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Lower Pennsylvanian Sandstone-Carbonate Cycles
on the West Flank of the Central Kansas Uplift,
Central Kansas

by

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LOWER PENNSYLVANIAN SANDSTONE-CARBONATE CYCLES ON THE WEST FLANK OF THE CENTRAL KANSAS UPLIFT, CENTRAL KANSAS

BY

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Abstract

LOWER PENNSYLVANIAN SANDSTONE-CARBONATE CYCLES ON THE WEST FLANK OF THE CENTRAL KANSAS UPLIFT, CENTRAL KANSAS

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Core studies and subsurface mapping of the Cherokee Group has been undertaken on an area on the Western Flank of the Central Kansas Uplift. Pennsylvanian rocks rest unconformably on the weathered, karstic, surface of the Mississippian. Most of the "lows" within this surface were filled in by the deposition of the Pennsylvanian Basal Conglomerate. The Cherokee Group consists of three major facies, these are:- 1) Mainly muddy tidal flat sediments, 2) predominantly sandy tidal channel sediments, and 3) low energy shallow marine limestones.

Two marine transgressions have been identified, during this time, limestone units were deposited over the entire study area. These can be correlated with transgressions in Eastern Kansas.

Cherokee sandstones produce oil within the study area. These are well-sorted, mature, contain little clay and were deposited in the point bars of tidal channels which traversed the area. Exploration for reservoir sands in the area is difficult because of rapid facies changes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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1) INTRODUCTION

The Cherokee Group is of considerable interest to petroleum geologists because Cherokee sandstones form the dominant reservoir rock in the study area.

The objectives of this study are:-

1) To determine the paleoenvironment at the time of deposition of the Cherokee Group, and to determine the modes of deposition of the Cherokee Group strata.
2) To relate the geologic characteristics of the Cherokee sandstones to the qualities of the existing, and potential, siliciclastic petroleum reservoirs in the study area.

The study is concentrated on the Cherokee Group (early Desmoinesian) which, in the study area, unconformably overlies eroded Mississippian strata. A varying thickness of Pennsylvanian Basal Conglomerate is present at the base of the Cherokee section.

Early Desmoinesian sediments were deposited during a major transgression onto the Mid-continent shelf. The Central Kansas Uplift remained exposed during this time. Close to the western flank of the Central Kansas Uplift, sedimentation was in a shallow water, marginal, setting. Water depth increased to the west. The paleogeography of the area during the Early Desmoinesian is shown in figure 1 (Rascoe and Adler, 1983).

There are two main sections within this thesis, the organization is shown below:-

1) Facies analysis. In this part, the methods of study, initially are described. This is followed by a description of the rock types present in the well-cores. This is followed by an introductory description of the interpreted environment of deposition of the Cherokee Group. Finally the interpreted environments of deposition of the Cherokee Group are given.

2) Porosity study. In this part, the methods of study initially are described. This is followed by a description of the pore systems within the Cherokee sandstones. This is succeeded by a summary of the pore systems, and the significance of the results.

The entire study is summed up in the conclusions.

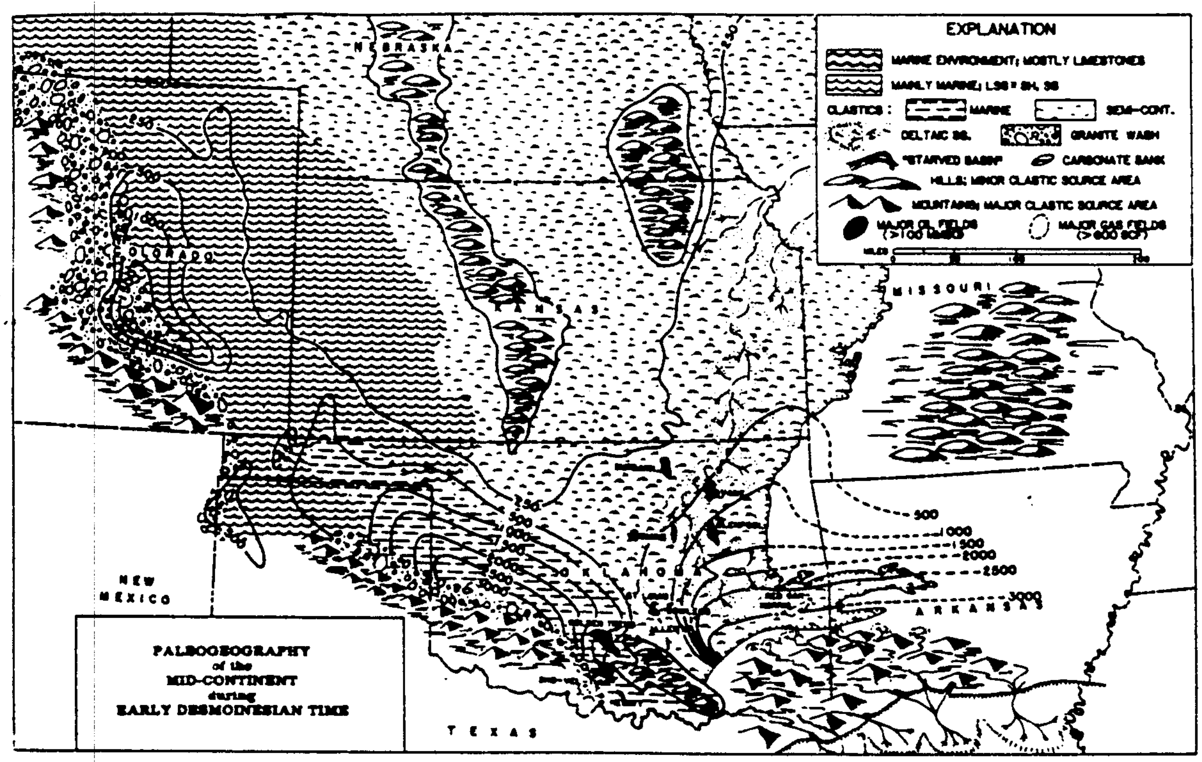


Figure 1. Paleogeography of the Mid-Continent during Early Desmoinesian Time (Rascoe and Adler, 1983).

2) STUDY AREA

The study area is located in northeastern Ness County, southeastern Trego County, southwestern Ellis County, and western Rush County (Fig. 2). The study area is on the western flank of the Central Kansas Uplift, and on the northeastern edge of the Hugoton Embayment of the Anadarko Basin (Fig. 3). The study is focussed on the Chaff Field (sec. 21,22 T16S, R21W), which is located in Ness County. However, the total study area extends north and south from T15S to T18S, and to the east and west from R20W to R22W, an area of 432 square miles.

The data available include Cherokee Group cores taken from three wells in northeast Ness County, and numerous petrophysical well logs within the study area. In order to determine the environments of deposition of the Cherokee strata, detailed examinations of lithology, texture, grain-size, and mineralogy were made of the well-cores. Thin sections were prepared from samples of the core, and were examined using a petrographic microscope. Extensive subsurface mapping helped to delineate the geometries of many of the rock units.

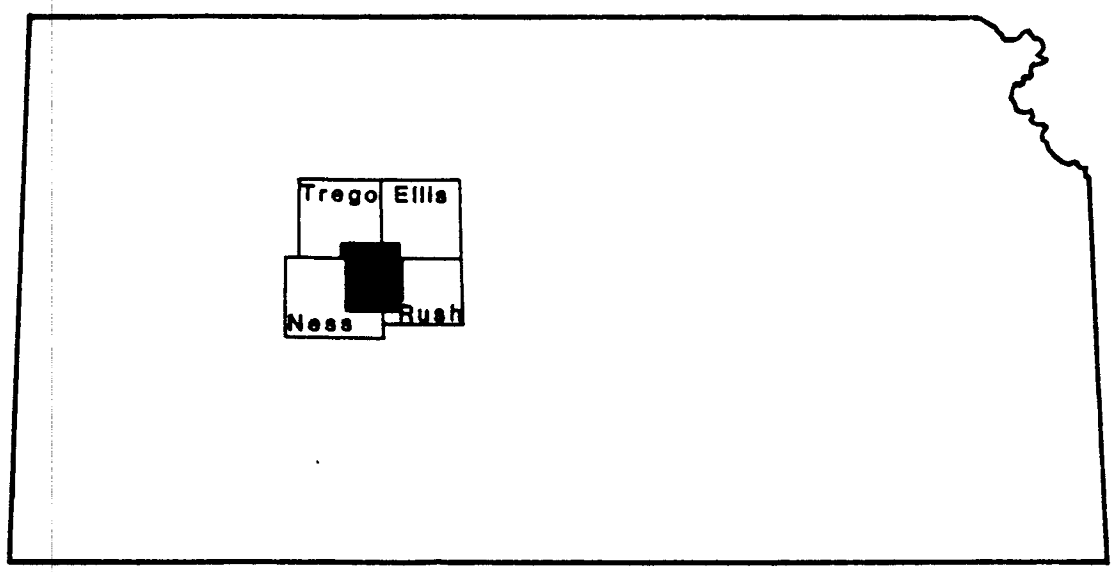


Figure 2. Location of the study area.

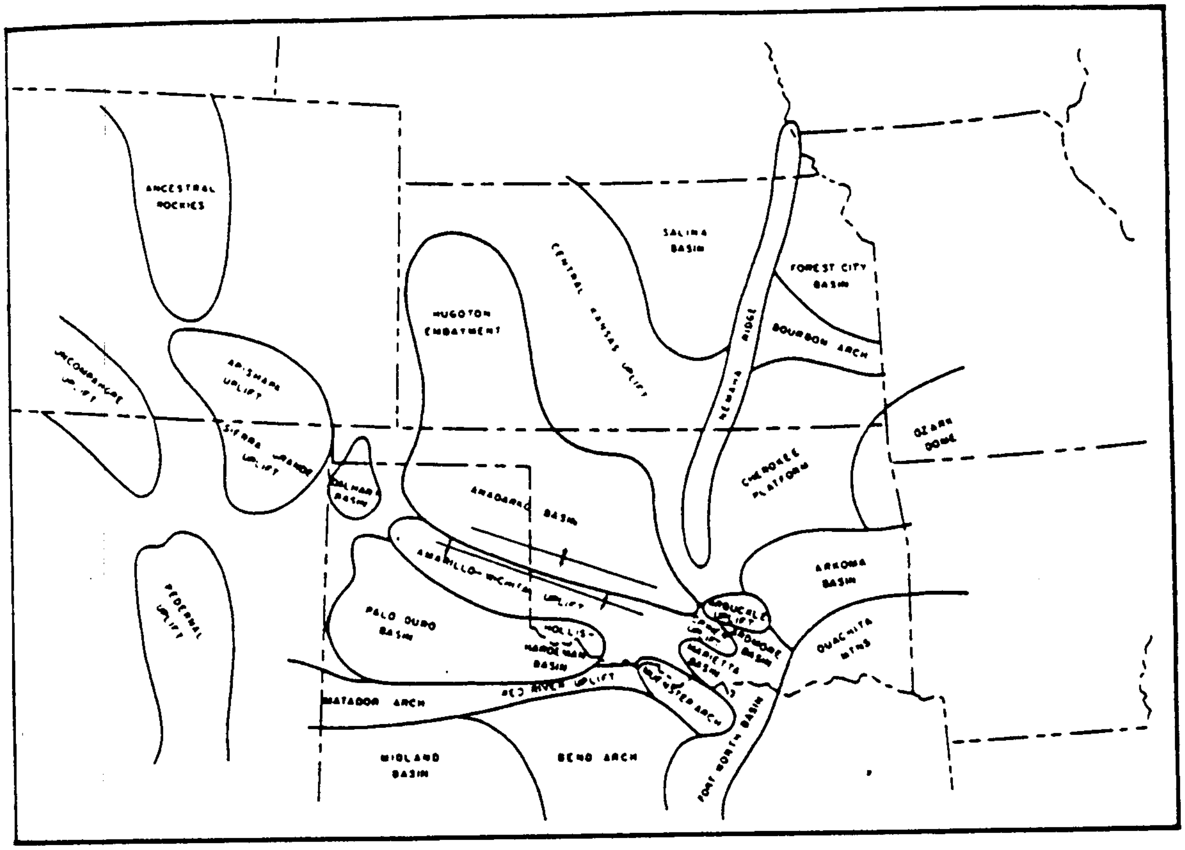


Figure 3. Principal Pennsylvanian physiographic and tectonic features of the southern Mid-Continent (Moore, 1979).

3) PREVIOUS WORK

Although much has been published on the Cherokee Group in eastern Kansas, there have been few publications dealing with the Cherokee Group in Central and Western Kansas. Walters and others (1979) described channel sands from the Cherokee Group in T17S, R24W (12 miles west of the study area). These sands may be good producers of oil, however, exploration for them is difficult because they fill sinuous valleys whose courses are difficult to predict. Most of these channel sandstone oil reservoirs have been discovered purely by chance while prospecting for oil in the underlying Mississippian dolomites (Walters and others, 1979). Nodine-Zeller (1981) published the results of a core study of the Pennsylvanian Basal Conglomerate in Ness County. Stoneburner (1982) made a general study of the Cherokee Group in this area.

On a more regional scale, Merriam (1963) briefly discussed the area in an overview of the geology of Kansas. More recently, Rascoe and Adler (1983) published an overview of Permo-Carboniferous hydrocarbons in the Mid-continent, which included a paleogeographic map of the Mid-continent during the early Desmoinesian (Fig 1).

McCrone (1964) discussed the cyclicity of the Desmoinesian in Kansas from a regional aspect. More recently Heckel (1985, 1986) has developed a sequence stratigraphy for the Pennsylvanian cyclothems of the Midcontinent. These cyclothems are related to eustatic sea level change and correlated within the study area.

4) REGIONAL SETTING

The Central Kansas Uplift, a northwest trending high, separates the Hugoton Embayment on the west from the Salina and Sedgewick basins to the east (fig 4). It is the largest structurally positive feature in Kansas, occupying an area of about 5700 square miles within the state (Merriam, 1963). It extends north into Nebraska, where it is termed the Cambridge Arch.

The Central Kansas Uplift and Cambridge Arch are major transverse components of the Transcontinental arch, and were formed by a cratonic epeirogeny which affected North America at the end of the Mississippian (Rascoe and Adler, 1983). This uplift coincided with a major eustatic lowstand, and produced a widespread regional unconformity. Mississippian and older Pennsylvanian beds were eroded from the Cambridge Arch, and parts of the Central Kansas Uplift. On parts of the Central Kansas Uplift, Pennsylvanian beds directly overlie the Precambrian basement. On the flanks, locally, Precambrian to late Mississippian beds are tilted, truncated, and overstepped by Atokan through Missourian beds (Merriam 1963, Rascoe and Adler, 1983).

Marine encroachment on this erosional surface was the

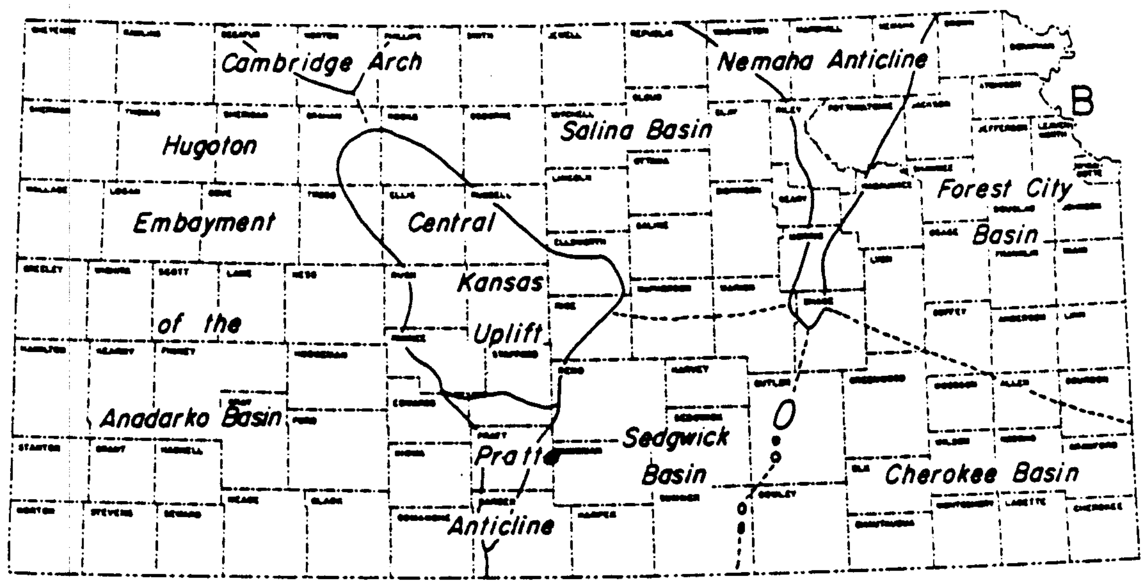


Figure 4. Major pre-Desmoinesian, post-Mississippian structural features of Kansas (Merriam, 1963).

major influence on sedimentation in this area throughout the lower Pennsylvanian and much of the Upper Pennsylvanian. Offshore carbonates farther west of the Central Kansas Uplift give way to fine-grained clastic strata which parallel the ancient shorelines (Rascoe and Adler, 1983). The Central Kansas Uplift was inundated by the end of the Missourian.

A shallow shelf was present to the west of the Central Kansas Uplift. The water depths over the whole shelf were approximately 15-25m (50-75 feet), and probably did not exceed 30m (100 feet) (McCrone, 1964). The sedimentation of the Upper Desmoinesian primarily consisted of carbonate beds that were separated by thinner shale units. Basinwards, farther from the clastic source, the carbonates thicken at the expense of the shales.

5) STRATIGRAPHY

The stratigraphic interval of interest in this study is the Cherokee Group, which in this area rests unconformably on an eroded Mississippian surface. The stratigraphy of the area is shown in Table 1.

A) Upper Mississippian Series

The youngest Mississippian beds present in the western part of the study area are those of the Warsaw Limestone. The Mississippian strata closer to the Central Kansas Uplift were eroded deeper, to expose strata of the Osagian Stage (fig. 5, Thompson and Goebel, 1968).

i) OSAGIAN STAGE

Rocks of the Osagian Stage consist of dolomite, limestone, chert, and cherty limestone and dolomite beds Osagian rocks are separated from the underlying Kinderhookian rocks by an angular unconformity. (Goebel, 1968).

ii) MEREMACIAN STAGE

Warsaw Limestone

STRATIGRAPHY WITHIN THE STUDY AREA

Series		Stage		Substage		Group		Formation
							-	Labette Shale
			-	Upper	-	Marmaton Group		
Lower Pennsylvanian Series	-	Desmoinesian Stage					-	Fort Scott Limestone
			-	Lower	-	Cherokee Group		
Upper Mississippian Series	-	Meremecian Stage			-	Warsaw Limestone		
Lower Mississippian Series	-	Osagian Stage						

Table 1. Stratigraphy within the study area.

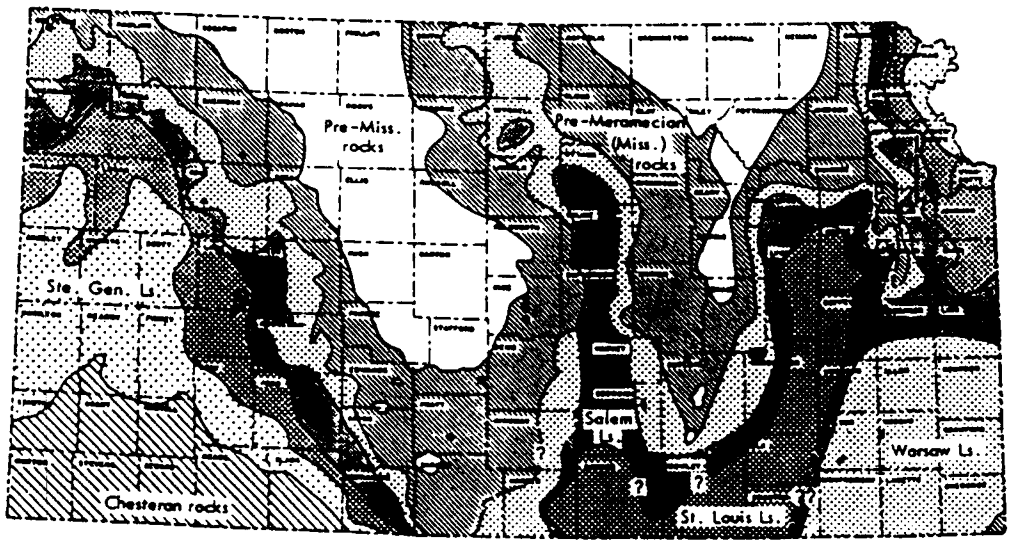


Figure 5. Subcrop geologic map of Mississippian rocks in Kansas (Thompson and Goebel, 1968).

The Warsaw Limestone is composed mainly of semigranular limestone interlaminated with sucrosic dolomite. Also present are large amounts of gray, mottled, opaque microfossiliferous chert (Goebel, 1968).

A) Lower Pennsylvanian Series

i) PENNSYLVANIAN BASAL CONGLOMERATE

Over much of Central Kansas, a breccia overlies the the weathered surface of the Mississippian. This breccia is the Basal Pennsylvanian Conglomerate (P.B.C.). It has been described by Nodine-Zeller (1981), who concluded, on biostratigraphic evidence, that it is either earliest Pennsylvanian, or possibly early Cherokee in age.

The breccia contains a mixture of weathered-in-place cobbles and boulders, and fluvially deposited pebbles and cobbles of Osagian, Meramecian, and Chesteran ages which were derived from the karstic terrain of the Mississippian (Nodine-Zeller, 1981).

ii) DESMOINESIAN STAGE

In the study area, strata of the Morrowan Stage and Atokan Stage are absent, and, with the exception of the

P.B.C., strata of the Desmoinesian Stage are the oldest from the Pennsylvanian present.

Cherokee Group

The Cherokee Group strata constitute the lowest division of the Desmoinesian Stage. They consist of an alternating sequence of sandstones, shales and limestones, and have been described extensively close to their outcrop area in southeast Kansas, where a detailed stratigraphy has been developed. In Central and Western Kansas, however, the depositional environment was different, and the stratigraphy of southeast Kansas is not appropriate.

Marmaton Group

The upper part of the Desmoinesian beds in Kansas are assigned to the Marmaton Group. These strata are more calcareous than those of the Cherokee Group (Jewett et al., 1968).

Fort Scott Formation

The Fort Scott Formation is the lowest formation of the Marmaton Group, and conformably overlies the Cherokee Group strata. It comprises two limestones and an intervening shale member, these are:-

i) Blackjack Creek Limestone Member

ii) Little Osage Shale Member

iii) Higginsville Limestone Member

Labette Shale

The Labette Shale conformably overlies the Fort Scott Formation. The Labette Shale consists of gray and yellow clay shale, sandy shale and sandstone, coal and limestone beds. A black shale is present in the lower part. Black shale also occurs locally in the upper part (Jewette et al., 1968).

6) DESCRIPTION OF THE CHEROKEE GROUP STRATA

A) Methods

i) CORE DESCRIPTION

Detailed examinations, of the lithology, textures, sedimentary structures, grain sizes, and compositions of the rock types within slabbed cores from three wells in northeast Ness County were made. The locations of the cored wells are listed in table 2. The full descriptions are given in appendix 1, and the lithologic logs are reproduced in figures 6, 7, amd 8. Each of the cores consists of a section from the Cherokee Group. The footages that are given in the descriptions of the well cores taken from the Cherokee Group were measured in feet below Kelly Bushing (K. B.).

The core also was examined using a binocular microscope. Detailed observations were made of grain size, mineralogy, contacts, graded bedding and other sedimentary structures, and the fauna present. All these features were described and logged (Appendix 1).

The size and angularity of the component grains in the sandstones were estimated using a chart supplied by the American/Canadian Stratigraphic Society. Details of the

Table 2. Location of the N.C.R.A. well-cores

PFAFF #2: SW NW SW, 21 16S 21W

PFAFF #3: NE NW SE, 20 16S 21W

THOMPSON A-#2: NE SW SE, 3 17S 21W

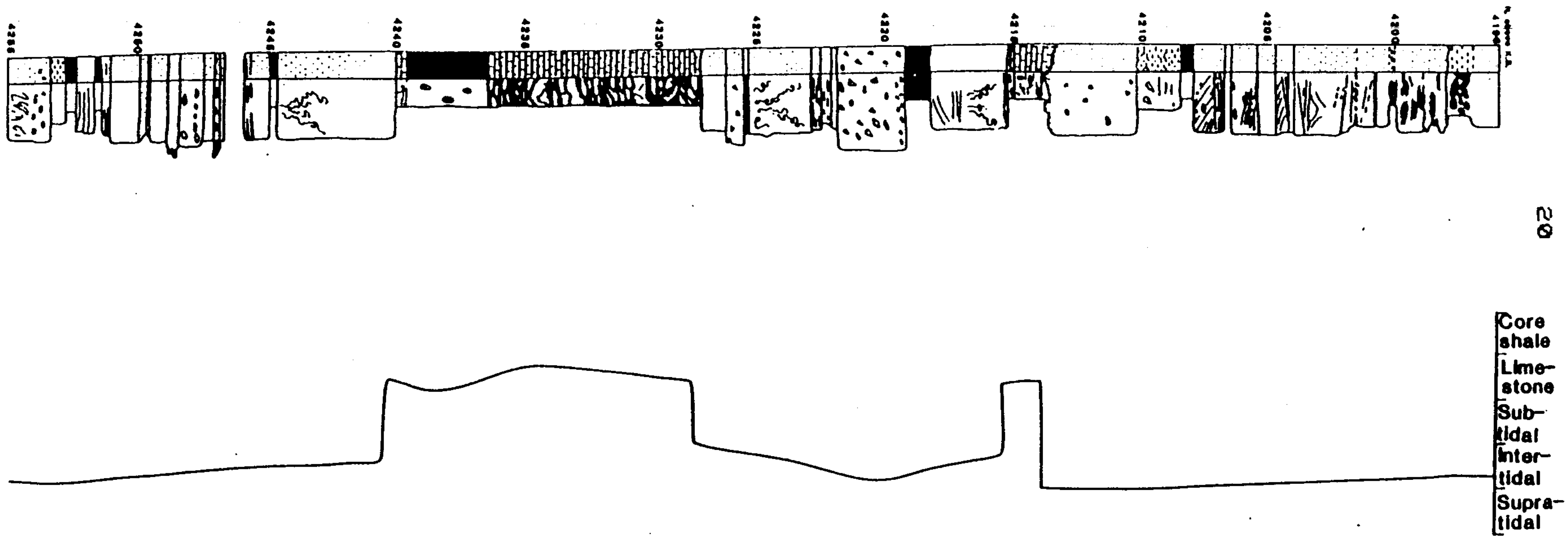


Figure 6. Log and sea level curve of the well-core N.C.R.A. Pfaff #2: SW NW SW sec. 21 T16S R21W. Key to symbols in figure 9

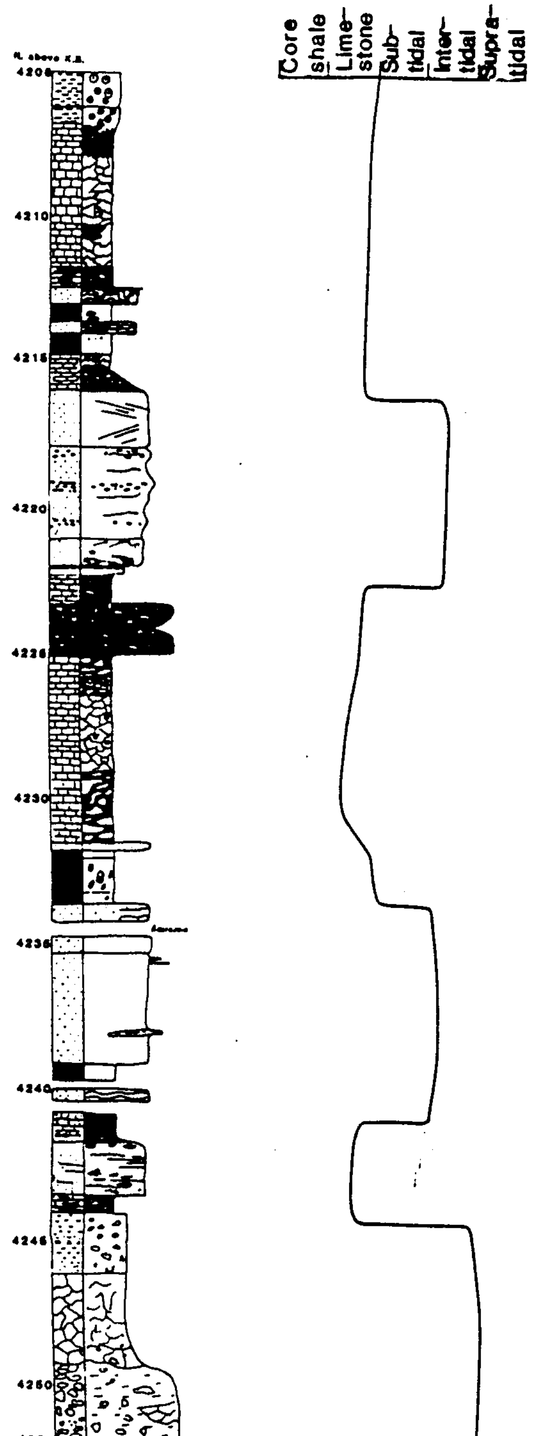


Figure 7. Log and sea level curve of the well-core N.C.R.A. Pfaff #3: NE NW SE sec. 20 T16S R21W. Key to symbols in figure 3.

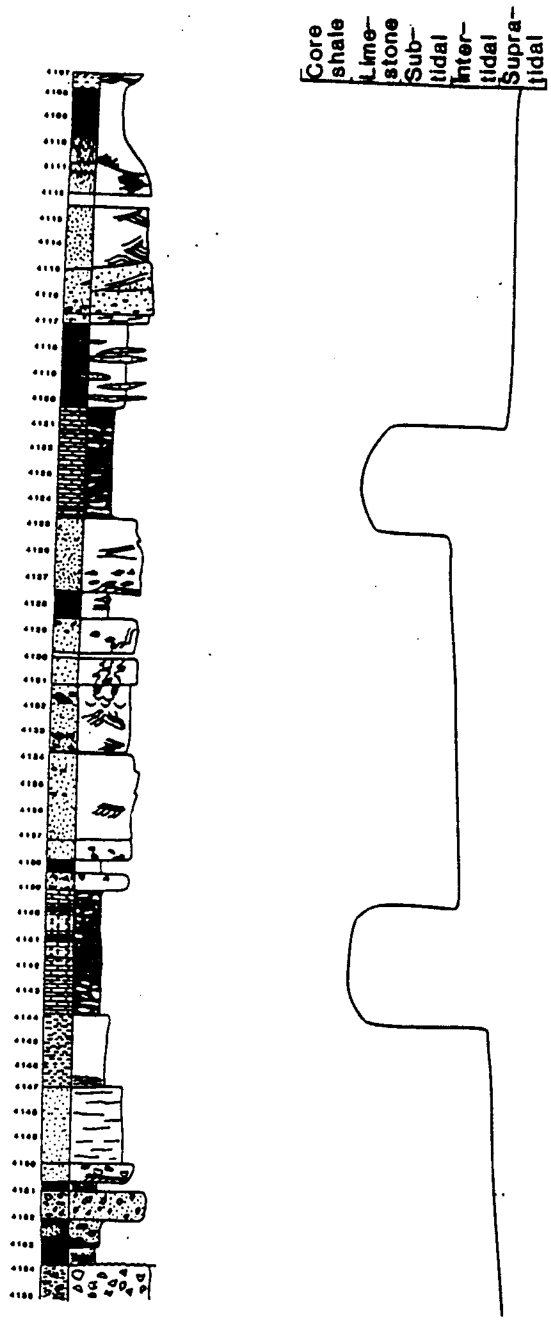


Figure 8. Log and sea level curve of well-core N.C.R.A. Thompson A-#2: NE SW SE sec. 3 T17S R21W. Key to symbols in figure 9.

