Sedimentology of the Bedford-Berea Sequence (Early Mississippian), Williams Field, Michigan

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SEDIMENTOLOGY OF THE BEDFORD-Berea SEQUENCE (EARLY MISSISSIPPIAN), WILLIAMS FIELD, MICHIGAN

by

David Alan Balthazor

A Thesis
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requirements for the
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SEDIMENTOLOGY OF THE BEDFORD-BEREA SEQUENCE (EARLY MISSISSIPPIAN), WILLIAMS FIELD, MICHIGAN

David Alan Balthazor, M.S.

Western Michigan University, 1991

The Berea Sandstone has produced in excess of 1.6 million barrels of oil in the Williams field since discovery in 1980. Seven lithofacies are identified from conventional core in the Bedford-Berea sequence. These facies are interpreted as deltaic deposits comprising prodelta (Bedford Shale), delta front, destructive marine shale, abandoned distributary channel-fill, interdistributary bay-fill, transgressive marine sandstone, and marine shale (Sunbury Shale) facies. Passive channel-fill facies truncate reservoir sandstone bodies and compartmentalize the field NW-SE across the trend of the northwest-plunging anticline.

The two reservoir facies in the Williams field are the delta front and transgressive marine sandstones. The sandstone framework grain composition is a subfeldsarenite. The reservoir sandstones can be subdivided into reservoir facies with distinct petrologic evolution and reservoir characteristics. Reservoir facies include ripple-laminated, bedded, and "structureless" sandstones. The paragenesis and reservoir quality in each reservoir facies is attributed, mainly, to the presence of ductile detrital material, clay and mica, which templated the diagenesis, including compaction, cementation, and decementation.
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David Alan Balthazor

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Balthazor, David Alan, M.S.
Western Michigan University, 1991

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INTRODUCTION

The Early Mississippian Bedford Shale and superjacent Berea Sandstone are genetically related formations (Asseez, 1969) found throughout the Appalachian basin of Ohio, western Pennsylvanian, northern West Virginia, northeastern Kentucky, and the Michigan basin (Cohee and Underwood, 1944). The Berea Sandstone in the Appalachian basin has long been known for its excellent reservoir properties and as a significant oil and gas producer (Pepper, de Witt, and Demarest, 1954). The Bedford-Berea sequence in the eastern half of the Michigan basin, while not as prolific, has also produced commercial quantities of oil and gas from the Berea. Twenty-eight Michigan oil and gas fields have produced nearly five million barrels of oil and an excess of 13 billion cubic feet of gas from the Berea Sandstone (Michigan Department of Natural Resources, 1989).

Previous Work

The Bedford Shale and Berea Sandstone were named and described from the outcrop belt of northern Ohio (Newberry, 1870; as cited by Rominger, 1876). Equivalents of the Bedford-Berea of Ohio were first recognized in the Michigan subsurface by Rominger (1876). Cuttings from a brine test-well recorded 92 feet of "gray sandstone" (Berea) and 100 feet of "blue shales,
with subordinate sandstone layers and seams of iron pyrites" (Bedford) at a depth of 330 feet (Rominger, 1876, p. 92).

Newcombe (1933) described the Berea as a fine-grained, well-sorted, angular, somewhat micaceous, usually transparent, sometimes friable sandstone containing calcareous and gray-shale partings. He also recognized the distribution of the Bedford-Berea within the Michigan basin, noting the sequence does not extend into the western half of the basin. Newcombe (1933) attributed the westward thinning and fan-shaped plan to a possible deltaic origin. Also, the Bedford-Berea sequence is not continuous from Michigan into Ohio across the Findlay Arch. Pepper et al. (1954) suggest that the Michigan and Appalachian basins were separated by the Findlay Arch during Bedford-Berea time. Bedford-Berea deposits in Michigan and Ohio were probably sourced from the same area and transported by a single river system that emptied first into the Ohio basin, was diverted from its course 200 miles or more upstream to discharge into the Michigan basin on the west side of the Findlay Arch.

Based on lithologic character, Cohee and Underwood (1944) divided the Berea sandstone into upper, middle, and lower units and correlated the three stratigraphic units from east-central Michigan into northeastern Ohio. Their correlation was based on stratigraphic position, sequence of beds, and lithologic character of the beds comprising the formation in both areas.

The culmination of an extensive 11-year mapping program by the U.S.
Geological Survey represents the most comprehensive work on the Bedford-Berea sequence. Pepper et al. (1954) interpret the two formations in the Appalachian basin as fluvio-deltaic, barrier-bar, and offshore, marine deposits. They hypothesize Bedford-Berea deposits in Michigan were deposited under similar circumstances and derived from the same source area. Sedimentologic evidence suggested deposits in Michigan are younger than those in Ohio; however, paleontological evidence concluded they are near temporal equivalents (de Witt, 1970).

Asseez (1969) addressed the paleoenvironmental aspects of the Bedford-Berea in the Michigan basin. He concluded these deposits are deltaic in origin consisting of prodelta, delta front, and marsh deposits. Also, petrographic, lithologic, and clay-mineral studies indicate that the sequences in Ohio and Michigan are related, although the exact relation is uncertain. Asseez (1969) suggested two possible hypotheses for the origin of the sequence in Michigan and its relation to that of Ohio. First, the Michigan succession could be the western extension of the Ohio sequence deposited laterally across the Findlay Arch. Second, the Michigan succession could have been deposited under a fluvial regime similar to that which deposited the Ohio sequence, proposed by Pepper et al. (1954). Asseez (1969) favors the second hypothesis, indicating it is supported by the sedimentary record.

Gunn (1988b) studied the depositional facies of the Berea Sandstone of Williams oil field. His study was based on the examination of four
conventional cores and a well-log database. The conclusions of his study indicate the Berea Sandstone in the Williams field is a very fine- to fine-grained feldspathic sandstone deposited in a tidally-influenced, strand plain/barrier-bar environment.

Williams Oil Field History: Berea Pool

The Williams oil field (Figure 1) was discovered in 1980 by K.P. Wood Jr. in the Arthur 1-8 well (sec. 8 T14N R3E). This well was originally drilled as a Middle Devonian Dundee limestone test, but encountered uphole Berea production. The top of the Berea is at 2403 feet and the well flowed at rates greater than 50 barrels a day (Gunn, 1988a). Since discovery, more than 120 oil wells (Gunn, 1988a) have been drilled in Williams field producing an excess of 1.6 million barrels of oil from 3,360 acres (Michigan Department of Natural Resources, 1989). The field is developed on 40-acre spacing. Designs for a secondary recovery waterflood project are currently being considered by Oryx Energy Company, Dallas, Texas, and Muskegon Development Company, Mt. Pleasant, Michigan.

Larkin oil field is located approximately 2 miles northwest of the Williams field (Figure 1). This field was discovered in 1935 by Marshal H. Bauman in the State of Michigan #1 well (sec. 32 T15N R2E). The top of the Berea is at 2,473 feet in this well. Larkin field, abandoned in 1945 and reactivated in 1984, has produced 36,440 barrels of oil from 690 acres.
Figure 1. Location Map for the Williams and Larkin Oil Fields and the Surrounding Berea Producing Fields.
Field development is on 40-acre spacing. For the purpose of this study, Larkin is included with the Williams field unless noted otherwise.

The estimated oil-in-place in the Williams and Larkin fields is 24 million barrels (Gunn, 1988a).

Geologic Setting

**Stratigraphy**

Williams oil field produces from the Early Mississippian Berea Sandstone and the Middle Devonian Dundee Limestone. The reservoir of interest is the Berea Sandstone. The Dundee in the Williams field is a marginal producer.

Middle Devonian through Late Mississippian stratigraphy fit well within the context of the transgressive Kaskaskia sequence defined by Sloss (1963, Figure 2). The carbonates of the lower Kaskaskia Sequence are interrupted at the Devonian-Mississippian boundary by shales (Sloss, 1963). The System boundary in the Michigan basin was originally placed within the Amtrim Shale (Newcombe, 1933). However, de Witt (1970) cited microfaunal evidence from the Appalachian basin which places the boundary at the top of the Cleveland Member of the Ohio Shale (Antrim equivalent). Age relations can be projected into the Michigan basin with confidence (Pepper et al., 1954). This places the Antrim Shale into the Devonian System and the overlying Bedford Shale, Berea.
Figure 2. Stratigraphic Succession in Michigan.

(Michigan Department of Natural Resources, 1964)
Sandstone, and Sunbury Shale into the Kinderhookian Series of the Early Mississippian (Figure 2). Most students of the Bedford-Berea sequence (de Witt, 1970; Pepper et al., 1954; Potter, DeReamer, Jackson, and Maynard, 1983) consider that the Devonian-Mississippian system boundary may lie near the Antrim-Bedford contact.

The three lithologic units in the Berea Sandstone determined by Cohee and Underwood (1944) include upper light gray, fine-grained dolomitic sandstone, middle fine- to medium-grained, friable, angular to subangular quartzose sandstone, and lower more shaly sandstone. The sandstones are generally well cemented with silica and dolomite, micaceous, pyritic, and very silty and shaly in places. Only the upper two units are present in the Williams field.

A deltaic origin of the Bedford-Berea sequence within the Michigan basin was originally proposed by Newcombe (1933). A regional isopach map (Figure 3) shows the lobate plan and westward thinning of the sequence, suggesting an eastern source for the "birdfoot" Bedford-Berea delta (Asseez, 1969). Uplifts associated with the Acadian Orogeny (Late Devonian) probably provided clastic sediment to the Michigan and Appalachian basins (Pepper et al., 1954; Sloss, 1963). The presence of Mississippian age conglomerates in New Brunswick, Canada strongly indicates that during the time of their formation large quantities of finer-grained sediments were probably supplied to the Ontario River system, which deposited the Bedford-Berea sediments in
Figure 3. Bedford-Berea Sequence Isopach Map.

Contour Interval = 50 feet

Williams Field

(from Aseez, 1969)
Michigan and Ohio (Figure 4, Pepper et al., 1954).

The Michigan and Appalachian basins were in an equatorial position during Early Mississippian time (Scotese, 1984). The regional paleogeography suggests two active deltas (Figure 4, Pepper et al., 1954). The Bedford-Berea delta was responsible for the Bedford-Berea sequence in the Michigan basin, while the Berea delta produced equivalent deposits in the Appalachian basin (Asseez, 1969, Pepper et al., 1954).

The Ellsworth shale, a greenish-gray shale with interbedded dolomite and limestone, occupies the same stratigraphic position as the Bedford-Berea sequence in the western half of the Michigan basin (Asseez, 1969). The Ellsworth and Bedford may locally interfinger (Asseez, 1969, Tarbell, 1941). The Ellsworth is deltaic(?) in origin and represents the prodelta shales of a western river system (Asseez, 1969). The Ellsworth "delta" is not encountered in the Williams field.

The Sunbury Shale overlies the Bedford-Berea sequence and the Ellsworth Shale. The Bedford-Berea sequence and the Ellsworth Shale are terrestrial clastic wedges sourced from the east and west respectively, and thin toward the basin center. The clastic wedges are generally absent in the central parts of the Michigan basin with minor interfingering of the two formations. Where the Bedford-Berea and Ellsworth are absent, the Sunbury Shale overlies the Antrim Shale. The deposition of the black organic-rich Sunbury Shale signaled the end of clastic sedimentation in Michigan and the reestablishment of a
Figure 4. Paleogeography During "Early" Berea Time.

(* From Scotese, 1984)
marine environment in Early Mississippian time (Asseez, 1969).

Structure

The Michigan basin is an intracratonic feature which includes the Southern and portions of the Northern Peninsula of Michigan, parts of Wisconsin, Illinois, Indiana, Ohio, and Ontario (Lilienthal, 1978). Phanerozoic sediments in the basin range in age from Cambrian to Jurassic and may be in excess 16,000 feet thick (Fisher, Barratt, Droste, and Shaver, 1988).

Structures in the Phanerozoic cover rocks of the Michigan basin are believed to be a product of intrabasinal and/or extrabasinal stress fields acting on preexisting lines of weakness in the Precambrian basement (Hinze, Kellogg, and O’Hara, 1975; Pirtle, 1932; Versical, 1990). Based on lithology, isotopic age dating, and magnetic and gravity anomaly trends, Hinze et al. (1975) constructed a basement structure province map (Figure 5). A parallel relationship is noted between basement structural trends in each province and the dominant structural trends observed in the overlying sedimentary cover which suggests the inherent zones of weakness are unique to each of the basement provinces (Hinze et al., 1975).

Figure 6 is a structure contour map on top of the Sunburry Shale in the Williams field. The structure is a northwest plunging anticline. Larkin field is about 2 miles to the northwest and lies on the same structural trend as the Williams field. This structure may have developed as a small isolated
Figure 5. Basement Structure Province Map Showing the Dominant Structural Trend in Each Province.
Figure 6. Williams Field Structure Contour Map on Top of the Sunbury Shale.
dome or as a northwest extension of the Williams anticline. The Berea also produces in the Saginaw field about 14 miles to the southeast (Figure 1). This field occurs in the same structural trend (Ells, 1969). The Williams, Larkin, and Saginaw fields occur over the Penokean province which is characterized by northwest-southeast trending structural features (Figure 5).

Research Objectives

Despite the economic potential of the Berea Sandstone as a proven oil and gas producer, the Bedford-Berea sequence has received little attention in Michigan. Limited access to the sequence, found only in the subsurface in Michigan, likely contributed to lack of published data. Facies studies are limited to information which can be obtained from cores, cuttings, and electric logs.

The purpose of this study is to relate sedimentary facies, facies geometry, and petrology in the Berea Sandstone to hydrocarbon production in the Larkin and Williams fields. The recognition and description of sedimentary facies is critical to the understanding of the depositional environment associated with the Berea Sandstone and the Bedford Shale in the Larkin and Williams fields. The depositional environment and its subenvironments can aid in the prediction of sedimentary facies geometries and their gross lithologies. This information could aid in the design of enhanced recovery projects currently being considered for the Williams field and could also add valuable insight to
future prospecting in the Berea Sandstone in the Michigan basin. The Williams field depositional model will also be used to evaluate the tidally-influenced, strand plain/barrier-bar depositional model proposed by Gunn (1988b) versus earlier delta interpretations.

The second aspect of this study is to relate the sedimentary facies to the detrital and authigenic mineralogy observed in the sandstones, and relate the mineralogy to reservoir quality, e.g., porosity and permeability. These relationships provide a linkage between depositional processes and reservoir quality and can aid in the prediction of reservoir quality from lithofacies characteristics. Predictive relationships between facies and reservoir quality may be important to future enhanced recovery projects and prospecting.

Research Methods and Techniques

This study is based on the examination of eight representative, conventional cores from the Williams Field (Appendix A). Two of the wells contain core from the entire Berea section. No well contains core from the entire Bedford section and only the upper 20 feet of the formation is available for direct examination. The conventional cores were described for lithologic character, grain size, primary sedimentary structures, fossils, and biogenic structures. Based on these criteria, the Bedford-Berea sequence was divided into sedimentary facies. The Neyer-Siebert 1-1 (sec. 1, T14N R2E) and the K.P. Wood-Sheets 2-6 (sec. 6 T14N R3E) were examined to confirm
depositional trends and facies relationships; however, these cores were not described in detail. Cores are curated at the Western Michigan University Core Research Laboratory, Kalamazoo, Michigan.

