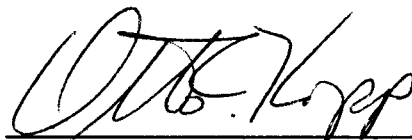


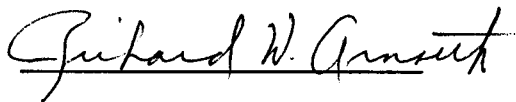
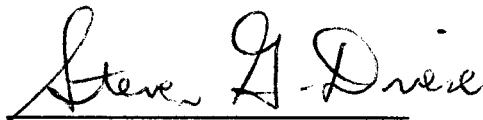
To the Graduate Council:

I am submitting herewith a thesis written by Joseph Calvin Faulkerson entitled Depositional History of the Porters Creek Clay of the Upper Mississippi Embayment Using Chemical, Stratigraphic and Trace-Fossil Data. I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.



Otto C. Kopp, Major Professor

We have read this thesis
and recommend its acceptance:



Accepted for the Council:



Vice Provost
and Dean of The Graduate School

DEPOSITIONAL HISTORY OF THE PORTERS CREEK CLAY
OF THE UPPER MISSISSIPPI EMBAYMENT
USING CHEMICAL, STRATIGRAPHIC AND TRACE-FOSSIL DATA

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Joseph Calvin Faulkerson
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ABSTRACT

The depositional history of the Porters Creek Clay (Paleocene) was determined using stratigraphic, trace-fossil, mineralogic, and chemical data. This approach made it possible to examine the relationship between the chemical and stratigraphic data and to determine whether it is possible to use a chemical-stratigraphic approach to the analysis of shale basins.

Samples were collected from three active clay pits located at Bloomfield, Missouri; Olmsted, Illinois; and Paris, Tennessee. All three locations are part of the Upper Mississippi Embayment. Samples were collected at about 1.5 meter intervals. Chemical data were obtained from X-ray fluorescence (XRF) analysis. Data were reported as percent oxides of sodium, magnesium, aluminum, silicon, phosphorus, potassium, calcium, titanium, manganese, and iron. Elements reported include sulfur, chromium, barium, rubidium, strontium and zirconium. The concentrations of the various chemical species were plotted versus depth in the pits and compared to the measured sections from each pit.

Trace-fossil data were used to gain some insight into the oxygenation conditions at the time of deposition that would effect the kinds of authigenic minerals that might occur. The mineral species present were constrained by petrographic and X-ray diffraction techniques. The dominant minerals

include quartz, siderite, goethite, chalcedony, glauconite, muscovite, kaolinite, illite, feldspar, pyrite, gypsum, and smectite.

The data indicate that the Bloomfield, Missouri and the Olmsted, Illinois deposits were deposited in similar environments. This is most evident in the plots of S, P_2O_5 , SiO_2 , and Al_2O_3 . At Bloomfield and Olmsted these chemical species behave in a similar fashion. In the plots of chemical variables versus depth, S and P_2O_5 tend to define a distinctive sedimentary package in the lower part of each pit and are considered to be related to the observed organics and pyrite that are prominent in the lower portion of the Bloomfield and Olmsted pits. Fe_2O_3 does not correlate well with sulfur due to the influence of detrital iron minerals throughout the section. High CaO concentrations (over 7 percent) at the base of the Bloomfield section correlate with the occurrence of the only foraminifera in the section. SiO_2 and Al_2O_3 are important constituents in the upper portion of the Bloomfield and Olmsted pits. An inverse relationship exist between the concentrations of SiO_2 and Al_2O_3 . SiO_2 dilutes Al_2O_3 as a result of higher silt concentrations in the upper part of both sections.

The occurrence of pyrite, glauconite and siderite are compared to the environmental criteria described by Berner (1981) and Maynard (1982), and indicate that the depositional environment of the Porters Creek Clay ranged from anoxic-

sulfidic to non-sulfidic post oxic.

Previous workers have interpreted that the deposition of the Porters Creek Clay as representing part of a transgressive-regressive sequence. The data from this research are in agreement with these conclusions. It was possible to define a transgressive and regressive facies in the Porters Creek based on the chemical-stratigraphic data, but it is important to note that the chemical data are sensitive to late events such as the intrusion of clastic dike seen at the Paris location. The inverse relationship between SiO_2 and Al_2O_3 seen at Bloomfield and Olmsted was also observed in the Paris data, but the relationships of other chemical species at Paris to the stratigraphy were not always clear. The differences between Bloomfield, Olmsted and Paris are thought to be due in part to the Paris clastic dike event and to the relative positions of the sections within the depositional basin. Whereas Bloomfield and Olmsted are very near the axis of the basin, Paris is located well off the axis of the basin. Principal Component Analysis (PCA) of the chemical data also indicated a fundamental difference at the Paris location.

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CHAPTER 1

INTRODUCTION

It is important to be able to determine the depositional history of ancient sediments, and how the physical, chemical and biological conditions of deposition are related to each other. Rocks such as limestone and sandstone contain readily visible physical features which make it possible to describe some of the important events of their depositional history, but it is commonly difficult or impossible to see comparable macroscopic features in shale. The term "shale" will be used throughout the text to include shale, mudstone and other argillaceous sedimentary rocks.

Most of the interest in shale has been in its geochemistry and mineralogy (Cody, 1971; Degens, 1957; Shaw, 1965; Sheppard, 1973 to list a few), in addition to microfauna studies of Tertiary and Mesozoic shale (Izett et al., 1971). Although shale has not been studied in as great detail as limestone and sandstone with which they are typically interbedded, they do represent an important part of the history of any sedimentary package. The main reason for the lack of interest in shale is because it is fine grained and lacks the well-defined sedimentary structures like those found in other sedimentary rocks (Potter, Maynard and Pryor, 1980).

Purpose

The major purpose of this study was to determine the depositional history of the Porters Creek Clay (Paleocene) using stratigraphic, chemical, mineralogic, and trace-fossil data. After preliminary investigation in the field, including the description of the exposed stratigraphic sequence an attempt was made to evaluate possible relationships between various facies which were identified by their geochemical signatures as well as their lithologic similarities. The results are compared to the interpretations made by other authors, in order to test the practicality of a combined chemical stratigraphic approach to basin analysis.

Trace-fossils were used as one type of data because of their response to the oxygenation conditions at the time of sediment deposition. Trace-fossil information gives some indication of the degree of oxygenation that existed at the time of deposition and this may aid in an understanding of early-formed authigenic minerals (Rhoads and Morse, 1971; Byers, 1974, 1977).

To achieve the above stated purpose, a combined approach, based on the work of Berner (1981) and Maynard (1982), as well as that of Pye and Krinsley (1986) was used. This approach may be useful in situations where shale sections appear nearly homogeneous and there is a need to subdivide the section to reflect its depositional and diagenetic history.

The Porters Creek Clay (Paleocene) was chosen for this study because it has a range of depositional environments from outer neritic to inner neritic (Pryor and Glass, 1961). This change of environments may be reflected in the trace-fossils and chemical signatures.

Previous Work

Authigenic Minerals and the Environment

Previous workers have attempted to interpret the diagenetic and depositional history of shale sections based on the authigenic minerals, but it is commonly unclear when a particular mineral formed (i.e., were the observed minerals early or late diagenetic products?). For example, Perry and Hower (1970) studied shale units ranging in age from Pleistocene to Eocene of the Gulf Coast region of North America. They concluded that there was an increase in the amount of illite with depth and that the reaction responsible was influenced to a greater degree by increased temperature than by increased pressure or age of the sediments. They also noted that there was no systematic change in the bulk chemistry of the sediments, except for that which was associated with the smectite-to-illite transformation and with the dissolution of carbonate. It should be noted that their samples were derived from well cuttings; hence, some degree of mixing might be expected. Or it is possible that, because

they were looking at fairly late diagenetic changes, bulk chemical values may reflect late diagenetic equilibration of chemical species.

Perry (1975) studied the formation of authigenic smectite by the alteration and weathering of submarine volcanic rocks and found that this transformation could be a major magnesium "sink" for sea water. Burst (1969) noted that there was a decrease in the amount of swelling clay with depth in Gulf Coast shale sections; however, Burst was primarily concerned with the behavior of clay minerals as they were being compacted therefore, he did not address any of the bulk chemistry implications.

The role of iron in the smectite-to-illite conversion was examined by Eslinger, et al. (1979) in the bentonites of the Disturbed Belt of Montana. They noted an increase in iron with increasing percentages of illite layers, which they attributed to a reduction reaction that involved organic matter in the sediment. Although they collected some bulk chemical data they did not address stratigraphic variations in these data.

Kobayashi and Kazama (1975) described five basic facies in argillaceous rocks, which they termed Type (I-V). Type (I) is subdivided into sub-types: (Ia) montmorillonite-illite-chlorite facies; (Ia1) montmorillonite-illite-scarce chlorite facies; (Ib) montmorillonite-illite-scarce chlorite-kaolinite

kaolinite facies; type (II) is subdivided into (IIa) hydrous illite-mixed-layer, and (IIb) hydrous illite-mixed-layer-kaolinite facies; type (III) is composed of illite-chlorite facies; type (IV) is made up of sericite and chlorite; and type (V) is termed the montmorillonite facies. Kobayashi and Kazama also noted that these facies represent various types of environments that were influenced by the sediment source area or its depositional environment. Type (I) corresponds to rocks of late syn-diagenetic stage and was influenced by the source area and the depositional environment. Rock types include normal marine sediments, marine pyroclastic detritus, and brackish water sediments. Type (II) rocks are type (I) sediments that have been transformed by diagenesis. Type (III) makes up the most stable of the facies and is due to late diagenetic alteration. Type (IV) rocks are the result of hydrothermal alteration and Type (V) is the result of early weathering.

Weaver (1958) noted that the major clay minerals could be found in abundance in any major depositional environment and there was no relationship between specific clay minerals and their environment. Carroll (1958) described iron associated with clay minerals as being either an essential component, a minor crystal lattice component, or a surface coating. Carroll also noted that changes in the depositional environment could cause the removal of iron by reduction of

Fe^{3+} to Fe^{2+} . Other works dealing with clay diagenesis include: Chang et al., 1986; Wen Yeh and Eslinger, 1986; Burtner and Warner, 1986; Colten, 1986; Moore and Hower, 1986; Srodon et al., 1986; Aronson and Douthitt, 1986; Nadeau and Bain, 1986; Brusewitz, 1986; Veld, Suzuki and Nicot, 1986; Anjos, 1986; Sheppard and Gude, 1973; Izett et al., 1971; Griffin, 1962; Shaw and Weaver, 1965; Cody, 1971; Russell, 1970; Degens et al., 1957.

Berner, et al. (1979) noted that there was a correlation between the pyrite-to-FeS ratio in modern anoxic sediments and sea water salinities. High values of the FeS_2 -to-FeS ratio (10) are indicative of marine sediments, whereas lower values are associated with brackish estuarine or fresh-water lake sediments.

Raiswell, et al. (1987) devised a technique that used the ratio of pyritic Fe to pyritic Fe plus acid-soluble Fe as an indicator of bottom-water oxygenation. This ratio was referred to as the Degree of Pyritization (DOP). High DOP values between 0.55 and 0.93 indicate conditions that are inhospitable to life. Degree of Pyritization values < 0.42 are indicative of aerobic bottom conditions.

Berner and Westrich (1985) considered that bioturbation added extra organic matter below the sediment-water interface and the amount of pyrite formed during burial accounts for only a fraction of the H_2S produced by bacterial sulfate

reduction. The excess H_2S is removed by the oxidation.

Pye and Krinsley (1986) suggested that it may be possible to identify various sedimentary facies in shale deposits based on chemical, petrologic, and microfabric data collected using backscatter electron microscopy. They compared chemical, petrologic, and microfabric data of the Whitby Mudstone in northeast England to previously described facies of the Whitby, which were based on trace fossil assemblages. They noted that the change in the diagenetic environment is reflected by a change in the abundance of various authigenic species and not by the existence of any particular authigenic mineral or minerals. Pye and Krinsley concluded that there was a relationship between the two types of data because of the oxygenation conditions implied by trace-fossil assemblages, and that these conditions would effect the types of authigenic minerals formed. This possible association was based on the work of Berner (1981), who concluded that early diagenetic mineral assemblages could give considerable insight into the geochemical conditions at the time of sediment deposition.

Previous workers attempted to use Eh and pH to describe geochemical environments, but Berner (1981) considered Eh to be difficult to quantify and pH to be relatively constant (6-8) throughout most natural systems. Maynard (1982) extended Berners idea to ancient deposits. The work of Berner (1981)

and Maynard (1982) makes use of hydrogen sulfide and oxygen concentrations to define environmental conditions. Figure 1 summarizes the diagenetic environments they described.

Berner (1981) described two basic chemical environments, which he termed oxic and anoxic, depending on the occurrence or absence of measurable oxygen. Oxic conditions are indicated by minerals such as hematite, goethite, and various manganese oxide minerals. Berner's anoxic environment is subdivided into sulfidic and non-sulfidic, which was further divided into post-oxic and methanic, based on the presence or absence of hydrogen sulfide. Typical anoxic sulfidic phases include pyrite and marcasite. Minerals found in the anoxic (post-oxic) environment include glauconite, iron silicates, siderite, and vivianite, but no sulfide minerals. Minerals of the anoxic, methanic environment include siderite, vivianite, and early-formed sulfides. Rhodochrosite was considered to be stable in all three environments.

The occurrence of organic matter is important to the above environments because the reduction of sulfate to hydrogen sulfide accompanies the decomposition of organic matter in sediments after oxygen depletion. Oxic and post-oxic environments contain minor organic matter, while sulfidic and methanic environments do contain organic material (Berner, 1981).

ENVIRONMENT	CHARACTERISTIC PHASES
I. Oxic (Conc. $O_2 \geq 10^{-6}$)	hematite, goethite, MnO_2 -type minerals no organic matter
II. Anoxic (Conc. $O_2 < 10^{-6}$)	
A. Sulfidic (Conc. $H_2S \geq 10^{-6}$)	pyrite, marcasite, rhodochrosite, alabandite; organic matter
B. Nonsulfidic (Conc. $H_2S < 10^{-6}$)	
1. Post-oxic	glauconite and other $Fe^{+2}-Fe^{+3}$ silicates (also siderite, vivianite, rhodochrosite); no sulfide minerals; minor organic matter
2. Methanic	siderite, vivianite, rhodochrosite earlier formed sulfide minerals; organic matter

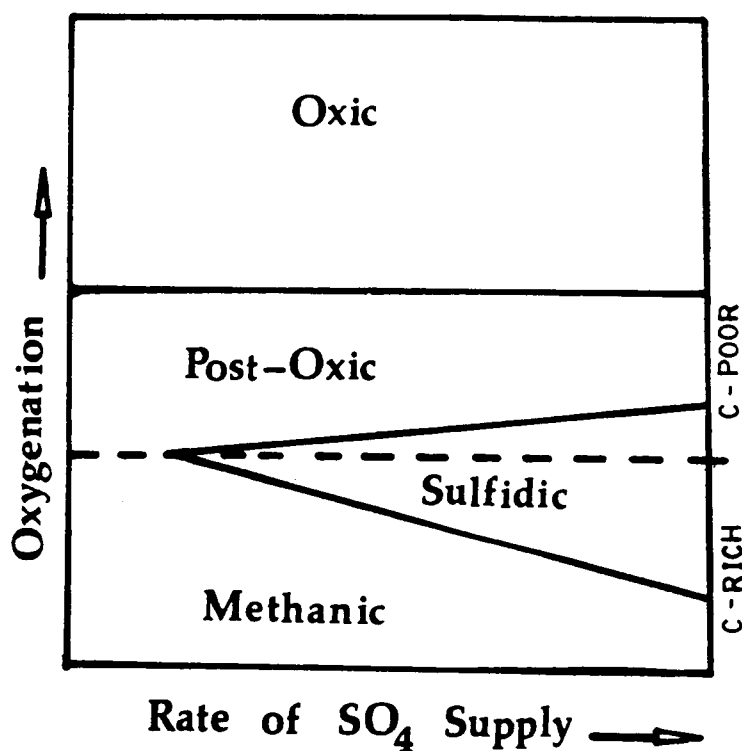


Figure 1. Classification of diagenetic environments as described by Berner (1981) and later modified by Maynard (1982). Concentration (Conc.) is in moles per liter.

Trace Fossils and the Environment

Trace fossils have long been thought to give some indication as to the nature of the depositional environment in which they were formed, but the precise relationship is often unclear. Trace fossils may be useful for environmental interpretations because the trace-making animals responded to environmental conditions and those responses are evident in the actual trace; however, any single trace type may be produced by different animals exhibiting different or similar types of behavior and a single type of trace-making animal may have had different behaviors that produce different trace types. Therefore, caution should be exercised in the use of trace-fossil data (Ekdale, et al., 1984).

Seilacher (1967) considered that trace fossils could be used as bathymetric indicators, because their distribution was controlled by the depth-related distribution of their food supply. He also proposed a sedimentological classification of trace fossils based on taxonomic, behavioral, and preservational aspects (Seilacher, 1964).

Rhoads and Morse (1971) studied recent sediments of the Black Sea, the Gulf of California, and the continental borderland basins of California. They observed that in waters with less than 0.1 milliliter of oxygen per liter, metazoans were absent (anaerobic), while at oxygen concentrations between 0.3 and 1.0 milliliter of oxygen per liter, a low diversity assemblage of small, soft-bodied infaunal species

existed (dysaerobic). As the oxygen concentration increased beyond 1.0 milliliters per liter, the size and diversity of species also increased (aerobic).

Ekdale and Mason (1988) reported that the transition from unburrowed to deposit-feeding, trace-fossil assemblages parallels increasing oxygen concentrations. Based on available data they concluded that aerobic conditions are indicated by oxygen concentrations at or above 1.0 milliliters per liter, dysaerobic conditions ranged from 0.1 to 1.0 milliliters of oxygen per liter, and oxygen concentration less than 0.1 milliliters of oxygen per liter indicated anaerobic conditions. They state that a high density, low diversity trace fossil assemblage is indicative of dysaerobic and anaerobic environments.

O'Brien (1970) observed shales using scanning and transmission electron microscopy (SEM and TEM) and noted a close correlation between fissility and clay flake orientation, i.e., shales that exhibited the best fissility had the highest degree of clay-flake orientation. O'Brien did not consider biologic factors important in the development of most shale fabrics. O'Brien concluded that shale fabrics were produced by the deposition of dispersed clay or by clay floccule collapse.

Byers (1974) suggested that fissility was a primary characteristic of the depositional fabric of marine shales, but the fabric is only maintained if infaunal burrowers are

absent from the sediment. He concluded the these relationships could be important to paleontologic and environmental reconstructions.

O'Brien (1987) examined shales from a wide range of sedimentary environments using X-radiography and SEM and concluded that unbioturbated, organic-rich shales from anoxic environments were characterized by fine laminations as well as parallel clay flakes. He also noted a high degree of bioturbation and indistinct bedding in shales that were deposited under oxic conditions.

Models have been developed to describe the oxygen content of sediments in a more quantitative fashion (Savrda and Bottjer, 1986; Droser and Bottjer, 1986), but they can only be applied where tiering and cross-cutting relationships can be seen clearly.

CHAPTER 2

GEOLOGIC SETTING

Location

The study area is located in the upper Mississippi Embayment of southeastern Missouri, southern Illinois, and Western Tennessee. The present-day topography, as described by Lamar and Sutton (1930), can be divided into three basic parts: the uplands, which are generally due to more erosion-resistant, consolidated rock; the alluvial plains of the Ohio and Mississippi rivers; and the gently rolling hills of Embayment deposits. The uplands mark the northern-most extent of Embayment deposits. Figure 2 illustrates the study area and the location of the clay pits studied. Figure 3 is a generalized geologic map of the same area.

Stratigraphy

Stearns (1957) described the deposition of the northern Mississippi Embayment Cretaceous-through-Eocene deposits as occurring as a single sedimentary cycle, which reached a maximum during the deposition of the Creek Clay (Paleocene Porters). The cycle is bounded above and below by unconformities, with a disconformity at the Cretaceous-Paleocene boundary. Stearns also concluded that the Porters Creek strata do not represent a regression, but as he called it a "stillstand", in which there was little change in sea

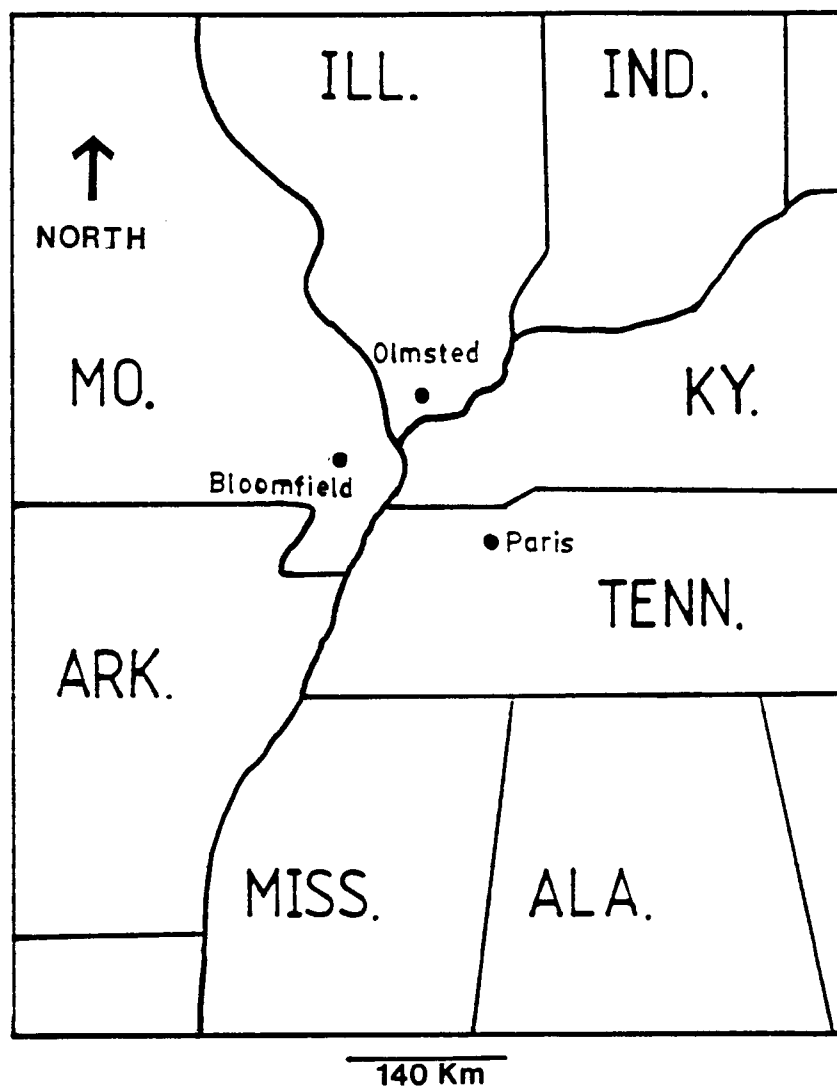


Figure 2. The study area with the location of the clay pits studied.

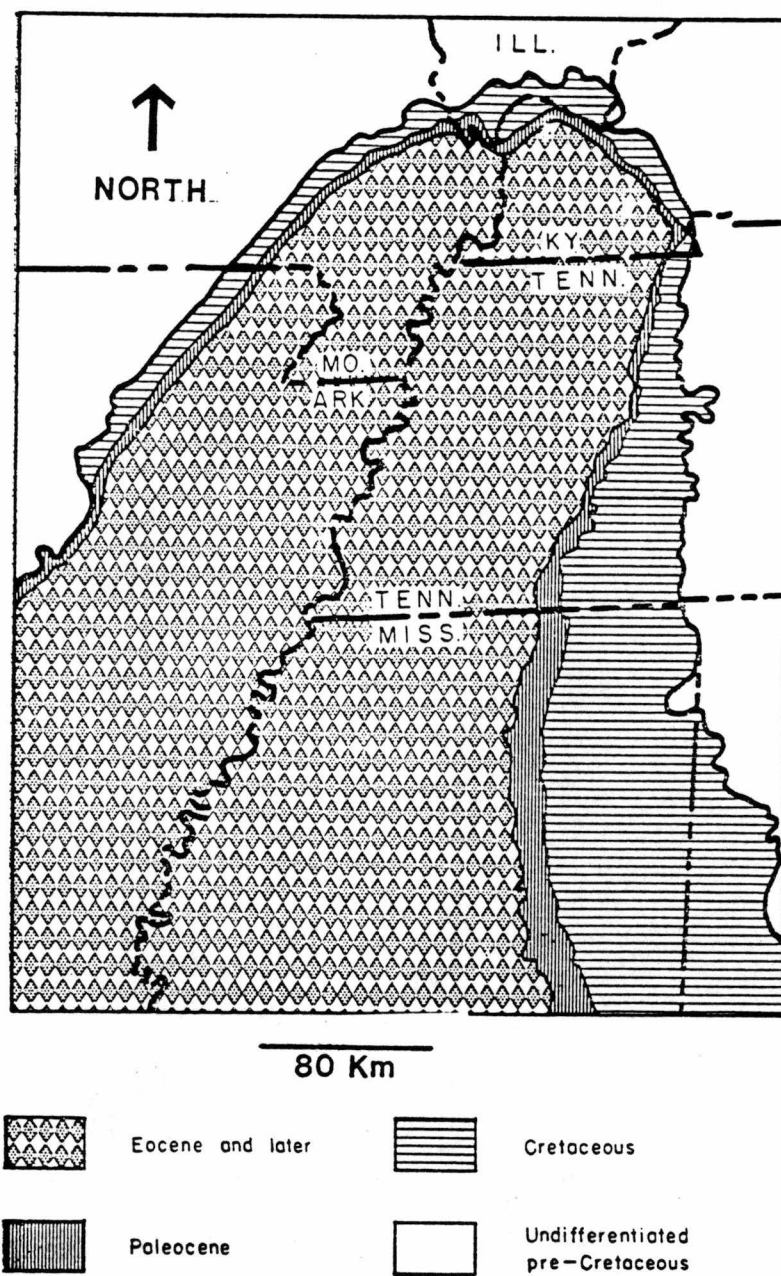


Figure 3. Generalized geologic map of the study area (after Stearns, 1957).

level. Figure 4 illustrates Tuscaloosa through Midway deposition. Figure 5 summarizes the environmental interpretations from upper Cretaceous to Eocene. The Tuscaloosa Formation marks the base of the upper Cretaceous (Gulf) Series and unconformably overlies Paleozoic rocks. The Tuscaloosa Formation is made up of nonmarine gravel composed of well-rounded, gray or white chert clasts, which are commonly cemented by silica or iron oxides (Lamar and Sutton, 1930). Cushing et al., (1964) noted that in Alabama and Mississippi the Tuscaloosa Formation is called the Tuscaloosa Group, which includes the Coker and Gordo Formations. Strata of the Tuscaloosa Formation attain a thickness of 55 meters.

The Tuscaloosa is overlain disconformably by the Eutaw Formation in the southern portion of the Mississippi Embayment. It is made up of two major facies: (1) in the north, there is a coarse clastic facies whereas (2) in the south, fine clastics and carbonate strata persist. The Eutaw Formation of Tennessee, Mississippi and Alabama as described by Cushing et al., (1964) is composed of a gray clay that is interbedded with fine glauconitic sand. It ranges in thickness from 0 to 120 meters. To the south, the Eutaw is overlain by the Tombigbee Sand Member, which is unconformably overlain by the Selma Formation. The Selma Formation is made up of impure, clayey chalk and may be as thick as 122 meters. To the north, the Formation grades into glauconitic,

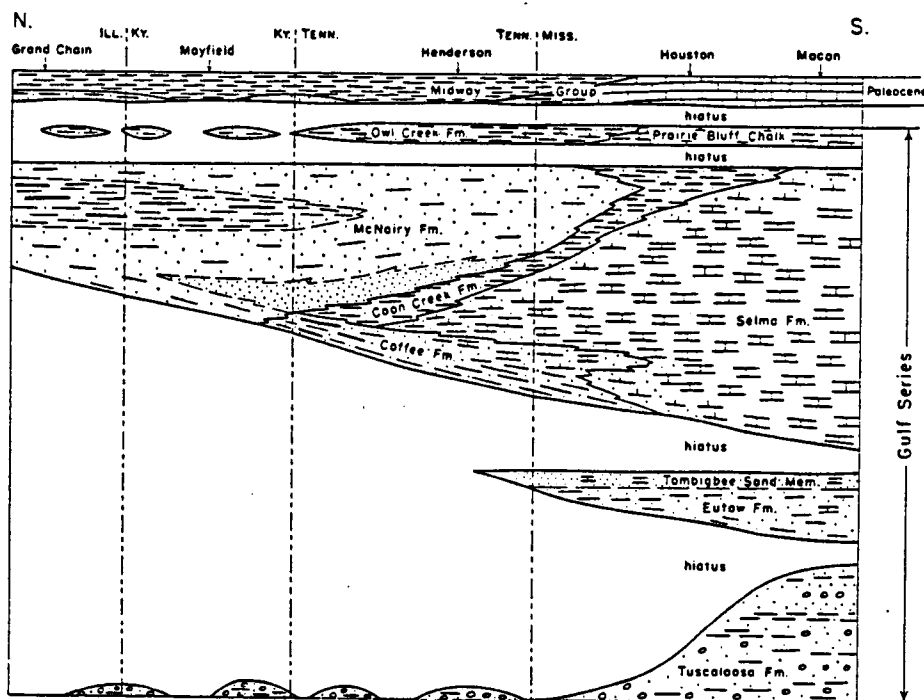


Figure 4. Tuscaloosa through Midway deposition with stratigraphic and facies relations of the Gulf series (after Pryor, 1960).

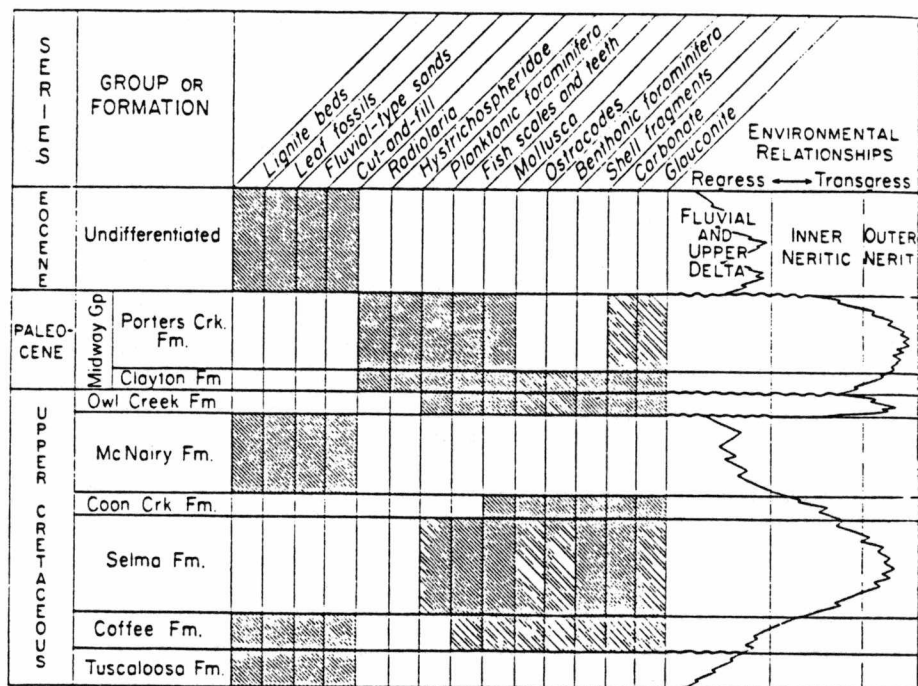


Figure 5. Observed criteria and interpretation of environments for the Tuscaloosa Formation through undifferentiated Eocene, shaded areas indicate the occurrence of criteria (after Pryor and Glass, 1961).

calcareous and fossiliferous clay. These facies grade into the Coffee and overlying Coon Creek Formations (Pryor, 1960).

The Coffee Formation is composed of sandy and calcareous clay to the south and it grades into lignitic sand and clay to the north. The Coon Creek Formation grades into the overlying McNairy Formation and is composed of fossiliferous silt and clay. It is commonly micaceous, calcareous and glauconitic, and it contains sand bodies that are up to 61 meters thick (Pryor, 1960).

The Coon Creek Formation is overlain by the McNairy Formation, which is the most widespread unit of the Upper Mississippi Embayment. It reaches a maximum thickness of 183 meters and is composed of lignitic, fine to medium grained, very micaceous, cross-stratified sand with clay beds and laminations (Pryor, 1960).

The McNairy Formation is in sharp unconformable contact with the overlying Owl Creek Formation. The Owl Creek Formation is made up of about 15 meters of glauconitic, fossiliferous, calcareous, and micaceous sandy clay. To the south, it grades into limestone and chalk and is called the Prairie Bluff Chalk. The top of the Owl Creek Formation is marked by a very sharp unconformity that has a locally developed soil zone (Pryor, 1960). This unit is overlain by Tertiary (Paleocene) Midway Group which is made up of the Clayton and Porters Creek Clay. The Paleocene Series reaches a maximum thickness of 300 meters at the axis of the

Mississippi Embayment (Cushing et al., 1964).

The Clayton Formation is composed of limestone, calcareous sand and sandstone of marine origin. In some places a basal conglomerate marks the contact (Cushing et al., 1964). The Porters Creek Formation conformably overlies the Clayton Formation and together both comprise the Midway Group (Tertiary) of northern Mississippi, Tennessee, Kentucky, Illinois, Missouri, and northern Louisiana. The Porters Creek is unconformably overlain by the Eocene Wilcox Formation in Missouri, Illinois, and Kentucky, but it attains Group status in Tennessee and Mississippi (Sims, 1972).

The Midway Group was deposited during the transgressive-regressive movements of the Cretaceous-Tertiary sea. The major portion of the Porters Creek Clay represents the maximum of a Middle Paleocene transgressive event (Sims, 1972). Figure 6 illustrates Tuscaloosa through Porters Creek deposition.

A regressive phase of deposition is represented by what has been called the "Paleocene Sand" (Stearns, 1957). Paleocurrent indicators are absent from the Porters Creek, but lithofacies indicate a possible eastern and northeastern sediment sources (Sims, 1972).

