36. Microporosity Created By Authigenic Kaolinite, 100X

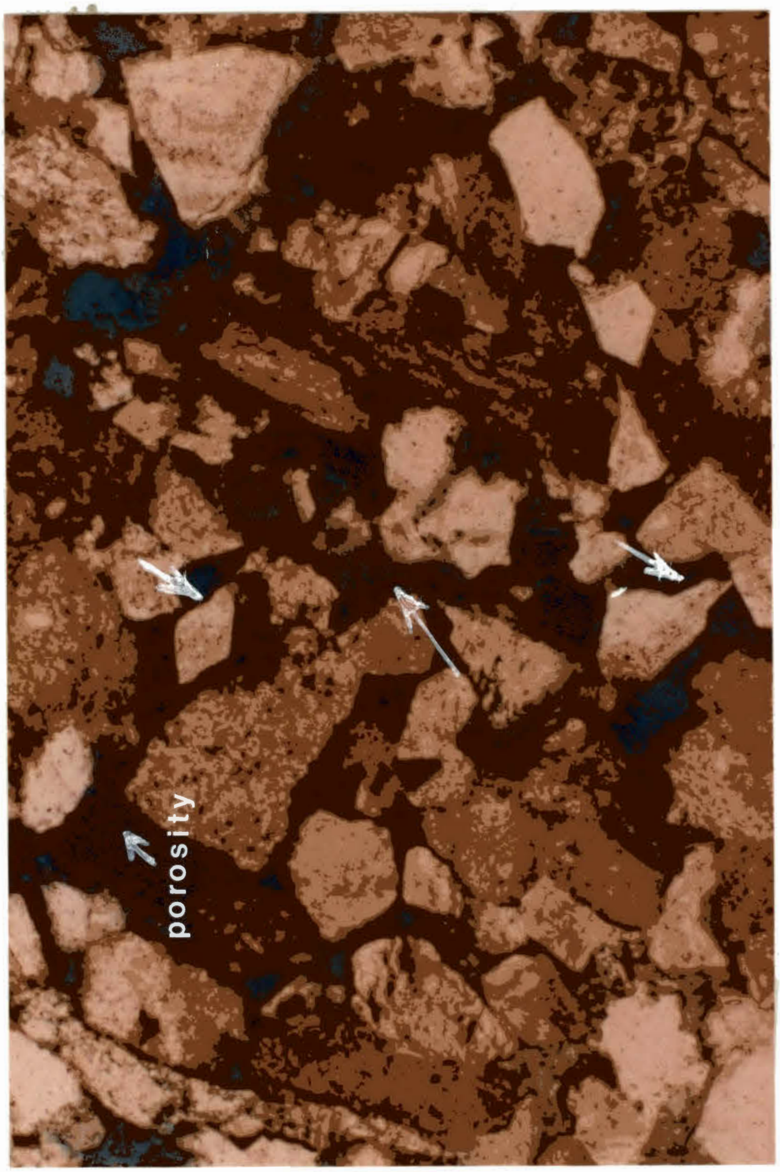


Figure 37. Floating and Corroded Grains, 100X

grains and rock fragments decrease, porosity increases. The percent of clay also increases with an increase of porosity, however, a large percent of clays can also be found in zones of low porosity. These graphs agree with the conclusions made concerning the relationship of secondary porosity to dissolution of mineral grains and clay precipitation.

CHAPTER VIII

THE IMPLICATIONS OF CLAYS ON RESERVOIR QUALITY

Introduction

The presence of clay minerals has wide implications in the search for and production of both oil and gas. Very few hydrocarbon bearing rocks are devoid of clay minerals. Authigenic clays have been found to control many petrophysical properties which play an important role in determining reservior quality. To obtain accurate values of electric-log responses, effective porosity, water saturation, and production methods, both the type of clay and volume or distribution of that clay must be understood. To obtain this information it is not feasible to conduct an expensive and time-consuming core analysis such has been done in this study. Advanced concepts in log interpretation in addition to diagenetic research has been completed which will answer many of these important questions.

Properties of Clay Minerals

Clay is used as both a mineral term and a grain size term. Scientists define clay size as being between two to four microns; however, the Wentworth scale classifies clay particles as being finer than four microns. This study deals with the mineral term of clay and more specifically, authigenic clay. This is a clay mineral that formed or precipitated in the place of deposition.

The Red Fork sand possesses three different types of authigenic clays. These are: (1) kaolinite, (2) illite, and (3) chlorite. To discuss their importance for exploration and production of hydrocarbons one must have a basic understanding of their morphology and crystal structure.

Kaolinite

Kaolinite is a hydrated aluminosilicate commonly found within the pore spaces of the sandstone. Its crystal structure is composed of a single silica tetrahedral sheet and a single alumina octahedral sheet stacked upon each other so that the tips of the silica tetrahedron face one of the layers of the alumina octahedral sheet. All tips of the tetrahedral sheet point towards the center of the layer made by the octahedral and tetrahedral sheets (Ruhovets and Fertl, 1981). This gives kaolinite its layered appearance as seen in thin-section as vermicular kaolinite and with the scanning electron microscope. Kaolinite is classified as a 1:1 type because of its one tetrahedral and one octahedral structure.

Kaolinite will align itself in this manner continuously in the a- and b-directions and stack one upon another in the c-direction. Kaolinite can vary depending upon the position of the Al atom which is open to different positions in the octahedral layer (Ruhovets and Fertl, 1981).

The chemical formula is $(OH)_8Si_4Al_4O_{10}$ with electrical charges within structural unit being balanced.

Illite

Authigenic illite forms either as a pore lining or pore bridging hydrosilicate. The scanning electron microscope displays the "lath-like" morphology which creates a large surface area (Figure 38) and microporosity.

Illite is composed of two tetrahedral sheets and an octahedral sheet. Thus, it is classified as a 2:1 type clay. The octahedral sheet is positioned in between the two tetrahedral sheets above and below. The unit layers extend indefinitely in the a- and b-directions and are stacked in the c-direction. An important potassium ion, however, is positioned in between unit layers of tetrahedral and octahedral sheets. Different types of illite clays exist because this potassium ion can be replaced by other possible cations namely, Ca^{++}, Mg^{++}, and H^+. H_3O^+ and K_2O can also replace the potassium ion which leads to a more random stacking in the c-axis (Ruhovets and Fertl, 1981).

The general chemical formula for illite is $(OH)_4K_2(Si_6 * A_{12})Al_4O_{20}$. Substitution can occur for aluminum by either of the cations Ca^{++}, Mg^{++}, H^+, Fe^{++}, or Fe^{+++}.

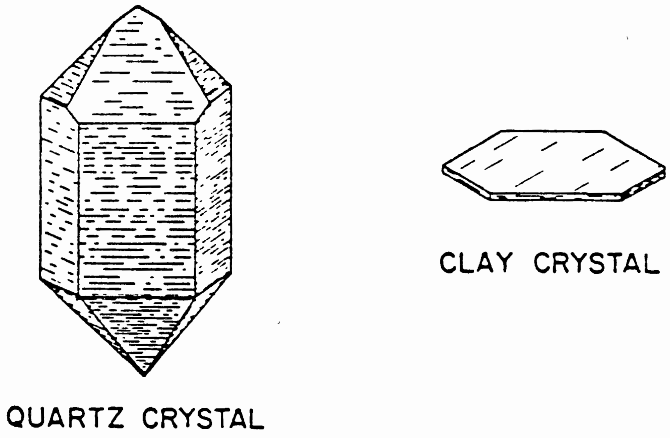


Figure 38. A Crystal of Quartz and a Crystal of Clay. The Clay Crystal is Much Smaller, However, It Has a Very High Surface Area to Volume Ratio

Chlorite

Authigenic chlorite, which commonly occurred as a pore lining or pore filling, is a hydrated aluminum silicate which is classified as a 2:1:1 type clay. This is because chlorite structure is made up of one tetrahedral, octahedral, and brucite layer. The tetrahedral and octahedral layer is defined as a "mica-like" layer which has the chemical composition of $(OH)_4(SiAl)_8(MG * Fe)_6O_{20}$. The brucite layer has a chemical composition of $(Mg * Al)_6(OH)_{12}$ (Ruhovets and Fertl, 1981). There can be dioctahedral and trioctahedral chlorite depending on the unit charge of the mica layer.

Clay Effects on Production

As previously stated, authigenic clays commonly precipitate in pore throats and lining around grains. This decreases effective porosity, permeability, creates microporosity, and increases surface area. These, unfortunately, are only a few of the problems created by authigenic clays.

Clay Effects on Electric Logs

Clay exhibit a negative charge due to (1) electrostatically unbalanced substitutions within their lattice or (2) weak or broken bonds around the edges of the silica-alumina units (Martin, 1962). The aim of the negatively charged clays is to balance their charge with an ion that is positively charged. They obtain this balancing charge by absorbing an oppositely charged cation from the pore fluids that surround the clay surface. The amount of exchangeable cations available is called the Cation Exchange Capacity. Johnson and Linke (1978) define the cation exchange capacity as the amount of positive ion substitution that takes place in a unit of rock. The cation exchange capacity is expressed in milliequivalents per 100 grams of dry clay. The most common exchangable cations are Ca, Mg, Na, K, and NHPV4PV (Mian and Hilchie, 1982). A high concentration of cations near the clay surface allows the clays to be more conductive. This cation concentration is independent of water salinity. However, Van Olphen (1963) concluded that in a highly saline environment, cations are compressed to the clay surface thus reducing mobility and decreasing electrical conductivity.

Wyllie (1955) concluded that clay minerals with high absorptive capacity for electrolytes, such as kaolinite and montimorillonite, will produce an increased spontaneous potential curve and a suppressed resistivity curve. These alterations in recorded log readings are caused by the abundance of cations that would disassociate at the clay mineral-water interface. Illite and chlorite have low absorption capacities, however, they would also effect these electric logging tools in the same manner because of their variable structure of interlayered cations.

Clay particles have been determined to hold irreducible water (water that is held because of the solid's attraction for the liquid) in micropores. This may indicate on the log as a sand that is water saturated, however, the well may produce water-free oil (Almon and Davies, 1978). This is caused by the positively charged hydrogen ion in water being attracted to the negatively charged clay surface.

Gamma-Ray Log Responses

The Gamma-Ray logging tool records the radioactivity or spontaneous disintegration of elements in a certain formation. The only radioactive element in clays is the potassium ion present in illite. The presence of a highly concentrated amount of illite would increase the gamma-ray curve.

Density and Neutron Log Response

The density log records the bulk density of the reservoir rock. The neutron log emits bombardment of neutrons into the formation and the neutron log records the development of secondary radioactivity. Variations of porosity of the formation calculated from these two types of logging methods is mainly due to the volume and type of clays present (Ruhovets and Fertl, 1981).

Clay Amounts

Bacon (1948), Pierson (1950) Griffiths (1952), Wyllie (1955), Hill and Milburn (1956), and Almon and Davies (1982) all have shown how minor amounts of clay (between one to five percent) within the reservoir rock can significantly effect electric log responses. Pierson (1950) stated that sand rich in illitic clay always exhibits low resistivity readings regardless of oil and gas saturations. Almon and Davies (1982) stated "Even a few percent of a diagenetic mineral can greatly reduce permeability, increase acid or fresh water sensitivity, totally alter electric log response characteristics, or increase irreducible water saturations". Bacon (1948) concluded that as little as one percent of clay in a sand body may have significant effects on both laboratory and field data.

Therefore, because of the relatively large amount of clay present in the Red Fork sand, interpretations and treatment for this clay must be undertaken.

Treatment for Authigenic Clays

Kaolinite

As identified by the use of the scanning electron microscope, booklets of kaolinite crystals are relatively large. As fluid flow through a formation increases and as hydrocarbons are pumped out of the well, kaolinite crystals will begin to break apart and migrate to clog pore throats. This eventually reduces reservoir permeability to the point where the well cannot economically produce any further.

This problem of migration of kaolinite fines can be reduced by using a variety of clay stabilizing agents (such as polyhydroxy aluminum). From a chemical point of view, kaolinite is very stable and any acid treatments will have no effect on the clay (Almon and Davies, 1981). The use of clay stabilizers should be utilized early in the history of the well to obtain maximum productivity.

Illite

A major problem with illite is that it can develop significant amounts of microporosity. This microporosity has been found to bind water to grains within the sand body. Pittman (1979) concluded that this would cause the electric log to display high water saturations. Permeability will be reduced because of the clay's delicate "lath-like" structure will break apart, as with kaolinite, and migrate to pore throats.

Many of these problems caused by illite can be reduced by avoiding contaminating the hole with fresh water and by using potassium chlorite or a petroleum based fluid system. Almon and Davies (1981) discovered that illite may be dissolved by using a mixture of hydrochloric and hydrofluoric acids, however, this may create additional problems with significant amounts of chlorite clay present in the sand.

Chlorite

Chlorite is also a hydrated alumino-silicate which has been found to contain significant amounts of iron and magnesium. It dissolves easily in hydrochloric acid and oxygenated waters (Wilson and Pittman, 1977). When chlorite dissolves in waters of pH greater than five, large amounts of iron will dissolve and go into solution which will reprecipitate as a gel of ferric hydroxide Fe $(OH)_3$. This ferric hydroxide will block pore throats and decrease permeability.

To avoid this problem, an oxygen scavenger and an iron chelating agent is added to the acids (Almon and Davies, 1978). If formation damage has already occurred, the problem can be reduced by using a mixture of a weak acid (5% HCL and 5% HF) along with the iron chelating agent and an oxygen scavenger (Almon and Davies, 1979).

Additional Techniques

New techniques for eliminating the problems caused by clays are top priority for many service companys. B. E. Hall (1978) of Halliburton Service developed an in-situ hydrofluric acid for deep clay removal which provides for a more efficient system for treating clay damaged formations (Robertson, 1980). Completion of each well must take into account the clay present and how to deal with them. One suggestion in the exploitation of a formation is to slow the pumping rate down and, if porosity and permeabilities allow it, perform a natural completion. This is where the formation is not treated with acids, except the possibility of a clay stabilizer, and the hydrocarbons are produced with natural formation porosity and permeability.