Supplementing the limited distribution of the conventional cores are 143 gamma-ray logs. The sedimentary facies identified from the core descriptions were correlated to the gamma-ray log character. This correlation provides diagnostic log facies which generally correspond to the sedimentary facies determined from core. Log facies are then used to identify and correlate sedimentary facies where core data are unavailable. The variation in the gamma-ray signature can be attributed to lithologic variation. An increasing gamma-ray log signature corresponds to increasing shale content (Figure 7). The gamma-ray logs, on and off structure, are used to determine the spatial distribution and geometries of sedimentary facies. The spatial distribution, geometries, lithofacies characteristics, and the associations between the sedimentary facies are used to construct the depositional model for the Williams field area.

Twenty-four blue epoxy-impregnated thin sections from the reservoir sandstone facies of Williams field were examined using a standard petrographic microscope. One half of each thin section was stained with Alizarin Red-S and potassium ferricyanide to determine calcite from dolomite, ferroan calcite from ferroan dolomite (Dickson, 1966). Each section was also stained with a sodium cobaltinitrite solution, permitting quick identification of potassium
Figure 7. Comparison of Gamma-Ray Log Signature to Lithology in the Bedford-Berea Sequence, the Williams Field.

(Wiser-Retzloff 2-31)
feldspar (Houghton, 1980). Two hundred-fifty points were counted from each thin section to determine the relative percentages of framework grains, cements, and porosity. Sorting (Harrell, 1984) and roundness (Powers, 1953) are based on visual estimates. Sandstones were described in accordance with the classification scheme for detrital sedimentary rocks devised by Folk, Andrews, and Lewis (1970).

Based on abundances noted in thin section, four clay-rich sandstones were prepared for X-ray diffraction analysis (XRD). Each sample was crushed in a ceramic mortar and pestle and disaggregated ultrasonically. Separation of the clay-sized fraction < 2 and < 4 microns was done by centrifugation based on Stokes' law for settling velocities. Oriented samples were prepared using the "glass slide" method (Moore and Reynolds, 1989). One random powder mount was also prepared for a carbonate cemented sandstone. X-ray diffraction provided a more specific assessment of the carbonate species present than could be determined from staining. Scanning Electron Microscopy (SEM) was used to confirm textural relationships and the mineralogy observed from thin section and XRD analysis.
LITHOFACIES DESCRIPTIONS AND INTERPRETATIONS

The deltaic origin for the Bedford-Berea sequence in the Michigan basin was first postulated by Newcombe (1933) and later supported by the paleoenvironmental study of the sequence by Asseez (1969). Asseez's study, based on the cuttings from over 400 wells distributed throughout the Michigan basin, recognized the westward thinning and the fan-shaped map geometry of the Bedford-Berea sequence. Asseez (1969) also identified the prodelta, delta front, and marsh subenvironments in the Bedford-Berea delta.

In contrast, Gunn (1988b) interpreted the Bedford and Berea deposits in the Williams field area as a tidally-influenced, strand plain/barrier-bar depositional environment. Gunn's interpretations are based primarily on the distribution and orientations of the sandstone bodies. Reading (1986) cautions the use of individual facies to make environmental interpretations indicating that "knowledge of the context of a facies is essential before proposing an environmental interpretation" (p. 4).

Based on data presented herein, the model suggested for the Bedford-Berea sequence in the Williams field is one which a shallow-water deltaic deposit prograded over a broad area of muddy shallow-marine deposits. The delta built seaward, eventually waned and, during the final stage of delta-building, subsided, allowing the deltaic deposits to be transgressed by marine
environments. The vertical sequence of the sedimentary facies produced from the progradation of the Bedford-Berea delta is consistent with this interpretation when compared with Mississippi River delta (Coleman, 1982) and mid-continent delta stratigraphy (Brown, 1979).

Descriptions of the facies encountered in the Williams field and their interpretations follow.

**Lithofacies 1--The Bedford Shale**

Lithofacies 1 coincides with the Bedford Shale and underlies the Berea Sandstone. This facies marks the lowermost portion of the Bedford-Berea sequence in the Williams field and is coincident with the Bedford shale as described by Asseez (1969) and Newcombe (1933). Only a few gamma-ray logs penetrate the entire Bedford section in the Williams field and indicate that the total formation thickness may exceed 70 feet with little variation throughout the study area. Only approximately the top 20 feet of the Bedford Formation is available for examination.

**Description**

Lithofacies 1 is composed of highly fissile interlaminated shale, silty shale, micaceous shale, and minor thin-bedded siltstone in variable proportions. The coarsening-upward character of the gamma-ray log (e.g., decreasing gamma-ray log character, Figure 8) suggests silt content, as thin beds and laminae,
Figure 8. Typical Gamma-Ray Log Showing the Stratigraphic Succession of the Lithofacies in the Bedford-Berea Sequence, the Williams Field.

(Wiser-R.H. Peters 1-I)
increase in abundance and thickness up-section. Mica grains and macerated carbonaceous debris are abundant and most commonly associated with laminae and bedding planes. The presence of abundant carbonaceous debris indicates a significant contribution of terrestrial sediments to this deposit.

Micro cross-laminated and lenticular siltstone laminae and beds are the two most abundant sedimentary structures and result from the winnowing of finer-grained sediments by upper-flow-regime currents. Siltstone lenses were probably deposited as incomplete sand ripples. These "starved ripples" indicate alternating flow regime conditions more favorable for the deposition and preservation of mud than for sand and silt laminae (Reineck and Singh, 1980). Planar and wavy-irregular laminations are also abundant indicating deposition of clays and silts from suspension (Figure 9). Minor deformed bedding in this facies may have resulted from rapidly deposited sediments prior to substantial dewatering. Bioturbation occurs as horizontal silt-filled burrows and feeding trails, and ranges in intensity from negligible to moderate (Figure 9).

Visher, Ekebafe, and Rennison (1975) describe thinly bedded, moderately bioturbated, coarsening-upward shale sequences from the Coffeyville Format of Oklahoma. Silty partings in the shale increase in abundance upward to form the coarsening-upward deposit. Bedding planes are defined by carbonaceous detritus and mica grains. The trace fossils are in the form of horizontal silt-filled burrows and feeding trails. Coleman and Gagliano (1965) recognized shale facies that are transitional into the shelf environment and associated with
Figure 9. Lithofacies 1 (Bedford Shale).

Interlaminated micaceous-carbonaceous shale, and micro cross-laminated siltstone (M). Bioturbation is slight and occurs as horizontal silt-filled burrows and feeding trails (H). Wood-Sampier 1-7, 2450.3 ft.
the prograding Mississippi River delta. Near the source, silty parallel and lenticular laminations are common, and have minor cross-laminations and current ripples. Silty laminations become thinner and less frequent seaward from the distributary mouths. Organic detritus is scattered throughout this shale facies and small burrowing is common.

**Interpretation**

Lithofacies 1 represents prodelta deposition for the Bedford-Berea delta. Coleman and Gagliano (1965) define the prodelta from the Mississippi River as an area of deposition of fine clays associated with a specific prograding delta system. The prodelta interpretation for Lithofacies 1 is based on:

1. The stratigraphic position and transitional nature between the mud-rich marine shelf deposits of the Antrim Shale and the coarser-grained terrigenous clastics of the Berea.

2. The lithologic character which includes interlaminated shales and siltstones resulting in a coarsening-upward succession that is attributed to the seaward progradation of the distributary system; sand and silt content decreasing seaward from the source. The introduction of sand and silt during periods of flood and the subsequent winnowing of the finer-grained sediments by waves and currents likely resulted in the lenticular nature and concentrations of sandstones and siltstones observed in this facies.

3. Moderately bioturbated sediments containing horizontal silt-filled
burrows and feeding trails. The presence of burrows confirms a marine depositional environment for the Bedford; however, because of the higher rates of deposition associated with the prodelta, these deposits may escape intense burrowing by marine organisms (Coleman, 1982). Fresh to brackish conditions, due to the influx of fresh water from the fluvial system, may also have contributed to the low abundance and low diversity of burrowing marine organisms within the prodelta.

Lithofacies 2--The "A Sand" and the "B Sand"

Lithofacies 2 is one of the two reservoir facies in the Williams field. Two sandstone units are included in Lithofacies 2 and are traditionally referred to as the "A sand" and the "B sand." This lithofacies constitutes the majority of "Middle" Berea stratigraphy (Figure 8, Cohee and Underwood, 1944) in wells in the Williams Field.

Description

The "A sand" of Lithofacies 2 is a secondary reservoir in the Williams field and ranges from 0-16 feet in thickness with an average of 9.7 feet. It is a very fine- to fine-grained, mostly very fine-grained, moderate- to well-sorted, angular to subrounded sandstone and silty sandstone. Shale and silty shale occur as planar laminations and floating mud-chips. Mica grains and macerated carbonaceous debris are primarily associated with laminae and bedding
planes, but are also found scattered throughout the sand matrix. The abundance of macerated carbonaceous detritus indicates rapid sedimentation rates and a proximal terrestrial source for this facies.

Sedimentary structures are dominated by horizontal to subhorizontal planar laminations and small-scale trough (festoon) cross-laminations. Apparent "structureless" sandstones may be due to extensive bioturbation (Blatt, Middleton, and Murray, 1972), lack of grain size variation (Hamblin, 1965), or the lack of mica, carbonaceous debris, and clayey material highlighting sedimentary structures and laminae. Current-ripple laminations are noted and confined to the approximate upper two feet of the "A sand." Rare current-ripple laminations are also found throughout the section. Current-ripple laminations have tangential bases which are evidence of erosion and migration of consecutive ripple sets across the surface (Figure 10). No bioturbation is observed in the "A sand" of Lithofacies 2.

The "A sand" has a distinct lobate morphology (Figure 11). Small-scale trough cross-laminations and horizontal to subhorizontal planar laminations dominate the section. Coleman and Gagliano (1965) describe similar sedimentary structures from lobate sandstone bodies associated with the Mississippi River delta and interpret them as products of wave and current reworking.

The "B sand" of Lithofacies 2 is the principal reservoir in the Williams field. The thickness of the "B sand" varies from 12-29 feet and averages
Figure 10. Lithofacies 2.

(A) Climbing-ripple cross-laminated (CL) to current ripple-laminated (CU) sandstone. The direction of climb is from left to right. Micaceous shale and carbonaceous detritus define lamination plains. Neyer-Siebert 1-1, 2446.2 ft. 

(B) Scour-and-fill (arrows) is the contact between a horizontal planar-laminated sandstone and a "structureless" sandstone containing abundant floating mud-chips (MC) and rare carbonaceous debris (CD). Wood-Sampier 1-7, 2434.5 ft. 

(C) Load cast (LC) at the base of the "B-sand" associated with abundant carbonaceous debris (CD). Wood-Sampier 1-7, 2436.5 ft.
Figure 11. Delta Front Sandstone Facies "A Sand" Isolith Map (Lithofacies 2).
19.7 feet. This lithofacies is described as a very fine- to fine-grained, mostly very fine-grained, moderate- to well-sorted, angular to subrounded, micaceous and carbonaceous sandstone.

Current-ripple laminations and depositional-stoss climbing-ripple cross-laminations are abundant and dominate the upper half of the "B sand" (Figure 10). Depositional-stoss climbing-ripple cross-laminations are deposited by unidirectional currents, attributed to waning depositional energies (Harms, Southard, and Walker, 1982), and are a common feature in fluvial sediments (McKee, 1966). Coleman and Gagliano (1965) attribute climbing-ripple cross-laminations to the decrease in current velocity and a reduction in carrying power at the seaward terminus of a distributary channel. The resultant shoaling and vertical accretion of sediment support the development of channel mouth-bar deposits (Brown, 1979; Coleman, 1982). The channel mouth-bars of many modern deltas are capped by abundant climbing-ripple laminations (Coleman, 1982). Climbing-ripple laminations are common to the localized thicks (20- >25 feet) seen on the "B sand" isolith map (Figure 12), suggesting similar origins. Reineck and Singh (1980) indicate environments characterized by the introduction of little new sediment and much reworking (e.g., siliciclastic shorelines) are unfavorable for the development of climbing-ripple laminations. Small-scale trough cross-laminations, horizontal to subhorizontal planar laminations, and structureless sandstones are abundant and most common in the lower half of the "B sand." Sedimentary structures and laminae are defined
Figure 12. Delta Front Sandstone Facies "B Sand" Isolith Map (Lithofacies 2).

Hatched regions are zero contour areas.
by macerated carbonaceous debris and micaceous shale. Carbonaceous detritus is most abundant in association with current-ripple and climbing-ripple laminations and supports the interpretation of rapid sediment accumulation rates and a proximal terrestrial source for the sediment. Scour-and-fill structures are also recognized and commonly associated with angular, floating mud-chips (Figure 10). Scour-and-fill structures result from an increase in the current velocity to produce a surface scour in unconsolidated sediment. When the current velocity decreases, conditions favorable for the deposition of sediment return, and the shallow depressions are in-filled (Reineck and Singh, 1980). Bioturbation is absent in this lithofacies.

The "B sand" has a gross lobate form (Figure 12). The lobate morphology and the abundance of fluviatile sedimentary structures (e.g., climbing-ripple laminations and scour-and-fill) that cap the sandstone suggest fluvial processes are associated with the deposition of this facies.

Coleman (1982) and Coleman and Gagliano (1965) describe sequences in the Mississippi River Delta composed almost entirely of sand and silt with occasional thin laminae of clay and plant debris. Trough cross-laminations are the dominant sedimentary structure and are interpreted as a product of wave and current processes constantly acting on the sediment. Shoaling and extremely high sediment accumulation rates, evidenced by climbing-ripple and current-ripple laminations, typically cap these sand deposits. Scour-and-fill, erosional truncations, and angular clay inclusions in the coarser-grained sediment...
reflect channel processes acting on the unconsolidated sediment. The sands
described by Coleman (1982) and Coleman and Gagliano (1965) typically have
a lobate form.

**Interpretation**

Sandstone sequences in the Bedford-Berea are analogous to delta front
deposits described from the Mississippi River delta by Coleman (1982) and
Coleman and Gagliano (1965). The interpretation for the delta front deposits
of Lithofacies 2 is based on:

1. The lithology which consists of sandstone, siltstone, and minor shale
   laminae. Delta front deposits concentrate coarsest fraction available delivered
   by the distributary system.

2. The sedimentary structures which support deposition by channel
   processes and shoaling at the channel mouth which cap the succession (e.g.,
   climbing-ripple and current-ripple laminations, and scour-and-fill) and indicate
   proximal depositional processes, and sediments reworked by current and wave
   processes (e.g., trough cross-laminations and horizontal to subhorizontal laminae)
   indicating distal depositional processes.

3. The abundance of carbonaceous debris defining the sedimentary
   structures and laminations. Carbonaceous debris confirms a proximal terrestrial
   source for this facies.

4. The absence of bioturbation attributed to the high sediment
accumulation rates and/or non-marine to brackish conditions resulting from the influx of fresh water from the distributary system.

5. The lobate geometries of the "A sand" and "B sand" delta fronts and the localized thick of the "B sand" interpreted as channel mouth-bar deposits.

Lithofacies 3

Lithofacies 3 overlies the "A sand" of Lithofacies 2 and is included with "Middle" Berea stratigraphy (Figure 8, Cohee and Underwood, 1944) in the Williams field. The lower contact is gradational to sharp and is conformable with the "A sand" delta front.

Description

Lithofacies 3 is composed of homogeneous and planar-laminated black shale and silty shale, and rare siltstone that occur with planar laminations, wispy laminations, lenses, and pebbles. Siltstones are typically micro cross-laminated and were likely deposited by upper-flow-regime currents, possibly during periods of flood or by storms. Laminae in the silt pebbles are commonly preserved (Figure 13). Bioturbation is confined to thin (< 3 cm) horizons and is evidenced by a mottled texture (Figure 13). Burrows are back-filled with shale and silty shale and are difficult to distinguish from the surrounding rock.
Figure 13. Lithofacies 3.

