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CITIES SERVICE OIL COMPANY

ENVIRONMENT OF DEPOSITION, PETROGRAPHY, AND GEOCHEMISTRY OF A BEREA (MISS.) FORMATION SAND CORE, CSO ISLAND CREEK COAL C-7, MCDOWELL COUNTY, WEST VIRGINIA

TECHNICAL REPORT #36

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EXPLORATION AND PRODUCTION RESEARCH TULSA, OKLAHOMA

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ENVIRONMENT OF DEPOSITION, PETROGRAPHY, AND GEOCHEMISTRY OF A BEREA (MISS.) FORMATION SAND CORE, CSO ISLAND CREEK COAL C-7, MCDOWELL COUNTY, WEST VIRGINIA

Technical Report #36

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December, 1974

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ABSTRACT

Cores of the Berea Sandstone (Mississippian) from the CSO Island Creek Coal C-7 well, McDowell County, West Virginia, were studied to determine: (1) the environment of deposition and (2) reservoir characteristics and porosity and permeability controls. Gas is produced from the "tight" Lower Berea Sandstone in the area although production is often marginal because of low porosity and permeability, and the susceptibility of the unit to reservoir damage during well completion.

The study area is in a part of the Appalachian Basin, located on the southern side of the Rome Trough. Tectonic activity affected the basin during the Alleghanian Orogeny. Mississippian, Pennsylvanian, and Quaternary deposits overlie the Berea in this well.

The Berea Sandstone is very fine grained, consisting primarily of quartz with minor feldspar and rock fragments (feldspathic lithic arenite). Sedimentary structures indicate that the unit was deposited in a nearshore (upper foreshore - "beach") environment. The external geometry of the Berea, therefore, should be linear parallel to depositional strike, relatively narrow in a dip direction and individual sandstones probably are relatively thin.

Diagenetic alteration of the original sediment strongly controls reservoir characteristics of the Berea. The diagenetic sequence is: (1) quartz overgrowth, (2) chlorite (chamosite) and illite clay film formation; (3) compaction, grain suturing and stylolite formation, (4) second generation quartz overgrowth, (5) carbonate (including siderite) cementation and (6) feldspar alteration. The overgrowths, clay films, grain suturing and and cementation reduce porosity and permeability; chlorite and siderite

cause formation damage during well completion if iron is released in solution and then oxidized.

The Berea Sandstone has been affected by high temperatures (between 220° and $\geq$ 310° F) in the geologic past; and, the well may be located in a thermal gas area of unknown extent. Evidence supporting this includes a thermal alteration index of organic-matter constituents of -4 (indicating temperatures between 220° and 310° F depending on the time of exposure) and a possible chlorite polytype of Ib (B = 90°) (indicating temperatures of formation of less than and not exceeding 260-390° F), while the reconstructed depth of burial is only approximately 4,000 feet (the present depth). Unless the paleo-geothermal gradient was drastically higher than the present gradient which produces a bottom hole temperature of 100° F, depth of burial alone does not explain the high temperatures the formation has experienced.

A working hypothesis to explain the higher geothermal regime is that tectonic activity during the Alleghanian Orogeny (Pennsylvanian to Permian in age) in the nearby Ridge and Valley Province of the Appalachians caused heat flow, possibly alteration of hydrocarbons to gas, and influx of silica and iron-rich solutions during stylolitization or migration from adjacent shale facies into the area. This hypothesis raises the question of similar alterations occurring elsewhere in McDowell County and possibly regionally in the Appalachian Basin. There are no igneous intrusives or extrusives present nearby.

Due to the abundance of iron in the chlorite (chamosite) and siderite in the Berea, the common practice of acidizing the reservoir causes formation damage. A stimulation technique compatible with the reservoir sandstone constituents was determined by L. P. Brown (CSO Tulsa Research Laboratory) for this well and has enhanced gas production.

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INTRODUCTION

This report discusses the depositional environment, petrographic characteristics and geochemical analysis of a Berea Sandstone core from the CSO Island Creek Coal C-7, McDowell County, West Virginia (Figure 1). The study was requested by production geologists L. P. Davis and M. L. Price of the Mid-Continent Region.

The objectives of this study are:

1. To describe the lithology and sedimentary structures of the slabbed, full diameter core and interpret the environment of deposition.
2. To determine reservoir characteristics (sandstone mineralogy and diagenetic alterations) and factors controlling porosity and permeability, using petrographic and scanning electron microscope techniques.
3. To analyze the geochemical data available (X-ray diffraction data, chemical analyses, formation water composition, etc.) in an attempt to quantify post-depositional chemical alterations and temperatures and pressures encountered with burial.

Gas and oil have long been produced from the Berea Sandstone in eastern Ohio, western Pennsylvania, western West Virginia, and eastern Kentucky. The Berea is Lower Mississippian (Kinderhook) and overlies a probable unconformity between the Devonian and Mississippian and underlies the Sunbury Shale.

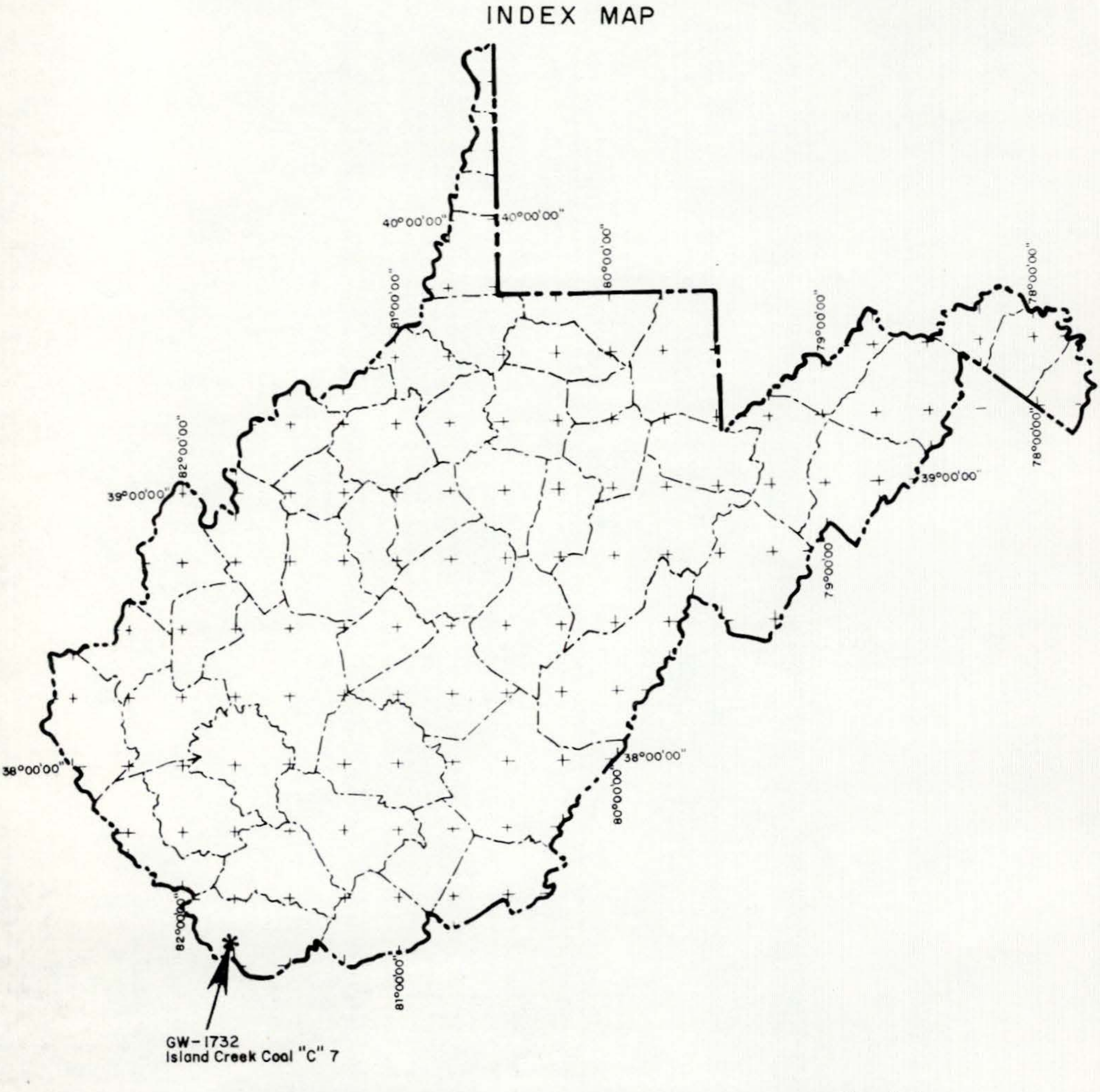


Figure 1. Location of Island Creek Coal Company "C"-7, West Virginia

McDowell County lies in the Appalachian Basin which geographically is part of the Allegheny Plateau. The area which includes the Island Creek Coal C-7 lies on the Southern side of the Rome Trough. Since Berea deposition, the area has been affected tectonically during the Alleghanian Orogeny (Pennsylvanian to Permian in age). Mississippian and Pennsylvanian rocks and surficial deposits of Quaternary Age overlie the Berea in this well. No Permian rocks were deposited in this area.

Gas is produced from "tight" lower Berea Sandstone in the area of the Island Creek Coal C-7, however, many wells are marginally economic with production of < 1 MMCF and > 100 MCF of gas/day. Production is often decreased due to formation damage by well completion practices, which produce red iron-oxide rich water along with the gas. Enhancement of production by adequate completion techniques is essential in making marginal wells commercial. Larry Brown, research engineer in Tulsa, co-ordinated a study of the Berea pay zone upon reaching TD in an attempt to promote practices that were compatible with the characteristics of the reservoir (type of cement, formation water composition or acid sensitive clays, etc.).

Presently this well is shut-in until a pipe-line is laid to this and an adjacent Berea gas well. In line with the findings of the engineering analysis by Brown, stimulation of the reservoir consisted of fracturing the formation and injecting synthetic formation water with an oxygen scavanger. Gas production was originally tested at 21 MCF PD (natural flow) with an increase to 50 MCF of gas/day following stimulation. The bottom-hole temperature of the well is 100° F at 4000'.