Clay Corrections for Electric Logs

Electric log patterns of the Red Fork Formation will display depressed resistivity values and high water saturations. This has resulted in evaluating the formation improperly and, in some cases, potential hydrocarbon productive wells may have been overlooked. By correcting for the cation exchange capacity (which is the amount of positive ion substitutions that takes place per unit weight of dry rock) a more accurate reading of the formation may be obtained.

Hill and Mulburn (1956), Waxman and Smits (1968), and Waxman and Thomas (1974) have described methods of calculating water saturations in clay-rich sediments. These methods relate water saturation to the common resistivity ratio and water resisitivity data and also the clay conductivity of the formation. Thus, the cation exchange capacity is accounted for which provides a more accurate value for water saturation in a hydrocarbon bearing zone.

This correction is called the Waxman and Smits equation and it can be found in Figure 39 with explanation of the nomenclature.

Graphic displays of water saturations determined by the Waxman and Smits equation for varing values of "n" can be found in Figures 40, 41, and 42.

Summary

The Red Fork sand in the area under investigation contains a significant amount of clays of kaolinite, illite and chlorite. Effective and efficient reservoir exploration and exploitation demands an understanding of these clays. Methods for correcting the highly active ion exchange surfaces of clays must be calculated for accurate interpretations of electric logs. Completion programs must design methods for proper control of the clays to extend the productivity of the well.

A Form of the Waxman and Smits Equation is:

$$S_w^{n*} = \frac{F_R^* \text{ x } R_w}{R_t(1 + R_w B Q_v / S_w)}$$

R_t = True Formation Resistivity, ohm-meters

R_w = Formation Brine Resistivity, ohm-meters

S_h = Formation Hydrocarbon Saturation, fraction

S_w = Formation Brine Saturation, fraction

Q_v = Quantity of cation exchangeable clay present, meq/ml of pore space

B = Specific counterion activity, (1/ohm-m)/(equiv./liter)

F_R = Formation Resistivity Factor

F_r^* = Formation Resistivity Factor where formation or formation sample is saturated with a very low resistivity brine

m^* = Cementation Exponent associated with F_R^*

n^* = Saturation Index Exponent at very low R_w values

a^* = Equation Coefficient associated with F_R^*

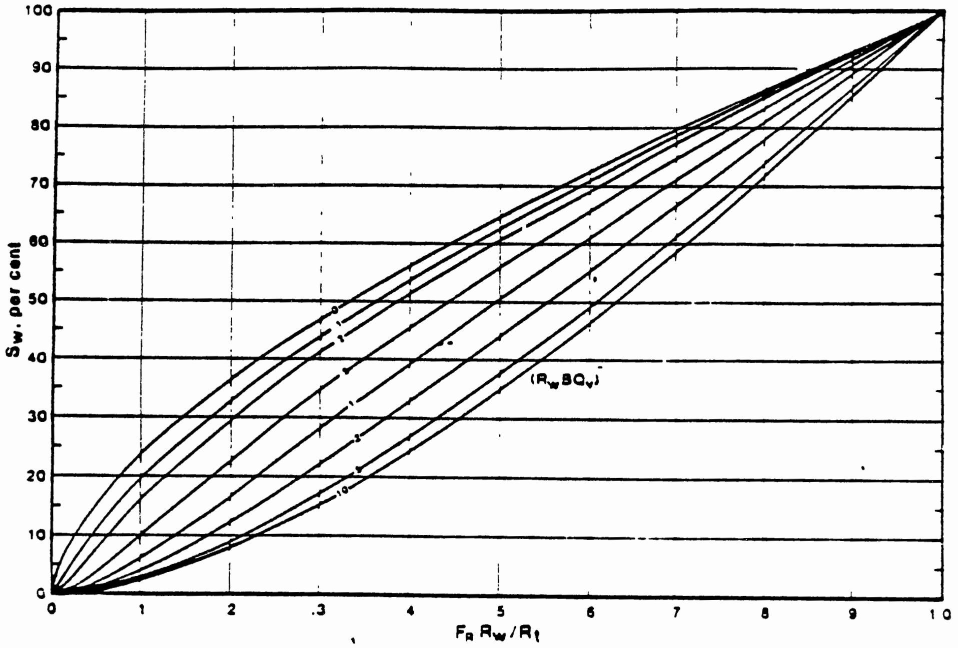
Ø = Porosity, fraction

CEC = Cation Exchange Capacity, meq/100 gm. of sample

ρma = Grain Density of rock solids, gm/cm^3

Figure 39. A Form of the Waxman and Smits Equation (after Bush, Losey, and Jenkins, Core Laboratories, 1977)

S_w DETERMINATION BY WAXMAN - SMITS EQUATIONS when $n^* = 1.6$



S_w DETERMINATION BY WAXMAN - SMITS EQUATIONS when $n^* = 1.8$

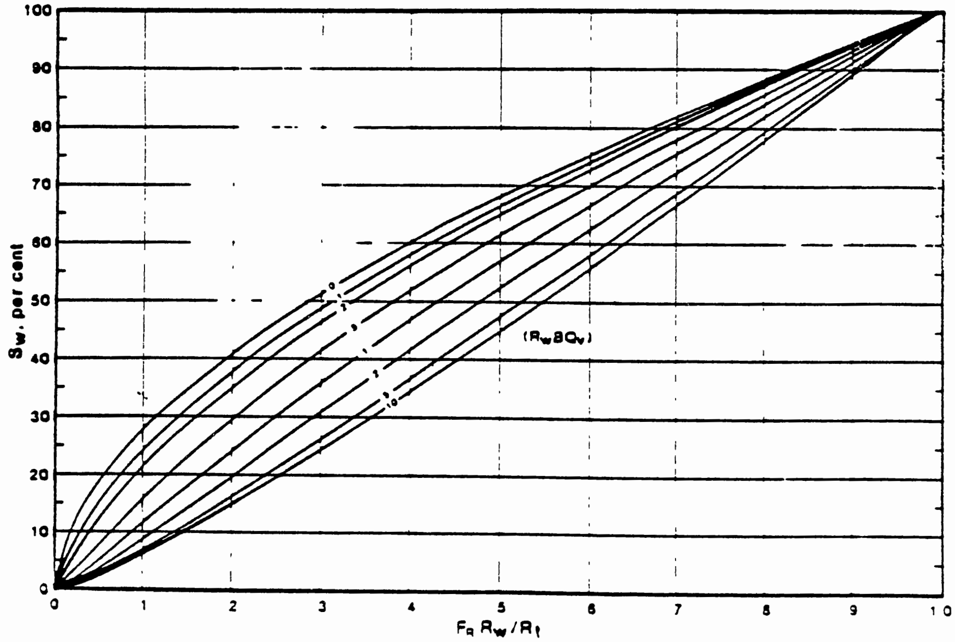


Figure 40. Determination of Water Saturations n = 1.6 and 1.8 (after Core Laboratories, Inc., 1977)

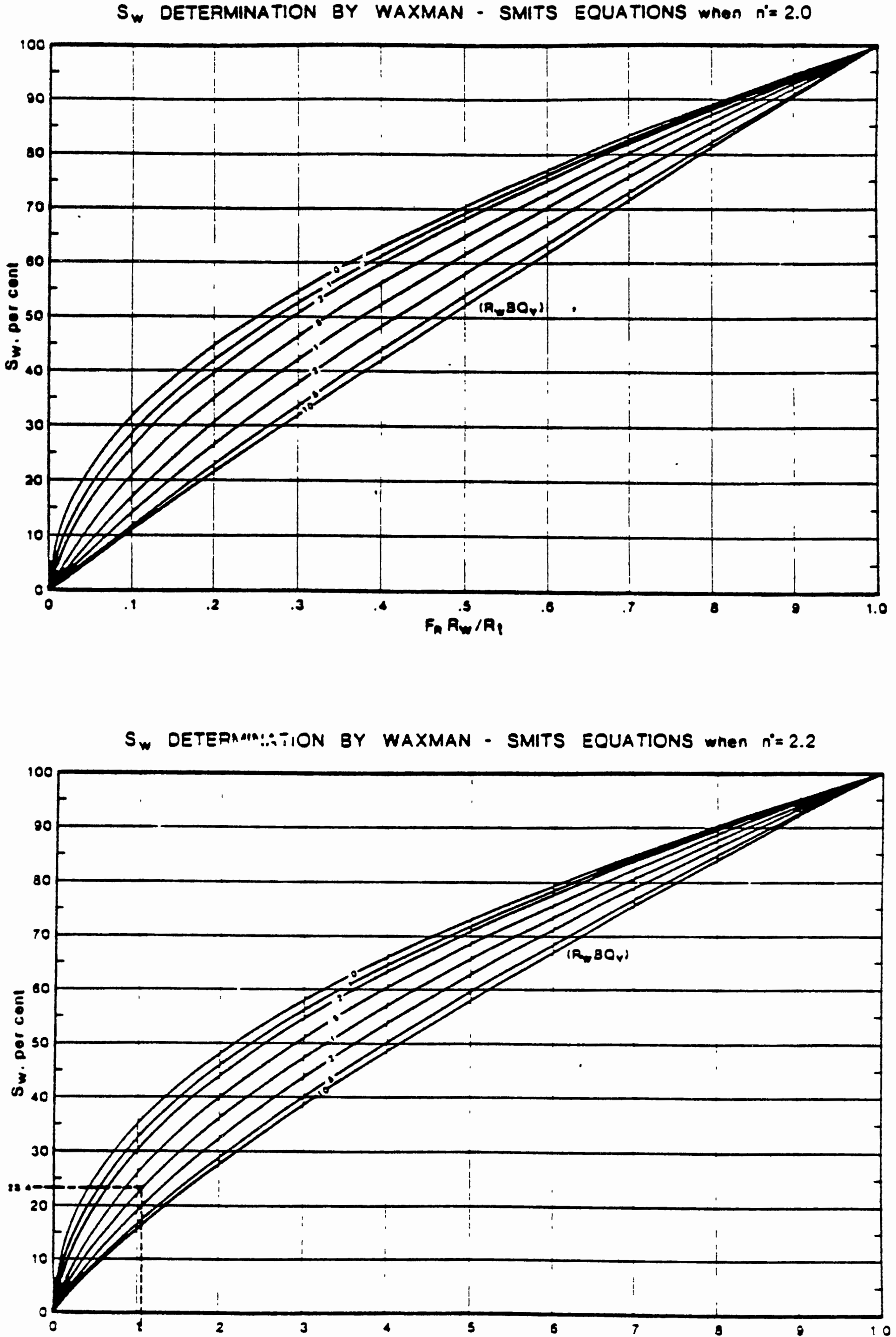
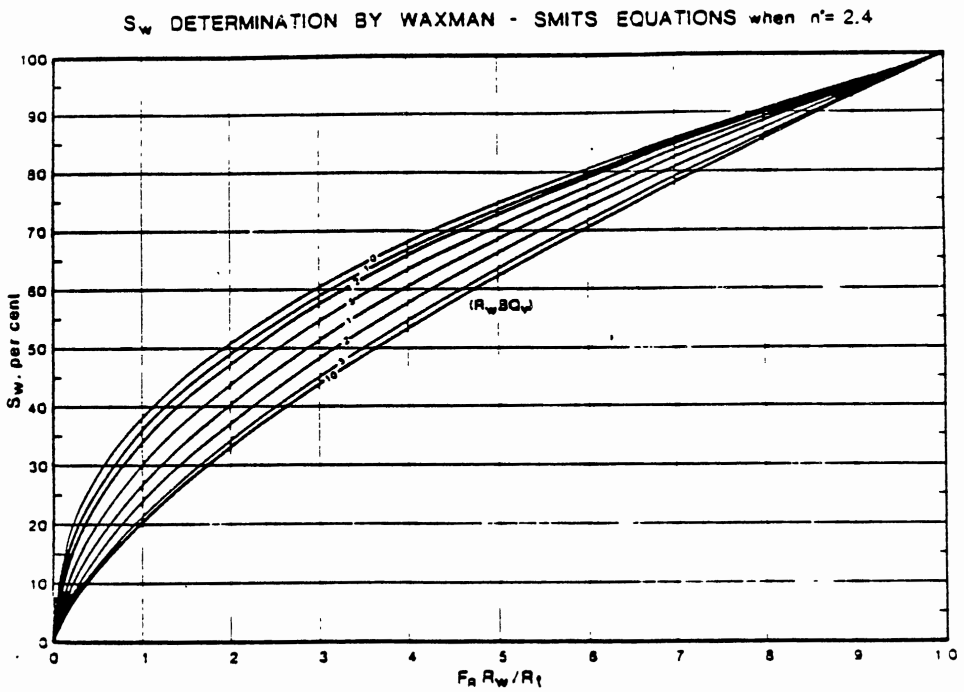


Figure 41. Determination of Water Saturations n = 2.0 and 2.2 (after Core Laboratories, Inc., 1977)



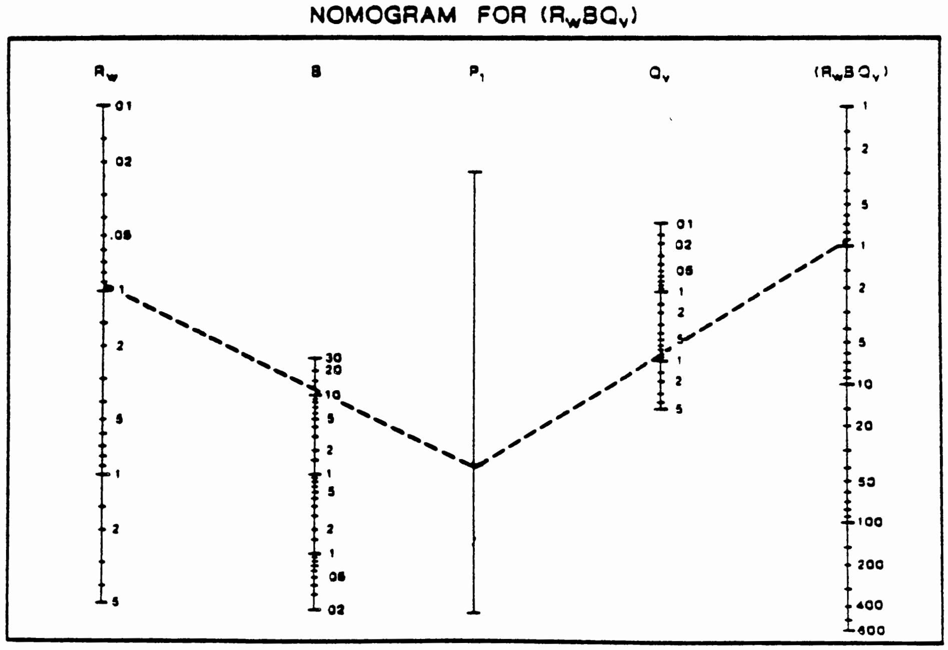


Figure 42. Determination of Water Saturations and Nomogram (after Core Laboratories, Inc., 1977)

CHAPTER IX

CONCLUSIONS

In summary, the following conclusions have been made from this study:

1. The Red Fork sandstone represents a regressive period of cyclic deposition during an overall transgression of the Cherokee Sea.