(A) Bioturbated shale and silty shale. Burrows are indicated by the mottled texture and are back-filled with shale and silty shale making them difficult to distinguish from the surrounding rock. Wood-Jenkins 2-6, 2436.8 ft. (B) Silty shale and micaceous shale containing siltstone rip-up clasts (R). Note rippled laminae preserved in the clasts. Wood-Mieske 1-6, 2427.7 ft. (C) Shale and silty shale with planar (PL) and wispy (WL) siltstone interlaminations. Wood-Jenkins 2-6, 2436.9 ft.
Shale facies associated with delta front sandstones are described by Galloway and Hobday (1983) from the Mississippi River delta and are also recognized by Fisher and McGowen (1969) in the delta deposits of the Wilcox Group (Eocene) of Texas. Thin, persistent, bioturbated, muds cap the distal portions of abandoned delta front lobes in the Mississippi River and Wilcox deltas. Subsidence of the delta lobe after abandonment promoted localized transgression and the deposition of suspended, fine sediment on the delta front sand. The distribution of the shale is determined by the amount of subsidence after the lobe was abandoned. Mud deposition occurs initially on distal portions of the subsiding lobe while near source areas of the abandoned delta front may be exempt (Galloway and Hobday, 1983). The relationship between the shale facies and abandoned delta front sandstones was used by Fisher and McGowen (1969) to identify the individual delta front lobes in the stacked and coalesced delta fronts in the Wilcox Group delta.

**Interpretation**

Fisher and McGowan (1969) and Galloway and Hobday (1983) characterize the deposition of clay on an abandoned, subsiding delta front lobe as a destructive phase of delta development. The shale of Lithofacies 3 is interpreted to have a similar origin. This interpretation is, however, equivocal in that it is dependent on the association with an abandoned delta front lobe. The interpretation for the "destructive" marine shale of Lithofacies 3 is based
1. The lithologic similarity and stratigraphic position of this facies compared to the Mississippi River and Wilcox deltas. Lithofacies 3 is primarily shale and silty shale with minor interbedded siltstone. The lithology and sedimentary structures are consistent with the interpretation of deposition by suspension.

2. A marine origin for the shale, indicated by bioturbated sediments and the absence of abundant carbonaceous detritus. Carbonaceous detritus is common to terrestrial sediments and generally absent in marine deposits in the Berea in the Williams field.

3. The relationship of the shale facies with an abandoned delta lobe. The interpretation of an abandoned lobe is supported by the absence of superjacent delta plain deposits associated with the "A sand" delta lobe, an indication of an abbreviated delta sequence. The normal deltaic succession consists of prodelta, delta front, and delta plain deposits (Brown, 1979).

Lithofacies 4

Recognition of Lithofacies 4 is keyed by the absence of the "B sand" delta front sandstone. Log response is moderately high and slightly serrated indicating this facies is dominated by shale with minor coarser-grained sediment (Figure 14). Thickness of this facies ranges from 30-35 feet. This lithofacies was not identified by Cohee and Underwood (1944) and, therefore, cannot be

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Figure 14. Typical Gamma-Ray Log Showing Stratigraphic Succession Associated With Lithofacies 4 (Channel-Fill Deposits).

Note the absence of the "B sand" of Lithofacies 2. (Wood-G.Mieske 1-31)
defined in the context of Upper, Middle, or Lower Berea Sandstone stratigraphy.

Description

Lithofacies 4 is characterized by a finely interlaminated shale, silty shale, micaceous shale, and siltstone in variable proportions. Oxidized sediments are evidence of shallow water deposition and/or near subaerial exposure (Visher et al., 1975). Planar laminations and finely interlaminated nature of this facies indicate silts and clays were deposited from suspension with varying flow regime conditions to produce the micro cross-laminated siltstone lenses and rare thin-bedded siltstone (Figure 15). No bioturbation is recognized in this lithofacies. The absence of trace fossils most likely indicates non-marine conditions associated with deposition.

Lithofacies 4 is deposited in slightly sinuous, narrow, bifurcating bands with a maximum width of half a mile. The width of this facies is determined from the 40-acre well spacing in the Williams field. This facies occurs as lateral equivalents to the "B sand" of Lithofacies 2. The distribution of this facies and its association with the "B sand" are seen in Figure 12. Zero contour areas (hatched) in the "B sand" isolith map outline the distribution of Lithofacies 4. Well spacing in the Williams was not dense enough to allow the contouring of this facies and only their lateral extents are determined.

Reineck and Singh (1980) describe laminated and very thin-bedded clays
Figure 15. Lithofacies 4.

Finely interlaminated shale and siltstone with micro cross-laminated siltstone lenses (M) and thin-bedded siltstones (T). Bioturbation is absent in this lithofacies. Wiser-Retzloff 1-31, 2426.0 ft.
and silts from the Brazos River channel-fill deposits. Channel-fill deposits represent sedimentation in stream channels that have been abandoned by the stream because of cut-off processes; processes that result in the formation of ox-bow lakes in meandering streams, and by avulsion; and the sudden abandonment of a part or the whole channel course (Reineck and Singh, 1980). If the cut-off or the avulsion is complete at an early stage in stream abandonment, little coarser-grained bedload sediment is available for channel-filling. The filling is done by overbank flows and a fine-grained, clay-dominated sequence is deposited. However, at the point in the channel where the cut-off or avulsion occurred, a silt and sand plug may characterize the channel-fill deposit (LeBlanc, 1972).

**Interpretation**

The geometry and lithology of Lithofacies 4 is analogous to the channel-fill deposits described by Reineck and Singh (1980) from the Brazos River. The distribution of the channel-fill deposits in the Bedford-Berea sequence in the Williams field is a product of the downcutting by distributary channel processes, removing the "B sand." The abandonment of the stream channel by cut-off or avulsion processes and the subsequent in-filling result in the linear distribution of the channel-fill deposits and their adjacent relationship with the sandstone of the delta front "B sand." The interpretation for the abandoned channel-fill deposits of Lithofacies 4 is based on:
1. The linear distribution of this lithofacies which is a product of downcutting by stream processes. Downcutting resulted in scour relationships between the channel-fill deposits and the delta front "B sand." The result is channel-fill deposits adjacent to the delta front "B sand."

2. Lithology and planar laminated nature consistent with deposition by suspension. Coarse-grained bedload sediment is not available in the abandoned channel and filling is by overbank deposits. The lenticular and thin-bedded siltstones in the Williams field channels result from upper-flow-regime currents most likely during periods of flood.

3. The absence of bioturbation in this facies which is consistent with the interpretation of non-marine conditions associated with deposition and supports fluvial, as opposed to, tidal channel-fill.

Lithofacies 5

Lithofacies 5 contains interbedded shales, siltstones, and sandstones in variable proportions. Total thickness of this lithofacies ranges from 30-45 feet. Based on lithologic character, this facies was divided into low-energy and high-energy subfacies. A serrated gamma-ray is to differentiate the low-energy, shale dominated subfacies (high gamma-ray) from the high-energy, silt and sand dominated subfacies (low gamma-ray). The two subfacies of Lithofacies 5 account for the majority of the "Upper" Berea stratigraphy (Figure 8, Cohee and Underwood, 1944) in wells in the Williams field.
Description

The low-energy subfacies of Lithofacies 5 is composed of interlaminated shale, micaceous shale, pyritic shale, silty shale, and siltstone in variable proportions. Pyritic shales are locally abundant and likely reflect the reducing conditions of the Michigan Bay (Asseez, 1969).

Lenticular and micro cross-laminated siltstones are the two most abundant sedimentary structures and result from the winnowing of finer-grained sediments by upper-flow-regime currents. Siltstone lenses were probably deposited as incomplete sand ripples. These "starved ripples" indicate alternating flow regime conditions more favorable for the deposition and preservation of mud than for sand and silt laminae (Reineck and Singh, 1980). Planar to wavy-irregular laminae are also common and result from deposition of clays and silts from suspension. Minor deformed laminae may have resulted from deformation of the sediments prior to substantial dewatering (Figure 16).

Bioturbation as horizontal and vertical silt-filled burrows and feeding trails ranges in intensity from nil to churned (Figure 16). Rare vertical escape structures are also noted (Figure 16). The increased abundance and the greater diversity (e.g., horizontal and vertical burrowing) of trace fossils distinguish this subfacies from the prodelta deposits of Lithofacies 1. The variation of trace fossils suggests lower rates of sedimentation and/or possible normal marine conditions for this subfacies versus the prodelta facies.
Figure 16. Lithofacies 5—Low-Energy Subfacies.

(A) Shale and silty shale with very-fine deformed siltstone laminae. Wood-Jenkins 4-7, 2411.0 ft. (B) Horizontal-planar to wavy interlaminated shale and siltstone with silt lenses (L) and micro cross-laminated (M) siltstones. Bioturbation occurs as horizontal silt-filled (H) and vertical silt-filled (V) burrows and feeding trails and is most extensive in the mud-rich zones. Wood-Mieske 1-6, 2412.5 ft. (C) Burrow-mottled, wavy-irregular interlaminated micaceous shale and siltstone with thin-bedded siltstone and siltstone lenses (L). Mica grains define laminae and bedding planes. Note the large vertical escape structure (ES). Wood-Mieske 1-31, 2368.4 ft.
The high-energy subfacies of Lithofacies 5 comprises sharp based, very fine-grained sandstone and silty sandstone and minor shale laminae. Thicknesses of the sandstone interbeds range from 0.5-5 feet. Macerated carbonaceous debris and micaceous shale commonly define lamination and bedding planes. The abundance of preserved carbonaceous debris suggests rapid sedimentation and a proximal terrestrial source for the sediment. Sediments are commonly oxidized suggesting shallow water deposition and/or near subaerial exposure (Visher et al., 1975).

This high-energy subfacies is characterized by a variety of sedimentary structures including micro cross-laminations, current-ripple laminations, horizontal to subhorizontal planar laminations, rare climbing-ripple laminations, rare trough cross-laminations, and scour-and-fill structures. Scour-and-fill are commonly associated with floating mud-chips. Sedimentary structures described indicate highly variable flow regime currents. Asymmetrical wave ripples are also recognized. Asymmetrical wave ripples have an irregular internal stratification and a slight asymmetry to the ripple crests and indicate deposition of sediments by wave processes indicating relatively shallow water conditions (Figure 17, Reineck and Singh, 1980). Minor sand- and silt-filled horizontal burrows and feeding trails in the high-energy subfacies are confined to the shale laminae (Figure 17). The absence of trace fossils in coarser-grained sediments is likely due to higher depositional rates associated with the silts and sands.

The delta plane deposits from the Mississippi River delta representing
Figure 17. Lithofacies 5--High-Energy Subfacies.

(A) Horizontal planar-laminated sandstone underlain and overlain by "structureless" sandstones. An oxidized zone (O) defines the lower contact of the planar-laminated bed. A scour-and-fill structure (arrows) truncates planar laminations and defines the upper contact. Wood-Mieske 1-31, 2364.8 ft.

(B) Wave ripple-laminated sandstone overlain by a lenticular laminated sandstone and micaceous shale. Note irregular internal stratification of the wave ripple. Wood-Mieske 1-31, 2373.1 ft.

(C) Contact between the sandstone and siltstone of the high-energy subfacies and shale dominated low-energy subfacies (large arrow). Trace fossils in the high-energy subfacies occur as horizontal sand- and silt-filled burrows and feeding trails and are confined to the shale laminae (small arrows). Note the asymmetrical wave ripple (W) at the top of the core. Wood-Mieske 1-31, 2376.7 ft.
interdistributary bay, overbank splay, and crevasse splay facies characterize interdistributary bay-fill sediments (Coleman, 1982). Crevasse splays and overbank splays periodically break off the main distributaries during periods of flood and gradually in-fill the muddy interdistributary bays with sands and silts. Deposition of the coarse-grained splay deposits reach a maximum, wane, and eventually become inactive. As a result of subsidence, the crevasse system is inundated by marine waters and returns to the original bay environment. Conditions favorable for the deposition of mud return, the crevasse deposits are buried by the marine muds, and the bay-fill cycle is completed. The stacking of multiple bay-fill cycles can result in thick bay-fill sequences (e.g., one bay-fill cycle from the Mississippi delta ranges from 3-15 meters).

Interdistributary bay deposits are characterized by abundant burrowing and lenticular laminae. Lenticular laminae are interpreted as a product of winnowing and reworking coarser-grained sediments by wind generated waves in the shallow bays. The coarser-grained splay deposits contain a variety of sedimentary structures including ripple-laminations, climbing-ripple laminations, and wave ripples. The exposure to subaerial oxidizing conditions commonly results in the formation of a large number of diagenetic products, especially iron oxides.

Interpretation

The sediments of the two subfacies of Lithofacies 5 are analogous to the
bay-fill deposits described by Coleman (1982) from the Mississippi River delta. The interpretation for the interdistributary bay-fill deposits of Lithofacies 5 is based on:

1. Interbedded lithologies that require greatly differing flow regime currents. The thicknesses (≤ 5 feet) and sedimentary structures of the high-energy subfacies indicate the high flow regime currents were operating for a relatively long period of time, e.g., longer than a single flood event. Currents eventually waned to allow the deposition of the suspended fine-grained sediment of the low-energy subfacies. Periodic breaches in a distributary channel and the eventual sealing of that breach would be consistent with this depositional scenario.

2. Bioturbated sediments indicate brackish to normal marine conditions. The general absence of trace fossils in the coarser-grained splay deposits is likely due to the higher rates of deposition associated with this subfacies and is supported by burrowing in the shale laminae within the sand- and silt-dominated splay deposits.

3. The abundance of oxidized zones indicating shallow water deposition and/or near subaerial exposure.

Lithofacies 6

Lithofacies 6 defines the uppermost portion of the Bedford-Berea sequence and is a secondary reservoir for Williams field. This facies is
typically less than ten feet thick and is included with "Upper" Berea stratigraphy (Figure 8, Cohee and Underwood, 1944) in the Williams field.

Description

Lithofacies 6 is composed of very fine- to fine-grained, well-sorted, subangular to rounded sandstone with occasional micaceous and silty shale laminations. Sedimentary structures include horizontal to subhorizontal planar laminations, wavy-irregular laminations, small-scale ripple-laminations, soft sediment deformation, and rare floating mud-chips (Figure 18). Zones of intense bioturbation, commonly less than ten centimeters thick, are recognized by churned sediments (Figure 18). Burrowing has likely destroyed all sedimentary structures in these zones and indicate marine conditions associated with the deposition of this facies. Rare trilobite and brachiopod (?) fragments confirm a marine origin for this sandstone (Figure 18). Articulate and inarticulate brachiopod are described from similar Berea sandstone facies which crop-out throughout Ohio (Coogan, Heimlich, Malcuit, Bork, and Lewis, 1981; Hyde, 1953).

The distribution of Lithofacies 6 is sheet-like in nature. Thickness ranges from 5-9 feet with localized thins (< 5 feet) and thick (> 10 feet, Figure 19).

Bioturbated, fossil baring sandstones commonly cap shallow water deltaic sequences from the Mississippi River delta (Fisk, 1955) and are also associated
Figure 18. Lithofacies 6.

(A) Planar-laminated sandstone containing a rare concentration of trilobite fragments (arrows). Wood-Mieske 1-31, 2353.1 ft.

(B) Ripple to planar to wavy-irregular laminated sandstone. Micaeous shale and silty shale define laminations. Mudstone rip-ups (arrows) were likely derived as the sand transgressed mud-rich interdistributary bay deposits. Neyer-Siebert 1-1, 2391.8 ft.