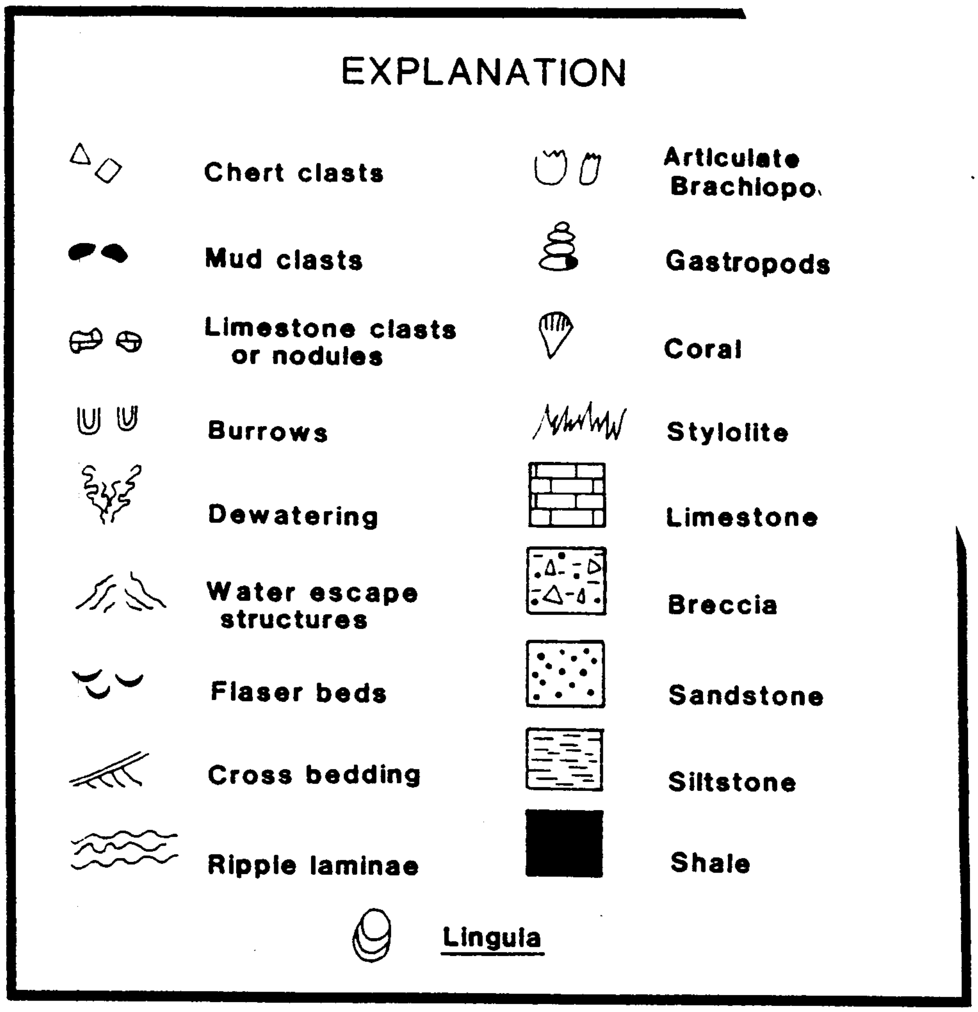


Figure 9. Explanation of the symbols used for figures 7, 8, and 9.

grain size classification are given in Table 3.

ii) PETROGRAPHY

Thin sections were prepared from all representatative lithologies within the National Cooperative Refinary Association (N.C.R.A.) well cores; N.C.R.A. Pfaff #2, N.C.R.A. Pfaff #3 and N.C.R.A. Thompson A-#2. In addition, thin-sections were prepared from vertical and horizontal samples taken in every reservoir zone, so that any anisotropies in the pore systems which may effect the flow of oil through the rock could be determined.

All of the sandstone thin-sections were stained for K-Feldspar, and were impregnated with blue-stained epoxy. In addition, those with a carbonate cement were stained with Alizarin Red S to determine the degree of dolomitization.

The limestone thin-sections were stained with Alizarin Red S, to determine the degree of dolomitization, and they also were impregnated with blue-stained epoxy, so that the pore systems could be better seen.

iii) LUMINOSCOPE PETROGRAPHY

Cathodoluminescent petrography was employed for many

Table 3. Three different ways of expressing the size of sand size grains.

Grain size (symbol)	Grain size (micrometers)	Grain size (phi)
vcU	1410 - 2000	-0.5 - -1.0
vcL	1000 - 1410	0.0 - -0.5
cU	710 - 1000	0.5 - 0.0
cL	500 - 710	1.0 - 0.5
mU	350 - 500	1.5 - 1.0
mL	250 - 350	2.0 - 1.5
fU	177 - 250	2.5 - 2.0
fL	125 - 177	3.0 - 2.5
vfU	88 - 125	3.5 - 3.0
vfL	62 - 88	4.0 - 3.5

samples to determine the original grain shape and sphericity of the quartz grains, and the amount of authigenic quartz in the form of overgrowths. In some of the samples it is possible to identify the original grain shape, and determine the extent of the quartz overgrowths by the presence of thin lines of impurities which collected along the rims of the detrital cores. In many of the samples, however, these are hard to observe, or are not present.

Compared to the cathodoluminescence of feldspars, carbonates and other minerals, the intensity of quartz luminescence is weak (Marshall, 1988). It has been demonstrated, however, that detrital quartz commonly shows a blue luminescence, whereas authigenic quartz is more often dull red (Smith and Stenstrom, 1965). This difference makes it easy to distinguish overgrowths from primary grains provided there is enough power to make the detrital quartz luminesce.

Thin-sections which had been prepared for the petrographic study, were used for the cathodoluminescence petrography. They were cleaned, any mineral oil was removed using detergent and water, and they were allowed to dry. The thin-sections were examined without a cover slip, because the electron beam penetration depth is only a few micrometers, and this is not great enough to allow the electrons to pass through the cover slip and retain sufficient energy to excite the specimen beneath (Marshall, 1988).

iv) SUBSURFACE MAPPING

Petrophysical logs were examined at the Kansas Geological Society library in Wichita for the area T15S to T19S and R20W to R22W.

The petrophysical log data were used to construct isopachous maps for the intervals:-

i) Labette shale to the top of the Mississippian.

ii) Top of the Cherokee to the top of the Mississippian.

The Labette Shale was chosen as a datum because it is of uniform thickness and is assumed to have been deposited over a flat surface. In addition, its signature easily can be identified on the petrophysical logs, and is uniform over the entire mapped area. The gamma ray log was found to be more useful than porosity and resistivity logs for correlation because it enabled simple identification of the Labette Shale, and allowed good resolution of the shaly and non-shaly units of The Cherokee Group.

Isopachous maps are more appropriate than structure contour maps because they remove the effects of post-Labette Shale uplift on the Central Kansas Uplift, and subsidence of the basin. The isopachous map of the Cherokee Group was constructed to illustrate the relationship between Mississippian topography and the Cherokee Group thickness.

On average, one well per section was used to construct the maps, though several sections have no available logs. Most of the logs in the mapped area penetrated the Mississippian, and therefore there was sufficient data for mapping on this scale.

Cross sections were constructed using petrophysical logs. Detailed cross sections were constructed in T16S R21W in the sections which contain, and surround, the N.C.R.A. wells: Pfaff #2 and Pfaff #3. The locations of these cross sections are shown in figure 10. These cross sections were constructed to determine the geometry and distribution of the strata that are observed in the cores. Isopachous maps were constructed using logs data from the same logs which were used to construct the cross sections to help in determining the geometry of individual rock units in the

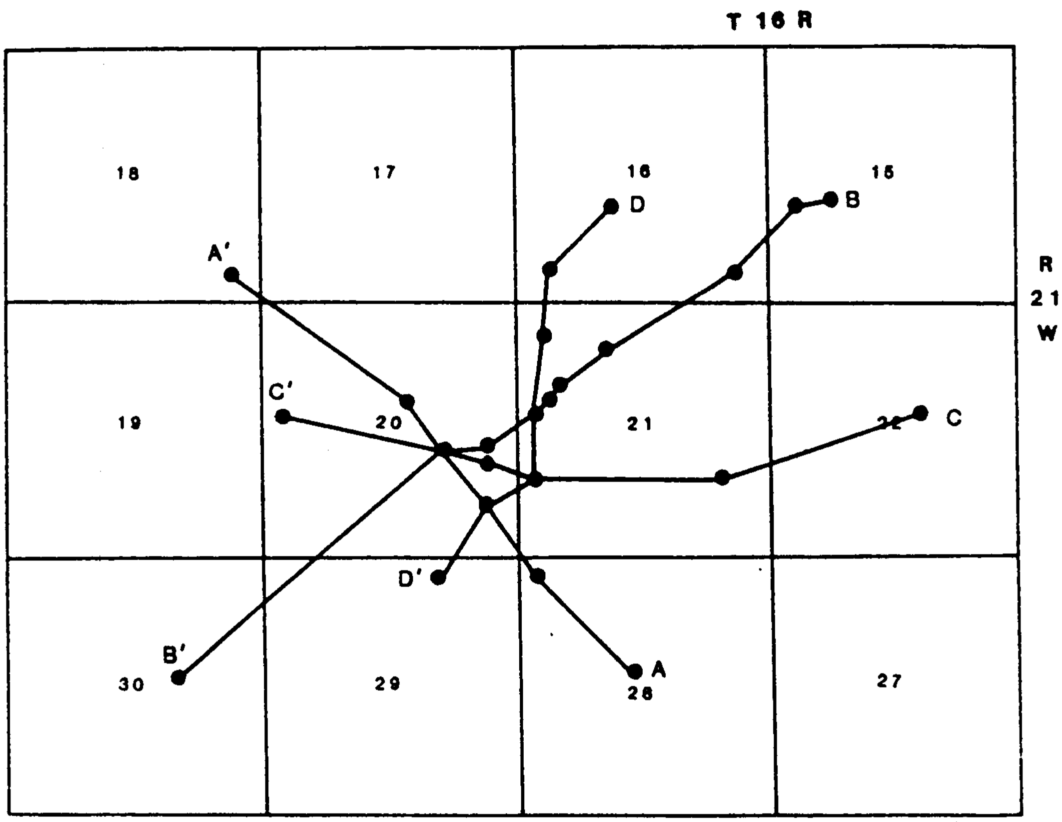


Figure 10. The locations of the cross sections within T16S R21W.

area surrounding the wells Pfaff #2 and Pfaff #3. The cross sections and isopachous maps helped to determine the environment and modes of deposition of the rock units.

The cross sections then were extended to the east, west, north, and south of T16S R21W, and continue to the margins of the area of study to determine the geometry of the more widespread units, such as the limestones. The locations of these, more extensive, cross sections is shown in figure 11, and are illustrated in figures 12 to 19.

Cross sections constructed from petrophysical log data indicate the presence of two limestone units over most of the study area, which have been termed the Upper and Lower Limestones. These are useful stratigraphic markers within the Cherokee Group, and provide a convenient framework to discuss the Cherokee in terms of five divisions. These are, in ascending order:

1) Base of the Cherokee to the Lower Limestone.
2) Lower Limestone
3) Top of the Lower Limestone to the base of the Upper Limestone
4) Upper Limestone
5) Top of the Upper Limestone to the top of the Cherokee Group.

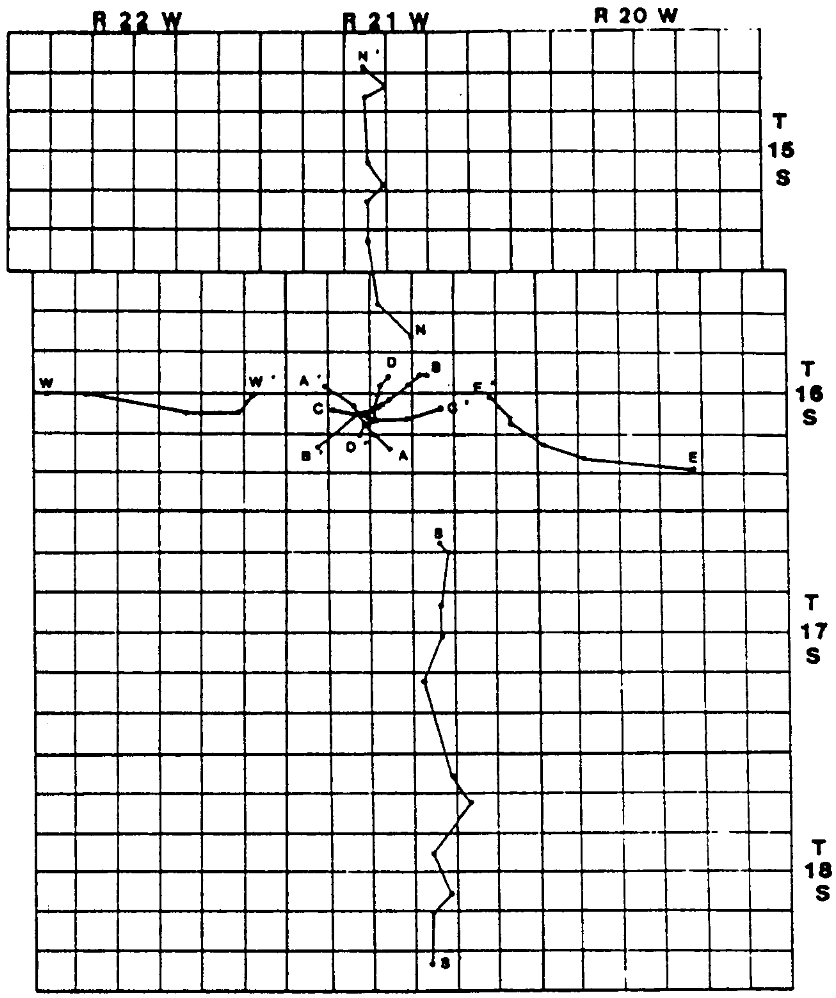


Figure 11. The locations of the stratigraphic cross-sections within the study area.

These five subdivisions overlie the Pennsylvanian Basal Conglomerate where it is present.

B) Descriptions

i) TOPOGRAPHY ON THE WEATHERED MISSISSIPPIAN SURFACE

Cherokee sedimentation commenced on the karstic surface of the Mississippian. Fig L1 (back sleeve) is an isopachous map from the Labette Shale to the base of the Mississippian in the study area. The karst topography can be seen clearly on it. Comparison of the topography on the Mississippian with the topography of many other karstified regions of the world shows a similarity of features. A similar example is the "cockpit topography" of Jamaica.

An isopachous map also was constructed for the Cherokee Group (Fig. L2, back sleeve). This indicates that the Cherokee Group is thickest overlying the lower ground, and is thinnest overlying the higher ground of the Mississippian paleosurface.

ii) PENNSYLVANIAN BASAL CONGLOMERATE

Examination of the cross sections indicates that many of the low-lying areas were infilled with shaly conglomeratic strata before "regular" Cherokee sedimentation began. This is also termed "Pennsylvanian Basal Conglomerate" (P.B.C.) by some authors (Nodine-Zeller, 1981). The top of the Pennsylvanian Basal Conglomerate is present in the N.C.R.A. well-core Pfaff #3. It is present from the base of the core (at 4252.0 feet) to 4249.0 feet. The rock is a matrix-supported breccia, containing clasts of white chert derived from the Mississippian. The clasts greatly vary in size, ranging from tens of centimeters to millimeters. Many of the clasts are highly irregular in shape, and are extremely angular. The enclosing silt is fine grained. It varies from maroon to pale green.

A thin-section of the breccia was prepared from Pfaff #3 at 4249.2 feet. The sample contains clasts of chert many of which have an internal structure of radiating blades, indicating that these have replaced anhydrite. The clasts are enclosed in a matrix of brown mud. The rock is very poorly sorted with the chert clasts present varying in diameter from silt-size to several centimeters. Clasts of quartzite and polycrystalline quartz also are present.

The breccia is overlain by a siltstone. The siltstone is very colorful, varying from maroon to green along fractures in the rock. Shades of blue also are present near its top. Isolated chert clasts are present, but decrease in abundance toward the top of the unit. A thin-section was prepared from Pfaff #3 at 4247.3. This shows that the rock is a sandy mudstone. A brown mud matrix encloses irregularly-shaped, angular, quartz grains. The rock is poorly-sorted; the grains vary in size from silt to fU sand. The siltstone is overlain by a friable, maroon siltstone which contains abundant chert clasts.

The signatures from the gamma ray logs indicate that the lower part of the Pennsylvanian Basal Conglomerate contains variable amounts of chert enclosed in siltstone and shale. At the top of the Pennsylvanian Basal Conglomerate there is an upward decrease in clasts, and an increase in the silt and shale content.

Interpretation

The angularity and poor sorting of the chert clasts indicate that they have undergone very little transport, and were probably eroded from the surrounding higher land of the Central Kansas Uplift. The chert clasts are enclosed in a yellow to maroon silt matrix, which indicates deposition in an oxidizing environment, in the supratidal zone. The increased siltiness upwards, as indicated on the gamma ray logs, implies that there was an upward decrease in the energy of turbulence as the topography became "smoothed" as a result of infilling of the "lows" by the P. B. C..

The Pennsylvanian Basal Conglomerate is overlain by a multicolored siltstone. A similar lithology was described by Nodine-Zeller (1981), and was interpreted as a weathered soil zone.

Stratigraphic sections which have been constructed from petrophysical log data indicate that the Mississippian paleotopography was "buried" over most of the mapped area by the Pennsylvanian Basal Conglomerate before sandstones and limestones were deposited. Cross section B-B' (Fig. 13) traverses a highly irregular Mississippian surface. All the "lows" of this surface are filled with the shaly Pennsylvanian Basal Conglomerate, the thickness of which, in the study area, varies from 0 to 50 feet.

Some depressions were not filled by the P.B.C.; these were filled with sandstones and shales. Section E-E' (fig. 17) illustrates both of these situations. A "low" on the westernmost part of this section has been filled with two sand bodies, whereas to the east, in sec. 24 16S 21W, a separate "low" has been infilled with a thick section of Pennsylvanian Basal Conglomerate.

After the topography had been "smoothed" due to burial, the deposition of laterally persistent shale and limestone units began.

iii) PENNSYLVANIAN BASAL CONGLOMERATE TO THE LOWER LIMESTONE

Lithology and distribution

Pfaff #3

In Pfaff #3, the shaly units of the P.B.C. are overlain by a nodular limestone (4244.0-4243.4 feet). The limestone nodules are composed of micrite. They are enclosed in a green and maroon shale. This limestone is overlain by a fine-grained, green sandstone (4243.4-4241.6 feet), containing layers of green expanding shale both near its base, and throughout the unit. Also present are patches and thin layers of black shale, and limestone nodules. Low-angle continuous lamination and ripple lamination can be seen in the sandier parts. Toward the top of the unit, the limestone nodules become more abundant, and at 4241.6 feet, the sandstone grades into a shale with limestone nodules. An isopachous map of the sandstone unit (4244.0 to 4241.6

feet) based on data derived from the cross sections A-A', B-B', C-C' and D-D' is shown in figure 20. The map indicates that the unit trends northeast-southwest. The isopachous map of the Labette shale to the Cherokee Group for the entire study area (fig L1) suggests that this is parallel to the paleoshoreline.

The shale enclosing the limestone nodules (4241.6 to 4240.6 feet) is very friable, and is maroon and green. Its distribution is not known, because it cannot be distinguished from the surrounding units on the petrophysical logs.

A quartz arenite overlies the shale and limestone unit (4240.3 to 4239.9 feet). The upper and lower contacts are not preserved in the core. It is very fine-grained, and contains little matrix. Most of the grains are composed of subangular quartz, with small amounts of muscovite present. The rock is well-cemented by silica.

The quartz arenite is overlain by a friable, gray shale unit which contains no limestone nodules (4239.6 to 4238.9 feet). The shale is overlain by alternating thin sandstone units (4238.9 to 4236.5 feet). The following two lithologies are present:-

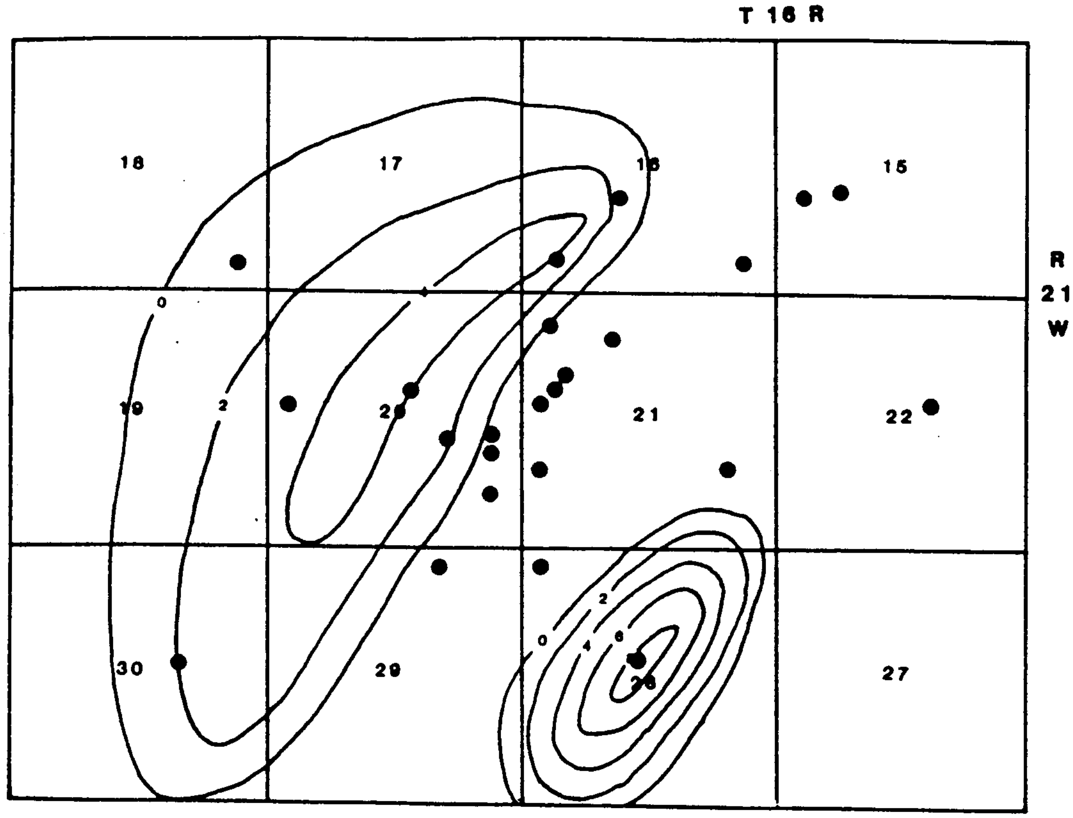


Figure 20. Isopachous map of a sandstone present in Pfaff #3 from 4244.0 to 4241.6 feet.

1) Pale green, well-sorted, fine grained sandstones with abundant clay in the matrix, and little porosity.

2) Medium grained oil stained sandstones with little matrix, and more porosity. Their sorting varies from good to moderate. Some coarser quartz grains (up to 5mm) are present in the moderately sorted units.

Both of these lithologies have been bioturbated, though they both retain crude horizontal laminations. A thin-section was prepared from a sample at 4237.2 feet. This thin-section shows that the sandstone grain-size distribution of the medium grained sandstones is bimodal, with the dominant grain sizes present being fU and cU. The grains are generally well-rounded, monocrystalline quartz and show a high sphericity. Little clay is present, and the rock is cemented by poikilotopic calcite.

Overlying these sandstones is a white, clay-rich, poorly-sorted sandstone (4235.4-4236.6 feet) containing bands of differing grain size, varying from mL to vcU. The clay matrix has sealed all the porosity. This is overlain by a well-sorted reservoir sandstone (4235.4-4233.6), which contains little clay. Some larger, chert clasts, and some black shale seams are present toward the top of the unit. Thin-sections of this unit were prepared from samples at

4233.8 feet and 4235.0 feet in Pfaff #3. These thin-sections show that the rock contains little clay, and that most of the cement is a thin silica cement. However, at 4233.8 feet, poikilotopic anhydrite is the major cement, and fills most of the pores. Some poikilotopic calcite cement is present, and is associated with the anhydrite.

The beds are present in N.C.R.A. Pfaff #2, Pfaff #3, and Thompson A-#2. Figure 21 is an isopachous map of the whole series of sandstones, illustrating that they do not have a widespread distribution, and that there is no clear trend in the distribution.

Pfaff #2

In Pfaff #2 the series of sandstones overlying the P.B.C. is 12 feet thick (4252.3 to 4240.1 feet). They overlie a thin (6 inch) green to maroon shale. The contact between the shale and the sandstones is sharp. At the base of the sandstone series is a fine-grained (fU), green graywacke (4252.3 to 4251.7 feet), which contains continuous wavy laminae near the base. A thin-section was prepared from a sample taken at 4252.1 feet. The rock is well-sorted, and very fine grained. Pressure solution has greatly altered the grain shape and angularity. Patches of poikilotopic

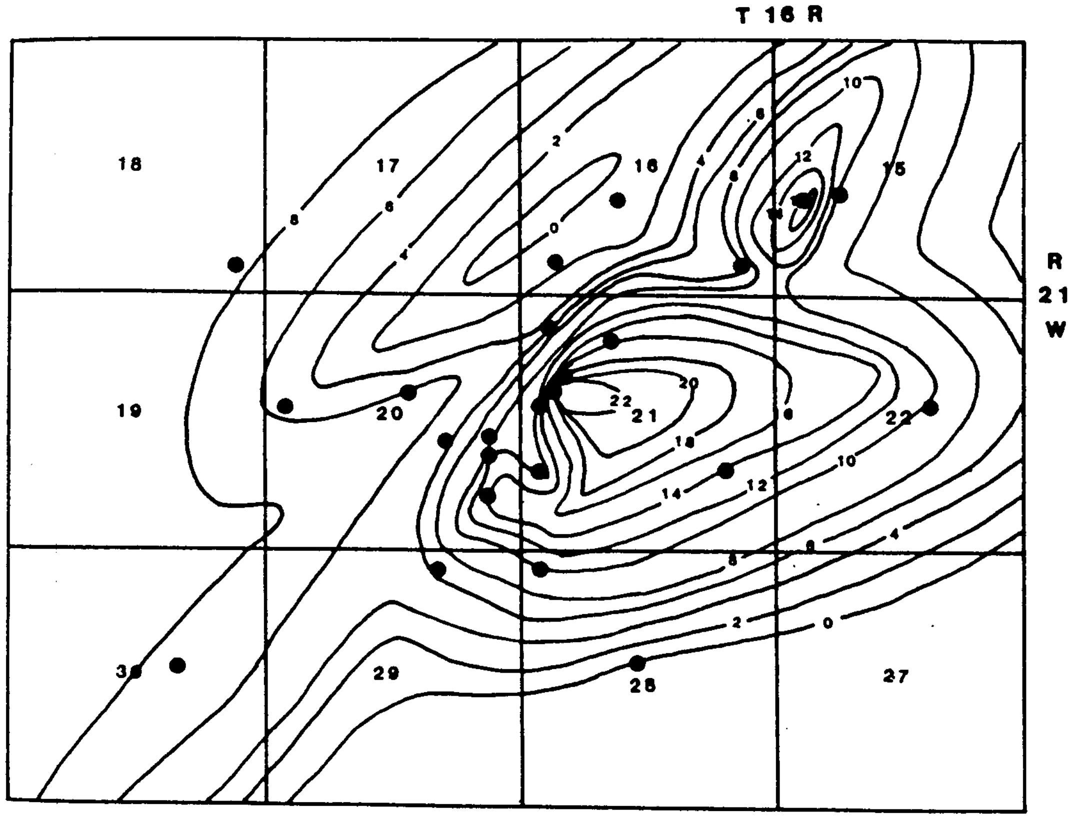


Figure 21. Isopachous map of the sandstone series below the Lower Limestone.

calcite cement (2.7%) are present throughout. Where cement is not present, the pores are filled with a clay matrix. Quartz grains make up 53% of the rock, clay makes up 15.3%, and feldspar grains make up 8.6% of the grains.

The graywacke is overlain by a thin bed of sandy, green, shale (4251.7-4251.4 feet). This, in turn, is overlain by a series of reservoir sandstones (4251.4-4247.5 feet). The sandstones vary from clay-rich, moderately-sorted, units which contain larger chert clasts, to finer grained beds with little clay. The finer grained units have much better developed porosity, because clay fills most of the pores in the coarser-grained beds. From 4250.7 to 4249.7 feet, a normally graded bed is present, with grain size grading from mL to vfU. Climbing ripple lamination is present in some of the units. Near the top of the series, the rocks are more poorly sorted, and have a higher clay content.

Thin-sections of these reservoir sandstones were prepared from samples at 4251.2, 4249.0 feet, and 4248.0 feet. At 4251.2 feet, the rock is an inhomogenous quartz arenite. It is well-sorted. About 90% of the grains are very fine grained, the rest are larger, ranging in diameter from 0.4 to 5mm. Most of the grains are quartz, though small amounts of chert, K-feldspar, and plagioclase are present. Many of the grains are well-rounded to subrounded. However, most are irregularly-shaped because of pressure solution. The rock is cemented mainly by clays, but small patches of poikilotopic calcite cement also are present. The sandstone is inter-layered with brown shale. This shale contains isolated, very fine, quartz grains.

At 4249.0, the rock is a homogenous arkose. It is moderately sorted, and is fine-grained. It contains thin hematite-rich mud layers throughout. The rock has undergone much compaction, which has reduced the primary porosity greatly. The unit is predominantly cemented by silica, however small patches of poikilotopic calcite cement the rock.

At 4248.0 feet, the rock is a, poorly-sorted, quartz arenite. The grains range in size from 0.07 to 10mm, and the average grain size is 0.4mm. The rock is cemented mainly by poikilotopic anhydrite which has filled most of the primary pores. In addition, silica cement, some clay cement, and isolated patches of poikilotopic calcite cement are present.

The "reservoir zone" beds are overlain by a coarser grained, poorly-sorted, clay-rich, matrix-supported, white to brown, conglomerate (4147.5 to 4146.8 feet). Most of the clasts are rounded quartz (up to 15mm in diameter). However, chert and granitic clasts also are present, enclosed in a matrix of medium grained quartz sand and clay.

The conglomerate is overlain by a medium grained, gray, quartz arenite (4247.0 to 4246.8 feet). Most of the grains are composed of sub-rounded to rounded, equant quartz. The rock is silica cemented, and contains very little clay. This is overlain, in turn, by a medium grained sandstone (4246.0 to 4245.0 feet) mainly maroon in color, and containing subrounded to rounded, equant, quartz grains. The unit contains a high clay content; slickensides are present as a result of compaction. The lower part of the unit contains thin bands of friable black shale.

The sandstone unit passes upward into a dark green shale which is present from 4245.0 to 4244.7 feet. The shale passes upward into a bioturbated, maroon, medium grained sandstone (4244.7 to 4240.1 feet). The sandstone is cemented by quartz and clay. Burrows filled with a clay-rich, green sandstone are present. Reduction spots are present throughout the unit. The rock is well-sorted, and the grains are well-rounded and equant in shape. This unit was analyzed using X-ray diffraction analysis, and the mineralogy was found to consist of quartz, kaolinite and hematite. This is evidence that the sandstone probably was deposited in the lower intertidal sand flat.