The environment of deposition and petrography was studied by Gary Flesch, the SEM microscopy was done by Flesch and William Almon, the geochemical analyses by Almon and the interpretations by Almon and Flesch.

W. C. Meyers analyzed organic material in the single shale sample available from the core to obtain its Thermal Alteration Index.

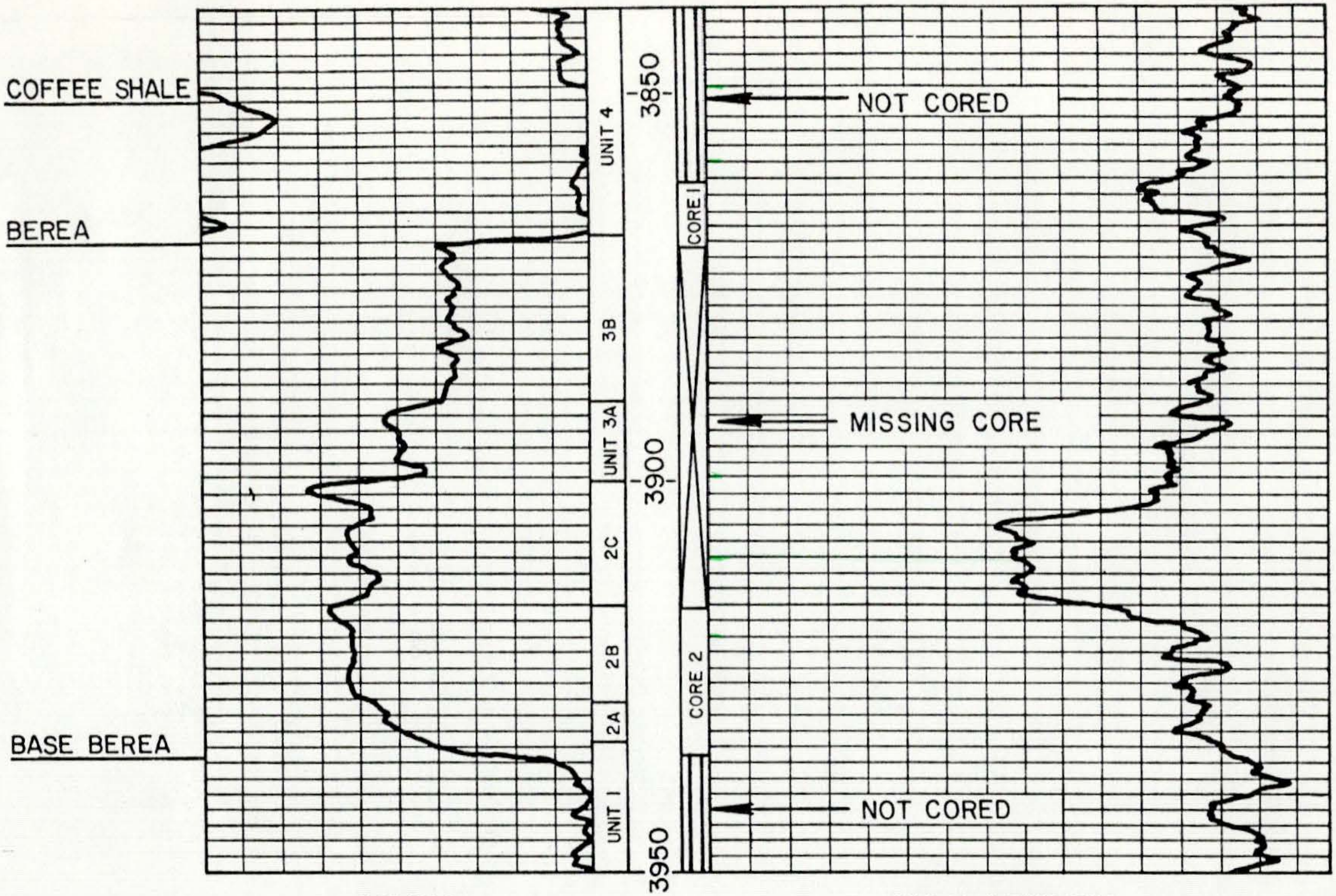
LITHOLOGY AND SEDIMENTARY STRUCTURES

Figure 2 illustrates the four units which comprise the Berea Sandstone. From the base upward they are: Unit-1, predominatly shale with minor siltstone; Unit-2, a fine-grained sandstone which may be subdivided into a basal transitional sandstone and siltstone (2A), a less porous fine-grained sandstone (2B), and a more porous fine-grained sandstone-the reservoir (2C); Unit-3A and 3B, fine-grained sandstone and siltstone subunits; and Unit-4, shale with minor siltstone.

Core 1 includes Unit 4 and the top 4 inches of Unit 3B. Core 2 includes Units 2B, 2A and the top 5 inches of Unit 1 (Figure 2). Units 2C (the reservoir), 3A and most of 3B were not cored. The core-to-log footage corrections were obtained by matching a hand-made sandstone to shale ratio log with the subsurface gamma log. A core to log footage correction of -8.5 feet was obtained for Core 1 and +6.5 feet for Core 2. All footages used in this report have been corrected to the log unless otherwise specified.

Unit 1, 3933.5' and below - Only the top 5 inches of this unit was observed and it consists of dark gray coarse to very fine siltstone and possibly shale. The rock is dense, as is the entire cored interval, and contains faint sub-horizontal parallel laminations.

Unit 2A, 3928 to 3933.5' - Siltstone, coarse to very fine-grained, to fine-grained sandstone with prominent coarsening upward, slightly inclined, parallel laminations (Figure 3B and 3C). Some medium to large scale current ripples and low angle cross-laminations occur at 3928' (Figure 3B) as well as small cohesive sand faults (Figure 3C). This unit is present as a transitional base to the fine-grained reservoir sandstone.



C.S.O. ISLAND CREEK COAL C-7

BEREA SANDSTONE (Miss.)

Figure 2. McDOWELL COUNTY, WEST VIRGINIA

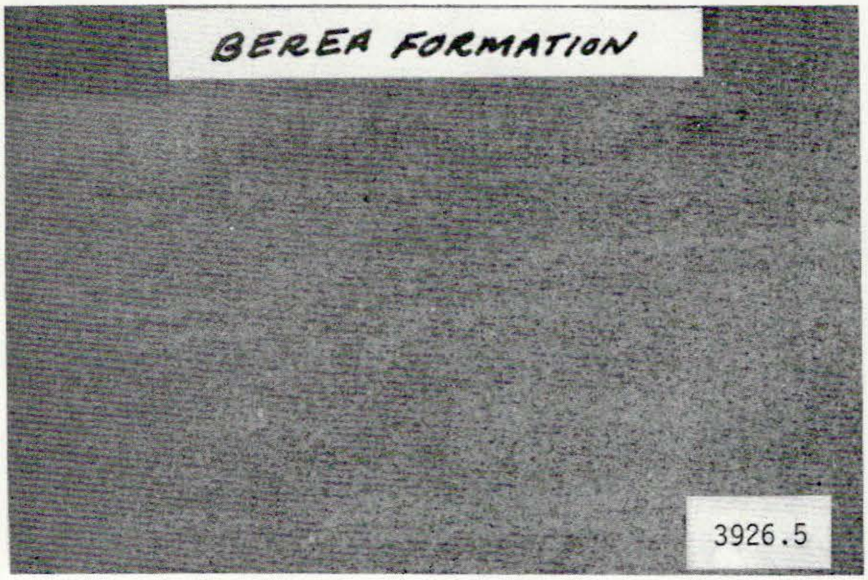
Unit 2B, 3915 to 3928' - Fine-grained sandstone. As indicated by the log, this sandstone is representative of the reservoir (which was not cored); however, this unit has less porosity. Structures consist primarily of faint to indistinct parallel laminations (Figure 4B, 4C and 5C). Irregular discoloration bands and "splotches" are present in the upper 6 feet of the core and become increasingly abundant in the top of that interval (Figure 4C and 3915.5', photo in Appendix A). The cause of these splotches is unknown.

Unit 2C, 3900 to 3915' - Not cored; reservoir sandstone. Gamma characteristics (Figure 2) show it to be more variable than Unit 2B, but primarily a sandstone, with porosity (based upon bulk density).

Unit 3A, 3890 to 3900' - Not cored, less resistive than Unit 2, probably consisting of siltstone and fine-grained sandstone.

Unit 3B, 3870 to 3890' - Only top 4 inches cored. Consists of siltstone and very fine sandstone with coarsening upward, slightly inclined parallel laminations (Figure 4A).

Unit 4, 3870' and above - Interbedded shale and siltstone, coarsening upward parallel laminations in the siltstone (Figure 5B) and faint laminations and pyrite-filled burrows in some of the shales (Figure 5A). Irregular vertical fracture at 3869.7' (Figure 5C).



A

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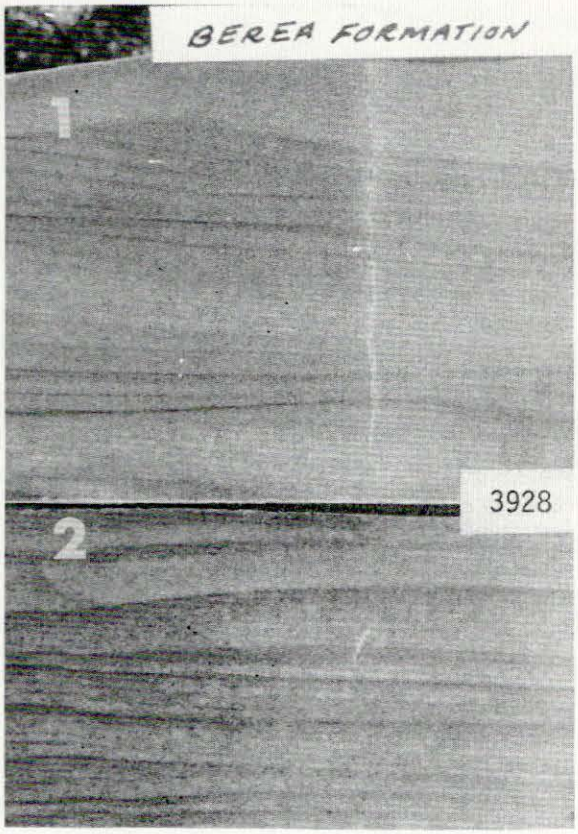

B

1 INCH

C

1 INCH

Figure 4. Unit 3B and 2B - Nearshore-"Beach"

A. Unit 3B, 3870' - Siltstone and very fine sandstone with reverse graded laminations. Coarser and finer layers are presumably the product of rising and falling water levels in the swash zone of a beach. Slightly inclined parallel laminations are indicative of upper-flow regime currents. Permeability 0.1 md, porosity 2 percent.