(C) Mottled texture is the result of burrowing by marine organisms which have destroyed all sedimentary structures. Burrow-mottled sandstone is overlain by planar-laminated sandstone containing a rare brachiopod(?) fragment (arrow). Wiser-Retzloff 2-31, 2370.8 ft.
Figure 19. Transgressive Marine Sandstone Facies Isolith Map (Lithofacies 6).

Map represents a sheet sand 5-10 ft. thick with localized thick (> 10 ft.) and thins (< 5 ft.).
with deltaic deposits from the mid-continent region of the United States (Brown, 1979). These sandstones are a final stage of destructive delta building and result from the abandonment of the distributary system and the subsidence of the associated delta complex. Localized marine transgression, resulting from the subsidence, promotes the reworking of the delta front sands and the deposition of these sands on the subsiding delta complex (Brown, 1979; Visher et al., 1975). Sands are deposited as littoral sheet sands, small barrier bars, and storm berms (Brown, 1979).

**Interpretation**

The sandstone of Lithofacies 6 is analogous to the transgressive sandstone cap which commonly cap abandoned delta deposits of the Mississippi River delta (Fisk, 1955) and delta deposits in the mid-continent region of the United States. The interpretation for the transgressive marine sandstone of Lithofacies 6 is based on:

1. The marine origin for this facies indicated by bioturbated sediments and rare macrofossil fragments.

2. The stratigraphic position of this sandstone. The sandstone is transitional between the terrigenous clastics of the Bedford-Berea delta and the marine, organic-rich Sunbury Shale which overlies the Berea Sandstone.

3. The sheet-like geometry of this sandstone. The sandstones associated with abandoned deltaic complexes are commonly deposited as transgressive sheet
sands.

Lithofacies 7—The Sunbury Shale

Lithofacies 7 (the Sunbury Shale) overlies the Bedford-Berea sequence and is easily identified by the twin spike gamma-ray log character which is commonly in excess of 300 API units (Figure 8). The contact between the two formations is sharp and conformable (Figure 20). Thickness of the Sunbury, determined from gamma-ray logs, is approximately 20 feet and remains constant throughout the study area. Only the lower two feet of the formation are available for examination in the Williams field.

Description

Lithofacies 7 can be described as a black, planar-laminated shale (Figure 20). The black color of the Sunbury Shale is attributed to the preservation of large amounts of organic matter (Asseez, 1969).

Interpretation

The Sunbury Shale is interpreted to have been deposited in a shallow, reducing marine environment (Asseez, 1969). The deposition of the Sunbury signaled the end of active detrital sedimentation and the reestablishment of a marine environment in the Williams field area.
Figure 20. Lithofacies 7 (Sunbury Shale).

Black, organic-rich marine shale (Sunbury) sharply overlying the transgressive marine sandstone (TMS) of Lithofacies 6. Wiser-Retzloff 2-31, 2364.6 ft.
DEPOSITIONAL MODEL

Modern Analog

The Bedford-Berea sequence was deposited in a deltaic system similar to parts of the modern Mississippi River delta. With the exception of the modern birdfoot delta currently building outward into the deep water near the edge of the continental shelf, all the subdeltas of the Mississippi River were formed by progradation into shallow (20-30 feet) inner-shelf areas (Gould, 1970). Such deltas are termed "shoal-water" deltas by Fisk (1955). The LaFourche delta, studied by Fisk (1955), Gould (1970), and many others, is a typical example.

The LaFourche delta formed through progressive outbuilding of sediments delivered by a complex network of distributary channels a quarter to half a mile wide. The great abundance of distributaries and the bifurcating map geometry can be attributed to the frequent filling of channels as the delta prograded, forcing the development of more efficient outlets (Gould, 1970).

Sediments carried by LaFourche distributary channels were greater than 75% silt and clay and less than 25% sand. The coarsest size fraction was fine sand. Sand, deposited at the seaward terminus of the channels, formed a sheet-like deposit comprising channel mouth-bars, spits, and brackish-marine environments. Sand deposits are typically crossbedded and laminated and attain
a thickness of 20-50 feet.

The finer grained silts and clays were carried seaward and deposited on the marine muds of the shallow shelf. Deposits grade upward from massive silty clays into thin-bedded clayey silts with occasional sand stringers forming the coarsening-upward sequence of the prodelta. Continued progradation and subsidence resulted in prodelta silts and clays to be gradationally overlain by the sheet sand of the delta front.

As the LaFourche delta advanced and the terminus of the river channels moved seaward, areas no longer undergoing active sedimentation began to subside due to compaction of water-laden sediments. The result was the formation of a brackish marsh. Marsh deposits marked the final stage of constructive delta development and provided an impermeable seal to the delta front sandstones. The constructive sequence consists of a base of prodelta silts and clays, overlain by the sheet sand of the delta front and capped by marsh deposits. Marsh deposits are included with the delta plain deposits (Figure 21, Brown, 1979).

LaFourche channel-fill sands lie in sharp erosional contact with the underlying prodelta silts and clays and grade upward into the interbedded sands and silty clays of the marsh environment. The channel-fill sands have no fauna associated with them.

Following abandonment, the LaFourche delta continued to subside, allowing marine waters to transgress the marsh deposits. This destructive phase
The LaFourche delta model from the Mississippi River delta shows the development of a shallow water delta and the resulting depositional sequence. This figure was modified to show the interdistributary bay deposits which are included with the delta front facies by Gould (1970).
of delta development is marked by the occurrence of a transgressive marine sand in sharp erosional contact with the underlying sands and silty clays of the marsh.

**Bedford-Berea Depositional Model**

The Bedford-Berea sequence of Williams field was deposited in a very similar manner to that described above. The distributary channels, as represented by deposits described from Williams field, are abundant, bifurcating, and have a maximum width of half a mile.

The Bedford-Berea delta is dominated by the deposition of silts and shales accounting for greater than 75% of the section. Sandstones account for less than 25%. The coarsest fraction is fine sand.

The initial phase of deposition is represented by the progradation of prodelta deposits into the shallow, quiet waters of the Michigan Bay (Asseez, 1969). The prodelta directly overlies the black, organic-rich marine Antrim Shale (Asseez, 1969). As the delta continued to build, distributary channels prograded into the area from the north(?) to deposit the delta front sandstone of the "A sand." With the end active sedimentation, compaction and subsidence followed. Muddy marine sediments (destructive marine shale) transgressed the abandoned lobe, capping to the "A sand" (Figure 22).

Shortly after, prograding distributary channels from the east to ENE(?) began depositing the delta front sandstone of the "B sand." The "A sand" and
the "B sand" represent deposition by two delta fronts which prograded into and across the area under similar circumstances at different times. The stacking of multiple delta fronts is a common characteristic of shoal-water deltas (Donaldson, Martin, and Kanes, 1970). The two sands are typically separated by the shale of the destructive marine shale facies (Lithofacies 3). The exception is in the southeast corner of the field where progradation of the "B sand" removed the uppermost "A sand" and the shale normally separating the sands (Figure 22). The product is a comparatively thick, cohesive sand. The contact between the "A sand" and the "B sand" is an erosional surface associated with a shale-pebble lag-conglomerate and floating mud-chips (Figure 23).

As the delta continued to build seaward, distributary channels incised through the delta front of the "B sand" and the development of interdistributary bay environments occurred in areas adjacent to the channels. Overbank deposits and small breaches in the channel resulted in the interbedding of sands and silts (high-energy bay-fill subfacies) with muddy marine bay deposits (low-energy bay-fill subfacies). Bay facies gradationally overlie and form an impermeable vertical seal to the delta front of the "B sand." Interdistributary bay deposits mark the end of the typical constructive delta sequence. The constructive sequence consists of a base of prodelta siltstones and shales, overlain by delta front sandstones and capped by delta plain deposits. Delta plain deposits comprise interdistributary bay sands, silts, and shales. The marsh deposits
Figure 22. Northwest to Southeast Cross Section, Williams and Larkin Fields.

The cross section shows the horizontal and vertical relationships between the depositional facies.
Williams Field

SE Cross Section
Index Map

Key

Abandoned
Al Well
Bedded
Replaced
X Well
(new) well this study

Top Sunbury Shale

• Fields.

• the depositional

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Figure 23. Erosional Contact Between the "A Sand" and the "B Sand".

The contact between the "A sand" and the "B sand" is a scour surface (arrows) associated with a thin-bedded shale-pebble lag conglomerate (C) and floating mud-chips (MC). The most likely source for the shale clasts is from the "destructive" marine shale of Lithofacies 3 which normally separates the two sands. Wood-Sheets 2-6, 2424.5 ft.
described from the LaFourche delta are found further to the east for the Bedford-Berea delta (Figure 24, Asseez, 1969).

Infilling of the channels forced the distributaries to find more favorable routes. Channel-fill deposits grade upward into and are overlain by interdistributary bay deposits and are found as lateral equivalents to the destructive marine shale, delta front sandstone of the "B sand," and the interdistributary bay-fill facies. This facies forms impermeable horizontal seals within the "B sand" (Figure 22).

The delta continued to compact and subside after abandonment and marine waters deepened and locally transgressed the interdistributary bay sediments. This destructive stage of delta development is marked by a transgressive marine sheet sandstone. A likely source for the sediment is from reworked delta front sands (Brown, 1979). At the end of Berea time, a regional transgression occurred (Pepper et al., 1954). The Bedford-Berea delta was inundated by the waters of the Michigan Bay and marine shale was again deposited in the Williams field area (Figure 22).

Hydrocarbon Trapping

Hydrocarbon trapping for Williams field is both structural and stratigraphic. The northwest plunging anticline provides most of the closure. The stratigraphic trap is provided, in part, by muddy interdistributary bay-fill deposits which overlie and form an impermeable vertical seal to the
Figure 24. Paleogeographic Map During Deposition of the Bedford-Berea Delta.

Note location of the Williams Field.
reservoir sandstone of the delta front "B sand" (Figure 22). Muddy channel-fill deposits provide impermeable horizontal seals within the reservoir sandstone. Channel-fill deposits, perpendicular to the structural trend, have compartmentalized this reservoir northwest to southeast. Williams, Larkin-Williams, and Larkin "compartments" are easily recognized (Figure 25) and supported by: (a) a separate oil-water contact for each compartment and, (b) a different formation pressure for each compartment (T. Maness, pers. commun.). More importantly, the lateral seals prevented the continued migration of hydrocarbons up-dip along the axis of the anticline.
Figure 25. Structure Contour Map on Top of the Sunbury Shale With Superimposed Locations of the Channel-Fill Deposits of Lithofacies 4.
Petrographic studies of the Berea reservoir sandstones were undertaken to relate sedimentary facies to the detrital and authigenic mineralogy observed in the sandstones, and relate the mineralogy to reservoir quality. These relationships provide a linkage between processes related to sandstone deposition and the reservoir quality of the sandstones, and can aid in the prediction of reservoir quality from lithofacies characteristics and possibly log response.

The reservoir sandstone from the Berea Formation in the Williams field include the delta front sandstones, the "A sand" and the "B sand" (Lithofacies 2), and the transgressive marine sandstone (Lithofacies 6). The delta front "B sand" is the primary reservoir in the Williams field. Detrital modes consist of quartz, feldspar, trace amounts of quartzose rock fragments, detrital clays as matrix and sedimentary clay clasts, and trace amounts of carbonaceous fragments. The average normalized framework grain composition of these sandstones is a subfeldsarenite (Folk et al., 1970), comprising 94.5% quartz, 4.2% feldspar, and 1.2% lithic rock fragments (Table 1). The framework grain composition of the three reservoir sandstones is relatively uniform. The main compositional variation is in the proportions and types detrital matrix and interstitial authigenic cements.

The sandstones are very fine-grained, moderately- to well-sorted, and
<table>
<thead>
<tr>
<th>Composition¹</th>
<th>Delta Front</th>
<th>Delta Front</th>
<th>Transgressive</th>
<th>Total Reservoir</th>
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<tr>
<td></td>
<td>&quot;A Sand&quot;</td>
<td>&quot;B Sand&quot;</td>
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<td>Sandstones</td>
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<td>Mica⁴</td>
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<td>Measured φ⁷</td>
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<td>Permeability⁷</td>
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<td>1.5md</td>
<td>26.2md</td>
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¹Composition based on thin section analysis.
²Mono- and polycrystalline quartz.
³Potassium and plagioclase feldspar.
⁴Biotite and muscovite.
⁵Quartz/Feldspar/Lithic Fragments as defined by Folk et al. (1970).
⁶Inter- and intragranular porosity.
⁷Porosity and permeability from whole-core analysis.
subangular to subrounded. Most grains are in point to long contact with occasional concavo-convex grain contacts, suggesting that only low to moderate compaction resulted, and that the Berea Sandstone may never have been buried very deeply.

In order to evaluate facies controls on reservoir quality, the reservoir sandstones are alternatively discriminated based on the dominant type of sedimentary structures. These reservoir sandstone facies are: (a) ripple-laminated sandstone that contain distinct thin laminae, (b) bedded sandstone having subtle horizontal stratification, but no laminae, and (c) massive or "structureless" sandstone having no obvious bedding or laminae (Table 2). Poor electric-log suites in most wells in the Williams field, consisting mainly of gamma-ray logs, prevented the characterization of reservoir sandstone facies based on the log signature.

Detrital Mineralogy

Quartz

Detrital quartz grains in the Berea Sandstone range from 55-72% and average 62% of the whole rock mineralogy of the sandstones (Appendix B, Table 1). The types of quartz observed are unstrained monocrystalline grains, strained monocrystalline grains, indicated by sweeping extinction patterns, and polycrystalline grains. Unstrained monocrystalline grains are the most common
Table 2

Average Compositions, Porosities, and Permeabilities of Reservoir Facies in the Berea Sandstone Reservoirs

<table>
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<tr>
<th>Composition¹</th>
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<th>Bedded Sandstone Facies</th>
<th>&quot;Structureless&quot; Sandstone Facies</th>
<th>Total Depositional Facies</th>
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<th></th>
<th>Quartz²</th>
<th>Chert</th>
<th>Feldspar³</th>
<th>Mica⁴</th>
<th>Clay Clasts</th>
<th>Clay Matrix</th>
<th>Carbonaceous Fragments</th>
<th>Q/F/L⁵</th>
<th>Ankerite</th>
<th>Dolomite</th>
<th>Siderite</th>
<th>Kaolinite</th>
<th>Chlorite</th>
<th>Illite</th>
<th>Qtz Overgrowths</th>
<th>Pyrite</th>
<th>Hematite</th>
<th>Porosity (φ)⁶</th>
<th>Measured φ⁷</th>
<th>Permeability⁷</th>
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<td>60.4%</td>
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<td></td>
<td></td>
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</tbody>
</table>

¹Composition based on thin section analysis.
²Mono- and polycrystalline quartz.
³Potassium and plagioclase feldspar.
⁴Biotite and muscovite.
⁵Quartz/Feldspar/Lithic Fragments as defined by Folk et al. (1970).
⁶Inter- and intragranular porosity
⁷Porosity and permeability from whole-core analysis.

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variety. Strained and unstrained monocrystalline grains commonly contain fluid and/or mineral inclusions. Polycrystalline quartz accounts for less than 8.0% of the total mineralogy (Appendix B).

Detrital chert grains are also present, but are volumetrically minor (≤ 4.0%, Appendix B). Chert is considered a detrital rock fragment under the sandstone classification scheme used in the context of this study (Folk et al., 1970). The variation in percent quartz and chert is negligible in the reservoir sandstones (Tables 1 and 2).