The sandstone is overlain by a compact limestone. The contact between these two units is sharp, and marks the base of the lower limestone.

Thompson A-#2

The N.C.R.A. well Thompson A-#2 does not contain a corresponding thick sandstone section unlike Pfaff #2 and Pfaff #3. In Thompson A-#2, the basal breccia is overlain by a mottled, oxidized shale. The shale contains large clasts of chert. Patches of yellow sandstone that have been greatly disrupted by dewatering are present in the upper part of the shale. These enclose irregularly-shaped mudstone clasts. The shale rapidly grades upward to a brick-red, matrix-supported breccia (4152.05-4150.85 feet). Angular and rounded chert, quartz and granite clasts (up to 30mm) are enclosed in a red siltstone matrix. The rock is poorly sorted, and massively bedded. This unit was analyzed using X-ray diffraction analysis. The minerals present were found to be quartz, kaolinite, hematite and anhydrite.

The breccia has a sharp upper contact with a maroon and green mottled shale (4150.85–4150.6 feet). The shale is overlain by a white litharenite (4150.6 to 4149.95 feet). It is coarsens upward from mL to cL. It contains low-angle cross laminae with the foresets made clearly visible by thin layers of green clay. Some red (oxidized) layers also are present. A thin-section of this unit was prepared from a sample at 4150.0 feet. Ninety two percent of the grains are composed of quartz. The remainder are composed of chert. All the pores have been filled with clay (15.6%), poikilotopic calcite cement (10.9%), and poikilotopic anhydrite cement (3.9%), and so there is no open porosity. It is not known if the clay is detrital or authigenic. Many of the quartz grains are well-rounded. However, most have been deformed by extensive pressure solution. The rock is poorly-sorted, the grain-size varying from vfL to vcU with an average grain size of mU.

This sandstone is overlain by a maroon sandstone (4149.95 to 4143.95 feet), which grades from a very fine-grained (vfL), ripple-laminated sandstone which grades up into a siltstone. Throughout the entire unit, larger (up to 20mm) isolated, angular, chert clasts are present. The siltstone grades to a purple shale. Isolated, green, reduction spots are present at the top of the unit, which could have been caused by burrows, or decayed plant roots. The top of the shale marks the base of the Lower Limestone.

Interpretation

Pfaff #3

The earliest Cherokee deposition which is present in the core taken from the well, Pfaff #3 is that of a nodular limestone. This was deposited seaward of clastic sedimentation in an environment with low wave energy. The overlying sandstone (4243.4 to 4241.6 feet) is was deposited in a sandbank in the subtidal zone. This sandbank eventually was buried by the build-up of carbonate mud, and clay, which was deposited in shallowing water.

A sandstone bed thought to be a storm bed overlies the shale with limestone nodules. This storm deposit is overlain by a series of sandstones, interpreted as having been deposited in channels in the subtidal to lower intertidal zone. Weimer and others (1981) stated that the tidal channel facies is the facies most likely to be preserved in the subtidal zone. This series of sandstones may reflect deposition by more than one tidal channel, which accounts for the lack of a distinctive geometry. The variations in grain size are a result of fluctuations in the tidal energy.

Pfaff #2

In the well core of Pfaff #2, the Pennsylvanian Basal Conglomerate is overlain by a green to maroon shale, deposited in the intertidal flats. The shale is overlain by a sandstone series, deposited by lateral accretion in a tidal channel. A graywacke is present at the base of this series indicating that deposition occured before a great amount of reworking had taken place. As the deposit was built up, there was an increase in shaliness, and poorer sorting of the sandstones, indicating a decrease in energy, and less winnowing because of a decrease in water depth.

The sandstone beds contain oil, with less oil near their top, where they are better-cemented, resulting in lower porosity. The overlying reservoir seal is a poorly-sorted, clay-rich, matrix-supported conglomerate deposited as a basal lag in a tidal channel. This basal lag deposit is overlain predominantly by clay-rich sandstones and some shales; these were deposited in tidal creeks and the intertidal flats.

Thompson A-#2

The well core Thompson A-#2 contains a section of poorly sorted sandstones which were deposited in low-energy tidal channels, and oxidized siltstones and very fine grained sandstones which were deposited on the supratidal flats, or the upper intertidal flats.

iv) LOWER LIMESTONE

The Lower Limestone is present in N.C.R.A. Pfaff #2, Pfaff #3 and Thompson A-#2. Thin-sections from this unit were examined from samples in Thompson A-#2 (4142.0 feet) and Pfaff #2 (4230.5 feet). A powder sample of this unit was analyzed using X-Ray diffraction analysis. Both the limestone nodules and shale were included in this analysis, and the mineralogy was found to be, calcite, quartz, kaolinite, smectite and glauconite.

Lithology

In Pfaff #2, the base of the limestone is at 4240.1 feet. The unit overlies a sandstone and there is an abrupt lithologic change between the two beds. The limestone is a "compact" fossiliferous micrite, and contains one thin horizontal band of green shale. The fossils present include brachiopods and corals.

The thin limestone is overlain by a dark gray shale (4239.7 feet). The shale is very fissile and contains abundant Lingula. It has a high "peak" on the gamma ray log, and so its signature can easily be recognized.

The shale is overlain by a much thicker limestone unit having a nodular texture. The nodules are composed of a fossiliferous micrite, and are enclosed in a maroon to gray shale. The shale and the limestone contain crinoids and brachiopods. Thin seams of green clay pass through the rock and separate some of the clasts.

A thin-section was examined from a sample at 4230.5 feet. This illustates that many of the limestone clasts are subangular. Organic remains present include recrystallized aragonite shells, echinoid plates, crinoid ossicles, and brachiopod shells and spines.

The well-core Pfaff #3 contains a section of limestone of equal thickness to Pfaff #2. Below the base of the limestone, a Lingula-rich shale is present (4233.6 to 4231.8feet).

The shale is separated from the limestone by a thin sandstone bed (4231.8-4131.5 feet), which has sharp upper and lower contacts, and an indistinct maroon and green horizontal color banding. Its grain size varies from fL to cL, and it contains a white clay matrix.

The overlying limestone, present from 4228.4 to 4222.3 feet, is a fossiliferous micrite, and has a nodular texture. The fossils present are brachiopods, sponges, crinoids and algae. Shale encloses the limestone nodules. The shale varies from green to maroon, and ranges from 0-20% of the total rock volume. More compact layers which contain crude laminae, are present within the rock.

The limestone is present in Thompson A-#2 from 4143.95 to 4138.9. However, neither the Lingula-rich shale and the underlying limestone are present. The lower contact of the limestone with red siltstone is sharp. From 4143.95 to 4142.25 feet the limestone has a nodular texture, with fossiliferous micrite nodules separated by a gray shale.

From 4142.25 to 4141.75 feet the limestone grades upward from a packstone to a wackestone. At the base, the clasts are separated by green shale. Higher, the shale is less abundant, and the pores are filled with sparry pore-filling calcite cement.

A thin-section of the packstone was taken from a sample 4142.0 feet. The framework grains mainly are micrite, though some recrystallized bivalve shell fragments are present. The average grain size is 5mm, and the grains range from 2-50mm in diameter. Other skeletal particles include crinoid ossicles and algae. The rounded micrite clasts are separated by coarse pore-filling calcite cement. The clasts also contain fractures which have been filled by pore-filling calcite cement. Neomorphism of both the clasts and cement has occurred. This is shown by patchy distribution of the larger crystals and irregular crystal boundaries. Occasional quartz grains are present within the rock; these are subrounded, irregularly shaped, and range in size from mL to cL.

The packstone is overlain by a shaly conglomeratic wackestone in which most of the grains are micrite. The average grain size is 3mm. This layer is rich in shells, shell fragments, and fish scales. The fossils present include:- brachiopods, sponges, rugose corals, and gastropods. Many of the micrite nodules are elongate. These, and all the shell fragments, are aligned parallel to the bedding, are enclosed in shale, and are not incorporated into the limestone.

This deposit is overlain by a maroon shale which encloses limestone nodules (4139.15-4141.15 feet). The limestone nodules are composed of mottled micrite. These become less abundant than the shale toward the top of the unit.

The limestone rapidly grades upward to a shaly, fine-grained sandstone. Limestone nodules are present at the base of the sandstone.

Diagenesis

The limestone has undergone extensive dissolution by meteoric waters, which led to the formation of the micrite nodules. Many non fabric-selective pores have formed from the dissolution of the micrite. Many of the pore spaces that have resulted from meteoric weathering have been filled by a muddy matrix. However, where the matrix is absent, the pores have been filled with calcite cement. Two phases of cementation are present:-

1) Isopachous calcite. This lines the pores locally throughout the rock; it is not present throughout.
2) Sparry pore-filling calcite. This is dominant throughout the rock, and fills all pores which have not been filled with a muddy matrix.

The micrite has undergone neomorphism of two types:-

1) Aggrading neomorphism:- the micrite contains patches of larger, irregularly-sized, calcite crystals with irregularly-shaped grain boundaries (fig 22).

2) Retrograding neomorphism:- The pore-filling calcite has partly altered to micrite. The micrite occurs in isolated patches within the calcite cement.

Distribution

An isopachous map of the unit is shown in figure 23. The unit is continuous in the area surrounding the N.C.R.A. wells; Pfaff #2 and Pfaff #3. To the north of T16S R21W, the lower limestone is a thin discontinuous unit (fig. 16). To the south it is continuous for about 9 miles, then pinches out between 11 18S 21W and 15 16S 21W (fig 18).

To the west, the limestone can be traced along the section W-W' as far as 19 16S 22W. Over this area it maintains a uniform thickness (5-6 feet). It pinches out, locally, in 22 16S 22W. The limestone bed pinches out within one mile to the east of the eastern end of the cross-section C-C'. It is absent to the east, with the exception of a thin (2 feet) body at 24 16S 21W.

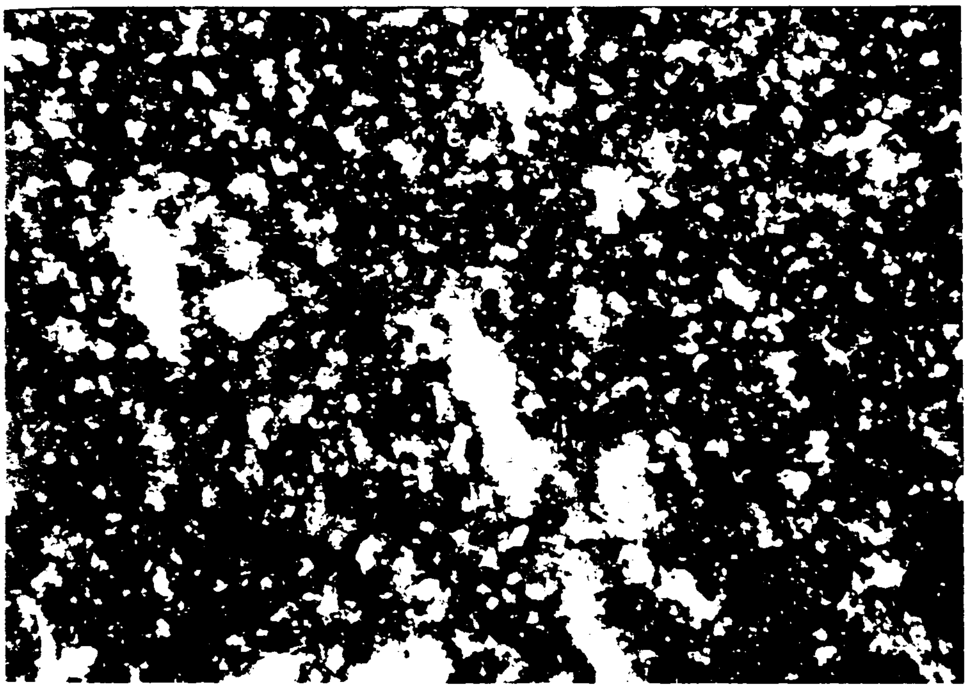


Figure 22. Photomicrograph of aggrading neomorphism in the Lower Limestone from Pfaff #2: 4130.2 feet. Irregularly-shaped sparry patches are present within the micrite. Plane polarized light. Length of photograph is 1.7mm.

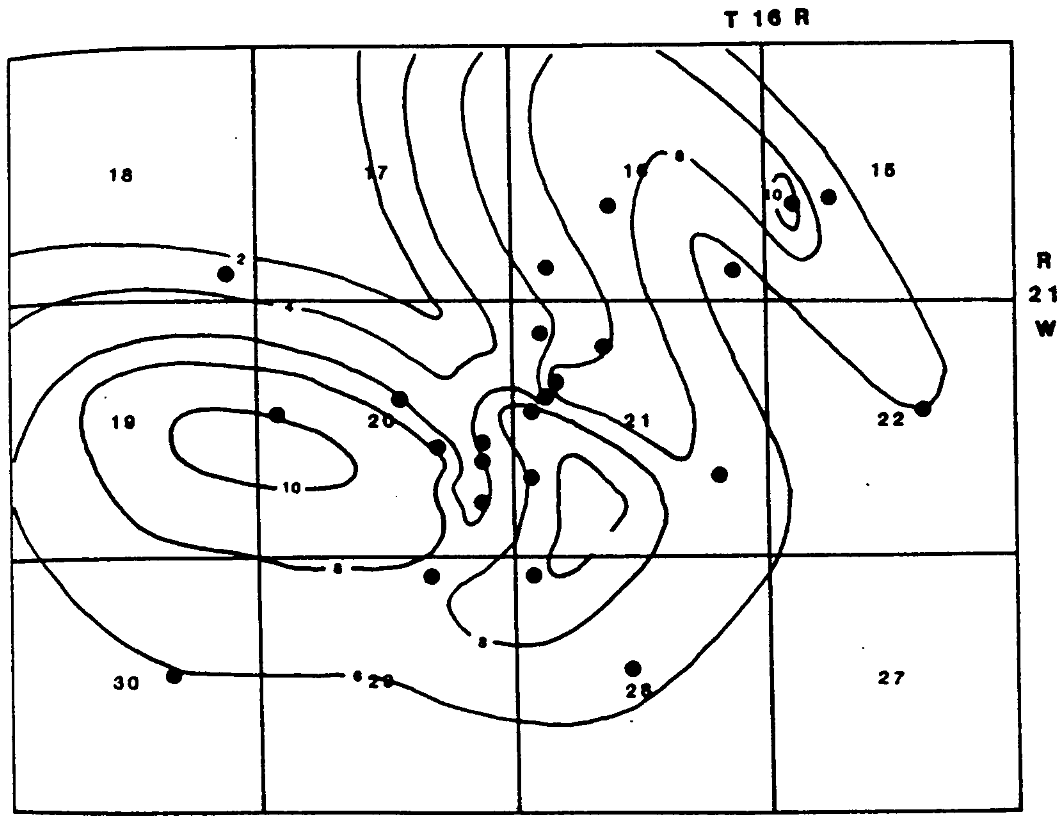


Figure 23. Isopachous map of the Lower Limestone

Interpretation

Using the criteria given by Heckel, 1985, this is interpreted as a regressive limestone. The most conspicuous feature is the nodular texture, which is thought to have formed as a result of meteoric weathering. The shale which encloses the limestone nodules was deposited during the period of meteoric weathering as sea level fell.

A gray, Lingula-rich, shale is present within the limestone unit, in Pfaff #2, and below the limestone in Pfaff #3; This is interpreted as a nearshore shale, deposited during a period of increased clastic input to the area. This shale is separated from the limestone in Pfaff #3 by a thin sandstone unit interpreted as a storm deposit.

The shelly lag deposit which is present within the limestone in the well core Thompson A-#2 is thought to have formed because of strong current activity.

v) LOWER LIMESTONE TO UPPER LIMESTONE

The beds between the lower limestone and the upper limestone mainly are sandstone units. The whole series has an average thickness of 10 feet. Thin shale beds are present within the sandstone sequences of all three well-cores. A clean cream-colored sandstone is present near the lower limestone in all three well cores. The description of this interval can best be described in terms of three parts:-

a) Units underlying the cream-colored sandstone

b) The cream-colored sandstone

c) Units overlying the cream-colored sandstone.

Units underlying the cream-colored sandstone

Pfaff #3

In Pfaff #3, a red and green mottled siltstone containing a few coarse (cU) quartz grains, directly overlies the lower limestone. This is overlain by a thin (0.1 inches) green shale seam at 4222.1 feet, which in turn is overlain by a fine-grained (fL), green, ripple-laminated, quartz arenite, which directly underlies the clean cream-colored sandstone, present from 4222.9 to 4221.9 feet. All the contacts are sharp. Unfortunately, these units are too thin for their signatures to be recognized on the petrophysical logs, so their geometries cannot be established.

Pfaff #2

In Pfaff #2, the cream-colored sandstone directly overlies the lower limestone.

Thompson A-#2

In Thompson A-#2, the Lower Limestone is directly overlain by a green and maroon, mottled, fine-grained (fL) sandstone which is present from 4138.9 to 4138.5 feet. This coarsens upwards, is clay-rich, and contains isolated chert clasts. A sandy shale is present at the base of this unit. The contact with the limestone is sharp.

Overlying the sandstone is a maroon shale with green reduction spots (4138.5 to 4138.0 feet). The contact is sharp. The shale is overlain by a poorly-sorted maroon sandstone from 4138.0 to 4137.25 feet. There also is a sharp contact between these two units. The sandstone ranges in grain size from fU to mL, has a high clay content, and contains angular chert clasts. The grains in this unit show a high sphericity. All of these units pinch out to the north and south of Thompson A-#2.

Interpretation

It is thought that the siltstone which is present is pfaff #3 was deposited on the upper intertidal flats, or the supratidal flats because of the presence of reduction spots, which formed as a result of burrowing, or decayed plant root. Burrowing activity is most intense in upper intertidal flats, and plants are sparse below the supratidal flats. The sandstone unit probably was deposited as point bars in a tidal channel.

The maroon sandstones which overlie the Lower Limestone in the well core Thompson A-#2 are thought to have been deposited in a low-energy tidal channel in the upper intertidal flats, or supratidal flats.

The cream-colored sandstone

Lithology

The clean, cream-colored sandstone directly overlies the lower limestone in the well-core N.C.R.A. Pfaff #2 (4227.2 to 4222.9 feet). The contact between them is sharp, and possibly represents a scour surface. At the base of the unit, thin shale seams are present. Although these are too thin to cause the rock to part, they produce faint green bands throughout the rock. The sandstone is well-sorted, though present throughout the rock are bands which contain larger chert clasts. The component grains of the sandstone are angular to subrounded, and the grain size within the bands ranges from fL to cU. One band within the unit contains horizontal laminations, but primary depositional structures of this type are not common throughout the entire unit because of bioturbation.

The same sandstone unit is present in the well-cores Pfaff #3 and Thompson A-#2. In Pfaff #3 the unit is present from 4221.2 to 4216.0 feet. It contains isolated limestone nodules, and some mud clasts. The sandstone contains bands with coarser clasts of chert, quartz, limestone and mud. The unit contains low angle cross bedding towards the top.

In Thompson A-#2 the sandstone unit is present from 4137.25 to 4133.85 feet. The rock contains calcite cemented patches. There are two upward coarsening cycles, with the grain size varying from fU to mU. Some coal fragments are present within the rock. These are the same size as the component grains. Bioturbation has obliterated most depositional structures. However some horizontal laminae and low-angle cross bedding are present.

Thin-sections were prepared from samples of the sandstone unit from the well-cores; Pfaff #2 at 4224.0 feet and 4226.0 feet: Pfaff #3 at 4216.5 feet, 4220.2 feet and 4221.9 feet:

and Thompson A-#2 at 4133.8 feet. These show that most of the grains are composed of monocrystalline quartz; polycrystalline quartz and chert also are present. The rock also contains isolated grains of K-feldspar. The porosity in the rock ranges from 10-25%, but is not indicative of original porosity, because the sandstone has been compacted, which has led to pressure solution and the formation of quartz overgrowths. The pores have partly been filled by poikilotopic calcite cement. Near the base of the unit, in Pfaff #3, some of the pore spaces are filled with oil.

A thin-section of this unit was prepared from a sample taken from 4133 feet. The rock is compositionally mature; 99% of the grains are composed of quartz. Fossils are present within the sandstone; recrystallized aragonite shells are present. Poikilotopic calcite cement has filled most of the pores throughout the rock (26.4%), leaving only 0.4% open porosity. The sandstone is moderately sorted. The average grain size is mL, however the grains range in size from fL to cL. Most of the grains are well-rounded and equant.

Distribution

The sandstone body is not continuous to the west of Pfaff

#3. Within 0.5 miles, the sandstone pinches out, and is replaced stratigraphically by a limestone unit. This limestone is three feet thick, and it is enclosed in shale. East of Pfaff #3 the sandstone continues, thinning slightly, and eventually pinches out about 7 miles east of Pfaff #3. The unit is split by a shaly unit in Pfaff #2, and pinches out to the east and west of Pfaff #2. The sandstone continues to the north for about 2 miles, and south for about 4 miles, Throughout this distance the sandstone maintains a constant thickness. The shaly unit, which splits the sandstone in Pfaff #2 is present to the north and south, throughout this whole section. North and south of T16S, R21W, sandstones enclosed in shale pinch in and out.

Interpretation

The cream-colored sandstone is thought to have been deposited in the point bars of a large tidal channel. However the geometry does not seem to approximate a channel geometry, and the unit seems more likely to form a sheet, which extends about six miles parallel to the shoreline, and seven miles perpendicular to it. Despite this, the presence of mud clasts and the rapid variation of the sedimentary structures argues more strongly for a tidal channel origin than a prograding sand bar, or sandbank. The lithology reflects a relatively higher energy as indicated by the paucity of silt and mud, and, therefore, the channel probably was much larger than most of the channel deposits in the Cherokee Group. The exact geometry of the unit is not demonstrable, because of the difficulty in distinguishing this unit from other sandstones which immediately overlie it.

In parts of the unit, the depositional structures have been destroyed by bioturbation. Bands which contain bioturbation probably were deposited more slowly than the units which have not been bioturbated.

Units overlying the cream-colored sandstone

Pfaff #3

In Pfaff #3, the cream-colored sandstone is directly overlain by the upper limestone.

Pfaff #2

Between Pfaff #3 and Pfaff #2, four units pinch in above the cream-colored sandstone. These are exposed in Pfaff #2. The lower of these units is a fine grained, ripple laminated, green sandstone (4222.9-4221.9 feet). It has a sharp contact with the underlying sandstone, contains subangular to subrounded, equant grains, and also contains isolated, larger, chert grains, up to 10mm in diameter. Fine silt bands pass through the rock, and near the base of the unit, green shale-rich layers are present.

The green sandstone is overlain by a clay-rich, poorly sorted breccia (4221.9 to 4219.3 feet), which is pale green, except at the top of the unit, where it grades to maroon. The contact between this unit and the underlying fine grained sandstone is sharp. The breccia is matrix-supported. The clasts consist of angular fragments of chert, and granite-derived quartz, which are well-rounded at the base and become more abundant and less rounded towards the top. They range in diameter from 2-20mm.

The matrix is a clay-rich, medium-grained, sandstone. The grains in the matrix are subrounded to rounded, and are equant. A thin section of this unit was prepared from a sample at 4219.9 feet. This shows that the sandstone is less mature compositionally than most of the Cherokee sandstones, because only 63% of the grains are composed of quartz, 30% are composed of chert, 3.5% are K- feldspar, and the remaining 3.5% are granitic fragments. The chert clasts are similar in texture to the fossiliferous micrite which is the dominant lithology within the limestone units, and were formed from the silicification of limestone. It has partially recrystallized so that isolated patches of larger crystals are present within a finely crystalline groundmass. The rock is poorly sorted, with grain size ranging from fine to coarse. The grains are angular to rounded, and elongate to equant in shape. They are enclosed in a clay matrix.

The breccia is overlain by a green shale (4219.3-4218.3 feet). This contains angular clasts of quartz and chert, up to 20mm in diameter. The upper and lower contacts of the shale are sharp.

The shale is overlain by a clean, cream-colored, fine-grained sandstone (4218.3-4215.1 feet). The lithology of this unit is the same as that of the clean sandstone below, which is present from 4227.2 to 4222.9 feet. A thin-section of this unit was prepared from a sample taken at 4217.9 feet. This shows that the rock is a porous, well-sorted, quartz arenite. The rock has undergone much compaction which has led to pressure solution and the formation of quartz overgrowths. The rock is mainly cemented by silica. However, small patches of poikilotopic calcite cement are present.

From 4215.3 to 4215.1 feet, thin green shale seams are present in the sandstone, and become more abundant near the top of this interval. Green shale is present in flaser beds, and in continuous horizontal seams. The top of the unit grades upward into green shale in a short distance, and then the upper limestone.

Thompson A-#2

In Thompson A-#2, the cream-colored sandstone is overlain mainly by sandstones, with some shale. The cream-colored sandstone is directly overlain by a medium grained, green sandstone (4133.85 to 4131.15 feet). The contact between the two units is sharp. The two units are separated by a thin green shale seam. Bioturbation has disrupted sedimentary structures over most of the unit. However, small-scale cross-bedding is present near the base, and flaser bedding and ripple laminations also are present throughout the unit. Bands of limestone nodules are present throughout. Most nodules are about 20mm long. The nodules are elongate parallel to the bedding where the fabric has not been disrupted by bioturbation. Most of the rock is cemented by silica cement, although patches of poikilotopic calcite cement also are present.

There is a sharp upper contact between the unit and a fine-grained, tan-to-green colored sandstone which is present from 4131.15 to 4130.0 feet. The unit contains isolated, angular, chert clasts (up to 15mm in diameter). Also small coal fragments are present. The rock has been extensively bioturbated. Most of the rock is silica cemented, but there are small patches of poikilotopic calcite cement near its base. A thin-section of this unit was prepared from a sample taken at 4130.2 feet. The rock is a moderately sorted, quartz arenite. The grain size ranges from vfU to vcL, with the average grain size of fU. In addition to the patches of poikilotopic calcite cement, one small patch of poikilotopic anhydrite cement is present. Quartz is the dominant grain type, with chert also abundant, and microcline feldspar and chlorite present.

The unit is overlain by a fine grained, green to gray, bioturbated, well-sorted, quartz arenite (4129.85-4128.55 feet) which coarsens up slightly. Some chert clasts and isolated mud clasts are present. The chert clasts become more common near the top of the unit. A thin section was prepared from a sample at 4129 feet, which shows that 96% of the grains are composed of quartz, the remainder are composed of K-feldspar, chert, and granitic fragments, in decreasing quantity. The rock is mainly cemented by quartz. However, isolated patches of poikilotopic calcite cement also are present. In addition, isolated patches of carbonate mud matrix are present throughout the rock. The porosity is 18%, and most of the pores are connected. X-ray diffraction analysis determined that the clay present is kaolinite, and that a small amount of anhydrite is present.

The sandstone is overlain by a green, sandy, shale (4128.55-4127.9 feet) interlaminated with siltstone. Larger clasts of quartz and chert are present within the siltstone, which also contains some carbonaceous seams.

The shale is overlain by a reservoir sandstone (4127.9-4124.95 feet). The contact between the two units is scoured. The sandstone is well-sorted, though isolated chert clasts are present. It is cemented by silica, and is porous. Most of the grains are composed of quartz, little shale is present. Three graded cycles are present within the unit, and the beds grade up from mU to fL. The unit is cross-bedded. Isolated mud and limestone clasts are present.

Thin-sections of this unit were prepared from samples at 4126 feet, 4125.6 feet and 4125.0 feet. The unit is a subarkose at 4126 feet; quartz grains are the dominant grain type. However, 8% of the grains are composed of K-feldspar. At 4125.6 and 4125.0 feet, the rock is a quartz arenite. All three units are fine to medium grained, though larger isolated quartz grains (up to cL) may be present. All three thin-sections suggest that the grain shape and angularity has been altered greatly by pressure solution. All three thin-sections indicate mainly quartz-cement, however they contain patches of poikilotopic calcite cement. At 4125.6 feet a small amount of poikilotopic anhydrite cement is present (0.6%).

Another sandstone unit overlies the reservoir sandstone. It is present from 4124.95 to 4124.75 feet. It is fine-grained and white. The base has been well-cemented by calcite. This has closed off all the porosity, and probably formed the seal for the underlying reservoir sandstone. Within this zone is abundant flaser bedding, with thin layers of green shale within the ripple troughs. This is overlain by the upper limestone.

The shale which is present from 4128.55 to 4127.9 feet is not present to the south, and cannot be traced to the north. The sandstone units which overlie the cream-colored sandstone cannot be distinguished from the cream-colored sandstone on the petrophysical logs, and therefore the geometry of these units is not demonstrable.

Distribution of the units

The petrophysical logs indicate that the clean sandstone which is present in Pfaff #2, Pfaff #3 and Thompson A-#2 is overlain by a shaly unit over the entire area covered by the cross-sections. It does not range greatly in thickness over the area, but the logs indicate that it does vary in lithology greatly. As a result it is clear that the lithologies of most of these individual units cannot be accurately determined by using the petrophysical log data, and their geometries cannot be determined..

The distribution of the green sandstone which is present in Pfaff #2 from 4222.9 to 4221.9 feet is shown in figure 24. The unit is less than 2 feet thick where it is present, and it trends parallel to the shoreline.

Interpretations

In Pfaff #2, the cream-colored sandstone is overlain by a thin sandstone which was deposited on a sand flat, or bar within the intertidal flats, which in turn is overlain by a poorly-sorted clay-rich breccia which is a channel-fill deposit. There is an increase in the angularity and a

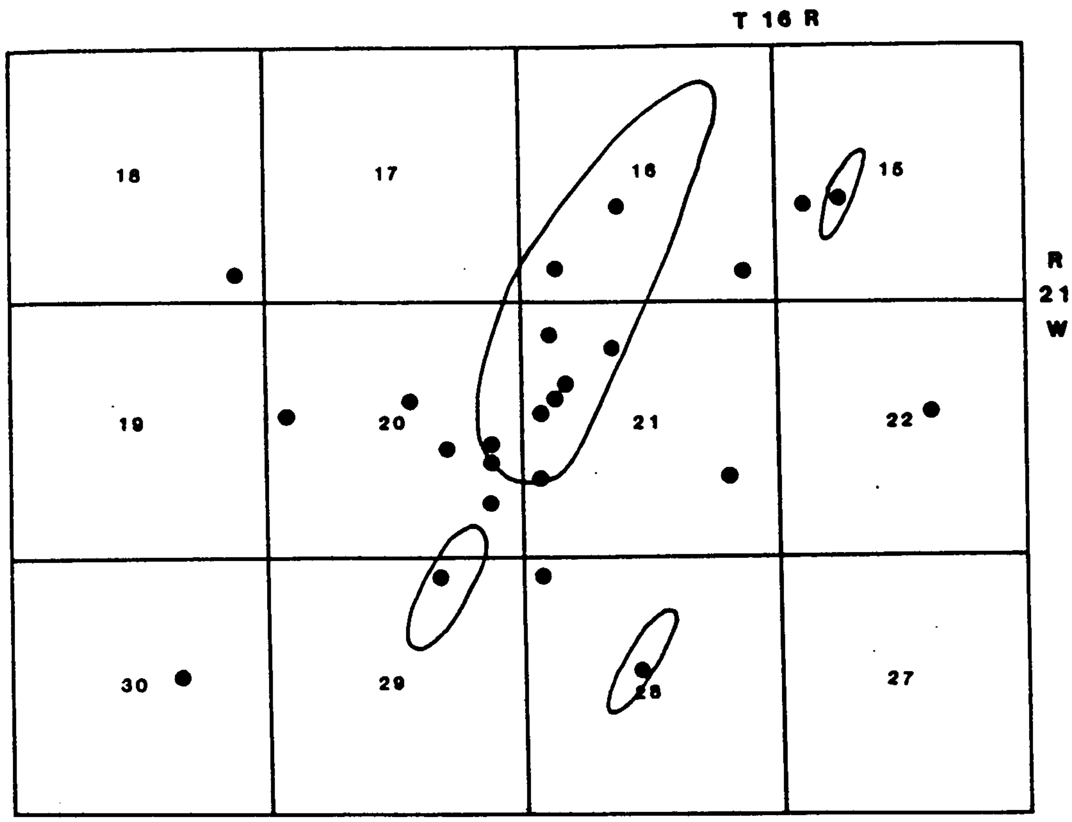


Figure 24. A distribution limits map of the sandstone which is present in Pfaff #2 from 4222.9 to 4221.9 feet.

decrease in the abundance of the chert clasts, indicating a decrease in reworking associated with a decrease in energy which occurred as the depth of the channel decreased as the sediments built up to the level of the intertidal flat. The overlying shale was deposited on the intertidal flats. Periods of high energy, such as storms, transported the chert fragments into the deposit.