2. Structure maps of the Mississippi Limestone, Red Fork Sandstone, and Pink Limestone illustrate that deposition of the Red Fork sediments was influenced by the paleotopography of the Mississippian Unconformity.

3. Stratigraphic cross sections and a Red Fork sand isopach map reveal a northwest to southeast trend. This would indicate a paleoslope which is directed toward the Anadarko Basin.

4. Through analysis of sedimentary structures of core, log signatures, and various subsurface maps the Red Fork interval was interpretated to be deposited in a fluvial-deltaic environment.

5. Compositionally, the Red Fork sand is primarily a sublitharenite.

6. Diagenetic events observed were (1) dissolution events (mainly feldspars and authigenic cements), (2)

precipitates (pre- dominately syntaxial overgrowths and authigenic clays), and (3) replacement events (mainly calcite cement replacing dolomite which was replaced by additional calcite and clay).

7. Secondary porosity was predominately created by the partial or complete dissolution of feldspar grains.

8. Authigenic clays in the Red Fork were identified to be: (1) kaolinite, (2) illite, and (3) chlorite.

9. Successful exploration and exploitation of the Red Fork sand must take into account the presence of authigenic clays. Problems which are caused by these diagenetic clays can be reduced through understanding the physical-chemistry of the clays.

BIBLIOGRAPHY

Akmal, M. Gawid, 1950, "Subsurface Geology of Northeast Lincoln and Southeast Payne Counties, Oklahoma": Shale Shaker, p. 5-16.

Almon, W. R., and D. K. Davies, 1977, "Understanding diagenetic zones vital": Oil and Gas Jour., p. 209-216.

Almon, W. R., and D. K. Davies, 1978, "Clay technology and well stimulation": Trans. Gulf Coast Assoc. Geol. Soc. v. 28, p. 1-6.

Al-Shaieb, Z., and J. W. Shelton, 1981, Migration of hydrocarbons and secondary porosity in sandstones: Am. Assoc. Petroleum Geologists Bull., v. 65, no. 11, p. 2433-2436.

Astarita, A. M., 1975, Depositional trends and environments of "Cherokee" sandstone, east-central Payne County, Oklahoma: Unpublished M. S. Thesis, Okla. State Univ., 54 p.

Baker, R. D., 1962, Organic geochemistry of the Cherokee Group in southeastern Kansas and northeastern Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 46, no. 9, p. 1621-1642.

Bass, N. W., 1934, Origin of Bartlesville shoestring sands, Greenwood and Butler Counties, Kansas: Am. Assoc. Petroleum Geologists Bull., v. 18, p. 1313-1345.

Bass, N. W., et al., 1937, Origin and distribution of Bartlesville and Burbank shoestring oil sands in parts of Oklahoma and Kansas: Am. Assoc. Petroleum Geologists Bull., v. 21, no. 1, p. 30-66.

Bennison, A. P., 1972, Structural Framework of Tulsa County: Tulsa Geological Society Digest, v. 37, p. 113-117.

Bennison, A. P., Dott, R. H., Jr., and Nilson, L. R., 1979, A Guidebook to the Desmoinesian Coal Cycles and Associated Sands of East Central Oklahoma: Tulsa Geological Society.

Benoit, E. L., 1957, The Desmoinesian Series, Edmond area, central Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 8, no. 3, p. 16.

Berg, O. R., 1969, Quantitative study of the Cherokee-Marmaton Groups, west flank of Nemaha Ridge, north-central Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 19, p. 94-110.

Berry, C. G., 1965, Stratigraphy of the Cherokee Group, Eastern Osage County, Oklahoma: Shale Shaker, Dec. 1965, p. 78-93.

Blatt, H., 1979, Diagenetic Processes in Sandstones: in Aspects of Diagenesis, Soc. Econ. Paleon. and Min., Special Publication No. 26, p. 141-157.

Bowman, E. A., 1956, The subsurface geology of southeastern Noble County, Oklahoma: Unpublished M. S. Thesis, Univ. Okla., 42 p.

Branson, C. C., 1954, Field Conference on Desmoinesian Rock of north-eastern Oklahoma: Okla. Geol. Surv., Guidebook 11, 41 p.

Brown, L. F., Jr., Cleaves, A. W., II, and Erxleben, A. W., 1973, Pennsylvanian Depositional Systems in North-central Texas - a Guide for Interpreting Terrigenous Clastic Facies in a Cratonic Basin: Texas Univ. Bur. Econ. Geology Guidebook 14, 122 p.

Brown, L. F., Jr., 1979, Deltaic Sandstone Facies of the Mid-Continent: in Pennsylvanian Sandstones of the Mid-Continent, Tulsa Geol. Soc. Spec. Publication No. 1, p. 35-63.

Busch, D. A., 1959, Prospecting for stratigraphic traps: Am. Assoc. Petroleum Geologists Bull., v. 43, no. 12, p. 2829-2843.

Bush, D. C., Losey, H. E., and Jenkins, R. E., 1977, Shaley Sand Log Analysis Using Cation Exchange Capacity Data: Core Laboratories, Inc.

Candler, C. E., 1976, Subsurface stratigraphic analysis of Prue, Skinner and Red Fork sandstones, southern Noble County Oklahoma: Unpublished M. S., Okla. State Univ., 49 p.

Candler, C. E., 1977, Subsurface Stratigraphic Analysis of Selected Sandstones of the "Cherokee" Group, Southern Noble County, Oklahoma: Shale Shaker, v. 28, nos. 3 & 4, p. 56-59; 72-83.

Choquette, P. W., and L. C. Pray, 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates: Am. Assoc. Petroleum Geologists Bull., v. 54, p. 207-250.

Clayton, J. M., 1965, Paleodepositional environments of the "Cherokee" sands of central Payne County, Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 16, p. 50-66.

Clements, K. P., 1961, Subsurface study of the Skinner and Red Fork sand zones, (Pennsylvanian) in portions of Noble and Kay Counties, Oklahoma: Unpublished M. S. Thesis, Univ. Okla., 62 p.

Cole, J. G., 1969, Stratigraphic study of the Cherokee and Marmaton sequences, Pennsylvanian (Desmoinesian), east flank of the Nemaha Ridge, north-central Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 19, p. 134-146.

Coleman, J. M. and Gagliano, S. M., 1965, Sedimentary Structures: Mississippi River Deltaic Plain: in Primary Sedimentary Structures and Their Hydrodynamic Interpretation, Soc. Econ. Paleon. and Min., Spec. Publication No. 12, p. 133-148.

Dalton, D. V., 1960, The subsurface geology of northeastern Payne County, Oklahoma: Unpublished M. S. Thesis, Univ. of Oklahoma, 69 p.

Dogan, N., 1970, Subsurface study of Pennsylvanian Rocks in east-central Oklahoma (From the Brown Limestone to the Checkerboard Limestone): Okla. City Geol. Soc., Shale Shaker, v. 20, p. 192-213.

Ernst, W. G. and Blatt, H., 1963, Experimental Study of Quartz Overgrowths and Synthetic Quartzites: Jour. Geology, v. 72, p. 461-469.

Ferguson, D. B., 1964, Subsurface Geology of Northern Lincoln County, Oklahoma: Shale Shaker, June 1964, p. 4-17.

Fisher, W. L., 1969, Facies Characterization of Gulf Coast Basin Delta Systems, With Some Holocene Analogues: in Geology of the American Mediterranean, Gulf Coast Assoc. Geol. Socs. Trans. v. 19, p. 239-261.

Fisher, W. L. and Brown, L. F., Jr., 1972, Clastic Depositional Systems - A Genetic Approach to Facies Analysis: Bureau of Economic Geology, The University of Texas at Austin, 211 p.

Fisk, M. N., 1961, Bar Finger Sands of the Mississippi Delta: in Geometry of Sandstone Bodies - A Symposium, Amer. Assoc. Petrol. Geol., p. 29-52.

Fisk, H. N., McFarlan, E. Jr., Kobb, C. R., and Wilbert, L. J., Jr., 1954, Sedimentary Framework of the Modern Mississippi Delta: Journ. Sed. Petrology, v. 24, p. 76-99.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphills Book Store, 170 p.

Frost, V. L., 1940, Ramsey Oil Pool, Payne County, Oklahoma: AAPG Bull., v. 24, no. 11, p. 1995-2005.

Glass, J. L., 1981, Depositional environments, reservoir trends, and diagenesis of the Red Fork sandstone in Grant and eastern Kay Counties, Oklahoma: Unpublished M. S. Thesis, Okla. State Univ., 99 p.

Graves, J. M., 1955, Subsurface geology of a portion of Lincoln and Payne Counties, Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 6, p. 1-38.

Hanke, H. W., 1967, Subsurface stratigraphic analysis of the Cherokee Group in north-central Creek County, Oklahoma: Oklahoma City Geol. Society, Shale Shaker, v. 17, p. 150-167.

Hatch, J. R. and J. S. Leventhall, 1982, Comparative organic geochemistry of shales and coals from Cherokee Group and lower part of Marmaton Group of Middle Pennsylvanian Age, Oklahoma, Kansas, Missouri, and Iowa: Am. Assoc. Petroleum Geologists Bull. (Abst.), v. 66, no. 5, p. 579.

Hawissa, I. S., 1965, Depositional environment of the Bartlesville, Red Fork, and the Lower Skinner sandstones in portions of Lincoln, Logan, and Payne Counties, Oklahoma: Unpublished M. S. Thesis, Univ. of Tulsa, 35 p.

Haworth, E. and M. Z. Kirk, 1894, A geologic section along the Noesho River from the Mississippian Formation of the Indian Territory to White City, Kansas, and along the Cottonwood River from Wyckoff to Peabody: Kansas Univ. Quart., v. 2, p. 105-106.

Hayes, J. B., 1979, Sandstone Diagenesis - The Hole Truth: in Aspects of Diagenesis, Soc. Econ. Paleon. and Min. Spec. Pub. No. 26, p. 127-139.

Heald, M. T. and Larese, R. E., 1973, The Significance of the Solution of Feldspar in Porosity Development: Jour. Sed. Pet., v. 43, no. 2, p. 458-460.

Hoffman, M. G., 1940, Structural History of Billings Field, Noble County, Oklahoma, Interpreted in terms of Isostacy. AAPG Bull., v. 24, no. 11, p. 2006-2018.

Hood, A., C. M. Gutjhar and J. L. Heacock, 1975, Organic metamorphism and the generation of petroleum: Am. Assoc. Petroleum Geologists Bull., v. 59, p. 986-996.

Howe, W. B. 1956, Stratigraphy of Pre-Marmaton Desmoinesian (Cherokee) rock in southeastern Kansas: Kansas Geol. Surv. Bull. 123, p. 123-132.

Hoyer, W. A. and Spann, M. M., 1975, Comments on Obtaining Accurate Electrical Properties of Cores, Trans., SPWLA.

Hudson, A. S., 1969, Depositional environment of the Red Fork and equivalent sandstones east of the Nemaha Ridge, Kansas and Oklahoma: Unpublished M. S. Thesis, Univ. of Tulsa, 80 p.

Huffman, G. G., 1960, Regional Relations of Pre-Desmoinesian Rocks, Central Mid-Continent Region in Northeast Oklahoma: Field Conference of the Kansas Geol. Soc., Guidebook 25, p. 49.

Hutchinson, L. L., 1911, Rocks asphalt, asphaltite, petroleum and natural gas in Oklahoma: Okla. Geol. Surv. Bull. 2, p. 230-260.

Johnson, W. L. and Linke, W. A., 1978, Some Practical Applications to Improve Formation Evaluation of Sandstones in the MacKenzie Delta: Transactions SPWLA.

Jordan, L., 1957, Subsurface stratigraphic names of Oklahoma: Okla. Geol. Surv. Guidebook VI, 220 p.

Jordan, L., 1967, Geology of Oklahoma - A Summary: Oklahoma Geology Notes, v. 27, no. 12, p. 215-228.

Keelan, D. K. and McGinley, D. C., 1979, Application of Cation Exchange Capacity in a Study of the Shannon Sand of Wyoming: SPWLA Twentieth Annual Logging Symposium.

Krumme, G. W., 1975, Mid-Pennsylvanian source reversal on the Oklahoma Platform: Unpublished Ph.D. Dissertation, Univ. of Tulsa, 1161 p.

Kurash, G. E., Jr., 1964, Subsurface Geology of West-Central Lincoln County, Oklahoma: Shale Shaker, v. 14, p. 2-25.

Leatherock, C., 1937, Physical characteristics of Bartlesville and Burbank sands in northeastern Oklahoma and southeastern Kansas: Am. Assoc. Petroleum Geologists Bull., v. 21, no. 2, 246 p.

Lojek, C. A., 1983, Petrology, Diagenesis and Depositional Environment of the Skinner Sandstones, Desmoinesian, Northeast Oklahoma Platform, Unpublished M. S. Thesis, Oklahoma State University.

Lowman, S. W., 1933, Cherokee structural history in Oklahoma: Tulsa Geol. Soc. Dig., v. 1, p. 31-34.