**Feldspar**

Feldspar constitutes, on the average, 3% of the whole rock mineral composition of the sandstones (Table 1). Potassium feldspar is the most common variety with trace amounts of twinned plagioclase feldspar (Appendix B). K-feldspar and plagioclase show varying degrees of grain dissolution (Figure 26). The alteration of K-feldspar ranges from slight (honeycombed grains) to near complete grain dissolution. Plagioclase grains also show dissolution textures; however, not nearly as extensive as the K-feldspar. The dissolution of plagioclase grains ranges from negligible to slightly honeycombed. The variation in percent feldspar is negligible in the reservoir sandstones (Tables 1 and 2).
Figure 26. Photomicrographs of Typical Berea Sandstone, the Williams Field.

(A) The majority of the grains are mono- and polycrystalline quartz (Q) with abundant overgrowths (arrows). Some porosity (φ) is the result of leached detrital grains, most likely feldspars (F). Porosity is occluded by ankerite cement (A). Plane light, Wood-Dattie 2-6, 2416.0 ft. (B) Sandstone with abundant interstitial clay matrix (X). Muscovite (M), biotite (B), carbonaceous fragments (C), and matrix (X) define sedimentary structures and laminae. Half-crossed nichols, Wood-Jenkins 2-6, 2426.0 ft.
Mica

The detrital origin of biotite and muscovite grains is indicated by frayed edges, concentration and preferred orientation on lamination and bedding planes, and their deformation between framework grains due to mechanical compaction. Mica grains may act as barriers to fluid flow by bridging pore throats resulting in lower porosities and permeabilities. Detrital mica grains are commonly associated with clayey laminae and carbonaceous fragments which serve to define sedimentary structures (Figure 26). Sandstone containing abundant sedimentary structures typically has lower porosities and permeabilities than "structureless" and bedded sandstones. Detrital mica is most common in ripple-laminated sandstone (4.4%) and present in bedded (2.6%) and "structureless" (2.6%) sandstones (Table 2).

The transgressive marine sandstone shows variation in percent mica (1.2%) versus the delta front "A sand" (3.0%) and "B sand" (3.4%, Table 1). The decrease in detrital mica is likely due to winnowing of mica grains, a result of slow sedimentation rates and reworking of the sandstone during transgression (Table 1).

Detrital Clay

Detrital matrix may account for as much as 17% (average 5%) of the sandstone composition (Appendix B). Mineralogy of the matrix is difficult to
determine due to its extremely fine-grained nature. The moderately birefringent, yellowish-brown appearance in thin section suggests illite clay is a dominant component (Figure 26).

Detrital matrix significantly reduces sandstone porosity and permeability by completely occluding pore space. Detrital clay matrix is most common in ripple-laminated sandstone (12.0% of the potential pore space) and present in bedded sandstone (3.7%) and "structureless" sandstone (3.3%, Table 2). Sedimentary structures are commonly defined by matrix material and mica grains. Decreased abundance of detrital matrix in the transgressive marine sandstone facies (1.2%) versus the delta front "A sand" (5.6%) and "B sand" (5.1%) is likely due to winnowing of the finer-grained clay material, a result of slow sedimentation and reworking of the sandstone during transgression (Table 1).

Sedimentary clay clasts occur as obvious well-rounded detrital grains or compacted between framework grains to the extent that original grain boundaries are no longer evident. Compacted clasts or "pseudomatrix" commonly occlude the entire pore space; however, they are a minor detrital component and do not significantly reduce porosity and permeability.

**Authigenic Mineralogy and Paragenesis**

Authigenic minerals include, in order of relative abundance, carbonate cements (predominantly ankerite), discrete authigenic clay minerals, and
accessory amounts of quartz cement (as syntaxial overgrowths), pyrite, and hematite (Table 1, Appendix B).

**Carbonate Cements**

Ankerite is the dominant cement in many samples, accounting for as much as 22% of the mode (Appendix B). Ankerite is associated with minor dolomite. Ankerite and dolomite are commonly patchy, coarsely crystalline, intergranular, and void-filling. Ankerite and dolomite cements in the Berea sandstones commonly replace detrital and authigenic modes. The replacement (or possibly displacement) of detrital matrix by ankerite is common. Well developed, euhedral ankerite crystals in the matrix are clearly authigenic in origin (Figure 27). Detrital quartz grains and quartz overgrowths are corroded and embayed by carbonate cement indicating replacement of quartz by carbonate (Figure 27). The presence of carbonate cement in pores partly occluded by syntaxial quartz overgrowths indicates the carbonate formed following quartz overgrowths. Ankerite cement also occupies secondary porosity after feldspar grain dissolution. This texture indicates the formation of carbonate cement after the dissolution of detrital feldspar grains (Figure 27).

Ankerite cement is derived from the iron enrichment of dolomite in the Berea sandstones. The dolomite precursor to ankerite cement is seen in large patches of carbonate cement where incomplete ankeritization has occurred. An interior dolomite core remains, surrounded by ankerite cement. The preferential
Figure 27. Photomicrographs of Ankerite Cement, Berea Sandstone.

(A) Ankerite cement (A) replacing detrital clay matrix (X) and detrital quartz grains (arrows). Half-crossed Nichols, Wood-Jenkins 3-7, 2355.0 ft. (B) Matrix (X) and ankerite (A) cemented sandstone. Note floating grain textures and replaced detrital grains (R) within ankerite. Half-crossed Nichols, Wood-Jenkins 2-6, 2424.0 ft. (C) Etched and embayed quartz grains (arrows) floating in ankerite cement. Dark patch (R) in the cement is a replaced K-feldspar grain. Half-crossed Nichols, Wood-Jenkins 2-6, 2424.0 ft.
ankeritization along dolomite cleavage planes suggests crystal cleavages provide conduits for the flow of iron enriched interstitial fluids through the dolomite cements, promoting ankeritization (Figure 28). The euhedral ankerite rhombs in the clay-rich matrix suggest matrix is a precursor to carbonate cement and, in part, controls its distribution. The replacement of matrix by carbonate is further supported by framework grains "floating" in carbonate cement, a common texture to matrix-rich sandstone (Figure 27). Ankerite is also believed to precipitate directly without a dolomite or matrix precursor.

Ankerite is most common in ripple-laminated sandstone (7.6%), but is also present in bedded sandstone (4.1%) and "structureless" sandstone (1.7%). The abundance of ankerite in ripple-laminated sandstone is associated with the replacement of detrital clay matrix.

Siderite cement occurs mostly in trace amounts as discrete euhedral carbonate rhombs and as small clusters of rhombs. Well developed crystals confirm their authigenic origin (Figure 29). The timing of siderite precipitation is equivocal. Siderite rhombs are found only within the detrital matrix and no cross-cutting relationships exist with other authigenic mineral phases. The percent siderite is minor and the effect on porosity and permeability is negligible.

Nodules of siderite are described in core from the Wood-Mieske 1-31 and the Wiser-Retzloff 1-31 from the transgressive marine sandstone facies (Appendix A). Nodular siderite cements are not extensive and their influence
Ankerite (A) replacement of intergranular dolomite (D) cement. Preferential ankeritization is noted along dolomite cleavage planes (arrows). Half-crossed nichols, Wood-Jenkins 2-6, 2424.0 ft.

Matrix-rich sandstone containing abundant authigenic siderite (S). Siderite rhombs are replacing and/or displacing the detrital matrix. Half-crossed nichols, Wood-Dattie 2-6, 2403.6 ft.
on porosity and permeability is not significant.

Clay Minerals

Three species of authigenic clay minerals occur in the Berea sandstones including kaolinite, chlorite, and illite. Initial abundances of clay minerals, based on thin section analysis, suggest kaolinite and chlorite are the dominant clay minerals (Appendix B). However, the relative intensities of the X-ray diffraction patterns indicate illite is approximately equally abundant as kaolinite and chlorite. It is likely that most of the illite identified from X-ray diffraction is detrital and incorporated in the clay matrix.

Kaolinite occurs as intergranular, loosely-stacked, pseudohexagonal, pore-filling plates which overly and postdate quartz overgrowths (Figure 30). Euhedral kaolinite crystals also occupy secondary porosity after detrital grain (feldspar?) dissolution (Figure 30). Kaolinite accounts for as much as 7% of the Berea Sandstone (see Wood-Mieske 1-31, 2347.5 ft., Appendix B). The large platy crystals and pore-filling habit are easily identified using standard petrographic techniques. The kaolinite crystals are similar to those described by Wilson and Pittman (1977). The delicate "booklets" of crystals free of detrital matrix and the pore filling habit clearly indicate their authigenic origin. Kaolinite is most common in bedded (3.3%) and massive (2.7%) sandstones and rare in ripple-laminated sandstone (0.5%, Table 2). The decreased abundance of interstitial authigenic clays may result from the early occlusion
Figure 30. Photomicrographs of Authigenic Kaolinite Clay, Berea Sandstone.

(A) Intergranular, pore-filling, authigenic kaolinite clay (K). Half-crossed nichols, Wood-Sampier 1-7, 2436.2 ft. (B) Inter- and intragranular authigenic kaolinite (K). Intragranular kaolinite likely occurs after feldspar dissolution (arrow). Dark patches are pyrite cement (P). Half-crossed nichols, Wood-Mieske 1-31, 2347.5 ft.
of pore space and inhibition of fluid flow by detrital clay matrix and mica grains in ripple-laminated sandstones.

Two stages of authigenic chlorite crystallization are identified from the Berea sandstones based on petrographic relationships: (1) early chlorite grain coats, and (2) late pore-lining cements. Early clay grain coats form dark-brownish rinds entirely surrounding detrital grains. Their early origin is supported by compacted chlorite coats at grain contacts, remnant clay coats defining leached detrital grains (K-feldspar?), and clay coated grains in pores completely filled with pseudomatrix (Figure 31). The pseudomatrix results from the compaction of detrital clay clasts which occluded porosity early in the diagenetic history of these sandstones. These textural relationships indicate that clay coats are precompactional. Scanning electron microscopy indicates chlorite crystallites comprising the detrital grain coats are commonly poorly crystallized and do not show a preferential orientation with respect to the substrate (Figure 31). Early chlorite coats are most common in "structureless" sandstones (3.5%) and present in bedded sandstones (1.7%) and ripple-laminated sandstones (2.0%, Table 2). The early clay coatings likely preserved primary porosity by inhibiting the precipitation of quartz cement as syntaxial overgrowths (Figure 31, Heald and Larese, 1974).

Pore-lining chlorite occurs as a late phase cement following carbonate (Figure 31). Late chlorite is dominantly pore-lining and rarely pore-filling. The bladed habit and crystallite orientations of late chlorite perpendicular to the
Figure 31. Photo- and Scanning Electron Micrographs of Authigenic Chlorite and Illite Clays, Berea Sandstone.

(A) Late, pore-lining chlorite (LC) possibly in a secondary pore (ϕ) after carbonate. Note rhombic embayments (large arrows) and corroded grain margins (small arrows). Half-crossed nichols, Wood-Dattie 2-6, 2411.0 ft. (B) Early chlorite coats (arrows) define remnant detrital grains and separate quartz overgrowths from their host detrital grain. Note pseudomatrix (PM) and the elongate pore (ϕe). Half-crossed nichols, Wood-Jenkins 4-7, 2426.0 ft. (C) Early chlorite coats (EC), late, pore-lining chlorite (LC), and illite (I). Note late chlorite after carbonate (small arrows) and minor quartz overgrowths (large arrows) on the early chlorite coated grain. Wood-Dattie 2-6, 2411.0 ft.
substrate are characteristic of an authigenic pore-lining clay (Figure 31, Wilson and Pittman, 1977). It is probable that secondary growth of late chlorite occurs on the preexisting early chlorite grain coats; however, this relationship is equivocal.

Illite occurs in trace amounts as a pore-filling clay after late chlorite (Figure 32). Delicate illite crystallites are intergrown with and bridge chlorite crystallites. The majority of the illite identified from X-ray diffraction is believed to be detrital clay matrix and authigenic illite associated with illitic detrital matrix (Figure 32).

**Quartz Overgrowths**

Quartz cement occurs as euhedral, subhedral, and anhedral syntaxial overgrowths and can be distinguished by "dust rims" at the boundary between the detrital grain core and the overgrowth. Some overgrowths lack any separation from the detrital grains and are recognized by their euhedral crystal terminations. Detrital quartz in the Berea commonly contain inclusions of various types. The relatively inclusion-free character of the overgrowths is also used to distinguish the cement from the detrital grain. Quartz cement in volumetrically minor (≤ 4.4%, Appendix B) and only rarely occludes all pore space (Figure 26). Chlorite grain coats separate which the detrital grain core from the overgrowth indicate quartz cement follows early chlorite (Figure 31).

Syntaxial quartz overgrowths are most common in bedded sandstone
Figure 32. Photo- and Scanning Electron Micrographs of Authigenic Illite Clay, Berea Sandstone

(A) Intergranular, pore-filling, authigenic illite (I) and kaolinite (K). Illite is distinguished from kaolinite by its higher birefringence. Clays are also found in a remnant detrital grain (R). Half-crossed nichols, Wood-Sampier 1-7, 2436.2 ft. (B) Authigenic illite (I) associated with detrital clay matrix (X). Wood-Dattie 2-6, 2411.0 ft.

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(3.3%) and "structureless" sandstone (2.5%) and rare in ripple-laminated sandstone (0.4%, Table 2). The decreased abundance of quartz cement in ripple-laminated sandstones is attributed to the early occlusion of pore space and inhibition of fluid migration by detrital clay matrix and mica grains in ripple-laminated sandstone. The greater abundance of early chlorite grain coats in "structureless" sandstones (3.5%) versus bedded sandstones (1.7%) likely contributed to the variation in percent quartz cement between these reservoir facies.

Pyrite and Hematite

Authigenic pyrite occurs in trace amounts in the Berea sandstones as a late pore-filling cement and as a replacement of detrital grains and authigenic pore-filling cements (Figures 30 and 33). Rare subhedral pyrite crystals are also noted along and displacing the cleavages of detrital biotite grains. Pyrite is most abundant in the transgressive marine sandstone facies (Table 1).

Hematite occurs in trace amounts exclusively in the transgressive marine sandstone facies (Table 1). The exact timing for hematite is inconclusive, but it is most likely a late phase cement replacing ankerite (Figure 33).

Evidence for Mineral Dissolution

Schmidt and McDonald (1979) recognized and defined a variety of dissolution textures in sandstones including the dissolution of detrital grains,
Figure 33. Photomicrograph of Pyrite and Hematite Cements, Berea Sandstone.

Pyrite (P) occurs as an intergranular void-fill cement and as a replacement to detrital grains and authigenic cements. Pyrite is seen here replacing detrital quartz and quartz overgrowths. Hematite (H) occurs as a replacement to carbonate cement. Half-crossed nichols and reflected light, Wood-Mieske 1-31, 2347.5 ft.
dissolution of cement, and fractures. These dissolution or secondary pore
textures are characterized in thin section by the partial dissolution of detrital
grains and cements, inhomogeneous packing, and elongate and oversized pores.

Similar secondary pore textures can be found throughout the Berea
Sandstone in the Williams field. Partially leached potassium and plagioclase
defidspar, seen as honeycombed and skeletal grains, indicate the unequivocal
development of secondary porosity from the dissolution of framework grains
(Figure 34). Complete leaching of detrital grains (feldspar?) was also noted
and is indicated by remnant chlorite clay coats which remained after dissolution
of the host grain. Oversized and elongate pores contain remnant clay coats
suggesting their origin is, in part, due to the dissolution of detrital framework
grains (Figure 34). The "secondary" porosity produced by the dissolution or
partial dissolution of detrital grains may account as much as 3.6% (average
1.5%) of the porosity in the Berea sandstone reservoirs (see Porosity--
intragrannular, Appendix B).