B Unit 2B, 3919.3' - Fine grained sandstone, with faint, slightly inclined parallel laminations. Deposition was as a nearshore, partially subaerially exposed beach. Permeability 0.3 md, porosity 10.8%.

C. Unit 2B, 3922.1' - Fine-grained sandstone, with indistinct parallel laminations and parallel discolored bands. Origin of discolored bands is not known. Nearshore "beach" depositional site. Permeability 0.3 md, porosity 9.7%.

A

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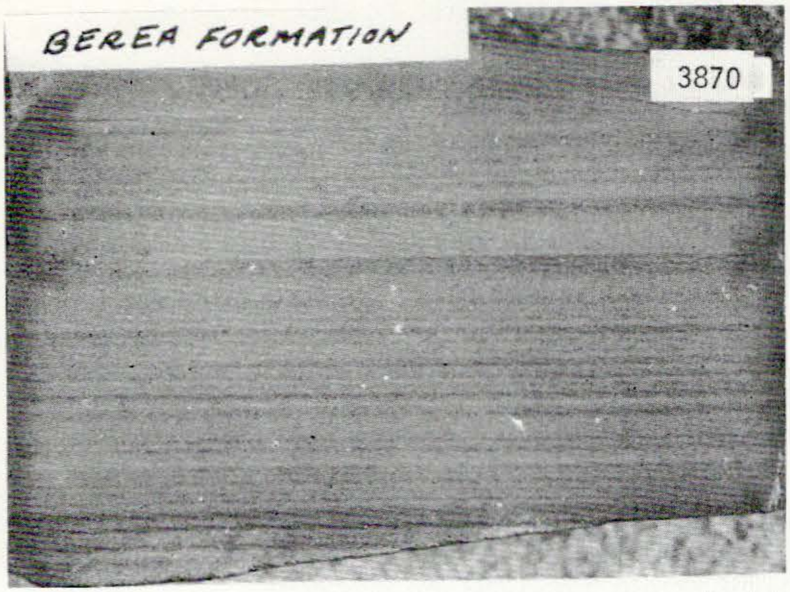

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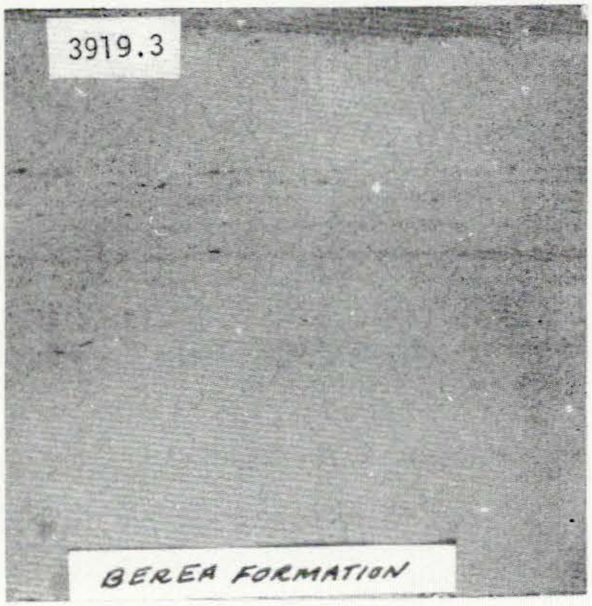

C

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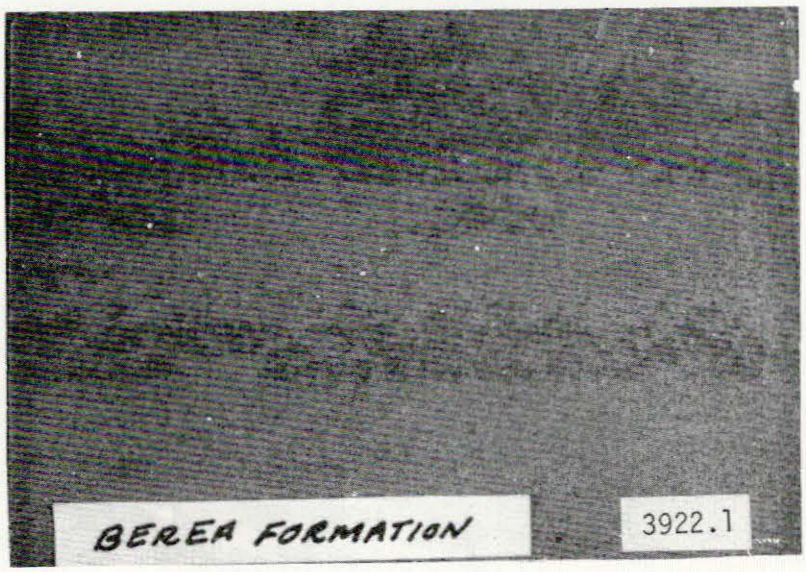
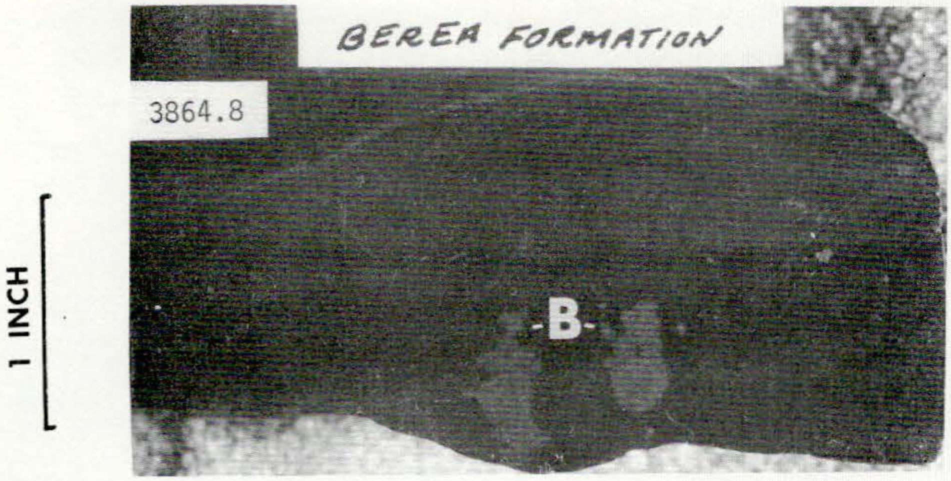


Figure 5. Unit 4 - Nearshore to Offshore?

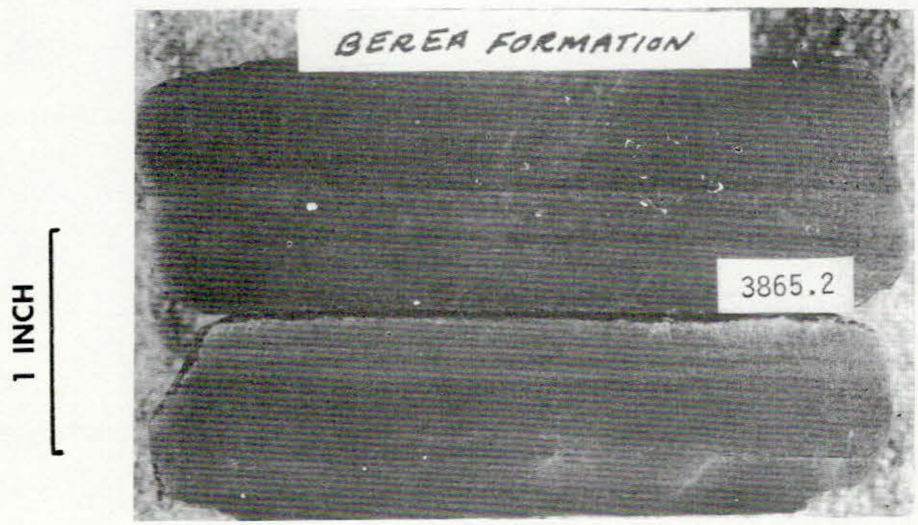
A. 3864.8' - Shale and minor siltstone, dark gray and dense with occasional pyrite-filled burrows (B). Possibly deposition was offshore in muddy waters below wave base. Permeability 0.1 md, porosity 1.5%.

B. 3865.2' - Siltstone and shale, dark gray and gray, dense with slightly inclined parallel laminations. Note coarsening upward, laminations from clay and fine silt to coarse silt. Deposition occurred nearshore in an area where only finer sediments were available or possibly offshore.

C. 3869.7' - Siltstone, gray and dense. Irregular, natural fracture (stylolite) that has been partially healed with silica. Deposition occurred nearshore; the stylolite (post-depositional) indicates horizontal compression. Permeability 0.1 md, porosity 2.0%.