Mason, E. P., 1982, The Petrology, Diagenesis and Depositional Environment of the Bartlesville Sandstone in the Cushing Oil Field, Creek County, Oklahoma: Unpublished M. S. Thesis, Oklahoma State University, 150 p.

McBride, E. F., Secondary Porosity - Importance in Sandstone Reservoirs in Texas: Gulf Coast Assoc. Geol. Soc. Trans., v. 27, p. 121-122.

McBride, E. F., Importance of Secondary Porosity in Sandstones to Hydrocarbon Exploration. AAPG Bull.: Associated Round Table, p. 747.

McElroy, M. N., 1961, Isopach and lithofacies study of the Desmoinesian Series of north-central Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 12, p. 2-22.

Meissner, F. F., Examples of Abnormal Fluid Pressure Produced by Hydrocarbon Generation. AAPG Bull.: Associated Round Table, p. 749.

Moore, G. E., 1979, Pennsylvanian Paleogeography of the Southern Mid-Continent: in Pennsylvanian Sandstones of the Mid-Continent, Tulsa Geol. Soc. Spec. Publication no. 1, p. 2-9.

Morgan, J. T. and Gordon, D. T., 1970, Influence of Pore Geometry on Water-Oil Relative Permeability: Jour. Petrol. Tech., no. 10, p. 1199-1208.

Oakes, M. C., 1953, Krebs and Cabaniss Groups of Pennsylvanian age in Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 1523-1526.

Page, K. G., 1955, The subsurface geology of southern Noble County, Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 5, p. 5-22.

Pittman, E. D., 1972, Diagenesis of Quartz in Sandstones as Revealed by Scanning Electron Microscopy: Jour. Sed. Pet., v. 42, no. 3, p. 507-519.

Pittman, E. D., 1979, Porosity, diagenesis, and productive capability of sandstone reservoirs: Soc. of Economic Paleontologists and Mineralogists, Special Pub. No. 26, p. 159-173.

Powers, S., Structural Geology of Northeastern Oklahoma. Journal Geology: v. 39, p. 117-132.

Reineck, H. E. and I. B. Singh, 1980, Depositional Sedimentary Environments: Springer-Verlag, New York, 549 p.

Robertson, K. S., 1980, Authigenic Clays Effect on Production: Unpublished work, Oklahoma State University.

Robertson, K. S., 1983, Stratigraphy, Depositional Environment, Petrology, Diagenesis and Hydrocarbon maturation related to the Red Fork Sandstone in North-central Oklahoma: Unpublished M. S. Thesis, Oklahoma State University.

Ruhovets, N. and Fertl, W. H., 1981, Digital Shaly Sand Analysis Based on Waxman-Smits Model and Log-Derived Clay Typing: Dresser Atlas, Dresser Atlas Industries, Inc.

Sarkisyan, S. G., 1972, Origin of Authigenic Clay minerals and their significance in Petroleum Geology. Institute of Geology and Exploitation, v. 7, no. 1.

Saxena, R. S., 1982, Exploration Models and Recognition Criteria for Deltaic Sand Bodies: GSA Short Course, 95th Annual Meeting, New Orleans, Louisiana.

Schmidt, V. and McDonald, D. A., 1979a, The Role of Secondary Porosity in the Course of Sandstone Diagenesis: in Aspects of Diagenesis: Soc. Econ. Paleon. and Min. Spec. Publication, no. 26, p. 175-207.

Schmidt, V. and McDonald, D. A., 1976b, Texture and Recognition of Secondary Porosity in Sandstones: in Aspects of Diagenesis, Soc. Econ. Paleon. and Min. Spec. Publication No. 26, p. 209-225.

Schmidt, V., D. A. McDonald, and R. L. Platt, 1977, Pore geometry and reservoir aspects of secondary porosity in sandstones: Bull. Canadian Petroleum Geol., v. 25, p. 271-290.

Scholle, P. A., 1978, A color illustrated guide to constituents, textures, cements, and porosities of sandstones and associated rocks: Am. Assoc. Petroleum Geologists, Memoir 28, 201 p.

Scott, J. D., 1970, Subsurface stratigraphic analysis, "Cherokee" Group northern Noble County, Oklahoma: Unpublished M. S. Thesis, Univ. Okla., 56 p.

Shelton, J. W., 1973, Models of Sand and Sandstone Deposits: A Methodology for Determining Sand Genesis and Trend: Oklahoma Geological Survey Bull. 118, 122 p.

Shelton, J. W. and Rowland, T. L., 1974, Guidebook to the Depositional Environments of Selected Pennsylvanian Sandstones and Carbonates of Oklahoma: Oklahoma Geological Survey Spec. Publication 74-1.

Shipley, R. D., 1975, Local depositional trends of "Cherokee" sandstones Payne County, Oklahoma: Unpublished M. S. Thesis, Okla. State Univ., 49 p.

Simons, H. F., 1941, Secondary Explotation used at Coyle Field of Oklahoma. Oil and Gas Journal: p. 34-35.

Stanton, G. D., 1977, Secondary Porosity in Sandstones of the Lower Wilcox (Eocene), Karnes County, Texas: Gulf Coast Assoc. Geol. Soc. Trans., v. 27, p. 197-207.

Stringer, C. P., 1957, Subsurface geology of western Payne County, Oklahoma: Okla. City Geol. Soc., Shale Shaker, v. 7, p. 3-20.

Swanson, D. C., 1979, Deltaic Deposits in the Pennsylvanian Upper Morrow Formation of the Anadarko Basin: in Pennsylvanian Sandstones of the Mid-Continent, Tulsa Geol. Soc. Spec. Publication No. 1, p. 115-168.

Swanson, D. C., 1980, Handbook of Deltaic Facies: Lafayette Geological Society, Subsurface Clastic Facies Workshop, 81 p.

Tissot, B. P. and D. H. Welte, 1978, Petroleum formation and occurrence: Springer-Verlag, Berlin, 538 p.

Verish, N. P., 1979, Reservoir Trends, Depositional Environments, and Petroleum Geology of "Cherokee" Sandstones in T11-13N, R4-5E, Central Oklahoma: Shale Shaker, v. 29, nos. 9 & 10, p. 209-214; 224-236.

Visher, G. S., Saitta, S. B., and Phares, R. S., 1971, Pennsylvanian delta patterns and petroleum occurrences in eastern Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 1206-1230.

Waxman, M. H. and Smits, L. J. M., 1968, Electrical Conductivities in Oil-Bearing Shaly Sands. J. Soc. Petr. Engr., p. 107-122.

Waxman, M. H. and Thomas, E. C., 1974, Electrical Conductivities in Shaly Sands-I. The Relation Between Hydrocarbon Saturation and Resistivity Index: II The Temperature Coefficient of Electrical Conductivity: J. Pet. Tech., p. 213-225.

Weaver, C. E., 1960, Possible uses in clay minerals in search for oil. AAPG Bull., v. 44, no. 9, p. 1505-1518.

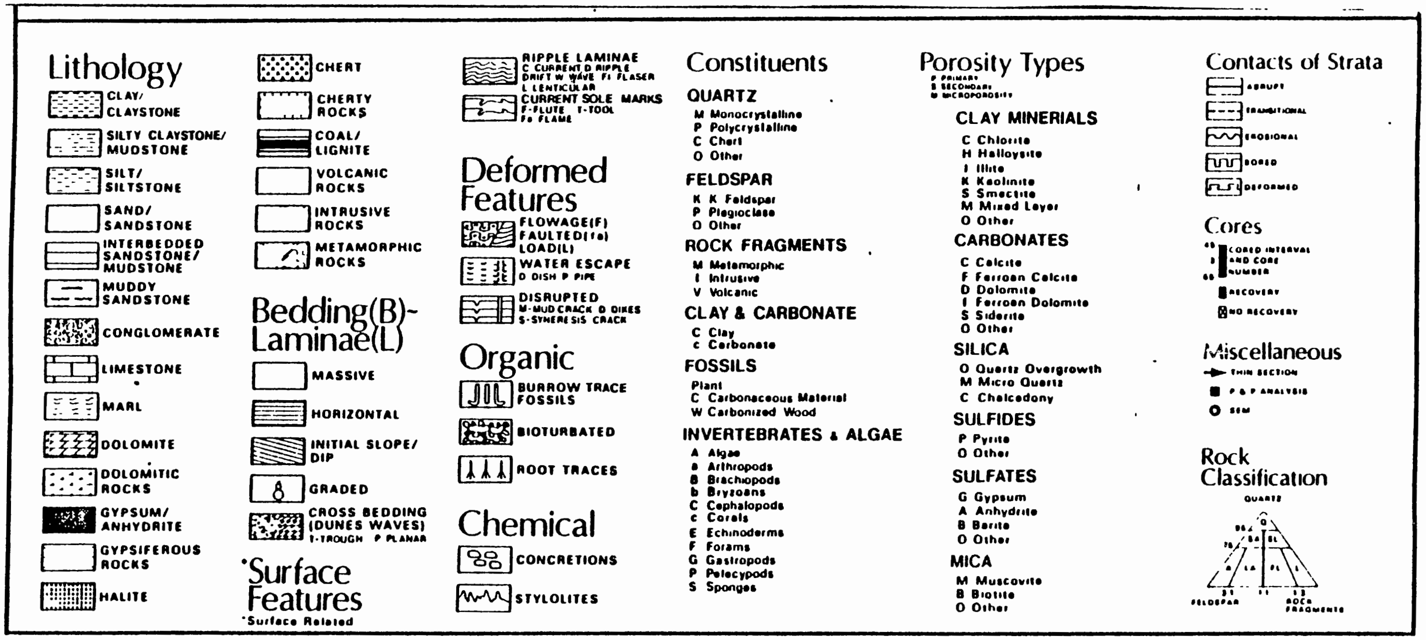
Weirich, T. E., 1953, Shelf principle of oil origin, migration, and accumulation: Am. Assoc. Petroleum Geologists Bull., v. 37, no. 8, p. 2027-2045.

Wilson, M. D. and E. D. Pittman, 1977, Authigenic Clays in Sandstones: Recognition and Influence on Reservoirs Properties and Paleoenvironmental Analysis: Jour. Sed. Pet., v. 47, no. 1, p. 3-31.

Withrow, P. C., 1968, Depositional environment of the Pennsylvanian Red Fork sandstones in north-eastern Anadarko Basin, Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 52, no. 10, p. 198-205.

APPENDIX A

PETROLOGIC LOG OF CORES



Lithology

CLAY/ CLAYSTONE

SILTY CLAYSTONE/ MUDSTONE

SILT/ SILTSTONE

SAND/ SANDSTONE

INTERBEDDED SANDSTONE/ MUDSTONE

MUDDY SANDSTONE

CONGLOMERATE

LIMESTONE

MARL

DOLOMITE

DOLOMITIC ROCKS

GYPSUM/ ANHYDRITE

GYPSIFEROUS ROCKS

HALITE

CHERT

CHERTY ROCKS

COAL/ LIGNITE

VOLCANIC ROCKS

INTRUSIVE ROCKS

METAMORPHIC ROCKS

Bedding(B)-Laminae(L)

MASSIVE

HORIZONTAL

INITIAL SLOPE/ DIP

GRADED

CROSS BEDDING (DUNES WAVES)
T-TROUGH P PLANAR

*Surface Features

*Surface Related

RIPPLE LAMINAE
C CURRENT D RIPPLE DRIFT W WAVE Fl FLASER
L LENTICULAR

CURRENT SOLE MARKS
F-FLUTE T-TOOL
Fa FLAME

Deformed Features

FLOWAGE(F)
FAULTED(fa)
LOAD(L)

WATER ESCAPE
D DISH P PIPE

DISRUPTED
M-MUD CRACK D DIKES
S-SYNERESIS CRACK

Organic

BURROW TRACE FOSSILS

BIOTURBATED

ROOT TRACES

Chemical

CONCRETIONS

STYLOLITES

Constituents

QUARTZ
M Monocrystalline
P Polycrystalline
C Chert
O Other

FELDSPAR
K K Feldspar
P Plagioclase
O Other

ROCK FRAGMENTS
M Metamorphic
I Intrusive
V Volcanic

CLAY & CARBONATE
C Clay
c Carbonate

FOSSILS
Plant
C Carbonaceous Material
W Carbonized Wood

INVERTEBRATES & ALGAE
A Algae
a Arthropods
B Brachiopods
b Bryzoans
C Cephalopods
c Corals
E Echinoderms
F Forams
G Gastropods
P Pelecypods
S Sponges

Porosity Types

P PRIMARY
S SECONDARY
M MICROPOROSITY

CLAY MINERALS
C Chlorite
H Halloysite
I Illite
K Kaolinite
S Smectite
M Mixed Layer
O Other

CARBONATES
C Calcite
F Ferroan Calcite
D Dolomite
f Ferroan Dolomite
S Siderite
O Other