Oversized and elongate pores, and sandstone showing inhomogeneous or
open packing adjacent to patchy ankerite cemented sandstone may suggest that
these pores were once filled with carbonate cement which has since dissolved
(Figure 35). Corroded grain margins, and rhombic and irregular embayments
suggest the dissolution of carbonate cement contributed to the development of
the secondary porosity (Figure 35). Corroded textures and embayments;
however, are subtle and equivocal due to the very fine-grained and angular
Figure 34. Photo- and Scanning Electron Micrographs of Secondary Porosity Resulting From Framework Grain Dissolution, Berea Sandstone.

(A) Oversized pores ($\phi_0$) and open packing result from leaching of detrital grains and possibly from the dissolution of authigenic cement. Half-crossed nichols, Wood-Jerkins 4-7, 2423.0 ft. (B) Honeycombed feldspar (H) and unequivocal secondary porosity ($\phi_s$). Wood-Dattie 2-6, 2411.0 ft.
Figure 35. Photomicrographs of Secondary Porosity Resulting From the Dissolution of Intergranular Cement, Berea Sandstone.

(A) Embayments (arrows) in detrital quartz grains and their overgrowths (O) suggest the dissolution of ankerite (A) to create secondary porosity. Note partial replacement of detrital matrix (X) by ankerite (A). Half-crossed nichols, Wood-Jenkins 3-7, 2355.0 ft. (B) Embayed quartz grains associated with an oversized pore (φo) suggesting the dissolution of interstitial carbonate cement. Note the patchy ankerite cement (A) adjacent to the oversized pore. Half-crossed nichols, Wood-Dattie 2-6, 2416.0 ft.
nature of the sandstones. Schmidt and McDonald (1979) caution the use of corroded grain margins as a criterion for the recognition of secondary porosity in fine-grained, angular sandstone suggesting mildly corroded grains may be of sedimentary origin. The recognition of corroded grains in the Berea Sandstone is further complicated by late pore-lining chlorite which masks the grain margins and the corroded grain textures.

Reservoir Facies and Principal Diagenetic Pathways

Three reservoir facies are recognized in the Berea reservoir sandstones in the Williams field. The three reservoir facies, found within the delta front "A sand" and "B sand," and the transgressive marine sandstone are: (1) ripple-laminated sandstones that contain distinct thin laminae consisting primarily of detrital clay matrix and mica grains; (2) bedded sandstone having subtle horizontal stratification, but no laminae; and (3) massive or "structureless" sandstone having no obvious bedding or laminae. Reservoir facies are discriminated based on the dominant sedimentary structure type. Reservoir facies subdivisions are intended to relate depositional processes and detrital mineralogy of the sandstones to their reservoir properties.

Ripple-Laminated Sandstone Facies

The ripple-laminated sandstone facies include all ripple- and cross-laminated sandstones. The detrital mineralogy is characterized by abundant
interstitial clay matrix (12%) and mica grains (4.4%) which serve to define sedimentary structures (Table 2). Early occlusion of all porosity by detrital clay matrix and mica grains at the time of deposition is common (Figure 26).

Diagenesis of the sandstone is dominated by the replacement of detrital clay matrix by ankerite. Percent ankerite cement is most abundant in ripple-laminated sandstone, averaging 7.6% of the total mineralogy (Table 2). The precipitation of interstitial cements, e.g., quartz overgrowths and clay, was apparently inhibited by intergranular detrital matrix. These cements are minor in this facies (Table 2).

Most effective porosity is developed from the minor dissolution of carbonate. Porosity which developed from the early dissolution of detrital feldspar grains is typically occluded by the subsequent precipitation of ankerite (Figures 27 and 36). Measured porosity and permeability average 12.6% and 1.7 millidarcies, respectively, while visible porosity, determined from thin section analysis, averages only 4.0% (Table 2). The variation between measured and observed porosity suggests abundant microporosity, likely within the clay-rich matrix. Porosity enhancement by additional dissolution of carbonate cement may account for higher than expected porosity and permeability values in this facies elsewhere in the Williams field area. Ripple-laminated sandstone has poor reservoir quality in Berea sandstones in the Williams field (Figure 37) and is most common in upper portions of the delta front "B sand."
Ripple—Laminated Sandstone Facies

As Deposited

Bedded Sandstone Facies

As Deposited

"Structureless" Sandstone Facies

As Deposited

Figure 36. Principal Diagenetic Sequences of the Reservoir Facies in the Williams Field.

The sequences represent major diagenetic trends and may exclude minor authigenic minerals.

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Overgrowths Ankerite Dissolution

Minor Quartz Overgrowths

Ankerite

Quartz Overgrowths

Kaolinite

Ankerite Dissolution

Minor Quartz Overgrowths

Ankerite

Kaolinite

Ankerite Dissolution

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Figure 37. Porosity-Permeability Plot of the Berea Reservoir Sandstones in the Williams Field.
**Bedded Sandstone Facies**

The bedded sandstone facies is characterized by subtle horizontal stratification. Sedimentary structures, defined by mica grains and clayey laminae, are minor. Detrital mineralogy is characterized by the partial occlusion of porosity by moderately abundant interstitial clay matrix (3.7%) and mica grains (2.6%).

Diagenesis of bedded sandstone is dominated by initial precipitation of syntaxial quartz overgrowths in open pores followed by precipitation of pore-filling kaolinite and ankerite cements. Ankerite also occurs as a replacement to detrital matrix (Figures 35 and 36). Ankerite cement accounts for 4.1% of the total mineralogy in bedded sandstones (Table 2) and suggests much of the original detrital matrix may have been replaced. Complete occlusion of porosity by cements is noted in many samples.

Porosity developed mainly from the dissolution of ankerite cement and detrital feldspar grains. Some porosity is likely primary; however, discrimination between primary porosity and secondary porosity resulting from the dissolution of ankerite is equivocal. Measured porosity and permeability average 15.2% and 3.7 millidarcies, respectively, while visible porosity, determined from thin section analysis, averages 9.2% (Table 2). Bedded sandstone in the Berea reservoir sandstones in the Williams field has moderate reservoir quality (Figure 37). The Bedded Sandstone Facies is the most...
common Berea reservoir sandstone.

"Structureless" Sandstone Facies

The "structureless" sandstone facies is characterized by the absence of sedimentary structures and horizontal stratification. The absence of sedimentary structures in sandstone may be due to extensive bioturbation (Blatt et al., 1972), lack of grain size variation (Hamblin, 1965), or the lack of mica, carbonaceous debris, and clayey material highlighting the sedimentary structures and laminae. Detrital mineralogy is characterized by minor detrital clay matrix (3.3%) and mica grains (2.6%, Table 2).

Diagenesis of "structureless" sandstone is dominated by the precipitation of early chlorite grain coats (3.5% of the total mineralogy). Ankerite and quartz cements are minor and account for 1.7% and 2.5% of the whole rock mineralogy, respectively (Table 2). It is probable the early chlorite coats and only minor detrital clay matrix resulted in the preservation of abundant primary porosity. Clay coats prevented the precipitation of quartz cement as syntaxial overgrowths (Heald and Larese, 1974). Without a detrital clay matrix precursor, little ankerite precipitated (Figures 31 and 36). Chlorite coated sandstones form thin discontinuous units (≈2 feet thick) in the delta front "B sand." The origin of these early clay coated sandstones is equivocal. The relative absence of detrital clay matrix (and subsequently ankerite cement) suggests winnowing of the fine-grained clayey material to produce a well-
sorted, matrix-free sandstone. Localized beach or off-shore bar deposits are two possible depositional scenarios for the "structureless" sandstones.

Porosity is dominantly primary interparticle with minor secondary leaching of detrital feldspar grains. Measured porosity and permeability average 22.7% and 102.3 millidarcies, respectively, while visible porosity, determined from thin section analysis, averages 14.7% (Table 2). Structureless sandstone in the Berea reservoir sandstones in the Williams field has good reservoir quality (Figure 37).

**Paragenesis of the Berea Reservoir Sandstones**

From textural relationships observed in thin section, the following paragenetic sequence for the Berea was determined: (a) precipitation of early chlorite clay coats on detrital grains; (b) dissolution of detrital potassium and plagioclase feldspar grains; (c) precipitation of quartz overgrowths; (d) precipitation of intergranular dolomite cement; (e) ankeritization of the precursor dolomite, precipitation of ankerite and kaolinite; (f) dissolution of intergranular ankerite cement and precipitation of late chlorite; and (g) precipitation of illite, pyrite, and replacement of ankerite by hematite (Figure 38).

The authigenic mineral suite of the Berea sandstones is very similar to that of the Wilcox Group (Eocene) of Texas as described by Boles (1978) and Boles and Franks (1979). Boles (1978) and Boles and Franks (1979) attribute
Figure 38. Paragenetic Sequence of the Berea Reservoir Sandstones in the Williams Field.

The dashed lines indicate the relative timing is equivocal.
the sandstone cements of the Wilcox Group to the illitization of illite/smectite mixed-layer clay (I/S MLC) in the clay-rich sandstone matrix and in the shales surrounding the sandstones. To a lesser extent, the dissolution of detrital potassium feldspar grains also contributes to the sandstone cements. They concluded that the products of illitization and the K⁺ and Al³⁺ released from the dissolution of K-feldspar account for the cements observed in the Wilcox sandstones by means of the following reaction:

\[
\text{smectite} + \text{K}^+ \rightarrow \text{illite} + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Fe}^{3+} + \text{Si}^{4+}
\]

Some of the silica released is transferred into the sandstones and precipitated on detrital quartz grains as quartz overgrowths. Excess silica and the potassium and aluminum released from K-feldspar dissolution precipitate as authigenic kaolinite. Calcium combined with CO₂, possibly from organic reactions in the shales, may have been incorporated into an early calcite cement. At greater depths and higher temperatures, magnesium and iron may react with the calcite to form ankerite, and kaolinite to form high aluminous chlorite (Figure 39, Boles and Franks, 1979).

Boles and Franks (1979) indicate the temperatures necessary to convert smectite to illite range from \(55°\text{-}210°C\) in the Wilcox sandstones (Figure 39). The current formation temperature of the Berea Sandstone in the Williams field is \(30°C\) (Wiser-Gerstacker 3-36, sec. 36 T15N R2E, T. Maness, pers. commun.), significantly lower than those reported by Boles and Franks (1979) from the Wilcox sandstones. The similarities between the authigenic minerals
Figure 39. Schematic Diagram of the Influence of Illite/Smectite Clay Reactions on Wilcox Sandstone Cements.

The vertical arrows depict ion transfer between illite/smectite clay reactions and phases in the sandstones (Boles and Franks, 1979).
in the Berea and Wilcox sandstones suggest an elevated geothermal gradient in the Michigan basin during diagenesis of the Berea Sandstones to produce the observed authigenic mineral assemblage. Elevated geothermal gradients in the Michigan basin in pre-Permian time are supported by Cercone (1984) and Illich and Grizzle (1985).
CONCLUSIONS

1. Seven depositional facies are recognized from studies of core in the Williams oil field. The facies characteristics, associations between the facies, and the stratigraphic succession of the facies are attributed to processes associated with a shallow-water, fluvial-dominated, delta depositional system. The seven depositional facies recognized are: (1) prodelta (Bedford Shale), (2) delta front, (3) destructive marine shale, (4) abandoned distributary channel-fill, (5) interdistributary bay-fill, (6) transgressive marine sandstone, and (7) marine shale (Sunbury Shale).

2. Hydrocarbon trapping is both structural and stratigraphic. A northwest plunging anticline provides most of the closure in the field. Impermeable interdistributary bay-fill deposits provide a vertical seal for the delta front sandstone reservoir and the marine Sunbury shale is the seal for the transgressive marine sandstone. Passive, mud-dominated channel-fill deposits occur as lateral equivalents to the delta front sandstone reservoir and have compartmentalized the reservoir NW-SE. The compartmentalization prevented the continued migration of hydrocarbons up-dip along the axis of the anticline.

3. The fluvial-dominated, shallow water delta model presented here for the Bedford-Berea sequence in the Williams and Larkin field areas is in direct contrast to the tidally-influenced, strand plain/barrier-bar depositional model
proposed by Gunn (1988b). This interpretation is inconsistent with the core data from the Williams field. Gunn’s interpretation is based primarily on the distribution and orientations of the sandstone bodies and does not consider the depositional facies associated with the sandstones.

4. The average composition of the reservoir sandstone facies is a subfeldsarenite. Porosity is dominantly interparticle with significant amounts of intraparticle porosity that resulted from the leaching of detrital feldspar grains. Porosity development is further enhanced by the dissolution of carbonate cement. Most porosity is occluded by detrital clay matrix as well as intergranular authigenic clays, quartz cement as syntaxial overgrowths, and ankerite and dolomite.

5. Three reservoir facies are recognized from the Berea sandstone reservoirs in the Williams field. The three reservoir facies are: (1) rippled-laminated sandstone (poor reservoir quality), (2) bedded sandstone (better reservoir quality), and (3) "structureless" sandstone (best reservoir quality). The reservoir quality is attributed to the original depositional mineralogy which templated the diagenesis and, therefore, the porosity and permeability characteristics in each of the reservoir facies.
Appendix A

Core Descriptions
KEY TO CORE DESCRIPTIONS

Lithologies

Shale
Siltstone
Sandstone

Interbedded Lithologies

< 10% siltstone
10-50% siltstone
50-75% siltstone
75-90% siltstone
> 90% siltstone

< 10% sandstone
10-50% sandstone
50-75% sandstone
75-90% sandstone
> 90% sandstone

Lithologic Qualifiers

Pyrite
Shale Pebbles
Trilobite Fragments
Siderite Nodules
Silt Pebbles
Brachiopod Fragments

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### Sedimentary Structures

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<td>Load Cast</td>
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<tr>
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<tr>
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### Samples

- Thin Section
- X-Ray Diffraction

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<td>Lithofacies 5. Interlaminated black, micaceous, silty shale (50%) and siltstone (50%). Siltstone laminae may be planar, wavy, and lenticular. Mottled texture is due to bioturbation and possibly dewatering.</td>
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<td>PRODELTA</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Lithofacies 1 (Bedford Shale)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Black, micaceous shale (75%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>with siltstone laminations and lenses (25%).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Siltstones are commonly micro cross-laminated.</td>
<td></td>
</tr>
<tr>
<td>LITHOSTRATIGRAPHY</td>
<td>DEPTH</td>
<td>LITHOLOGY</td>
<td>GRAIN SIZE</td>
<td>SEDIMENTARY STRUCTURES</td>
<td>SAMPLE</td>
<td>DESCRIPTIVE REMARKS</td>
<td>INTERPRETIVE REMARKS</td>
</tr>
<tr>
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</tr>
<tr>
<td>UPPER BREA SANDSTONE</td>
<td>2,410'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 5. Black, micaceous, silty, black shale with planar and wavy siltstone laminae and lenses. Siltstones are commonly carbonate cemented and oxidized. Slight to moderate bioturbation as horizontal silt-filled burrows and feeding trails.</td>
<td>INTER-DISTRIBUTARY</td>
</tr>
<tr>
<td></td>
<td>2,415'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BAY-FILL</td>
</tr>
<tr>
<td></td>
<td>2,420'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 3. Planar-laminated, silty black shale with rare siltstone lenses and laminae. Bioturbation is nil to slight indicated by a mottled texture.</td>
<td>DESTRUCTIVE</td>
</tr>
<tr>
<td></td>
<td>2,425'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DESTRUCTIVE MARINE SHALE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,430'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 2. Light tan, very fine-grained, well-sorted, micaceous sandstone containing abundant floating mud-chips.</td>
<td>DELTA FRONT SANDSTONE</td>
</tr>
<tr>
<td></td>
<td>2,435'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(continued)</td>
<td>&quot;B SAND&quot;</td>
</tr>
<tr>
<td></td>
<td>2,440'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 2. Light tan, very fine-grained, well-sorted, micaceous sandstone containing abundant floating mud-chips. (continued)</td>
<td></td>
</tr>
</tbody>
</table>

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### CORE DESCRIPTION

**WELL NAME:** Wood-Jenkins 2-6  
**LOCATION:** 6-14N-3E, Bay Co., MI  
**API NUMBER:** 21017355920000  
**DEPTH:** 2,405'—2,460.5'  
**DATE:** 10/5/89  
**SCALE:** 1" :5'  
**PAGE:** 2 of 2  
**DESCRIPTED BY:** D.A. Balthazor

<table>
<thead>
<tr>
<th>LITHOSTRATIGRAPHY</th>
<th>DEPTH</th>
<th>LITHOLOGY</th>
<th>GRAIN SIZE</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>SAMPLE</th>
<th>DESCRIPTIVE REMARKS</th>
<th>INTERPRETIVE REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDDLE BEREA</td>
<td>2,445'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sedimentary structures are defined by carbonaceous debris and micaceous shale laminae. scour and fill at 2445.1 ft.</td>
<td>Delta front sandstone &quot;A Sand&quot;</td>
</tr>
<tr>
<td></td>
<td>2,450'</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEDFORD SHALE</td>
<td>2,455'</td>
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<tr>
<td></td>
<td>2,460'</td>
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</tr>
</tbody>
</table>

**Lithofacies 1 (Bedford Shale):** Interlaminated micaceous, silty shale (65%) and siltstone (35%). Siltstone laminae may be planar, wavy, or lenticular and are commonly micro cross-laminated. Bioturbation is slight as horizontal burrows and feeding trails and rare vertical burrows.