The shale is overlain by a clean sandstone which was deposited in point bars of a tidal channel. The sandstone contains green shale seams, which become more abundant near the top of the deposit as the tidal channel shallowed. The sandstone is overlain by a thin green shale which was deposited on the intertidal flats.

A rapid transgression followed the deposition of the shale, but there was no net accumulation of sediment until the deposition of the upper limestone.

In the well core Thompson A-#2, the cream-colored sandstone is overlain by a series of sandstones which were deposited in tidal channels. A shale, probably deposited on the intertidal flats, is present within these sandstones.

vi) UPPER LIMESTONE

Lithology

The Upper Limestone is, stratigraphically, the highest limestone unit in the Cherokee Group in this area. It consists of nodules of fossiliferous micrite enclosed in a green or brown shale. The fossils within the limestone include crinoids, brachiopods, fusulinids, and bryozoa. The shale which encloses the limestone nodules is slickensided. The slickensides formed as a result of later compaction. The shale varies from brown to green in color, and in places, contains large amounts of disseminated pyrite (Pfaff #2, 4213.5-4215.3 feet). The shale is fossiliferous with *Crurythyris*, and other undetermined brachiopods, sponge spicules, fusulinids, conodonts, *Rhombopora*, and plant fragments. The shale also contains isolated quartz grains, which might have been derived from the overlying units, or might have been washed in from outside the environment.

The upper limestone is present in Pfaff #2 from 4213.5-4215.3 feet. A thicker section of limestone is present in Pfaff #3 (4206.7 to 4212.5 feet). A 4.4 foot thick section is present in Thompson A#2 (4120.35 to 4124.75 feet).

Two thin-sections have been studied from the upper limestone. These are from samples taken from Pfaff #3 at 4207.2 feet and 4211.3 feet respectively. The lower thin section, from 4211.3 feet is more typical of the entire unit. The limestone is a fossiliferous micrite. The fossils present include brachiopod shells, echinoid plates and algal laminae. The limestone occurs as nodules separated by green expanding clay shale. Shale is absent from some pores, these are filled with pore-filling calcite. Intraparticle and moldic porosity are the dominant porosity types. Isolated, subrounded, quartz crystals are present throughout the limestone, which average 0.1mm in diameter.

Three separate limestone lithologies are present in the upper thin section (4207.2 feet). These are indicative of deposition in shallower water. The lowest lithology is a fossiliferous micrite as described above. The fossils present are brachiopods, bryozoa, and crinoids. Many fractures are present in the rock which have been filled with coarse sparry cement. Skeletal fragments that were originally composed of aragonite also have recrystallized to sparry calcite.

The fossiliferous micrite is overlain by a 0.5cm thick band of laminated limestone, which contains thin, contorted laminae of micrite. Sparry calcite cement has grown within elongate fractures which have developed parallel to the laminations. This caliche crust is overlain by a calcarenite. The framework particles of the calcarenite are coated grains, which are enclosed in a sparry cement. The grains average 0.35mm, but vary from 0.1 to 2.5mm in diameter, and the rock is poorly sorted. Most of the coated grains are micrite; the remainder contain skeletal particles. Some composite grains consisting of micrite, and one or more skeletal particles, have been coated. These grains may have been reworked, following subaerial weathering, and the coatings were precipitated as the clasts were agitated. Most of the coatings on the grains are thin, with only two or three layers present. In Pfaff #3, small coated grains and angular blocks of micrite fill some of the void spaces. Several broken blocks contain laminated caliche crusts. The caliche crusts are present only at the top of the bed.

Contained within the limestone, near the base, are a series of interbedded sandstones and shale (4214.8 to 4212.1 feet). The upper and lower contacts of this series are sharp.

At the top of the series, there is a thin, green, bioturbated sandstone (4213.5 to 4212.1 feet). The sandstone is calcite-cemented in patches, and contains abundant limestone nodules. This is underlain by a thin, fissile, green shale (4213.1 to 4213.7 feet). The shale contains maroon patches and brachiopods. The shale is underlain by a very fine grained, green, sandstone, (4214.1 to 4214.8 feet). The contact between the two units is sharp. The sandstone does not contain any limestone nodules or calcite-cemented patches. It contains continuous wavy lamination. The laminae are about 1mm thick. This sandstone is underlain by a gray shale (4214.1 to 4214.8 feet).

The limestone underlying the sandstone and shale series is the same lithology as the unit above the sandstone and shale beds. It is compact and contains little shale in the top half of the unit. A fossil sponge is present at 4215.3 feet. Green shale encloses irregular-shaped nodules of micrite in the lower half of the unit. The lower contact is gradational with the underlying sandstone. The overlying sandstone beds, probably are storm deposits.

Diagenesis

Evidence of dissolution is present in this limestone. In one portion, partly dissolved grains with irregular shaped outlines appear to "float" in sparry cement. Shell fragments, which were originally composed of aragonite, have been dissolved , and replaced by sparry calcite.

Partial neomorphism also has occurred. This can best be seen where widespread dissolution is not evident. Neomorphic crystals appear as patches of coarser calcite crystals, which can be distinguished from sparry pore-filling calcite because they have irregularly-shaped boundaries which may have embayments at the margins of the sparry masses, and are not of the same size as each other. These criteria have been documented by Bathurst (1975) to distinguish neomorphic sparry calcite, or "neospar" from pore-filling "sparry" calcite cement.

Fractures are present throughout the rock which cut through the the nodules, and have not been displaced by movement of the micrite nodules which would have occurred at the time of meteoric diagenesis. These fractures have been filled with a sparry calcite cement.

Distribution

The limestone can be traced over the whole of the mapped area with the exception of 15 16S 21W where it pinches out. Figure 25 shows an isopachous map of the unit, based on data

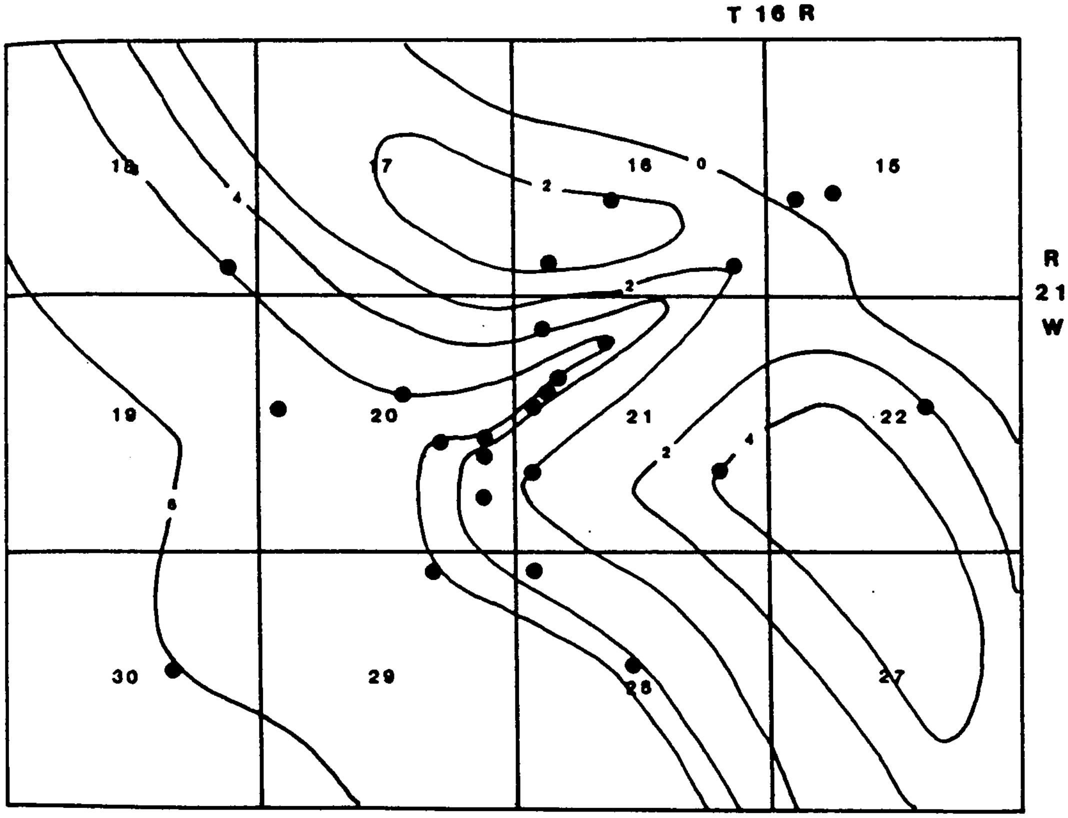


Figure 25. Isopachous map of the Upper Limestone.

obtained from the logs used to construct the cross sections within T16S R21W. This indicates that the limestone has an irregular thickness, and may have formed carbonate mudbanks on the shallow Cherokee shelf.

Discussion

The limestone was originally deposited as a clean, shale-free bed. The shale was deposited later. Before deposition of the shale, the limestone was lithified and weathered in the meteoric zone. This led to dissolution and the formation of the micrite nodules. The shale then was deposited and filled most of the void spaces created by weathering of the limestone. Following this, the overlying sediments were deposited, filling in any remaining void spaces. This can be seen in the top of the limestone in the core from Pfaff #2, in which sand from the overlying sandstone body has infilled a large void which was left unfilled by shale near the top of the limestone.

The weathering of the limestone may have occurred at a period of emergence. Coated grains and caliche crusts are more common at the top of the limestone. This indicates that the top of the limestone was deposited in shallower water than the fossiliferous micrites, and further indicates that the limestone is a regressive limestone.

If a full cyclothem sequence were present, one would expect to see marine "core shale" below the limestone. However, this is not present. The limestones are underlain by nearshore sandstones. Therefore the limestone was deposited at times of maximum transgression, and was deposited both by marine transgressions and regressions. The intense weathering following deposition then masked any transgressive characteristics that the limestone may have had.

vii) UPPER LIMESTONE TO THE TOP OF THE CHEROKEE

In the three examined cores, the upper limestone is overlain by a sequence of sandstones and shales. The sequence averages 20 feet in thickness.

Thompson A-#2

In Thompson A-#2, the limestone is overlain by a maroon siltstone which is present from 4120.35 to 4117.0 feet. The contact between the two units is sharp. The siltstone contains thin, horizontal, interbedded layers of green and brown fine-grained sandstone. Some low-angle cross-bedding is present. It is immature in composition and texture, contains 6.7% feldspar, and is poorly sorted.

The siltstone is overlain by a series of green/gray sandstones (4117.0 to 4110.0 feet). Overall the sandstones fine upward, from medium-grained at the base to fine-grained at the top, and are green/gray in color. Horizontal laminations are present at the base, above which there is low-angle cross lamination. The rock is well-sorted, and the grains are composed mainly of quartz. However, near the base, larger chert clasts are present. A coarse grained unit is present from 4115.0 to 4114.75 feet. This unit contains angular mud clasts.

Thin-sections were prepared from this series from samples at 4116.2 feet and 4113.4 feet. At 4116.2 feet, the rock is an arkose. It is poorly sorted, and the grain size ranges from very fine to very coarse. Silicified dolomite clasts are present within the rock. At 4113.4 feet, the rock is well-sorted and fine-grained. Most of the grains are composed of quartz, though about 5% feldspar is present. Little open porosity is present because most of the pores are filled with a quartz-rich, muddy matrix.

The sandstone rapidly grades upward to an interlaminated red and green shale which is present from 4110.0 feet to the top of the core at 4107.0 feet. Near the top, the shale grades upward to a siltstone. The shale contains carbonaceous coatings near its base.

Pfaff #2

In Pfaff #2, the upper limestone is overlain by a red and green, mottled, fine grained sublitharenite (4213.5 to 4210.2 feet). The contact between the sandstone and the limestone is highly irregular, because the upper surface of the limestone had been weathered prior to the deposition of the sandstone. Some larger chert grains are present within the rock. A thin-section of this unit taken from a sample at 4211.9 feet shows that the rock is poorly sorted. The average grain size is fU, however the grain size ranges from vfL to vcU. The grain shape and angularity also ranges from well-rounded and equant to subangular and irregular. Most of the grains are composed of quartz, however some feldspar grains also are present. All the pores are filled with a clay-rich mud matrix, and so there are no open pores. This is overlain by a maroon siltstone which is present from 4210.2 to 4208.2 feet. The contact between these two units is abrupt. The siltstone contains 2-4% of sand size quartz grains.

The siltstone is overlain by a gray shale which is present from 4208.2 to 4208.0 feet. This shale also contains isolated quartz grains. The shale is overlain by a series of sandstones (4208.0 to 4198.0 feet). Overall, the sandstones are green to gray and medium-grained, with low angle (about 10 degrees) cross lamination, isolated mud clasts, occasional chert clasts, some bioturbation, and thin silty layers. The lowest unit in this series (4208-4207) is a medium grained gray sandstone which is more poorly sorted than the overlying units. It is rich in chert clasts, and contains low angle (about 10 degrees) cross bedding.

The series of sandstones is overlain by a series of reservoir sandstones (4207-4204 feet). It is not clear what the seal is, because the core is incomplete. However, it is likely that a thin shale band which was not recovered from the core formed the seal. The reservoir sandstones contain cross stratification and, in parts, ripple lamination. A layer of angular mud clasts is present. The sandstones are well sorted, medium grained and contain little clay.

A thin-section was examined from a sample at 4207 feet. It is a very well-sorted quartz arenite. The grain size is mL. It is mature in texture and composition; that is, there is no matrix, and all the grains are composed of quartz. It is cemented mainly by silica. However, also present, are patches of poikilotopic calcite cement. The total porosity is 8.9% and oil fills 55% of the pores. The rock has undergone much compaction, which has led to pressure solution, and the formation of quartz overgrowths.

Thin-sections were examined from samples taken at 4206.0 feet, 4205.2 feet, 4204.5 feet and 4204.0 feet. At 4206.0 feet, the sandstone is moderately sorted and fine to medium grained. The grains are mainly composed of monocrystalline quartz, though, polycrystalline quartz, chert, and a few K-feldspar grains are present. It is banded with thin (2-3mm) finer grained (fL) layers. Oil is "patchily" distributed throughout the rock.

At 4205.2 feet, the sandstone is mature and well-sorted. The average grain size is 0.2mm. Thin, finer grained (0.14mm, fL) bands are present throughout the rock, but contain less oil than the enclosing rock. The layers contain well-rounded, spherical quartz grains.

At 4204.5 feet, the sandstone also is mature and well-sorted. It contains small patches of poikilotopic calcite cement. The average grain size is fL (0.125-0.177mm).

A clean, cream-colored colored sandstone overlies the reservoir sandstones. It is present from 4204.0-4202.1 feet, is medium grained, and contains mud clasts at the very top. It also shows low angle cross bedding, and contains no clay. The cream-colored sandstone is overlain by a gray sandstone which is present from 4202.1 to 4201.9 feet. These beds meet at an irregular contact which trends at an angle of 25 degrees. Broken mud clasts which are present throughout the overlying sandstone, are all elongate parallel to the bedding and line the contact. The contact most likely was formed as a result of low-energy channeling. The sand body was deposited in that channel, and the mud clasts were eroded from the surrounding tidal flats.

The gray sandstone is overlain by a thin band of green to gray siltstone which is present from 4201.8 to 4201.7 feet. This was most likely deposited by vertical accretion in the intertidal flats. It is a quartz-rich siltstone. Bioturbation has led to a mottled texture with no primary depositional structures. It is fossiliferous with brachiopods.

The siltstone is overlain by a fine to medium grained, quartz arenite which is present from 4201.7 to 4198.0 feet. It is pale green to gray in color. The contact between these units is abrupt. The sandstone contains thin bands and seams of black silty shale, cross-lamination, ripple lamination, dewatering structures, and mottling due to bioturbation. The unit contains no matrix, and is quartz cemented.

The sandstone series is overlain by a highly bioturbated, gray, siltstone which is present from 4198.0 to 4197.0 feet. Which in turn is overlain by a fine-grained, bioturbated, green/gray sandstone.

Pfaff #3

In Pfaff #3 the limestone is overlain by maroon to green siltstones and shales; these extend from 4206.7 feet to the top of the core at 4205.0 feet.

Distribution

The cross sections show that the sandstone series which is present in Pfaff #2 trends north-south for at least 6 miles, and east-west for 2-3 miles. An isopachous map for this unit has been constructed from data derived from these cross sections and is shown in figure 26. The map shows a north-south trend of the thickest part of the body; this is parallel to the postulated paleoshoreline. It represents the

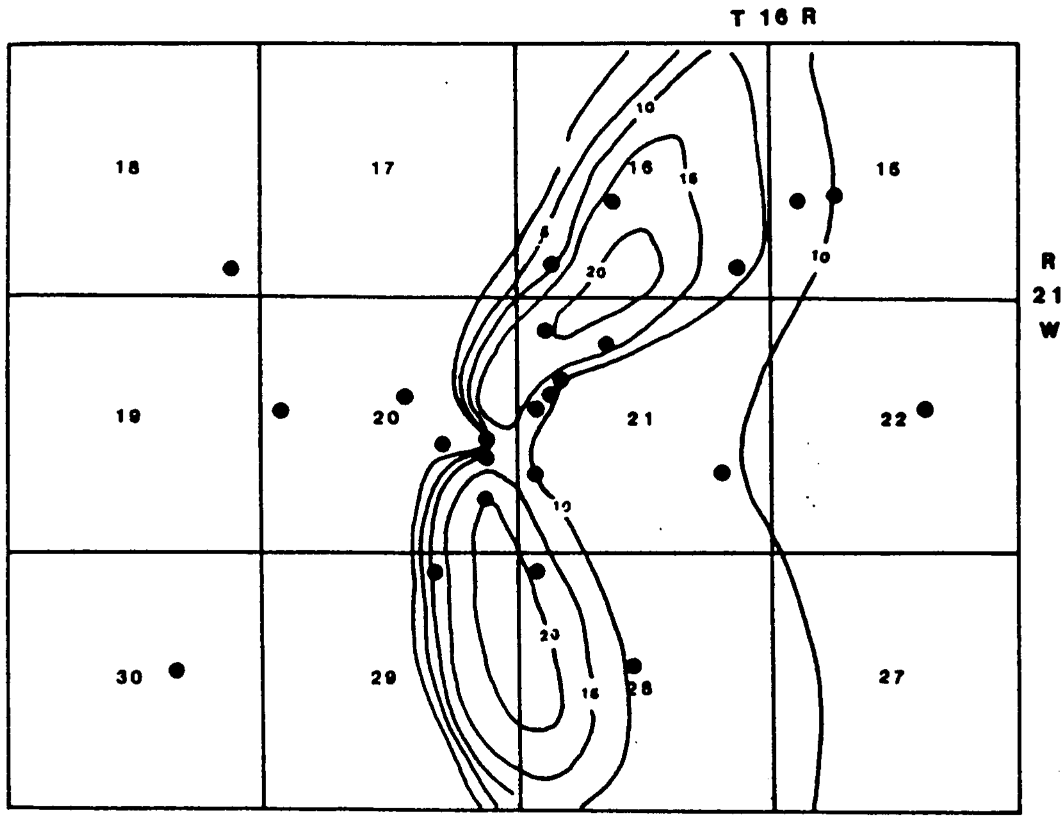


Figure 26. Isopachous map of the sandstone series present in Pfaff #2 between the Upper Limestone and the top of the Cherokee Group.

zone of maximum thickness of the channel deposits. The map also shows that the body continues to the east. For about two miles, a thin sandstone body can be traced to the east in T16S R20W. The unit is about two feet thick and may be the same sandstone unit. The sand body cannot be traced to the north and south of the township (figs. 16, 18). This is due to pinchout.

To the east of the sandstone series, the upper limestone is overlain by two to five feet of shale with little sand (fig 13).

To the west and southwest of Pfaff #3, two thin sandstone bodies (approximately two feet thick) are enclosed in shale. These pinch out to the west within two miles. West of that, a 20 feet thick section of shale is present, which encloses a 10 feet thick sandstone body in sections 22 and 20 of T16S R22W. To the south of T16S R21W, thin sandstone bodies pinch in and out (fig 18). To the north of T16S R21W, a wide sand body, which is at least three miles wide, is present from 28 15S 21W north to 21 15S 21W. and reaches a thickness of 13.5 feet.

Interpretation

In Thompson A-#2 and Pfaff #3, the Upper Limestone is overlain by strata that were deposited in the supratidal zone. The supratidal flat deposits consist of maroon siltstones and shales with isolated green reduction spots. These reduction spots have formed around plant roots which have since decayed. The sandstones were deposited in tidal channels as channel-fill and point bar deposits. Occasional mud clasts are present within them; these were eroded from the banks, and were incorporated into the point bar deposit. Some of the shales contain carbonaceous coatings. These are plant remains, and are more indicative of deposition in the supratidal flats than the intertidal flats.

In Pfaff #3, siltstones and shales overlie the Upper Limestone. These continue to the top of the Cherokee Group. They were deposited in the supratidal, or intertidal, flats.

Following deposition of the sand bodies, shale was deposited. This buried any existing topography before the deposition of the Fort Scott Formation.

7) INTERPRETATIONS

A) Interpretations from the core studies

Detailed examination of core from the N.C.R.A. wells:- Pfaff #2, Pfaff #3 and Thompson A-#2 indicates that the Cherokee Group strata in this area are highly variable. The Cherokee Group consists of a series of alternating limestones, sandstones, siltstones, and shales. The logs are shown in figures 6, 7, and 8, and the descriptions are given in appendix 1. Most of the units in the Cherokee in this area are relatively thin. They range in thickness from less than one inch to ten feet, the average bed thickness is approximately one foot. The Cherokee Group siliciclastics were deposited close to a shoreline, and any thick accumulations which may have developed were reworked by changing sea levels.

It is evident that the sea level fluctuated during the deposition of the Cherokee Group because of the repetition of similar rock units characteristic of deposition in different water depths. The lithologic variations within the well-cores taken from the Cherokee formed as a result of: (1) Lateral facies migration within the depositional environment, and (2) Sea level fluctuations.

Cyclicity has long been recognized in the Pennsylvanian rocks of the Midcontinent. Moore (1931) first described this cyclic alteration of limestones and shales that dominates the Middle and Upper Pennsylvanian sequence along the Midcontinent outcrop belt from Iowa to Oklahoma. Wanless and Weller (1932) applied the name "cyclothem" to the component unit of repeating rock types in Illinois. This term was soon adopted in the Midcontinent outcrop area by Moore (1936). Wanless and Shepherd (1936) first proposed that cyclothems resulted from widespread marine transgressions and regressions over the shelf, in response to the waxing and waning of Gondwanaland glaciation.

Recognition of sea-level changes in the section forms the basis of the stratigraphy and is fundamental to the development of a facies model in this area. Sea-level changes were determined using the cyclothem model which was developed by Moore (1931, 1936), and Wanless and Weller (1932), and more recently refined by Heckel (1985, 1986, 1989).

According to Heckel (1986), an ideal mid-continent cyclothem consists of:-

1) a thin transgressive marine limestone which is often termed the "middle limestone".

2) a thin, offshore, non-sandy, conodont-rich shale with black phosphatic nodules which is often termed the "core shale".

3) a thicker, shoaling-up, regressive limestone which is often termed the "upper limestone".

4) nearshore to terrestrial non-carbonate beds which is often termed the "outside shale".

Figure 27 shows a model for deposition on a sloping tropical shelf showing positions of the rock types that become superimposed with transgressions and regressions to produce a Kansas cyclothem, Heckel (1984, 1986).

The cyclothems are usually asymmetric with thin transgressive units (Middle Limestone and Core Shale) and thicker regressive units (Upper Limestone and Outside Shale). These units are indicative of rapid transgressions and slow interrupted regressions. It has been noted, however, that well-known Kansas cyclothems may include both asymmetric and symmetric cycles (Moore and Merriam, 1965).

Heckel (1985) described Core Shale as:-

> "typically a thin non-sandy gray to black phosphatic shale deposited at a very low level of sediment influx."

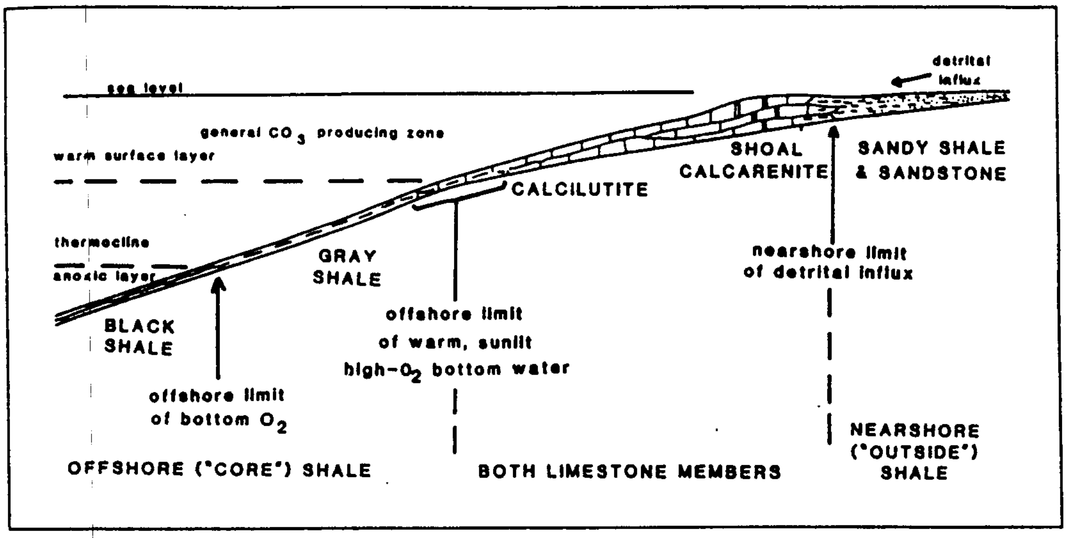


Figure 27. A model for deposition sloping tropical shelf showing positions of the rock types (After Heckel, 1986).

The core shales formed at maximum transgression and, for most cyclothems, covered the lower part of the shelf. The Cherokee section examined contains no Core Shale. The limestones present were deposited at sea level highstands by the combined effects of sea level transgressions and regressions respectively.

Regressive limestones were deposited in shallowing water, and typically are thick marine skeletal calcilutites deposited below wave base, and may grade upward into skeletal calcarenites with abraded grains, algae, and cross bedding (Heckel, 1985). Subaerial exposure surfaces may also be present. This often leads to a mottled to rubbly to rusty appearance when various amounts of overlying shale and iron oxides were carried down into the open spaces of the limestone (Heckel, 1985).

Exposure surfaces of regressive limestones frequently can be traced over large areas. This widespread distribution cannot be explained by a depositional model involving delta shifting alone, and has more firmly corroborated the eustatic model for cyclothem formation in the northern Midcontinent (Watney, 1984).

Transgressive limestones were deposited in deepening water. They are typically thin marine skeletal calcilutites deposited below wave base, but locally they include calcarenites at the base that were deposited in shallower water earlier during the transgression (Heckel, 1985). Transgressive limestones typically are dense, dark, non-pelleted calcilutites with neomorphosed aragonite grains, and overpacked calcarenites that generally lack evidence of early marine cementation or meteoric leaching and cementation (Heckel, 1985). These contrast with regressive limestones in which most of the aragonite grains have been leached and replaced with blocky calcite, and are lighter colored, more porous and more conspicuously sparry (Heckel, 1985).

The limestones within the Cherokee Group in the examined core all possess regressive characteristics. There is no Core Shale in the sequences, and so it appears that the limestones are products of both transgressions and regressions. Most of the units consist of skeletal calcilutite which has undergone subaerial exposure and meteoric leaching leading to a nodular texture with calcilutite nodules enclosed in a dark gray shale, which would tend to obliterate any transgressive characteristics that the limestone may have originally possessed.

B) Interpretations from the subsurface mapping

The geometry of the rock units has been determined from cross-sections derived from petrophysical logs of the area. These cross-sections, especially those covering a larger area, should be regarded with caution. The more detailed cross-sections reveal that units may pinch out and reappear within a short distance. Therefore it is very likely that the less detailed cross-sections could suggest erroneous geometries because the distance between the logs which are used is too great to reveal the pinch-outs and reappearances of units on a fine enough scale.

The lateral and vertical variations of the rock units in this area may be closely spaced, and leads to problems in the correlation of units from one well to another with confidence. The limestone units were deposited at sea level highstands, and therefore can be traced over the whole study area, which makes them valuable stratigraphic markers in the Cherokee section.

The cross-sections illustrate that there is little overall change in facies from north to south. However there are considerable variations from east to west. The limestone units generally thicken at the expense of the sandstones, until, at the western edge of the study area, no sandstone units are present, and the Cherokee Group consists of an alternating series of limestones and shales. This sedimentation pattern indicates that the west of the study area is farther from the coastline, which trends approximately north-south to north east-south west.

C) Environment of deposition of the clastic units

After the karstic topography of the Mississippian had been buried by the sediments which formed the Pennsylvanian Basal Conglomerate, the geomorphologic environment was that of an almost featureless plain, which dipped gently to the west. submerged during major marine transgressions. As the sea level fell, the plain was gradually exposed, and formed a wide tidal flat.

It is not clear whether the area began as an open tidal flat, or as a barred lagoon. Because the sediments deposited could be indicative of either environment. No barrier, however has been found in this study, or described in any others.

i) GENERAL DESCRIPTION OF TIDAL FLATS

In general, tidal flats comprise featureless plains which are dissected by numerous tidal channels or creeks. They occur on open coasts of low relief and relatively low wave energy, and in protected areas of high energy coasts (Weimer and others, 1981). Tidal flats form in areas with mesotidal ranges (2-4m) and macrotidal ranges (greater than 4 meters) (Elliott, 1978, p. 174-177). Sediments deposited in the tidal flats are elongate parallel to the shoreline over tens of kilometers, and are intersected by river estuaries, tidal channels, and numerous, smaller, tidal creeks. Major channels may generate thicker sediment sequences from the formation of levees and deltaic sequences.

Tidal flats are subdivided into intertidal and subtidal environments. The intertidal zone is subdivided into the upper intertidal zone (also called the supratidal zone by some authors), and the lower intertidal zone (Weimer and others, 1981). Landward, the intertidal flats pass into the salt marsh, which is truly supratidal.

Supratidal Zone: Salt marsh

The supratidal zone is flooded only by storm surges or storms which cause waves to inundate the area. Hence the area is covered with water infrequently, and may be subjected to extended periods of high temperatures and desiccation (Weimer and others, 1981). In the North Sea, the salt marsh is an area vegetated by salt tolerant plants. There is less biogenic activity than in the tidal flats, and most bioturbation results from the growth of plant roots. Overall there is little sand. However, thin sand layers are present, and thicken towards any tidal channels which traverse this environment (Weimer and others, 1981). Coarse material also may be washed in from storms to form thin layers. Coarser sediment may be found in channels which traverse the salt marsh. However, movement of water in these tends to be very sluggish, and the channels do not migrate rapidly because of their stabilization by vegetation (Weimer and others, 1981).