The Porters Creek Clay was named by Safford (1864) to describe outcrops in southeastern Hardeman County, Tennessee. The Porters Creek Clay crops out parallel to the northern margin of the Mississippi Embayment. The Porters Creek crops out in a 6.4 kilometers wide belt in Stoddard County,

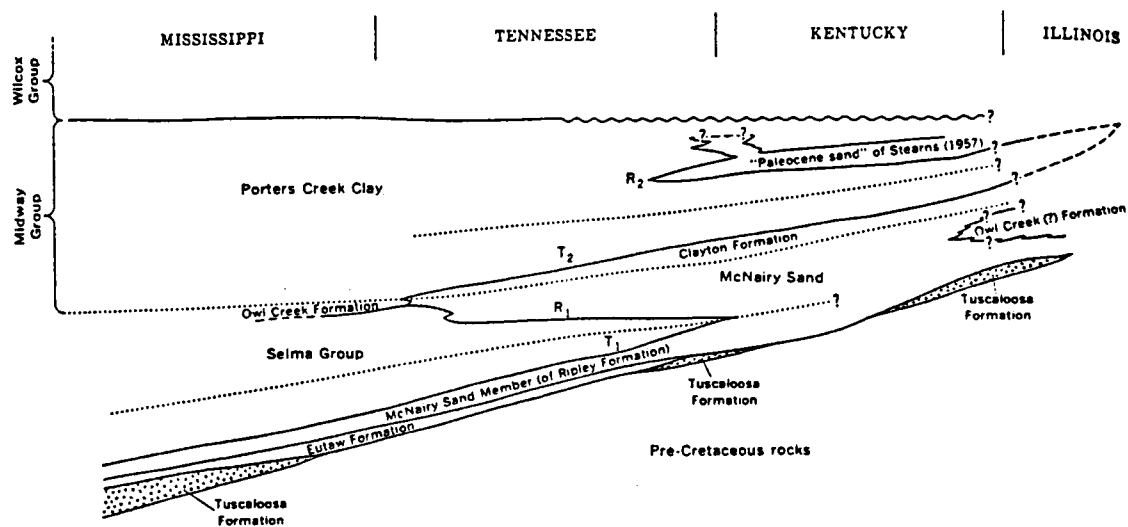


Figure 6. Schematic stratigraphic reconstruction of Lower Tertiary- Upper Cretaceous rocks showing transgressions (T) and regressions (R) with facies relations (modified from Stearns, 1957 by Sims, 1972).

Missouri, but it is generally poorly exposed due to widespread Pleistocene loess deposits. It ranges in thickness from 35 to 49 meters. In Stoddard County, the Porters Creek is a hard, dark-gray clay that is almost black when wet, but is light gray to light-cream in color when dry. Locally, it appears massive with weakly defined bedding planes (Farrar and McManamy, 1937).

Whitlatch (1940) noted that the Porters Creek Clay of Tennessee is dark-gray to black and silty with a massive, jointed appearance and conchoidal fracture. He observed thin layers and lenses of fine, micaceous sand and some minor glauconitic layers. The maximum outcrop width in Tennessee is approximately 12.8 kilometers, but in some locations it narrows to less than 1.6 kilometers. The greatest outcrop thickness observed by Whitlatch was 27 plus meters, but he noted that up to 110 meters of Porters Creek has been reported from drill holes located near the axis of the Mississippi Embayment.

The Porters Creek of Tennessee contains numerous clastic dikes that vary in width from a few centimeters up to nearly 7 meters. These dikes are thought to be the result of earthquakes which opened fissures that were filled with sand from sub-Porters Creek sources (Whitlatch, 1940). Clastic dikes which ranged in size from 2 centimeters to 61 centimeters in width were also reported in Kentucky (Larmar and Sutton, 1930). In the vicinity of Cairo, Illinois the

Porters Creek Clay is described as massive, un laminated, blocky, and sparsely fossiliferous, black to grayish-tan clay. It ranges in thickness from 15 to 46 meters thick and is observed to thicken to the south (Pryor and Ross, 1962).

In the subsurface of western Kentucky the Porters Creek Clay is less than 55 meters thick, but it thickens to approximately 305 meters near the axis of the Mississippi Embayment's southern limit. A thickness of less than 30 meters has been observed over some structural highs (Cushing et al., 1964).

A portion of the Porters Creek Clay is considered to be the result of the diagenetic alteration of volcanoclastic material, based on the observation of glass shards and mineral associations that appear consistent with a volcanoclastic origin (Sims, 1972; Reynolds, 1970). However, Grim (1933) thought this was unlikely due to the massive amount of ash that would be required. Pryor and Glass (1961) noted the possibility of a volcanic ash source for the Porters Creek Clay and recognized that there was some late Cretaceous and Tertiary volcanism, but they consider the amount deposited to be insignificant to that required to account for the Porters Creek. Figures 7 through 9 illustrate the paleogeography during Porters Creek deposition.

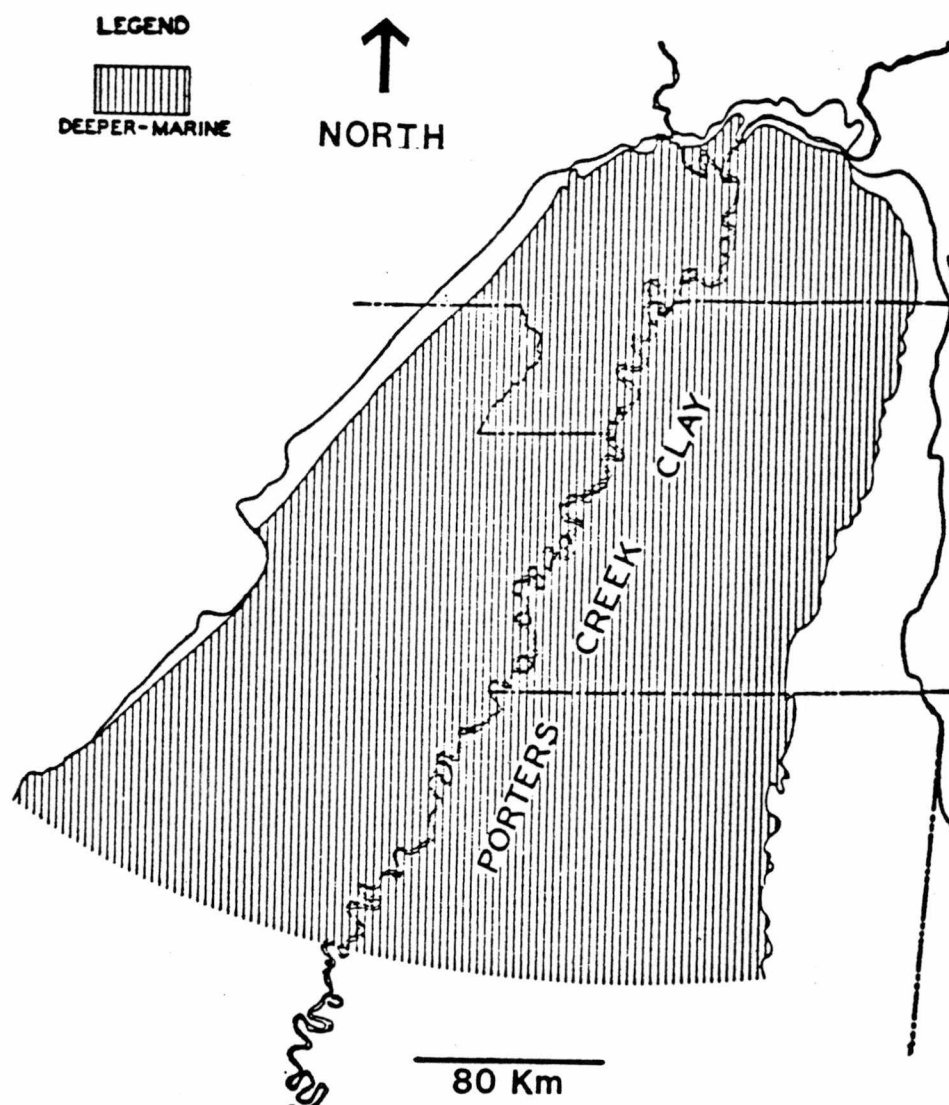


Figure 7. Paleogeography at the maximum Paleocene transgression (after Stearns, 1957).

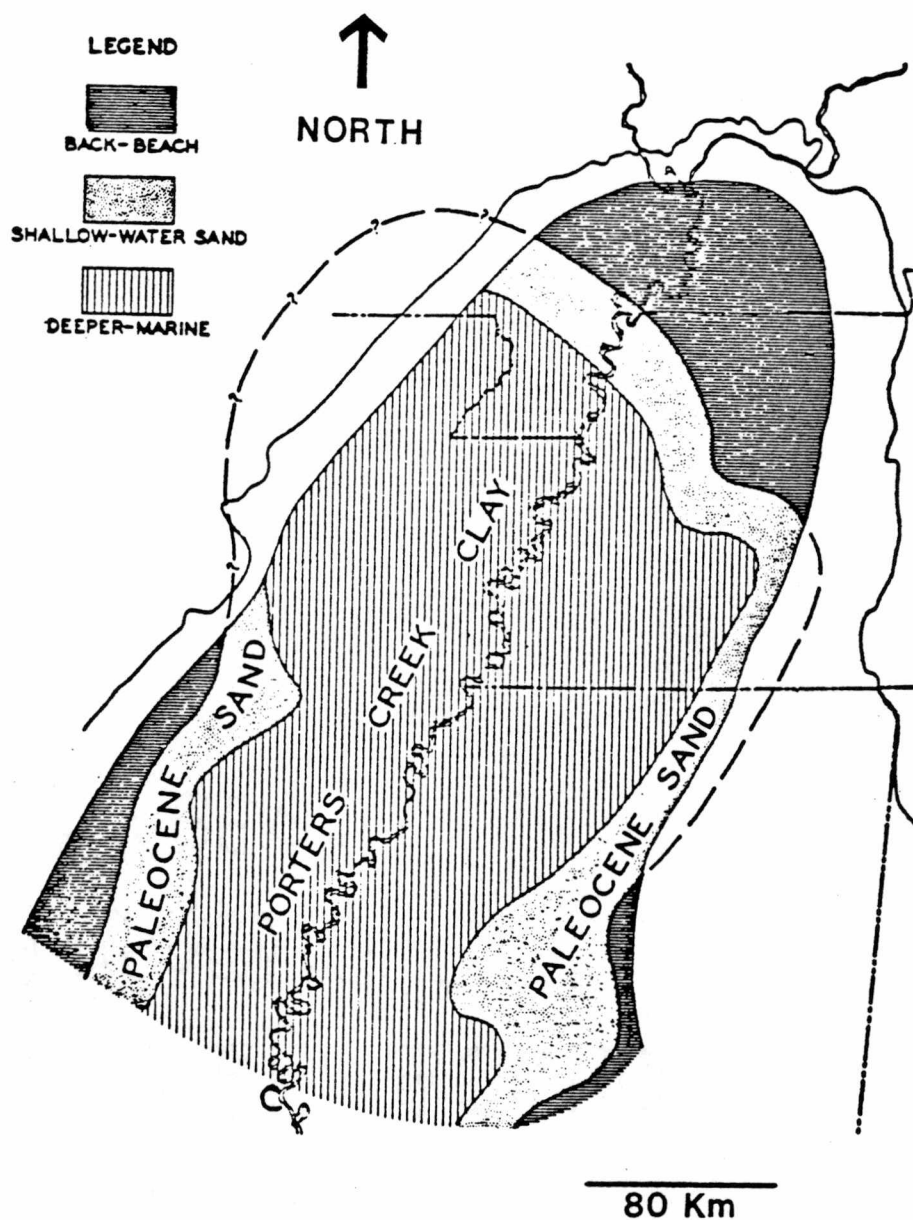


Figure 8. Paleogeography of the Upper Paleocene regression (after Stearns, 1957).

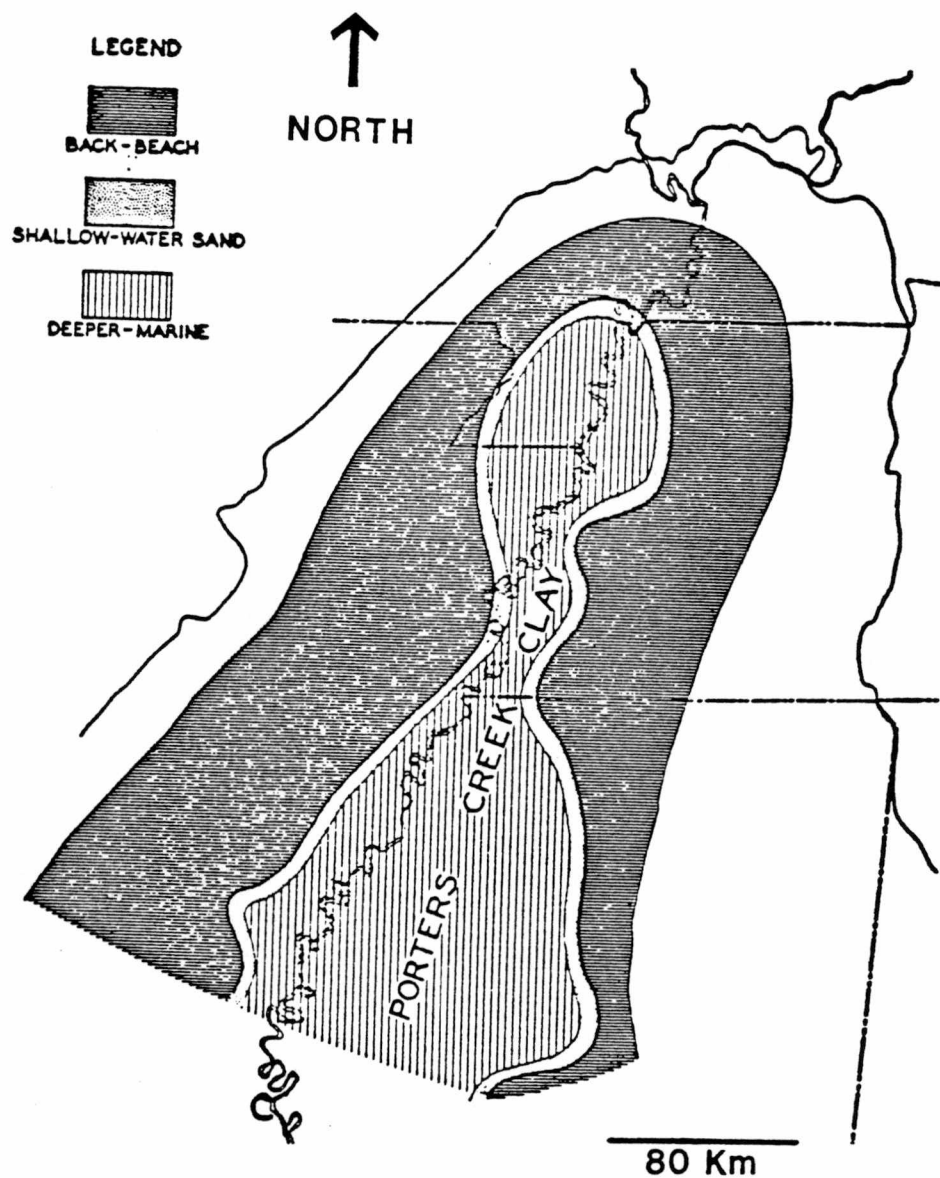


Figure 9. Paleogeography at the end of the Paleocene (after Stearns, 1957).

Regional Structure

The modern day Mississippi Embayment is a south-plunging trough whose axis roughly follows the present course of the Mississippi River. The strata within the embayment range in age from Jurassic to Recent and have been modified by various structural influences (Cushing et al., 1964).

The tectonic activity that formed the Mississippi Embayment syncline may have been part of Appalachian orogeny near the close of the Paleozoic Era. The Appalachian Mountain uplift was accompanied by subcrustal movement during which subsidence in the southwestern part of the embayment may have occurred. By the end of the Paleozoic Era the syncline was not fully developed, but by the beginning of the Mesozoic Era the eastern Ouachita Mountains, the southwestern Appalachian Mountains and the Ozark uplift, which was in place by the Precambrian, were becoming important sediment sources. These uplifts have provided sediments to the Mississippi Embayment since the Triassic Period to develop the present sedimentary assemblages (Cushing et al., 1964).

The units generally thicken downdip with post-Paleozoic sediments reaching a thickness of approximately 5500 meters at the extreme southern end of the embayment (Cushing, et al., 1964). Figure 10 is a generalized structure map of the Mississippi Embayment.

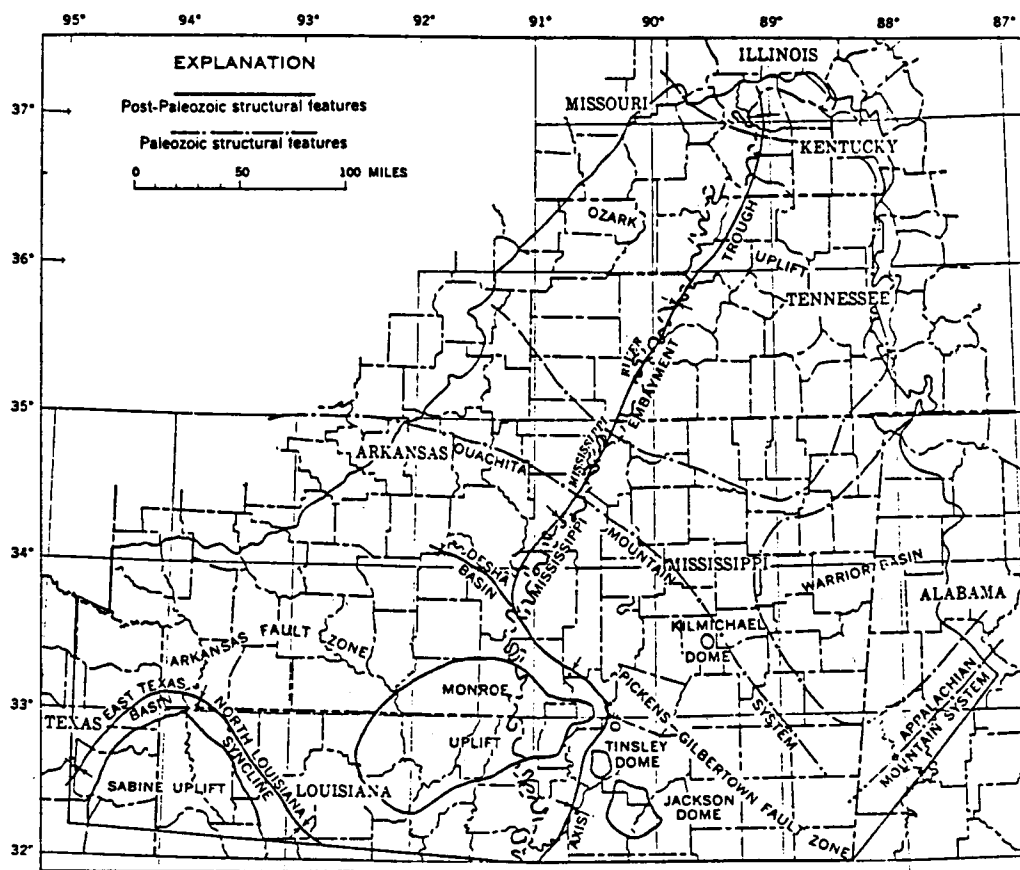


Figure 10. Mississippi Embayment structure map (after Cushing et al., 1964).

CHAPTER 3

METHODS

In order to get the least weathered material for study, samples were collected from three active clay pits near Bloomfield, Missouri; Olmsted, Illinois; and Paris, Tennessee (see Figure 2). In the descriptions which follow, each pit will be designated simply by Bloomfield, Olmsted, or Paris. Samples were collected at approximately 1.5 meter intervals at each location, but sampling was limited by the depth of each pit. Anomalous or unusual samples were also collected.

A total of 56 samples were collected including 22 from the Bloomfield, 15 from the Olmsted, and 19 from the Paris localities. A total of 80.4 meters of section was measured; 34.5 meters at Bloomfield, 16.6 meters at Olmsted, and 29.3 meters at Paris. All sample identifications used in this report were designed to make it possible to determine relative sample positions of a sample based on the sample identification. (Sample designations begin with M, I, or T which corresponds to Missouri, Illinois, or Tennessee respectively. This designation was used at the beginning of the research to facilitate multiple sample locations in each state, but ordinary outcrops were found to have suffered more weathering than was considered acceptable and a decision was made to limit the sample sites to active clay pits. The letter designations are followed by numerical values. The greater the value, the higher in the section was the sample.

Missing numerical values indicate levels in the pits at which it was impossible to collect a sample. In some cases an A or B was used at the end of a sample designation to indicate that these samples were taken from the same level in the pit. (Note one exception: sample I64 was taken 1.2 meters above sample I6).

Concretions that were found at the Missouri pit were difficult to collect due to their large size and highly fractured nature. Therefore, only the smaller, less fractured ones and pieces of the larger ones were collected.

Representative splits were taken from each specimen, dried at 105°C for one hour and then ground for six minutes in a swing mill (shatter box) which reduced the samples to less than 200 mesh (< 75 microns). The resulting powders were made into pressed pellets for X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis of bulk mineralogy and chemistry.

Because moisture content affected the color of samples in the field, the colors of the pressed pellets were used to standardize color terms for descriptive purposes. The color terms used in the stratigraphic sections represent pellet colors and not outcrop colors, which were generally darker. The color terms used are found in the Standard Munsell System Rock Color Chart (1975).

Trace-fossil identification was verified from the Trace Fossil and Problematica supplement to The Treatise on

Invertebrate Paleontology by Walter Häntzschel (1975) and personal communication with Steven G. Driese of the University of Tennessee Department of Geological Sciences.

X-ray Diffraction

X-ray diffraction (XRD) was used to determine the mineral phases present using Cu K α radiation at 35 kV and 17 ma. The data were collected at one degree 2 θ per minute, from 2° 2 θ to approximately 55° 2 θ for bulk sample analysis.

Elutriated mounts of the < 5 μ m size fraction were used to study the clay-size material. Sieve and gravity separations were combined with chemical dispersion and flocculation when appropriate. Note that the generally accepted upper limit of clay size material is 2 microns; however, the 5 micron size limit was selected to determine if the slightly coarser zeolites were present in the Porters Creek as reported by Sims (1972). Heat treatments to 550°C and glycolation were used to identify the clay minerals present.

X-ray Fluorescence

X-ray fluorescence (XRF) was used to determine the bulk chemical composition of all samples. The EG&G ORTEC 6110 tube-excited X-ray fluorescence analyzer was capable of

detecting elements as low as atomic number 11 (sodium). The data were reported as percent oxides of sodium, magnesium, aluminum, silicon, phosphorus, potassium, calcium, titanium, manganese, and iron. Other elemental concentrations reported include sulfur, chromium, barium, rubidium, strontium and zirconium. A table containing the standard error of calibration of XRF data is in the appendix to this report. The values reported there represent one standard deviation.

The concretions were cut into 5.0 x 7.5 x 1.0 centimeter thick sections and analyzed using a macroprobe option in the XRF analyzer software. It was possible to analyze spots approximately 5 millimeters in diameter, which made it possible to examine chemical trends from the exterior to the interior of zoned samples.

Petrography

Standard 5.0 x 7.6 centimeter glass slides were used for thin-section preparation of select samples from each of the clay pits studied. Due to the disintegration of the samples in water it was necessary to grind the samples by hand using various grades of sand-paper until the desired surface was obtained. The prepared slides were examined with a petrographic microscope for fabric variations, mineralogy, and evidence of biological activity. Due to the fine grain size of the Porters Creek strata, petrographic analysis in most cases did not permit an accurate identification of all mineral

species, whether detrital or authigenic, but it did give considerable insight into the relationship of the biogenic fabric to the depositional fabric.

Statistical Analysis of Chemical Data

All chemical data were entered into a "LOTUS 1-2-3" spreadsheet format which enabled the plotting of chemical concentrations versus depth to compare chemical changes with lithological changes. Many of the plots revealed apparent trends with depth for the chemical data.

A simple RUNS TEST was performed on observed trends. The RUNS TEST is designed to test for trends in a group of observations that are arranged in the order they occur. The data must be in two mutually exclusive categories or states (Davis, 1986). In the case of the present data set, the mean of the variable in question was used as the category or state. If the value of the variable was greater than the mean it was considered positive and if the value of the variable was less than the mean it was considered negative. Using this rationale the result was a " RUNS UP AND DOWN TEST " (Mckinney, personal communication).

In general, the test verified trends that were intuitively evident in data plots, therefore there will be no further discussion of the "RUNS TEST" in this report. However it was discovered that in some cases the test appeared sensitive to the number of data points available. This was

particularly true for the Olmsted location which had only 15 samples. The apparent sensitivity was reflected in a disagreement of intuitively obvious trends with those calculated.

Principal Component Analysis (PCA) was used on the entire data set. Sub-sets of the data (such as individual sample locations) could be examined using the graphic representation provided by the software. PCA is sometimes referred to as "factor analysis", but PCA is not true factor analysis (Davis, 1986). PCA is a multivariate technique that makes it possible to look for other components or variables that may explain a significant portion of the variation in the data. The important components may not be readily evident in the data set or the components may be related to a more fundamental property of the samples. The data are expressed geometrically as vectors in multidimensional space. The vectors are termed "eigenvectors" and have "eigenvalues" which define the vector or axis length. Principal Component Analysis may also be used to reduce the number of variables for regression, clustering or other statistical methods (Ray, 1982). A discussion of the PCA for each of the sampling locations will be undertaken in a later section.

CHAPTER 4

RESULTS

Stratigraphic Descriptions

Previous workers did not divide the Porters Creek into members but, for the purpose of this research, it was necessary to divide each pit section into logical subdivisions. The divisions were based on the lithologic character observed in the field. All lithologic, and petrographic descriptions proceed from the pit bottom upward through the measured section. Due to the fine-grained nature of the Formation it was necessary to make note of such features as laminae and their frequency, bioturbation, weathered versus unweathered surfaces, fissility, and any other features that could provide a means of recognizing various facies. Note that most of the stratigraphic contacts are gradational in nature. The stratigraphic sections were constructed prior to the plotting of any of the chemical data versus depth so as not to bias the sections.

Bloomfield

At the Bloomfield, Missouri location about 30 meters of section was measured. Figure 11 illustrates the measured Bloomfield stratigraphic section. At base of this section is a 4.32 meter thick medium gray to medium dark-gray clay with discontinuous laminae and intense bioturbation near its base.

Bloomfield Stratigraphic Section

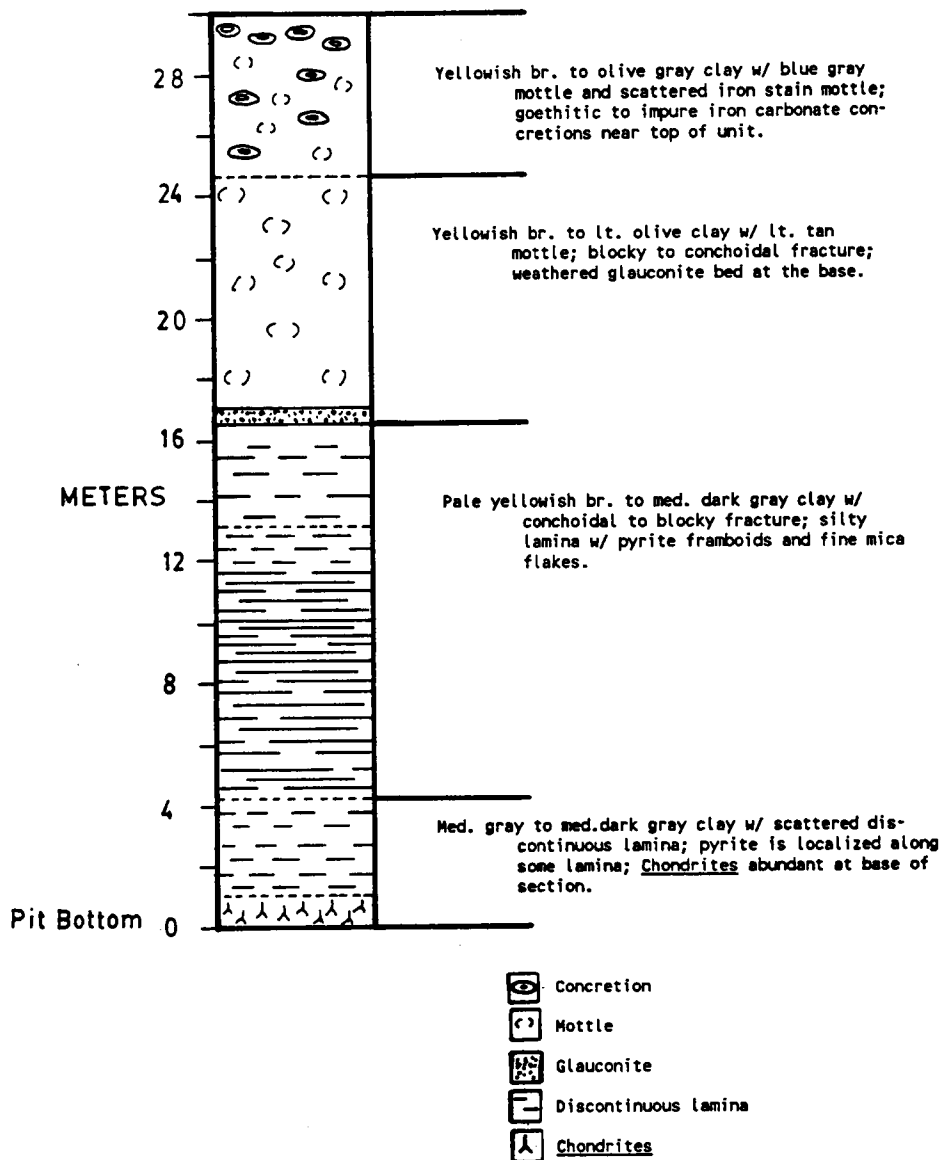


Figure 11. Bloomfield stratigraphic section.

Pyrite framboids in unlaminated shale as well as some pyrite framboids localized along laminae were observed. The discontinuous nature of the laminae appears to be related to activity of unknown trace makers. Much of their activity appears restricted to bedding planes, although some local burrowing cuts across bedding planes. Chondrites traces from 1 to 3 millimeters in diameter were observed.

Bioturbation in the Chondrites zone appears to have been very intense, and there is little evidence of any kind of lamination. This observation was made more evident by the occurrence of a moderate amount of fissility above the zone. Local escape burrows were observed that appear to cut across the Chondrites traces but, due to poor exposure their exact importance is not known.

From about 4.3 meters up to about 16.7 meters, the section changes to a pale yellowish-brown to medium dark-gray clay with blocky to conchoidal fracture, silty laminae, pyrite framboids, and fine mica flakes. There is an increase in observable fissility which appears related to an increase in the frequency and lateral continuity of laminae. Fairly well-developed Thalassinoides traces were observed, but due to the dominance of blocky and conchoidal fracture, very few good bedding plane exposures were available to observe bedding plane traces.

Laminae frequency varied from approximately 2 laminae per centimeter to 6 laminae per centimeter. The greatest laminae

frequency was observed in the middle of the 4.3 to 16.7 meter package, while the lowest laminae frequency bounded the package. Laminae in this part of the section ranged from 1 to 3 millimeters thick.

From 16.7 to 24.8 meters the section is yellowish-brown to light-olive clay with a light-tan mottle, conchoidal to blocky fracture with what appears to be a weathered glauconite sand unit at the base of the package. Where mottling is absent the sediment appears almost homogeneous except for local burrow concentrations. Some of the mottling appears to be related to the oxidation of disseminated iron minerals. There was no obvious order to their distribution and it was unclear from outcrop observations whether they were detrital or authigenic.

From 24.8 to 30.0 meters the Formation is yellowish-brown to olive-gray with a blue-gray mottle and scattered iron stain mottle. Goethitic to impure iron carbonate concretions occupy the upper portion of the section. The concretions will be discussed in more detail later in this report. Some burrows are evident by the occurrence of local silty-mottles. Also observed was a very local, nodular white clay cemented by siderite, which is thought to be related to concretion formation. There was a moderate degree of bedding plane deflection around the nodules and concretions. These nodules and concretions comprise the only occurrences of carbonate cements in the entire measured section.

Foraminifera:

Select samples from all sampling locations were disaggregated in order to determine whether foraminifera were present. They were only present at the bottom of the Bloomfield pit. Table 1 lists the taxa identified by Charles Smith of the Alabama Geologic Survey. The foraminifera assemblage is considered to be early Paleocene (Danian age) and represents an open-marine middle neritic depositional environment. Water depths may have ranged from 15 to 60 meters.

Olmsted

The material at the base of the measured section at Olmsted (Figure 12) is medium dark-gray clay with scattered pyrite framboids and no laminations. Generally, the strata at the Olmsted pit are rather non-descript so far as physical features are concerned. Slickensides occur on some joint surfaces and in the clay surrounding the pyrite framboids. Generally this part of the section appears massive and structureless with conchoidal fracture, but weathered surfaces tend to be more fissile. This lithologic type continues from the bottom of the pit to about 2.9 meters at which there is a gradational contact.