SILICA
O Quartz Overgrowth
M Micro Quartz
C Chalcedony

SULFIDES
P Pyrite
O Other

SULFATES
G Gypsum
A Anhydrite
B Barite
O Other

MICA
M Muscovite
B Biotite
O Other

Contacts of Strata

ABRUPT

TRANSITIONAL

EROSIONAL

BORED

DEFORMED

Cores

CORED INTERVAL AND CORE NUMBER

RECOVERY

NO RECOVERY

Miscellaneous

THIN SECTION

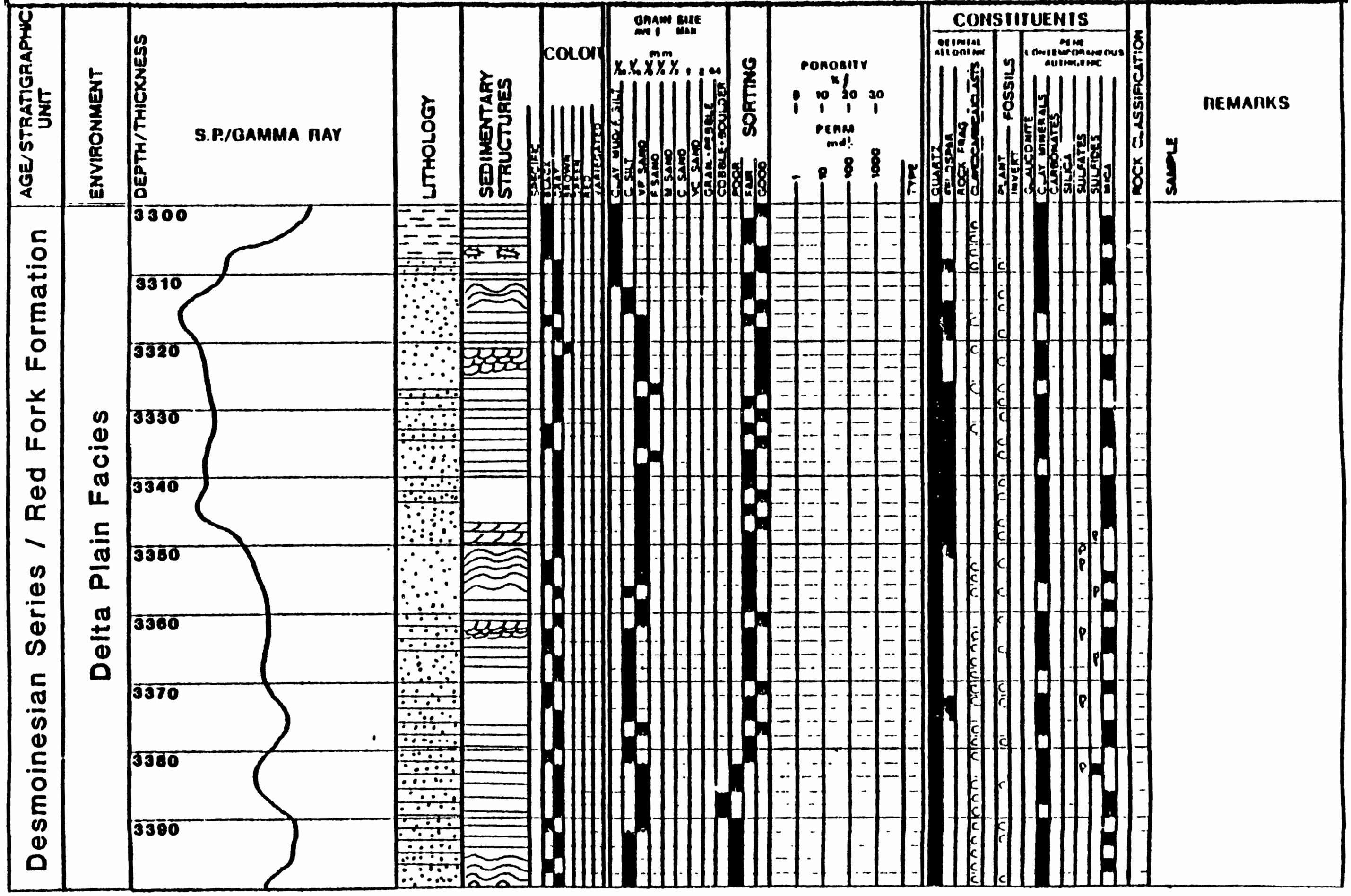
P & P ANALYSIS

SEM

Rock Classification

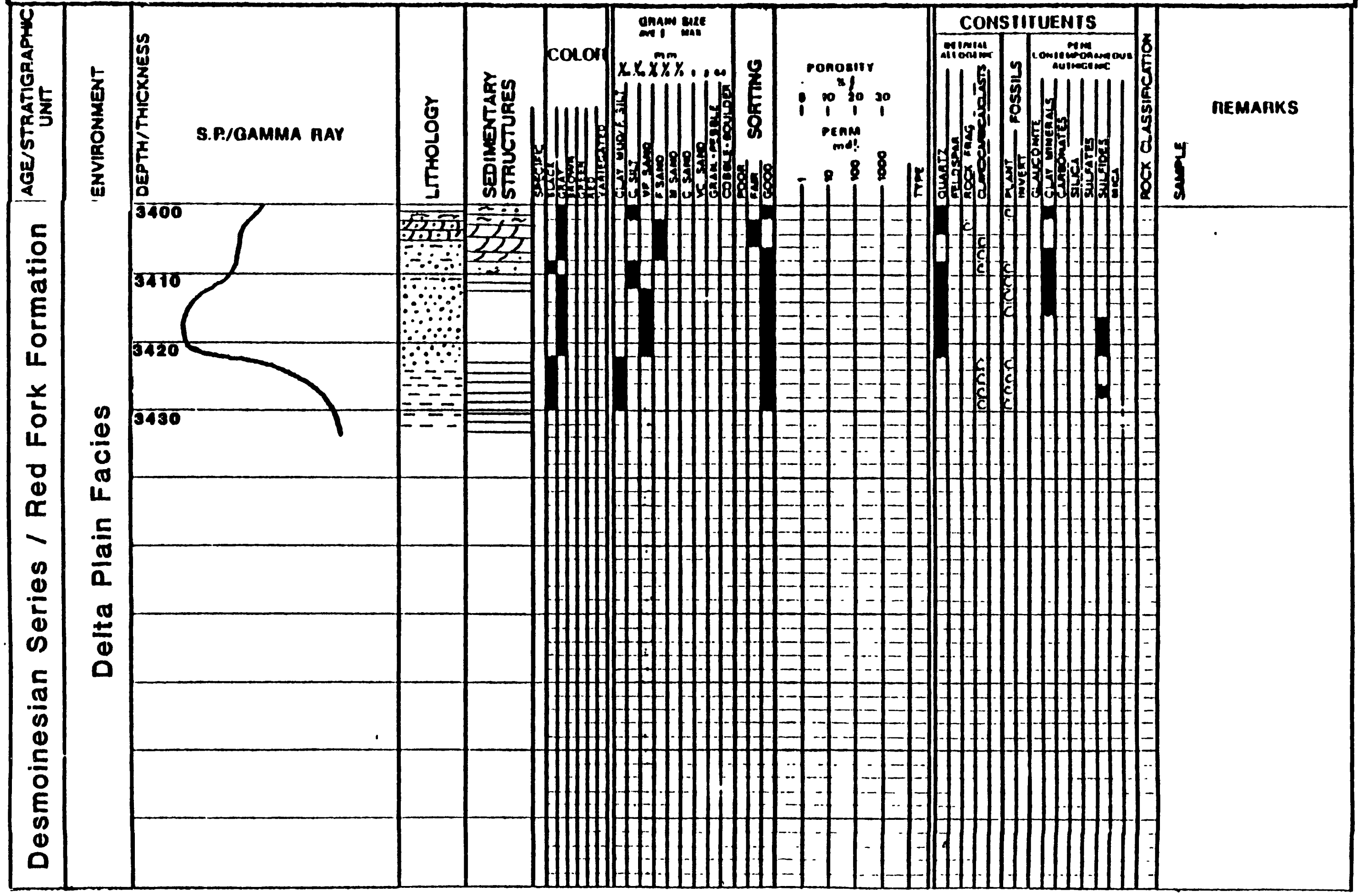
Petrologic Log

Company Ames Oil and Gas Company
Well Location Rogers #2 Sec. 13-T22N-R4E



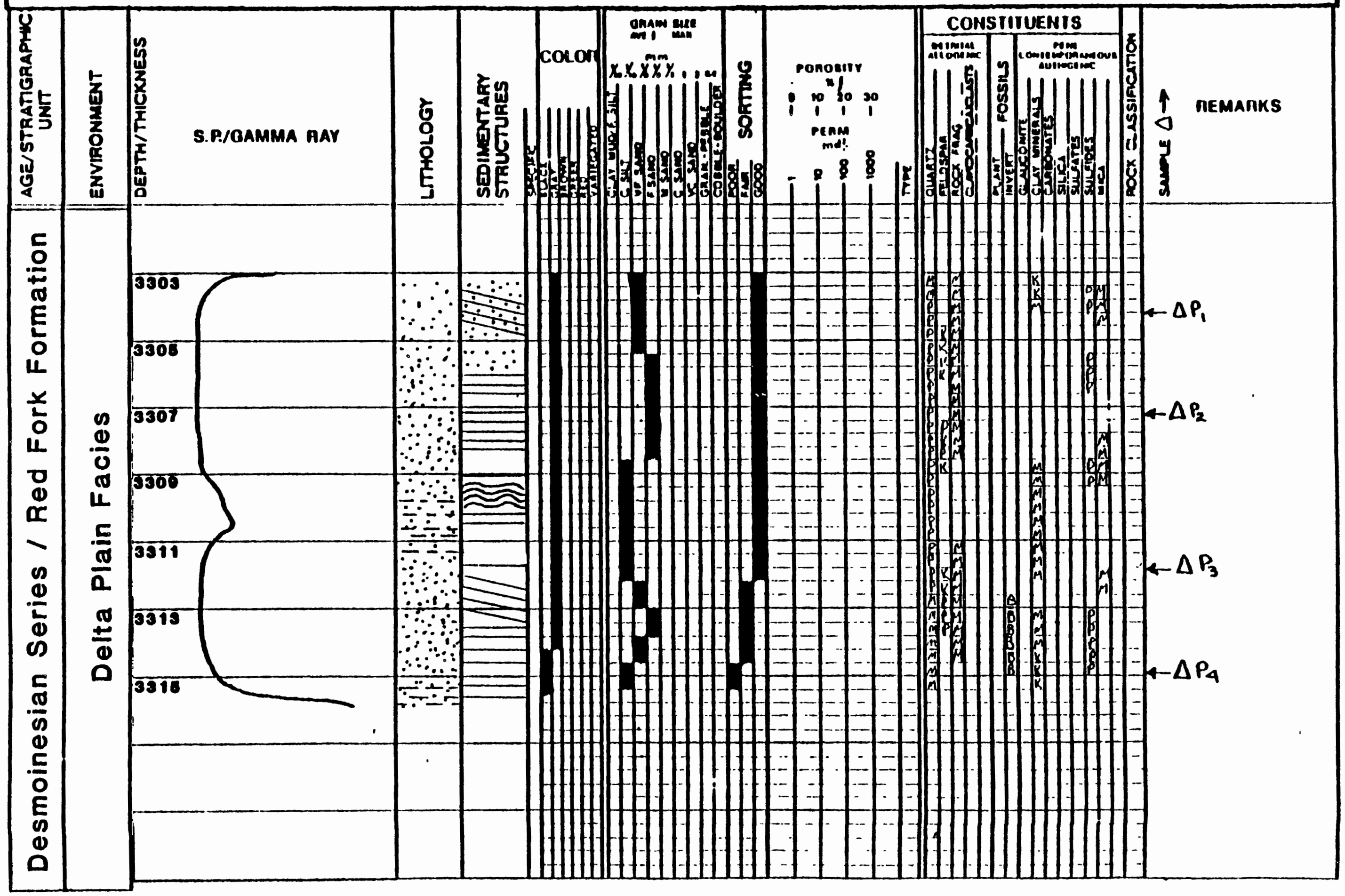
Petrologic Log

Company Ames Oil and Gas Company
Well Location Rogers #2 Sec. 13-T22N-R4E



Petrologic Log

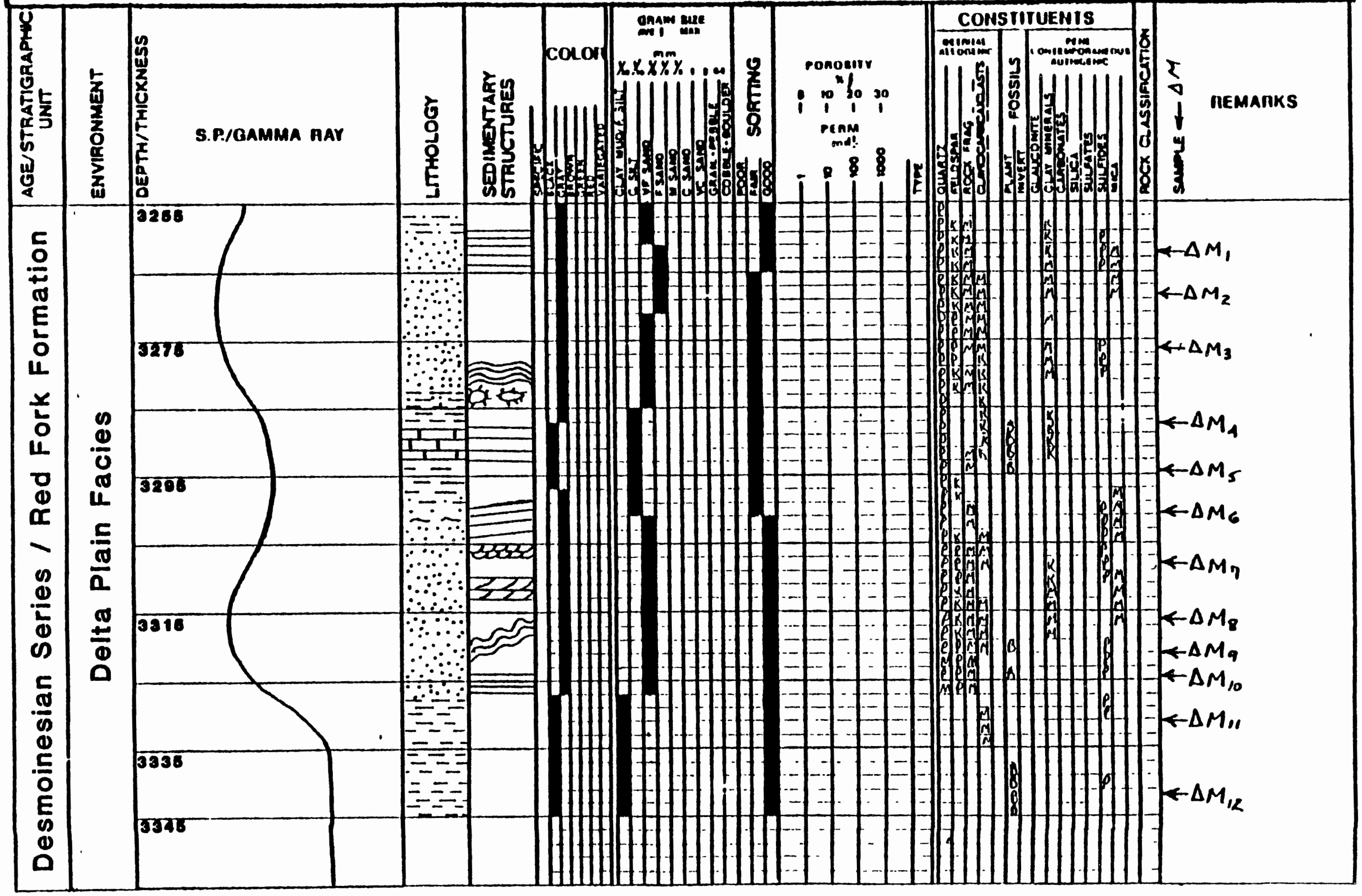
Company Perkins Production Company
Well Location Buchanan #1 Sec. 20-T21N-R5E