Intertidal Zone

The intertidal zone is located between the mean high water mark (MHWM) and the mean low water mark (MLWM). This usually covers a vertical range of 2-3m, depending on the tidal range. Fluctuations of the water level due to tides causes tidal currents which lead to the formation of tidal channels and creeks (Reineck and Singh, 1980, p. 430-444). Tidal currents of a high tidal range erode deeper channels than currents of a low tidal range. Terwindt (1988) reviewed criteria in an effort to enable an estimate of the paleotidal range. He stated that no diagnostic features of the low water zone had been found, and in general, determination of the paleotidal range is very difficult.

Intertidal flat deposits and shallow channel deposits are the sedimentary facies deposited in the intertidal flats. Deeper channel deposits are considered to be a part of the subtidal zone, because deposition occurs at a depth greater than that of the intertidal flats. Small tidal channels also are known as tidal creeks (Weimer and others, 1981). Because of the shallow depth and low energy of tidal creeks, sediments deposited within them tend to be poorly-sorted, silty, clayey sandstones (Weimer and others, 1981). These generally have insufficient porosity to form reservoir rocks. The tidal creeks gradually shallow, become less abundant, and have lower energy in the upper parts of the tidal flat (Weimer and others, 1981).

Deposition in the intertidal part of the tidal flats is primarily the result of vertical accretion, except in areas of small, laterally meandering tidal creeks (Weimer and others, 1981). Bioturbation increases as the rate of sedimentation decreases, and therefore sediments that were deposited rapidly will have better preserved sedimentary structures than sediments that were deposited slowly. The sedimentation rates in the intertidal flats is low, and the biogenic activity often is high, and therefore the sediments usually are highly bioturbated.

Reineck (1975) proposed the terms:- Sand flats, mixed flats, and mud flats to subdivide the lower, middle, and upper parts of the intertidal flats. The sand flats occupy the lowest part of the intertidal flats. They are subjected to the strongest wave and current activity, and so finer sediments are winnowed out. Sand flat sediments may contain both wave and current ripple laminae. Muddy lenses and layers usually present as flaser and wavy bedding often are present (Weimer and others, 1981). Flasers are incomplete mud laminae trapped in ripple troughs during periods of slack water as shown in figure 28B (Elliott, 1978).

The sand flats grade landward into mixed flats. Mixed flats contain more mud than the sand flats. The sedimentary structures present include flaser bedding, wavy bedding, lenticular bedding and interbedded sand and mud. Lenticular beds are muddy with discontinuous layers of sand (fig 28A).

The mixed flats are overlain by mud flats. On mud flats there are mainly thick mud layers deposited with thin sandy intercalations (Reineck and Singh, 1980, p. 432-434). The

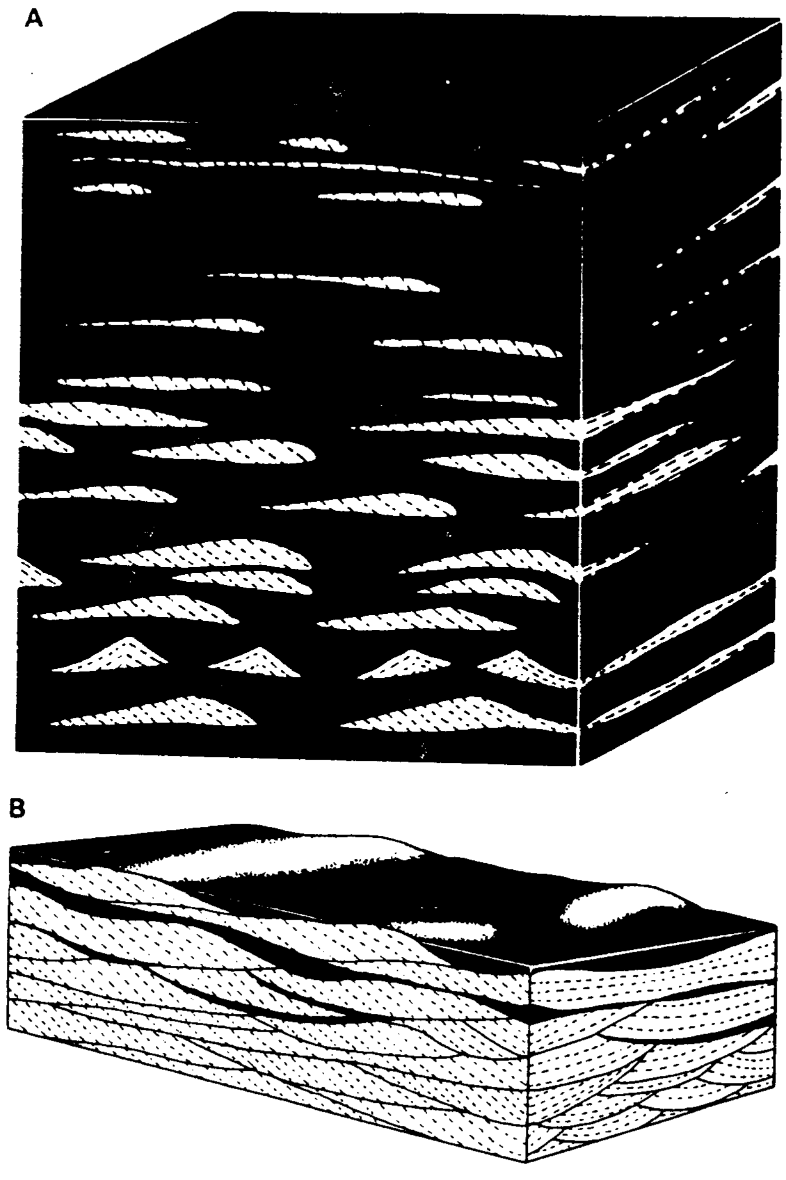


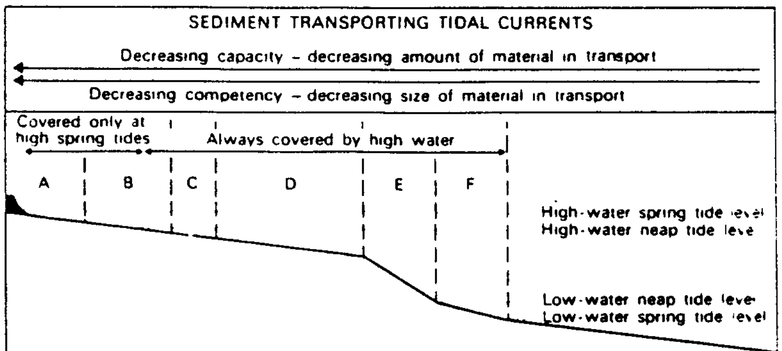
Figure 28. (A) Lenticular bedding with thin sand lenses and isolated ripple form sets in mud; (B) flaser bedding composed of mud-draped ripples (Reineck and Singh, 1980).

bedding may be disrupted by plant roots from the overlying upper intertidal marsh, if it is buried by prograding deposition (Weimer and others, 1981). Generally this is the muddiest of the intertidal flats, and contains the most bioturbation (Weimer and others, 1981).

The tidal flats off the East coast of Britain show a more complex arrangement of facies belts within the intertidal zone. These are summarized in figure 29 (Elliott, 1978). These zones are present in "The Wash" in England, and the Eden Estuary in the East coast of Scotland.

Subtidal Zone

The subtidal zone lies below the mean low water mark. It is mostly occupied by channels subtidal sandbars, and sand shoals (Reineck and Singh, 1980). Channel-fill deposits are, from a exploration standpoint, the most important tidal facies because they are the facies which are the most likely to be preserved (Weimer and others, 1981). The larger tidal channels will form better reservoir rocks than small tidal channels, not only because they are larger, but also because they formed as a result of greater energy than the small channels. Therefore, they are better sorted and usually contain less clay (Weimer and others, 1981).



A Salt marsh	No reworking by waves or organisms Fairly slow sedimentation Sediment bound by plants. Filter effect of plants
B Higher mud flats	Very limited reworking by waves and organisms Fairly rapid sedimentation Sediment bound by algae
C Inner sand flats	Limited reworking by waves, extensive reworking by *Corophium* Slow sedimentation
D *Arenicola* sand flats	Extensive reworking by waves and *Arenicola* Slow sedimentation
E Lower mud flats	Limited reworking by waves or organisms Rapid sedimentation
F Lower sand flats	Little or no organic reworking, minor wave-action, strong tidal currents Slow sedimentation

Figure 29. Facies belts in tidal flats of the Wash embayment, eastern England (Elliott, 1978, after Evans, 1965).

Longitudinal cross-beds, megaripples and ripple laminae are the major bedding types in subtidal deposits. Interbedded sands and mud, resulting in lenticular and flaser bedding, are common in subtidal facies, and result from fluctuations in energy (Weimer and others, 1981). These principal small-scale sedimentary structures are a form of ripple bedding, and vary with the sand-mud ratios (fig. 30) (Reineck and Wunderlich, 1968).

Tidal creeks and tidal channels have highly sinuous patterns. They are dynamic features that constantly shift position because of meandering. Erosion proceeds on the outer bank of the meander, and the deposition of the point bars proceeds on the inner bank. During low tides, wetted channel sediments in the intertidal zone are exposed, and blocks of sediment slump into the channel along rotational slip planes. This process contributes substantially to channel bank erosion, and also can produce rotated blocks of mud, which are preserved in the point bar facies (Elliott, 1978, p. 174). Mud balls and mud chips, and occasional slide blocks of tidal flat mud have been found by Smith (1988) in Holocene and Pleistocene point bar deposits in several tidally influenced, meandering, rivers.

In the tidal flats of the North Sea, the thickness of

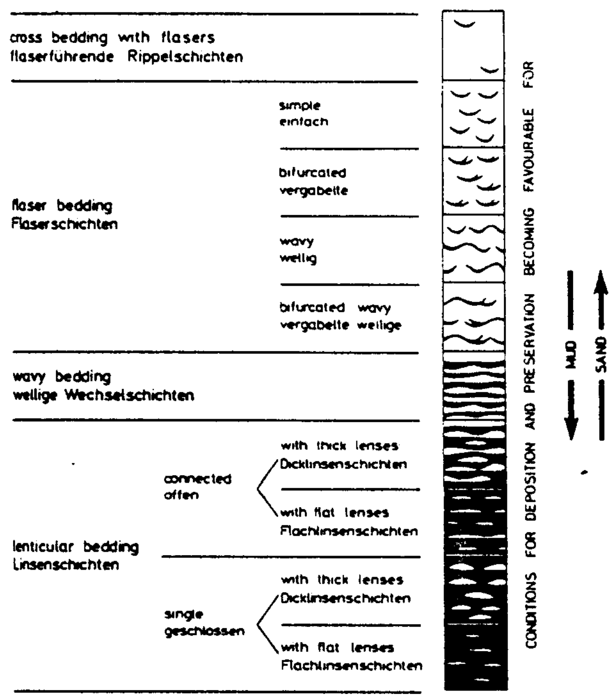


Figure 30. Classification of flaser and lenticular bedding, black mud, white sand (Reineck and Singh, 1980, modified after Reineck and Wunderlich, 1968).

major tidal channel sediments may exceed 15m (45 feet) (Weimer and others, 1981). Through time, the intertidal deposits build across channel-fill sequences, but in comparison, they represent only a thin capping veneer (Weimer and others, 1981). The sediments deposited by a tidal channel will become finer-grained upwards. If the sediment source is sandy, they may deposit a sequence of beds with bedding structures described by Allen (1963), which is shown in figure 31. These features will be better preserved in larger channels. A basal lag deposit will floor the channel. This consists of relatively coarse sands, with larger clasts, shell debris and abundant mud clasts (Elliott, 1978). The point bar consists of thinly laminated sands and silts dipping gently into the channel (Reineck, 1967, Figure 32). These may contain inclined erosion surfaces which formed due to scouring during exceptional discharge conditions (Bridges and Leader, 1976). These pass upwards into the intertidal flat deposits.

Progradation of tidal flats

The progradation of tidal flats tends to produce a fining upward sequence which reflects an upward transition from low tide level sandflats, to high tide level mudflats, and

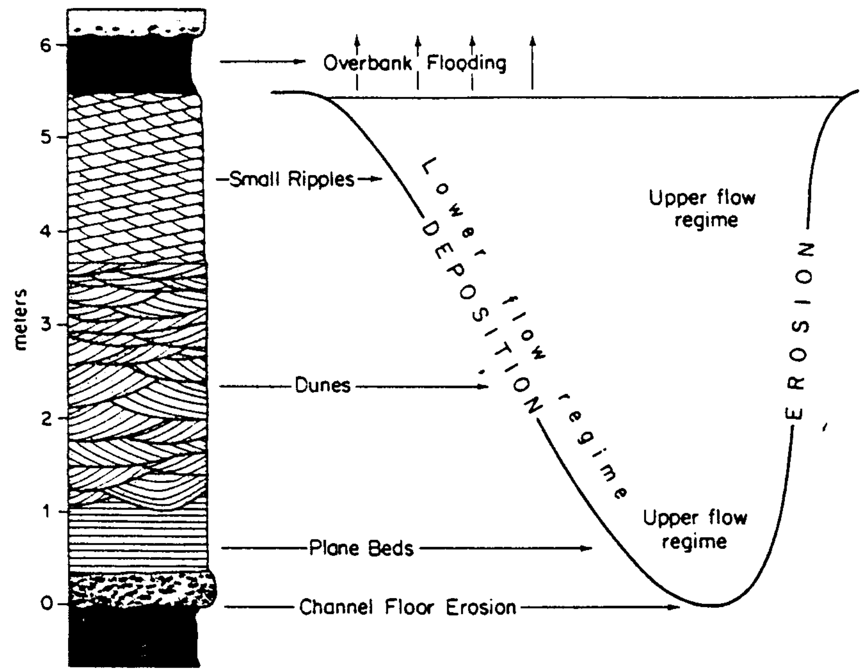


Figure 31. Interpretation by Allen (1963) of a British Old Red Sandstone cyclothem in terms of flow regimes in a meandering channel model. Successively higher deposits correspond to sediments deposited successively higher on the point bar, under progressively lower flow regimes. (Blatt, Middleton, and Murray, 1980)

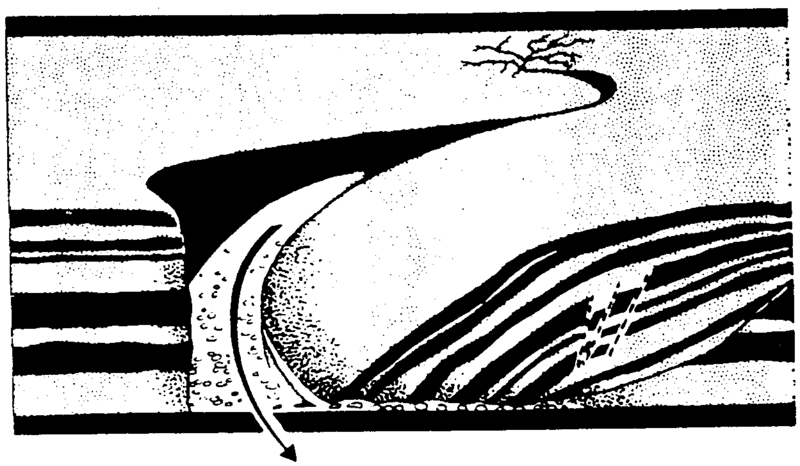


Figure 32. Lateral accretion bedding in alte--ating sands and mud-silts developed by point bar migration in meandering tidal channels (Reineck and Singh, 1980).

eventually upward into supratidal flats. This sequence may be disrupted at any level, and in some cases, may be replaced entirely by erosive based tidal channel deposits (Reineck, 1967, 1972).

MacKenzie (1968) compiled data from studies of North Sea tidal flats into a model for a vertical sequence in a prograding intertidal sand flat. The model shows a deposit which has an upward decrease in energy, indicated by changes in sedimentary structures, fining upward grain size, and a general upward increase in bioturbation. Terwindt (1988) stated that a complete development of the subtidal, intertidal, and supratidal sequences is rare.

Location of modern tidal flats

The most thoroughly studied tidal flats in the world are from the North Sea coast of Europe (fig 33). These are considered to be the "type locality" for tidal flats (Weimer and others, 1981). It is from these that the above descriptions were taken. Other well-studied examples include the Bay of Fundy and the Gulf of California.

The Bay of Fundy is a large coastal embayment of rapid progradation. It is sand-dominated, and has a very high tidal range of 11.5m (Weimer and others, 1981). The Gulf

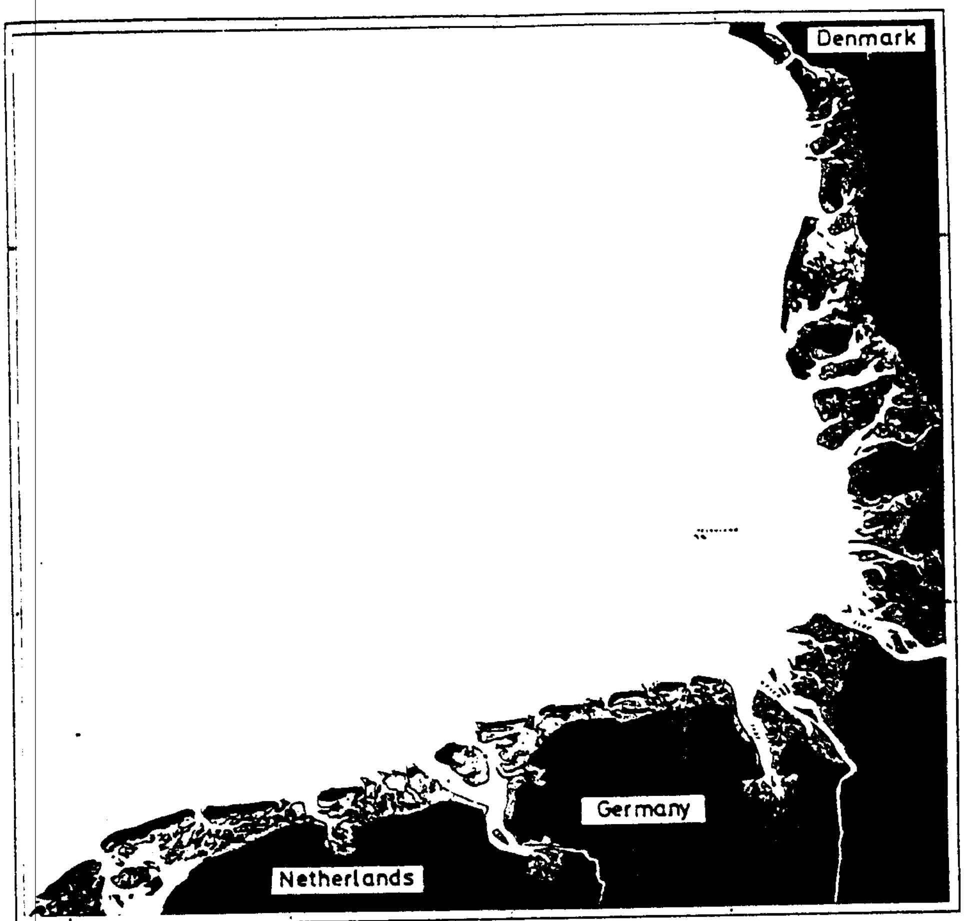


Figure 33. General map showing tidal flats along the Dutch, German, and Danish coasts (Reineck and Singh, 1980).

of California is a hot and extremely arid region, where evaporation greatly exceeds precipitation. These tidal flats contain few tidal channels, and so channel-fill deposits are of little significance (Weimer and others, 1981).

Ancient examples

Many descriptions of tidal flat deposits exist in the literature. These show that not all the features of tidal flats are present in a single deposit. Singh (1968, 1969) describes tidal flat deposits from Proterozoic quartzites of Telemark, Southern Norway. Button and Vos (1977) describe a Proterozoic sequence of intertidal and subtidal clastics and carbonates from a macrotidal setting in South Africa. Beukes (1977) described siliciclastic and carbonate sediments in tidal flats in the Proterozoic of South Africa. Many more recent tidal deposits have been described. The tidal channel facies within them may form important petroleum reservoirs in some areas. For example, oil and gas production has proceeded from tidal channel deposits of the Cretaceous Almond Formation in the West Desert Springs, and Patrick Draw Fields of Wyoming (McCubbin and Brady, 1968, Weimer and others, 1981). Tidal channel sandstones also have produced oil in the Mississippian Aux Vases zone of the Rural Hills Field, Illinois (Weimer and others, 1981).

ii) SEDIMENTARY FACIES PRESENT IN THE CHEROKEE GROUP

Four facies have been recognized in the Cherokee Group, these are:-

1) Tidal channel facies
2) Tidal flat facies
3) Storm facies
4) Shallow water carbonate facies

Tidal Channel Facies

Sediments which were deposited in the tidal channels comprise a large part of the Cherokee Group. They have been divided into two distinctive subfacies which are:-

1) Point bar deposits
2) Channel-fill deposits

Point bar deposits generally are well-sorted. They contain bands of varying grain size related to fluctuating energy levels in the tidal channel. Little clay is present overall, but a characteristic feature is the presence of mud clasts within the bedding. The mud clasts may be angular, and therefore they may have undergone very little transport. They have been eroded from the banks of the channels which are composed of muddy tidal flat sediments.

Point bar deposits contain a variety of sedimentary structures. These include ripple laminations, wavy lamination, cross-lamination, and flaser bedding. However bioturbation and dewatering often has disrupted these structures.

Channel fill deposits are more poorly sorted than the point bar deposits. They usually contain a higher proportion of gravel and pebble-sized clasts than point bar deposits. The clasts usually are composed of Mississippian-derived chert. The channel-fill deposits also may contain a large amount of mud as matrix, deposited at times of low energy, which may fill the pores in the underlying coarser sediment.

The channel-fill deposits usually have a scoured base. A basal lag deposit sometimes is present. If the channel is low-energy, the basal lag may contain clasts derived from the underlying unit.

Tidal Flat Facies

The tidal flats can be divided into the subtidal flats, intertidal flats, and the supratidal flats. Weimer and others state than the dominant facies preserved in the subtidal flats are tidal channel deposits.

The intertidal flats contain a mixture of sandstones, siltstones and shales. Over most of the intertidal flats, the sediments were extensively bioturbated, and therefore bedding structures often are absent. Also, any fine alternations of sandstone and shale beds may be lost because of biogenic reworking. Sedimentary structures include planar bedding, ripple lamination, lenticular bedding, and flaser bedding. The shales present show colors which indicate varying degrees of oxidation.

Mainly siltstones and shales were deposited in the supratidal flats. These were deposited in an oxidizing environment, and are maroon in color. Green reduction spots which probably formed around decayed plant roots are present throughout. Well-rounded coarse grains of quartz sand are present within these finer units; originally these may have been deposited in thin sandstone beds which were destroyed when the sediment was homogenized by bioturbation.

Storm Facies ("Tempestites")

Several thin units within the Cherokee Group may be storm-deposited. Storm-deposited units have been called "tempestites" by Seilacher (1982). Tempestites are thin sandstone units which, in this area, reach a maximum thickness of two inches. The sandstones are well-sorted, mature in composition, and contain very little clay. They have sharp upper and lower contacts with the enclosing units. These may be laterally extensive units but they are too thin to be distinguished on the petrophysical logs.

Shallow water carbonate facies

The sediments which form this facies were deposited and precipitated in shallow water where there is little clastic input. They were precipitated as carbonate mud in a low energy environment. Fossils present in this facies include fusulinids, brachiopods, conodonts, crinoids and gastropods. The limestones were subjected to meteoric weathering during marine regressions. This led to the partial dissolution of the rock, and the formation of nodules of the fossiliferous micrite, which are enclosed in shale that was deposited after the weathering of the limestone.

D) Cementation

All of the clean sandstones contain abundant quartz overgrowths, many of which are euhedral (fig 34). The boundary between the host grain and the overgrowth is often marked by "dust line" on the detrital grain. Where the "dust line" is absent, it is not possible to distinguish between an overgrowth and the host grain, using a standard petrographic microscope.

Many of the sandstone units have been partially cemented by poikilotopic calcite, such that areas within the rock will be tightly cemented, and other areas are lacking any cement (Fig. 35). The distribution of the cement patches may be related to the occurrence and distribution of original shell debris in the sediment (Scholle, 1979). Poikilotopic anhydrite also cements patches of many clean sandstones. Usually it is associated with poikilotopic calcite cement.

E) Secondary fabrics

Compaction because of burial has altered the fabric of the Cherokee sandstones greatly. In addition to syntaxial quartz overgrowths, pressure solution has resulted in the destruction of much porosity. Many grain to grain contacts

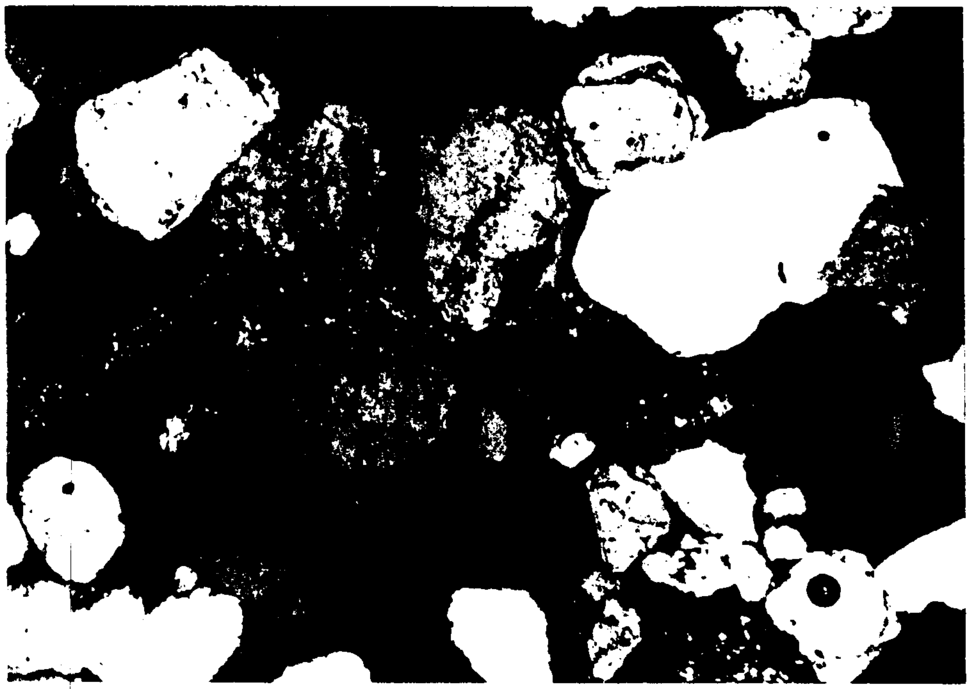


Figure 34. Photomicrograph of a clean sandstone from Pfaff #2 at 4207.0 feet. Euhedral overgrowths on some grains. The boundary between the host grain and the quartz overgrowth is marked by a "dust line" on some grains. XN. Length of photograph is 1.7mm.

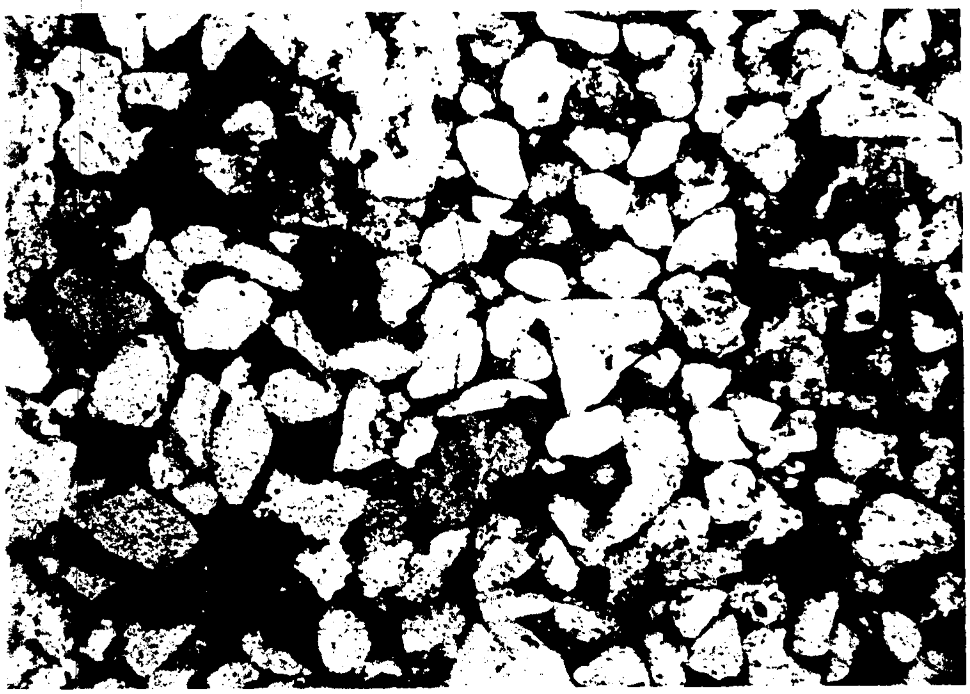


Figure 35. Photomicrograph of a sandstone from Thompson A-#2 at 4129 feet. Poikilotopic calcite cement completely fills the intergranular pores where it is present (brown). The open pores are stained blue. Plane polarized light. Length of photograph is 1.7mm.

are flattened. The grains themselves show signs of strain. The deformation fabrics present in the Cherokee sandstones, include Boehm lamellae and fractured quartz grains.

F) Alteration within the siliciclastic units

The most altered mineral which is still present in most of the sandstones is K-feldspar. Most feldspar grains have partly altered to clay minerals. Much of the authigenic clay which is present in the less mature units may have formed from the alteration of feldspar grains.

Chert grains are common in some sandstones. These are assumed to have been derived from Mississippian beds. Some of these grains have replaced dolomite, as indicated by small relict rhombs within the chert. Many silicified shell fragments also are present in some units. The original structures have not been preserved in any of these shell fragments.

Some of the units originally contained aragonite shells. These have either been silicified, or have recrystallized to calcite. In both instances, the original structure of the shells has been lost.

8) FUSULINID BIOSTRATIGRAPHY

Fusulinids are an extinct group of relatively large foraminifera that evolved from smaller foraminifera in the Early Pennsylvanian, and died out in the Late Permian (Reid, 1989). Fusulinids evolved rapidly during that time, and are abundant in many sequences of rock strata. For example, in the Permian Basin, fusulinid tests often form grainstones which, in some cases, are important hydrocarbon reservoirs (Reid, 1989).

Fusulinid zonations have been produced, for many years, by the Hollingsworth Paleontological Laboratory in Midland, Texas, for the Permian Basin (Reid, 1989). These zonations can be applied to Western Kansas to correlate the rock strata with the strata in the Permian Basin, thus forming a more complete regional stratigraphy.

For many years, the Cherokee Group has been considered to be of the same age as the Strawn in the Permian Basin (Chenoweth, 1979). Fusulinids recovered from the shale within the nodular limestone units in the N.C.R.A. cores; Pfaff #2, Pfaff #3 and Thompson A-#2 were collected, and thin sections of them were examined to test this correlation.

A fusulinid test is elongate. Two orientations of thin sections are generally cut from the fusulinids:

1) The axial section:- This shows the internal features of the fusulinid, providing enough detail of the internal morphology for the genus to be determined, and therefore to date the rocks. An axial section is made along the axis of coiling, which is an imaginary line running from pole to pole, through the proloculus (initial chamber) around which the fusulinid coiled.