BEREA FORMATION
3864.8
B
1 INCH

A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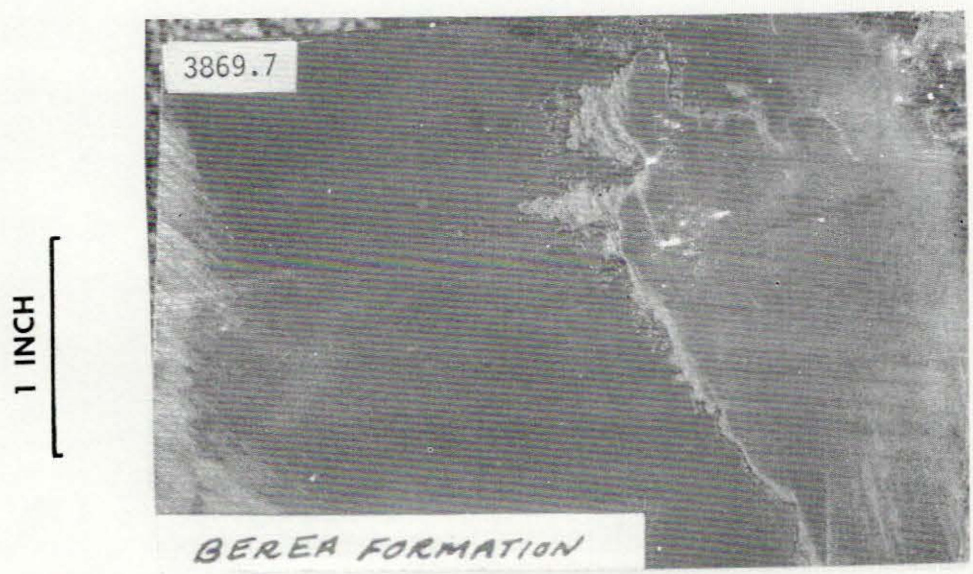
B


3869.7
BEREA FORMATION
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C

ENVIRONMENT OF DEPOSITION

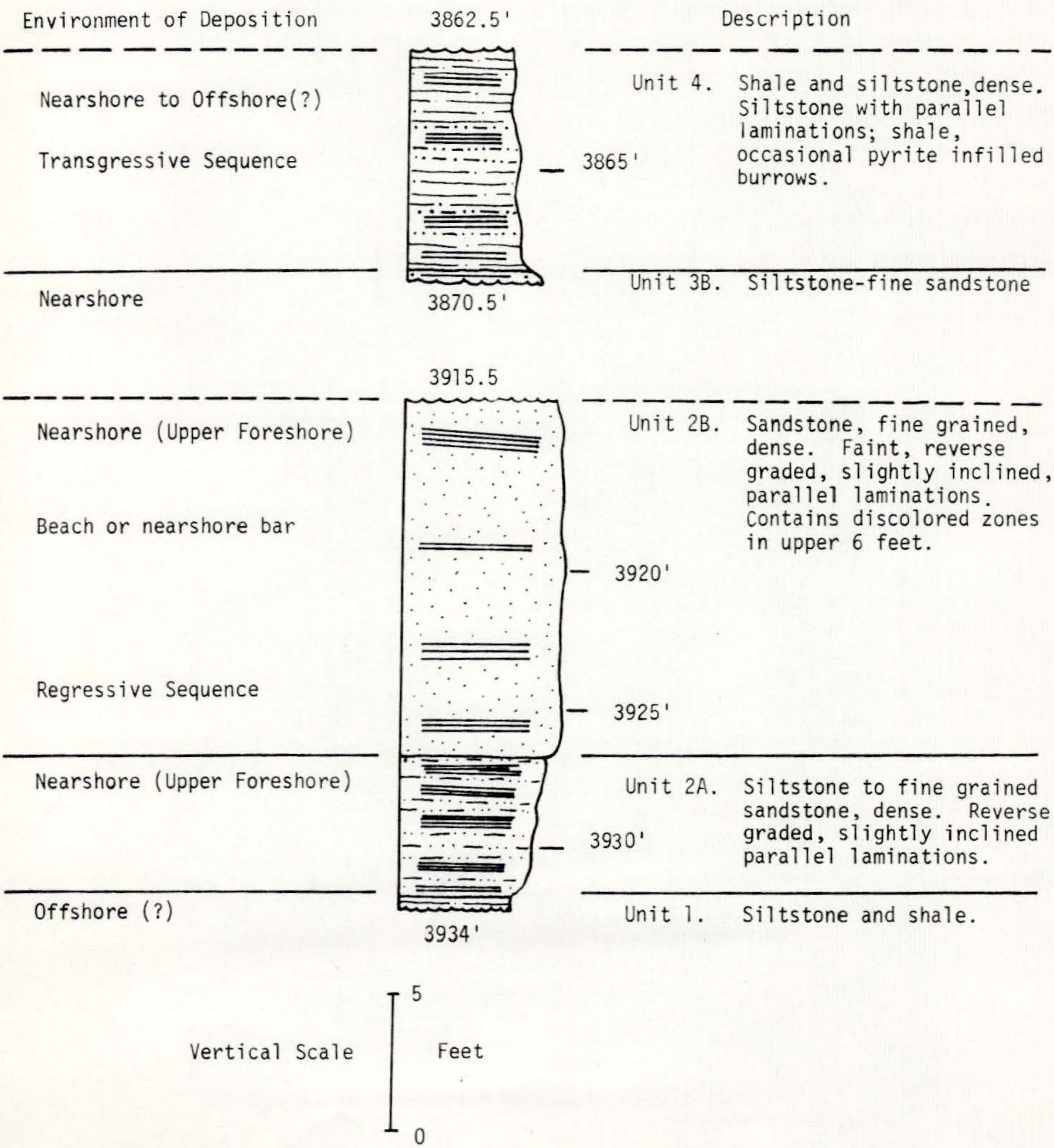
The cored interval of the Berea Sandstone is interpreted as having been deposited primarily in the upper foreshore beach zone by wave swash and backwash during Lower Mississippian times (Figure 6). In this study the term nearshore is defined as the relatively narrow zone extending seaward of the shoreline in the zone of wave-induced nearshore currents (after Clifton, et al., 1971). The offshore zone lies seaward of the nearshore zone and includes shallow water below wave base. Deposition appears to have been in the upper foreshore (beach) environment for the fine-grained sandstone of Unit 2B and the fine- and very fine-grained sandstones and siltstones of Unit 2A and 3B. The siltstone, shales, and very fine sandstone of Unit 1 and Unit 4 were deposited nearshore or possibly partially offshore, where fine suspended particulate matter is more common. Wunderlich (1972) has commented on mud deposition within the beach zone, which does not appear to be uncommon.

The primary evidence of a nearshore environment is the predominance of slightly inclined parallel laminations in all of the units (Figures 3 and 4). These structures indicate sediment deposition by the swash and backwash of waves (Clifton, 1969). These laminations are fine sand and/or heavy mineral rich layers which grade upward into coarser and/or heavy mineral poor layers (Figures 3C and 4A). Key features of beach sandstones determined for the Belly River Formation, Alberta, Canada by Tillman (1972) are compared for the Berea units in Figure 7.

Unfortunately, not all the reservoir was cored and the four main units represented by the log (Figure 2) could not all be examined, including Unit 2C,

Figure 6. LOWER BEREA SANDSTONE (MISS.)
ISLAND CREEK COAL C#7
MCDOWELL COUNTY, WEST VIRGINIA

SEDIMENTARY STRUCTURES, LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS



BEACH SANDSTONE

A - Abundant
C - Common
M - Minor
Tr - Trace

	Unit 1 (3933.5-3940')	Unit 2A (3928-3933.5')	Unit 2B (3915-3928')	Unit 3B (3870-3870.4')	Unit 4 (3862.5-3870')
1. Low angle laminations, subhorizontal, subparallel	-	A	A	A	A
2. Low angle truncations of sets	-	M	-	-	-
3. Relationship of adjacent lamina					
a) Sharp contrast in grain size of adjacent laminations	-	A	A	A	A
b) Well sorted	-	-	-	-	-
4. Graded bedding: a) Normal b) Reverse	-	b	b	b	b
5. Burrowed:					
a) Vertical crab burrows (Backshore)	-	-	-	-	-
b) <u>Ophiomorpha</u> (Foreshore)	-	-	-	-	-
c) Other	-	-	-	-	M
6. Ripples	-	-	-	M	-
7. Glauconitic(?)	Tr	Tr	Tr	Tr	Tr

Figure 7. Environment of deposition checklist used for the Berea Formation units, Island Creek Coal C-7 (format from R. Tillman, 1972).

the more porous reservoir sandstone facies. However, the lithologic units not examined have nearshore deposits underlying and overlying them. It is suggested that these units also were deposited in a nearshore environment. Owing to the incomplete vertical sequence, a more detailed interpretation of the Berea Sandstone, including understanding lateral facies changes thru time, is not possible.

The geometry of the Berea should be linear, narrow in width (depending upon possible progradation), elongate parallel to depositional strike and individual sand bodies should be relatively thin, compared to the other axes. Often topographic surfaces within the overall deposit are undulatory, due to ridge and runnel formation and/or nearshore bars (longitudinal or traverse) within the upper foreshore environment.

RESERVOIR CHARACTERISTICS

The present reservoir quality of the Berea Sandstone is the result of primary depositional environment controls on the sandstone and post-depositional (paragenetic) alterations on the original sandstone porosity and permeability. By understanding the physical characteristics of the reservoir sandstone and especially the diagenetic components, porosity and permeability controls may be identified. Proper stimulation techniques (which did not damage the reservoir) were determined for the Berea in this well (L. Brown, personal communication). These techniques are described in this report along with their geochemical significance.

Petrography

Analysis of four samples representative of the main Berea Sandstone lithologies was completed. This included petrographic examination of thin-sections and scanning electron microscopy (SEM) of aggregate samples. Quantitative checks on these findings were obtained from X-ray diffraction analysis of bulk and fractionated ($< 5\mu$ size) samples and elemental analysis of authigenic and detrital components in the samples by X-ray energy spectrometer.

The basic sandstone components, including detrital grains, matrix, cement and pore spaces, were analyzed. Matrix and cement will be discussed together as diagenetic components because in the Berea they are both authigenic in origin.

Pertinent articles concerned with the petrography of the Berea include Pepper, DeWitt and Demarest (1954, p. 91-95) and Heald, who discussed Berea authigenesis (1950) and feldspar solution (1973), and porosity controls (1974).

Detrital Components: Rock constituents present in the Berea Sandstone are summarized in Table 1 and consist of detrital components (75-80%), diagenetic components (15%) and pore spaces (5-10%). Thin-section photomicrographs of these features are included in Figures 8-13. Detrital grains primarily consist of monocrystalline quartz (65-70%) with feldspar (10%), rock fragments (5-10%) and accessory grains (8%) important subordinates. Following the sandstone classification proposed by Pettijohn, Potter and Siever (1972) the rock is a feldspathic lithic arenite.