From 2.9 meters to about 5 meters the sediment is medium light-gray with scattered pyrite framboids and 2 to 3 millimeter diameter Chondrites burrows, with a few 5 to 10

Table 1

Foraminifera taxa identified from the bottom of the
Bloomfield pit (Smith, personal communication 1989)

TAXA	TAXONOMIST
<u>Lenticulina midwayensis</u> var. <u>carinatus</u>	(Plummer)
<u>Cibicides alleni</u>	(Plummer)
<u>Nodosaria affinis</u>	(Reuss)
<u>Vaginulina longiforma</u>	(Plummer)
<u>Loxostomum applinae</u>	(Plummer)
<u>Dentalina</u> sp., perhaps <u>D. colei</u>	(Cushman and Dusenbury)
<u>Anomalina midwayensis</u>	(Toulmin)
<u>Alabamina wilcoxensis</u>	(Toulmin)
<u>Pillenia quinqueloba</u>	(Reuss)
<u>Chrysalogonium</u> sp., perhaps <u>C. granti</u>	(Plummer)
<u>Anomalina acuta</u>	(Plummer)
<u>Subbotina pseudobulloides</u>	(Plummer)
<u>Planorotalites compressa</u>	(Plummer)
<u>Bulimina</u> sp., perhaps <u>B. quadrata</u>	(Plummer)
<u>Parrella expanasa</u>	(Toulmin)
Questionable <u>Cibicides alleni</u>	(Plummer)

Olmsted Stratigraphic Section

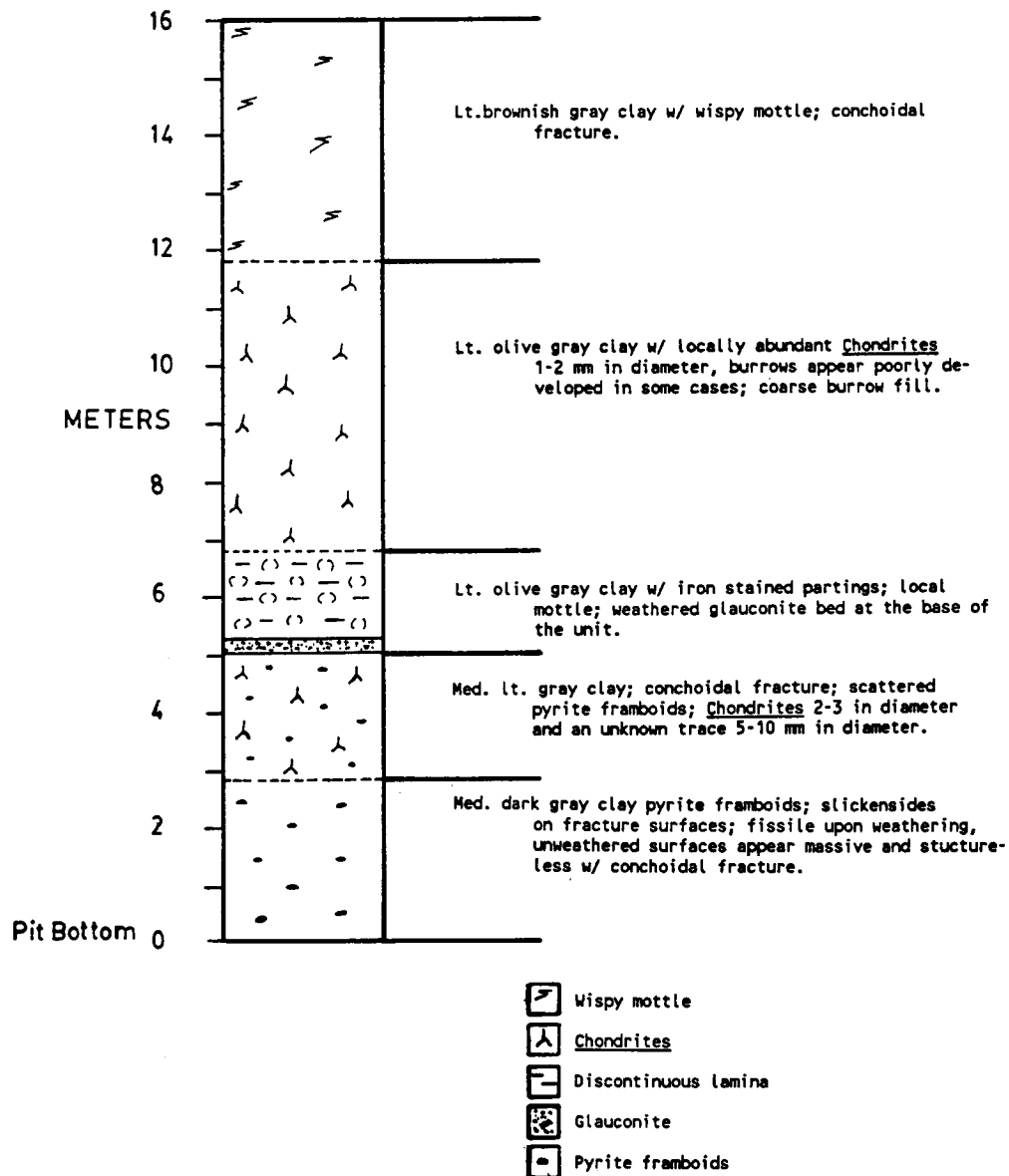


Figure 12. The Olmsted, Illinois stratigraphic section.

millimeter diameter burrows of an unknown trace.

This package is overlain by a 15 centimeter thick bed that may be a weathered glauconite bed like that observed at the Bloomfield pit. This bed occurs at 4.9 meters from the bottom of the pit and is overlain by a light olive-gray clay with local light tan mottled and iron oxide stained partings, which extend up to 6.9 meters.

Above 6.9 meters is a 5 meter thick section consisting of light olive-gray clay with light tan-mottle and locally abundant 1 to 2 millimeter diameter Chondrites traces some of which contain coarse burrow fill. Some of the burrows do not appear as well developed as those seen at the Bloomfield location. Finally, the section is capped by a light brownish-gray clay with conchoidal fracture and light tan, wispy-mottle.

The relative stratigraphic position of the two pits discussed so far is not known. One of the goals of this research was to try to determine the environmental characteristics of each pit and to see if they can be put in a logical framework that agrees with what is already known about the Porter Creek Clay.

Paris

The base of the Paris section (Figure 13) is composed of a medium gray to olive-gray clay with very minor silt, micaceous laminae, conchoidal fracture and Chondrites burrows.

Paris Stratigraphic Section

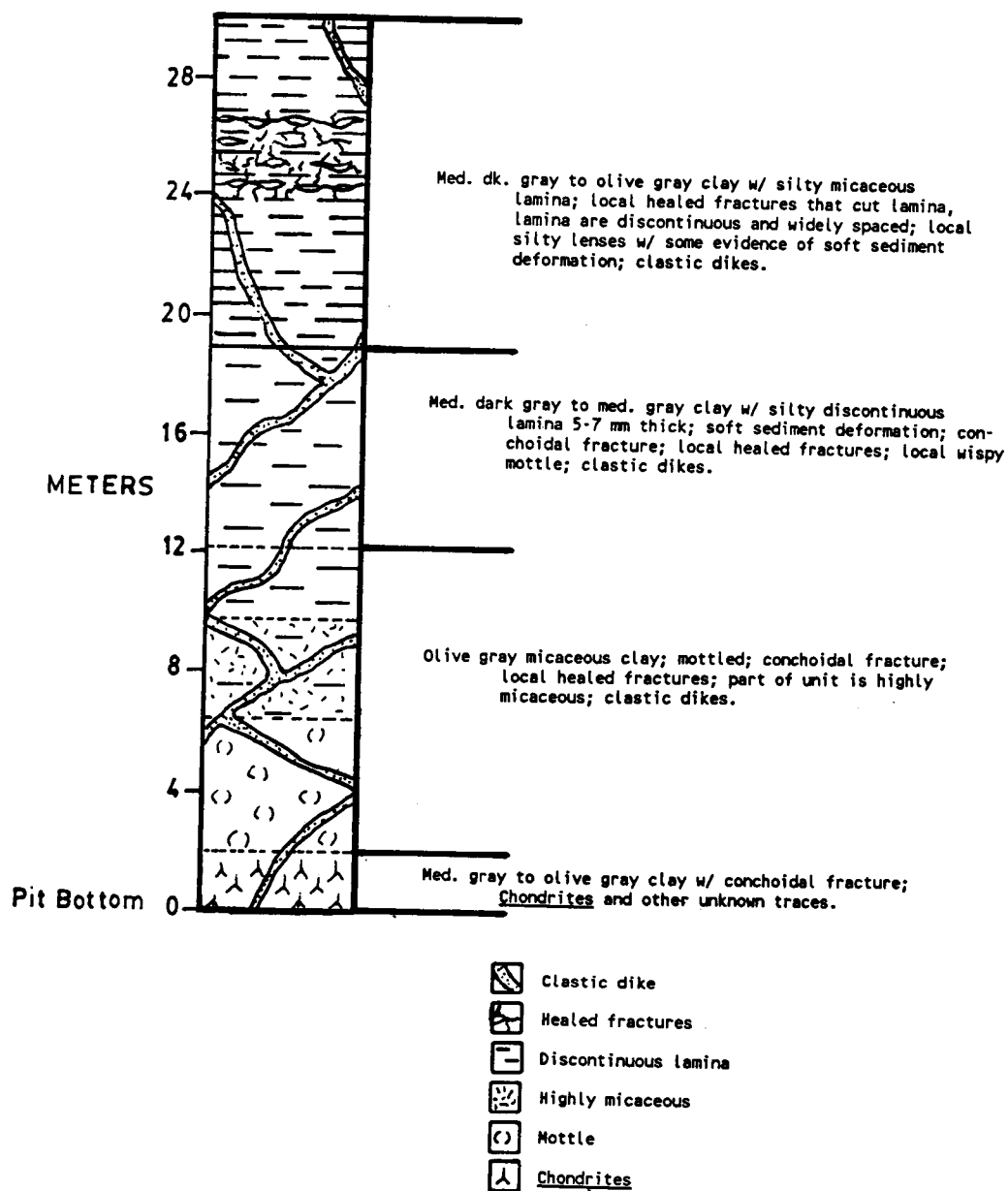


Figure 13. The Paris, Tennessee stratigraphic section.

This lithology extends from the bottom of the pit up to 1.98 meters.

This unit is overlain by an olive-gray micaceous clay with conchoidal fracture, minor mottle and local, healed fractures. The central portion of the unit appears highly micaceous. This package extends from 1.98 meters up to 12.3 meters.

At the 12.3 meter level, the clay appears more sandy than the underlying strata and this change may also be reflected in the color change. From 12.3 meters up to 18.9 meters the Formation is medium dark-gray to medium-gray clay with discontinuous laminae that range in thickness from 5 to 7 millimeters, and occur at a frequency of about 2 laminae per centimeter. Some minor soft sediment deformation, local healed fractures and wispy-mottle were noted.

The uppermost part of the Paris section is composed of medium dark-gray to olive-gray clay with silty, micaceous, and moderately discontinuous laminae cut by local, healed fractures, which in turn are cut by the clastic dikes. The laminae occur at a frequency of about one lamina per centimeter but they may be more widely spaced. Locally important silty lenses range in thickness from 5 to 7.5 centimeters. The entire Paris section is cut by a series of clastic dikes composed of well-sorted sand-size quartz. Some of the dikes are offset by faults, with displacement of about half a meter, but dikes appear to have formed later than the

healed fractures, although they could have been contemporaneous.

Petrographic Descriptions

Bloomfield

The base of the section at Bloomfield is generally very fine grained with abundant calcareous foraminifera which appear to have suffered little destruction due to diagenetic, chemical or compactive processes. In thin-section the base of the section appears weakly laminated based on the absence of strong parallel extinction of the clay fabric. Silt-sized quartz grains are angular and fairly evenly distributed throughout the deposit. Besides ubiquitous smectite other minerals observed include glauconite, chlorite, opaques (most are detrital iron minerals and organics), mica, and pyrite framboids. With the exception of glauconite and pyrite all minerals appear detrital in origin, although some of the glauconite has been redistributed by biogenic processes. Quartz grains are generally 0.03 millimeters and less in size. Glauconite ranges in size from 0.02 to 0.05 millimeters. The larger glauconite grains occur mostly in silty laminae, while the finer grains occur in the matrix surrounding the laminae.

In the 4.3 to 16.7 meter part of the section, smectite is dominant with accessory detrital mica, glauconite, opaques, chlorite and authigenic chalcedony. Angular, evenly distributed quartz grains range in size from 0.01 to 0.07

millimeters. There is a local diffusion of iron oxide stain around detrital iron minerals that are in close proximity to silty laminae, but the diffusion is not very extensive. This part of the section is more strongly laminated than the base of the section. Discontinuous silty laminae were also seen in outcrop. From 16.7 to 24.8 meters clay is the dominant component with detrital quartz, mica, opaque minerals, and authigenic glauconite and pyrite. Quartz grains have an average diameter of 0.01 millimeters, with glauconite averaging 0.02 millimeters in size. The opaques (primarily hematite) range in size from 0.01 to 0.05 millimeters.

The 16.7 to 24.8 meter package contains two different types of burrows. The first contains concentrations of non-clay minerals cutting across the dominant clay fabric (Figure 14). The second occurs in "boudin-like" outlines with re-orientation of the clay fabric internal to the outline (Figure 15). The latter contains only clay-size material. It appears that the maker of the second trace type had limited ability to manipulate material larger than clay size. With the exception of burrowed areas, clay laminations are fairly widespread. Detrital iron minerals have limited iron oxide halos.

The overlying 24.8 to 30.0 meter interval is very similar to the strata between 16.7 to 24.8 meters. It also includes the two burrow



Figure 14. Typical silt-filled burrow cutting clay fabric. The burrow is about 2 millimeters wide and bedding is at an oblique angle to the burrow wall.



Figure 15. "Boudin-like" burrow ? or fecal pellets ? The structures are approximately 0.3 millimeters across their short axis. Bedding is parallel to the long axis of the structures.

types described above. Quartz grains range in size from 0.01 to 0.10 millimeters.

In general, the color mottling observed macroscopically from 16.7 to 30.0 meters has little relation to the degree and style of bioturbation with the exception of some of the iron-stain halos, which are cut by some burrows.

Olmsted

The deposits at the base of the Olmsted section appear very fine grained, but it is difficult to see details of the depositional fabric in thin-section due to the apparent high organic content that masks many of the important features. From the pit bottom up to about 2.74 meters, the sediment is generally medium dark-gray. The dark color is considered to be due to a high organic content. Besides the dominant clays, minerals observed include quartz, glauconite, and muscovite. Burrows were observed that had coarser grains of glauconite and quartz in them, but they also contained grains that were the same size as those outside the burrow. The average grain size of glauconite inside the burrows was about 0.5 millimeters, whereas outside the burrow 0.1 millimeters was the average. Quartz averaged 0.5 millimeter in size, but grains less than 0.1 millimeters were observed.

Above 2.74 meters the contribution of organics appears to diminish based on the lighter color of this interval. The sediment is generally fine grained with bedding-parallel

extinction of the clay fabric. Although clay minerals are dominant, other minerals include quartz, muscovite, opaques (generally detrital iron minerals) and glauconite. Very minor, 0.2 millimeter rock fragments composed of quartz grains were observed, but the type of cementing agent was unclear due to the fine grain size. Minor authigenic chalcedony in framboidal shapes about 0.12 millimeters in size, were observed.

The portion of the section from 5.17 meters to 6.84 meters appears to be a transitional in character, based on thin-section and outcrop data. Pyrite framboids were not observed in outcrop as was the case for all strata below this point, but they were fairly prominent in thin-section. They were not as large as pyrite nodules seen in outcrop (up to a few centimeters). The framboids seen in thin-section were about 0.15 millimeters in size. Other minerals include quartz that ranged in size from 0.05 to 0.10 millimeters, glauconite averaged about 0.15 millimeters and scattered fine flakes of muscovite. The clay fabric showed good bedding-parallel extinction as well as good bedding-parallel orientation of muscovite flakes.

Above this transitional package no pyrite framboids were observed in thin-section or in outcrop. From 6.84 meters up to 11.86 meters the deposit is dominated by clay with fairly good bedding-parallel extinction, but also included are zones that appeared disturbed, which are thought to be due to the

bioturbation observed in outcrop. Minerals include quartz, ranging in size from 0.05 to 0.10 millimeters, muscovite, glauconite and detrital iron minerals. From 11.86 to 16.0 meters, the strata appear to be moderately bioturbated. This is evident from the weak bedding-parallel extinction of the clay fabric and the fairly random orientation of muscovite flakes. Minor rock fragments that reached a maximum size of 0.35 millimeters were observed. Quartz averages 0.25 millimeters in size, but was as small as 0.01 millimeters. Other minerals include muscovite, glauconite and scattered, detrital iron minerals. "Boudin-like" burrows similar to those seen in the Bloomfield thin-sections were noted here. These burrows have no grain size difference between material inside the burrow and material outside the burrow, but the burrows do not have bedding-parallel extinction that was observed surrounding the burrow.

Overall, the petrography of the Olmsted section is very similar to that seen in the Bloomfield pit. Although this does not prove that their relative positions are equivalent, the deposits may represent similar depositional environments.

Paris

The material at the base of the Paris pit is composed of clay that has fairly good bedding-parallel extinction of the clay fabric, with minor evidence for disruption. There is no evidence of significant compaction, and there are local

concentrations of quartz and glauconite along bedding planes. The quartz ranges in size from 0.01 to 0.50 millimeters and the glauconite is also about 0.50 millimeters in size. The 0.50 millimeter size-fraction of quartz and glauconite is generally restricted to minor, discontinuous laminae which were not apparent in outcrop. Other minerals include muscovite, detrital iron minerals and detrital chlorite in trace amounts.

From about 1.98 meters to 12.3 meters, the clay exhibits good bedding-parallel extinction with some scattered, obliquely oriented muscovite flakes, but most of the mica flakes maintain a fairly good bedding-plane orientation. Quartz grains are angular as well as moderately rounded and range in size from 0.01 to 0.05 millimeters. Evidence for bioturbation such as the light tan-mottle observed in outcrop is weak. It was not seen at thin-section scale.

Above 12.3 meters, and up to the 18.9 meter level, the clay has a rather weak bedding-parallel extinction and reveals a high degree of mica flake disruption. Quartz and muscovite become more important detrital components with trace amounts of biotite and glauconite and minor detrital iron minerals.

From 18.9 meters to the top of the pit, the clay has fairly well-developed bedding-parallel extinction except in burrowed zones. Burrows are filled with coarser quartz and muscovite with quartz grains averaging about 0.01 millimeters in size. Glauconite was absent in this part of the section.

Bulk Chemistry

Bloomfield

The most prominent features of the Bloomfield bulk chemistry are the pronounced breaks in the plots of S and P_2O_5 versus depth. These breaks occur at approximately the 11 meter level in the pit (Figures 16a and 16b). Sulfur ranges in concentration from not detected up to a maximum of 0.68 weight percent, whereas P_2O_5 concentrations range from 0.125 percent to a maximum of 0.256 percent. These variations are considered to be related to the occurrence of pyrite framboids and nodules as well as to the organic matter, whose occurrence is based on the dark color of the lower part of the section. Sulfur is thought to be pyritic in origin, whereas the higher P_2O_5 concentrations may be due to phosphorus being tied-up in phosphate minerals, but their concentration was too low for them to be identified in thin-section or XRD the organic matter.

The plot of Fe_2O_3 concentration (Figures 17a and 17b) versus depth appears weakly related to the sulfur concentration plot below the 11 meter level in that Fe_2O_3 remains fairly constant and changes at the bottom of the pit. Above the 11 meter level iron oxide variations have no obvious relation to sulfur concentrations. If the iron and sulfur in this section were due only to authigenic iron sulfide minerals, S and Fe_2O_3 concentrations would be expected to have

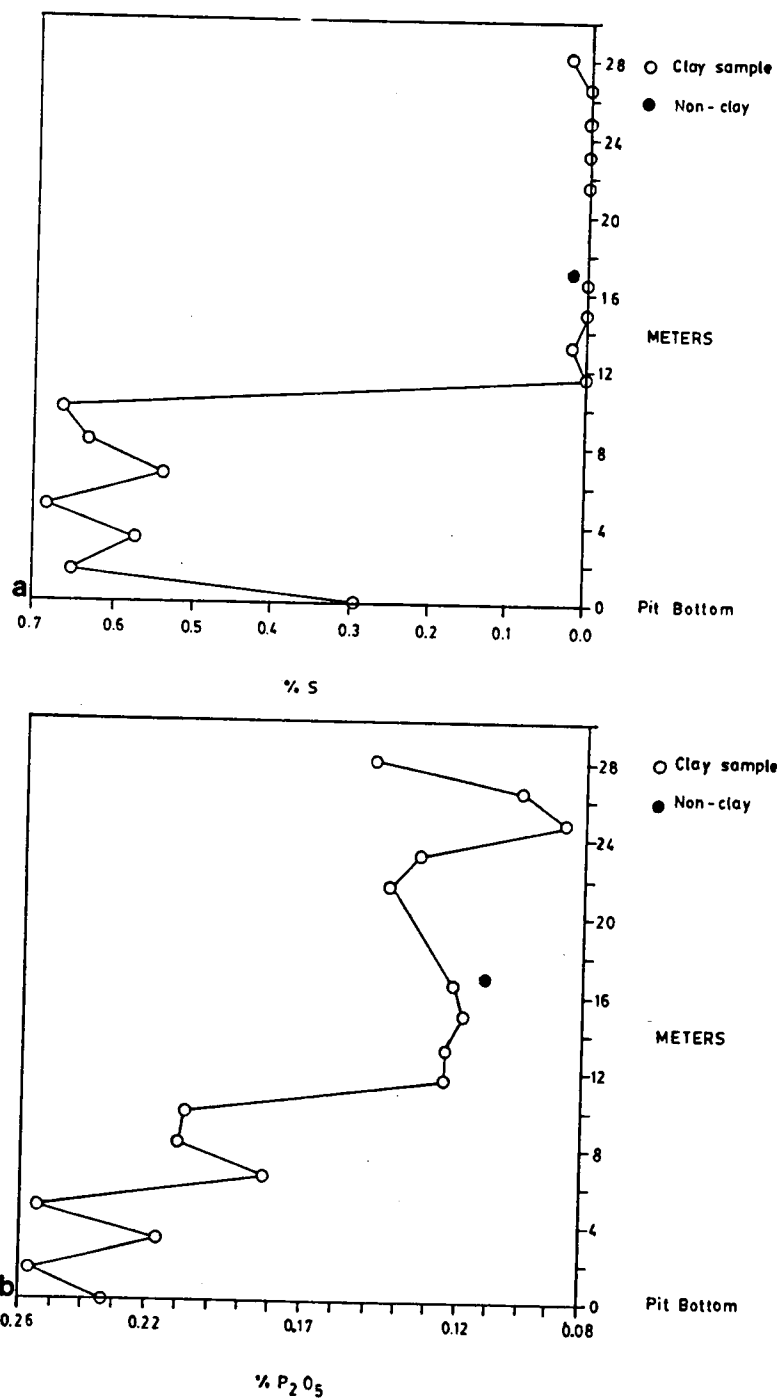


Figure 16. Bloomfield plot of S concentration versus depth (a), plot of P_2O_5 concentration versus depth (b). Note: the non-clay sample is from the weathered glauconitic horizon.

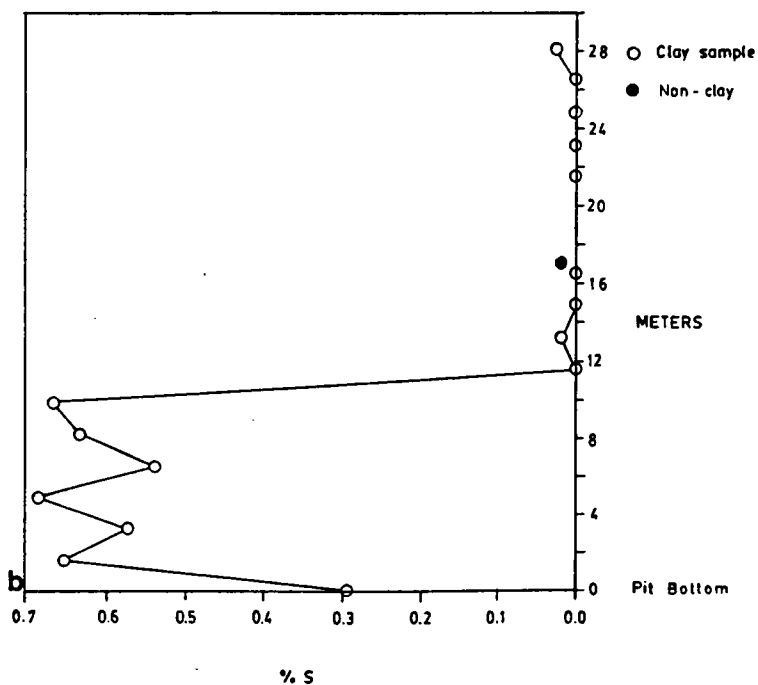
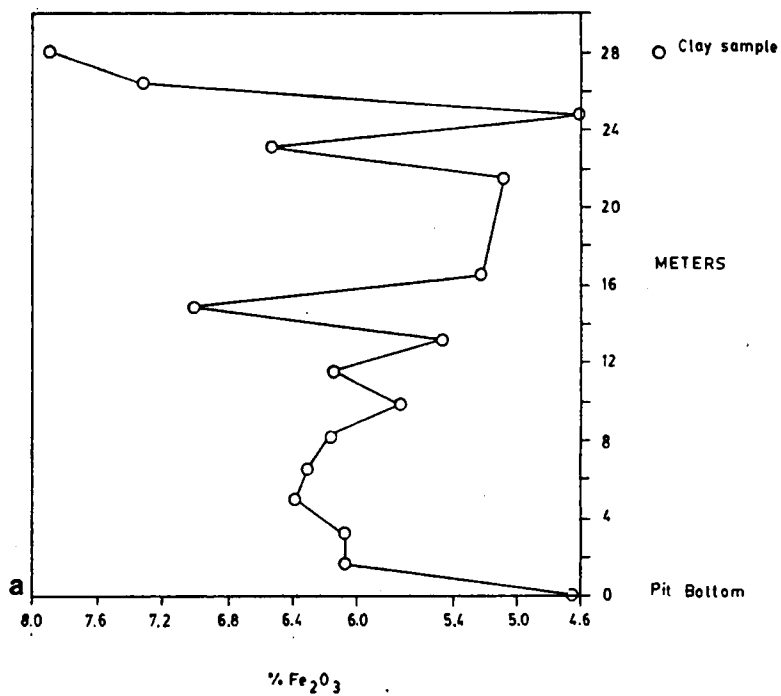


Figure 17. Bloomfield plot of Fe_2O_3 concentration versus depth (a), plot of S concentration versus depth (b). Note: the non-clay sample was omitted from the plot because of its high Fe_2O_3 concentration.

similar trends, but this is not true of the entire section at Bloomfield. This apparent disagreement is probably due to the influence of detrital iron minerals on the bulk chemistry of the section.

Another interesting feature of the section is the relationship shown by the plots of SiO_2 and Al_2O_3 concentrations versus depth (Figures 18a and 18b). Silica tends to increase from the pit bottom up to about the 22 meter level in the pit above which there is a reversal in the trend. With the exception of the pit bottom and above the 22 meter level, Al_2O_3 concentrations remain fairly constant. Above the 22 meter level an inverse relationship is observed between sample points. When SiO_2 concentration increases Al_2O_3 concentration decreases for a given sample. The variations seen above the 22 meter level are considered to be the result of variations in the supply of quartz silt to this part of the section. This is consistent with the contention of Pryor and Glass (1961) that the upper, silt-rich portion of the Porters Creek Clay was deposited during a regressional phase of the Porters Creek sea.

At the pit bottom there are other chemical changes shown in the plots of Al_2O_3 , S, Fe_2O_3 , and CaO concentrations versus depth. Al_2O_3 concentrations (Figure 18b) increase from 11.6 percent up to 14.6 percent at the 1.7 meter level. Sulfur concentrations (Figure 16a, page 54) range from about 0.3

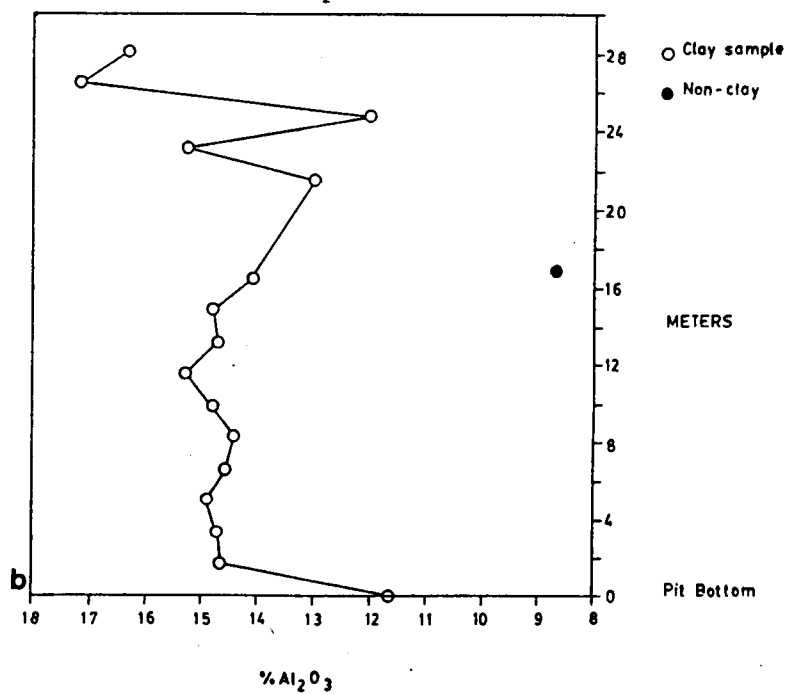
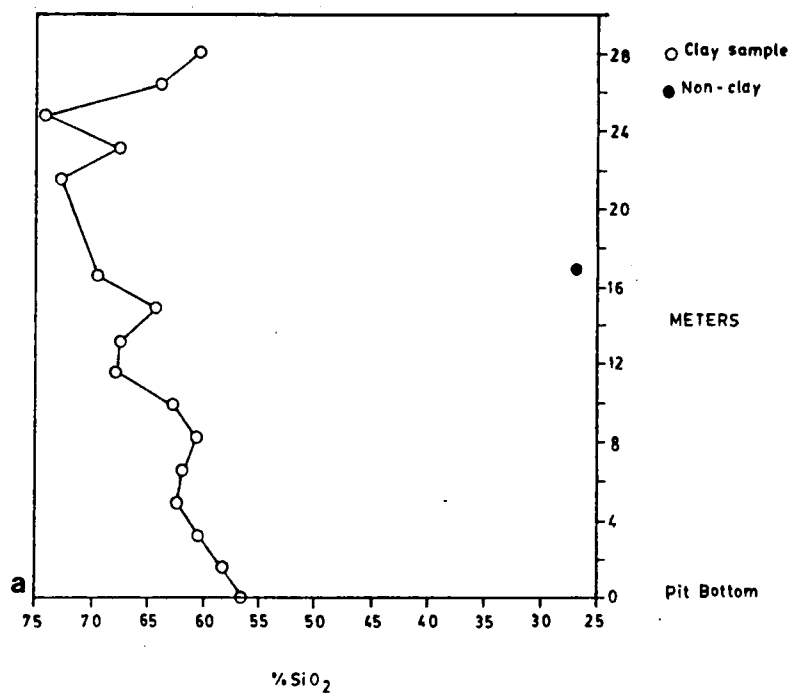


Figure 18. Bloomfield plot of SiO₂ concentration versus depth (a), plot of Al₂O₃ concentration versus depth (b). Note: the non-clay sample is from the weathered glauconite bed.

percent at the pit bottom to 0.65 percent at the 1.7 meter level. Fe_2O_3 concentrations (Figure 17a page 55) range from about 4.6 percent at the pit bottom and up to 6 percent at the 1.7 meter level. In contrast, the CaO concentration (Figure 19a) decreases from over 7 percent at the pit bottom to about 3 percent at the 1.7 meter level. These chemical variations are considered to be due to the abundant foraminifera observed in thin-section and disaggregated samples from the pit bottom.

Samples from other select parts of the section did not yield foraminifera upon disaggregation nor were they observed in thin-section.

Figures 19b, 20a and 20b illustrate the behavior of K_2O , MgO, and MnO concentrations. The K_2O concentration is generally fairly constant ranging between about 1.3 percent and 2 percent, except at the top of the pit. At the top of the pit, the K_2O concentration (Figure 19b) reaches a maximum of 2.6 percent, which may be due to more illite in the clay fraction. The plot of MgO concentration versus depth (Figure 20a) indicates a decrease in MgO concentration upward; however, the MgO concentration also increases near the top of the pit. The behavior of MgO parallels the behavior of K_2O . Both are considered due to changes in the composition of the clay minerals from mostly smectite to mostly illite. The concentration of MnO versus depth (Figure 20b) remains fairly constant except for the sharp increase in the uppermost level in the pit.

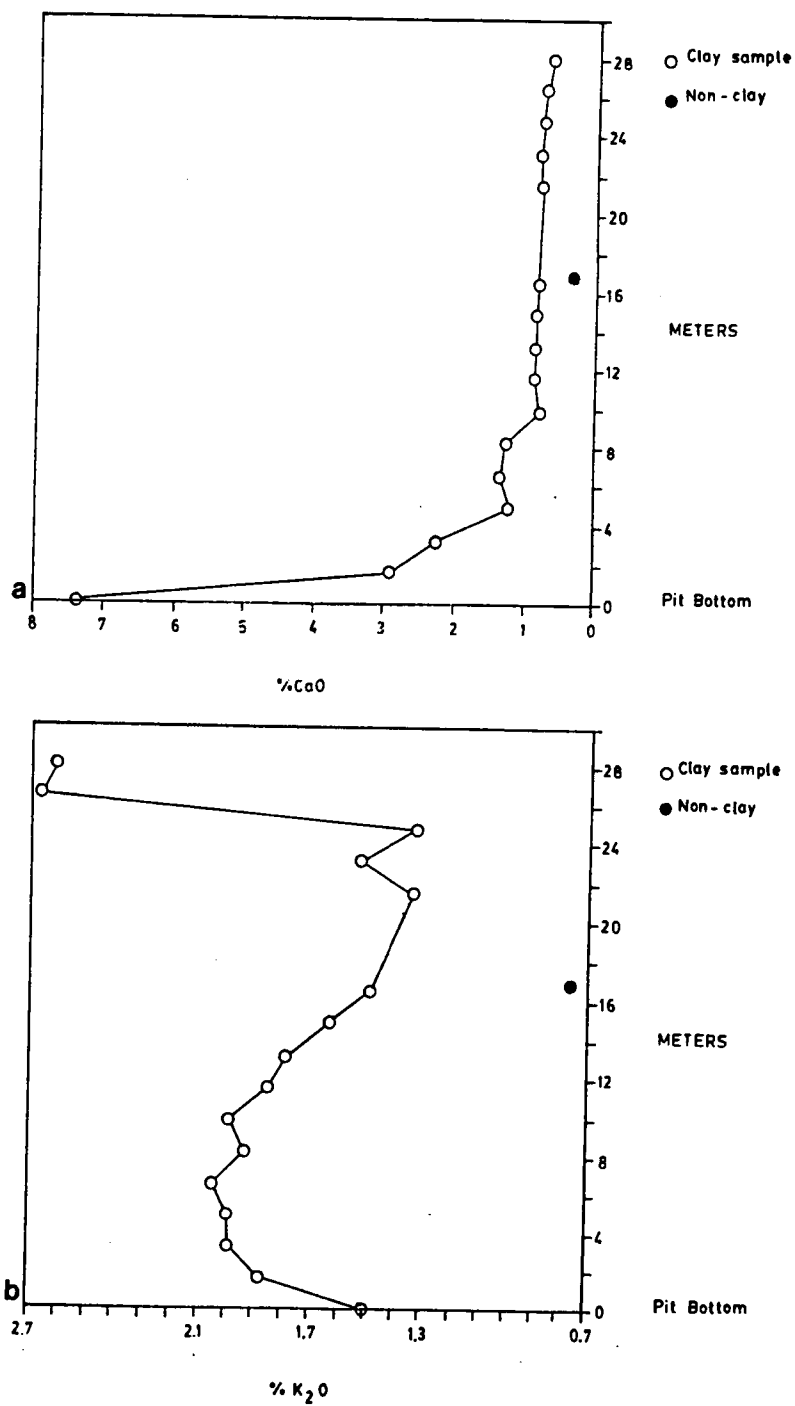


Figure 19. Bloomfield plot of CaO concentration versus depth (a), plot of K_2O concentration versus depth (b). Note: the non-clay sample is from the weathered glauconite bed.