Petrologic Log

Company Bandara Energy Company

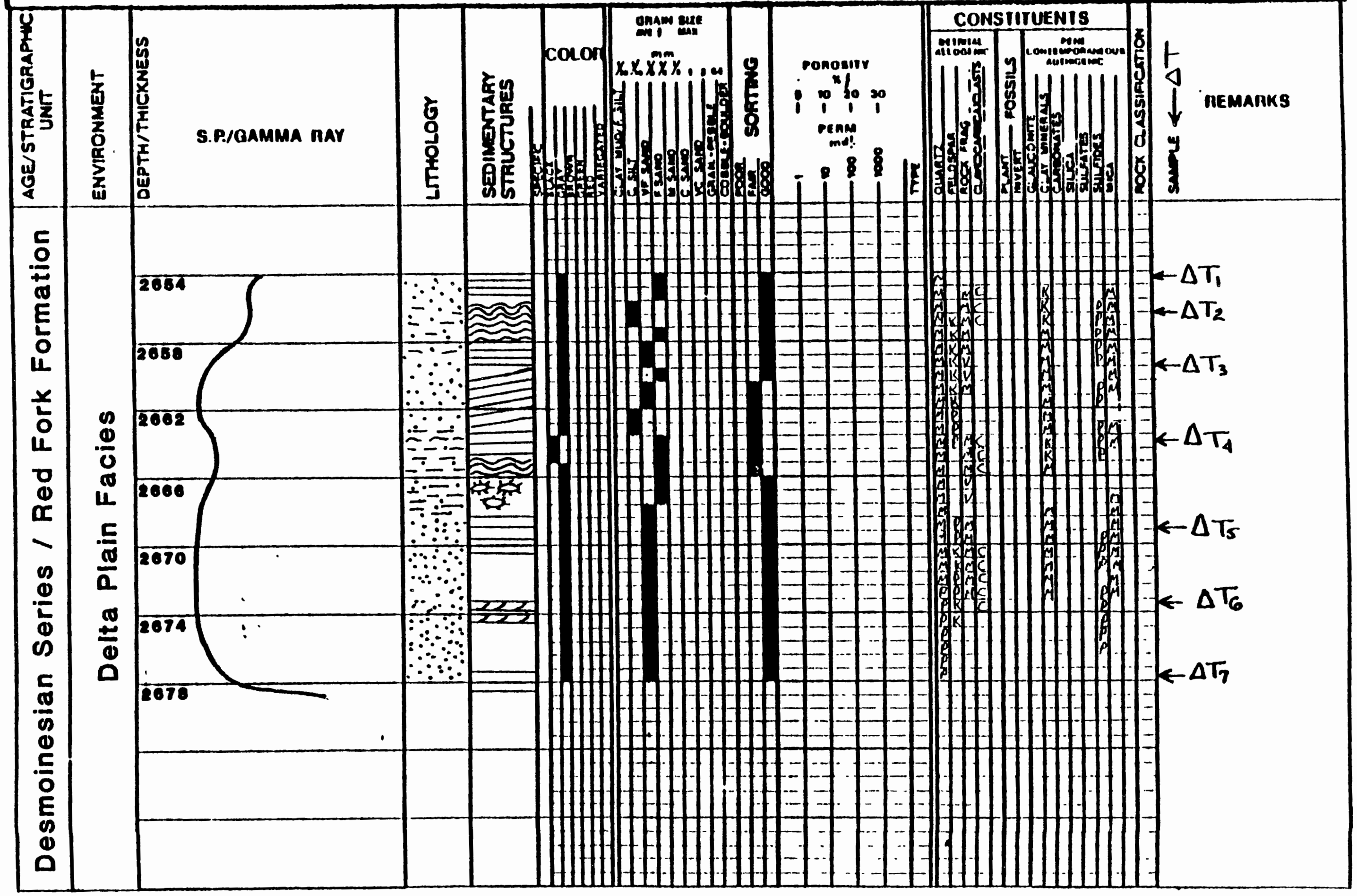
Well Location Martin 1-8 Sec. 8-T22N-R5E



Petrologic Log

Company Thompson-Tye Company

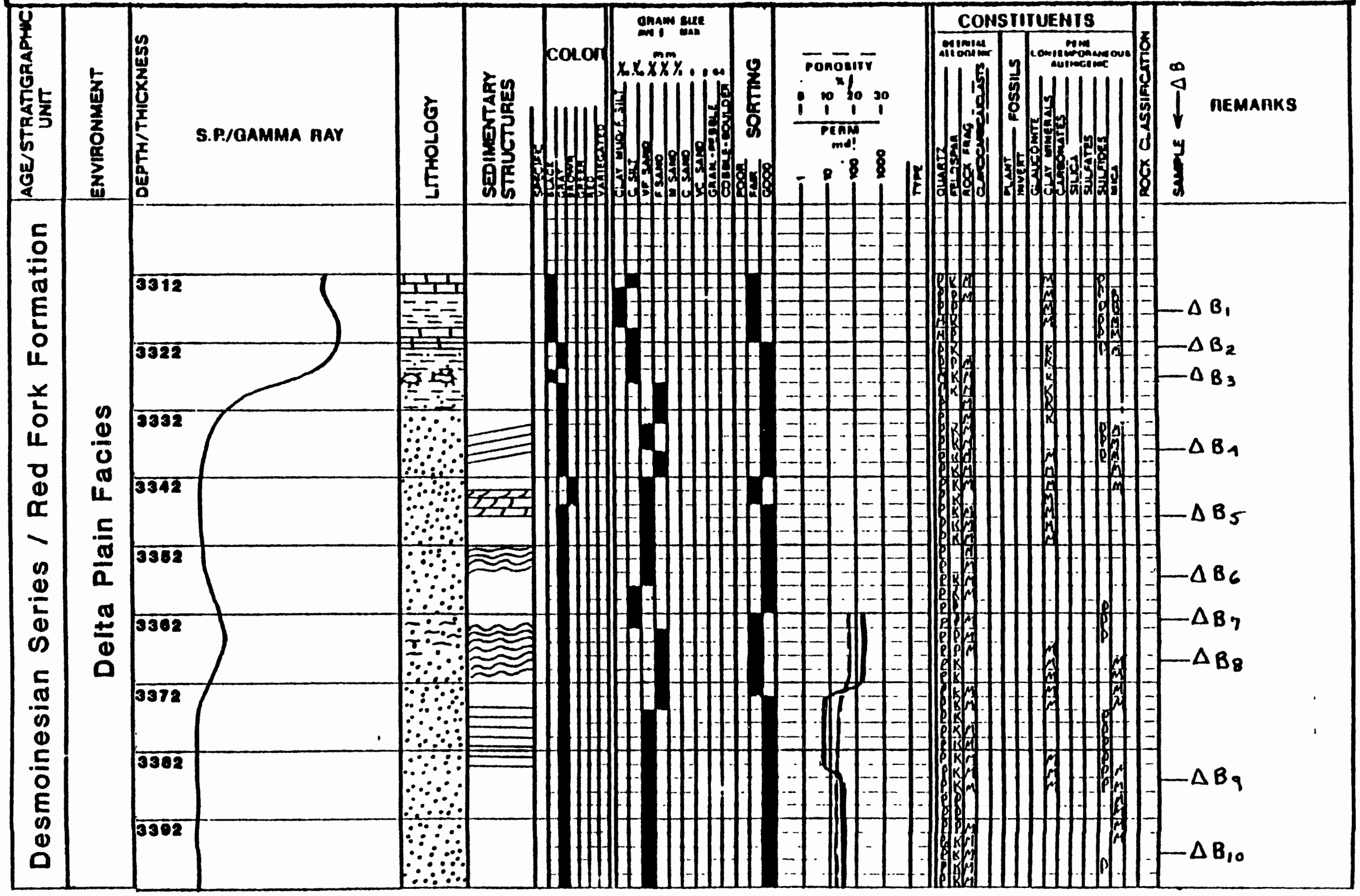
Well Location #3 Shields Sec. 2-T21N-R5E