Diagenetic Components: Diagenetic components consist of chlorite (chamosite) and minor illite clay films (matrix), quartz overgrowths and in-fillings, and carbonate (including siderite) cement. Porosity and permeability have been greatly reduced by these features and porosity was not visible in most thin-sections. The denseness of the Berea results from these diagenetic components (especially quartz overgrowths and cement) and possibly from effects of tectonism or moderate pressure solution due to burial(?).

The sequence of diagenetic events for the Berea is included in Table 2 and are illustrated in several of the thin-section photomicrographs (Figures 8-13) and the SEM photomicrographs (Figures 14-22). There appears to have been two generations of quartz overgrowth formation, the earliest occurring in the beginning of the diagenetic sequence and the latest post-dating the formation of chlorite and illite clay films and post-dating to partially contemporaneous with moderate pressure solution effects and compaction with burial and tectonic heating. Heald (Figure 2, 1950) has also reported two periods of quartz overgrowth formation with chlorite growths between them for the Berea in West Virginia.

Table 1. Generalized Mineralogic Compositions for Berea Sandstone

Rock Constituents	Percentages	Comments
Detrital Components	75-80	Framework grains.
Quartz	65-70	Contains numerous inclusions, undulatory extinction, overgrowths and clay films.
Monocrystalline	60	
Polycrystalline	5	Crenulated and normal grain boundaries.
Feldspar	10	Commonly are undergoing alteration.
Albite	7	Albite twinning, unaltered and altered.
Microcline	2	Some pericline twinning, unaltered.
Orthoclase	1	Not readily distinguishable, altered.
Rock Fragments	5-10	Commonly altered and seriticized.
Volcanic and igneous		Volcanic(?) varieties predominate.
Chert	Trace	Fine grained variety.
Accessories	8	
Opaques	3	Non-metallic and metallic.
Muscovite	2	Often deformed.
Zircon	1+	Subrounded to rounded.
Tourmaline	1	Subrounded, schorlite?
Clay clasts	Trace	May be altered feldspar or volcanics.
Green grains	Trace	Unknowns, probable cleavage.
Glauconite	Trace	Pellets in morphology.
Diagenetic Components	15	Post depositional in origin.
Matrix	7	Authigenic.
Chlorite (clay films)	6	Green, needle-like, surface coverings.
Illite (Clay films)	1	Based on SEM and X-ray analyses.
Cement	8	Grain coatings and pore-fillings.
Quartz	6	Overgrowths
Carbonate	2	Fills pores and partial replacement of grains.
Pore Spaces*	5-10	Primarily intergranular

*Based upon core analyses.

TABLE 2. Diagenetic Sequence for the Berea Sandstone

<u>Stage</u>

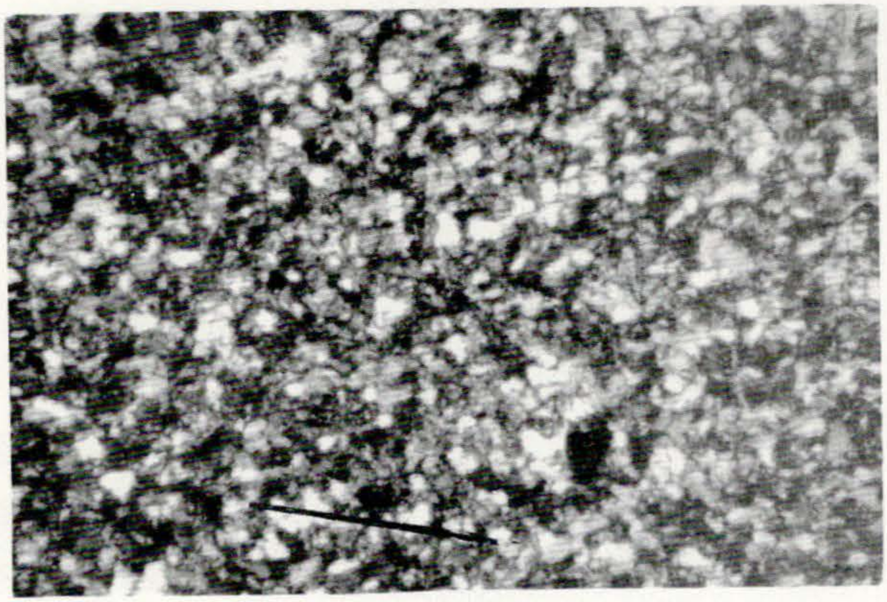
1. Quartz overgrowths-extensive to common.
2. Chlorite clay films.
3. Illite clay films.
4. Compaction, deformation of micas stylolite formation and grain suturing due to moderate pressure solution effects with burial. (The exact timing of stylolitization however is not known)
5. Quartz overgrowths, and especially pore infillings.
6. Carbonate (including siderite) cementation.
7. Alteration of feldspars (minor alteration precedes carbonate cementation).

Figure 8. Unit 4, 3868.5'

A. 3868.5' - General view illustrating preferred (inclined from left to right) grain orientation (line) and silt and fine-sand size detrital grains and matrix with high birefringence. Monocrystalline quartz grains are dominant. Crossed nicols, 37X magnification.

B. 3868.5' - Close-up monocrystalline quartz grains with prominent green chlorite clay films (arrow). Plain light, 150X magnification.

A



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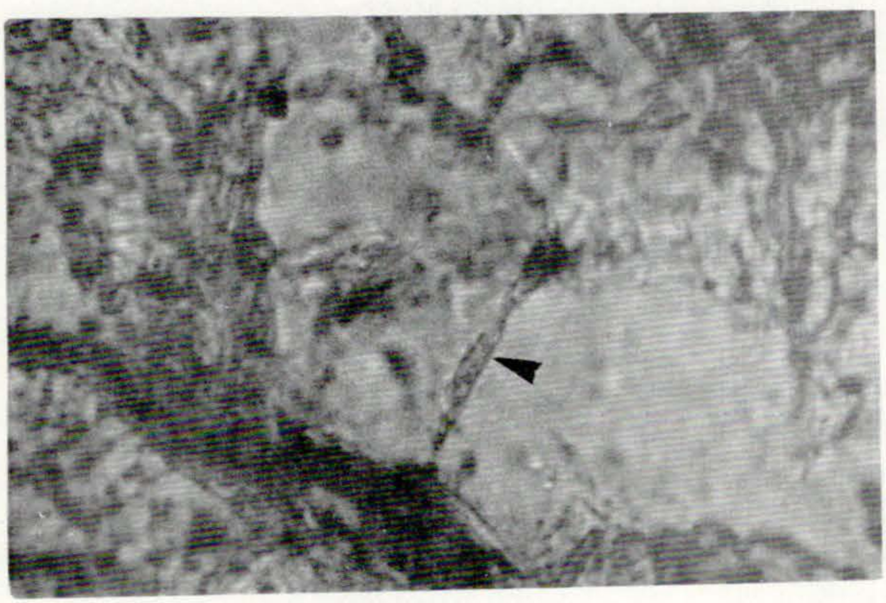


Figure 9. Unit 2B, 3919.5'

A. 3919.5' - Alteration of plagioclase grains (p), numerous mineral inclusions, and volcanic rock fragments (v) are apparent. Chlorite clay films (arrows) are typical of grain boundaries in all samples. Plain light; 37X magnification.

B. 3919.5' - Crossed nicols of previous sample. Chlorite films are less apparent (arrow); volcanic rock fragments (v) however, are more apparent, generally containing biotite, quartz and minor feldspar.

A

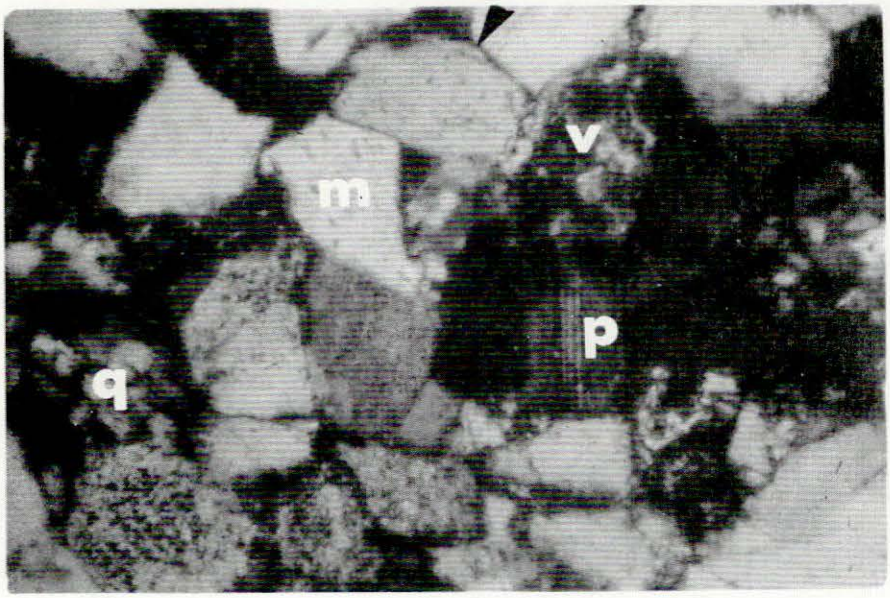
B

Figure 10. Unit 2B, 3919.5' and 24.5'

A. 3919.5' - Typical view of Unit 2B sandstone illustrating detrital grains of monocrystalline (m) and polycrystalline (q) quartz, plagioclase feldspar (p) and a volcanic rock fragment (v). Quartz grains have silica overgrowths (arrow) and chlorite clay films are thin rims with higher birefringence. Crossed nicols, 93X magnification.

B. 3924.5 - General view of sandstone, classified as a feldspathic lithic arenite, which translated means a sandstone containing feldspar (10%), volcanic and igneous lithic fragments (5-10%) and dominantly quartz ($\geq$ 65%). Crossed nicols, 37X magnification.