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### Core Description

**Well Name:** Wood-Jenkins 4-7  
**Location:** 7-14N-3E, Bay Co., MI  
**API Number:** 21017361280000  
**Date:** 10/9/89  
**Scale:** 1" :5'  

**Depth:** 2,400'-2,444.5'  
**Page:** 1 of 2  

**Described By:** D.A. Balthazor

<table>
<thead>
<tr>
<th>Litho-stratigraphy</th>
<th>Depth</th>
<th>Lithology</th>
<th>Grain Size</th>
<th>Sedimentary Structures</th>
<th>Sample</th>
<th>Descriptive Remarks</th>
<th>Interpretive Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Berea Sandstone</td>
<td>2,405'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>INTER-DISTRIBUTARY BAY-FILL</td>
</tr>
<tr>
<td></td>
<td>2,410'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 5. Intermixed black, micaceous shales (65%) and siltstone (35%). Mottled texture is due to bioturbation and possibly dewatering. Laminations are planar to wavy.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,415'</td>
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</tr>
<tr>
<td>Middle Berea Sandstone</td>
<td>2,420'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 2. Light to medium tan, very fine-grained, well-sorted, micaceous sandstone. Ripple and planar laminae common, mostly structureless.</td>
<td>DELTA FRONT SANDSTONE &quot;B SAND&quot;</td>
</tr>
<tr>
<td></td>
<td>2,425'</td>
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<tr>
<td></td>
<td>2,430'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 3. Planar-laminated black shale and siltstone with carbonate cemented siltstone laminae and lenses.</td>
<td>DESTRUCTIVE MARINE SHALE</td>
</tr>
<tr>
<td></td>
<td>2,435'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 5. Intermixed black, micaceous shales (65%) and siltstone (35%). Mottled texture is due to bioturbation and possibly dewatering. Laminations are planar to wavy.</td>
<td>DELTA FRONT SANDSTONE &quot;A SAND&quot;</td>
</tr>
<tr>
<td>Bedford Shale</td>
<td>2,440'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRODELTA</td>
</tr>
</tbody>
</table>

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**CORE DESCRIPTION**

**WELL NAME:** Wood-Jenkins 4-7  
**LOCATION:** 7-14N-3E, Bay Co., Mi  
**API NUMBER:** 21017361280000  
**DEPTH:** 2,400'–2,444.5'  
**DATE:** 10/9/89  
**SCALE:** 1" : 5'  
**PAGE:** 2 of 2  
**DESCRIPTED BY:** D.A. Balthazor

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>LITHOLOGY</th>
<th>GRAIN SIZE</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>SAMPLE</th>
<th>DESCRIPTIVE REMARKS</th>
<th>INTERPRETIVE REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,440'</td>
<td>BEDFORD SHALE</td>
<td>SAND</td>
<td></td>
<td></td>
<td></td>
<td>PRODELTA</td>
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</tbody>
</table>

End of Core

Lithofacies 1 (Bedford Shale). Black, micaceous, silty shale (75%) with planar and lenticular siltstone laminations (25%). Siltstone pebbles at 2436.2 ft. and 2439.0 ft. Carbonate cemented siltstone bed 2442.0–2443.0 ft.
**CORE DESCRIPTION**

**WELL NAME:** Wood-Sampier 1-7  
**LOCATION:** 7-14N-3E, Bay Co., MI  
**API NUMBER:** 2117361290000  
**DEPTH:** 2,408'-2,459'  
**DATE:** 10/7/89  
**SCALE:** 1":5'  
**PAGE:** 1 of 2  
**DESCRIBED BY:** D.A. Balthazor

---

**LITHO-STRATIGRAPHY**  
**DEPTH**  
**LITHOLOGY**  
**GRAIN SIZE**  
**SEDIMENTARY STRUCTURES**  
**SAMPLE**  
**DESCRIPTIVE REMARKS**  
**INTERPRETIVE REMARKS**

**Lithofacies 5.** Interlaminated black, micaceous shale (50%) and siltstone (50%). Mottled appearance due to bioturbation and possibly dewatering. Bioturbation as horizontal silt-filled burrows ranges in intensity from slight to moderate. Siltstone occurs as planar to wavy laminations and cross-laminated lenses. Shaly zones are highly fissile. Oxidized zones and soft sediment deformation are also common.  
**INTER-DISTRIBUTARY BAY-FILL**

**Lithofacies 2.** Medium tan, very fine-grained, well-sorted micaceous sandstone. Lamination and bedding planes are defined by micaceous shale and carbonaceous debris. Tight, carbonate cemented sand at 2425.5 ft.  
**DELTA FRONT SANDSTONE "B SAND"**

**Lithofacies 3.** Fissile, planar-laminated black shale.  
**DESTRUCTIVE MARINE SHALE**

**Lithofacies 2.** Medium tan, very fine-grained, well-sorted micaceous sandstone.  
**DELTA FRONT SANDSTONE "A SAND"**

**PRODELTA**
# Core Description

**Well Name:** Wood-Sampier 1-7  
**Location:** 7-14N-3E, Bay Co., Mi  
**API Number:** 21017361290000  
**Date:** 10/7/89  
**Depth:** 2,408'-2,459'  
**Scale:** 1":5'  
**Described By:** D.A. Balthazar

<table>
<thead>
<tr>
<th>Litho-stratigraphy</th>
<th>Depth</th>
<th>Lithology</th>
<th>Grain Size</th>
<th>Sedimentary Structures</th>
<th>Sample</th>
<th>Descriptive Remarks</th>
<th>Interpretive Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedford Shale</td>
<td>2,450'</td>
<td></td>
<td>Velvety</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2,455'</td>
<td></td>
<td>Coarse</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>End of Core</td>
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</tr>
</tbody>
</table>

**Lithofacies 1 (Bedford Shale):** Interlaminated, black, micaceous shale (75%) and siltstone (25%). Siltstone occurs as lenses and wavy laminations. Bioturbation occurs as horizontal silt-filled burrows and ranges from negligible to slight.

**Interpretive Remarks:** PRODELTA

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**CORE DESCRIPTION**

**WELL NAME:** Wood-Mieske 1-31  
**LOCATION:** 31-15N-3E, Bay Co., Mi  
**API NUMBER:** 21017357190000  
**DEPT:** 2,347.5'-2,432'  
**DATE:** 10/3/89  
**SCALE:** 1":5'  
**PAGE:** 1 of 3  
**DESCRIBED BY:** D.A. Balthazor

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>LITHOLOGY</th>
<th>GRAIN SIZE</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>DESCRIPTION</th>
<th>INTERPRETIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,355'</td>
<td></td>
<td>sandstone</td>
<td></td>
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</tr>
<tr>
<td>2,360'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,365'</td>
<td>Upper Berea Sandstone</td>
<td>sandstone</td>
<td></td>
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</tr>
</tbody>
</table>
## Core Description

**WELL NAME:** Wood—Mieske 1-31  
**DEPTH:** 2,347.5'—2,432'  
**DATE:** 10/3/89  
**LOCATION:** 31-15N-3E, Bay Co., Mi  
**SCALE:** 1":5'  
**API NUMBER:** 21017357190000  
**DESCRIBED BY:** D.A. Balthazor

### Litho—Stratigraphy

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Finely interlaminated black shale, silty shale, and siltstone in variable proportions. Ripple laminae are locally abundant.</td>
</tr>
<tr>
<td>3</td>
<td>Black shale and silty shale with minor silt pebbles with preserved laminae.</td>
</tr>
<tr>
<td>2</td>
<td>Light tan, very fine-grained, well-sorted sandstone. Ripple and planar laminations, and silty shale laminae common towards the top. The bottom is predominantly planar-laminated sandstone.</td>
</tr>
</tbody>
</table>

### Sedimentary Structures

<table>
<thead>
<tr>
<th>Sample</th>
<th>Descriptive Remarks</th>
</tr>
</thead>
</table>

### Interpretable Remarks

- **Channel—Fill**
- **Destructive Marine Shale**
- **Delta Front Sandstone**
**CORE DESCRIPTION**

**WELL NAME:** Wood—Mieske 1–31  
**DEPTH:** 2,347.5'—2,432'  
**DATE:** 10/3/89  
**LOCATION:** 31–15N–3E, Bay Co., Mi  
**API NUMBER:** 21017357190000  
**SCALE:** 1":5'  
**PAGE:** 3 of 3  
**DESCRIBED BY:** D.A. Balthazor

<table>
<thead>
<tr>
<th>LITHO-STRATIGRAPHY</th>
<th>DEPTH</th>
<th>LITHOLOGY</th>
<th>GRAIN SIZE</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>SAMPLE</th>
<th>DESCRIPTIVE REMARKS</th>
<th>INTERPRETIVE REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIDDLE BEREA</td>
<td>2,425'</td>
<td>Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DELTA FRONT</td>
</tr>
<tr>
<td>2,430'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lithofacies 1 (Bedford Shale).</td>
<td>PRODELTA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interlaminated, black, micaceous shale (65%) and siltstone (35%). Siltstones are planar to wavy to lenticular.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Lenticular siltstones are micro cross-laminated. Tight, carbonate cemented siltstones at 2429.0 ft.</td>
<td></td>
</tr>
<tr>
<td>BEDFORD SHALE</td>
<td></td>
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<tr>
<td>End of Core</td>
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<td></td>
<td></td>
<td></td>
<td>and structureless sandstones. Prominent shale-pebble lag at 2421.7 ft.</td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>LITHOSTRATIGRAPHY</th>
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<th>LITHOLOGY</th>
<th>GRAIN SIZE</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>SAMPLE</th>
<th>DESCRIPTIVE REMARKS</th>
<th>INTERPRETIVE REMARKS</th>
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</thead>
<tbody>
<tr>
<td>Wood–Mieske 1–6</td>
<td>2,400'–2,444'</td>
<td>DEPTH: 10/22/89</td>
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<td>LOCATION: 6–14N–3E, Bay Co., MI</td>
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<td>API NUMBER: 21017355910000</td>
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</tr>
</tbody>
</table>

**Lithofacies 1.** Siltstone (65%) with fine, micaceous shale laminae (35%) and interbedded planar-laminated, black shales and very fine-grained, cross-laminated, micaceous sandstone. Bioturbation occurs as horizontal silt-filled burrows and feeding trails.

**Lithofacies 2.** Light to medium tan, very fine-grained, well-sorted sandstone. Mostly structureless with occasional horizontal to subhorizontal planar laminae defined by micaceous shale and carbonaceous debris.

**Lithofacies 3.** Planar-laminated black shale with rare silt pebbles.

**Lithofacies 2.** Light to medium tan, very fine-grained, well-sorted, micaceous sandstone.

**DESTRUCTIVE MARINE SHALE**

**DELTA FRONT SANDSTONE”A SAND”**

**PRODELTA**

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# Core Description

**WELL NAME:** Wood—Mieske 1–6  
**LOCATION:** 6–14N–3E, Bay Co., Mi  
**DATE:** 10/22/89  
**SCALE:** 1" : 5'  
**PAGE:** 2 of 2  
**API NUMBER:** 21017355910000  
**DESCRIBED BY:** D.A. Balthazor

<table>
<thead>
<tr>
<th>LITHO–STRATIGRAPHY</th>
<th>DEPTH</th>
<th>LITHOLOGY</th>
<th>GRAIN SIZE</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>SAMPLE</th>
<th>DESCRIPTIVE REMARKS</th>
<th>INTERPRETIVE REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEDFORD SHALE</td>
<td>2,440'</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>PRODELTA</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Lithofacies I (Bedford Shale), Black, micaceous shale (75%) with subordinate siltstone lenses and laminae (25%). Siltstones are ripple laminated. Bioturbation is nil to slight and occurs as horizontal silt-filled burrows and feeding trails.</td>
<td></td>
</tr>
</tbody>
</table>
## Core Description

### Well Name: Wiser-Retzloff 1-31
### Location: 31-15N-3E, Bay Co., MI
### API Number: 21017347880000
### Date: 10/31/89
### Scale: 1" : 5'

**Lithostratigraphy**

<table>
<thead>
<tr>
<th>Depth</th>
<th>Lithology</th>
<th>Grain Size</th>
<th>Sedimentary Structures</th>
<th>Descriptive Remarks</th>
<th>Interpretive Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,367'—2,455'</td>
<td>Lithofacies 7 (Sunbury Shale)</td>
<td>Black planar-laminated shale</td>
<td></td>
<td></td>
<td>Marine Shale</td>
</tr>
<tr>
<td>2,370'</td>
<td>Lithofacies 6</td>
<td>Light to medium tan, very fine-grained, well-sorted sandstone with minor micaceous, silty shale laminae. Slight bioturbation is indicated by mottled texture. Rare trilobite and brachiopod (?) fragments are also noted.</td>
<td>Marine Sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,375'</td>
<td>Lithofacies 5</td>
<td>Interlaminated, black, micaceous shale (50%) and micro cross-laminated siltstone (50%) with interbeds of planar-laminated, black shale and planar-laminated, very fine-grained sandstone and silty sandstone. Horizontal silt-filled burrows are moderately abundant and restricted to shale laminae and beds.</td>
<td>Inter-Distributary Bay-Fill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,380'</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>2,385'</td>
<td></td>
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<tr>
<td>2,390'</td>
<td></td>
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<tr>
<td>2,395'</td>
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<tr>
<td>2,400'</td>
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<td>2,405'</td>
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### Core Description

**WELL NAME:** Wiser-Retzloff 1-31  
**LOCATION:** 31-15N-3E, Bay Co., MI  
**API NUMBER:** 21017347880000  
**DEPTH:** 2,367'-2,455'  
**DATE:** 10/31/89  
**SCALE:** 1"=5'  
**PAGE:** 2 of 3  
**DESCRIBED BY:** D.A. Balthazor

<table>
<thead>
<tr>
<th>Litho-Stratigraphy</th>
<th>Depth</th>
<th>Lithology</th>
<th>Grain Size</th>
<th>Sedimentary Structures</th>
<th>Sample</th>
<th>Descriptive Remarks</th>
<th>Interpretive Remarks</th>
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<tbody>
<tr>
<td>Upper Berea Sandstone</td>
<td>2,410'</td>
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<tr>
<td></td>
<td>2,415'</td>
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<td>2,420'</td>
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</tr>
<tr>
<td>Middle Berea Sandstone</td>
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<tr>
<td></td>
<td>2,435'</td>
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<tr>
<td></td>
<td>2,440'</td>
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</tr>
</tbody>
</table>

**Lithofacies 4:** Finely interlaminated shale and siltstone in variable proportions. Laminae are planar to wavy to lenticular. Siltstone laminae and lenses are commonly micro cross-laminated.