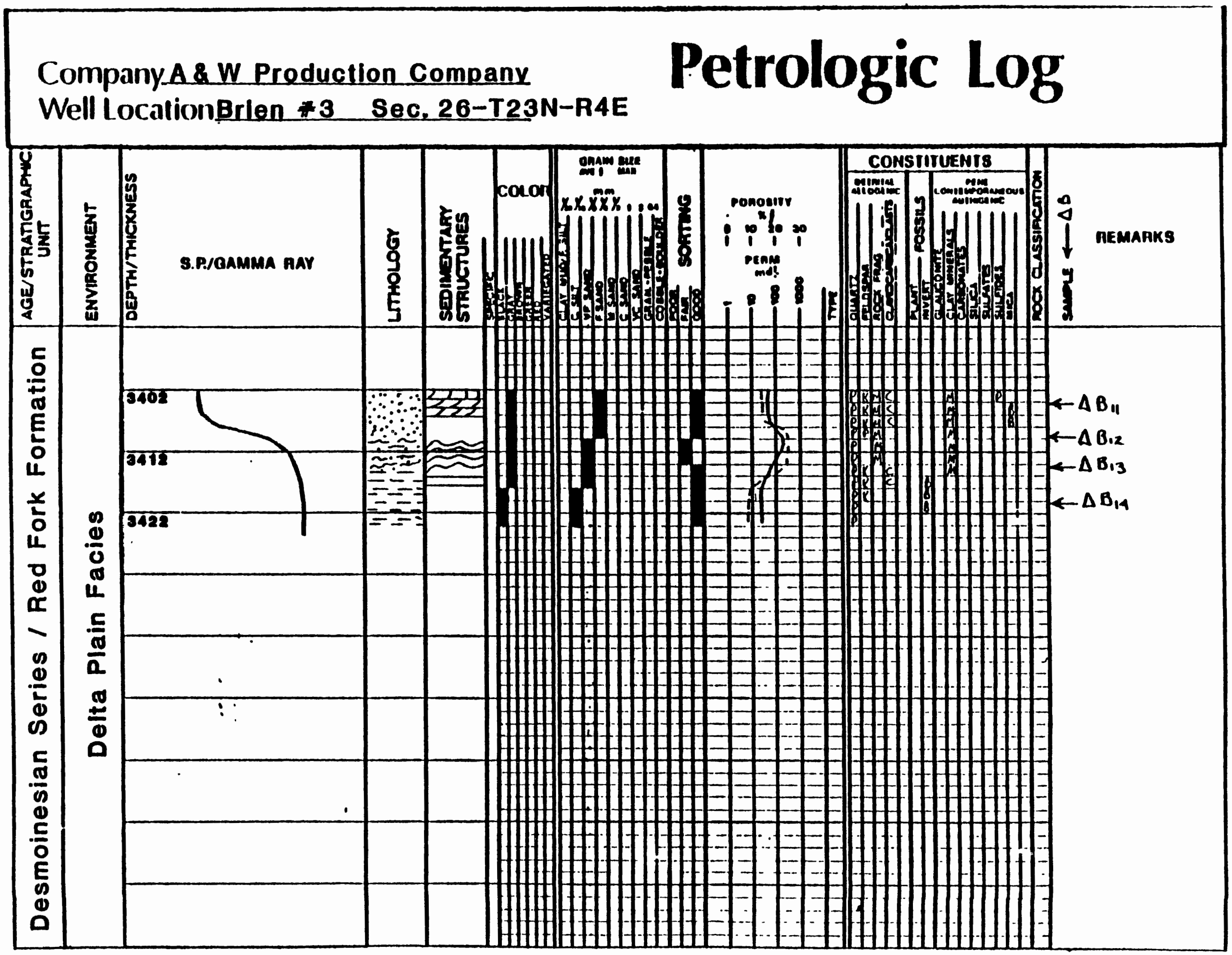


Company A & W Production Company

Well Location Brien #3 Sec. 26-T23N-R4E

Petrologic Log





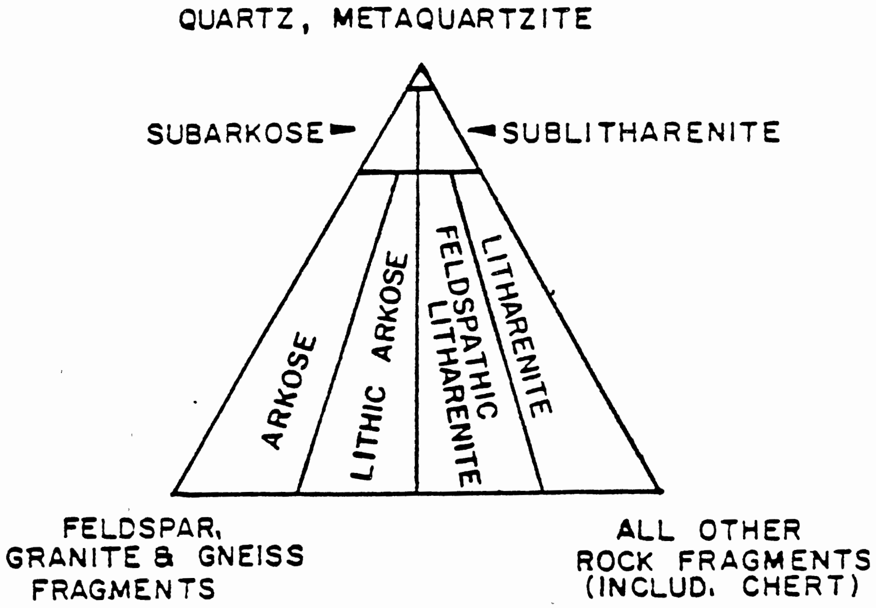
Petrologic Log

Company A & W Production Company

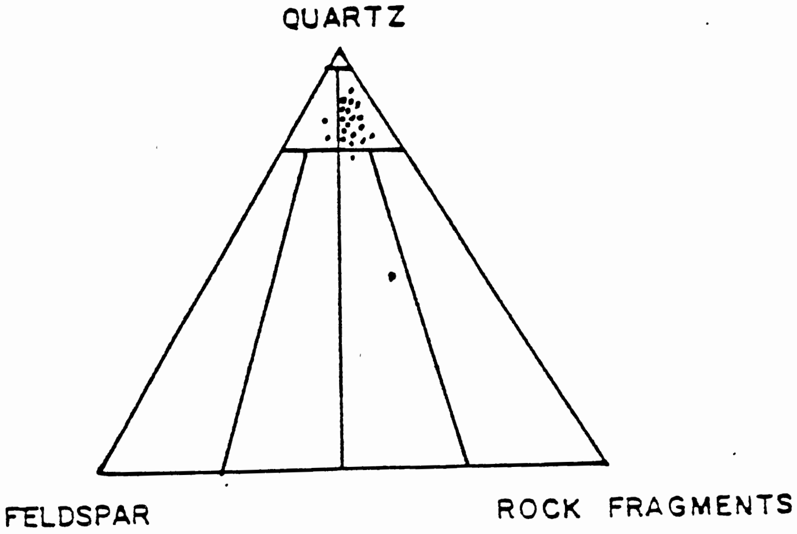
Well Location Brien #3 Sec. 26-T23N-R4E

APPENDIX B

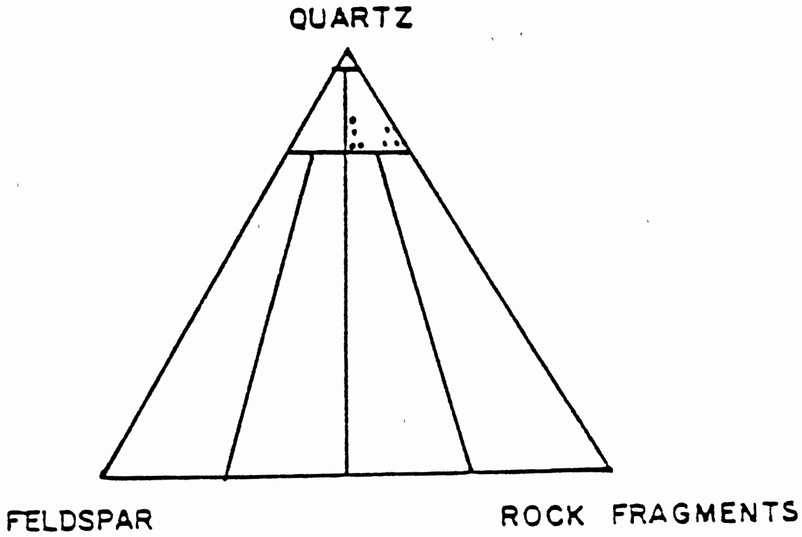
CLASSIFICATION OF SAND



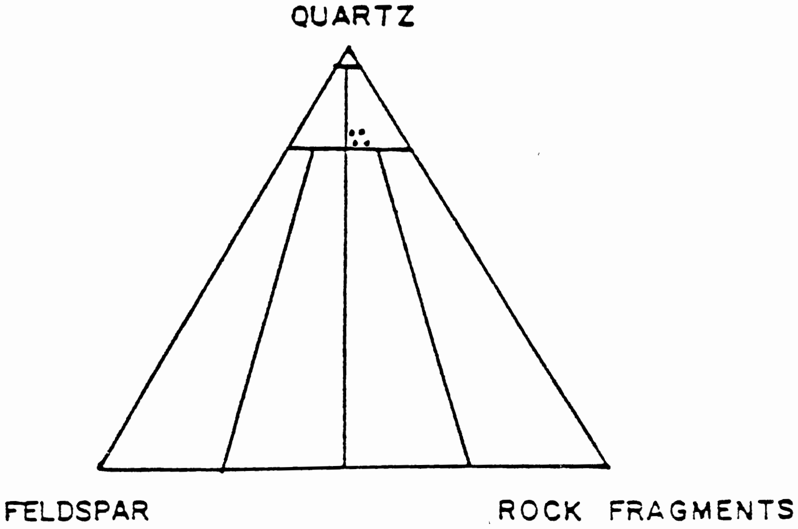
AMES OIL & GAS COMPANY
ROGERS No. 2
SEC. 13-T22N-R4E



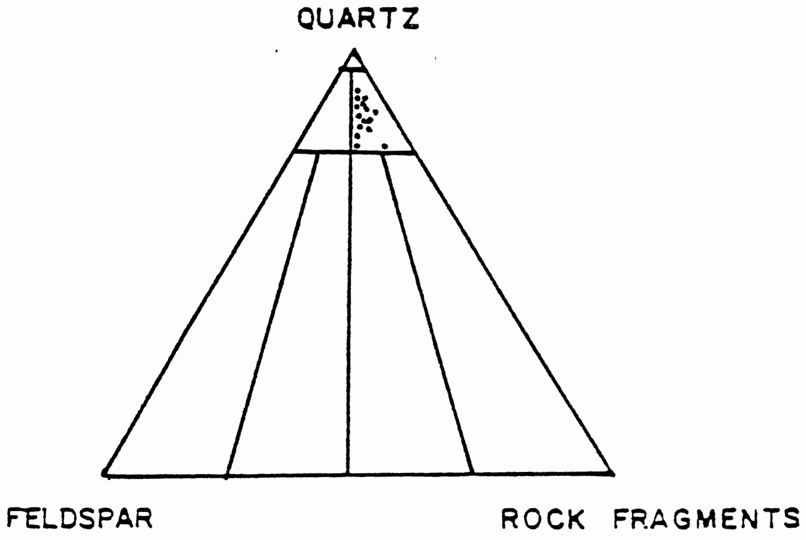
THOMPSON-TYE DRILLING COMPANY
No. 3 SHIELDS
SEC. 2-T21N-R5E



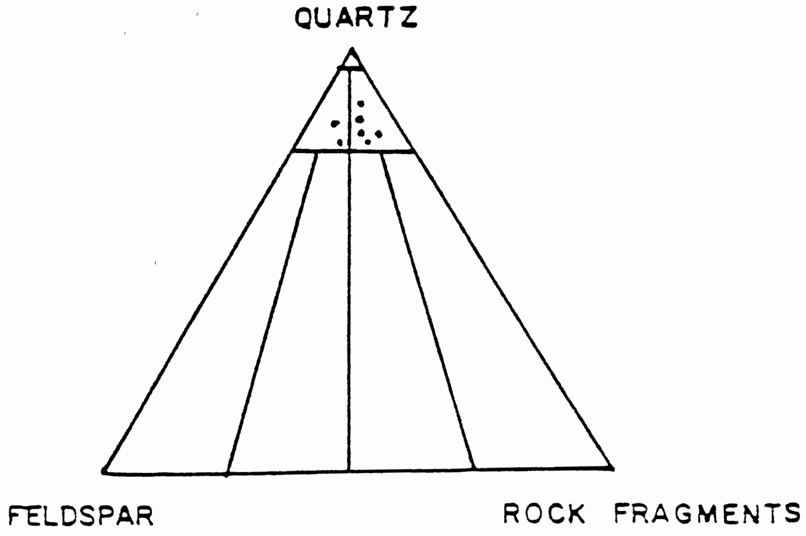
PERKINS PRODUCTION COMPANY
BUCHANAN No. 1
SEC. 20-T21N-R5E