2) The sagittal section:- This is cut normal to the axial section. It enables the number of volutions and chambers of the fusulinid to be counted, and is important for species identification.

Fusulinids were collected from:-

Pfaff #3 in the interval 4211.8 to 4212.5 feet.

Thompson A-#2 in the interval 4122.5 to 4122.9 feet.

Both of these samples are from the Upper Limestone. The fusulinids were enclosed in the shale which separates the limestone nodules. They were broken free from the shale before they were prepared for thin sections.

Axial thin sections of the fusulinids are prepared in the following way:-

1) Epoxy is melted onto a clean glass slide, and the fusulinid is placed in the epoxy such that its axis of coiling is parallel to the glass slide. The epoxy is allowed to cool so that the fusulinid is cemented in place.

2) The fusulinid is gently ground down, keeping the axis of coiling parallel to the slide, until the proloculus is reached. If the fusulinid is oriented, and ground down, parallel to the plate, the axis of coiling should be exposed.

3) The epoxy is remelted, and the fusulinid is turned over such that the surface is pressed against the glass slide. Any the bubbles are squeezed out.

4) The fusulinid is ground down until the wall structure becomes clear.

Figure 36 shows the sequence of steps to make an oriented axial thin section of a fusulinid (Reid, 1989).

Results

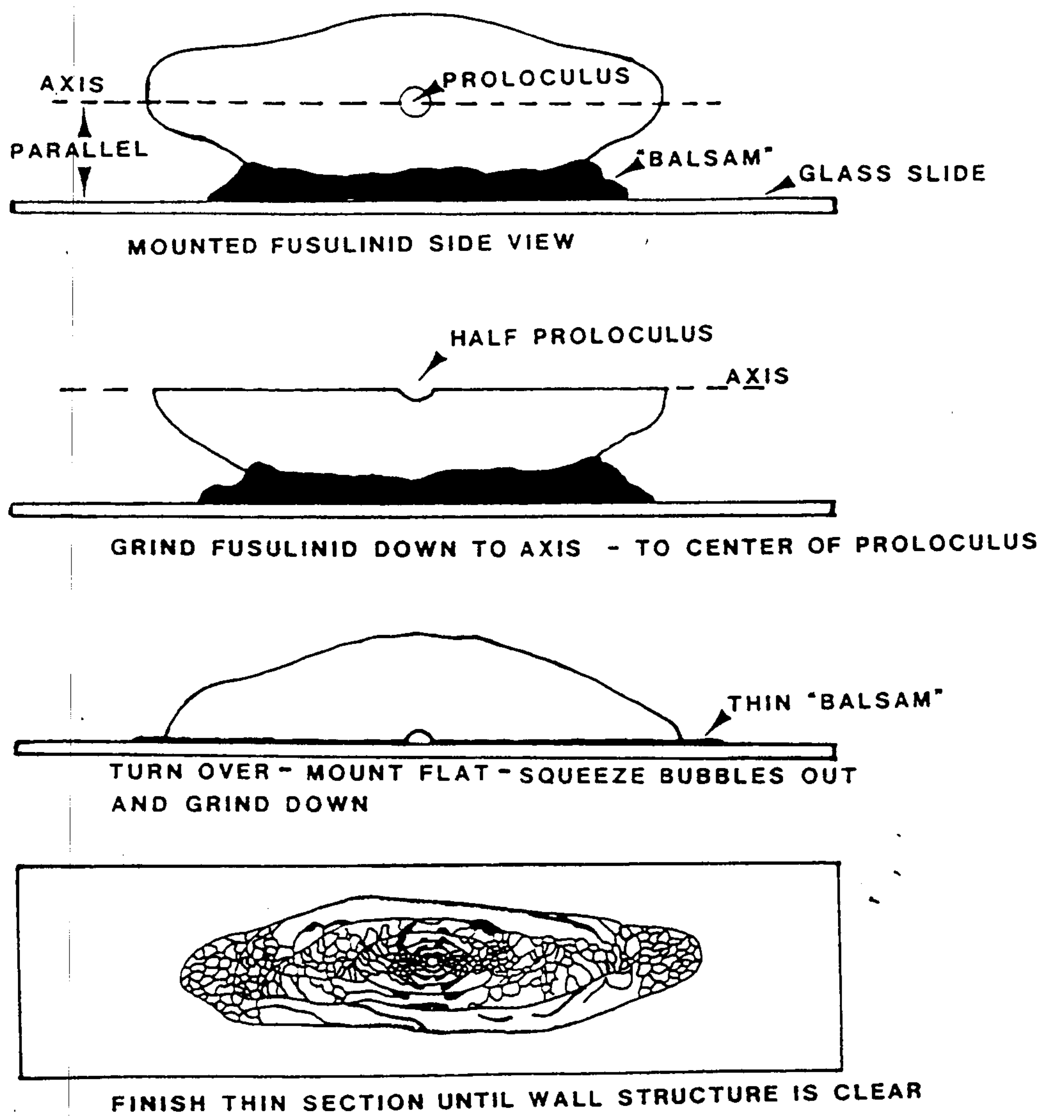


Figure 36. Sequence of steps to make an oriented axial thin section of a free fusulinid through the center of the proloculus (Reid, 1989).

Two genera were found to be present in the upper limestone. These are, Beedeina, and Wedekindellina (figs. 37, 38). From this evidence it can be deduced that the age of the upper limestone is between Middle Early and Early Middle Strawn. This has been correlated with the Lower Cherokee by the Hollingsworth Paleontological Laboratory (Reid, 1989).

Figure 37. Photomicrograph of the Axial section of Beedeina. Length of the photograph is 1.7mm.

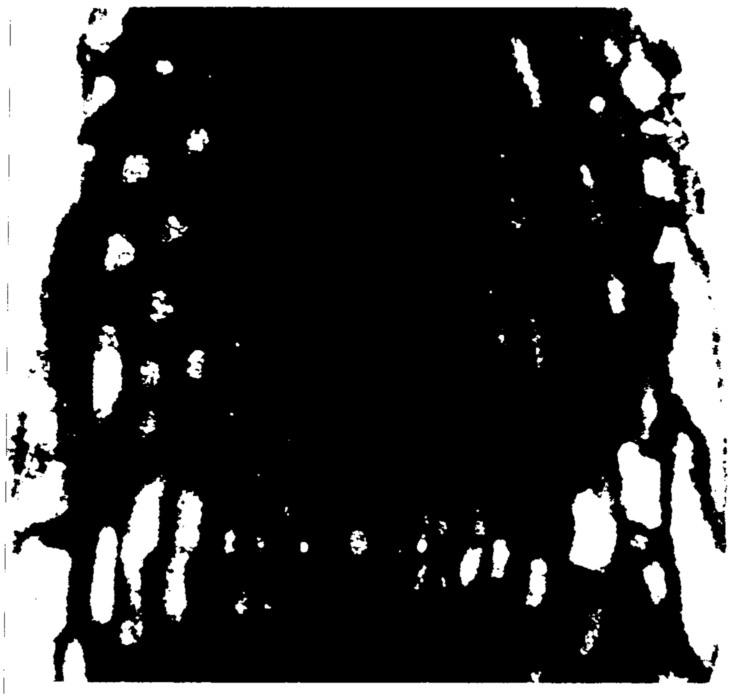


Figure 38. Photomicrograph of an axial section of *Wedekindellina*. Length of photograph is 1.7mm.

9) PORE SYSTEMS OF THE CHEROKEE SANDSTONES

A) Introduction

The Cherokee Group in this area is of economic interest because all of the oil produced in the proximity of the study area is from sandstone reservoirs of the Cherokee Group. Porosity is of fundamental importance in modeling the performance of a sandstone as a reservoir rock, because recovery efficiency is directly related to the total porosity, and to the pore shapes and interconnectivity of the pore systems (Wardlaw and Cassan, 1979).

Following a waterflood, residual oil is distributed in two ways. There is residual oil remaining in regions which were by-passes or unswept by the flood waters. Secondly, there is the residual oil that remains trapped on a microscopic scale in individual pores, in the swept portion of the formation. The total recovery efficiency is the product of the volume of the formation contacted by the flood waters, and the pore-by-pore displacement efficiency which is related to the microscopic properties of the reservoir rocks (Wardlaw and Cassan, 1979).

Mercury capillary-pressure tests provide estimates of the efficiency with which oil can be withdrawn from the pore system of a rock (Wardlaw and Cassan, 1979).

Porosity may be primary or secondary. Primary porosity is that which the rock possesses at, or shortly after, deposition, before diagenetic processes have started to modify the sediment. Secondary porosity is additional pore space caused by dissolution of grains or cement, or by fractures. This may form after the primary porosity has been reduced.

Schmidt and others (1977) studied the porosity types in many Canadian oil and gas fields. They found that secondary porosity is the main form of porosity in many sandstones which have undergone a long-lasting and deep burial, and that in the fields studied, secondary porosity constitutes the predominant or exclusive form of porosity in sandstone reservoirs.

Secondary porosity usually is readily distinguishable from primary porosity. Schmidt and others (1977) gave eight petrographic criteria for the recognition of secondary porosity (Fig. 39), these are:-

(1) Partial dissolution of grains due to the leaching of soluble constituents.

(2) Molds of precurser crystals or grains.

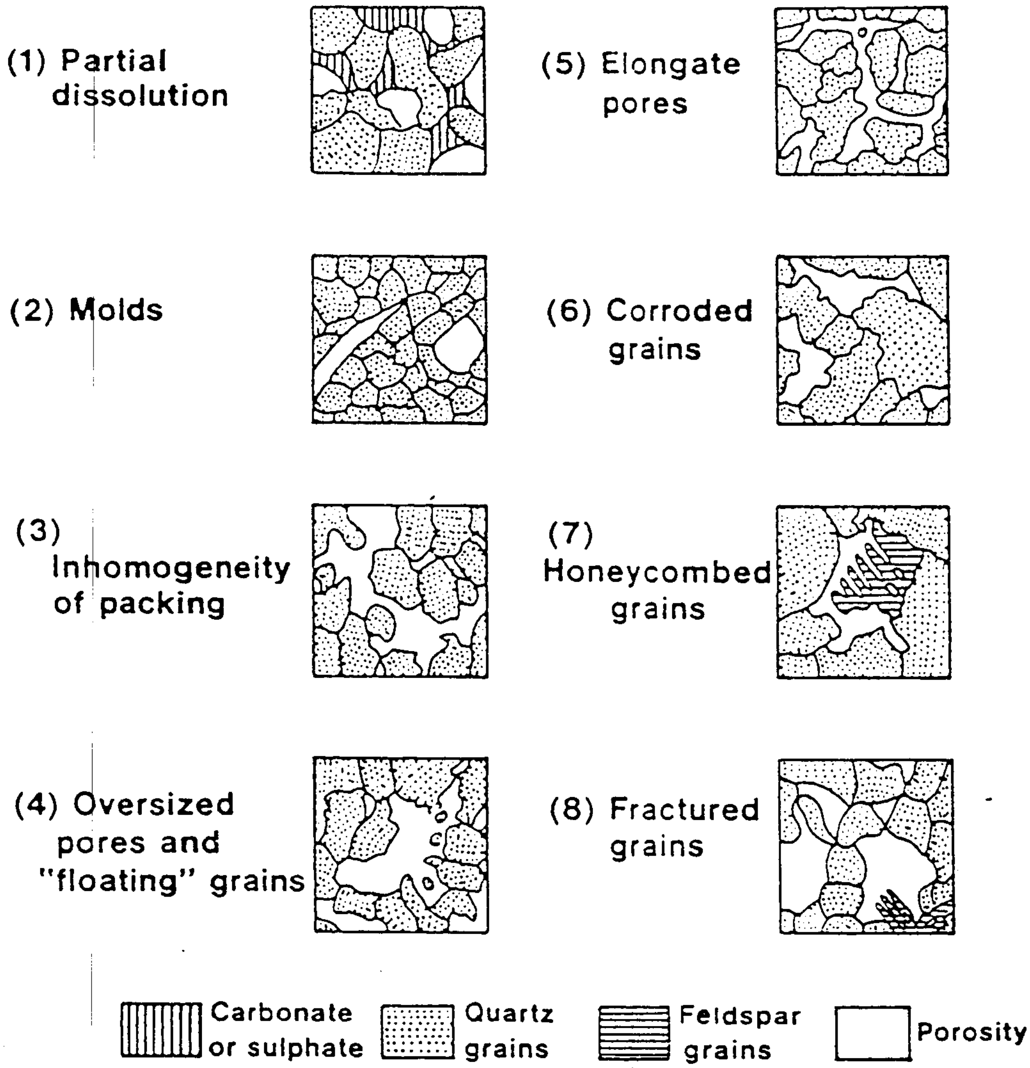


Figure 39. Petrographic criteria for secondary porosity. (Schmidt and others, 1977).

(3) Inhomogeneity of packing. Areas of tighter packing are a result of mechanical compaction which led to dissolution of the grains. Open packing is a result of soluble cement or matrix.

(4) Oversized pores. Pores that have a diameter larger than the surrounding grains usually indicate secondary porosity, however they also can be created by sedimentary processes.

(5) Elongate pores. Grain boundaries are often flattened out during dissolution, elongate pores follow these grain boundaries.

(6) Corroded quartz grains. This occurs due to replacement by a, now-dissolved, mineral.

(7) Honeycombed feldspar grains. Feldspar grains are often subject to replacement by calcite. The removal of calcite leads to grains honeycombed by intergranular voids. These would be too delicate to withstand sedimentary transport, and thus are an excellent indicator of secondary porosity.

(8) Fractured grains. These are common in sandstones with a large degree of secondary porosity. Fracturing occurs because of an increase in stress at grain boundaries following the dissolution of large amounts of soluble constituents.

A sandstone with secondary porosity will usually contain several of these features. Secondary pores are more irregularly shaped than primary pores and have more variable shaped pore throats.

The total porosity is very important when assessing the reservoir potential of a sandstone. North (1985, p. 115) made a qualitative assessment of reservoir potential with a range of porosities (Fig. 40).

Average values for the porosities and permeabilities of the sandstone units in Pfaff #2 have been determined by Core Laboratories of Denver. These show a positive correlation between the porosity and permeability (Fig. 41).

Wardlaw and Cassan (1979) investigated the relationships between pore system properties of some sandstone reservoirs and recovery efficiency. They stated that the rock-pore properties that are significantly related to high recovery efficiency are: high porosity, small pore-to-throat size ratio, small mean particle size, low percentage of carbonate, and high coordination numbers.

The coordination number is defined as the number of throats that connect with each pore, and is a measure of the

Porosity (%)	Qualitative evaluation
0 - 5	negligable
5 - 10	poor
10 - 15	fair
15 - 20	good
20+	very good

Figure 40. A qualitative assessment of reservoir potential with a range of porosities (North, 1985).

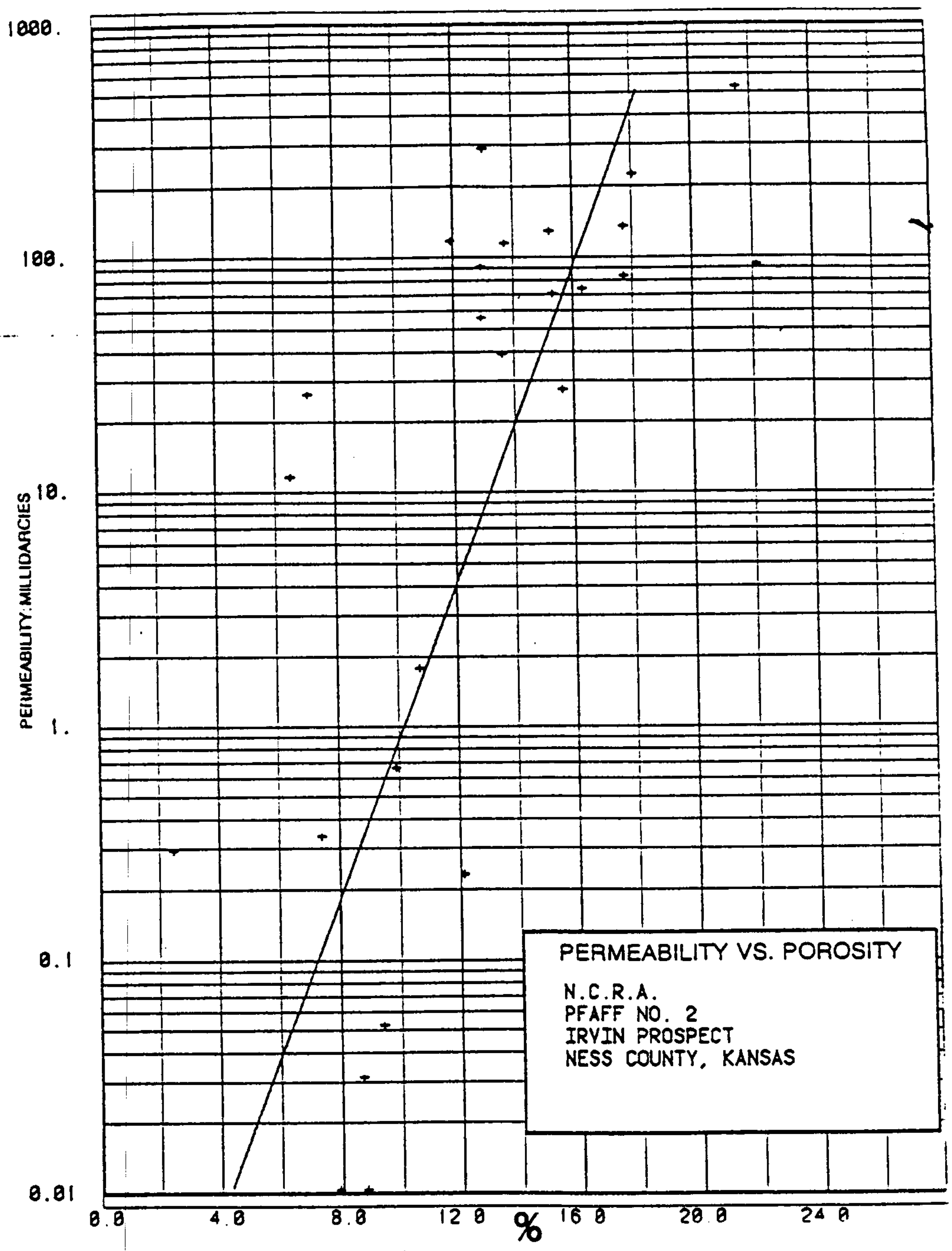


Figure 41. A plot of permeability vs. porosity for Pfaff #2.

interconnectivity of the system (Wardlaw and Cassan, 1978). The coordination number has a significant effect on the recovery efficiency. A higher coordination number means that the pore network is more open, and therfore the recovery efficiency will be higher. Wardlaw and Cassan (1979) also found that all the samples with relatively high mercury recovery efficiencies had small pore-to-throat ratios. This is because capillary trapping of oil during imbibition is likely to be minimized in rocks with a small pore-to-throat ratio. Samples of small particle size have small pores and throats, however samples of large particle size may have pores and throats of variable size, and therefore are likely to give more variable recovery efficiencies. Figure 42 shows the relationship between coordination numbers, pore-to-throat ratio and recovery efficiency (Wardlaw and Cassan, 1978).

Wardlaw and Cassan (1979) estimated pore throat diameter from capillary-pressure curves. Capillary pressure curves can be used to determine pore-throat sizes, because the injection pressures of mercury in a capillary-pressure test are controlled by the size of the throats, and not by the size of the pores (Dullien and Dhawan, 1974, Wardlaw and Cassan, 1979). Pore size was obtained directly from etched resin casts, by measuring the diameters of the maximum

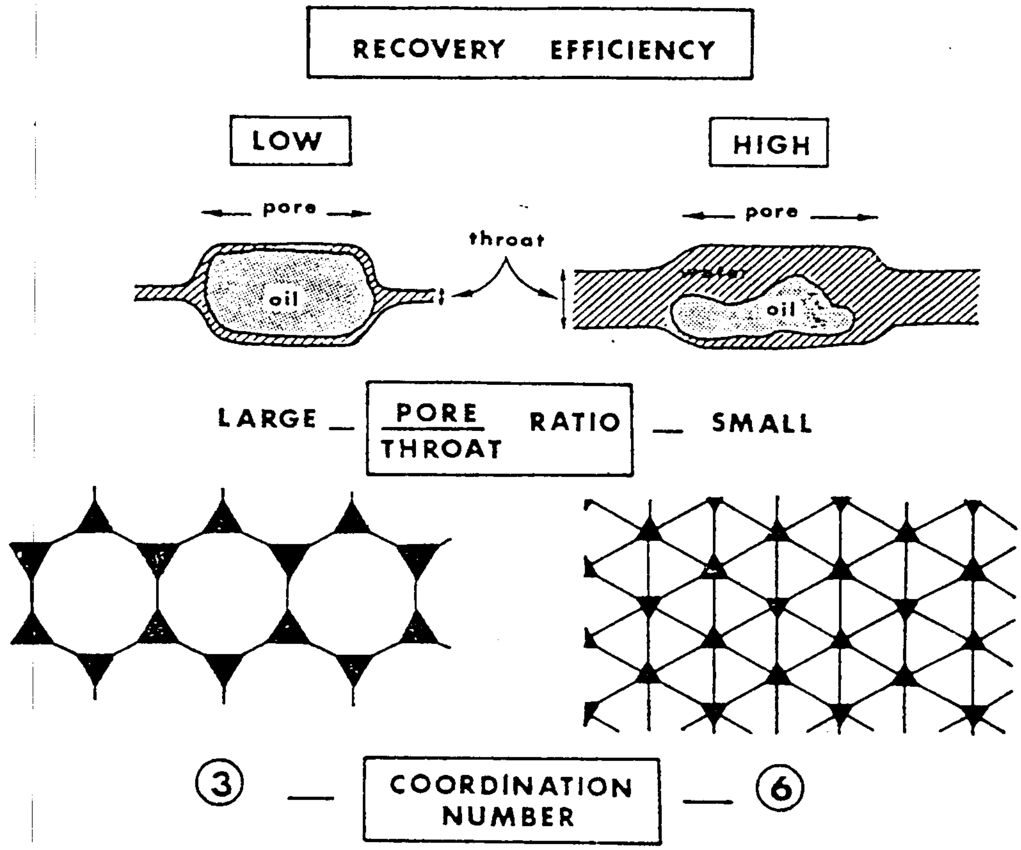


Figure 42. Illustration of pore-to-throat size contrast and coordination number and their effects on nonwetting-phase recovery efficiency (Wardlaw and Cassan, 1978).

inscribed circles of 100 successive pores, in random traverses of each resin cast. In addition to this, mean particle size was obtained from point counts on thin sections. Wardlaw and Cassan (1979) found that as particle size decreased, pore size also decreased, but porosity increased.

Wardlaw and Cassan (1978) found that low porosity rocks (less than 5%) have low recovery efficiencies. However some high porosity rocks also have low recoveries. In these cases, the pore-to-throat size is invariably large (Wardlaw and Cassan, 1978).

B) Methods

For this study, only thin sections were examined. Pore studies were carried out on the reservoir zones in the cores from Pfaff #2, Pfaff #3 and Thompson A#2, to determine the efficiency with which oil can be recovered. Oriented thin sections of the reservoir sandstones were prepared to determine any vertical and horizontal anisotropies in the pore systems. The following features were noted:-

(1) Pore size

(2) Pore type and distribution

(3) Coordination number (C.N.)

(4) Pore-to-throat ratio

(5) Total porosity

The total porosity was determined by point counts. The distribution of porosity, distribution of oil, and reasons for these variations also was noted from the thin sections. The porosity types were noted following the examples given by Schmidt and others (1977).

The coordination numbers were determined by point counts on the thin sections. This has yielded coordination numbers for two-dimensions as compared to coordination numbers for three-dimensions obtained from the study of pore casts made by Wardlaw and Cassan (1979). These cannot be correlated directly with the results obtained by Wardlaw and Cassan (1979), and therefore they cannot be used to predict the recovery efficiency of the rocks. However they do give an estimate of which reservoirs will have a higher recovery efficiency than others.

The average width of the pore throats and maximum pore widths were measured using a micrometer eyepiece on the petrographic microscope. It would have been much more accurate to have used resin casts such as those used by Wardlaw and Cassan (1978, 1979). However the samples from which the thin sections used for this study were prepared, were insufficiently impregnated with resin for the pore systems to have been perfectly preserved upon dissolution of the sample. The values obtained for the pore-to-throat ratios from the thin sections therefore are not be accurate because the thin section will not necessarily cut the widest portions of the pores and the pore throats. However the average values shouldwill be indicative of the true pore-to-throat ratios.

Photomicrographs of several samples taken from a Scanning Electron Microscope were available from the National Cooperative Refinery Association (N.C.R.A.) for this study. The Scanning Electron Microscope photomicrographs gives useful information about the surface of the pores. Surface roughness may affect the recovery efficiency, and it also may lead to the trapping of oil by increased capillarity. The Scanning Electron Microscope also is useful to allow interpreatations of the mineralogy and crystallinity of the clays, and it may indicate whether the clays are authigenic or detrital. This information is useful, because it may be used to predict whether clays will break off during flooding and occlude the pore throats.

C) Description of the Reservoir Zones

i) PFAFF #2: 4207 TO 4204 FEET

The sandstone series overlying the Upper Limestone in Pfaff #2 contains a reservoir zone, which extends from 4207 to 4204 feet. These sandstones contain low-angle cross stratification and, in places, ripple lamination. Contained within these laminae are textural differences which affect the distribution of oil. The beds also contain patches of mud, which are impermeable, and form obstacles to the flow of oil.

The dominant porosity type within the reservoir zone is secondary interparticle porosity. This is indicated by the presence of corroded grains, elongate pores, honeycombed grains, and enlarged pores. Dissolution of the quartz grains occurred after the formation of quartz overgrowths, which are abundant in the reservoir sandstones. The pore shapes and sizes have been altered by dissolution, and by pressure solution, and the pores are irregularly shaped. Isolated chert grains within the zone contain intraparticle microporosity.

Four thin sections were examined from the reservoir zone. These show that the grain size varies throughout the zone, which leads to variations in the porosity and pore geometries. Oil is distributed patchily throughout the reservoir zone. The finer grained layers contain less oil than the coarser bands. The rock is cemented primarily with thin quartz "meniscus" cements. However, small patches of poikilotopic calcite cement also are present. These patches completely fill the pores, and present an impermeable barrier to the flow of oil throughout the rock.

The porosity within the unit varies from 8.3% to 24.9%. In the most porous section, only 69% of the pores are filled with oil, however, in the rest of the zone, over 90% of the pores are oil-filled.

The reservoir zone is overlain by six feet of sandstones up to 4198 feet. However these contain little oil. Within some of these units, bands containing oil-stained grains are present. The porosity within these units is highly variable, and the variations are mainly caused by the irregular distribution of mud associated with depositional structures and bioturbation.

The mean coordination numbers of the pores within the thin sections taken from the reservoir zone varies from 0.98 to 2.7. The mean coordination numbers in the top and base of the zone are close to unity, with higher numbers in the center. This suggests that the pores have a greater interconnectivity in the center of the reservoir, and, therefore, the recovery efficiency may be greater.

The pore-to-throat ratio varies from 3.5 to 6.0, and the mean value is 4.5. The shape of the pores has been greatly altered by pressure solution, which is responsible for the variation in the pore-to-throat ratios.

The mean coordination number is higher in the vertical sections than in the horizontal sections, and there is no anisotropy for the values of the pore-to-throat ratios and total porosity. This difference is not likely to be great enough to affect the flow of oil through the rock.

This reservoir zone has been analyzed by Core Laboratories of Denver. This analysis shows that the porosity ranges from 15.1 to 17.9 percent, and that approximately 34% of the pores are filled with oil. The point count values for these features obtained from the thin sections are more variable than these values, because these values are averages for one foot intervals.

Barriers to permeability

The textural features which form barriers to permeability in the reservoir zone described above are given below:-

1) Patches and layers within the zone with no porosity, because of cementation by quartz or poikilotopic calcite.
2) Finer grained bands within the rock. Compaction appears to have had a greater effect in reducing the porosity in the finer grained bands.
3) Mud is present locally throughout the unit. It fills some pores, and blocks others at the pore throats. Clay particles also forms a thin coating on many grains which reduces the porosity. The clay coatings also may break off during flooding to clog the pores.
4) Pressure solution has flattened grain boundaries. It also has closed many pore throats.
5) Quartz overgrowths and cement have reduced the porosity and blocked many pores.

It is not clear what forms the seal. The unit is overlain by a cream-colored sandstone which contains patches of poikilotopic calcite cement, and isolated pyritohedrons. Little shale is present in this unit. A thin section was not prepared from this unit, but it is assumed that the permeability of the rock is very low and this is responsible for the seal.

THOMPSON A-#2: 4127.9 TO 4124.95 FEET

A reservoir sandstone is present from 4127.9 to 4124.95 feet in Thompson A-#2. This unit is thought to have been deposited in the point bars of a tidal channel. The sandstone is well-sorted, though isolated chert clasts are present. The reservoir sandstone is overlain by a fine-grained, clay-rich, pale maroon, sandstone, which forms the seal to the reservoir.

Three thin sections were examined from this zone; they indicate that there is little oil present in the rocks, although from examination of the core they appear to be saturated.

The main porosity type is secondary, interparticle porosity. Partial dissolution of the grains occurred after the formation of quartz overgrowths, and extensive pressure solution. Some intraparticle microporosity also is present, however this is not significant with respect to the reservoir properties of the unit. The total porosity varies from 10% to 15%, However, many of these pores are isolated, and, therefore, the effective porosity is much lower.

The sandstone is cemented mainly by quartz cements. This has greatly reduced the porosity of the sandstone. The greatest reducers of porosity are quartz overgrowths, which comprise up to 11% of the total rock volume. They increase the volume of the grains by 18% In addition, patches of poikilotopic calcite cement, and smaller patches of poikilotopic anhydrite are present throughout the rock; these completely fill the pores. Within the rock there also are small patches of mud which block and fill many pores.

PFAFF #2: 4249.7 TO 4248.5 FEET

A fine grained sandstone which contains oil-stained grains is present from 4249.7 to 4248.5 feet in Pfaff #2. A thin section taken from this unit shows that it contains very little oil (less than 0.2%). The main porosity type is secondary interparticle. Flattened grain boundaries indicate that this unit has undergone much compaction. Compaction has greatly reduced the porosity of the rock. Most of the cement is quartz, however small patches of poikilotopic calcite cement further reduce the porosity. The total porosity of the rock is 1.8%. This is too low for the rock to produce oil.

Thin hematite-rich mud layers are present throughout the unit. These divide the unit into separate flow units and prevent any vertical mixing of fluids.

The reservoir zone is underlain by fine-grained sandstones which contain little oil from 4251.4 to 4249.7 feet. A sample from 4250-51 feet was examined using a scanning electron microscope. Smooth quartz overgrowths line many pores, and occlude many pore throats. Kaolinite is the principal clay type in this sample, and it occludes many pores. Minor detrital clay is present.

Pfaff #3: 4235.2 to 4233.6 Feet

A fine to medium grained sandstone is present from 4235.2 to 4233.6 feet in Pfaff #3. Capillary pressure tests have been carried out on a sample from 4234-4235 feet by the method of mercury injection to determine pore throat size distribution. The sample shows a very well interconnected pore network with approximately 78 percent of the pores being accessed by mercury below 237 psi injection pressure (ie. 78 percent of the pores are macropores having a pore aperture greater than 0.5 microns).

The sandstone is overlain by a dark green shale, and underlain by a sandstone with a clay-rich matrix. It is well sorted, and contains a variable amount of clay. Where clay is abundant in the matrix, no oil is present, and vice versa. A thin section of this unit was prepared from 4235.0 feet. The rock contains secondary interparticle porosity. The total porosity is low at 6%, and oil fills about 20% of these pores. The porosity has been reduced greatly by pressure solution and the formation of quartz overgrowths. Patches of poikilotopic calcite cement further reduce the porosity. Bands are present with a muddy matrix. This separates the unit into thin horizontal flow units.