**Lithofacies 3:** Planar-laminated, fissile black shale.

**Lithofacies 2:**

**Lithofacies 1:**

**Interpretive Remarks:**

**Channel-Fill**

**Destructive Marine Shale**

**Delta Front Sandstone**

"A Sand"
## CORE DESCRIPTION

**WELL NAME:** Wiser—Retzloff 1-31  
**LOCATION:** 31-15N-3E, Bay Co., MI  
**API NUMBER:** 21017347880000  
**DEPTH:** 2,367'-2,455'  
**DATE:** 10/31/89  
**SCALE:** 1" : 5'  
**PAGE:** 3 of 3  
**DESERIBED BY:** D.A. Balthazor

<table>
<thead>
<tr>
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<tr>
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<td>2,445'</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>DELTA FRONT SANDSTONE &quot;A SAND&quot;</td>
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<tr>
<td></td>
<td>2,450'</td>
<td></td>
<td></td>
<td></td>
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<td>PRODELTA</td>
</tr>
<tr>
<td>BEDFORD SHALE</td>
<td>2,455'</td>
<td></td>
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</table>

**Lithofacies 2:** Light to medium tan, very fine-grained, well-sorted, planar-laminated, micaceous sandstone with micaceous, silty shale laminae.

**Lithofacies 1 (Bedford Shale):** Black, micaceous shale (75%) with siltstone lenses and laminae (25%). Bioturbation as horizontal burrows and feeding trails is slight.
# CORE DESCRIPTION

**WELL NAME:** Wiser-Retzloff 2-31  
**LOCATION:** 31-15N-3E, Bay Co., MI  
**API NUMBER:** 21017348020000  
**SCALE:** 1' : 5'  
**DATE:** 10/10/89  
**PAGE:** 1 of 3  

**DESCRIBED BY:** D.A. Balthazor

## Litho-Stratigraphy

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<td>2,370'</td>
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<td>2,390'</td>
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<td>2,400'</td>
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</table>

### Lithofacies 2 (Sunbury Shale)
- Black, planar-laminated, organic-rich shale.
- Descriptive Remarks: Black, planar-laminated, organic-rich shale.
- Interpretive Remarks: Marine Shale

### Lithofacies 4
- Medium tan to light brown, very fine-grained, well-sorted sandstone. Some horizons completely burrow mottled. Rare trilobite and brachiopod (?) fragments noted. Pyritic zone at 2374.0 ft.
- Descriptive Remarks: Medium tan to light brown, very fine-grained, well-sorted sandstone.
- Interpretive Remarks: Transgressive Marine Sandstone

### Lithofacies 5
- Black, micaceous shale and siltstone in variable proportions. Siltstones are planar, wavy, and lenticular laminated. Interbedded sandstones are commonly planar and cross-laminated and oil stained. High-angle (~35°) cross-laminations at 2384.5 ft. Pyritic zone at 2379.1 ft.
- Descriptive Remarks: Black, micaceous shale and siltstone in variable proportions.
- Interpretive Remarks: Inter-Distributary Bay-Fill

---

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## CORE DESCRIPTION

**WELL NAME:** Wiser-Retzloff 2-31  
**LOCATION:** 31-15N-3E, Bay Co., MI  
**API NUMBER:** 21017348020000  
**DEPTH:** 2,365' - 2,455'  
**DATE:** 10/10/89  
**SCALE:** 1" : 5'  
**PAGE:** 2 of 3  
**DESCRIBED BY:** D.A. Balthazor

### LITHO-STRATIGRAPHY

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<thead>
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<th>Depth</th>
<th>Lithology</th>
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<th>Sedimentary Structures</th>
<th>Sample</th>
<th>Descriptive Remarks</th>
<th>Interpretive Remarks</th>
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<tr>
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<td>2,410'</td>
<td>Upper Berea Sandstone</td>
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<td>INTER- DISTRIBUTARY</td>
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<td>DELTA FRONT SANDSTONE</td>
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<td>&quot;B SAND&quot;</td>
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<tr>
<td>2,440'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Destructive Marine Shale</td>
</tr>
</tbody>
</table>

Lithofacies 2: Light to medium tan, very fine-grained, well-sorted, micaceous cross-laminated and ripple-laminated sandstone. Floating mud-chips common.

Lithofacies 3: Planar-laminated, black shale. Bioturbation occurs as rare vertical burrows. Truncated, deformed silty lamination at 2438.1 ft.
**CORE DESCRIPTION**

**WELL NAME:** Wiser-Retzloff 2-31  
**DEPTH:** 2,365'–2,455'  
**DATE:** 10/10/89  
**LOCATION:** 31-15N-3E, Bay Co., Mi  
**SCALE:** 1" : 5'  
**API NUMBER:** 21017348020000  
**DESCRIPTED BY:** D.A. Balthazor

### LITHO-
STRATIGRAPHY

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<th>SAMPLE</th>
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<td>2,450'</td>
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<td>BEDFORD SHALE</td>
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</tbody>
</table>

End of Core

**DESTRUCTIVE MARINE SHALE**

Lithofacies 2, Medium tan, very fine-grained, well-sorted sandstone. Horizontal and subhorizontal planar laminations dominate with occasional planar cross-laminations and ripple laminations. Abundant closed fractures are also noted.

**DELTA FRONT SANDSTONE**

"A SAND"

Lithofacies 1 (Bedford Shale), interlaminated black, micaceous shale (50%) and siltstone (50%). Horizontal silt-filled burrows and feeding trails are moderately abundant.

**PRODELTA**

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Appendix B

Point Count Data
<table>
<thead>
<tr>
<th>Composition</th>
<th>Wood Dattie 2-6</th>
<th>Wood Dattie 2-6</th>
<th>Wood Jenkins 2-6</th>
<th>Wood Jenkins 2-6</th>
<th>Wood Jenkins 2-6</th>
<th>Wood Jenkins 2-6</th>
<th>Wood Jenkins 2-6</th>
<th>Wood Jenkins 2-6</th>
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</thead>
<tbody>
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<td>Quartz (m) 65.6%</td>
<td>65.6% (164)</td>
<td>66.0% (165)</td>
<td>55.2% (138)</td>
<td>58.8% (137)</td>
<td>60.0% (150)</td>
<td>59.2% (148)</td>
<td>49.2% (123)</td>
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<td>(polycrystalline)</td>
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<td>0.4% (1)</td>
<td>0.4% (1)</td>
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<tr>
<td>K-Feldspar 1.2%</td>
<td>1.2% (3)</td>
<td>1.6% (4)</td>
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<td>2.4% (6)</td>
<td>2.4% (8)</td>
<td>3.2% (8)</td>
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<td>Plagioclase 0.8%</td>
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<td>Biotite 0.0%</td>
<td>0.4% (0)</td>
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<td>2.4% (4)</td>
<td>2.4% (7)</td>
<td>2.8% (8)</td>
<td>0.8% (1)</td>
<td>0.4% (1)</td>
<td>3.6% (9)</td>
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<tr>
<td>Muscovite 0.8%</td>
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<td>2.4% (8)</td>
<td>2.8% (7)</td>
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<tr>
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<td>2.4% (8)</td>
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<td>17.2% (43)</td>
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<td>11.2% (28)</td>
<td>21.6% (54)</td>
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</tr>
<tr>
<td>Porosity (φ)</td>
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<tr>
<td>Total 100% (250)</td>
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<td>100% (250)</td>
<td>100% (250)</td>
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<td>13.3%</td>
<td>15.9%</td>
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<td>6.7%</td>
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<td>2409.0'</td>
<td>2410.0'</td>
<td>2423.0'</td>
<td>2433.0'</td>
<td>2423.7'</td>
<td>2438.5'</td>
<td>2437.3'</td>
<td>2438.5'</td>
</tr>
<tr>
<td>Quartz (monocrystalline)</td>
<td>58.4% (146)</td>
<td>60.0% (150)</td>
<td>54.8% (137)</td>
<td>48.4% (121)</td>
<td>62.4% (156)</td>
<td>57.6% (144)</td>
<td>60.0% (150)</td>
<td>54.4% (136)</td>
</tr>
<tr>
<td>Quartz (polycrystalline)</td>
<td>1.6% (4)</td>
<td>1.6% (4)</td>
<td>2.8% (7)</td>
<td>6.8% (17)</td>
<td>3.2% (8)</td>
<td>3.6% (9)</td>
<td>5.6% (14)</td>
<td>10.8% (27)</td>
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<tr>
<td>Chert</td>
<td>1.2% (3)</td>
<td>0.4% (1)</td>
<td>2.4% (6)</td>
<td>4.0% (10)</td>
<td>0.4% (1)</td>
<td>0.4% (1)</td>
<td>0.4% (1)</td>
<td>0.4% (1)</td>
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<tr>
<td>K-Feldspar</td>
<td>0.8% (2)</td>
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<td>1.6% (4)</td>
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<td>2.4% (6)</td>
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<tr>
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<tr>
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<td>2.0% (5)</td>
<td>1.2% (3)</td>
<td>2.0% (5)</td>
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<tr>
<td>Qtz/Feldspar/</td>
<td>95/3/2</td>
<td>95/4/1</td>
<td>93/3/4</td>
<td>90/4/6</td>
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<td>96/3/1</td>
<td>94/1/5</td>
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<tr>
<td>Lithic Fragments</td>
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<tr>
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<td>1.2% (3)</td>
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<tr>
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<td>2.0% (5)</td>
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<td>2.4% (6)</td>
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<td>4.0% (10)</td>
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<tr>
<td>Chlorite</td>
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<td>3.6% (9)</td>
<td>5.2% (13)</td>
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<tr>
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<td>1.2% (3)</td>
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<tr>
<td>Pyrite</td>
<td>0.0% (0)</td>
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<td>0.4% (1)</td>
<td>0.0% (0)</td>
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<tr>
<td>Hematite</td>
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<td>17.6% (44)</td>
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<td>18.4% (46)</td>
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<td>6.4% (16)</td>
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<tr>
<td>(intergranular)</td>
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<td>Porosity (φ)</td>
<td>1.2% (3)</td>
<td>2.8% (7)</td>
<td>2.4% (6)</td>
<td>0.8% (2)</td>
<td>1.2% (3)</td>
<td>0.8% (2)</td>
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<td>(intergranular)</td>
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<tr>
<td>Total</td>
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<td>100% (250)</td>
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</tr>
<tr>
<td>Measured φ</td>
<td>20.6%</td>
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<td>23.5%</td>
<td>23.7%</td>
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<td>13.2%</td>
<td>15.3%</td>
<td>17.4%</td>
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<td>53.00md</td>
<td>118.00md</td>
<td>144.00md</td>
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<td>Wood Sampier 1-3</td>
<td>Wood Mieske 1-3</td>
<td>Wood Mieske 1-3</td>
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</tr>
<tr>
<td>----------------------</td>
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<td>-----------------</td>
</tr>
<tr>
<td>Quartz (monocrystalline)</td>
<td>62.0% (155)</td>
<td>51.6% (129)</td>
<td>49.2% (123)</td>
<td>57.6% (144)</td>
<td>66.0% (165)</td>
<td>59.6% (149)</td>
<td>58.4% (146)</td>
<td>64.0% (160)</td>
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<tr>
<td>Quartz (polycrystalline)</td>
<td>2.4% (6)</td>
<td>8.0% (20)</td>
<td>8.0% (20)</td>
<td>5.2% (13)</td>
<td>5.6% (14)</td>
<td>6.0% (15)</td>
<td>4.8% (12)</td>
<td>3.6% (9)</td>
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<tr>
<td>Chert</td>
<td>1.6% (4)</td>
<td>0.4% (1)</td>
<td>0.8% (2)</td>
<td>0.4% (1)</td>
<td>0.8% (2)</td>
<td>0.0% (0)</td>
<td>1.2% (3)</td>
<td>0.8% (2)</td>
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<tr>
<td>K-Feldspar</td>
<td>3.6% (9)</td>
<td>2.8% (7)</td>
<td>1.6% (4)</td>
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<td>4.4% (11)</td>
<td>3.6% (9)</td>
<td>3.2% (6)</td>
<td>3.6% (9)</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>0.0% (0)</td>
<td>0.0% (0)</td>
<td>0.4% (1)</td>
<td>0.0% (0)</td>
<td>0.0% (0)</td>
<td>0.4% (1)</td>
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<td>0.0% (0)</td>
</tr>
<tr>
<td>Biotite</td>
<td>2.8% (7)</td>
<td>0.0% (0)</td>
<td>1.6% (4)</td>
<td>0.8% (2)</td>
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<tr>
<td>Clay Clasts</td>
<td>2.8% (7)</td>
<td>5.2% (13)</td>
<td>4.4% (11)</td>
<td>1.6% (4)</td>
<td>1.6% (4)</td>
<td>2.8% (7)</td>
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<td>Clay Matrix</td>
<td>8.8% (22)</td>
<td>0.4% (1)</td>
<td>0.4% (1)</td>
<td>6.8% (17)</td>
<td>5.6% (14)</td>
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<td>4.0% (10)</td>
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<tr>
<td>Qtz/Feldspar/Lithic Fragments</td>
<td>93/5/2</td>
<td>95/4/1</td>
<td>95/3/1</td>
<td>96/3/1</td>
<td>93/6/1</td>
<td>94/6/0</td>
<td>93/5/2</td>
<td>94/5/1</td>
</tr>
<tr>
<td>Ankerite</td>
<td>0.4% (1)</td>
<td>1.2% (3)</td>
<td>5.6% (14)</td>
<td>4.8% (12)</td>
<td>2.8% (7)</td>
<td>2.0% (3)</td>
<td>0.8% (2)</td>
<td>2.4% (6)</td>
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<td>Dolomite</td>
<td>0.4% (1)</td>
<td>0.4% (1)</td>
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<td>Siderite</td>
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<tr>
<td>Kaolinite</td>
<td>1.6% (4)</td>
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<td>4.8% (12)</td>
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<tr>
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<tr>
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<td>0.0% (0)</td>
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<tr>
<td>Qtz Overgrowths</td>
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<td>7.2% (18)</td>
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<td>0.0% (0)</td>
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<tr>
<td>Porosity (φ) (intergranular)</td>
<td>7.6% (19)</td>
<td>6.0% (15)</td>
<td>8.8% (22)</td>
<td>7.2% (18)</td>
<td>3.2% (8)</td>
<td>4.4% (11)</td>
<td>15.2% (35)</td>
<td>10.0% (25)</td>
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<tr>
<td>Porosity (φ) (intragenular)</td>
<td>0.0% (0)</td>
<td>3.6% (9)</td>
<td>1.6% (4)</td>
<td>0.4% (1)</td>
<td>0.0% (0)</td>
<td>0.8% (2)</td>
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<td>0.4% (1)</td>
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<tr>
<td>Total</td>
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<td>100% (250)</td>
<td>100% (250)</td>
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<tr>
<td>Measured φ</td>
<td>N/A</td>
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<td>9.8%</td>
<td>15.3%</td>
<td>17.1%</td>
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BIBLIOGRAPHY


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Gunn, G.R., 1988b, Isopaching may help find Berea strat traps: Oil and Gas Journal, v. 86, no. 50, p. 74-76.