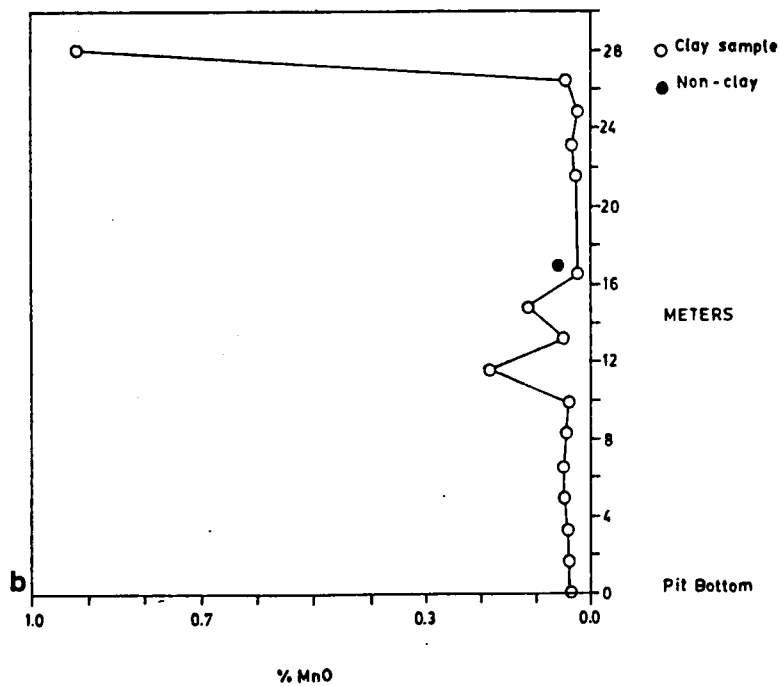
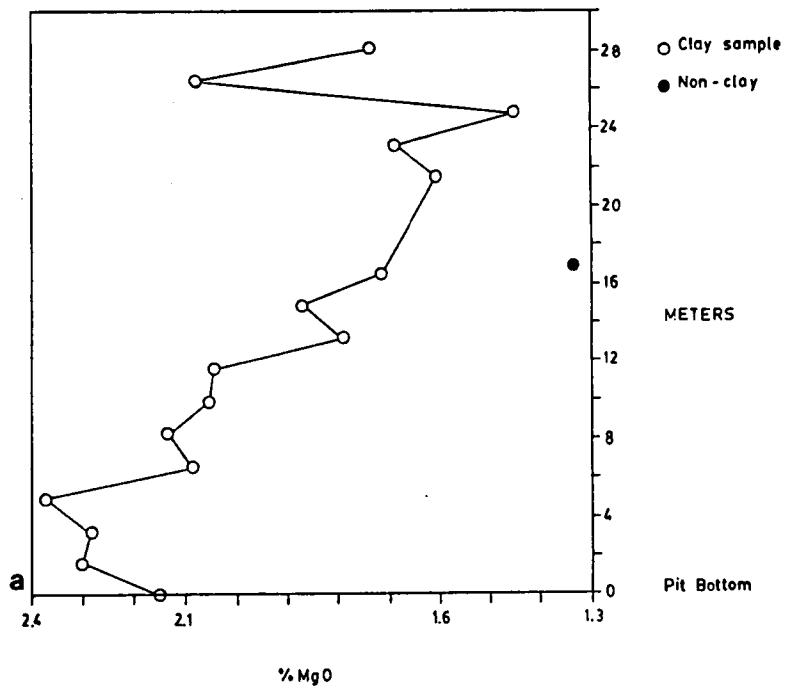


Figure 20. Bloomfield plot of MgO concentration versus depth (a), plot of MnO concentration versus depth (b). Note: The non-clay sample is from the weathered glauconite bed.

Bloomfield Concretions:

A more complete discussion of the nature and the origin of the concretions is beyond the scope of this research, but they are considered to provide important evidence about the diagenetic processes that occurred in the Porters Creek Clay. The following discussion is intended only to serve as an introduction to any later studies done on the concretions.

The concretions range in size from about 10 centimeters (Figure 21) up to about a meter, when measured along their longest axis. They all have bedding-parallel elongation or flattening. Most of the large concretions have well-developed septarian fractures that appear to have never been filled by any mineral precipitate, as is normally the case with septarian nodules. Some septarian fractures are so well developed that polygonal, "pillar-like" structures are evident. These structures extend to within about 5 to 10 centimeters of the concretion rim. The polygonal structures are generally enclosed by a 5 to 10 centimeter thick rim. Generally, the larger the concretion the more intense the degree to which it has been fractured. This is thought to be due to late compaction and the brittle nature of the concretions. Bulk analysis indicates a fairly consistent chemical composition with 34 to 38 percent Fe_2O_3 , 12 to 27 percent SiO_2 , and minor Al_2O_3 .

Based on the data from this study, one possible mode of concretion formation may be related to burrowing organisms.



Figure 21. Typical concretion from the Porters Creek of Missouri (the long axis of the concretion is approximately 75 centimeters in length).

The internal portions of many of the large concretions were found to preserve burrowing of an intensity not observed in the surrounding clay. There was also some deformation of laminae around concretions indicating that their formation was fairly early in the diagenetic history of the formation, i.e., shortly after burial of the incipient concretion horizon.

Large, nodular concentrations of clay cemented with siderite also occur in the same horizon. Texturally they are totally different from the surrounding clay sediments. The nodules appear to be very porous when compared to the surrounding strata, and siderite occupies much of that pore space.

The precipitation of siderite in these nodules is thought to be the result of the decay of dead, burrowing organisms. Ammonia produced by decay would result in a high pH micro-environment where siderite precipitation would be possible (Weeks, 1957). Other authors contend that marine siderite is unlikely. Berner (1971) suggested that for the low Eh values where siderite is stable, sulfate reduction must be complete or inhibited. He considered the situation unlikely in marine deposits, and in addition, it has never been observed in modern marine sediments.

Curtis and Coleman (1986) stated that carbonate concretions are common in organic-rich clastic sediments of ancient deltas and flood plains. They considered that in these environments siderite was

precipitated from meteoric waters low in dissolved sulfate, whereas higher concentrations (like those found in sea water) would inhibit siderite formation.

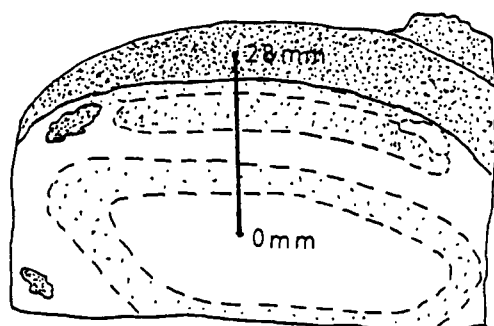
Shannon (1977) studied siderite concretions of the Ribband Group of Ireland. These strata are generally siltstone and shale. He noted that the concretions occur associated with horizontal grazing trails. Shannon contended that concretion formation was associated with decay of soft-bodied burrowers. Their decay occurred well below the sediment-water interface where the available sulfate could be depleted (after enough compaction had occurred) to exclude the downward diffusion of sulfate. At this point in time the decay produces NH_3 and CO_2 , which are accompanied by a pH increase associated with excess ammonia like that described by Weeks (1957). These conditions, combined with the readily available supply of detrital iron-bearing minerals, makes the precipitation of siderite possible.

The models for siderite precipitation proposed by Weeks (1957) and Shannon (1977) and similar arguments put forth by Duursma (1965), Hodgson (1968) and Berner (1968) are likely to have been the case in the Porters Creek concretions.

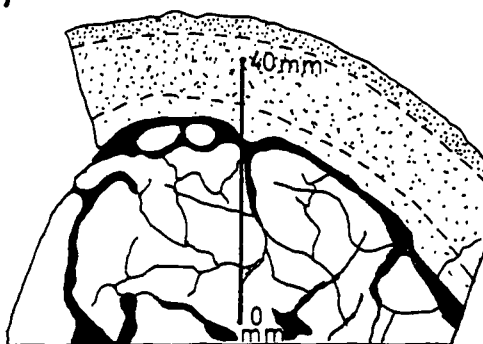
The siderite-cemented nodules were later altered by meteoric waters to the observed goethitic and limonitic concretions. This alteration proceeded from the exterior to the interior of the siderite-cemented nodules. In some cases clay was preserved at the core of concretions or at the core

of "pillar-like" polygonal structures. This is probably due to a limiting thickness of material that can be altered and still allow the altering fluid to enter. In the concretions that are completely altered, fracturing appears to have occurred along with alteration, making it possible to alter more of the siderite-cemented clay. Figure 22 is a sketch of the analyzed concretions and illustrates the orientation of the analytical traverses. The material labeled "marine resin" was use to hold the fractured sample together during collection, preparation and analysis. Figures 23a, 23b, 24a, and 24b illustrate the behavior of Al_2O_3 and SiO_2 concentrations along analytical traverses done on samples CM165A1 and CM207. The concentrations of SiO_2 and Al_2O_3 decrease from the center towards the rim of sample CM165A1 (Figure 23a and 23b). However, the relative contribution of silica is different in sample CM207 as is evident by the lower SiO_2 concentration at the core (Figure 24b). The difference is considered to be due to sample CM207 being more clay-rich at the core than CM165A1. The reduced Al_2O_3 and SiO_2 concentrations seen at the rim of both concretions is thought to be due to alteration at the rim that formed the iron-oxide rind.

Figures 25a, 25b, 26a, and 26b are plots of Fe_2O_3 and S concentrations for samples CM165A1 and CM207. In sample CM165A1 Fe_2O_3 and S concentrations (Figure 25a and 25b) decrease from the rim toward the core, but in sample CM207



CM207



CM165A1

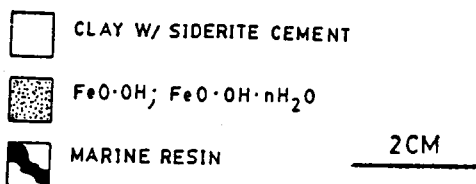


Figure 22. Sketch of the analyzed traverses across samples CM165A1 and CM207.

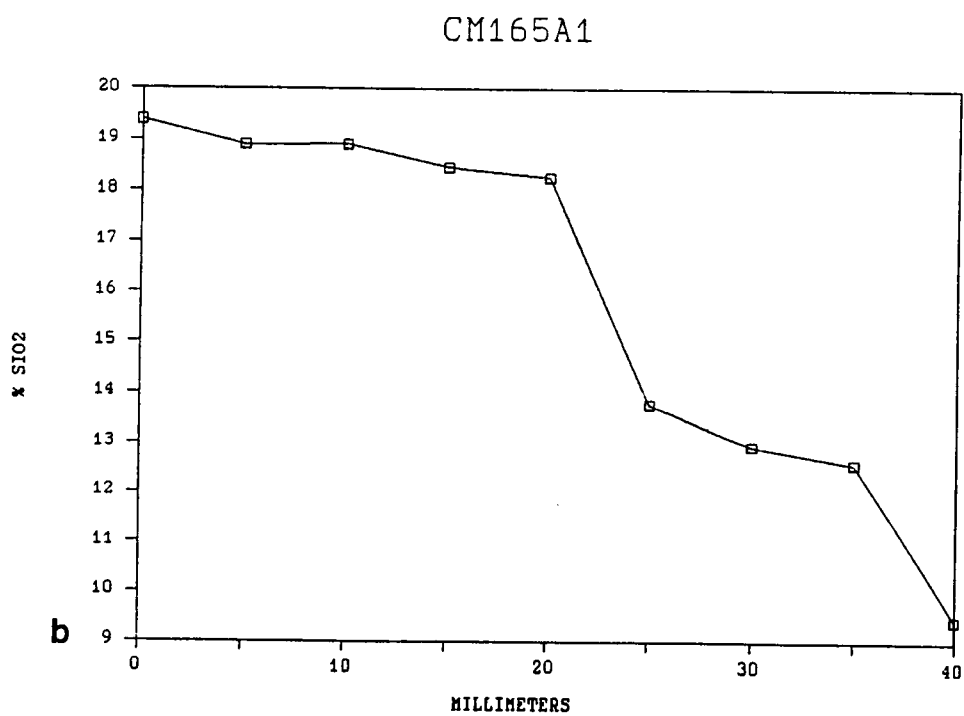
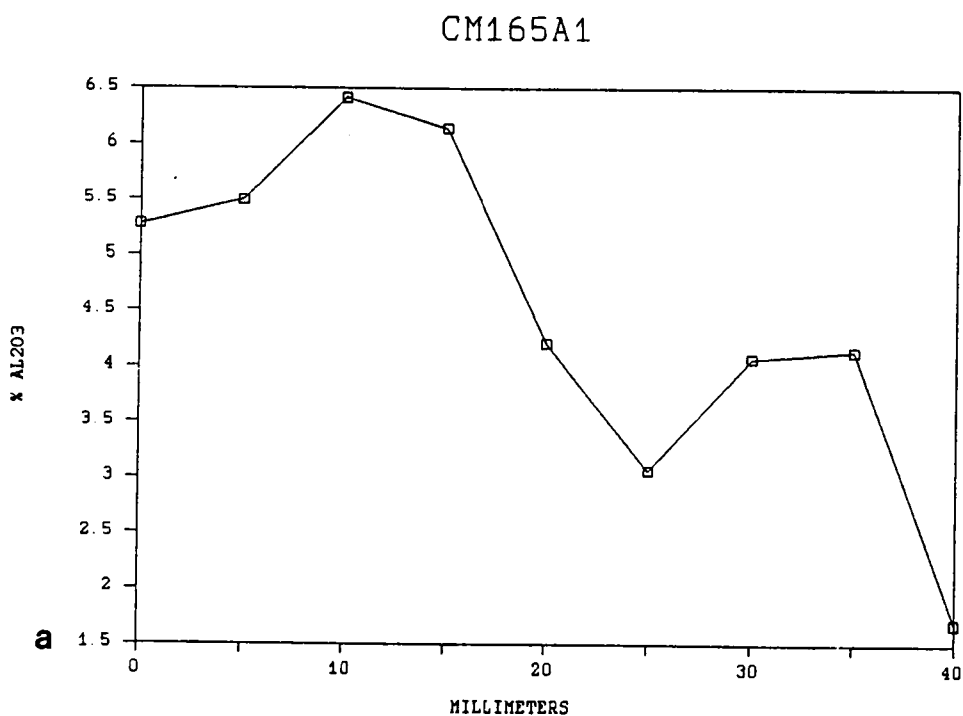


Figure 23. Analytical traverse across concretion CM165A1, Al_2O_3 (a) and SiO_2 (b).

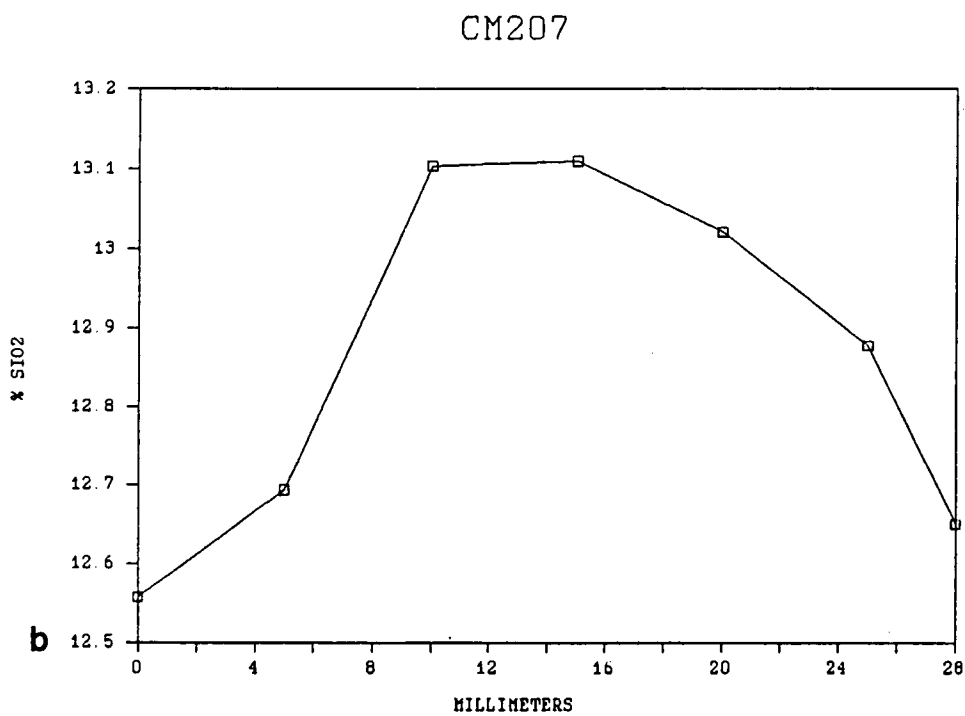
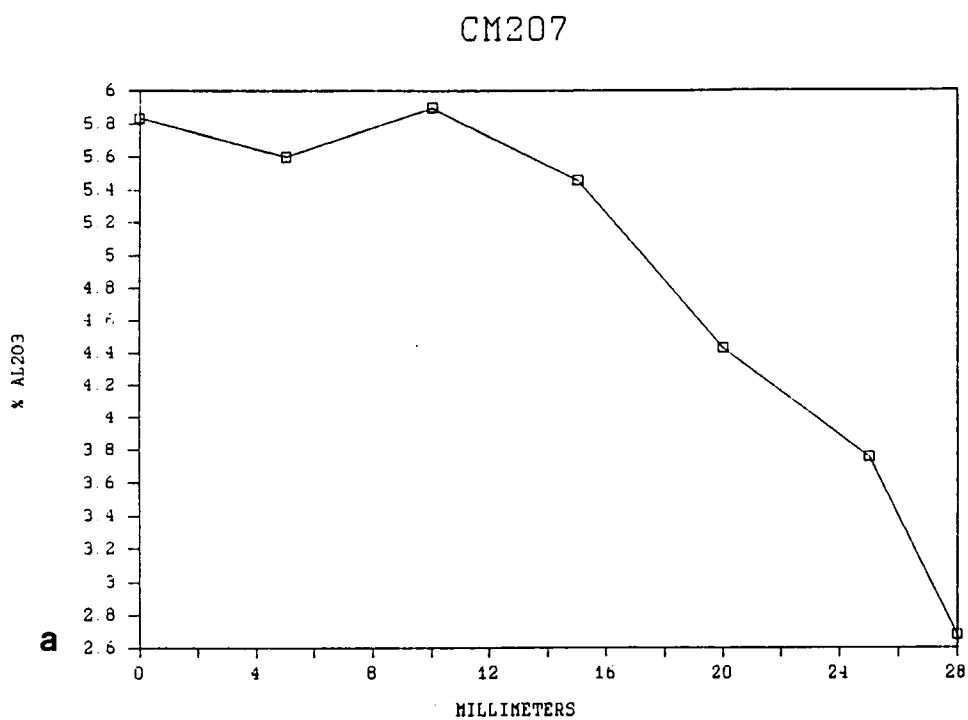


Figure 24. Analytical traverse across concretion CM207, Al_2O_3 (a) and SiO_2 (b).

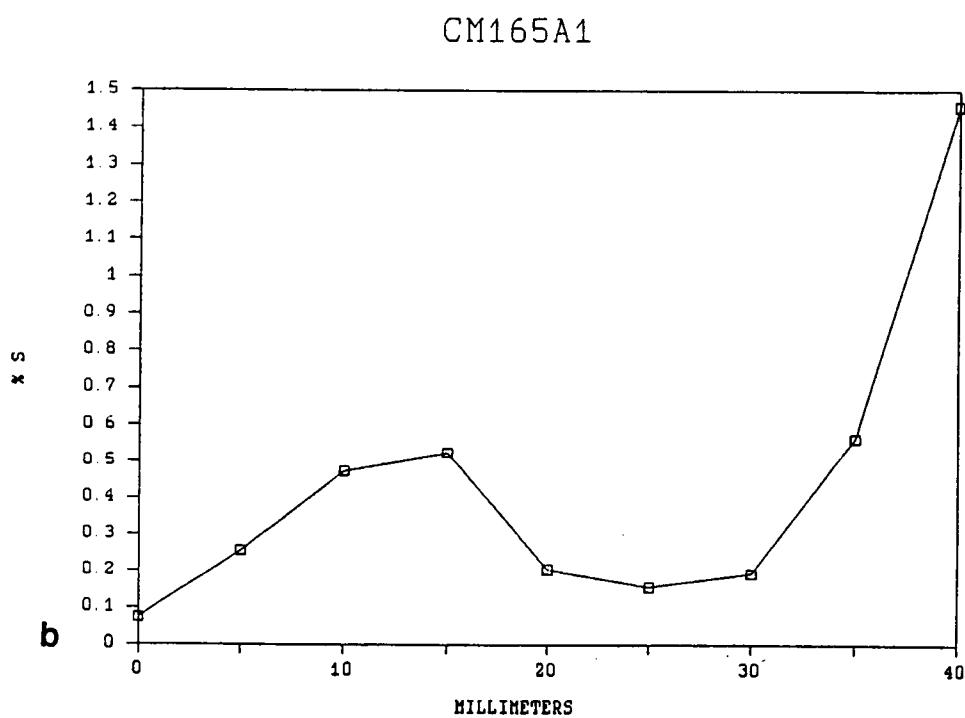
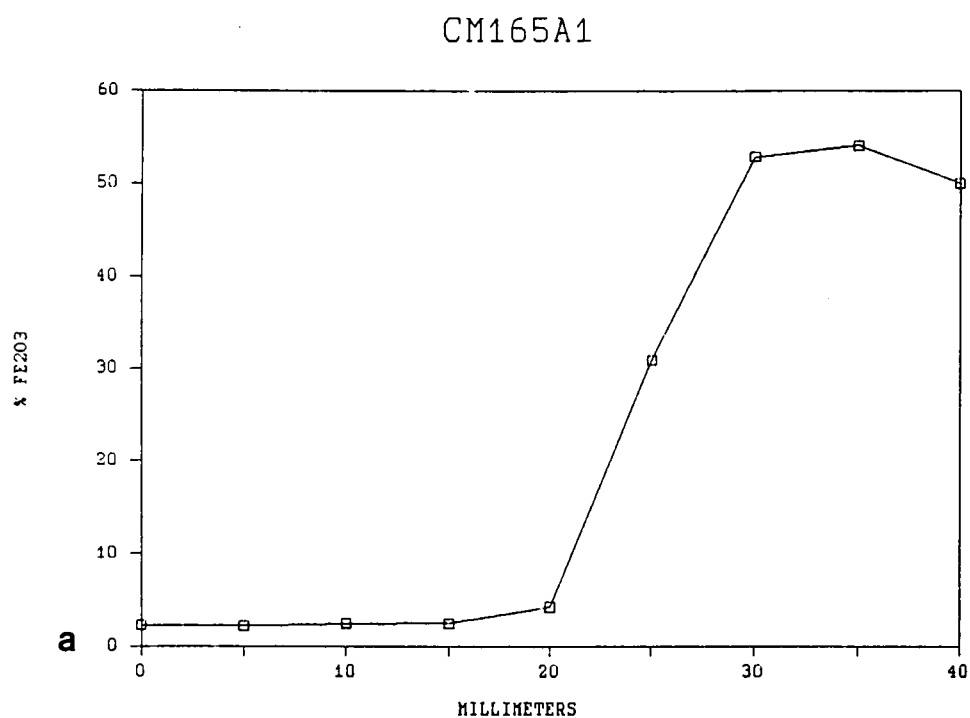


Figure 25. Analytical traverse across concretion CM165A1, Fe_2O_3 (a) and S (b).

these two variables (Figures 26a and 26b) have an inverse relationship, and S is highest at the core.

Figures 27a, 27b, 28a and 28b illustrates the behavior of CaO and S concentrations in samples CM165A1 and CM207. Figures 27a and 27b indicates that the concentration of CaO and S are highest at the rim of sample CM165A1, but in sample CM207 the concentration of CaO and S are highest in its core (Figures 28a and 28b).

Based on the plots of Fe_2O_3 and S concentration across the concretions, it is thought that iron sulfides such as pyrite are not important at the core of the concretions. But the plots of CaO and S concentration indicate that late-formed gypsum may be important at the core of sample CM207 (Figure 28a and 28b) and at the rim of sample CM165A1 (Figure 27a and 27b). The reason for this relationship between CM207 and CM165A1 is unclear at this time, but may be related to changes in porosity with time. Concretion CM207 may have formed while porosity was such that late, cementing fluids could reach the core of the sample. But sample CM165A1 could have been cemented at a time when lower porosities allowed fluids to enter only the outer surface.

Figures 29a, 29b, 30a, 30b, 31, and 32 are plots of MgO , K_2O , and Sr concentrations across concretions CM165A1 and CM207, and all values increase from the rim to the core of both samples. This is due to higher proportions of clay minerals at the core of the concretions than at the rim.

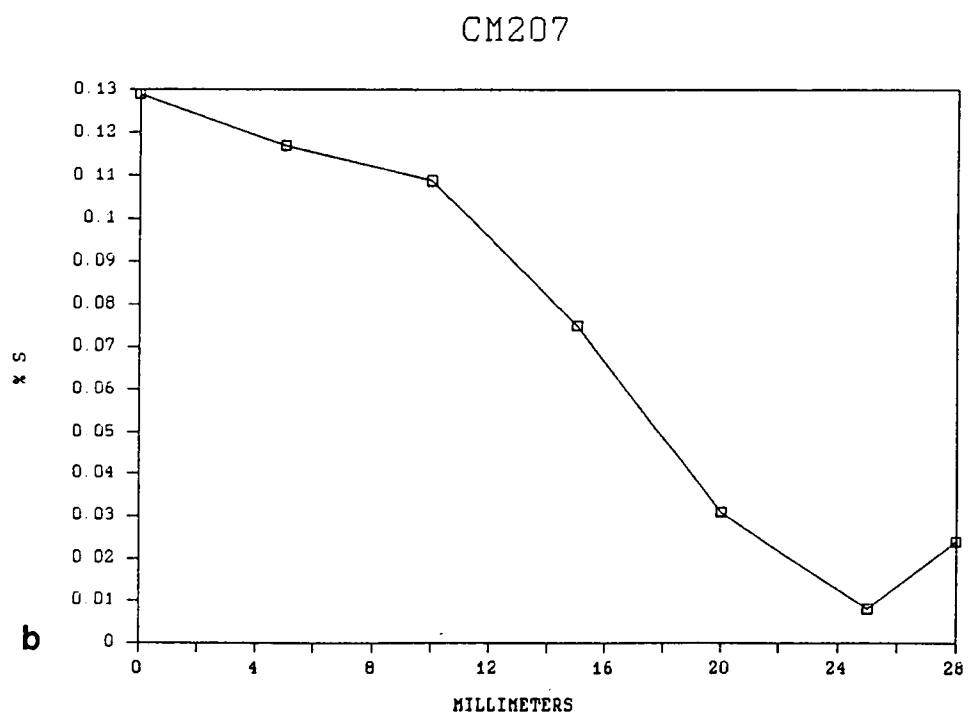
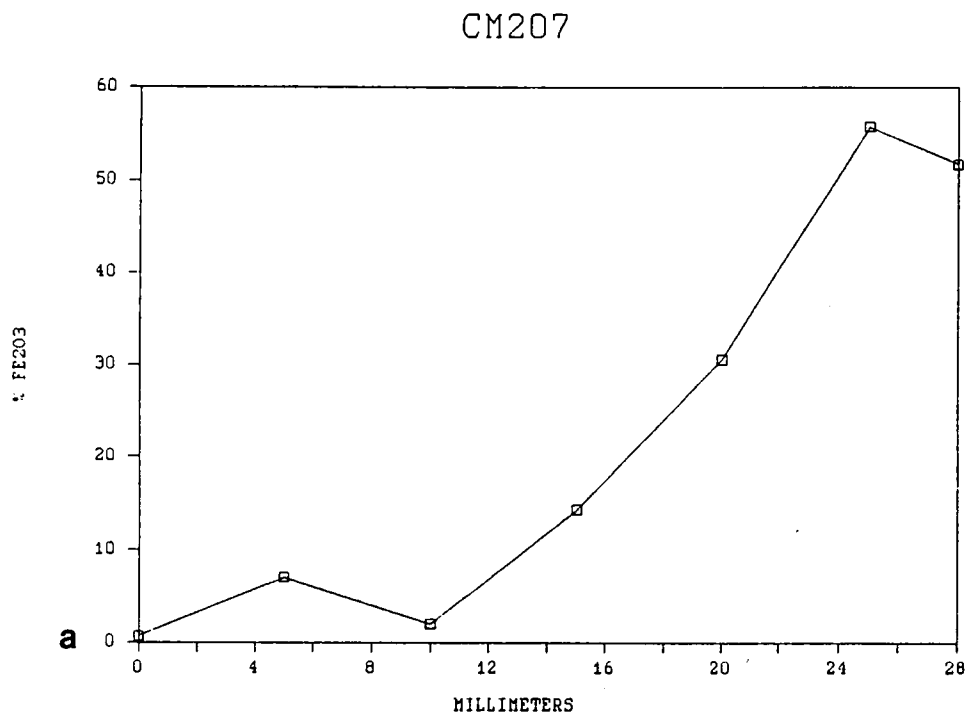
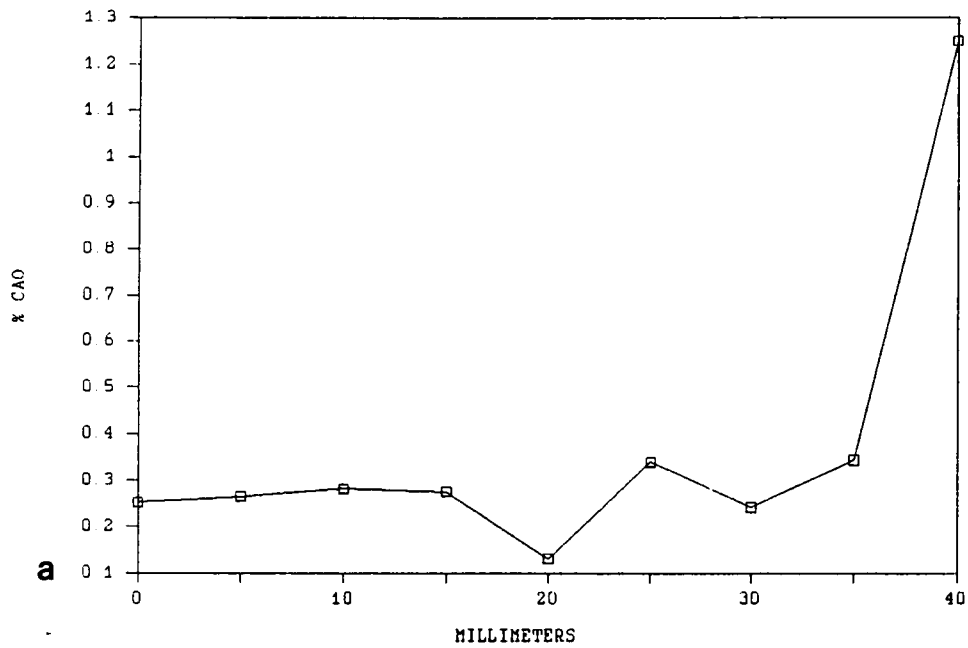


Figure 26. Analytical traverse across concretion CM207, Fe₂O₃ (a) and S (b).

CM165A1



CM165A1

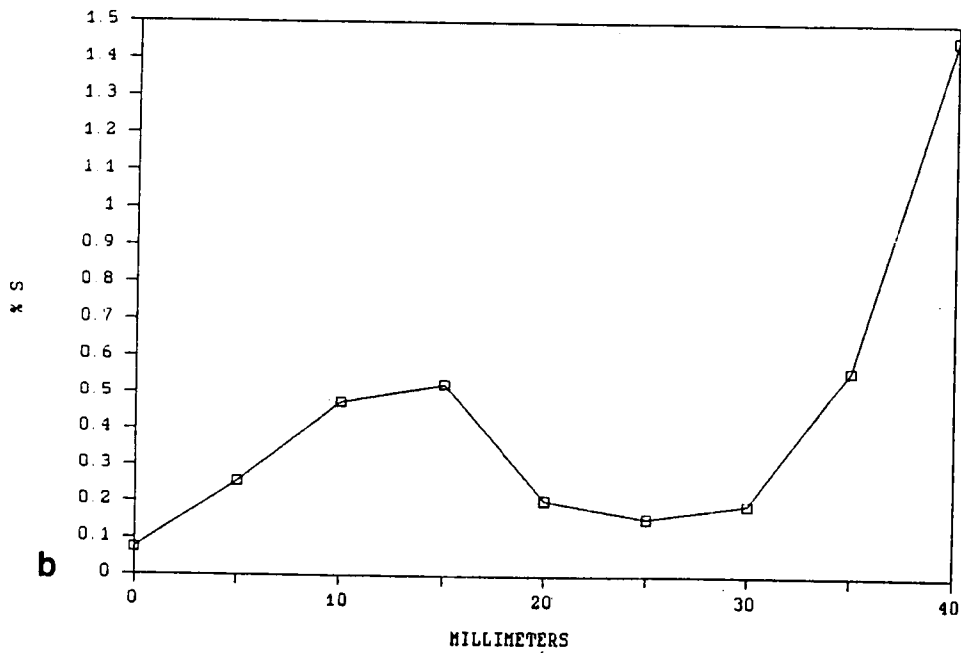


Figure 27. Analytical traverse across concretion CM165A1, CaO (a) and S (b).