The reservoir zone is underlain by white to tan sandstones which contain thin shale seams. These are not rich in oil, however many of the grains are oil-stained. The reservoir zone, and these underlying rocks were examined using a scanning electron microscope at 4234-35 feet, 4235-36 feet, and 4238.6 feet.

At 4234-35, feet many of the pores are extremely clean, and are angular in shape because of overgrowths on the quartz grains. Subhedral chlorite grains coat some grains. Associated with these is abundant microporosity.

At 4235-36 feet, no intergranular porosity is present because of an extensive matrix of chlorite and illite/smectite mixed-layer clays. Much microporosity is associated with this.

At 4238.6 feet some interparticle porosity is present. Where this porosity type is present the grains are oil-stained. Most of these interparticle pores are partially occluded by quartz overgrowths. Also authigenic booklets of kaolinite partially occlude some pores. These may break off during flooding and clog the pore throats. Where the grains are not oil stained, the interparticle pores are completely occluded by illite/smectite, kaolinite and quartz overgrowths.

D) Summary and Interpretation of the porosity zones

i) LITHOLOGY

The rocks within the reservoir zones all are well-sorted, clean, sandstones. These have been deposited in the point bar deposits of tidal channels which traversed the supratidal and intertidal flats, and the subtidal zone. Thin clay seams are present within some of the reservoir zones. The other facies contain abundant mud in the matrix, or are interbedded with shaly units, and do not possess enough porosity to be able to function as petroleum reservoirs. Storm-deposited units are an exception: however these are thin, and on their own do not form reservoirs, but nevertheless they may be present within larger units which do form reservoirs.

ii) POROSITY TYPE

The most important form of porosity in the reservoir sandstones is secondary interparticle porosity. This is modified primary porosity. Primary porosity initially was reduced due to compaction, pressure solution, and the formation of quartz overgrowths, then there was partial dissolution of the quartz grains, which can be seen at the corroded edges of many overgrowths. In places, the porosity was then further reduced by the growth of patches of poikilotopic calcite cement, and less common poikilotopic anhydrite cement (figs. 35, 43).

iii) BARRIERS TO PERMEABILITY AND DESTROYERS OF POROSITY

Much of the porosity is reduced by quartz overgrowths, poikilotopic calcite cement, and a clay matrix. The barriers to permeability are similar in all the reservoir zones. Mud layers have the dominant effect on the permeability reduction where they are present. Thin layers of mud, or layers of mud matrix, separate the reservoir into

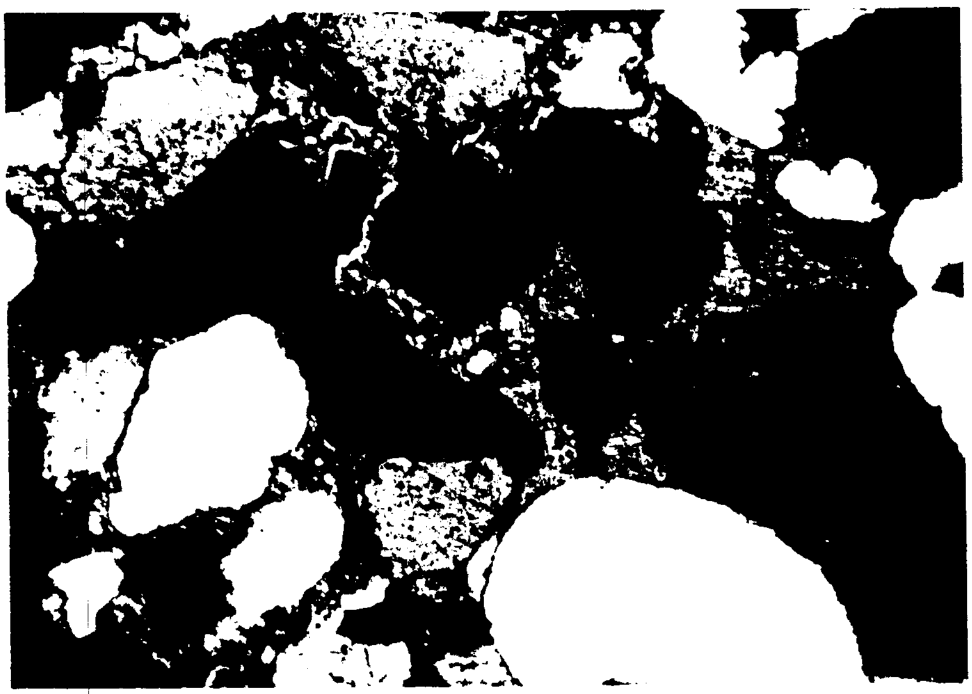


Figure 43. Photomicrograph of sandstone from Pfaff #2 at 4248.0 feet. Total destruction of porosity by poikilotopic calcite cement (right), and poikilotopic anhydrite cement (left). XN. Length of photograph is 1.7mm.

separate flow units. However, most of the reservoir zones contain little mud, and so it does not exert an influence on their permeability. Within the reservoir zones examined, the two major processes that have reduced the porosity the greatest are:-

1) Pressure solution which reduces the size of the pore, and increases the lengths of the grain to grain contacts.
2) Quartz overgrowths which cause a large reduction in the porosity.

Microporosity also is present throughout the rock where clay is present. Micropores are less than 0.5 microns in diameter. Authigenic clay, partially and fully, occludes many of the intergranular pores. Micropores are present between the clay crystals. This porosity type is not considered to affect the recovery efficiency within the rock.

Bands are present within the zones which are finer grained, and contain a lower effective porosity. The bands were deposited as a response to fluctuating energy levels. Amyx, Bass, and Whiting (1960) report that permeability decreases with decreasing grain size, and therefore the finer grained bands are less permeable. Pettijohn and others (1973) state that cross-bedded and horizontally laminated sections might exhibit maximum permeability parallel to the bedding fabric. Therefore bedding structures might diminish the flow of oil of both native and injected fluids. This appears to be very likely because the finer grained bands have been more extensively cemented than the coarser grained bands, the coarser bands as a result have a higher permeability.

iv) CLAYS

Over much of the reservoir zones, there is very little clay. However the mineralogy of the authigenic clays within the point bar deposits includes kaolinite, chlorite, smectite, and mixed-layer clays. The authigenic clays occur as pore-filling and pore-occluding particles. These clay particles may detatch from host grains and migrate into pore throats during hydrocarbon production. The formation damage caused by the mobilization of kaolinite platelets may be minimized using a suitable clay stabilizer offered by various oilfield service companies (Emery, 1985). Illite and mixed-layer clays expand when introduced to freshwater. Elimination of this problem may be achieved by acidization with a combination of hydrochloric and hydrofluoric acid, combined with a suitable pre-flush and after-flush solution. However calcite and ankerite are sensitive to hydrofluoric and hydrochloric acids. The reaction products are calcium fluoride and iron hydroxide which are gelatinous precipitates that can diminish substantially the ability of a reservoir to transmit pore fluid. To overcome the precipitation of these compounds, a spacer of hydrochloric acid with an iron chelating agent can be applied (Ali, 1981, Emery, 1985).

v) DISTRIBUTION OF THE RESERVOIR ZONES

Examination of reservoir zones, and possible reservoir zones in the well cores; Pfaff #2, Pfaff #3, and Thompson A-#2, and determination of their geometries from the stratigraphic sections constructed from petrophysical log data, indicates that most of the reservoir units in the Cherokee Group are likely to be less than 10 feet thick, and will not be persistent over a great distance.

10) CYCLICITY WITHIN THE CHEROKEE GROUP

The Cherokee Group was deposited during a major marine transgression onto the Mid-Continent shelf (Rascoe and Adler, 1983). Core studies combined with subsurface mapping within the study area indicates that minor cycles also are present within this overall trend. Sea level curves have been produced from the three N. C. R. A. well cores (Figs. 6, 7, 8).

It is assumed that the cycles present within the study area are eustatically controlled. The deposition of marine limestones and marginal marine sandstones and shales, in addition to the subaerial exposure of the limestone units is taken as evidence of sea level changes. The Cherokee Group strata has not been traced out of the study area and so it is not possible to be sure that the facies variations are not autocyclic.

Heckel (1986) compiled data from several sources to derive a sea level curve for part of the Middle to Upper Pennsylvanian sequence along the Mid-Continent outcrop belt. The sea level curve for the Cherokee Group is reproduced in figure 44. This shows that two major transgressions are present within the Cherokee Group. In Eastern Kansas, these

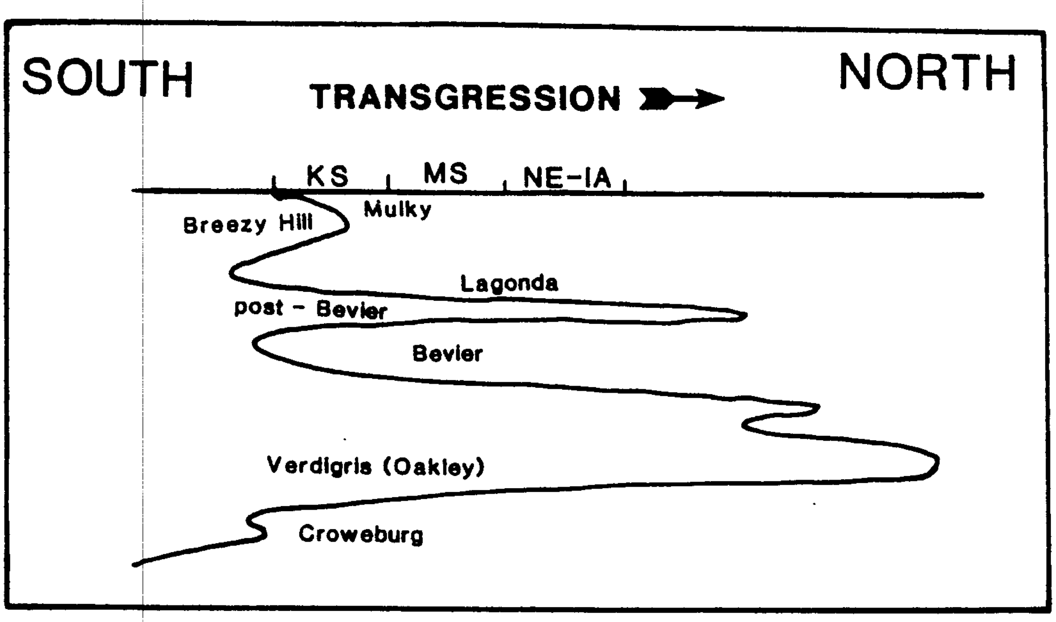


Figure 44. Sea-level curve for the Cherokee Group (Heckel, 1986).

deposited:-

1) The Verdigris Limestone member and the Upper Ardmore Limestone in the lower transgression.

2) The post-Bevier Limestone in the upper transgression.

The Lower Limestone, and the Upper Limestone were deposited respectively in these transgressions.

11) CONCLUSIONS

Sedimentation in the Pennsylvanian commenced on the weathered, karstic, surface of the Mississippian. A varying thickness, of Pennsylvanian Basal Conglomerate was deposited on this surface over most of the study area. This smoothed off the topography before deposition of the laterally extensive units within the Cherokee Group began. This indicates that Mississippian bedrock control of the Cherokee Group sedimentation patterns is not large.

The strata which occur in the Cherokee Group consists of an alternating sequence of limestones, sandstones, and shales. The limestone units were deposited in shallow water away from the influence of a clastic source. Four distinct sedimentary facies have been recognized, these are:-

1) Tidal channel deposits
2) Tidal flat deposits
3) Storm deposits
4) Shallow marine limestone facies

The depositional setting of the Cherokee Group was a uniform marine shelf. This shelf was exposed during marine lowstands, during which time clastic sedimentation occurred. Most of the sandstones were deposited in tidal channels, and most of the shales were deposited in the tidal flats. It is not known if the sedimentary environment was a barred lagoon, or open tidal flats. A barrier was not discovered; however, the sedimentary facies could have been deposited in either setting.

Subsurface mapping has revealed that the facies variation within the Cherokee Group may be extremely rapid. Therefore correlations that are carried from one petrophysical well log to another must be treated with caution.

During marine transgressions, the entire area was inundated, and limestone units were deposited. These were exposed as the sea level dropped, and were subjected to subaerial weathering, which caused much dissolution and led to the formation of limestone nodules.

The inundation of the area during the time of maximum marine transgression was never sufficiently deep to allow the formation of an offshore, "core", shale. The limestone units were deposited both in marine transgressions and regressions.

Some of the Cherokee sandstones in the area produce oil. All the reservoir zones are present in well-sorted, "clean" sandstones. These were deposited in the point bars of tidal channels. Sandstones which were deposited in the other depositional environments contain too much mud, and too little open porosity to be useful reservoir rocks.

The main form of porosity in the reservoir zones is secondary, interparticle porosity. The pores mainly are replicas of residual primary porosity, and some enlarged replicas of residual primary porosity are present. Clays partially occlude may of the pores in the reservoir zones. The mineralogies present include:- kaolinite, chlorite, and illite/smectite. These clays should be stabilized before flooding, because they may break off to block the pore throats.

The main reducers of porosity are:-

1) Compaction of the sandstone which has led to pressure solution and flattened grain-to-grain contacts.
2) Quartz overgrowths.
3) Clay within the pores, and in layers.
4) Poikilotopic calcite cement.

Exploration for oil in the area should be concentrated in point bar deposits of tidal channels. The location of these deposits is difficult to predict with accuracy because small tidal channels often follow extremely sinuous courses.

Detailed cross-sections from data derived from petrophysical logs and careful examination of all available core and well cuttings can increase the accuracy of a prediction. However, the facies may change rapidly between closely-spaced wells.

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APPENDIX 1

Core descriptions

All footages are given for the tops of the intervals in feet below K. B..

Pfaff #2

4196.0-4197.0	Quartz arenite, fL, many chert grains (fL), subangular, green/gray, massive, mottled (bioturbated).
4197.0-4198.0	Siltstone, coarse, gradational contact, massive, intense bioturbation has led to a mottling, black and pale gray.
4198.0	Quartz arenite, fL, irregular upper contact at $\sim 15^{\circ}$, pale green/gray, bioturbated, no matrix, subangular to subrounded quartz grains. Oil-free, no porosity.
4198.1	Quartz arenite, mL, irregular contact, gray color, well sorted, no matrix, massive. Oil stained grains.
4198.3	Quartz arenite, fL, abrupt contact, gray, subrounded to subangular grains, thin laminae of organic-rich silt, ripple-laminated, bioturbated.
4198.8	Quartz arenite, mL, gray, oil-stained grains, well sorted, no matrix, massive.
4198.9	Quartz arenite, fL, gray, subrounded to subangular grains, thin horizontal laminae of black silt.
4199.0	Quartz arenite, mL, gray, subangular to subrounded, equant grains, oil stained grains, darker silt bands, cross laminated (15 degrees), mudstone clasts at 4139.6, dewatering.

4200.0 Siltstone, fine, quartz-rich, isolated muscovite flakes, interbedded with quartz arenite as above and below. Gray color.

4200.3 Quartz arenite, fL, gradational contact, well-sorted, subrounded to rounded grains, pale green/gray, some oil-stained grains, black silt layers, most laminae horizontal, cross-laminated near base, some dewatering, ripple lamination.

4201.7 Siltstone, sharp upper and lower contact, mottled, quartz-rich, as 4197.00. Contains brachiopod shells.

4201.8 Quartz arenite, fU, sharp horizontal upper contact, green/gray, subangular to subrounded grains, elongate to equant, some chert, siltstone layer at base - broken up, blocks found in arenite already lithified (rip-up clasts. Yellow to gray color. Channel deposit.

4201.9 Quartz arenite, mL, irregular channelled contact at ~25 degrees. Gray color, subangular to subrounded grains elongate to equant, some chert, contains calcite cemented patches, contains green/gray shale clasts.

4202.1 Quartz arenite, mU, cream colored, as above, but no shale clasts, isolated pyrite-rich agglomerations (up to 5mm). Dewatering structures present. Gradational contact. Some horizontal laminae.

4203.7 As above, low angle cross lamination (~10 degrees). Patches of calcite cement.

4204.0 Reservoir sandstone.
Gray sandstone, mL, well-sorted, contains some larger chert grains. Sharp upper contact. Patchy distribution of oil.

4204.3 Quartz arenite, mL, gray, no matrix, v. clean, subangular to subrounded grains, elongate to equant, oil stained grains, ripple lamination and low angle cross lamination present.

4204.6 As above, mU, continuous planar lamination.

4204.8 Gray sandstone, well-sorted, ripple laminated mU.

4205.3 Quartz arenite, mU, oil stain, contact not visible. Ripple laminated (~20^), lower part disrupted by dewatering and bioturbation. Some isolated chert grains (up to 2mm, <0.5%).

4206.4 As above, green/gray siltstone clasts (up to 1 inch).

4206.5 Section missing.

4206.8 Quartz arenite,mL, abrupt contact, subangular to angular grains, oil in some pores, patches of calcareous cement, no matrix, larger chert grains (1-2mm) common, some chert grains larger (up to 10mm), chert grains are angular. Low angle cross lamination present (~15^).

4208.0 Shale, abrupt upper contact, black, extremely friable. Isolated quartz grains and chert grains (<0.5%).

4208.5 Siltstone, medium, contact not clear. Friable, maroon, slickensided in parts, Well-rounded, equant quartz grains present (~2%), quartz-rich, reduction spots present. Contains larger quartz grains (1-4mm).

4210.2 Sublitharenite, mL, abrupt upper contact. Well-rounded, equant, quartz grains (70-90%) enclosed in a siltstone matrix (red or green). Larger angular chert grains also present (2-5%). Bioturbated and dewatered. Possibly cross-bedded. Clay present throughout, rock is friable, very weak in contact with water. Lower contact w/ limestone is microkarstic. Basal sediment is cL - this infills the depressions and coats the base - Disconformity - Marine to non-marine.

4213.5 Limestone, microkarstic upper contact, clay seam on top, and macropores contain sand as above. Clay seams present throughout. Limestone is micrite - extensively diagenetically altered - Nodular texture. Fossiliferous with crinoids, brachiopods, fusilinids. Limestone nodules generally separated with green shale - fissile (clay-rich), large amounts of disseminated pyrite - reducing environment.

4215.3 Quartz arenite, fU, sharp contact. Angular to subrounded, elongate to equant grains, no matrix. Occasional flaser green shale (1mm thick). Some pyrite present - REDUCTION, some clay seams, mottled - bioturbation. Some chert clasts (up to 10mm, (1%).

4215.4 Quartz arenite, fU, gradational contact, no clay, few chert clasts. Cream colored, mottled at top - calcite cemented patches present, cement is mainly quartz. Angular to subrounded, equant, grains. Contains darker, more porous bands, (?)cross-laminated (~15^). Bioturbated, dewatered.

4218.3 Shale, sharp contact. Green, fissile, contains larger, angular clasts of chert and quartz (up to 20mm).

4219.3 Breccia, sharp contact. Angular clasts, 2-20mm, mainly chert and quartz (from granite), some agate. Matrix supported. Matrix - quartz grains, mL, subrounded to rounded, equant. Some clay. Red. Clasts become more abundant and less rounded toward top. Well-rounded at base.

4219.5 As above, green, gradational change.

4221.9 Quartz arenite, fL, sharp contact, no matrix. subangular to subrounded, equant grains. Isolated larger chert and quartz grains (up to 10mm). Alternating light and dark green. Ripple laminated.

4222.1 As above, vfU. Fine silt bands run through the rock.

4222.5 Quartz arenite, fL, sharp contact, poorly sorted, angular to subrounded grains. Clasts (up to 10mm) of chert and quartz present. Green shale rich layers present.

4222.9 Quartz arenite, fU to mL, sharp contact, cream color, no matrix, quartz cement, subangular grains.

4224.9 As above, larger quartz and chert grains (up to 0.5mm). Bioturbated.

4225.3 As above, abrupt change, faint continuous horizontal lamination.

4225.5 As above, cU, abrupt change, quartz grains are from granite. Some v. thin green clay layers.

4225.9 As above, mU to cU, gradational change. Alternating coarse and medium grained bands. Larger chert clasts (<0.5%) subangular, up to 10mm.

4226.2 As above, fL. Discontinuous, parallel layers of clear (darker colored) quartz. Bands frequently green, due to shale. Some dewatering.

4227.2 Limestone, sharp contact, possibly a scour surface. Nodular texture as lower. Fossiliferous with crinoids and brachiopods.

4236.4 Gray shale, fissile, gradational contact, fossiliferous w/ abundant Lingula.

4239.1 Gray shale, friable.

4239.7 Limestone, fossiliferous with brachiopods and coral. Sharp contact. Mottled, micritic. One thin gray horizontal shale bed.

4240.1 Quartz arenite, mL, Sharp upper contact. Well-rounded, equant grains. Well cemented, originally very porous. Well sorted. Cement is quartz and clay. Black/violet in color at top; overall mottled maroon with green. Contains reduction spots. Burrows present - filled with clay-rich arenite.

4244.7 Shale, rapid change. Mainly dark green, oxidized to maroon in parts. Friable.

4245.0 Quartz arenite, mL, rapid change. Mainly maroon, green in parts. Subrounded to rounded, equant quartz grains. Large clay content - slickensided.

4245.4 As above, contains thin bands of friable black shale.

4246.0 Section missing.

4246.8 Quartz arenite, mL, gray color. Subrounded to rounded, equant quartz grains. No matrix, quartz cement.

4247.0 Conglomerate, clasts of quartz, chert, and granitic fragments are enclosed in a medium grained quartz arenite. Sharp upper contact. Matrix is normally-graded, grain-size varies from fU to vcL, Subrounded to rounded quartz grains, mud present in matrix. Brown and white banded.

4247.3 Quartz arenite, mL, sharp contact. Brown. Well sorted, subrounded to rounded quartz grains. Clay cement - friable rock. Oil stain. Some larger particles (up to 10mm).

4247.7 Quartz arenite, cL, abrupt contact. Larger chert and quartz grains (up to 15mm), subrounded grains. Well sorted overall. Tight- reservoir seal

4248.5 Quartz arenite, two grains sizes, rock is broken and bagged so the distribution of these different lithologies cannot be seen.
1) mL, very tightly packed, oil stained.
2) vcL, poorly sorted, oil stained, larger clasts of chert are present.

4248.9 Fine grained quartz arenite, homogenous, ripple laminated. Brown.

4249.6	Quartz arenite, fL, brown, quartz cement, no matrix, subangular to subrounded equant grains. Contains a thin white clay seam. Climbing ripple lamination is present.
4249.7	Quartz arenite, vfU, sharp contact - marked by a thin green clay band. Quartz cement, no matrix. Pale green with pale brown blotches. Thin (1mm) band of black shale 0.5" from base. Normally graded, mL to vfU. Subrounded to subrounded, equant grains.
4250.7	Green shale, sharp contact, friable and fissile.
4250.9	Quartz arenite as above. Sharp contact, laminae dip at 10 degrees.
4251.1	Quartz arenite, vfU. Patchy green and brown. Interbedded with thin black shale layers. Horizontal layers. Abrupt upper contact.
4251.4	Shale, green/black, fissile and friable.
4251.7	Quartz arenite, vfL, green, irregular contact with green shale, horizontal laminae.
4252.2	Quartz arenite, fU, rapid change. Subangular grains, iron stained patches, continuous horizontal laminae, clay at base with chert clasts. Green in color.
4252.3	Shale, green and maroon, slickensided. friable. Abrupt upper and lower contact.
4252.8	Siltstone, maroon, quartz-rich, some clay, friable.
4253.4	Quartz arenite, fU, angular to subangular quartz, multicolored, angular chert fragments (up to 10mm) at top (~10%). Clay cement and matrix, dewatered.
4254.0	Quartz arenite, fL, angular to subangular quartz grains, larger (up to 3mm) subrounded chert clasts. High clay content, though amount varies greatly. Highly dewatered.

Maroon color.

4255.0 END OF CORE

Pfaff #3

4205.0 Siltstone, fine, maroon, contains larger subrounded quartz grains (up to vcU). Friable, mainly quartz high clay content.

4216.3 Siltstone, abrupt contact, green, calcareous. Contains larger (up to 10mm), subangular to subrounded, quartz grains. High clay content, extremely friable. Contains small limestone nodules at base.

4206.7 Limestone, gradational contact. More shale at top. Contains large broken fossiliferous blocks, fractures are infilled with green clay and smaller limestone particles, including coated grains. Breakage could be due to subaerial exposure. One block contains a laminated crust on top (algal or sponge). Stylolites are present throughout the rock.

4207.4 Limestone, gradational contact, limestone nodules separated by brown shale. Shale common at 4208.0. Fossiliferous with Brachiopods, fusulinids, crinoids. Pressure solution abundant.

4208.2 As above, nodules separated by green shale.

4211.8 Limestone, abrupt contact. Massive, green, mottled. Rich in fusulinids (collected), also present - conodonts, crinoids, bryozoa.

4212.0 Limestone and shale, nodules of limestone enclosed in a gray shale. Fossiliferous with - fusulinids, conodonts, crinoids, brachiopods. Very friable.

4212.5 Quartz arenite, abrupt contact, fL, green, calcite cemented in patches, mottled, bioturbated. Ripple-laminated. Subrounded grains set in a clay-rich matrix. Abundant irregularly-shaped calcite nodules.

4213.1 Green shale, sharp contact, maroon patches, fissile, slightly fossiliferous with brachiopods. Perhaps some limestone nodules.

4213.7 Quartz arenite, vfL, rapid gradational contact, green. Interlaminated with maroon bands. Some finer bands. Continuous wavy lamination present. Very thin (1mm) bands.

4214.1 Green shale, abrupt contact. Contains small (~1mm) crystals of calcite. Very friable - disintegrates with water.

4214.8 Limestone, abrupt contact. Fossiliferous with brachiopods. Highly compacted, stylolites common. Sponge present at base.

4215.3 Limestone nodules and green shale. Shale is graded to mL sand. Nodules elongated horizontally.

4216.0 Quartz arenite, mL, irregular contact, no change in grain size, sudden absence of limestone nodules and mud clasts. Cream colored, subangular to subrounded, equant quartz grains. Mottled with calcite-cemented patches. Cross-bedded (~15^), well sorted.

4217.95 Quartz arenite, fU to mL, sharp horizontal contact, No parting along the lithologic change. Contains subangular to rounded clasts of chert, quartz, limestone and some mud clasts. Sand/clast ratio varies 5% to 100%. Faint laminations, poorly sorted.

4221.2 Quartz arenite, fL, sharp horizontal contact, slightly uneven. Calcareous cement, isolated limestone nodules. Thin bands of oil stained grains. Cream-colored, no matrix.

4221.9 Quartz arenite, fL, rapid lithologic change, green, ripple laminated.

4222.1	Green shale, 0.1" thick.
4222.1	Siltstone, red, abrupt upper contact, mottled with green, friable, especially when wet, slickensided, contains a few larger (cU) quartz grains.
4222.3	Limestone, sharp upper contact, micrite nodules are contained in a green shale. Fossiliferous with brachiopods.
4223.4	Conglomerate, highky weathered limestone, medium, gradational upper contact, subrounded limestone and chert clasts are enclosed in a green and maroon shale. The limestone clasts have corroded edges. Poorly sorted. Grain-supported in upper part, and matrix-supported in lower part. The unit is rich in green shale at the base.
4224.3	As above. Limestone clasts enclosed in maroon shale, fossiliferous with brachiopods.
4225.1	Nodular limestone. Nodules separated by thin green shale bands. Some clear calcite cement in pores. Gradational upper contact.
4225.8	Sponge within compacted limestone.
4225.9	Limestone, gradational contact, compacted, possibly algal, fossiliferous with crinoid ossicles and sponges.
4226.1	Limestone, abrupt contact, fossiliferous with crinoid ossicles, brachiopods and algae (possibly framework). Lighter colored, larger sparry cemented areas.
4226.3	As 4225.9, stylolite contact, mottled light and dark brown, fossiliferous with (?)rhodolites (or sponges), and brachiopods.
4226.6	Nodular limestone, sharp contact, green shale between nodules. Brachiopods. Darker color. Contains nodules of the lighter and darker limestone (4226.8-4227.0). One nodule has a vertical fracture (5mm wide) which is filled with green shale.

4227.9	Nodular limestone, sharp contact. Limestone nodules enclosed in black/purple shale. Brachiopods present. Nodules are gray.
4228.4	Nodular limestone, abrupt change. Nodules enclosed in green shale (0-20%)) Brachiopods present, frequently mottled.
4231.5	Quartz arenite, abrupt contact. Banded crudely pale brown and green. Moderate sorting fL to cL. Subrounded, equant quartz grains. White clay matrix and cement.
4231.8	Green shale, abrupt change, friable.
4232.1	Black shale, abrupt change, very fissile, rich in <u>Lingula</u>
4233.2	Dark green shale, rapid change, dark gray in places, friable, especially in water, some <u>Lingula</u>.
4233.6	Quartz arenite, fU, sharp contact, clay matrix. Subrounded, equant quartz grains, many oil stained. Thin (~0.05") horizontal black shale seams present. Some calcite cemented patches.
4234.2	SECTION MISSING (WITH RESERVOIR INC.)
4234.7	Quartz arenite, mL, oil-rich, dark brown, homogenous, angular to subangular grains.
4235.2	Quartz arenite, fU, sharp contact, white, clay matrix, Grain size varies in bands - poorly sorted, fL to gravel. Angular to rounded grains. Chert ~1%.
4235.8	Quartz arenite, fL to fU, inverse graded, oil stained, Larger (up to 20mm), subrounded clasts of chert. Well cemented, little clay, calcite cemented bands present, faint horizontal laminae, mottled tan to white due to patchy calcite cementation.
4236.6	As above, less clay, better cemented. Part of the same grading cycle.

4237.1	Quartz arenite, fL, gradational contact, crudely banded, mottled white-tan-brown. Chert clast ~1% (up to 10mm), calcareous cement, angular to rounded grains, clay matrix - (minor to cement).
4237.7	Quartz arenite, as above, fU, patches of calcareous cement, bioturbated, well sorted. At 4237.9 Quartz arenite, cL, sharp contact, well cemented, some clay, lensoid form. Thin horizontal green shale seams cut the bed.
4238.9	Shale, gray , green and maroon, friable, bagged.
4239.6	SECTION MISSING
4239.9	Quartz arenite, vfU, alternating light gray and green laminae, some muscovite, little matrix, well cemented, subangular grains, ripple laminated.
4240.3	SECTION MISSING
4240.6	Shale and limestone, friable, bagged, slickensided, green and maroon.
4241.6	Nodular limestone and green shale. The shale encloses the nodules, shale is very friable. The nodules follow horizontal layers. Black shale layer ~8mm thick present at 4242.8.
4241.6	Sandstone, fine grained, green. Layers of green expanding shale throughout the unit, more abundant near base. Patches and thin layers of black shale present. Limestone nodules present. These are up to 2cm in diameter. Gradational upper contact. Low-angle cross lamination and ripple lamination visible in the sandier parts. Limestone nodules more abundant near the top of the unit; these are enclosed in a shaley sandstone matrix. At the top, the sandstone grades into a shale with enclosed limestone nodules.
4243.4	Nodular Limestone. Micrite nodules enclosed

in green and maroon shale.