A



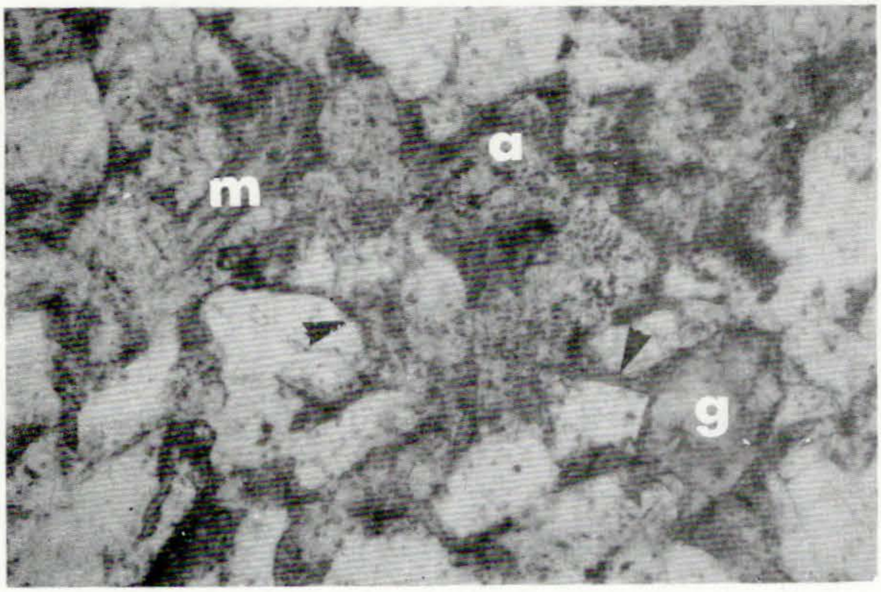
B

Figure 11. Unit 2B, 3924.5'

A. 3924.5' - Altered grains (a) probably including feldspar and volcanic rock fragments are common (15-20%) although they are subordinate when compared to quartz grains. Many grains exhibit well developed chlorite clay films (arrows). Also present are a deformed mica grain (m) and glauconite pellet (g). Plain light, 37X magnification.

B. 3924.5' - Sutured grain contacts appear commonly (arrow), as well as long and concavo-convex contacts. Silica overgrowths to the quartz are not readily apparent in this photo but were apparent when this sample was viewed with the SEM.

A



B

Figure 12. Unit 2A, 3933.5'

A. 3933.5' - General shot of sample showing preferred orientation of detrital grains (line). Monocrystalline quartz grains and patches of carbonate cement are easily discerned. Crossed nicols, 37X magnification.

B. 3933.5' - Large patches of carbonate cement are common. Monocrystalline quartz grains have a high ratio of grain to grain contacts. These contacts may be considered sutured (due to pressure solution) and/or the result of optically continuous quartz overgrowths. Dark borders to some grains are chlorite clay films (matrix). Crossed nicols, 97X magnification.

A

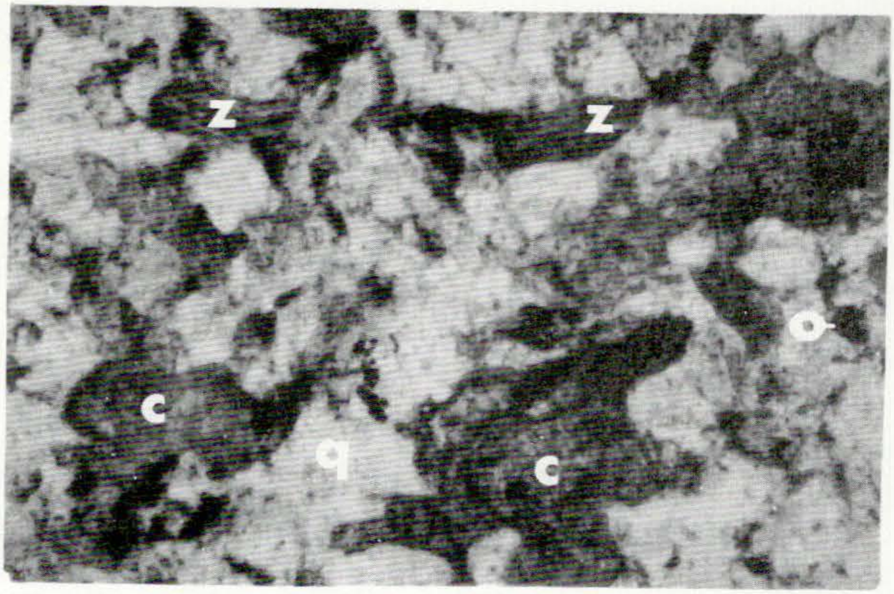
B

Figure 13. Unit 2A, 3933.5'

A. 3933.5' - Monocrystalline quartz grains (q) predominate with distinct boundaries often difficult to identify. Darker matrix (chlorite) grain coatings and carbonate cement (c) patches are common. Zircon (z) and opaques (o) are minor accessory grains. Plain light, 93X magnification.

B. Crossed nicols of A. Several grain contacts (arrows) appear to be sutured, indicating possible alteration by pressure solution.

A



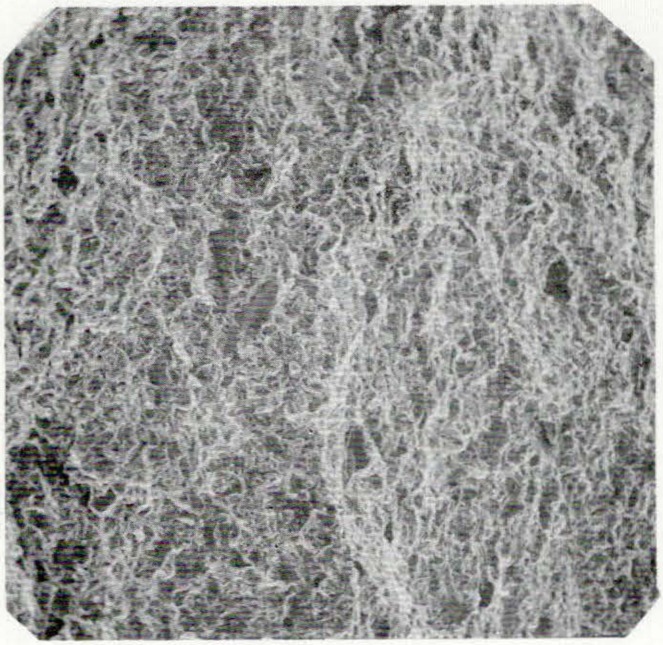
B

Figure 14. SEM Photomicrography - Unit 4 3868.5'

A. General view of dense shale and siltstone of Unit 4. Porosity is apparently lacking. 67X magnification (150μ = 1cm).

B. Close-up of previous field of view illustrating quartz overgrowths resulting in a subangular appearance to the grains. Very minor patches of authigenic chlorite are present; asterisk denotes authigenic illite. 2000X magnification (5μ = 1cm).

A



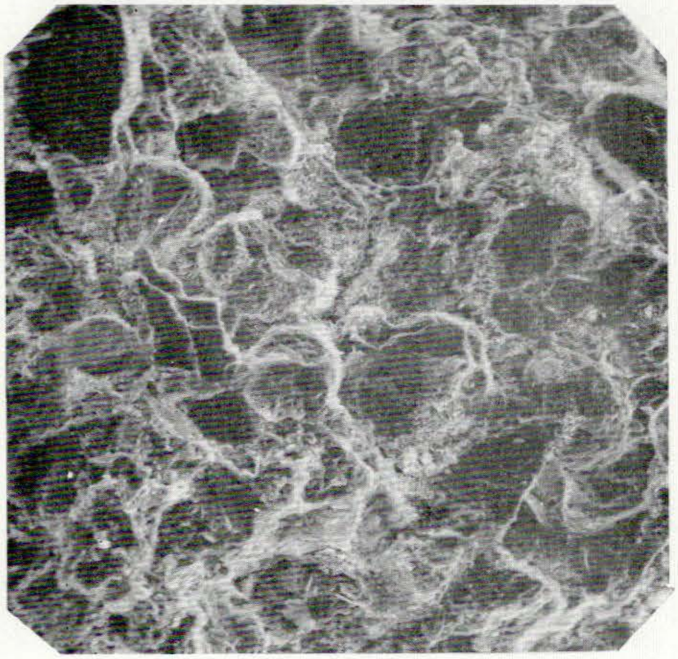
B

Figure 15. SEM Photomicrograph - Unit 2B, 3919.5'

A. General view of fine grained sandstone of Unit 2B including detrital grains and aphanitic matrix. Some grains with (geometric?) outlines typical of overgrowths descernable. 160X magnification (62.5μ = 1cm).

B. Prolific chlorite psuedohexagonal plates coating detrital grains. Note preservation of porosity. 800X magnification (12.5μ = 1cm).

A



B

Figure 16. SEM Photomicrographs - Unit 2B 3919.5'

A. Abundant psudohexagonal plates of chlorite coating detrital grains and extending into intergranular pores. Compare with thin-section photomicrograph of chlorite at 3868.5' (Figure 9B). 1200X magnification (8.3μ = 1cm).

B. Close-up of interlocking chlorite plates typical of all Berea samples observed from the Island Creek Coal C-7. 3000X magnification (3.3μ = 1cm).