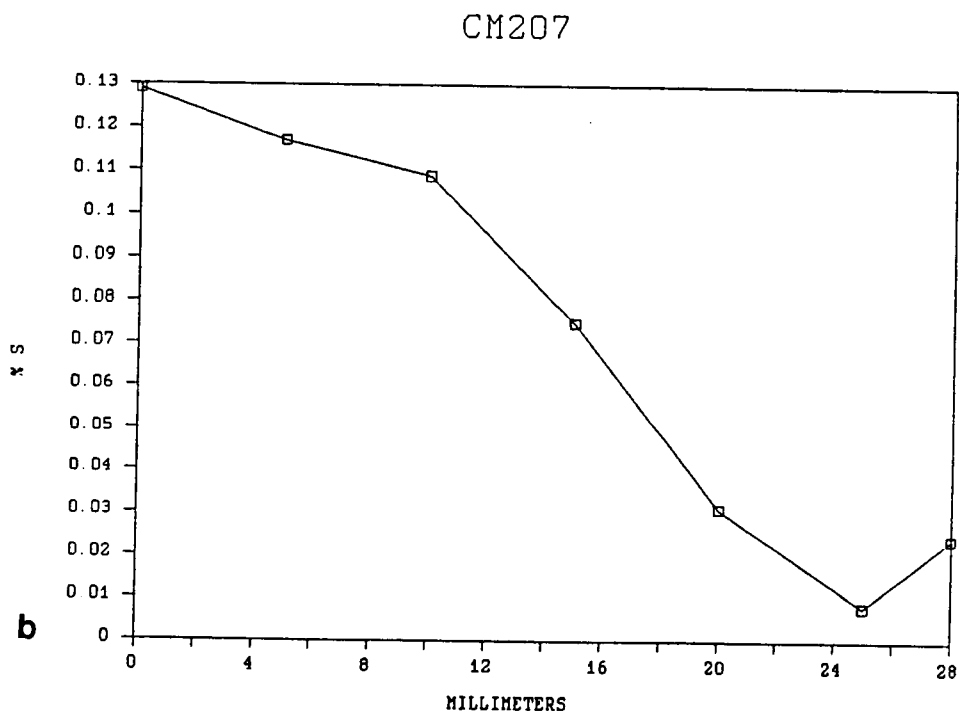
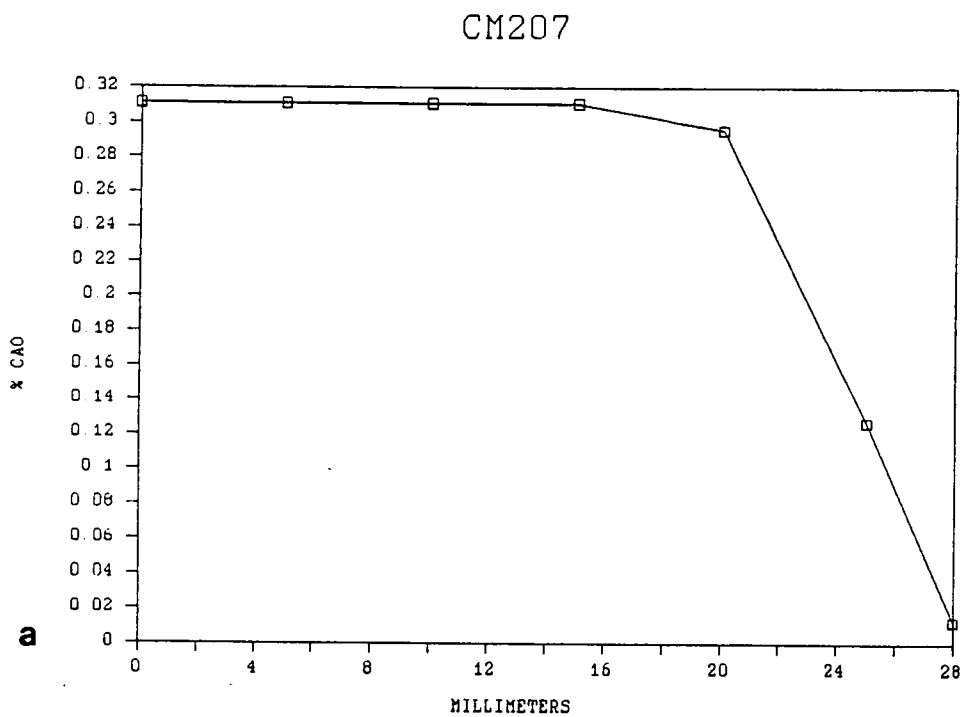


Figure 28. Analytical traverse across concretion CM207, CaO (a) and S(b).

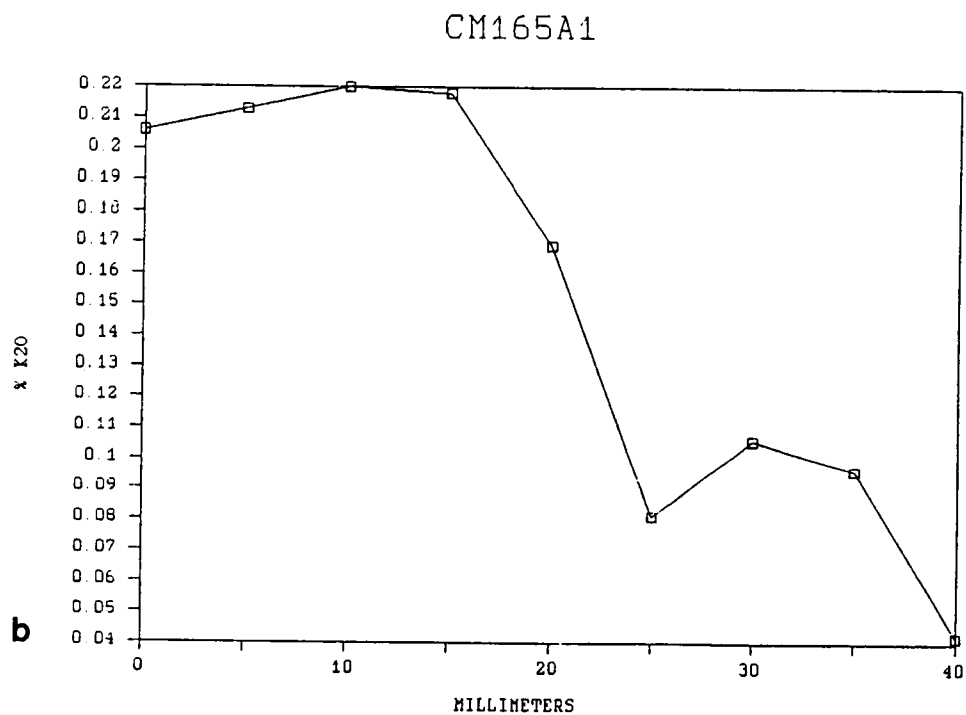
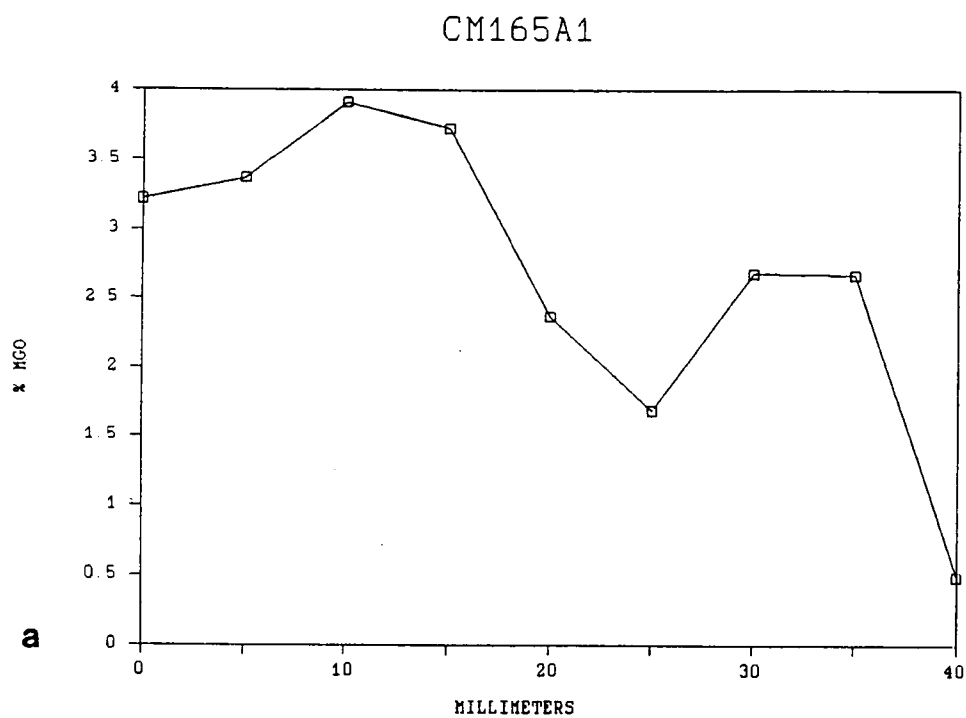


Figure 29. Analytical traverse across concretion CM165A1, MgO (a) and K₂O (b).

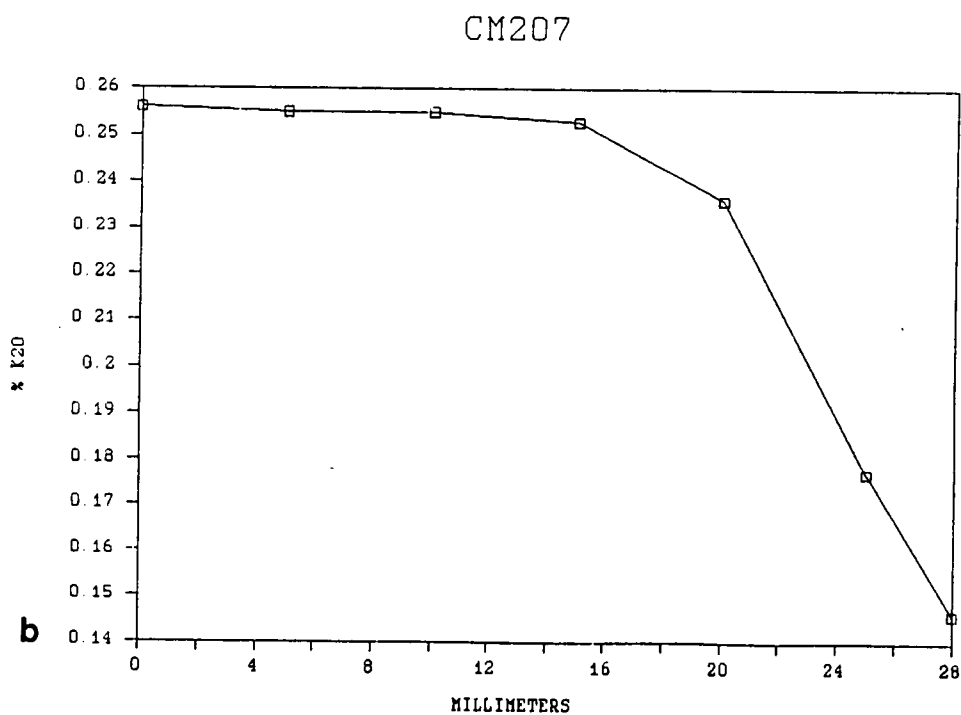
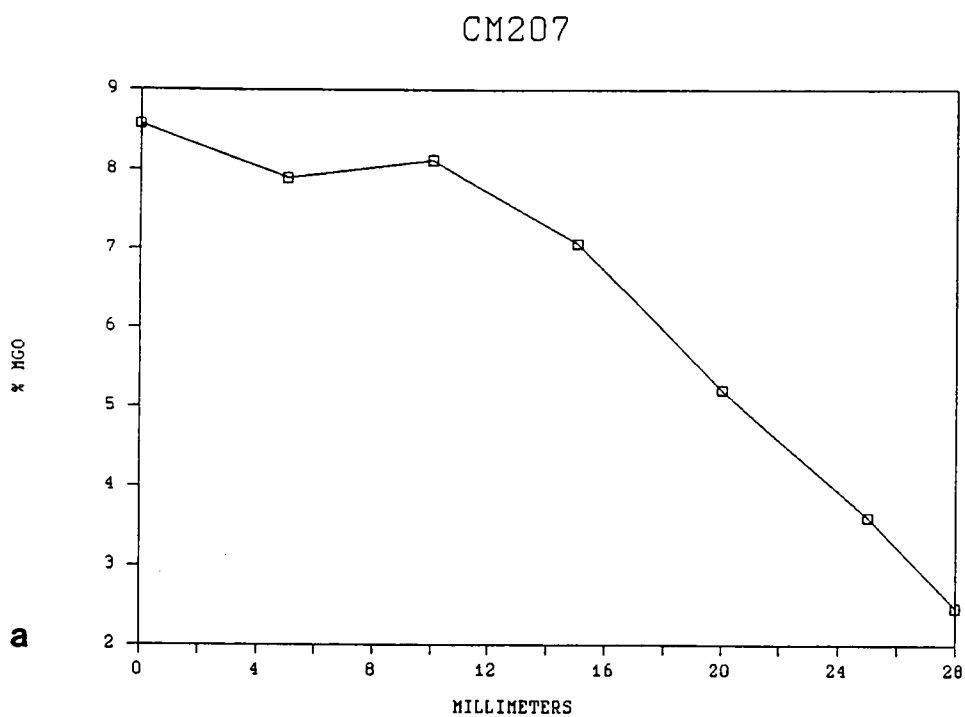


Figure 30. Analytical traverse across concretion CM207, MgO (a) and K₂O (b).

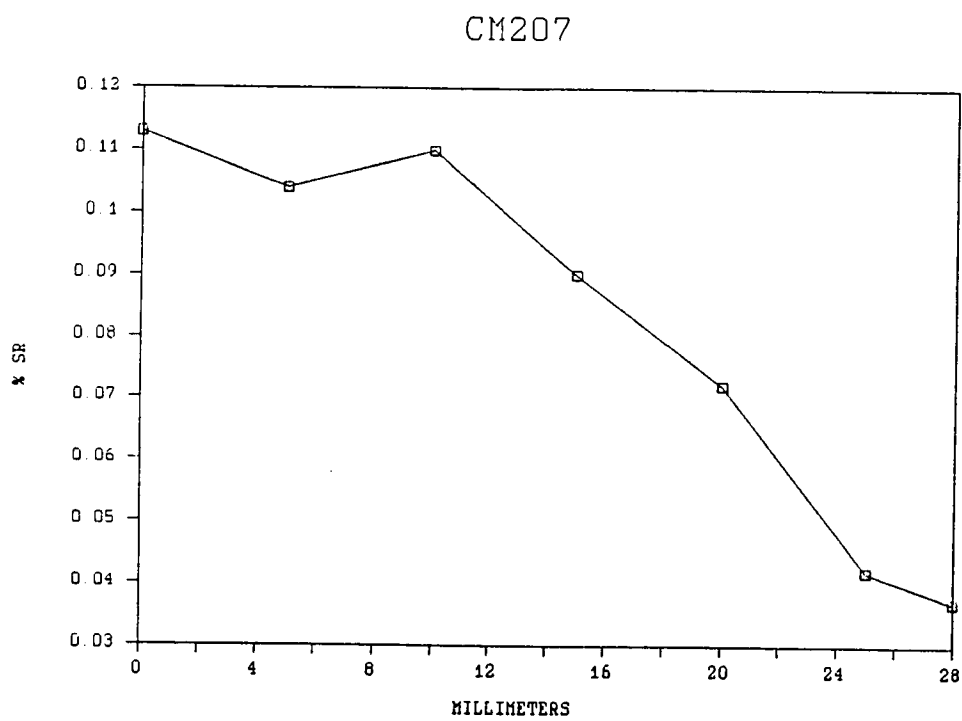


Figure 31. Analytical traverse across concretion CM207 for Sr.

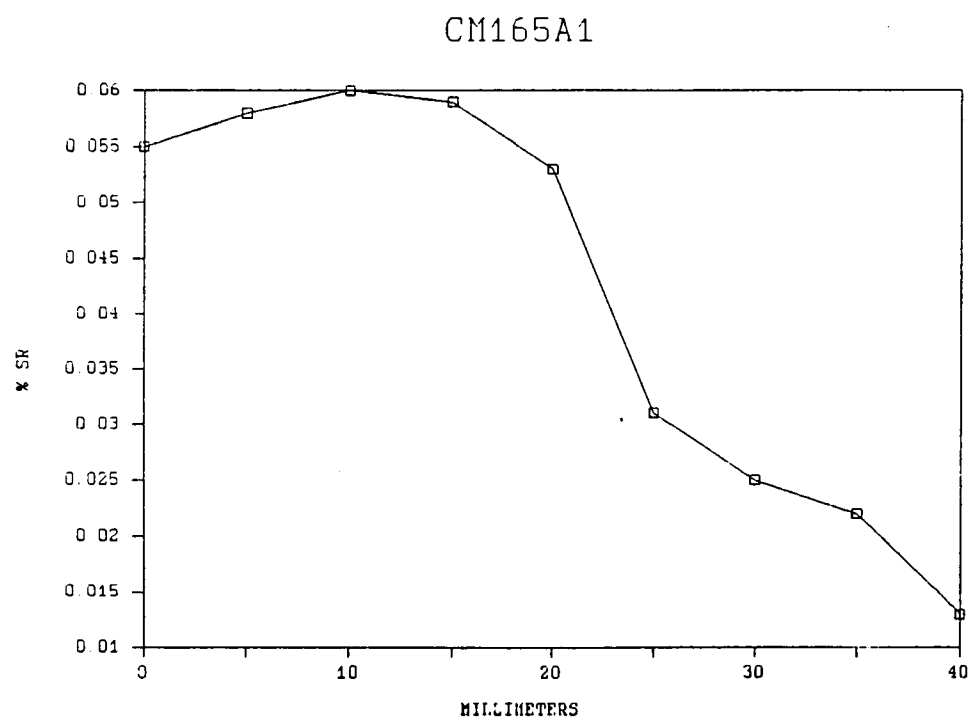


Figure 32. Analytical traverse across concretion CM165A1 for Sr.

Olmsted

Figures 33a and 33b illustrates the behavior of S and P_2O_5 concentrations in the Olmsted pit. The concentration of S and P_2O_5 is relatively high below about the 5 to 6 meter level. The change in the sulfur concentration is considered to be due to pyrite, whereas the P_2O_5 concentration is thought to be related to phosphorus in the organics. The fairly high P_2O_5 concentration seen at the 12.8 meter level in the pit may be associated with detrital phosphate in the form of either detrital phosphate minerals or fine invertebrate shell fragments. Due to the low P_2O_5 concentration, discrete mineral phases were not observed in thin-section or in XRD data. The relationship between these two variables is very similar to the behavior of the same variables at Bloomfield.

Figures 34a and 34b shows the behavior of SiO_2 and Al_2O_3 concentrations and the generally inverse relationship between them. Silica is fairly constant from the top of the pit down to the 8 meters level. Below this point SiO_2 shows a steady decrease from almost 75 percent to about 54 percent at the pit bottom. In contrast, Al_2O_3 has considerable variation from the top of the pit down to the 8 meter level, where the Al_2O_3 concentration begins a steady increase from about 12.5 percent up to over 18 percent at the pit bottom. The described variations in SiO_2 and Al_2O_3 are considered to be due to the occurrence of more quartz silt above the 8 meter level of the pit. The fluctuations of the Al_2O_3 concentration seen above

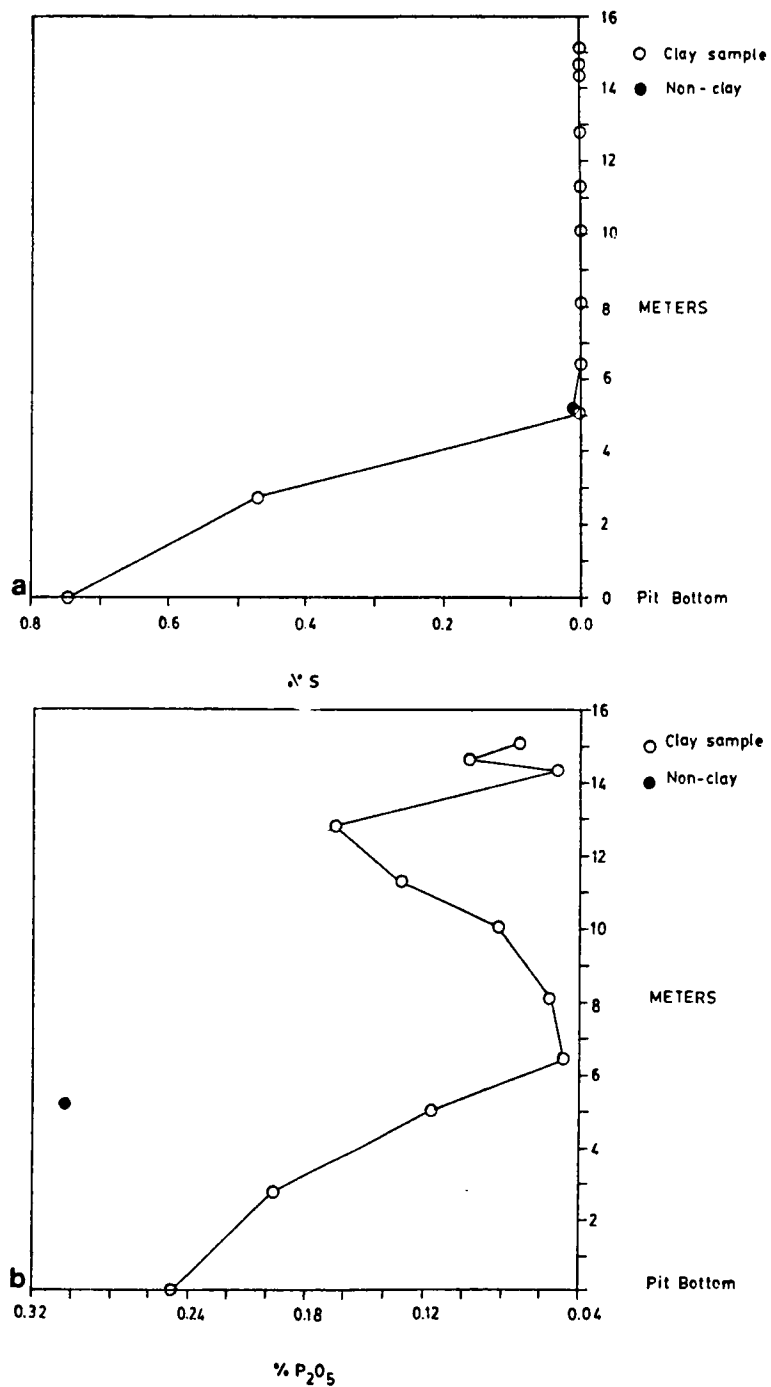


Figure 33. Olmsted plot of S concentration versus depth (a), plot of P₂O₅ concentration versus depth (b). Note: the non-clay sample is the weathered glauconitic bed.

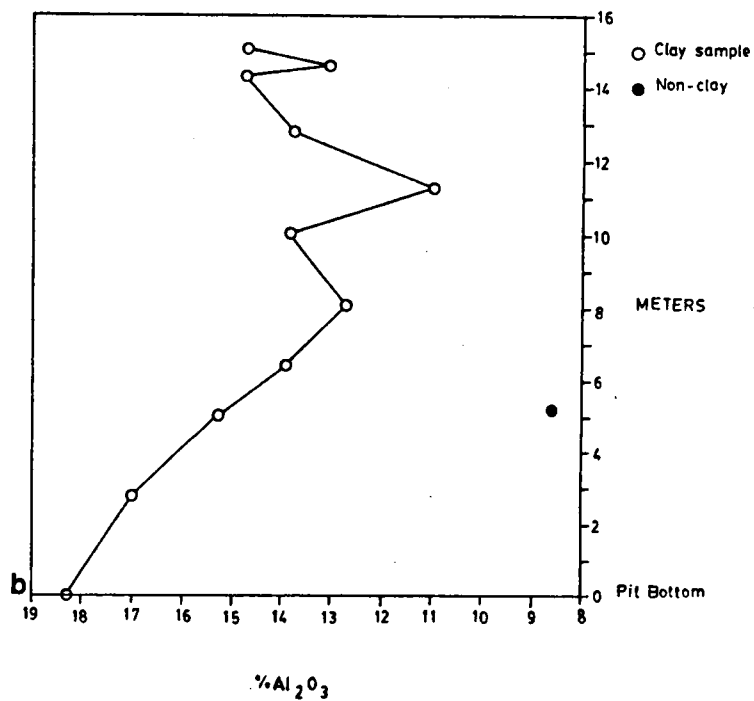
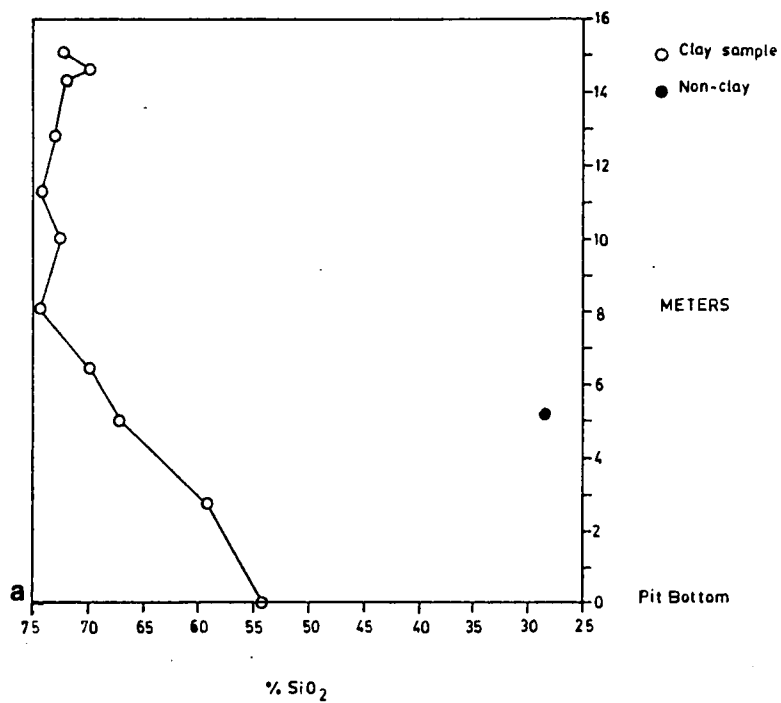


Figure 34. Olmsted plot of SiO_2 concentration versus depth (a), plot of Al_2O_3 concentration versus depth (b). Note: The non-clay sample is the weathered glauconite bed.

the 8 meter level are thought to be related to the dilution of the amount of clays present by the quartz silt.

Figures 35a and 35b are plots of Al_2O_3 and Fe_2O_3 concentrations versus depth. Generally, both illustrate an increase in their concentration with depth, but note that an inverse relationship between sample points is observable above the 8 meter level, i.e. when the Fe_2O_3 concentration of a sample is high the Al_2O_3 concentration for that sample is low. This relationship is thought to be related to the fluctuation in the influx of detrital iron minerals above the 8 meter level. Below this level there is a general smoothing of both curves. Below the 8 meter level, the change in the Fe_2O_3 is thought to be related to an increased importance of authigenic pyrite

Figures 36a, 36b, 37a, and 37b are plots of the concentration of K_2O , MgO , MnO , and CaO . The K_2O and MgO concentrations (Figures 36a and 36b) tend to increase with depth and are considered to be related the dilution of clays by quartz silt in the upper part of the section. The MnO concentration is greatest at the top of the pit (Figure 37a). Below about 13 meters there is a gradual increase in the MnO concentration. This increased MnO concentration at the top of the pit is considered to be due to the same kind of groundwater processes that produced a similar trend in the Bloomfield section. Note that the change in the MnO

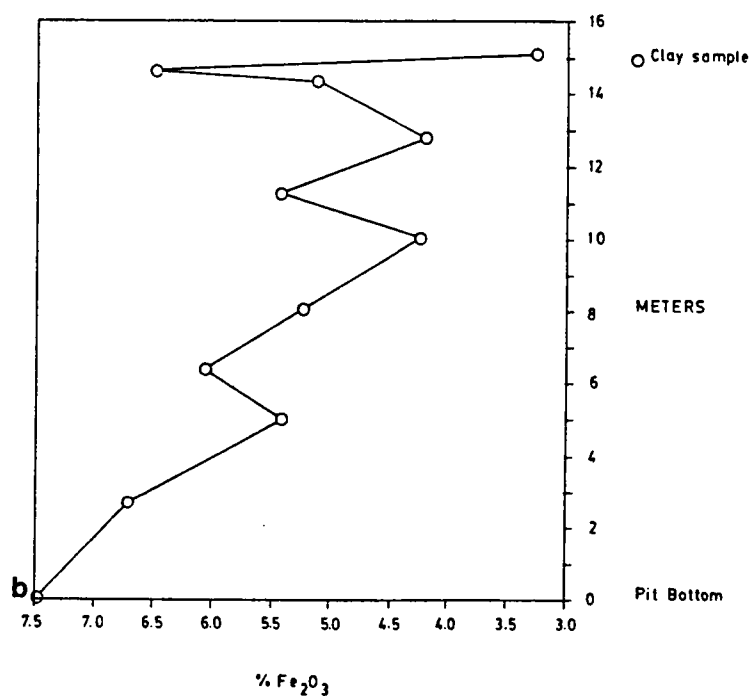
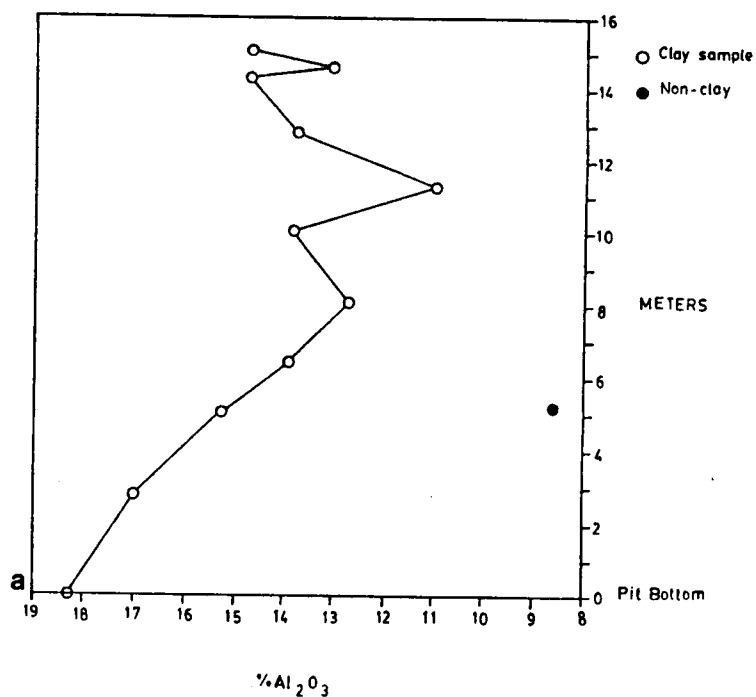


Figure 35. Olmsted plot of Al_2O_3 concentration versus depth (a), plot of Fe_2O_3 concentration versus depth (b). Note: The non-clay sample is from the weathered glauconite bed.

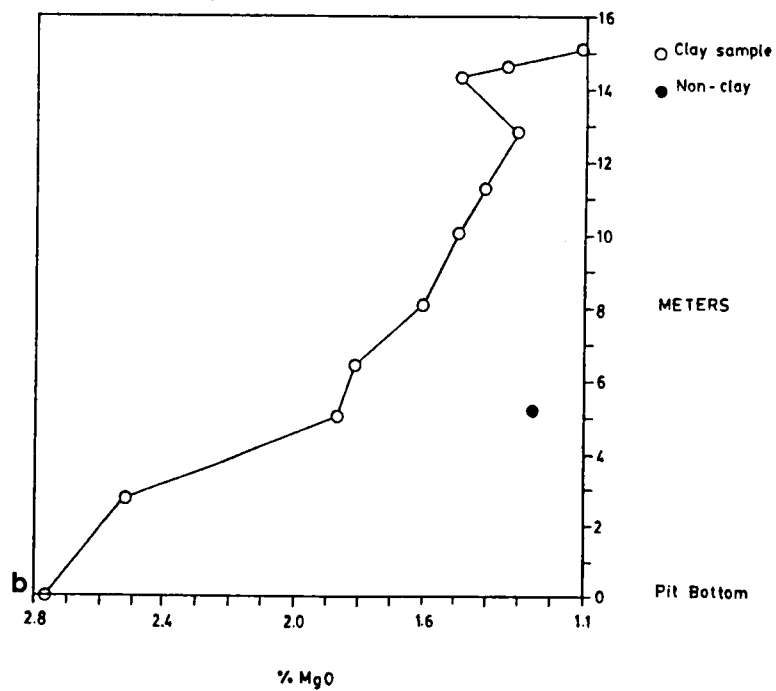
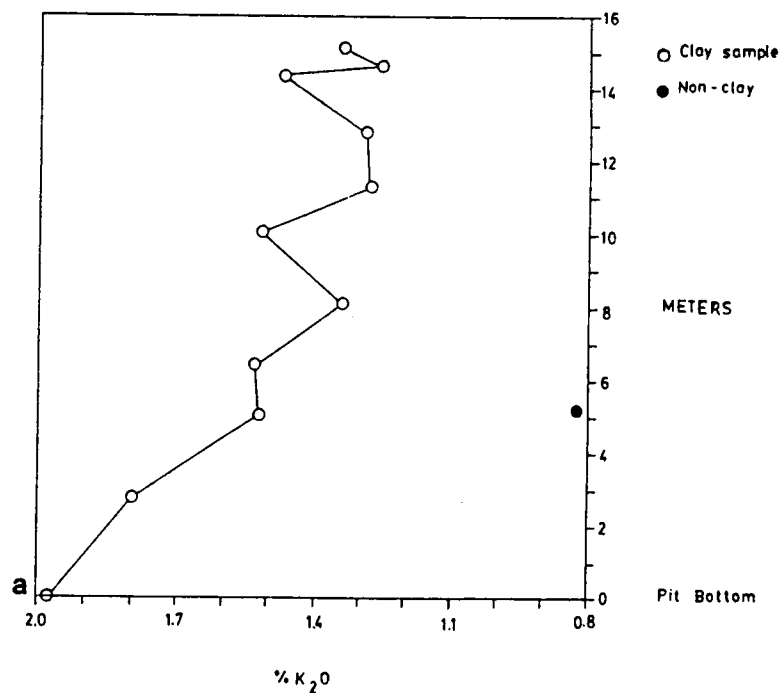


Figure 36. Olmsted plot of K_2O concentration versus depth (a), plot of MgO concentration versus depth (b). Note: The non-clay sample is from the weathered glauconite bed.