A & W PRODUCTION COMPANY
BRIEN No. 3
SEC. 26-T23N-R4E

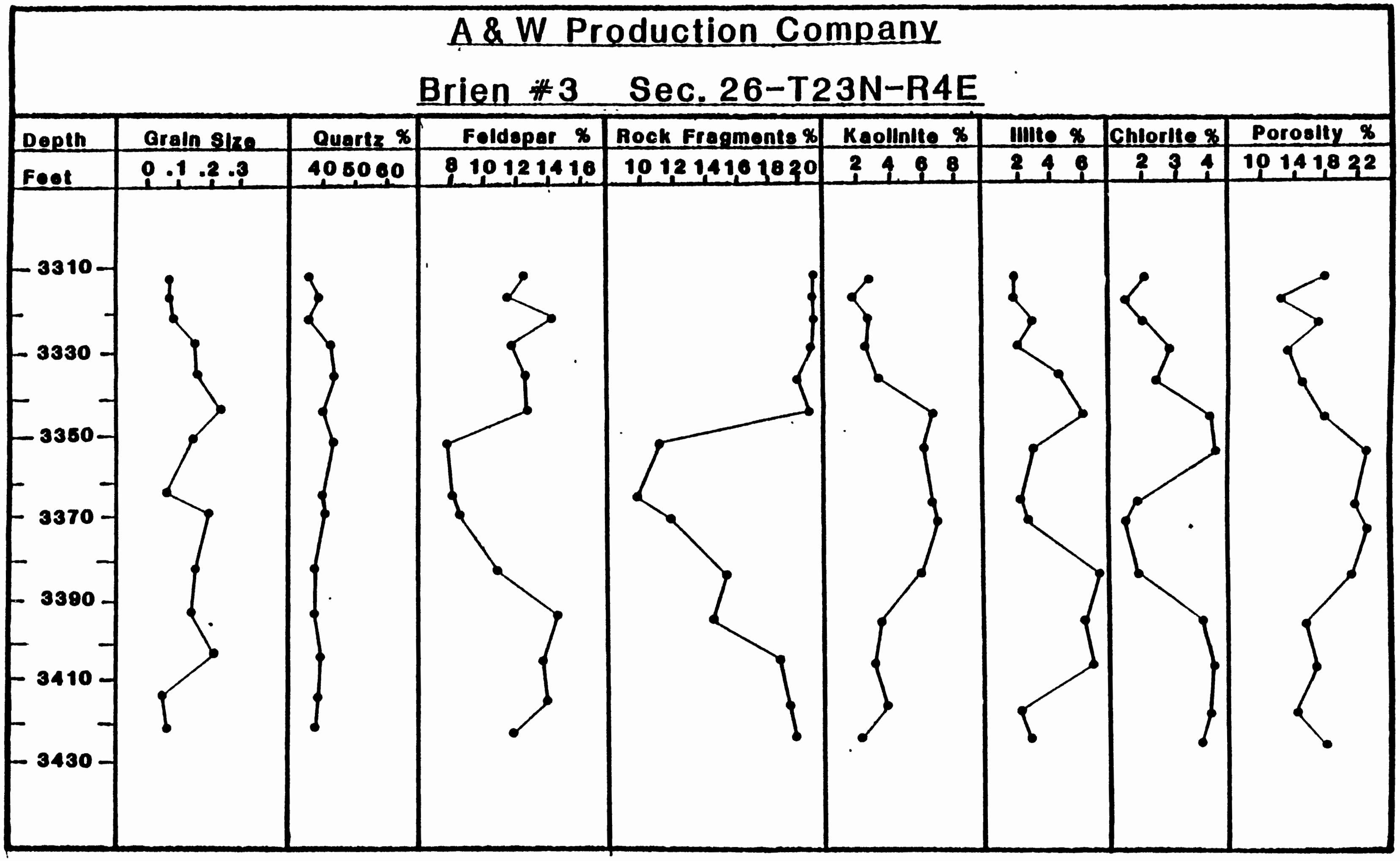


BANDERA ENERGY COMPANY
1-8 MARTIN
SEC. 8-T22N-R5E



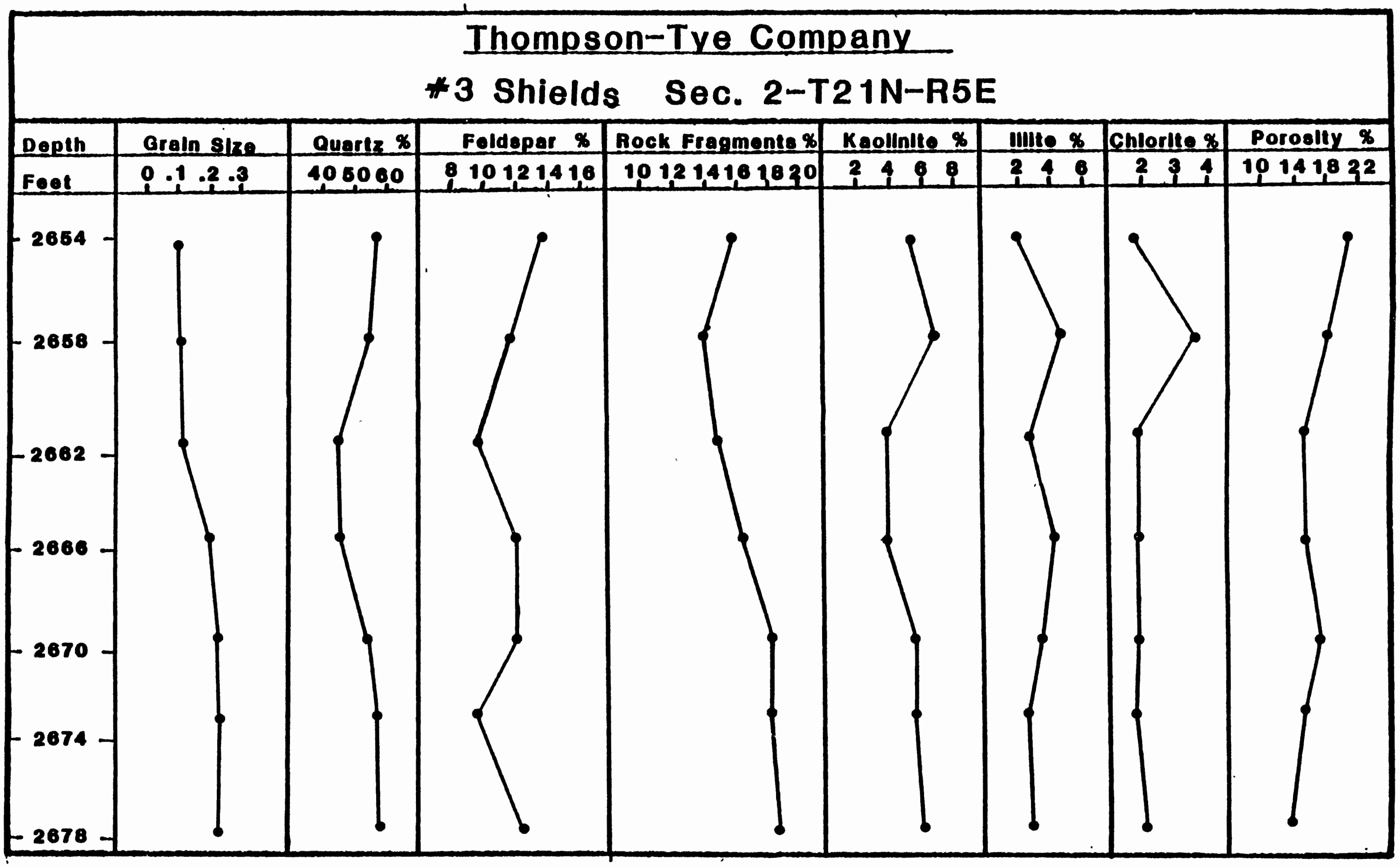
APPENDIX C

GRAPHIC REPRESENTATION OF SAND



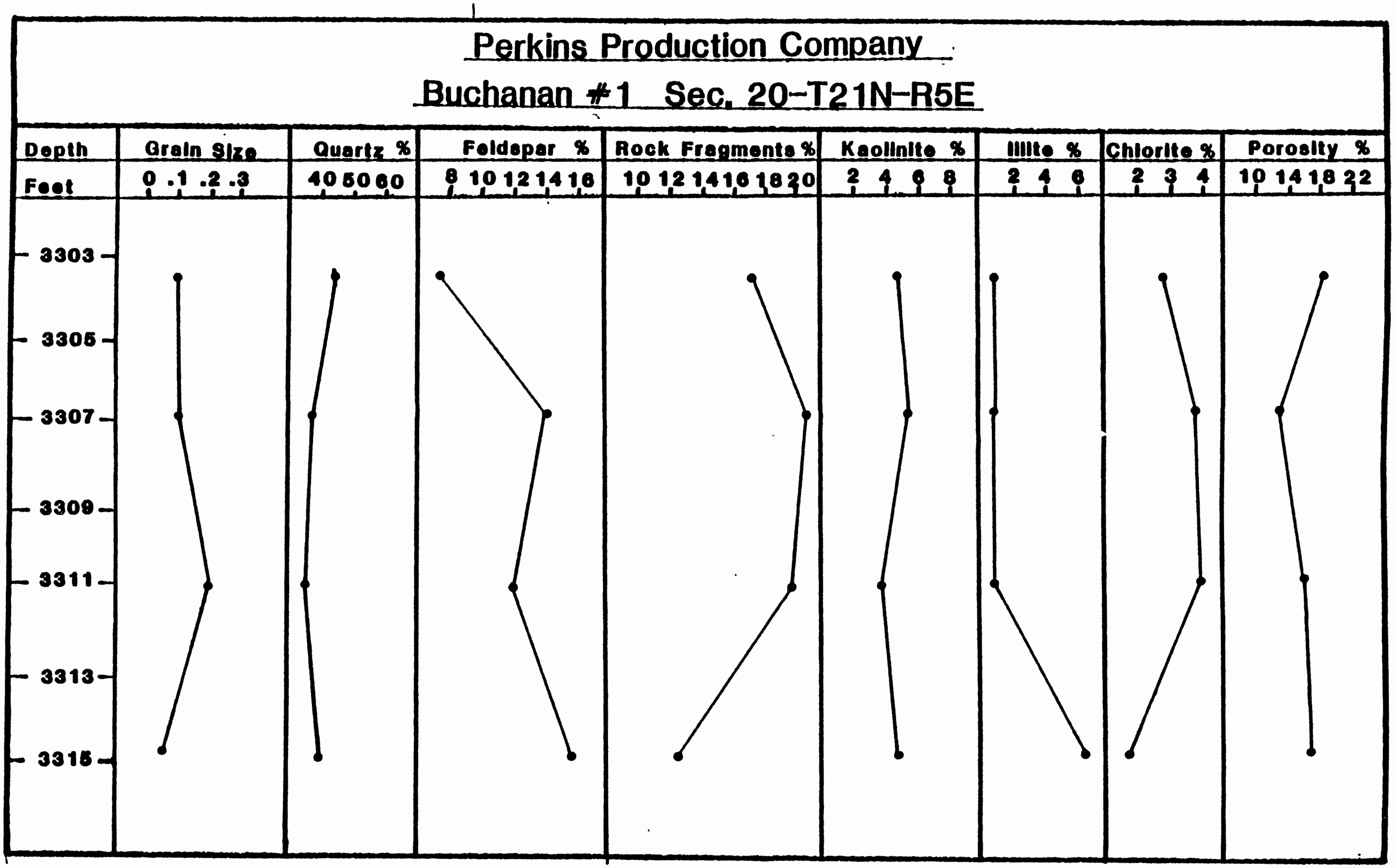
A & W Production Company

Brien #3 Sec. 26-T23N-R4E



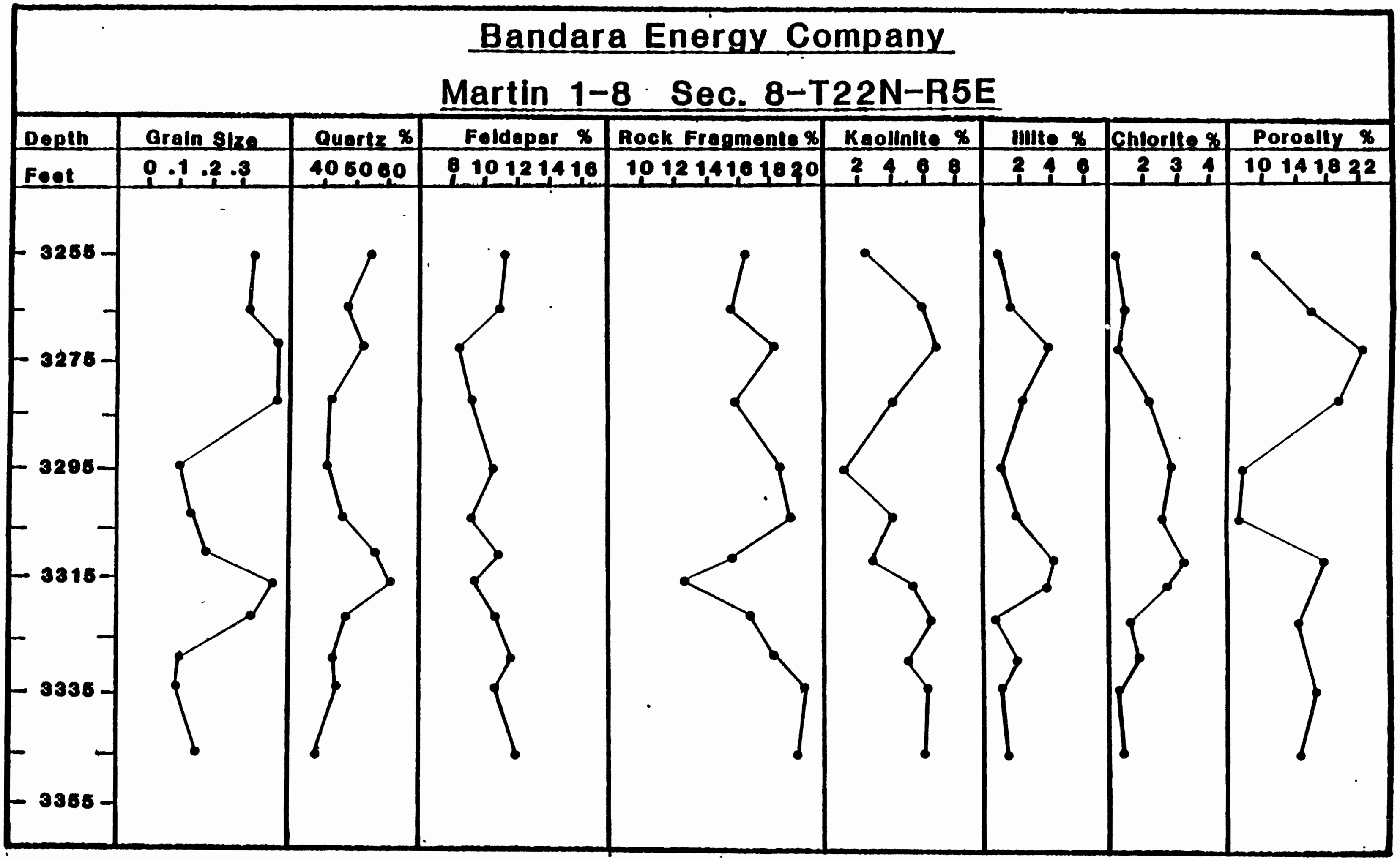
Thompson-Tye Company

#3 Shields Sec. 2-T21N-R5E



Perkins Production Company

Buchanan #1 Sec. 20-T21N-R5E

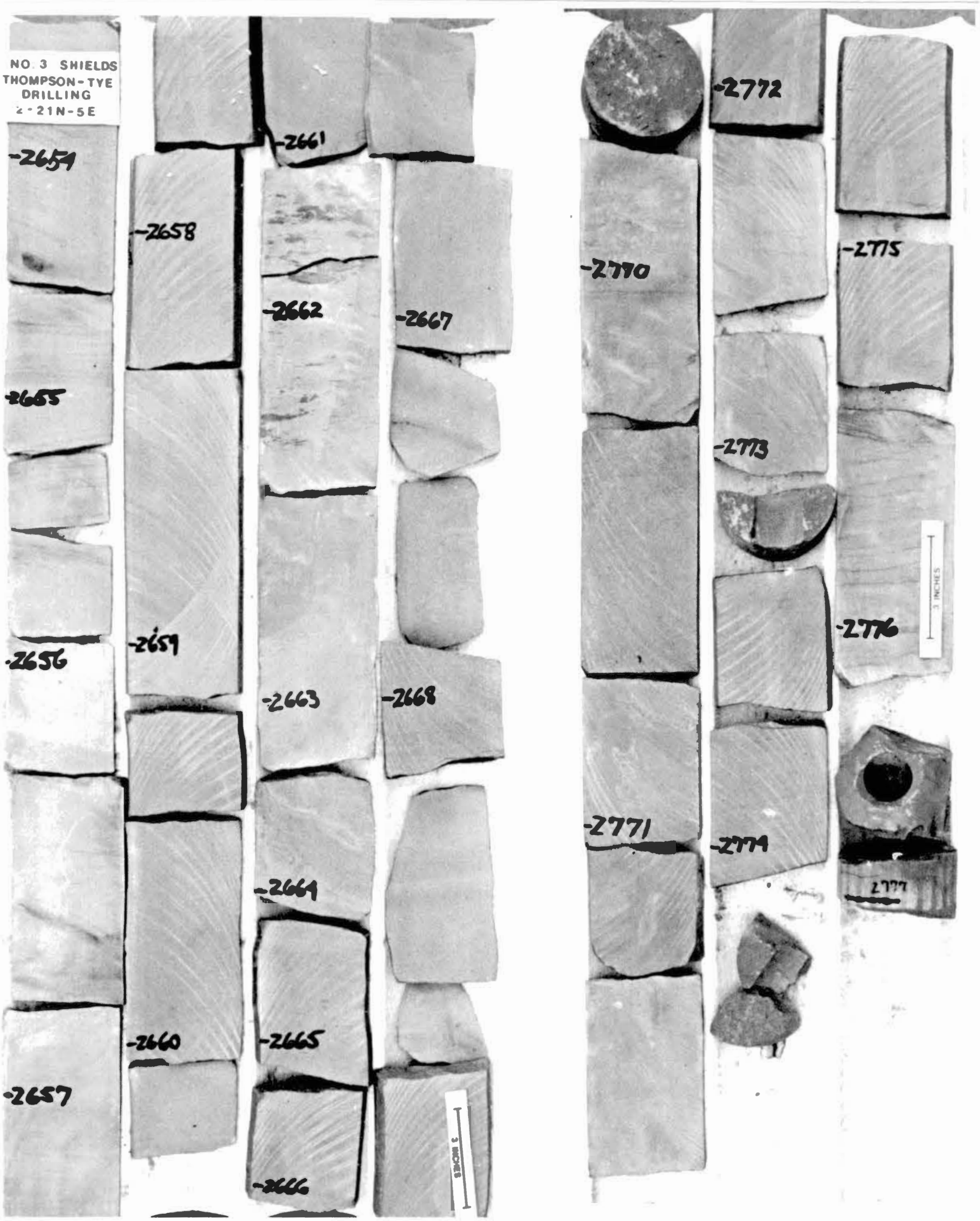


Bandara Energy Company

Martin 1-8 Sec. 8-T22N-R5E

APPENDIX D

REPRESENTATIVE CORE


NO. 3 SHIELDS
THOMPSON-TYE
DRILLING
2-21N-5E
-2654
-2655
-2656
-2657
-2658
-2659
-2660
-2661
-2662
-2663
-2664
-2665
-2666
-2667
-2668
3 INCHES
-2770
-2771
-2772
-2773
-2774
-2775
-2776
2777
3 INCHES

VITA

Scott Carter Balke

Candidate for the Degree of

Master of Science

Thesis: THE PETROLOGY, DIAGENESIS, STRATIGRAPHY, DEPOSITIONAL ENVIRONMENT, AND CLAY MINERALOGY OF THE RED FORK SANDSTONE IN NORTH-CENTRAL OKLAHOMA

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Professional Experience: Teaching assistant, Department of Geology, Oklahoma State University, August, 1982 to May, 1984; consulting geologist for A & W Production Company, May, 1984 to present.