A

B

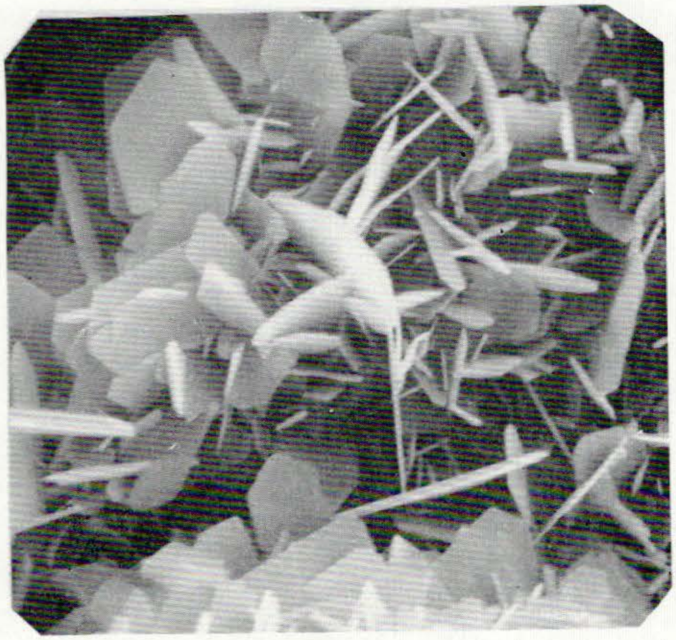
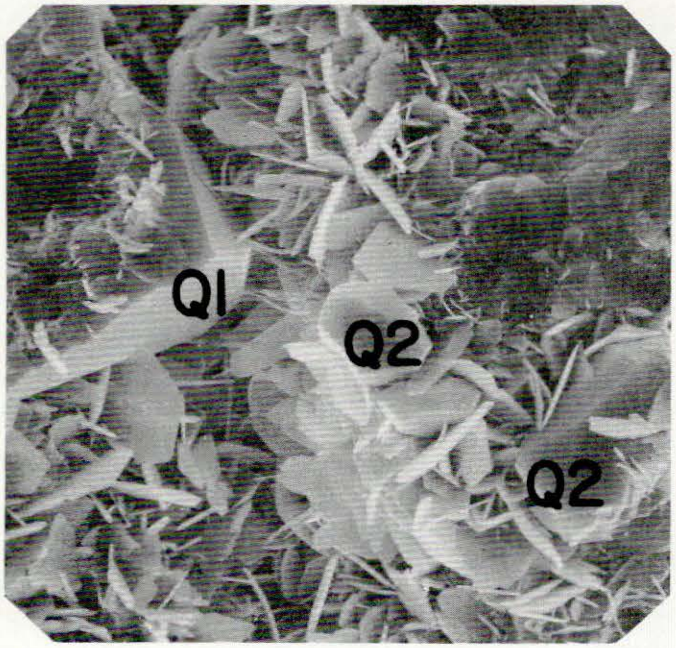


Figure 17. SEM Photomicrograph - Unit 2B, 3924.5'

A. Interrelationship of diagenetic quartz overgrowths (Q1 & Q2) interlocking psuedohexagonal plates of chlorite. First generation of quartz overgrowths (Q1) underlies chlorite (older) while second generation of quartz overgrowths (Q2) overlies the chlorite (younger). 600X magnification (6.25μ = 1cm).

B. Close-up of lower right corner of previous photo. The quartz overgrowth extends out of the interlocking chlorite plates and has grown around several plates (second generation quartz overgrowth, younger than the chlorite). 3500X magnification (2.9μ = 1cm).

A



B

Figure 18. SEM Photomicrograph - Unit 2B, 3919.5'

A. "Ribbon-like" illite extending from within and on top of the chlorite plates. All illite observed formed later than the chlorite. 1600X magnification (6.25μ = 1cm).

B. Close-up of fragile "ribbons or spines" of illite with chlorite in the background. 5000X magnification (2μ = 1cm).

A

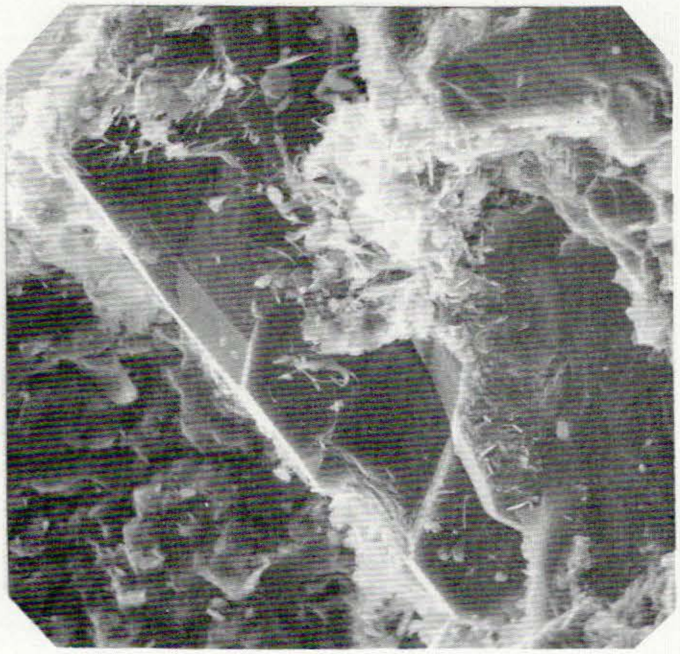
B

Figure 19. SEM Photomicrographs - Unit 2B, 3919.5'

A. Quartz overgrowths with coating of interlocking chlorite plates (younger). 800X magnification.

B. Detrital grain with first generation quartz overgrowth (Q) and abundant coating of chlorite pseudohexagonal plates. 600X magnification.

A



B

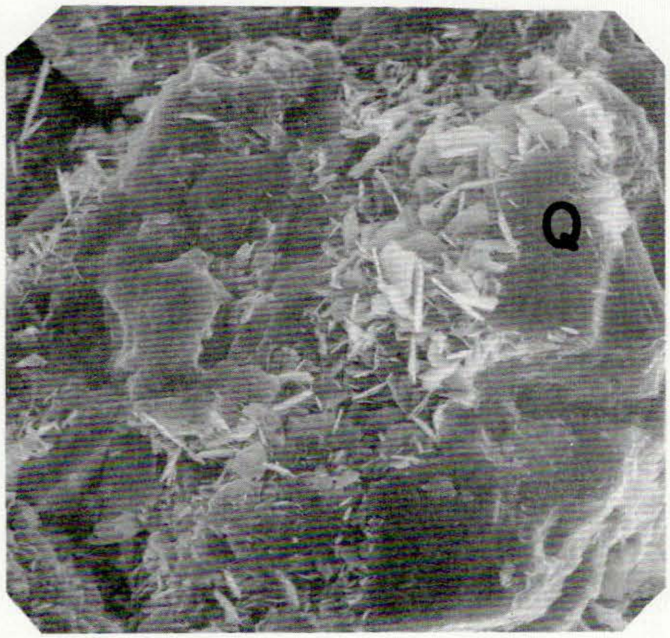


Figure 20. SEM Photomicrographs - Unit 2B, 3919.5'

A & B. Stereo pair of upper right corner of Figure 19B illustrating three dimensional aspect of first generation quartz overgrowths and chlorite plates. Use of stereoscope will illustrate cross-cutting relationship of chlorite with partial silica overgrowth, indicating chlorite is younger than overgrowth (which it cuts). 2000X magnification.

A

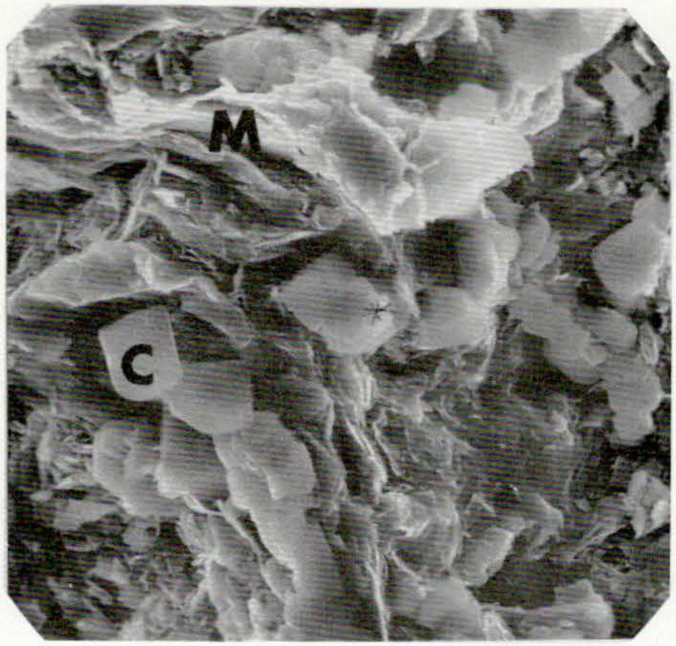
B

Figure 21. SEM Photomicrographs - Unit 2B, 3924.5'

A. Deformed muscovite grain (m) and carbonate cubes (c) which are rearly pure $Ca(CO_3)$? when analyzed with the X-ray energy spectrometer. 1600X magnification (5µ = 1cm).

B. Illite "spines" growing from within chlorite plates indicating the illite formed later. 3000X magnification (5µ = 1cm).

A



B

Figure 22. SEM Photomicrograph - Unit 2A, 3933.5'

A. Cross-cutting relationships between illite (younger) and psuedohexagonal chlorite plates (older). 2000X magnification (5μ = 1cm).

B. Cleavage faces of siderite rhombohedron X-ray energy spectrometer analysis yielded components of Ca, Fe, Si, Mg and Mn (in decreasing abundance). 1200X magnification (8.33μ = 1cm).

A

B

Chlorite clays occur as films coating the first generation quartz overgrowths and in some cases were found to have illite "growing" on top (Figures 18 & 21B). These clay films are missing from points of grain contact, making them authigenic rather than detrital in origin. Compaction and possible grain suturing due to moderate pressure solution post-dates these events because they have been involved in these alterations (Figures 11B, 12B & 13B). Difficulty in identifying pressure solution grain contacts from optically continuous quartz overgrowths have been discussed by Sippel (1968). Thus the importance of pressure solution is not readily apparent for the Berea. The second generation of quartz overgrowths and especially pore infillings appear to exhibit only minor compaction effects and thus post-date grain suturing.

Carbonate (including siderite) cement occurs in patches and post-dates the previously mentioned diagenetic components because they are not excluded by its presence and have themselves been cemented. The alteration of feldspar occurs last in the cycle; however, in some cases it precedes cementation because some of the feldspar has carbonate replacing altered portions of the grain.

Heald (1950) has noted some kaolinite in altered feldspars in some Berea samples; however, this does not occur in these samples. No feldspar overgrowths were present in the Berea samples, and this is in agreement with Heald (1950).