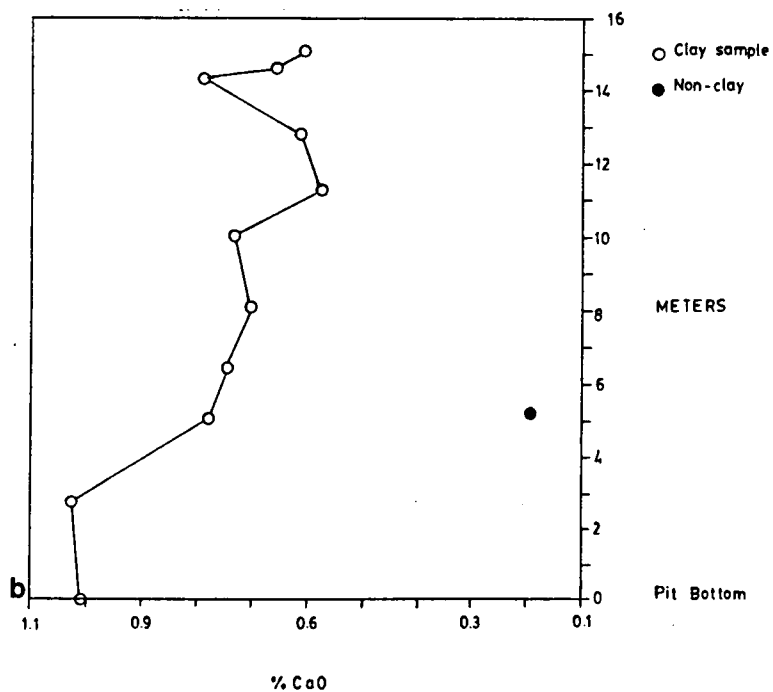
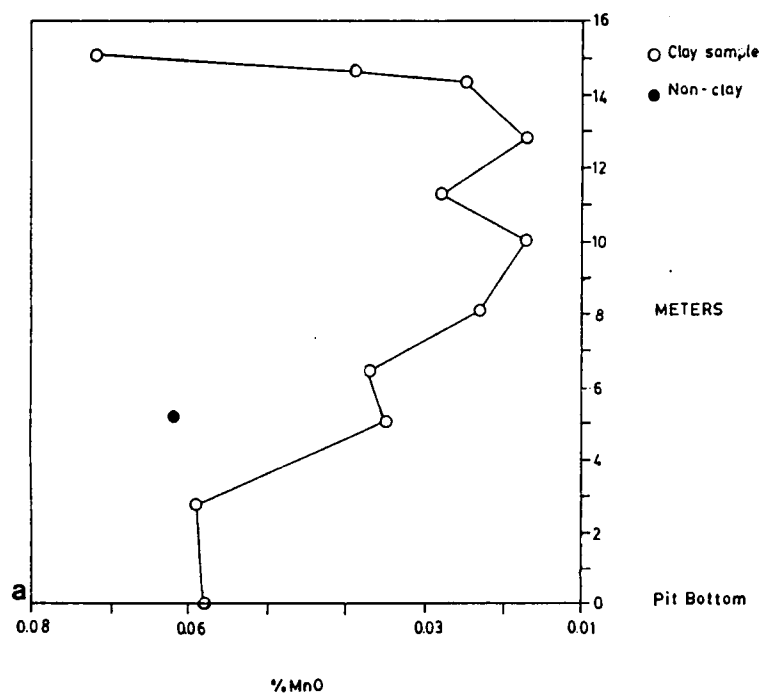


Figure 37. Olmsted plot of MnO concentration versus depth (a), plot of CaO concentration versus depth (b). Note: The non-clay sample is from the weathered glauconitic bed.

concentrations at the top of the pit could be related to recent groundwater processes or to groundwater processes associated with the unconformity at the top of the formation. Although at this time it is unknown what the exact nature of the groundwater processes were.

The plot of CaO concentrations versus depth (Figure 37b) illustrates a fairly small change in concentration, ranging from 0.58 percent to a little over 1 percent. This change is considered small and unimportant when compared the range of CaO concentrations seen at the Bloomfield pit.

Paris

In general, it has been possible to relate many of the chemical trends at Bloomfield and Olmsted to lithologic variations, but at Paris the correlation between lithologic changes and bulk chemical changes are not always clear. This lack of clarity is thought to be due to the disruption of the Paris section by clastic dikes.

The most obvious relationship is seen between SiO_2 and Al_2O_3 concentrations (Figures 38a and 38b). Their inverse relationship is most evident at about the 22 meter level in the pit. Similar relationships were noted at Bloomfield and Olmsted. When there is an increase in the silica concentration there is a decrease in the Al_2O_3 concentration. As with Bloomfield and Olmsted, this relationship is considered to be associated with the higher quartz silt concentration above the 18 to 20 meter level of the pit.

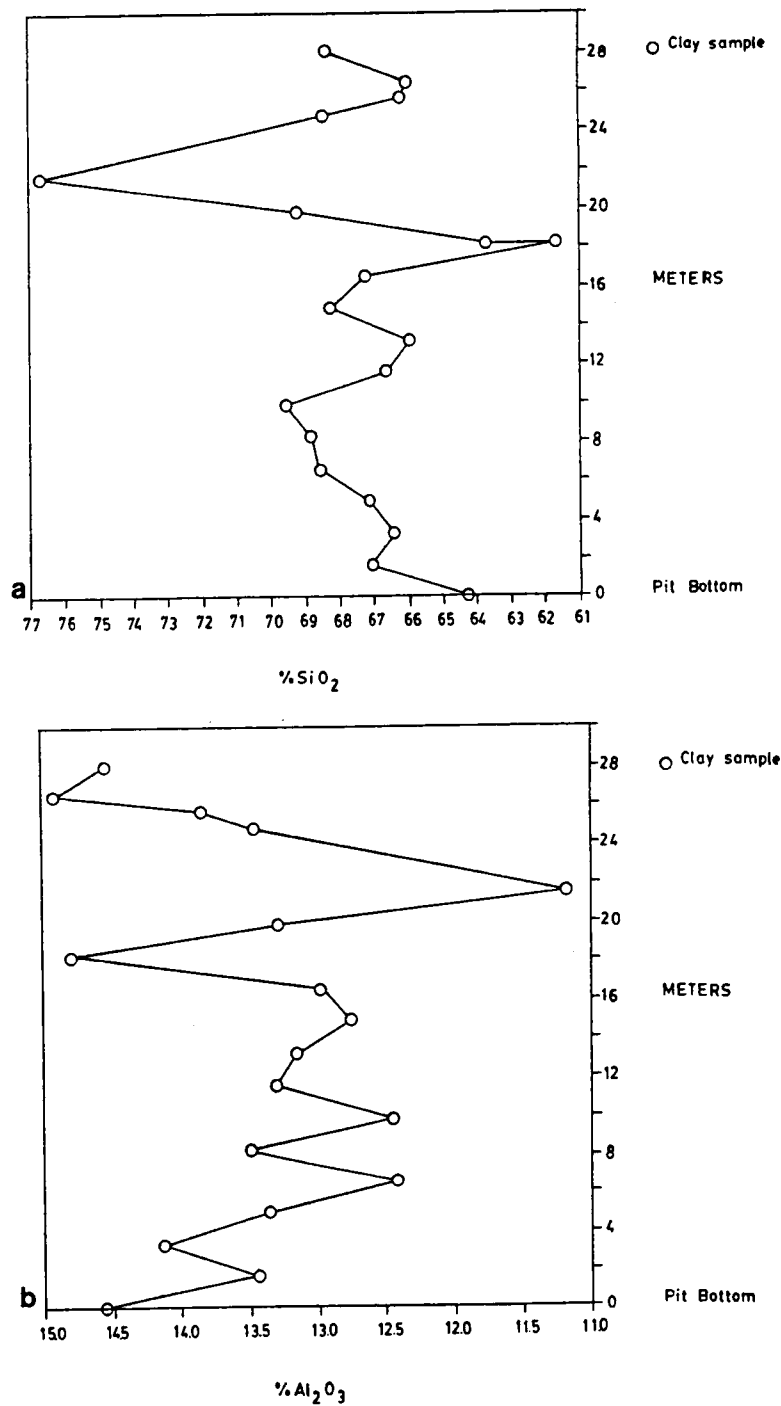


Figure 38. Paris plot of SiO₂ concentration versus depth (a), plot of Al₂O₃ concentration versus depth (b).

Figures 39a, 39b, and 40a illustrate the behavior of Fe_2O_3 , MnO and MgO concentrations. From about the 24 meter level to about the 26 meter level, a zone of healed fractures was observed in outcrop. This zone appears to correlate with the elevated MnO , Fe_2O_3 and MgO concentrations in this interval. The presence of healed fractures is thought to be the reason for the relatively high MnO , MgO , Fe_2O_3 also seen at about the 18 meter level. However, the healed fracture zone at the 18 meter level was too small to be included in the Paris stratigraphic section.

Below the 18 meter level the MgO concentration (Figure 40a) remains fairly constant and is thought to be related to the clay mineral composition. Healed fractures cut the laminae where they occur in the section, and are considered to be late. It is not clear if they are related to the intrusion of clastic dikes, or to groundwater processes which could have been associated with the unconformity at the top of the section, or to fairly recent groundwater processes. Note that the concentrations of Fe_2O_3 , MnO , and MgO (Figures 39a, 39b, and 40a) appear to be diminished by the high-silica horizon at the 22 meter level in the pit.

Figures 40b, 41a, 41b, and 42 are plots of P_2O_5 , S , K_2O , and CaO concentrations versus depth. The most obvious feature of the P_2O_5 , S , and K_2O plots is the apparent dilution of their concentration by the high silica horizon at the 22 meter level. As with Fe_2O_3 and MnO , this dilution is considered to

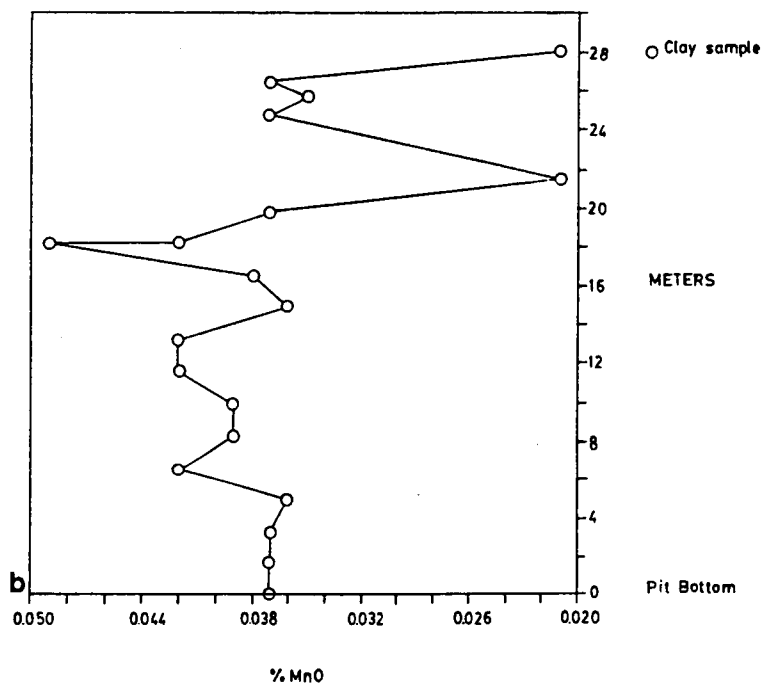
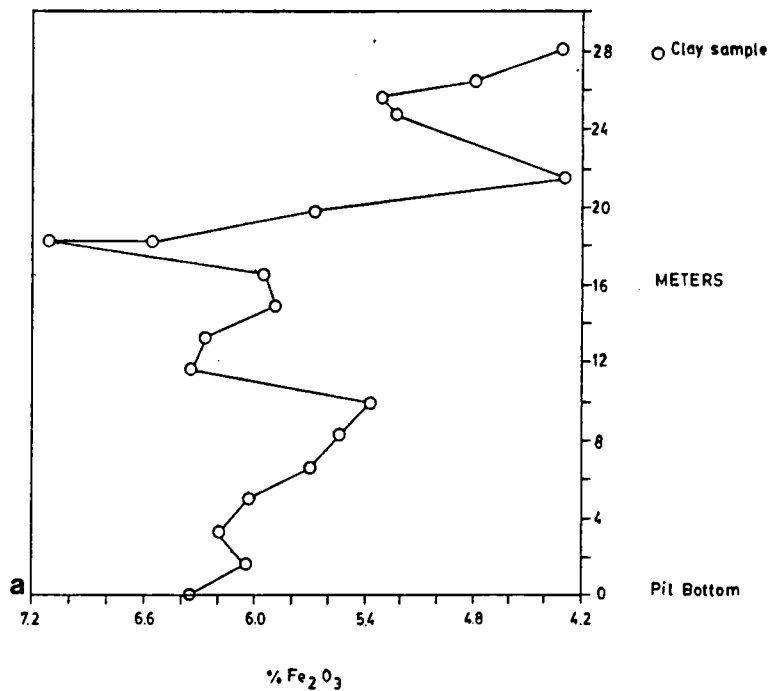


Figure 39. Paris plot of Fe_2O_3 concentration versus depth (a), plot of MnO concentration versus depth (b).

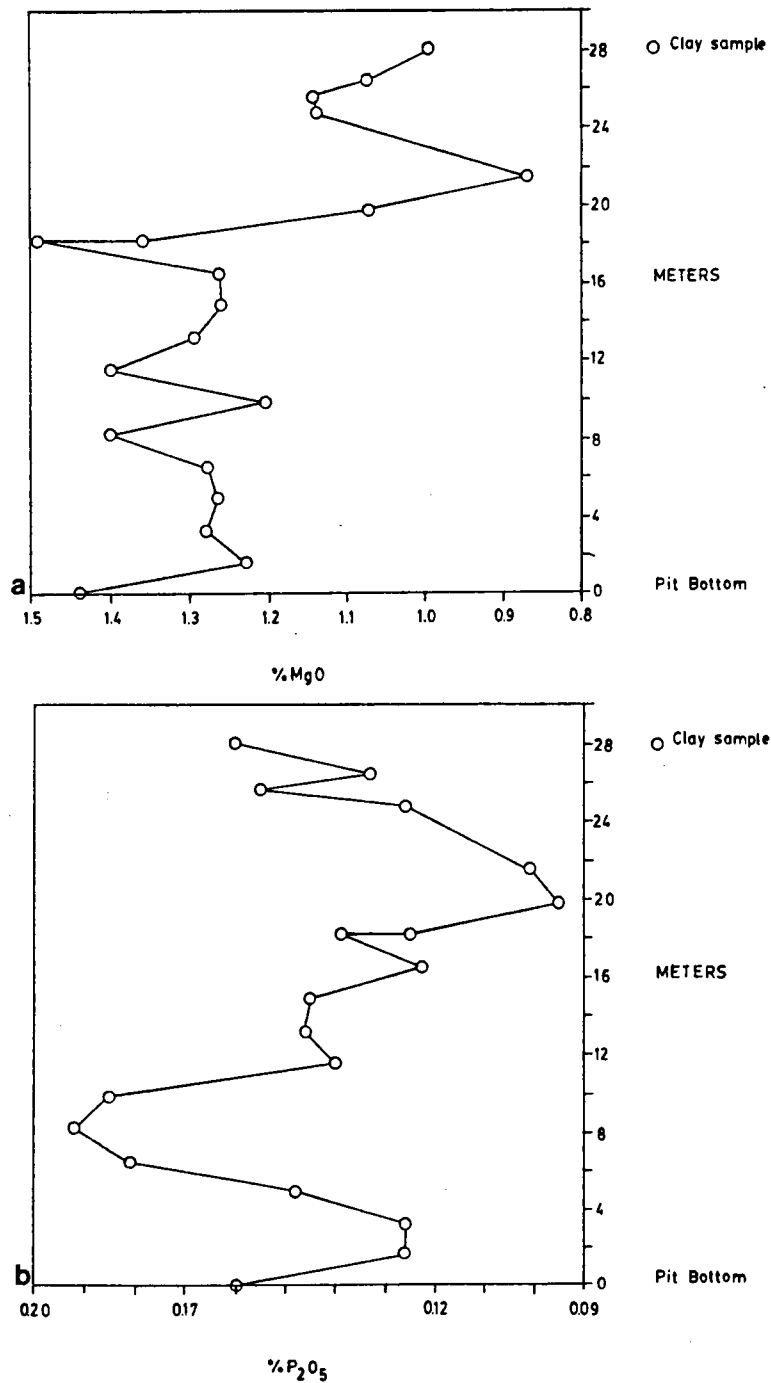


Figure 40. Paris plot of MgO concentration versus depth (a), plot of P₂O₅ concentration versus depth (b).

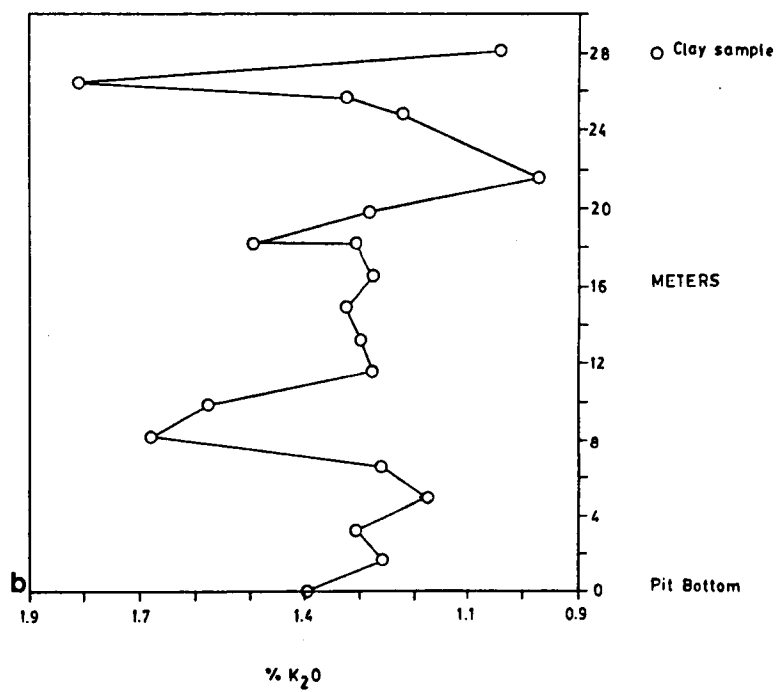
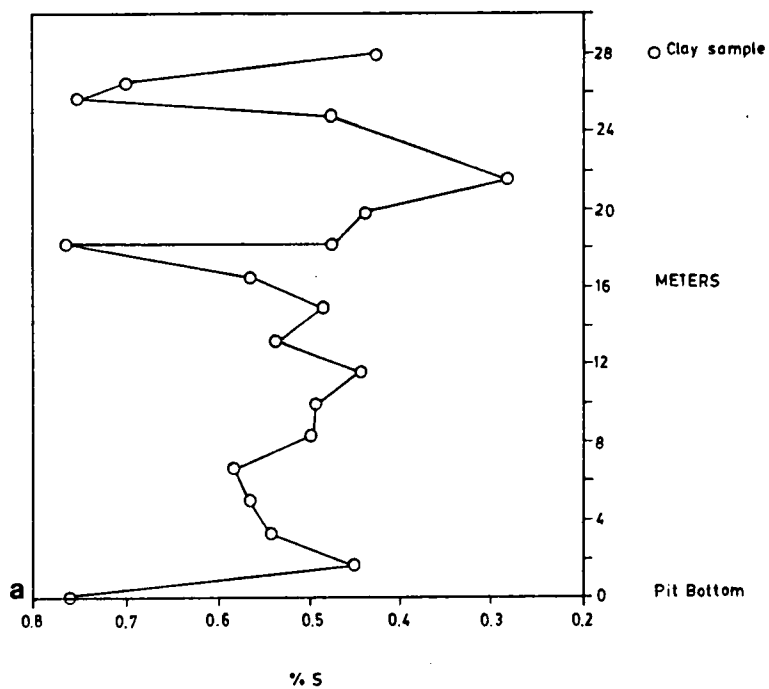


Figure 41. Paris plot of S concentration versus depth (a), plot of K₂O concentration versus depth (b).

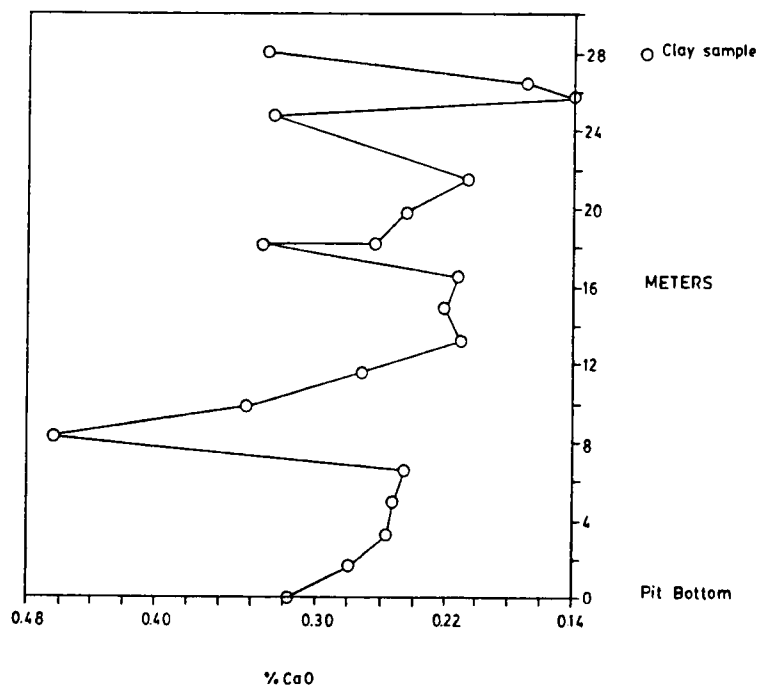


Figure 42. Paris plot of CaO concentration versus depth.

be due to the occurrence of more quartz silt at this level in the pit. The range in concentration of CaO does not appear to be very strongly related to the silica dilution.

The plots of P_2O_5 and S concentrations (Figures 40b and 41a) illustrate a moderate increase in concentration at the bottom of the pit which is considered to be related to the high organic content and pyrite framboids observed at the pit bottom. Also observed was a muscovite-rich zone in the interval from about the 6.5 meters up to about the 10 meters, which correlates fairly well with the increased concentrations of P_2O_5 , K_2O , and CaO. The elevated K_2O values are considered to be related to the muscovite, while CaO and P_2O_5 may be related to invertebrate shell fragments.

Principal Component Analysis

Principal Component Analysis (PCA) was used to see if it was possible to find a variable, or variables, which would explain the most variation in the chemical data and to determine if a dominant variable could be discovered, it could be used to help define chemical-stratigraphic facies.

When all the raw data were first entered and tabulated in a spreadsheet format it was discovered that samples from the weathered glauconite beds and concretions tended to bias the data. This bias resulted from high concentrations of iron in these samples; therefore, these samples were omitted from the data set so that it would better represent the bulk

composition of the Formation. Also, it should be noted that due to the nature of PCA, members of the sample population that are similar tend to cluster together when plotted as one principal axis (or eigenvector) versus another (McKinney, personal communication 1989).

Table 2 illustrates the eigenvalues for eigenvectors PRIN 1, PRIN 2, PRIN 3, and PRIN 4, which correspond to the various compounds and elements detected for the entire data set. The larger the absolute value on an axis (PRIN 1, PRIN 2, PRIN 3, or PRIN 4) the more important the corresponding compound is to that axis.

Figures 43 and 44 are plots of principal axis 1 versus principal axis 2 (PRIN 1 vs. PRIN 2) for Bloomfield and Olmsted. These plots indicate that most of the variation seen in the Bloomfield and Olmsted data is related to changes in SiO_2 . This is evident from the large, positive loading on silica seen on the PRIN 1 axis of Table 2. This axis describes 89 percent of the sample variation. Table 2 also indicates that the highest loading on the PRIN 2 axis is on Al_2O_3 but it explains only 6 percent of the sample variation. Note that most of the variation seen in the Paris data (Figure 45) is related to changes in the Al_2O_3 values. This is evident in the general parallel alignment of the Paris data to the PRIN 2 axis. The fact that SiO_2 and Al_2O_3 explain most of the sample variation was not unexpected due to the dominance of quartz and aluminosilicate minerals in the

Table 2

Eigenvalues for the eigenvectors PRIN 1, PRIN 2, PRIN 3, and PRIN 4, with the corresponding compounds and elements for 54 samples from all locations (concretions and the weathered glauconite bed were excluded). Underlined values indicate those compounds with the highest loading.

COMPOUND	EIGENVECTORS			
	PRIN 1	PRIN 2	PRIN 3	PRIN4
Na ₂ O	-0.17991	-0.06665	0.00597	-0.02640
MgO	-0.06085	0.01659	0.18825	0.29001
Al ₂ O ₃	-0.17612	<u>0.73494</u>	<u>0.60193</u>	-0.01201
SiO ₂	<u>0.96886</u>	0.10840	0.12313	0.15403
P ₂ O ₅	-0.00703	-0.01046	-0.00453	-0.01643
S	-0.02725	-0.01896	-0.15739	-0.26165
K ₂ O	-0.04269	0.08260	0.11933	0.19714
CaO	-0.09921	<u>-0.59823</u>	<u>0.56846</u>	0.41528
TiO ₂	0.00087	0.05409	-0.03658	-0.03234
Cr	-0.00009	0.00053	0.00019	0.00096
MnO	-0.00627	0.02262	-0.00615	0.06391
Fe ₂ O ₃	-0.11736	0.27337	-0.47261	0.77848
Ba	-0.00166	0.00683	0.00929	0.01043
Rb	-0.00011	0.00051	0.00011	0.00055
Sr	-0.00145	-0.00380	0.00562	0.00129
Zr	-0.00019	0.00042	-0.00028	-0.00139
VARIATION	0.89431	0.06401	0.02535	0.01168

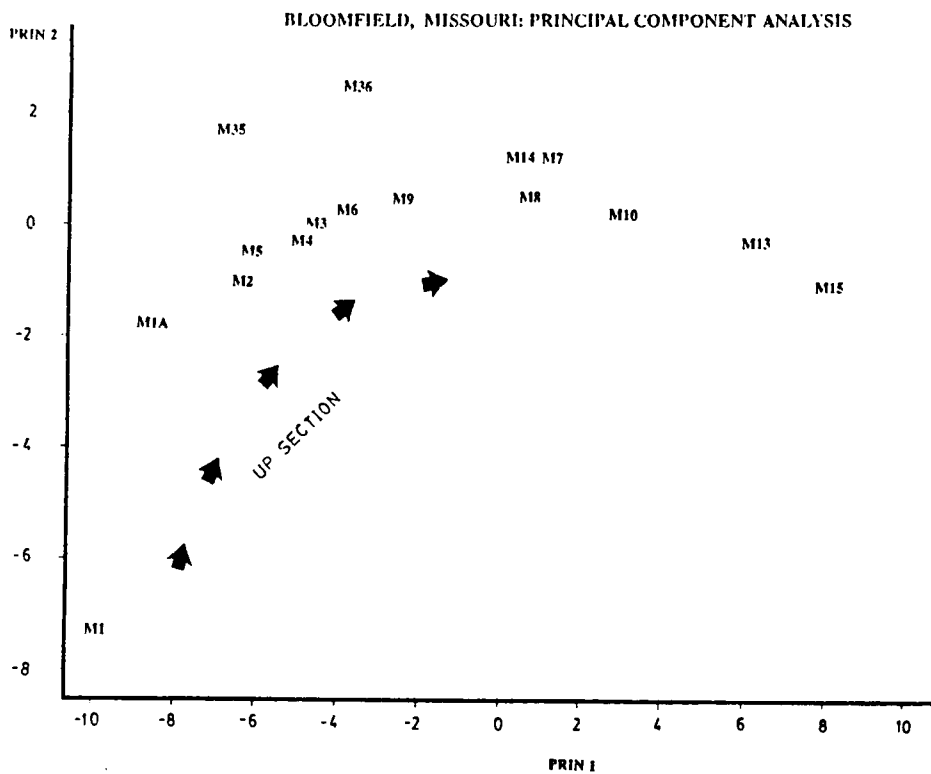


Figure 43. A plot of PRIN 1 vs. PRIN 2 for the Bloomfield, Missouri sample set.

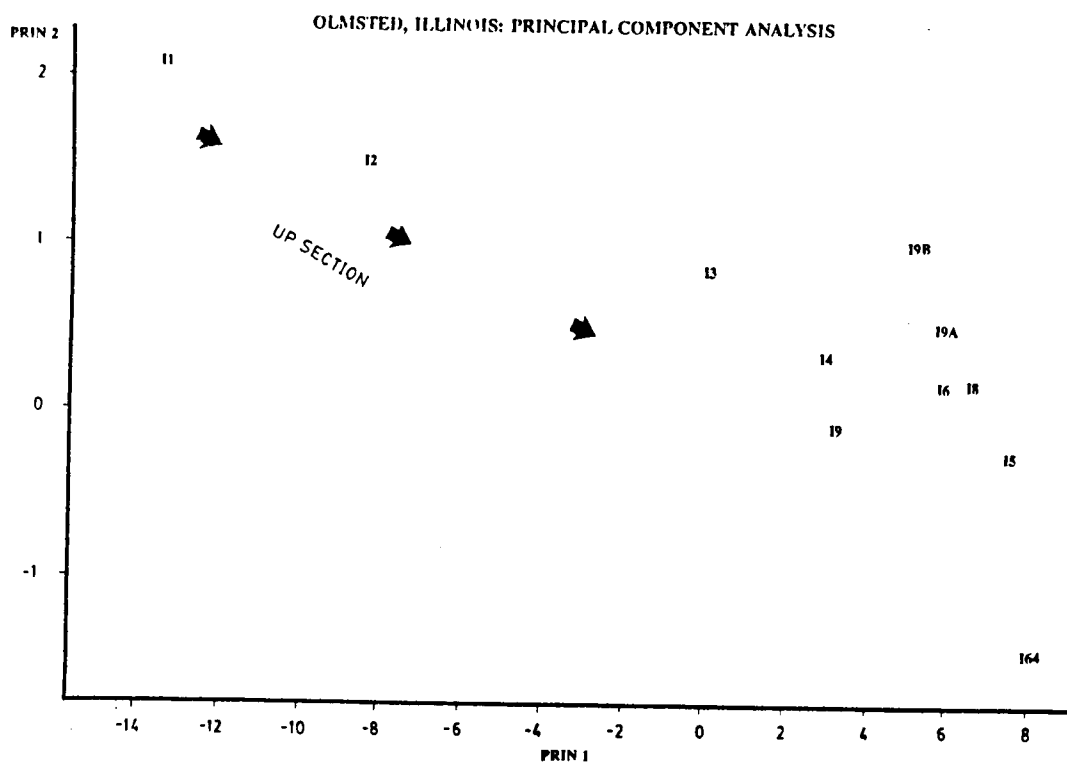


Figure 44. A plot of PRIN 1 vs. PRIN 2 for the Olmsted, Illinois sample set.

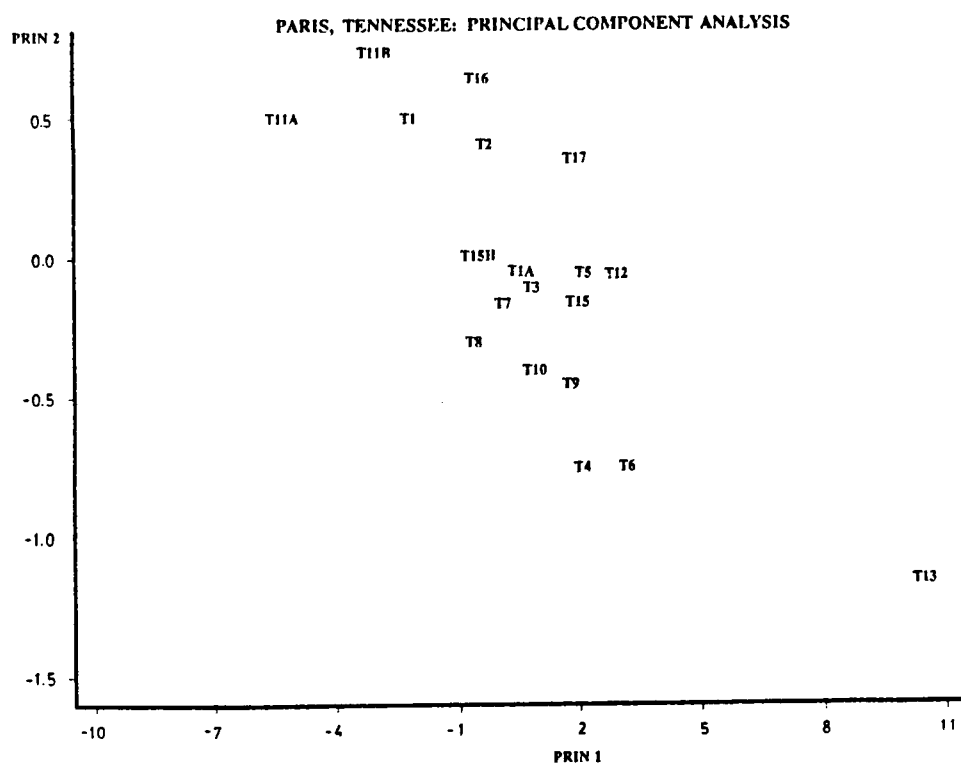


Figure 45. A plot of PRIN 1 vs. PRIN 2 for the Paris, Tennessee sample set.

Porters Creek Clay. The axis loadings and the amount of variation attributed to each axis were obtained from the SAS (Statistical Analysis System) out-put.

The highest loading on the PRIN 3 axis (Table 2), which explains only 2 percent of the variation, is on Al_2O_3 but CaO is also important and the two compounds define what is seen on the plot of PRIN 2 vs. PRIN 3 (Figure 46). Although PRIN 3 explains only 2 percent of the variation, this plot is very important because it indicates a fundamental difference between the sample locations. Most of the Paris, Tennessee samples (indicated by "T") tend to cluster together, which indicates they have similar chemical properties, but Bloomfield, Missouri and Olmsted, Illinois (indicated by "M" and "I" respectively) generally group together which indicates they have components in common. In general, PCA indicates there is something different about the depositional history of Paris when compared to Bloomfield and Olmsted. These differences will be discussed in the concluding section of this thesis.

The plots of PRIN 1 vs. PRIN 2 (Figures 43 and 44) for Bloomfield and Olmsted appears to segregate the samples. Samples M1, M1A, M2, M3, M4, and M5 from Bloomfield follow a rough stratigraphic succession. Also, samples I1 and I2 from Olmsted are excluded from the rest of the data set, indicating there is something different about them. Samples I1 and I2 are from the bottom of the pit, and I2 stratigraphically

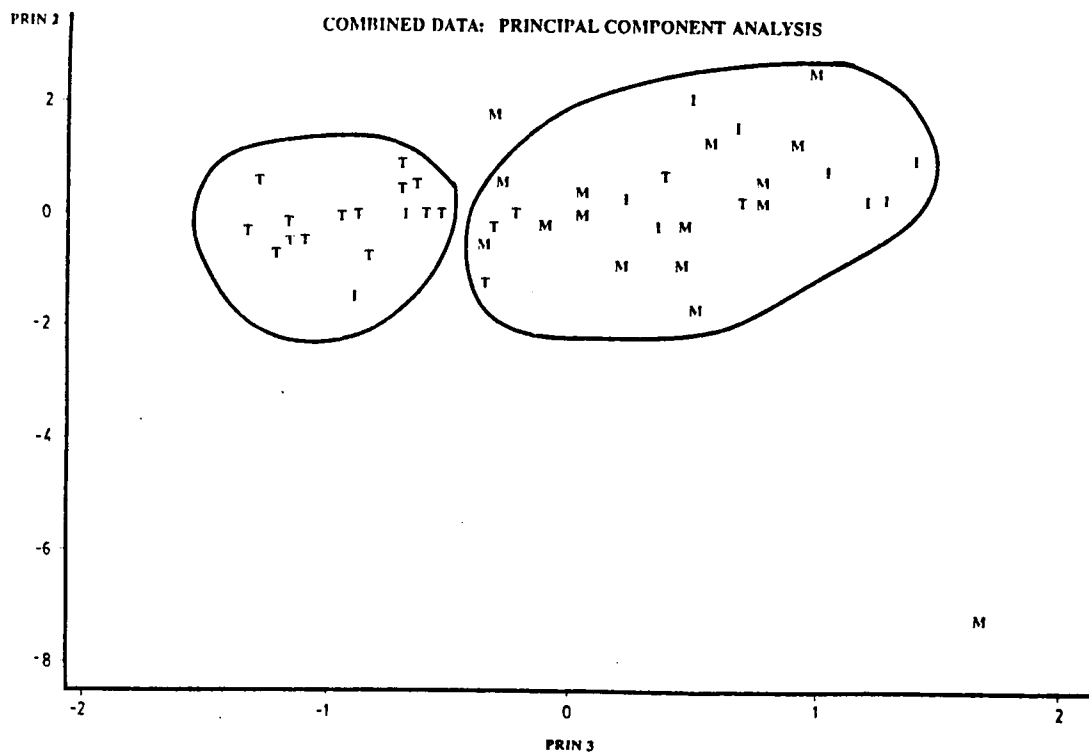


Figure 46. Combined Bloomfield (M), Olmsted (I), and Paris (T) principal component data. Circled regions are used only to define sample clustering.

overlies I1. Paris shows no clear clustering of lithologies (Figure 45). It is thought that the clustering seen at Bloomfield and Olmsted could be a function of systematic chemical variations that were controlled by lithologic variations. The fact that no lithologic clustering is seen in the Paris data may be due to the intrusion of clastic dikes, which may have added chemical components in a haphazard manner.