4244.0		Siltstone, blue/gray in color, some yellow patches, very friable, larger angular chert fragments are present.
4246.2		Siltstone, gradational upper contact, very colorful - maroon to green along fractures in the rock, shades of blue near top. Isolated chert clasts, more common toward base.
4249.1		Conglomerate, gradational contact, isolated chert clasts within a silt matrix. Clasts are subangular, 5-60mm, poorly sorted.
4252.0		END OF CORE

<u>Thompson A-#2</u>

4107.0	--	Green siltstone w/ bivalve casts, white limestone nodules, ripple laminations, interlaminated green shale, some quartz-rich parts.
4107.15		As above, no bivalves, no limestone nodules.
4107.30		As above, discontinuous red mudstone lenses, fissile.
4107.50	--	Shale, interlaminated red and green, fissile, ripple laminated. Green at top, maroon at base. Gradational contact with above. Contains coal fragments, mottled, friable toward base. Carbonaceous coatings present near base,
4110.0	--	Fine qz arenite rapid contact, mottled, bioturbated, interlaminated maroon and green.
4110.35	--	Qz arenite, vfU-fU, gradational contact, graded, planar cross bedding~15^. Laminated light and dark grey. Dark laminae 2mm thick, light laminae 10mm thick. Clay matrix, subrounded to rounded grains, porous, biotite

((0.5%), coal ((0.5%).

4112.05 SECTION MISSING

4112.4 -- Qz arenite, fL, trough cross bedding, subangular to subrounded quartz grains, clay in matrix, biotite/coal (0.5%, light and dark green/grey laminae.

4113.15 As above, dewatering.

4114.15 As above, dewatering, ~0.5% red chert, planar cosets.

4114.75 -- Litharenite, cU, sharp contact at 15^, chert clasts, fine to coarse, lithic clasts (mudstone) subangular to subrounded, coal.

4115.00 -- Qz arenite, mL, light and dark grey laminae, cross bedded at 20^, some pink chert.

4115.65 -- Quartz arenite, mU, Contact is a reactivation surface-erosion-SUPRATIDAL?
Normally graded, grains of quartz and chert, up to 4mm, coal, green.

4116.65 -- Quartz arenite, mL, sharp contact, coarser chert fragments, subrounded quartz grains, calcareous matrix, green/grey, poor horizontal laminations.

4117.00 -- Siltstone, sharp contact, mainly quartz grains, coal fragments, maroon, patches of green/grey, fissile.

4118.15 As above, laminated with green sandstone, planar low angle cross beds ~15^.

4119.05 As above, not laminated.

4119.75 As above, laminated, some larger quartz grains.

4120.35 -- Limestone, sharp contact, micrite nodules present within shale. Shale has fusulinids, conodonts, criniod ossicles, brachiopods, is slickensided.

4124.75	--	Quartz arenite, fL, sharp upper contact, mottled, bioturbated, green, calcareous, subangular to subrounded quartz grains, well sorted, brecciated zone in center.
4124.95	--	Quartz arenite, fL to mL, oil-stained at top, very porous, slightly calcareous, well sorted, subangular to subrounded. Two graded cycles present. Cross-bedded 15^
4126.0	--	Quartz arenite, fL, porous bands, larger, up to 5mm, quartz and chert clasts, cross-bedded at base, isolated limestone and mud clasts.
4127.6	--	Quartz arenite, mU, interbedded with green shale. Poorly cemented, well sorted, many oil-stained grains. Scoured contact with underlying shale.
4127.9	--	Shale, medium grey, very fissile, carbonaceous seams.
4128.25	--	Shale, green fissile, interbedded with siltstone, friable, porous, with quartz and chert.
4128.55	--	Quartz arenite, fU, green, reverse graded, quartz w/ some chert, bioturbated, clay clasts, coal fragments.
4129.85		SECTION MISSING
4130.0	--	Quartz arenite, mL, green, bioturbated, quartz grains subangular to subrounded, frequently oil stained. Small amount of coal fragments. Patches of carbonate cement.
4130.45		Quartz arenite, mL, tan to green color (mottled). Some coal fragments, clay-rich matrix, calcite cement.
4131.15	--	Quartz arenite, vfU, abrupt contact, oil stained grains, coal fragments, slightly laminated, pale green shale partings, green.
4131.60		As above, contains limestone clasts-compacted bed? Flaser bedding below, and red cracked limestone nodules. Ripple laminated.

4132.15		As above, many limestone clasts, elongate, not all parallel. Disrupted by dewatering and bioturbation. Limestone clasts vary in size from microscopic to 3cm.
4133.15		As above, high organic content. Limestone layer.
4133.30	--	Quartz arenite, vfU, calcareous cement, small scale bedding, subrounded grains, limestone nodules present throughout. Base marked by green shale.
4133.85	--	Quartz arenite, fU to mU, calcareous patches and bands, some coal.
4134.55		As above, cycle of inverse grading, limestone and chert clasts at top.
4135.45		As above, cycle of inverse grading, indistinct horizontal lamination.
4135.85		As above, cross-bedded (15^), oil stained bands.
4137.25	--	Quartz arenite, fU to mL, high clay content, some angular chert clasts, content graded, grains sub-rounded, high sphericity, maroon.
4138.0	--	Shale, maroon, sharp contact, reduction spots.
4138.5	--	Quartz arenite, fL, clay rich, some chert clasts, inverse graded, mottled, green and maroon. Faint low-angle cross-lamination, some bioturbation.
4138.90		Limestone clasts surrounded by thin green shale, Sandy shale at base of cycle.
4139.15	--	Limestone, nodular, sharp upper contact, 10-95% limestone. Separated by fissile, calcareous, maroon, sandy, shale. Nodules are 3-50mm in diameter. Abrupt lower contact. Shale more abundant near the top.
4141.15	--	Limestone, conglomerate. Fossiliferous with

brachiopods, sponges, gastropods, solitary corals, and fish scales. Limestone generally white micrite. Separated by green fissile shale. Limestone fragments are aligned.

4141.75 -- Limestone, channelled(?) contact with above. Wackstone grades up to packstone. Micrite grains are the framework grains. Wackstone grains separated by green shale, less shale upwards. At top, pores filled with calcite. Poorly sorted. Some bivalve fragments. Grain size is about 5mm, varies from 2-20mm. Grains are rounded.

4142.25 -- Limestone, biomicrite, nodular, gradational contact. Clasts are separated with shale. Contains Productus and other brachiopods.

4143.95 -- Siltstone, sharp upper contact, brick red Massively bedded, graded, well rounded quartz at top, enclosed in a finer silt. Some fine-grained sandstone units present; one is present at base. This is ripple laminated. Isolated small green reduction spots present. Unit rapidly grades up to a purple shale at the top, followed by an abrupt change to limestone.

4146.90 -- Quartz arenite, vfU, gradational upper contact, well-rounded, spherical often oil-stained grains, clay matrix, faintly laminated. Brick red in color.

4149.95 -- Litharenite, mL to cL, sharp contact, inverse graded, no matrix, white with green seams and red bands. Cross-laminated.

4150.60 -- Shale, sharp contact, mottled maroon and pale green.

4150.85 -- Breccia, sharp upper contact. Quartz, chert and granite clasts, subrounded to subangular. Maroon mudstone matrix. Poorly sorted, massively bedded, Coal fragments? Matrix supported.

4152.05 -- Intraformational conglomerate. White quartz arenite separates irregular shaped clasts of

		mudstone. Gradational upper contact.
4152.20	--	Shale, mottled (mauve, green, maroon, red) with clasts of chert. Gradational upper contact.
4152.80	--	Chert layer with minor shale.
4153.05	--	Shale, mauve, broken with light gray shale infilling the cracks. Black organic-rich seams are present. Minor chert.
4153.85	--	BASE OF PENNSYLVANIAN Basal breccia present, at least six inches thick.

APPENDIX 2

Thin-section descriptions

Key to abbreviations used:-

mqx - monocrystalline quartz
pqz - polycrystalline quartz
Kfs - K- feldspar
px - polycrystalline
mx - monocrystalline
subang. - subangular
subro. - subrounded
ro. - rounded
ang - angular
w.ro. - well-rounded
ppl - plane polarized light
xpl - cross polarized light

<u>Pfaff #2 - 4197.3 feet</u>

Brown mottled mudstone. Contains many small mx qz and occasional chalcedony, grains. Grains have corroded margins.
<u>Texture</u> - Bimodal 0.1- 0.3 mm
0.02 mm
Subro. to subang. grains
clays aligned parallel to bedding.

<u>Pfaff #2 - 4200.5 feet</u>

Quartz arenite with muddy matrix wwich is present in patches and layers.
Grain size - vfU to fL
Sorting - good
Rounding - subro.
Extensive qz overgrowths

Modal analysis (%)

overgrowth	5.5
pore	6.2
clay cement	0.2
oil	0.2
monocrystaline quartz	56.4
chert	13.4
mud matrix	18.1

feldspar, muscovite, zircon present

<u>Pfaff #2 - 4201.9 feet</u>

Fine green quartz arenite with broken, finer, darker laminations. Darker bands are quartz-rich, clay-rich silstone. Variable amount of clay-rich matrix. Much pressure solution has occured.
Post quartz overgrowth clay cement present.
Sorting - good.
Rounding - high
Porosity varies corresponding to clay content. Clay coatings to grains isolated many pores.

Modal analysis (%)

monocrystaline quartz	41.8
siltstone clasts	43.2
mud matrix	1.5
pore	11.3
chert	1.8
polycrystaline quartz	0.2
feldspar	0.2

<u>Pfaff #2 - 4204.0 feet V</u>

Reseroir sandstone.
Sorting - good
Grain size mL
Rounding - subang. to ro.
Abundant overgrowths
Homogenous texture

Modal analysis (%)

overgrowth	8.8
polycrystaline quartz	2.1
chert	3.2
monocrystaline quartz	64.8
oil	15.5
pore	5.6
monocline present in small corroded grains	<0.2

Pfaff #2 - 4204.5 feet

Reservoir sandstone.
Well-sorted.
Rounding: w.ro. to subang. affected by disulution compaction and overgorwths.
Cement - mainly by overgrowths. Patches of poikilotopic calcite cement.
Patchy distribution of oil.
no clay.
Grain-size - fL average.

Modal analysis (%)

overgrowth	3.6
chert	3.6
polycrystaline quartz	1.1
calcite	0.2
monocrystaline quartz	66.6
oil	17.1
pore	7.8

Pfaff #2 - 4205.2 feet V

Reservoir sandstone
Bands present 10mm apart, 2-3mm thick which contain less oil than surrounding unit, less open pores.
Mudstone cement present in places.
Much pressure solution.
Grain size - finer bands - 0.14mm average (0.1 - 0.18mm)
coarser bands - 0.2mm average. (0.18 - 0.5mm)

Rounding - high
Sorting - good

Modal analysis (%)

overgrowth	4.3
polycrystaline quartz	0.8
chert	5.3
cement	1.5
mud	0.4
monocrystaline quartz	71.2
oil	14.5
clay	2.0

Pfaff #2 - 4206.0 feet H

Reservoir sandstone.
Moderate sorting. Angular grains. Abundant overgowths. Well-sorted. Average grain size - 0.2mm (range 0.07 - 0.4mm). No open porosity. Pores not filled with oil are filled with clay matrix. Rare mudstone clasts. Many elongate pores because of compaction, dissolution and formation of overgrowths.

Modal analysis (%)

polycrystaline quartz	3.4
overgrowth	14.4
oil	8.1
pore	0.2
chert	2.6
muscovite	0.2
clay	4.1
quartz	67.0

Pfaff #2 -4206.0 feet V

Modal analysis (%)

polycrystaline quartz	4.0

feldspar	).1
pore	.7
oil	9.9
overgrowth	5.0
cement	2.8
quartz	70.6
clay	3.5
mud	2.1
chert	1.4

Pfaff #2 - 4207.0 feet

Reservoir sandstone.
Very well-sorted, some w.ro. grains. Good overgrowths. No matrix. Isolated patches of poikilotopic anhydrite cement. Grain size - mL. Porosity varies.

Modal analysis (%)

monocrystaline quartz	75.9
oil	4.9
pore	4.4
chert	.5
overgrowth	7.6
K feldspar	0.2
polycrystaline quartz	1.3
anhydrite poikilotropic cement	0.2

Pfaff #2 - 4211.9 feet

Clay-rich sandstone. Green (chlorite) and red (haematite). Poorly sorted. Much compaction pressure solution, and overgrowths. Average grain size - fU (ranges vfL to vcU).

Modal analysis (%)

polycrystaline quartz	2.9
overgrowth	1.0

feldspar	0.4
clay/mud matrix	36.3
monocrystaline quartz	56.5
chert	2.7
muscovite	0.2

Pfaff #2 - 4217.9 feet

Quartz arenite. No oil. Porous, many pores are interconnected. Many quartz overgrowths. Isolated patches of Poikilotopic calcite cement.

Modal analysis (%)

monocrystaline quartz	69.1
pore	15.3
overgrowth	9.5
polycrystaline quartz	1.6
K feldspar	2.6
calcite cement	1.4
chert	0.5

Pfaff #2 - 4219.9 feet

Poorly sorted quartz arenite. Clay-rich. Grain shape varies greatly. Common larger chert grains, some of which have replaced calcite. Microporosity in chert. Many of the chert grains are spicular. Much pressure solution, also some grains are fractures from compaction.

Modal analysis (%)

monocrystaline quartz	42.2
pores	19.5
polycrystaline quartz	6.1
chert	23.8
K feldspar	2.8
overgrowth	2.1
granite	3.1
biotite	0.2

Pfaff #2 - 4224.0 feet V

Clean cream-colored sandstone. Average grain size 0.25mm (ranges 0.1 - 0.25 mm). No clay-filled pores. No oil. Much compaction, pressure solution etc.
Larger grains present. Overall well-sorted.

Modal analysis (%)

polycrystaline quartz	0.2
overgrowth	4.1
chert	0.9
feldspar	0.2
monocrystaline quartz	82.8
pore	11.8
poikilotopic calcite present	

Pfaff #2 -4226.0 feet V

Poorly sorted quartz arenite. Grain size ranges 0.1mm (vfU) to 2.0mm (vcU). Some larger gravel-size grains present. Bed is graded. Well-sorted bands present.
Cement type is Poikilotopic calcite cement. Original texture modified greatly by compaction etc. All large grains are pqz.

Modal analysis (%)

pore	0.4
chert	3.5
polycrystaline quartz	11.5
K feldspar	1.9
overgrowth	0.2
plagioclase	0.2
monocrystaline	55.0
calcite	27.3

Pfaff #2 - 4230.5 feet

Limestone. Fossiliferous micrite. Grecciated because of subaerial weathering. Patchy meomorphism to coarser clacite crystals has occured throughout.

Fossils present: Echinoid plates, recrystallized aragonite shells, brahiopod shells and spines.

One generation of isopachous calcite cement present locally. Succeeded by more widespread generation of pore-filling calcite.

(?) Fenestrae may be present.

Thin seams of post-deposition green clay pass through the rock.

Pfaff #2 -4248.0 feet

Oil-stained quartz arenite. Average grain size 0.14mm (ranges 0.07 - 10mm). Poorly sorted. Patches of Poikilotopic calcite cement present. Compaction etc. have greatly altered the original texture of the unit. Poikiliotopic anhydrite cement is present locally.

Modal analysis (%)

polycrystaline quartz	6.7
chert	6.1
feldspar	1.7
overgrowth	1.2
pore	1.7
monocrystaline quartz	62.9
poikilotopic anhydrate	17.4
clay	2.3
calcite cement present	

Pfaff #2 - 4249.0 feet V

Fine grained (fL) sandstone. Moderately sorted. Little porosity, little oil. Highly compacted, etc. Red/brown mud layers are present. Contains small patches of Poikilotopic calcite cement.

Modal analysis (%)

pore	1.8
chert	0.9
calcite	0.2
quartz	80.0
K feldspar	14.9
clay	2.2
plagioclase and muscovite present	

Pfaff #2 -4251.2 feet

Inhomogenous sandstone. Horizontal to subhorizontal brown shale layerrs are present throughout the sandstone. The shale contains isolated (vfL) quartz grains.

Sandstone is bimodal - Most grains are very fine grained. About 5% of the grains are larger 0.4 - 5mm. These are composed of quartz. Highly compacted.

Modal analysis (%)

overgrowth	6.5
pore	2.5
chert	1.6
silicone cement	0.7
K feldspar	2.2
polycrystaline quartz	6.1
calcite	2.0
mud	0.7
plagioclase	0.2
monocrystaline quartz	64.8
clay	12.6

Pfaff #2 - 4252.1 feet

Graywacke. Very fine grained and well-sorted. Grain sahpe and rock texture greatly affected by pressure solution, dissolution etc.

Matrix rich in clay, and chert. Both are pervasive throughout. Patches of Poikilotopic calcite cement present locally. No open porosity.

Modal analysis (%)

monocrystaline quartz	47.3
siliceous matrix	22.2
clay	15.3
chert	2.5
calcite cement	2.7
K feldspar	4.6
polycrystaline quartz	5.0
biotite	0.2
opaque minerals	0.2

<u>Thompson A-#2 - 4113.4 feet</u>

Graywacke. Quartz grains are enclosed in a quartz-rich mudstone. Well-sorted. Matrix is distributed unevenly. Grains are w.ro. to subro. Much pressure solution etc. has modified grain shape. Matrix may be formed partly from the alteration of feldspar.

Modal analysis (%)

monocrystaline quartz	58.2
pore	2.7
siliceous muds	26.2
overgrowth	6.6
K feldspar	3.1
polycrystaline quartz	1.6
quartz cement	1.4
chert	0.2

<u>Thompson A-#2 4116.2 feet</u>

Arkose. Microcline has broken down to clay. Dolomite has altered to chert (rhombs are visible in the chert). Calcareous algae originally present in the unit has now been silicified.

Poorly sorted unit vfL to vcU. Slightly bimodal fU and cL. Pressure solution etc. has modified origial grain shape and texture of rock.

Modal analysis (%)

monocrystaline quartz	28.8
polycrystaline quartz	12.5
K feldspar	10.5
granite	11.9
overgrowth	1.8
pore	1.3
clay	0.2
chert	3.6
muscovite	0.2
silicified algae	0.2
poikiliotopic calcite	0.2
siliceous mud	28.8

<u>Thompson A-#2 4118.0 feet</u>

Subarkose. Well-sorted. fL. Much pressure solution. Hematite-rich matrix which contains very fine quartz grains which probably were derived from pressure solution.

Modal analysis (%)

monocrystaline quartz	36.0
clay	36.6
hematite	15.5
overgrowth	2.4
polycrystaline quartz	0.6
K feldspar	6.7
quartz cement	0.4
chert	0.7
microcrystaline quartz cement	0.4
pore	0.6

<u>Thompson A-#2 4125.0 feet V</u>

Quartz arenite. Well-sorted, fU (range vfU to cL). Cemented mainly by quartz overgrowths. Isolated patches of Poikilotopic calcite cement the rock. Much compaction, pressure solution etc. Isolated patches of oil fill the pores.

Modal analysis (%)

monocrystaline quartz	68.3
oil	1.0
pore	13.0
overgrowth	7.6
chert	1.2
K feldspar	3.0
polycrystaline quartz	3.0
poikiliotopic calcite cement	3.0

Thompson A-#2 4125.6 feet V

Reservoir sandstone. Similar texture to 4125.0 feet. In addition there are patches of poikilotopic anhydrite cement which are associated with the calcite.

Modal analysis (%)

Monocrystaline quartz	62.7
pore	9.9
overgrowth	11.3
poikiliotopic calcite cement	5.8
chert	1.0
polycrystaline quartz	4.0
K feldspar	2.8
clay matrix	0.8
oil	0.8
poikiliotopic anhydrite cement	0.6
plagioclase	0.2

Thompson A-#2 4126 feet

Subarkose. Lower part of reservoir zone. Grain size varies patchily throughout the rock because of bioturbation. Poorly sorted (fL to cL). Most of the rock is cemented by quartz overgrowths. Small patches of mud matrix are present within the rock. Silicified shell fragment is present. Poikilotopic calcite cement has partly silicified locally.

Modal analysis (%)

monocrystaline quartz	56.4
pore	15.8
polycrystaline quartz	14.0
K feldspar	6.7
poikiliotopic calcite cement	1.8
clay matrix	1.6
overgrowth	2.3
chert	1.1
granite	0.3

Thompson A-#2 4129 feet

Quartz arenite. Moderately sorted, bimodal (fL and mU). Rock is mainly cemented by overgrowths. Isolated patches of Poikilotopic calcite cement are present. Locally a calcareous mud matrix is present. Compaction etc. has occured. Porosity 18.8%, open network, pores are mostly unfilled and unlined by clay.

Modal analysis (%)

monocrystaline quartz	70.2
pore	18.8
chert	1.1
polycrystaline quartz	1.8
overgrowth	4.5
K feldspar	1.6
poikiliotopic calcite cement	0.7
mud matrix	0.9
granite	0.4

Thompson A-#2 4130.2 feet

Quartz arenite. Moderately sorted. Grain size averages fU (ranges vfU to vcL). A samll patch of poikilotopic anhydrite cement is present.

Thompson A-#2 4133 feet

Quartz arenite. Abundant patches of Poikilotopic calcite cement. Recrystallized, originally aragonite, shell fragments are present. Some cementation by quartz overgrowths. Rock is compacted etc.

Modal analysis (%)

monocrystaline quartz	64.1
calcite	26.4
polycrystaline quartz	5.3
chert	0.4
overgrowth	3.1
pore	0.4
K feldspar	0.2

Thompson A-#2 4142.0 feet

Limestone. Consists of rounded micrite clasts separated by coarse pore-filling calcite cement. Clast size is as large as 20mm. Some shell fragments are present, these were originally composed of aragonite. Fractures are present within the nodules which have been filled with coarse calcite cement. The probably are shrinkage cracks. Some neomorphism of the micrite has occured. Occasionalquartz grains are present.

Fossils include crinoid ossicles, algae, and mollusc shells.

Two phases of cementation:-

1) Local isopachous calcite.
2) Pore-filling calcite.

Thompson A-#2 4150.0 feet

Quartz arenite. Poorly sorted (vfL to vcU) average grain size is mU. Much pressure solution, etc. Patches of Poikilotopic calcite cement are present. Clay-rich matrix fills all pores which are not filled by calcite. Some anhydrite is present within the matrix.

Modal analysis (%)

monocrystaline quartz	56.7
poikiliotopic calcite cement	10.9
polycrystaline quartz	5.2
anhydrite cement	3.9
chert	5.0
clay matrix	15.6
overgrowth	2.7

Pfaff #3 - 4207.2 feet

Limestone. Three textures present are separated by horizontal boundaries.

1) Fossiliferous micrite at base
2) Caliche crust in center. Coarsely laminated texture. Contains horizontally elongated pores.
3) Calcarenite. Contain micrite clasts and shells are separated by a sparry calcite cement.

Stylolites are present within the unit.

Pfaff #3 4211.3 feet

Fossiliferous micrite. Contains interparticle porosity, and moldic porosity. Fossils include, brachiopods, and echinoid plates.

The limestone clasts are separated by green shale. Some nodules are separated by pore-filling calcite.

Pfaff #3 - 4216.5 feet

Quartz arenite. Grain size fU (70%), mL to vcL (30%). patches of Poikilotopic calcite cement present. Pressure solution etc. has modified the texture. Unfilled pores may be lined or unlined with isopachous calcite.

Modal analysis (%)

monocrystaline quartz	72.0
calcite cement	8.6
pore	10.1
K feldspar	2.0
sheared quartz grain	0.2
polycrystaline quartz	2.0
overgrowth	3.3
quartz cement	1.1
mud	0.2
chert	0.4

Pfaff #3 - 4220.2 feet

Quartz arenite. Moderately sorted. Average grain size is mL, larger isolated grains are present. Patches of Poikilotopic calcite cement are present. Compaction, dissolution, etc. has modified original texture.

Modal analysis (%)

monocrystaline quartz	66.0
calcite	3.8
pore	8.1
quartz cement	3.8
K feldspar	2.1
polycrystaline quartz	10.0
overgrowth	5.0
chert	1.0
clay	0.2

Pfaff #3 - 4221.9 feet

Cream-colored sandstone. Layered with thin bands containing different grain sizes. Average grain size is fU (90%), range is vfL to gravel (5mm). The larger grains present include quartz, chert, kfs, and chalcedony. Patches of Poikilotopic calcite cement are present.

Modal analysis (%)

monocrystaline quartz	62.0
oil	5.2
pore	12.2
calcite cement	6.6
overgrowth	2.4
K feldspar	2.2
quartz cement	1.4
chert	4.0
polycrystaline quartz	4.0

Pfaff #3 - 4233.8 feet

Quartz arenite. Well-rounded grains.
Cementation: i) Poikilotopic anhydrite cement.
ii) Poikilotopic calcite cement
iii) Quartz overgrowths.

The calcite and anhydrite cements are post-overgrowth. Grain size: fU to mL, larger (up to 3mm) grains also are present. Grains are well-rounded overall.
Small amounts of mud are present as the matrix of unfilled pores.

Modal analysis (%)

monocrystaline quartz	66.4
clay matrix	15.6
anhydrite cement	9.1
calcite cement	0.9
overgrowth	3.0
polycrystaline quartz	3.7
zircon	0.2
quartz cement	0.4
pore	0.2
chert	0.2
K feldspar	0.2

Pfaff #3 - 4235.0 feet

Reservoir sandstone. Moderately sorted. Average grain size is fU, ranges from fL to vcU. Cementation mainly by quartz overgrowths. Also present are patches of Poikilotopic calcite cement. A band with a muddy matrix is present. Compaction, dissolution, etc. has modified original texture.

Modal analysis (%)

monocrystaline quartz	77.7
overgrowth	6.3
microcrystaline quartz cement	1.1
pore	4.8
K feldspar	1.1
polycrystaline quartz	3.5
quartz cement	2.2
poikiliotopic calcite cement	0.9
mudstone matrix	0.9
oil	1.1
chert	0.4

Pfaff #3 - 4237.2 feet

Texture is similar to 4235.0 feet. More Poikilotopic calcite cement is present, and infills most pores.

Modal analysis (%)

monocrystaline quartz	60.2
poikiliotopic calcite cement	17.9
chert	1.5
quartz cement	1.0
polycrystaline quartz	9.0
overgrowth	3.1
microcrystaline quartz cement	2.7
clay	0.6
K feldspar	4.0

APPENDIX 3

Table of values obtained from the pores studies of Pfaff #2

N.C.R.A Pfaff #2

4204.0 feet

POROSITY TYPE:- Secondary interparticle, good interconnectivity, enlarged elongate pores.

POROSITY DISTRIBUTION:- The porosity throughout the rock is relatively homogeneous. The porosity is present in a discontinuous network. Barriers to porosity are quartz overgrowths, and thin clay coatings which surround many grains.

	VERTICAL	HORIZONTAL
Coordination number		
0	28.4%	35.2%
1	44.8%	40.1%
2	21.6%	16.0%
3	5.2%	7.4%
4	---	1.2%
AVERAGE	1.03	0.99
Total porosity	20.1%	19.0%
Pore to throat ratio	3.9	4.9

4204.5 feet

POROSITY TYPE:- Interparticle, secondary. In some chert grains there is intraparticle microporosity. Some enlarged pores.

POROSITY DISTRIBUTION:- Irregular distribution of oil in pores. Not clear why oil remains in some pores and not in others. Oil fills 69% of the pores. Pores vary greatly in shape. Much oil is found in pores with very jagged outlines due to corrosion. Most oil is found in the smaller pores. The patches with more oil are generally tighter. The porosity is the same as the rest of the rock, but the pore to throat ratios are smaller.

Coordination number:- (percentages of the porosity).

0	----
1	7.7%
2	28.0%
3	55.2%
4	7.7%
5	0.7%
6	0.7%

Average C.N. is 2.7

Pore to throat ratio = 4.4
Porosity = 24.9%

4205.2 feet

POROSITY TYPE:- Secondary, interparticle. Pores are enlarged with honeycombed margins due to corroded grains, also many are elongate.

POROSITY DISTRIBUTION:- The pores are well coordinated, and well connected. Greatly affected by quartz overgrowths. Quartz overgrowths have greatly reduced the porosity. Thin layers (~4mm) and isolated lenses of tight rock are present. This is due to larger quartz overgrowths. Within the layers isolated oil-free pores are present. These layers are inclined at about 25

	VERTICAL	HORIZONTAL
Coordination number (C.N.)		
Numbers expressed as a percentage of the porosity.		
0	17.3	20.2
1	16.7	38.1
2	41.0	31.5
3	23.7	10.1
4	1.3	----
5	----	----
	Average C.N. is 2.26.	Average C.N. is 1.32
Pore to throat ratio (Average)	4.6	3.5
Total porosity	14.5%	

4206.0 feet

	VERTICAL	HORIZONTAL
Average C.N.	0.38	1.2
Ave. pore to throat ratio	4.025	6.0
Total porosity	10.6%	

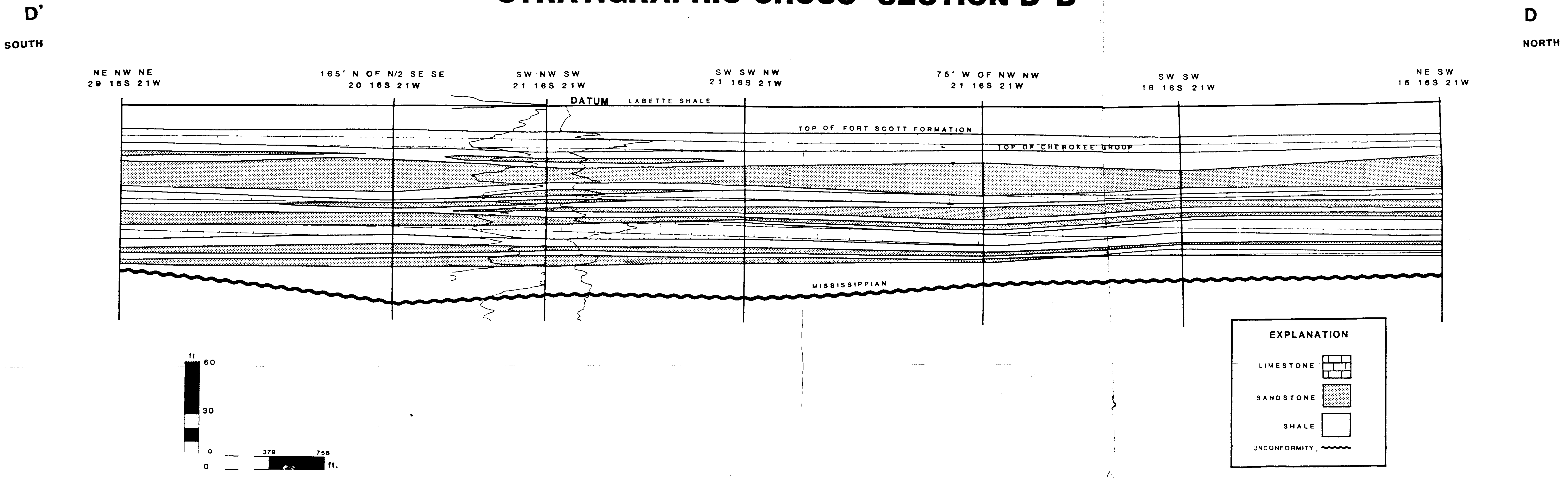
STRATIGRAPHIC CROSS SECTION A-A′

STRATIGRAPHIC DIAGRAM B–B′

Figure 14

STRATIGRAPHIC CROSS SECTION C–C'

STRATIGRAPHIC CROSS SECTION D–D′



STRATIGRAPHIC CROSS SECTION E-E′

STRATIGRAPHIC CROSS SECTION N–N′

STRATIGRAPHIC CROSS SECTION S-S'

Kansas Geological Survey
Open-file Report 90-52

STRATIGRAPHIC CROSS SECTION W-W'