Mineralogy

The main goal of the XRD analysis was to test for any major mineralogical changes in the sections and to try to determine whether they were caused by variations in the sediment supply or by later diagenesis. Pye and Krinsley (1986), were concerned with the relative abundances of mineral species, because they found that specific mineral occurrences yielded little information about the depositional environment. They noted the occurrence of environmentally diagnostic minerals throughout the Whitby Mudstone, but they observed that the relative abundance of these minerals were more important to environmental interpretations.

The XRD data indicate that the mineralogies of all three sections (Bloomfield, Olmsted, and Paris) are very similar in so far as the types of minerals present, but there do appear to be variations in the concentrations of minerals present as indicated by the intensities of X-ray peaks. Quantitative X-

ray analysis was not undertaken in this study.

Major mineralogical variations might indicate the dominance of depositional or diagenetic processes. The total absence of a mineral species or unique mineral occurrences would be considered important. But the observed similarity at all three locations made it possible to compare chemical data from site to site.

Sims (1972) studied the Porters Creek Clay in the Jackson Purchase region of western Kentucky and noted the occurrence of smectite, kaolinite, mixed-layer clays, cristobalite, illite and chlorite. Quartz silt occurs in concentrations ranging from 5 to 50 percent. Sims also identified what he considered to be heulandite based on the work of Reynolds (1970), who studied the Porters Creek of Alabama and noted heulandite as the only zeolite in the Formation there. Other minerals observed by Sims include dolomite, calcite, K-feldspar, plagioclase and gypsum.

Bennett (1976) reported a wide variety of minerals in the Porters Creek from some of the same sampling locations used in this study. These minerals were detrital as well as authigenic and included: pyrite, ilmenite, magnetite, goethite, tourmaline, rutile, zircon, epidote, andalusite, siderite, garnet, staurolite, kyanite, sillimanite, feldspar, cristobalite, kaolinite, smectite, gypsum, chlorite, and illite. Although Bennett did not observe anything that he considered to be heulandite, he observed most of the minerals

noted by Sims (1972).

In the present study, emphasis was placed on the XRD analysis of bulk samples in order to determine all mineral phases present. Select samples of clay fractions were analyzed to determine the clay species. Mineral separates were analyzed only when considered useful. The minerals observed in this study were consistent at all sampling locations and include: quartz, siderite, goethite, chalcedony, glauconite, muscovite, kaolinite, illite, feldspar, pyrite, gypsum, and smectite. It was necessary to verify the occurrence of some minerals by their presence in thin-section. In general, the minerals found in this study were identical to those reported by previous workers.

The dominant detrital components found were quartz, feldspar (some possibly authigenic), smectite, illite, kaolinite, and muscovite. Quartz and muscovite are easily observed in thin-section, but presence of feldspar was only evident from XRD data. It was not possible to identify the specific feldspar present, but it is thought that the detrital feldspar owes its preservation to the same rapid burial (Bennett, 1976) required to preserve the organic matter seen in the Formation. Smectite, illite, and kaolinite occur in the fine-grained matrix and were distinguished only by X-ray methods.

The authigenic minerals observed include: siderite, goethite, chalcedony, pyrite, gypsum, and glauconite. Gypsum

was observed only at Bloomfield. The goethite concretions observed at Bloomfield appear to be an altered siderite. Disseminated goethite is considered to be an alteration product of detrital iron minerals. Siderite occurs in clayey nodules that were observed near the top of the Bloomfield section. The siderite occurs as a cement and is localized in these nodular structures, but it does not take part in the cementation of the surrounding clay matrix. The clayey-sideritic nodules are thought to be the precursors of the goethitic concretions found in the upper few meters of the Bloomfield section.

Gypsum was observed only in fractures at the top of the exposed Bloomfield section and was probably deposited by groundwater processes. Chalcedony, which was identified in thin-section, appears to be a fairly late pore-filling.

Pyrite occurs in framboids whereas glauconite occurs as pellets that in some cases have been reworked by bioturbation. Glauconite is concentrated in burrows as well as being fairly evenly distributed throughout the clay matrix.

The minerals that appear to give the most insight into the depositional history of the Porters Creek are quartz, pyrite, and glauconite. Quartz is present in the silt to fine-sand fraction and its abundance appears to be related to slight changes in sediment supply. Pyrite appears to be related to interstitial fluid oxygenation as well as the supply of iron, organics and sulfur. The glauconite could be

related to reduced sediment supply that would allow glauconite to form at the sediment-water interface. The relationships are discussed in the concluding section of this report.

CHAPTER 5

INTERPRETATIONS AND CONCLUSIONS

The results of this research suggest that it may be useful to combine chemical, stratigraphic, and paleontological data in the study of argillaceous sediments. In many studies, emphasis is placed on obtaining stratigraphic and paleontological data to establish facies. In some cases, geochemical information may make it possible to recognize chemical facies where good stratigraphic and paleontological data are lacking. In the discussion which follows, an attempt will be made to summarize this research and to discuss any problems or other questions that would be of interest in this type of study.

When comparing the Porters Creek Clay to Berner's (1981) classification (see Figure 1, page 9) it appears that the environment of deposition of the Porters Creek ranged from anoxic-sulfidic to non-sulfidic post-oxic. This interpretation is based on the co-occurrence of pyrite, glauconite and siderite. Pyrite would correspond to the anoxic-sulfidic environment, whereas glauconite and siderite would be related to the non-sulfidic, post-oxic environment. Bell and Goodell (1967) considered authigenic glauconite to have mineralogic similarities to their associated clay fractions, and detrital and relic glauconite grains to have different mineralogies than their associated clay fraction. The glauconite of the Porters Creek is considered here to be authigenic, but it

authigenic, but it occurs in such low concentrations that its exact mineralogy could not be determined. Berner (1971) noted that glauconite is of marine origin and forms in areas of low sedimentation rates. He concluded that glauconite forms slowly at the sediment-water interface and in association with organic matter. He also noted that glauconite does not form in environments where pyrite is stable.

Glauconite was found throughout the entire Porters Creek and its occurrence with pyrite in the lower parts of the Bloomfield and Olmsted sections could indicate that the depositional environment had fluctuations in the sediment supply. During times of lowest sediment accumulation rate glauconite formation would be possible. During higher sedimentation rates the preservation of organic matter and detrital feldspar would be possible, providing the proper environment for the formation of pyrite. It is important to note that the pyrite environment is considered to have only been present below the sediment/water interface and does not indicate an anoxic basin. The Bloomfield and Olmsted sediments were deposited in similar environments which may have been different from the depositional environment at Paris. The similarities between the Bloomfield and Olmsted deposits is based on occurrence of similar stratigraphic, petrographic and chemical characteristics described in the "results" section of this report.

One of the important similarities is in the behavior of

S and P_2O_5 concentrations at the Bloomfield and Olmsted pits. At both locations, these two species have their highest concentration below about the 12 meter level at Bloomfield and below the 5 to 6 meter level at Olmsted. It is thought that these respective sedimentary packages represent a period of time when the sediment accumulation rates were at their highest. A similar relationship between S and P_2O_5 concentrations and depth is not seen at Paris.

Another important similarity is the behavior of SiO_2 and Al_2O_3 at the Bloomfield and the Olmsted pits, which indicate a gradual increase in the amount of silt, with a corresponding decrease in clays in the upper portion of each section. Although this relationship is also seen at Paris, it should be pointed out that the change in SiO_2 and Al_2O_3 concentration is relatively abrupt at about the 22 meter level and is considered to be due to a sudden change in the sediment supply from clay-rich to fairly silt-rich.

Bennett (1976) noted an average of 4.3 percent sand-sized material and 32 percent silt-sized material at Bloomfield, an average of 7 percent sand-sized material and 29.6 percent silt-sized material at Olmsted. In contrast, Paris had 8 percent sand-sized material and 46.6 silt-sized material on the average. These variations are consistent with changes in the amounts of silica and Al_2O_3 discussed in the bulk chemistry section of this report. Bennett also noted that the major increase in silt occurred in the upper part of

the sections at each location. It is thought that the similarity in SiO_2 and Al_2O_3 concentration variation at all three locations is due to the shift in the depositional environment that accompanied the Paleocene regression described by Stearns (1957). The intrusion of clastic dikes at Paris is considered to have altered many of the chemical signatures; therefore the chemical trends seen in the Paris data are more difficult to relate to stratigraphic and depositional variations. Stearns (1957) considered the Porters Creek to be of deep marine origin, but foraminifera from the base of the Bloomfield section indicate that the water depth may have ranged only from 15 to 60 meters. The trace-fossil data appears to indicate a change in the depositional environment at Bloomfield and Olmsted. Chondrites was the dominant trace type observed, although minor Thalassinoides was observed at Bloomfield only in bedding plane exposures. Bromley and Ekdale (1984) noted that Chondrites generally occurs in black, laminated muds associated with chemically reducing conditions. Ekdale and Mason (1988) considered that as the oxygen concentration of interstitial fluids increases there is a transition from unburrowed sediments to more diverse trace-fossil assemblages. Chondrites is considered by some to represent a trace-maker that could tolerate low oxygen concentrations that ranged from dysaerobic to anaerobic (Ekdale and Mason, 1988; Savrda and Bottjer, 1986). Savrda and Bottjer (1986) described

Chondrites as being able to occupy sediments that would exclude all other trace-makers due to low oxygen levels. They also noted that low diversity and small trace size is also considered to indicate a low degree of oxygenation.

The results of this study suggest that the Porters Creek was deposited in generally dysaerobic waters where the available oxygen was depleted from the sediment by anaerobic decomposition below the sediment/water interface. The occurrences of Thalassinoides indicates there was a change in the environment, corresponding to an increase in the available oxygen. Due to poor exposures in the pits studied, their precise relation to the degree of oxygenation is unclear.

The "boudin-like" structures described at the Bloomfield and Olmsted pits have an uncertain origin, but are considered important because they occur in upper portion of the Bloomfield and Olmsted sections above the weathered, glauconitic sand that occurs at both locations. Regardless of whatever process produced these structures, they occurred at both locations; hence, the "boudin-like structures are considered to be additional evidence that Olmsted and Bloomfield sediments may have been deposited in very similar sedimentary environments. The exact nature of these unusual structures is unclear and it is possible that they may be the result of some kind of diagenetic process.

The Principal Component Analysis (PCA) indicates that there are similarities between the Bloomfield and Olmsted

samples that are not seen in the Paris samples (see figure 46, page 99). This difference is thought to be related to a shallower depositional environment at Paris as well as to the presence of intruded clastic dikes.

Paris is well off the axis of the depositional basin at the time of deposition of the Porters Creek and more proximal to an eastern sediment source, which is considered to have been important during the deposition of the Upper Mississippi Embayment sediments (Pryor and Glass, 1961). Bloomfield and Olmsted are closer to the axis of the basin although Olmsted is located up-dip from Bloomfield (Figure 47). Principal Component Analysis (PCA) was done on the entire data set excluding the late diagenetic concretions and the weathered glauconitic unit. The Bloomfield and Olmsted data tend to cluster together, indicating the two locations are similar in so far as the chemical data is concerned, but the Paris data did not cluster with Bloomfield and Olmsted, indicating that the bulk chemistry of the Paris section is different from that seen at Olmsted or Bloomfield (see Figure 46, page 99). The relationship between the Bloomfield-Olmsted cluster and the Paris cluster is considered to be due to the sequential stratigraphic separation of the PCA done on each location (see Figures 43, 44, and 45, pages 95, 96 and 97). Clustered data points indicate similarities in the samples clustered (McKinney, personal communication 1989). It is still unclear

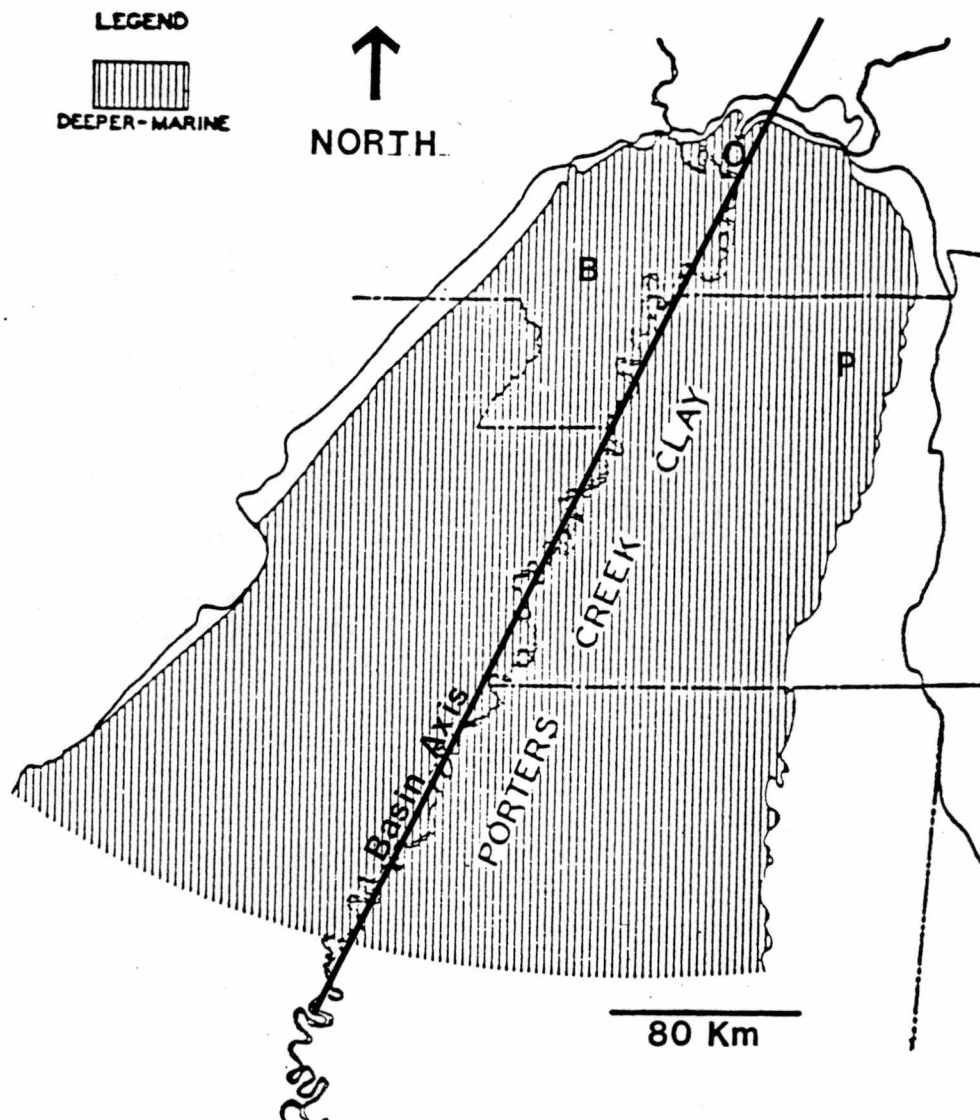


Figure 47. The location of Bloomfield (B), Olmsted (O), and Paris (P) at the maximum Paleocene transgression (after Stearns, 1957).

how important the clastic dike event was to the bulk chemistry of the Porters Creek section at Paris.

Based on the data in this report, it appears possible to define at least two chemical-stratigraphic facies within the Porters Creek Clay. Figure 48a is a plot of percent P_2O_5 versus percent Fe_2O_3 for Bloomfield. This figure illustrates the segregation of samples based on the P_2O_5 concentration. Samples in the region labeled "A" occur in the same stratigraphic package and this package will be referred to as "Facies A". Samples in the region labeled "B" all occur in a different stratigraphic package which will be referred to as "Facies B". Figure 48b shows the segregation of the same suites of samples using a plot of S concentration versus Fe_2O_3 to define facies A and B. Figure 49 is a plot of P_2O_5 concentration versus CaO concentration and also illustrates the segregation of the same suites of samples described above. In all three figures (48a, 48b, and 49), sample M1 does not group with the other members of facies A and this is due its high foraminifera concentration. Facies B stratigraphically overlies Facies A. Figure 50 illustrates these facies stratigraphically. Sample M6 (at about the 10 meter level) that defines the upper limit of chemical facies in Figures 48a, 48b, and 49, M6 occurs just below what is termed the "transitional zone". The transitional zone is considered to be the result of a relatively sudden change in the redox conditions of the sediment at the 10 meter level

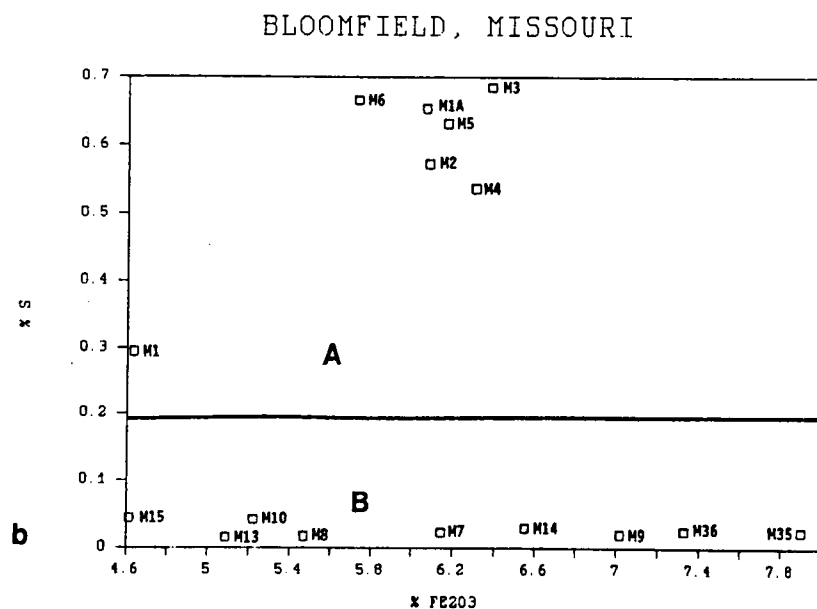
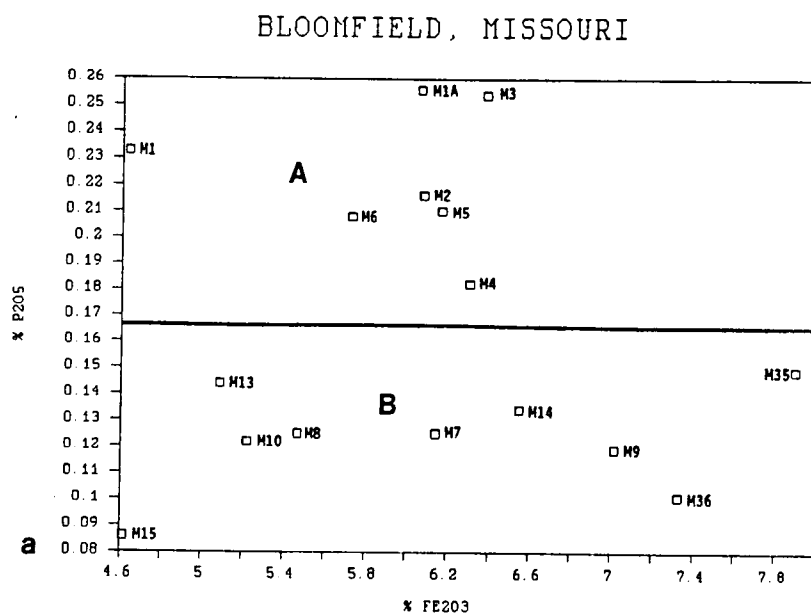


Figure 48. A plot of P_2O_5 vs. Fe_2O_3 concentrations (a), and a plot of S vs. Fe_2O_3 concentrations (b) for Bloomfield.

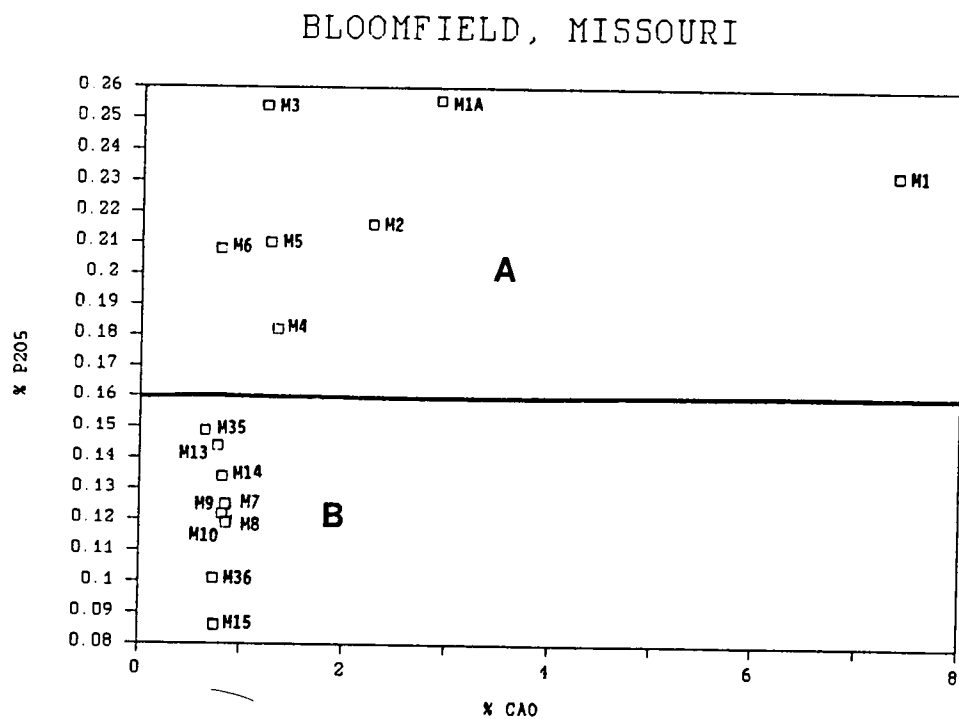


Figure 49. A plot of P_2O_5 vs. CaO concentrations for Bloomfield.

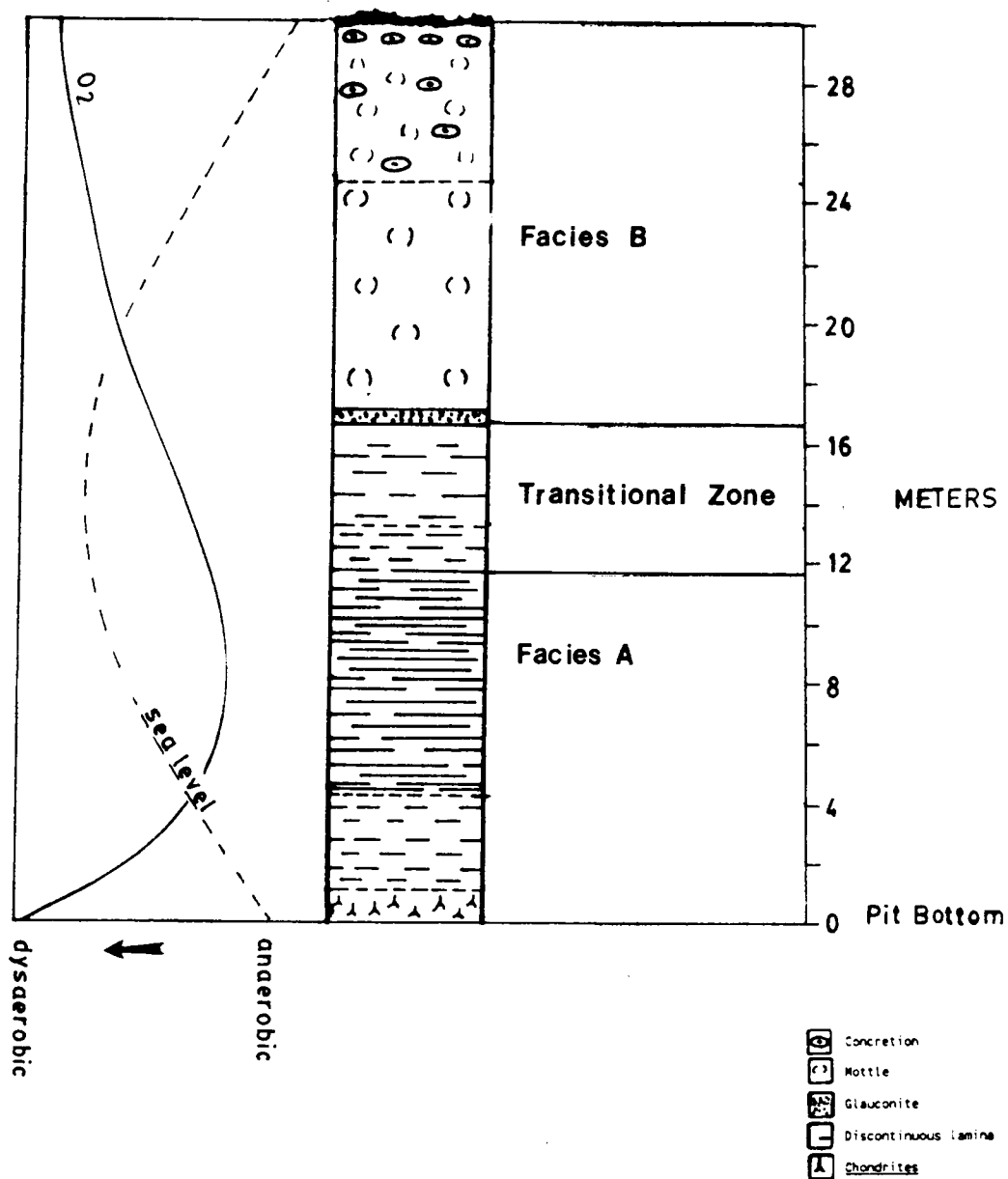


Figure 50. Facies relationships for the Bloomfield, Missouri section with proposed relative sea level and oxygenation curves. The arrow indicates increasing sea level.

followed by a slower change in the rate of deposition and the degree of bioturbation. Figure 51a illustrates a plot of P_2O_5 concentration versus Fe_2O_3 concentration and Figure 51b is a plot of S concentration versus Fe_2O_3 . Both plots illustrate the segregation of sample I1 and I2 in the region labeled "A" and this segregation is related to the fairly high P_2O_5 , Fe_2O_3 , and S concentrations for these samples. These samples define what will be termed "Facies A" at Olmsted. All other samples in the region labeled "B" shall be termed "Facies B" at Olmsted. Note that facies B stratigraphically overlies facies A. Figure 52 is a plot of P_2O_5 concentration versus CaO concentration at Olmsted and illustrate the same kind of separation of sample I1 and I2 from the other samples. This is considered to be related to the relatively higher CaO and P_2O_5 concentration for these samples. Sample I2 is the stratigraphically highest member of "facies A" and it occurs at about the 3 meter level below what will be termed the "transitional zone" at Olmsted. As at Bloomfield, the "transitional zone" is consider to reflect a relatively rapid change in the redox conditions followed by a slower change in the depositional style and degree of bioturbation. Figure 53 illustrates the distribution of facies at Olmsted.

The conclusion that there was a relatively sudden change in the redox conditions is based on the stratigraphically abrupt change in S and P_2O_5 concentrations at the top of facies A at both Bloomfield and Olmsted. The subsequent change in

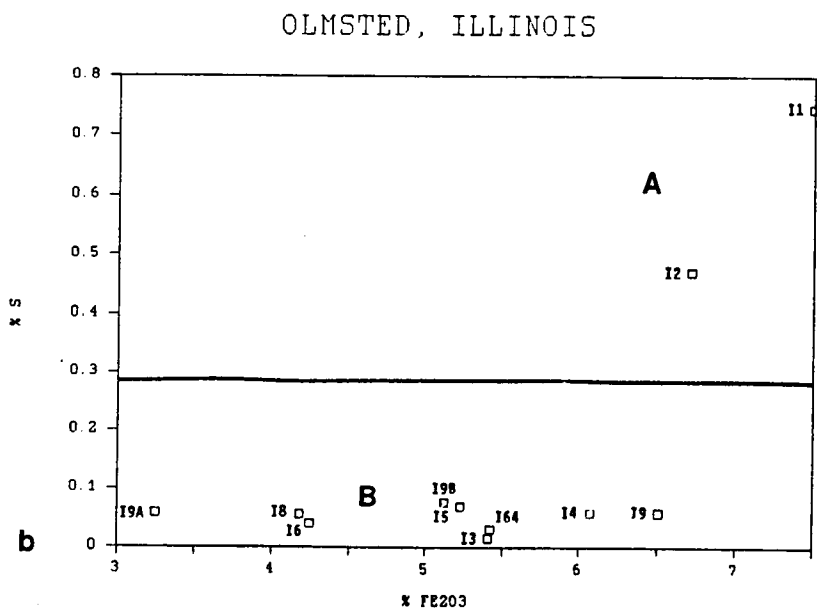
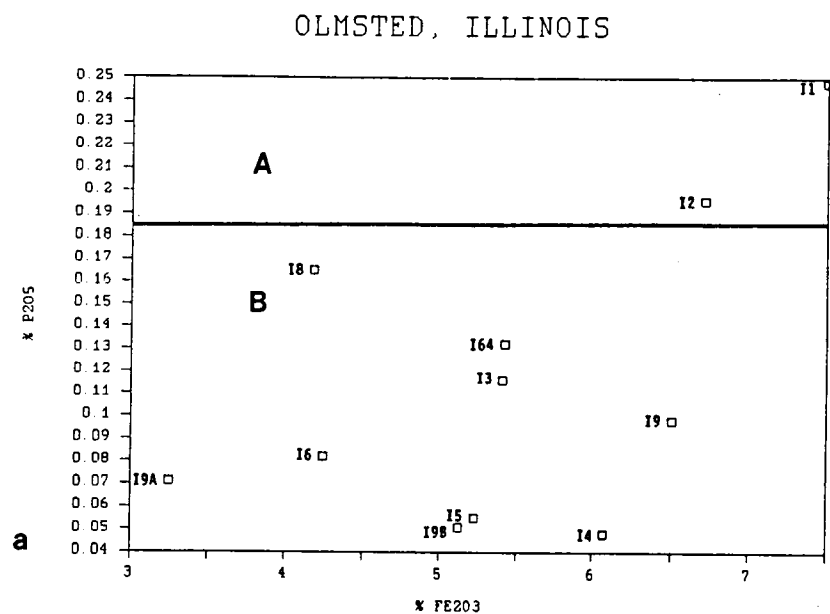


Figure 51. A plot of P₂O₅ vs. Fe₂O₃ concentrations (a), and a plot of S vs. Fe₂O₃ concentrations (b) for Olmsted.

OLMSTED, ILLINOIS

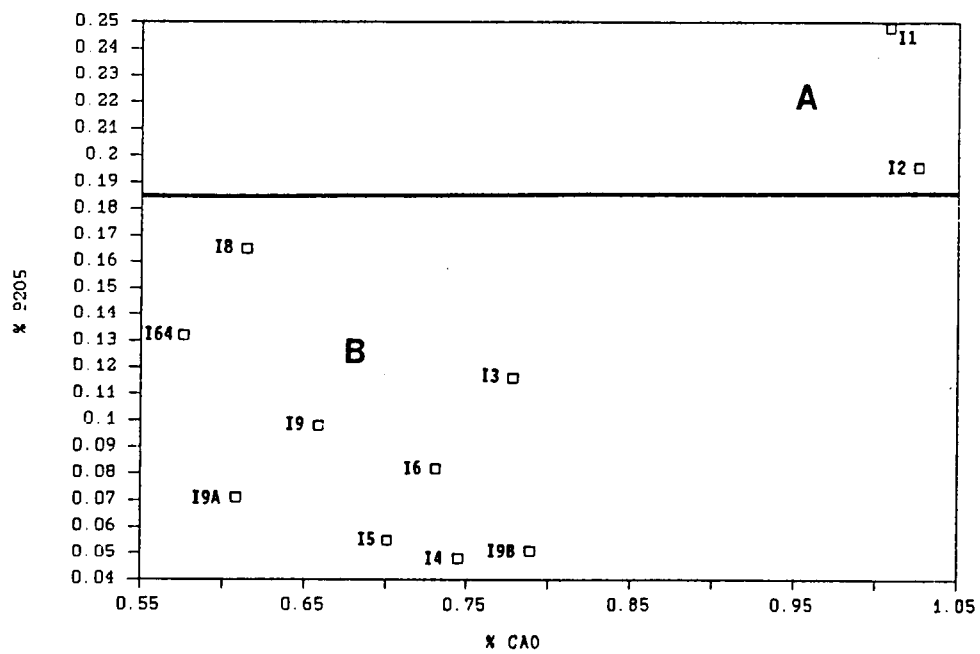


Figure 52. A plot of P_2O_5 vs. CaO concentrations for Olmsted.

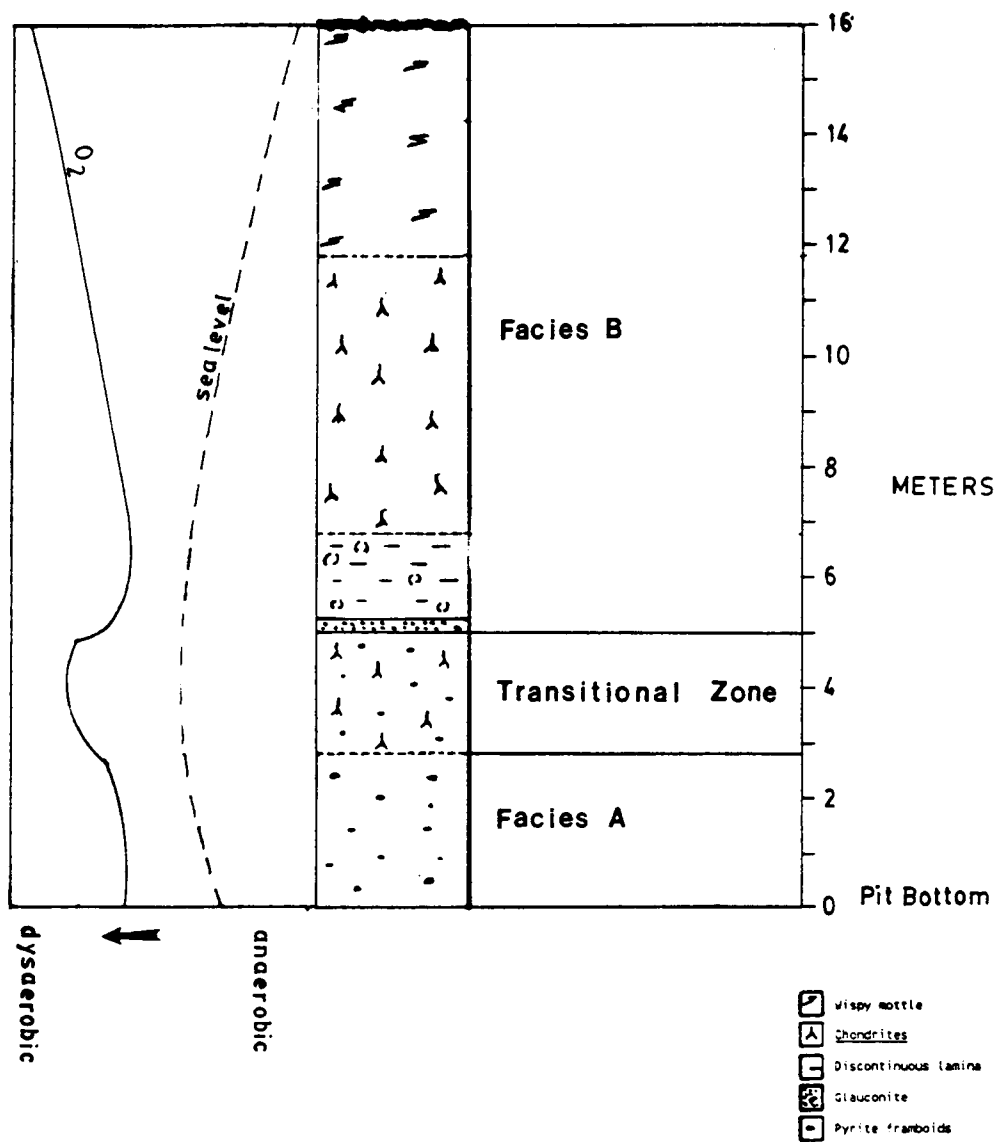


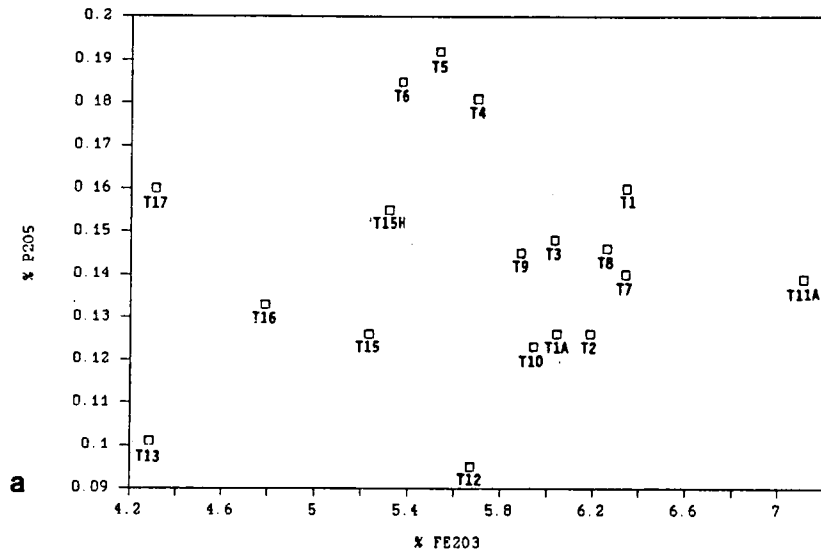
Figure 53. Facies relationships for the Olmsted, Illinois section with proposed relative sea level and oxygenation curves. The arrow indicates increasing sea level.

the style of deposition would be more gradual and related to the time it would take for burrowing organisms to colonize the sediment and changes in the sediment supply. The glauconitic unit at the top of the transitional zone at Bloomfield and Olmsted may represent a time when the sedimentation rate was very low.

Figures 54a, 54b, and 55 plots the concentrations of P_2O_5 versus Fe_2O_3 , S versus Fe_2O_3 , and P_2O_5 versus CaO respectively for Paris. These plots indicate no obvious stratigraphic segregation of samples, although the increase in silica at the top of the section (seen in the plot of SiO_2 concentration versus depth, Figure 36a, page 83) is similar to Facies B at Bloomfield and Olmsted. Therefore, the occurrence of Facies A could be assumed, but the bulk chemical signatures may have been affected by the clastic dike event. It is also unclear where the transitional zone would occur, but because the glauconitic unit does not occur at Paris, perhaps the depositional environment was different from Bloomfield or Olmsted. This idea is feasible in light of the relative spatial position of all three locations as illustrated in Figure 47. Figure 56 illustrates the possible facies relationships at Paris. Figure 57 is a photograph of the Olmsted high-wall with the typical facies labeled.

In summary, the data from this report confirm the results of previous workers who contended that the lower part of the Porters Creek Clay was deposited during a Paleocene

PARIS, TENNESSEE



PARIS, TENNESSEE

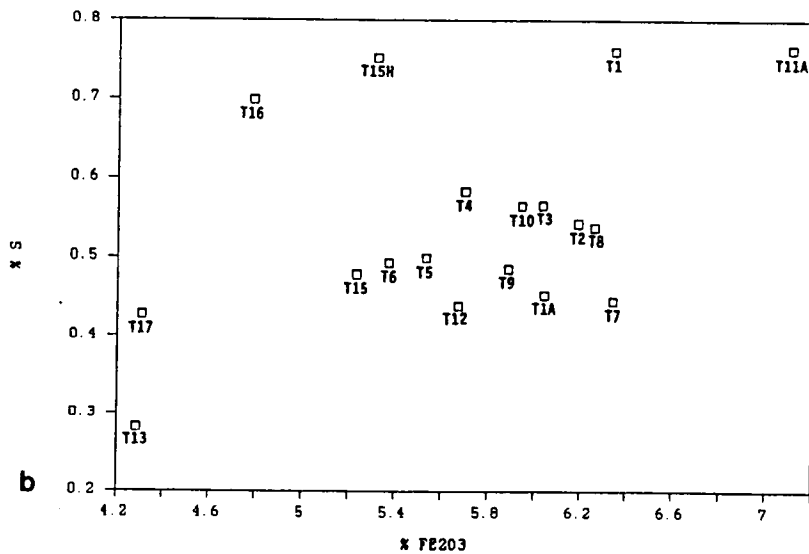


Figure 54. A plot of P₂O₅ vs. Fe₂O₃ concentrations (a), and a plot of S vs. Fe₂O₃ concentrations (b) for Paris.

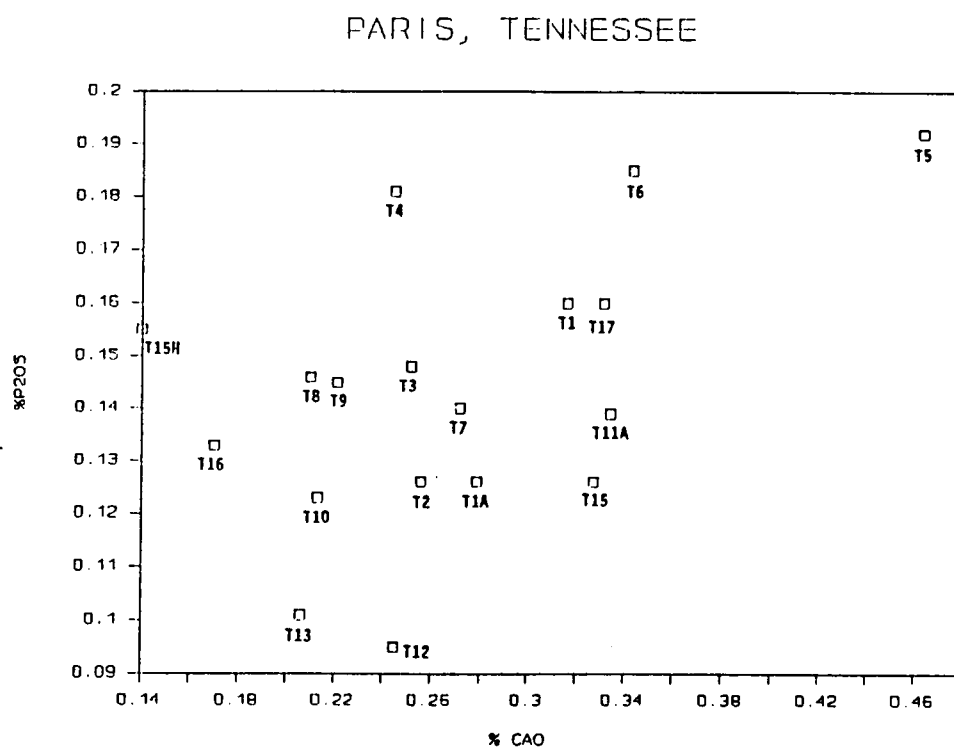


Figure 55. A plot of P₂O₅ vs. CaO concentrations for Paris.

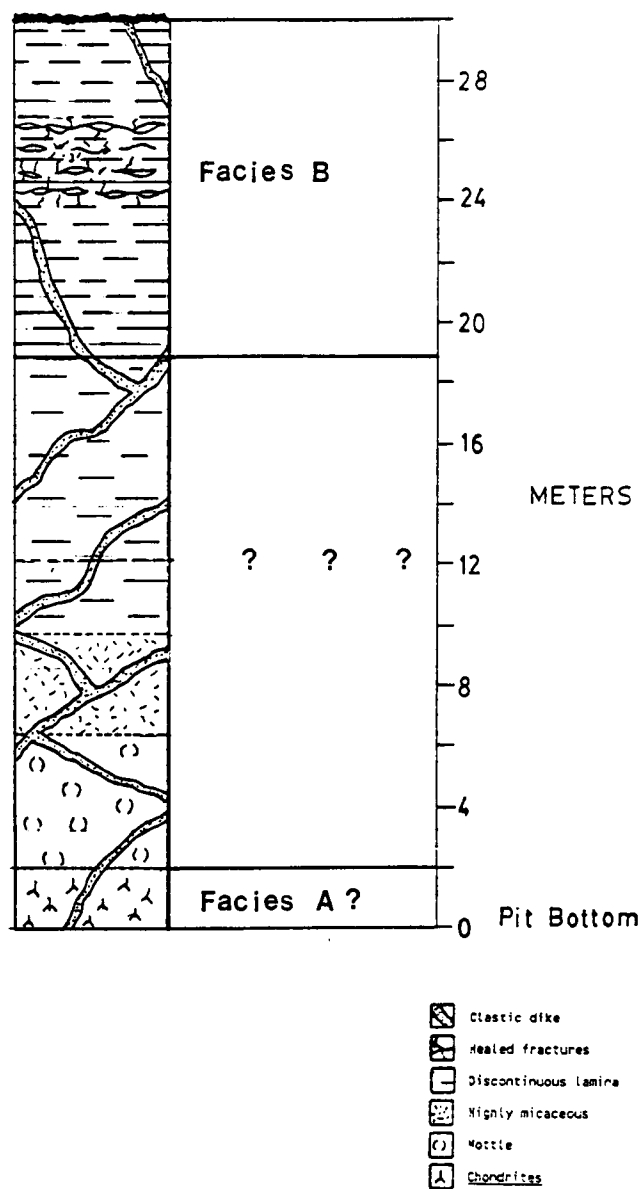


Figure 56. Possible facies relationships for the Paris, Tennessee section.

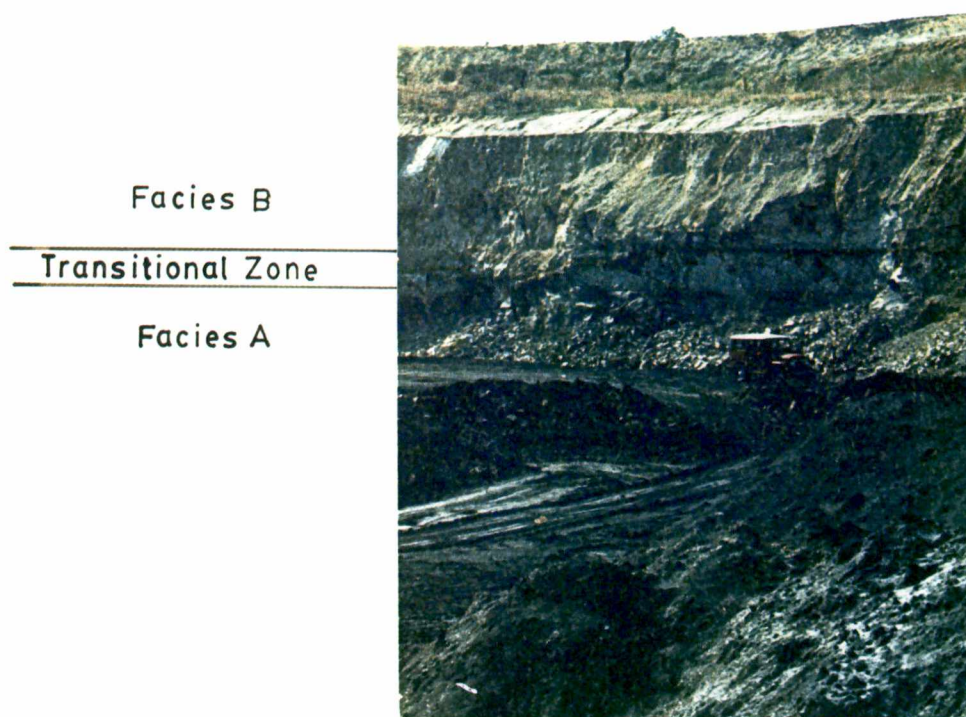


Figure 57. Photograph of the typical stratigraphic section as seen at Olmsted with the facies labeled.

transgressive event, while the upper portion was deposited during a Paleocene regression. In this report, "Facies A" corresponds to the transgression and "Facies B" corresponds to the regressive event. The "transitional zone" is thought to represent a time when there was little change in sea level and a diminished influx of sediments. The differences between the three locations are considered to be related to the positions of the sample locations in the basin. With the exception of the Paris location, chemical-stratigraphic facies can be defined. But the clastic dike intrusion is thought to be a prohibitive factor in acquiring chemical data that could reflect the depositional history of the Porters Creek at Paris.

The transgressive event would have had to be fairly rapid in order to produce the dysaerobic conditions indicated by the Chondrites zone. The glauconitic unit (occurring at Bloomfield and Olmsted) indicates a relative sea-level still stand in which there was reduced sediment supply to the basin. The upward coarsening of the oxygenated sequence (Facies B) could be related to a regressive event but, it could be an apparent regression caused by clastic progradation into the basin.

The results of this research are also in fairly good agreement with the global sea level curves (Figure 58) proposed by Vail (1977) for Tertiary time. Note the rising sea level Vail reports for the Danian stage. Note that

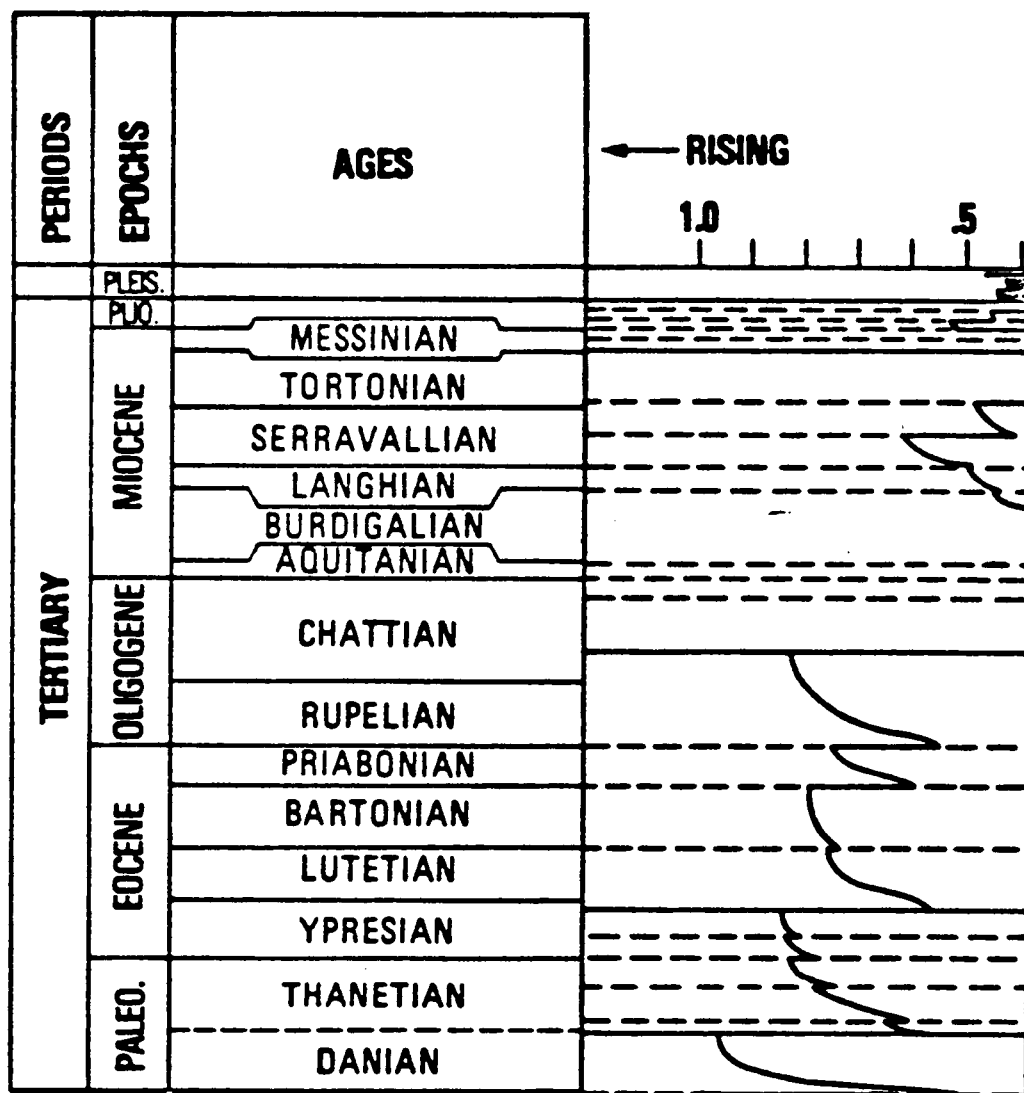


Figure 58. Global sea level cycles for the Tertiary (Vail, 1977). Note: the foraminifera from this research is Danian in age.

foraminifera of Danian age were found at the base of the Bloomfield section.

The use of both chemical, mineralogic, trace-fossil and stratigraphic criteria have helped to gain a better understanding of the depositional environment of the Porters Creek Clay. It may be possible to use the same combined approach on more lithified strata; however, it will be necessary to determine the effects of later diagenetic processes (such as those during deep burial) on the chemical trends and this could prove difficult.

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APPENDIX

APPENDIX

RAW CHEMICAL DATA

BLOOMFIELD

STATE	SAMPLE	METERS	NA2O	MGO	AL2O3	SiO2	P2O5	S	K2O
Mo.	ML1	0.000	0.925	2.149	11.645	56.493	0.233	0.295	1.501
Mo.	ML1A	1.650	0.662	2.297	14.642	58.350	0.256	0.654	1.873
Mo.	ML2	3.300	0.489	2.282	14.711	60.546	0.216	0.573	1.983
Mo.	ML3	4.960	0.472	2.371	14.917	62.404	0.254	0.685	1.985
Mo.	ML4	6.610	0.399	2.085	14.587	61.889	0.182	0.537	2.044
Mo.	ML5	8.260	0.366	2.133	14.429	60.592	0.210	0.632	1.927
Mo.	ML6	9.910	0.488	2.053	14.831	62.743	0.208	0.666	1.988
Mo.	ML7	11.560	0.359	2.042	15.315	67.863	0.125	0.000	1.850
Mo.	ML8	13.220	0.347	1.790	14.739	67.491	0.125	0.017	1.782
Mo.	ML9	14.870	0.281	1.867	14.824	64.279	0.119	0.000	1.635
Mo.	ML10	16.520	0.106	1.718	14.123	69.767	0.122	0.000	1.492
Mo.	M601*	16.900	0.265	1.337	8.662	26.837	0.112	0.024	0.759
Mo.	ML13	21.480	0.366	1.607	12.998	72.821	0.144	0.000	1.347
Mo.	ML14	23.130	0.000	1.689	15.282	67.662	0.134	0.000	1.529
Mo.	ML15	24.780	0.090	1.451	12.053	74.239	0.086	0.000	1.338
Mo.	M306	26.430	0.246	2.079	17.179	63.758	0.101	0.000	2.665
Mo.	M305	28.080	0.172	1.739	16.332	60.450	0.149	0.024	2.616
SUM			6.410	34.732	256.348	1124.321	2.950	4.364	32.209
AVG			0.377	2.043	15.079	66.137	0.174	0.257	1.895
Std. Dev.			0.395	0.160	0.409	0.545	0.040	0.014	0.108

STATE	SAMPLE	METERS	CaO	TiO2	CR	MNO	FE2O3	Ba	Rb
Mo.	ML1	0.000	7.381	0.257	0.015	0.035	4.633	0.025	0.008
Mo.	ML1A	1.650	2.912	0.497	0.018	0.040	6.065	0.030	0.003
Mo.	ML2	3.300	2.256	0.603	0.020	0.041	6.079	0.144	0.009
Mo.	ML3	4.960	1.209	0.654	0.020	0.047	6.379	0.036	0.009
Mo.	ML4	6.610	1.342	0.685	0.019	0.049	6.302	0.091	0.009
Mo.	ML5	8.260	1.266	0.676	0.019	0.043	6.166	0.094	0.009
Mo.	ML6	9.910	0.779	0.713	0.019	0.040	5.727	0.068	0.010
Mo.	ML7	11.560	0.849	0.727	0.019	0.182	6.143	0.043	0.011
Mo.	ML8	13.220	0.848	0.761	0.019	0.046	5.467	0.132	0.011
Mo.	ML9	14.870	0.859	0.759	0.022	0.114	7.017	0.121	0.009
Mo.	ML10	16.520	0.816	0.617	0.018	0.022	5.223	0.026	0.009
Mo.	M601*	16.900	0.330	1.001	0.003	0.058	56.652	0.025	0.007
Mo.	ML13	21.480	0.768	0.595	0.018	0.024	5.088	0.028	0.009
Mo.	ML14	23.130	0.816	0.715	0.020	0.032	6.549	0.039	0.009
Mo.	ML15	24.780	0.755	0.592	0.016	0.022	4.616	0.021	0.009
Mo.	M306	26.430	0.736	0.726	0.015	0.045	7.326	0.068	0.014
Mo.	M305	28.080	0.645	0.805	0.020	0.921	7.899	0.143	0.012
SUM			26.102	12.094	0.319	1.871	162.914	1.205	0.172
AVG			1.535	0.711	0.019	0.110	9.583	0.071	0.010
Std. Dev.			0.141	0.328	0.008	0.011	0.423	0.016	0.002

* Indicates the weathered glauconitic horizon.

BLOOMFIELD CONT.

STATE	SAMPLE	METERS	SR	ZR
Mo.	ML1	0.000	0.051	0.008
Mo.	ML1A	1.650	0.052	0.011
Mo.	ML2	3.300	0.058	0.012
Mo.	ML3	4.960	0.051	0.011
Mo.	ML4	6.610	0.051	0.012
Mo.	ML5	8.260	0.048	0.012
Mo.	ML6	9.910	0.045	0.012
Mo.	ML7	11.560	0.016	0.012
Mo.	ML8	13.220	0.016	0.013
Mo.	ML9	14.870	0.015	0.009
Mo.	ML10	16.520	0.013	0.005
Mo.	M601*	16.900	0.008	0.001
Mo.	ML13	21.480	0.012	0.002
Mo.	ML14	23.130	0.013	0.006
Mo.	ML15	24.780	0.012	0.005
Mo.	M306	26.430	0.014	0.012
Mo.	M305	28.080	0.028	0.014
	SUM		0.534	0.167
	AVG		0.031	0.010
	Std. Dev.		0.002	0.004

OLMSTED

STATE	SAMPLE	METERS	NA2O	MGO	AL2O3	SI02	P2O5	S	K2O
Ill.	IL1	0.000	0.507	2.762	18.297	54.047	0.248	0.746	1.974
Ill.	IL2	2.740	0.299	2.520	17.012	59.011	0.196	0.471	1.796
Ill.	IL3	5.030	0.247	1.869	15.293	67.149	0.116	0.000	1.519
Ill.	IL3A*	5.180	0.431	1.260	8.605	28.493	0.303	0.010	0.821
Ill.	IL4	6.400	0.219	1.813	13.935	69.839	0.048	0.000	1.526
Ill.	IL5	8.080	0.124	1.603	12.734	74.323	0.055	0.000	1.341
Ill.	IL6	10.060	0.061	1.493	13.879	72.483	0.082	0.000	1.515
Ill.	IL6A	11.280	0.273	1.412	11.034	74.271	0.132	0.000	1.279
Ill.	IL8	12.800	0.219	1.311	13.806	72.986	0.165	0.000	1.293
Ill.	IL9B	14.330	0.103	1.489	14.808	72.068	0.051	0.000	1.472
Ill.	IL9	14.630	0.309	1.349	13.094	69.855	0.098	0.000	1.259
Ill.	IL9A	15.090	0.273	1.111	14.743	72.355	0.071	0.000	1.343
	SUM		3.344	21.809	182.444	858.415	1.707	1.339	18.696
	AVG		0.279	1.817	15.204	71.535	0.142	0.112	1.558
	Std. Dev.		0.395	0.160	0.409	0.545	0.040	0.014	0.108

* Indicates the weathered glauconitic horizon.

OLMSTED CONT.

STATE	SAMPLE	METERS	CAO	TI02	CR	MNO	FE203	BN	RB
III.	IL1	0.000	1.008	0.733	0.019	0.058	7.494	0.048	0.012
III.	IL2	2.740	1.026	0.741	0.023	0.059	6.708	0.148	0.011
III.	IL3	5.030	0.778	0.696	0.022	0.035	5.405	0.144	0.009
III.	IL3A*	5.180	0.194	1.012	0.004	0.062	52.415	0.021	0.003
III.	IL4	6.400	0.745	0.638	0.019	0.037	6.073	0.035	0.009
III.	IL5	8.080	0.701	0.622	0.019	0.023	5.226	0.034	0.009
III.	IL6	10.060	0.731	0.734	0.020	0.017	4.245	0.164	0.009
III.	IL64	11.280	0.576	0.662	0.018	0.028	5.421	0.110	0.008
III.	IL8	12.800	0.614	0.645	0.022	0.017	4.181	0.046	0.007
III.	IL9B	14.330	0.789	0.730	0.022	0.025	5.122	0.064	0.009
III.	IL9	14.630	0.658	0.695	0.019	0.039	6.506	0.052	0.008
III.	IL9A	15.090	0.608	0.731	0.014	0.072	3.250	0.038	0.009
	SUM		9.194	9.424	0.241	0.515	122.232	0.986	0.118
	AVG		0.766	0.785	0.020	0.043	10.186	0.082	0.010
	Std. Dev.		0.141	0.328	0.008	0.011	0.423	0.016	0.002

STATE	SAMPLE	METERS	SR	ZR
III.	IL1	0.000	0.018	0.013
III.	IL2	2.740	0.021	0.014
III.	IL3	5.030	0.018	0.011
III.	IL3A*	5.180	0.007	0.007
III.	IL4	6.400	0.014	0.006
III.	IL5	8.080	0.014	0.009
III.	IL6	10.060	0.016	0.019
III.	IL64	11.280	0.011	0.022
III.	IL8	12.800	0.058	0.008
III.	IL9B	14.330	0.012	0.009
III.	IL9	14.630	0.011	0.008
III.	IL9A	15.090	0.012	0.011
	SUM		0.231	0.149
	AVG		0.019	0.012
	Std. Dev.		0.002	0.004

* Indicates the weathered glauconitic horizon.

PARIS

STATE	SAMPLE	METERS	NA2O	MGO	AL2O3	SI02	P2O5	S	K2O
TN	TL1	0.000	0.431	1.436	14.562	64.279	0.160	0.761	1.394
TN	TL1A	1.650	0.192	1.228	13.446	67.055	0.126	0.452	1.256
TN	TL2	3.300	0.153	1.279	14.118	66.369	0.126	0.543	1.305
TN	TL3	4.960	0.273	1.264	13.359	67.154	0.148	0.566	1.175
TN	TL4	6.610	0.379	1.277	12.408	68.555	0.181	0.503	1.259
TN	TL5	8.260	0.423	1.399	13.496	68.775	0.192	0.499	1.679
TN	TL6	9.910	0.299	1.203	12.447	69.509	0.185	0.493	1.572
TN	TL7	11.560	0.332	1.398	13.306	66.569	0.140	0.445	1.276
TN	TL8	13.220	0.319	1.293	13.152	65.942	0.146	0.538	1.296
TN	TL9	14.870	0.362	1.259	12.749	68.224	0.145	0.486	1.324
TN	TL10	16.520	0.258	1.263	12.971	67.207	0.123	0.565	1.276
TN	TL11A	18.170	0.198	1.489	14.647	61.634	0.139	0.764	1.305
TN	TL11B	18.170	0.462	1.358	14.794	63.683	0.125	0.474	1.494
TN	TL12	19.820	0.170	1.071	13.285	69.161	0.095	0.439	1.281
TN	TL13	21.480	0.297	0.867	11.178	76.622	0.101	0.283	0.973
TN	TL15	24.780	0.335	1.138	13.460	68.389	0.126	0.478	1.220
TN	TL15H	25.610	0.402	1.144	13.850	66.142	0.155	0.752	1.323
TN	TL16	26.430	0.179	1.074	14.903	65.987	0.133	0.699	1.811
TN	TL17	28.080	0.290	0.994	14.533	68.337	0.160	0.427	1.039
SUM			6.074	24.736	270.923	1350.682	2.856	10.816	26.661
AVG			0.320	1.302	14.259	71.089	0.150	0.569	1.403
Std.Dev.			0.395	0.160	0.409	0.545	0.040	0.014	0.108

STATE	SAMPLE	METERS	CAO	TIO2	CR	MNO	FE2O3	PN	RN
TN	TL1	0.000	0.316	0.731	0.017	0.037	6.344	0.036	0.010
TN	TL1A	1.650	0.279	0.702	0.017	0.037	6.042	0.037	0.009
TN	TL2	3.300	0.256	0.735	0.017	0.037	6.187	0.037	0.010
TN	TL3	4.960	0.252	0.679	0.018	0.036	6.030	0.040	0.009
TN	TL4	6.610	0.245	0.712	0.017	0.042	5.696	0.033	0.009
TN	TL5	8.260	0.463	0.776	0.016	0.039	5.534	0.046	0.009
TN	TL6	9.910	0.343	0.760	0.015	0.039	5.372	0.040	0.009
TN	TL7	11.560	0.272	0.727	0.019	0.042	6.341	0.033	0.009
TN	TL8	13.220	0.210	0.742	0.018	0.042	6.259	0.041	0.009
TN	TL9	14.870	0.221	0.708	0.018	0.036	5.803	0.036	0.009
TN	TL10	16.520	0.213	0.733	0.018	0.038	5.941	0.040	0.009
TN	TL11A	18.170	0.334	0.794	0.021	0.049	7.109	0.049	0.010
TN	TL11B	18.170	0.264	0.838	0.019	0.042	6.557	0.049	0.010
TN	TL12	19.820	0.245	0.714	0.018	0.037	5.671	0.042	0.009
TN	TL13	21.480	0.206	0.602	0.015	0.021	4.285	0.038	0.008
TN	TL15	24.780	0.327	0.706	0.017	0.037	5.233	0.045	0.008
TN	TL15H	25.610	0.140	0.714	0.017	0.035	5.317	0.049	0.009
TN	TL16	26.430	0.170	0.858	0.016	0.037	4.787	0.049	0.009
TN	TL17	28.080	0.331	0.650	0.017	0.021	4.307	0.034	0.008
SUM			5.370	14.652	0.348	0.743	114.945	0.817	0.182
AVG			0.289	0.771	0.018	0.039	6.050	0.043	0.010
Std.Dev.			0.141	0.328	0.008	0.011	0.423	0.016	0.002

PARIS CONT.

<u>STATE</u>	<u>SAMPLE</u>	<u>METERS</u>	<u>SR</u>	<u>ZR</u>
TN	TL1	0.000	0.011	0.008
TN	TL1A	1.650	0.011	0.005
TN	TL2	3.300	0.011	0.005
TN	TL3	4.960	0.011	0.003
TN	TL4	6.610	0.010	0.011
TN	TL5	8.260	0.011	0.025
TN	TL6	9.910	0.011	0.024
TN	TL7	11.560	0.011	0.010
TN	TL8	13.220	0.010	0.011
TN	TL9	14.870	0.009	0.007
TN	TL10	16.520	0.010	0.010
TN	TL11A	18.170	0.011	0.019
TN	TL11B	18.170	0.011	0.014
TN	TL12	19.820	0.010	0.009
TN	TL13	21.480	0.009	0.003
TN	TL15	24.780	0.011	0.008
TN	TL15H	25.610	0.010	0.009
TN	TL16	26.430	0.009	0.030
TN	TL17	28.000	0.010	0.003
		<u>SUM</u>	0.208	0.226
		<u>AVG</u>	0.011	0.012
		<u>Std.Dev.</u>	0.002	0.004

VITA

Joseph Calvin Faulkerson was born in Kingsport, Tennessee on August 30, 1956, and raised in Rogersville, Tennessee where he attended Rogersville High School. He graduated from Rogersville High School in June of 1974. After working for several years, he entered Tennessee Technological University where he received a Bachelor of Science Degree, with a major in Geological Sciences in June 1983. From May 1985 to September 1986 the author worked as one of four mine geologists at the Jersey Miniere Zinc Company in Gordonsville, Tennessee. He terminated his employment with Jersey Miniere in September 1986 to enter the University of Tennessee at Knoxville Department of Geological Sciences as a Masters Degree Candidate. At the conclusion of his studies in November 1989 he took employment as an exploration geologist with the Amoco Production Company in Houston, Texas.