Grain Characteristics and Contacts

The reservoir sandstone (Unit 2) of the Berea consists primarily of fine sand size grains which have a preferred orientation, reflecting the slightly inclined parallel laminations (Figures 8A & 12A). Most grains are slightly elongate (quartz may be spherical, micas and tourmaline elongate) and subrounded to rounded. Grain boundaries are sometimes difficult to distinguish due to optically continuous overgrowths (Figures 12B & 13A). Grains commonly have chlorite clay films, but these do not occur at grain contacts.

The Berea Sandstone fabric consists mainly of long, concavo-convex and a few sutured grain contacts. The high ratio of grain to grain contacts indicates the Berea may have undergone moderate pressure solution (see Tables 3-5; Pettijohn, Potter and Siever, 1973). This may be checked by cathode luminescence microscopy (Sippel, 1968). The sandstone is well sorted and mature. Essentially all clay size material is the product of diagenesis.

Porosity and Permeability

Permeability is extremely low in all of the samples (0.1 to 0.3 md) and the thin-sections did not absorb dyed epoxy when impregnated. Little to no porosity could be observed in thin-section.

Intergranular porosity was observed with the SEM (Figure 15A) and was measured by standard core analyses techniques (Table 3) by Core Lab and the CSO Research Lab (Figure 23). These average figures are included in Table 1. Heald (1973) has reported intragranular porosity enhancement (2%) by post-depositional feldspar solution for the Berea, however, this does not appear to have significantly effected porosity in the observed samples.

Porosity and permeability in the Berea has been adversely affected as a result of diverse diagenetic alterations, which includes clay films, quartz overgrowths and in-filling, and carbonate cementation. Previous workers (Pittman and Lumsden (1968), Cecil and Heald (1971) and Whisonant (1970)) have indicated that authigenic clay coatings aid in preserving porosity by retarding pressure solution and the formation of quartz overgrowths. However, in the Berea sandstones observed in this study, the clay coatings were not complete enough to retard the second generation quartz overgrowths and in-fillings.

CORE LABORATORIES, INC.
Petroleum Reservoir Engineering
DALLAS, TEXAS

Page No. 1

CORE ANALYSIS RESULTS

Company CITIES SERVICE OIL COMPANY Formation BEREA SAND File 3402-8063
Well ISLAND CREEK COAL "C" NO. 7 Core Type Date Report 6-17-74
Field Drilling Fluid Analysts BOYLE
County McDOWELL State W. VA. Elev. Location

Lithological Abbreviations

SAND-SD, SHALE-SH, LIME-LM; DOLOMITE-DOL, CHERT-CH, GYPSUM-GYP; ANHYDRITE-ANHY, CONGLOMERATE-CONG, FOSSILIFEROUS-FOSS; SANDY-SDY, SHALY-SHY, LIMY-LMY; FINE-FN, MEDIUM-MED, COARSE-CSE; CRYSTALLINE-XLN, GRAIN-GRN, GRANULAR-GRNL; BROWN-BRN, GRAY-GY, VUGGY-VGY; FRACTURED-FRAC, LAMINATION-LAM, STYLOLITIC-STY; SLIGHTLY-SL/, VERY-V/, WITH-W/

SAMPLE NUMBER	DEPTH FEET	PERMEABILITY MAX.	PERMEABILITY 90°	PERMEABILITY VERT.	POROSITY PER CENT	RESIDUAL SATURATION PER CENT PORE: OIL	RESIDUAL SATURATION PER CENT PORE: TOTAL WATER	GRAIN DENS.	SAMPLE DESCRIPTION AND REMARKS
	WHOLE-CORE ANALYSIS								
1**	3871.0-72.0	0.1	0.1	<0.1	1.5	2.2	48.1	2.73	Sd, vert frac
	72.0-73.5								Sh
	73.5-77.0								Not Submitted
2	77.0-78.0	0.2	0.1	<0.1	1.4	2.4	28.0	2.68	Sd
3	78.0-79.0		<0.1*	<0.1	2.0	0.0	10.0	2.69	Sd
	79.0-10.0								Not Submitted
4***	3910.0-11.0	0.6	0.4	<0.1	11.0	0.0	15.2	2.68	Sd
5	11.0-12.0	0.3	0.2	<0.1	10.8	0.5	14.8	2.67	Sd
6	12.0-13.0	0.3	0.2	<0.1	10.8	0.5	15.1	2.67	Sd
7	13.0-14.0	1.0	0.8	<0.1	12.6	0.8	10.9	2.68	Sd
8	14.0-15.0	0.2	0.2	<0.1	8.8	0.7	18.9	2.67	Sd
9	15.0-16.0	0.3	0.2	<0.1	9.7	0.5	16.3	2.67	Sd
10	16.0-17.0	0.5	0.3	<0.1	11.9	0.5	16.7	2.67	Sd
11	17.0-18.0	0.2	0.1	<0.1	8.6	0.6	22.6	2.67	Sd
12	18.0-19.0	0.1	0.1	<0.1	9.6	0.7	29.1	2.67	Sd
13	19.0-20.0	0.2	0.1	<0.1	6.2	0.0	28.6	2.66	Sd
14	20.0-21.0	0.1	0.1	<0.1	4.7	0.0	34.8	2.65	Sd
15	21.0-22.0	0.3	0.1	<0.1	5.1	0.0	37.5	2.66	Sd
16	22.0-23.0	0.2	0.2	<0.1	0.9	0.0	50.0	2.72	Sd, shy, dol
17	23.0-24.0		<0.1*	<0.1	1.9	0.0	50.0	2.73	Sd, shy, dol
18	24.0-25.0	0.2	0.1	<0.1	3.6	0.0	22.2	2.67	Sd
19	25.0-26.0		<0.1*	<0.1	3.7	1.2	35.8	2.68	Sd, shy
20	26.0-27.0		<0.1*	<0.1	3.4	1.7	41.4	2.69	Sd
21	3927.0-28.0		<0.1*	<0.1	3.9	0.9	30.0	2.66	Sd, shy

The interval 3910 to 3921 feet appears to have gas productive significance. However, low permeability exists.

* DENOTES PLUG PERMEABILITY
** Core 1, corrected footages (3871-3879') -8.5 feet
*** Core 2, corrected footages (3910-3928') +6.5 feet

BEREA SANDSTONE TEST DATA

Sample Depth Feet	Permeability md	Porosity %	Saturation % Oil	Water	Grain Density	Toluene Extracted
3877	.005	1.0	0	100	2.67	Clear
3913	.086	9.5	.9	13.5	2.66	Clear
3918	.052	9.8	0	3.6	2.67	Clear
3927	.006	2.7	18.5	13.3	2.68	Clear

Figure 23. Core Analysis Results - CSO

Heald and Larese (1974) have recently commented on the beneficial role of chlorite clay coatings in the Berea in inhibiting quartz cementation (overgrowths). Figure 24 illustrates that as the percentage of clay coatings increase, porosity increases. They comment that other factors such as silica availability and temperature must also be considered.

Webb (1974) has commented on hydrocarbon migration prior to clay film and quartz overgrowth precipitation in Cretaceous Sandstones of Wyoming. Sandstones saturated with hydrocarbons contain little authigenic clay while the same sandstone body without hydrocarbons contains abundant clay. Heald and Larese (1974) comment that in some of the Berea Sandstone, dark hydrocarbon coatings are prominent on chlorite-coated grains, indicating the chlorite had impeded cementation before the entry of the hydrocarbon. An important aid in exploration may be to establish local trends of increasing chlorite percentages with corresponding increases of porosity. Superimposed upon other geologic information (i.e. depositional environment, structural setting, etc.) this may delineate perspective Berea drill sites.

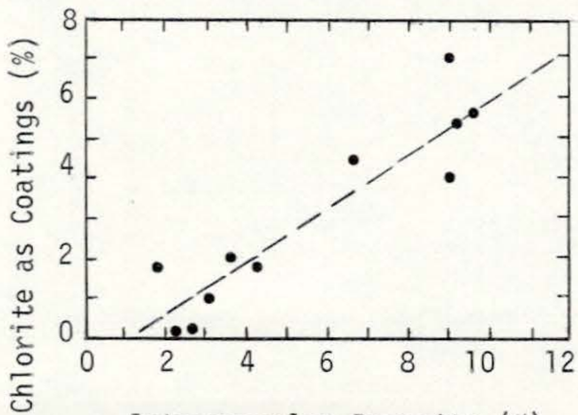


Figure 24. Relationship between amount of chlorite as coatings and intergranular porosity in the Berea Sandstone; primary type of cement in these speciments in quartz. Core samples; Hope Natural Gas Company well No. 10674, Fink Creek, West Virginia.

GEOCHEMISTRY

Figure 25. X-RAY DIFFRACTION ANALYSIS (< 2μ Fraction)
BEREA SANDSTONE (MISS.) MCDOWELL COUNTY, WEST VIRGINIA

Depth	Chlorite	Illite	Quartz	Calcite	Siderite	Other
3877'	4	4	4	x	1	Feldspar (2)
3913'	5	3	4	x	2	x
3918'	5	3	4	x	2	x
3927'	4	3	4	2	1	x

Code: 1 = Peak height 1-3 3 = Peak height 10-25 5 = Peak height >100
2 = Peak height 3-10 4 = Peak height 25-100 x = Absent

The x-ray diffraction patterns show minor 1st and 3rd order reflections and very intense 2nd and 4th order reflections. This indicates large concentrations of iron in both of the octahedrals layers of the chlorite lattice. The mineral acts as a seven angstrom grating; the chloritic mineral in these samples is more properly chamosite.

The uniformity of the clay mineral assemblage when compared with data from the SEM would seem to indicate that all of the clays occurring in these samples are diagenetic in origin.

Diagenetic Reactions

Quartz is the primary cementing material in the Berea samples observed in this project. The first stage of quartz overgrowths appear to have occurred early in the history of these rocks. It appears as thin, optically continuous partial coatings to detrital grains and as a result tends to obscure grain boundaries. This early generation of quartz overgrowths may be responsible for some of the apparent concavo-convex and sutured grain boundaries. Such grain overgrowths can be reproduced in the laboratory at room temperature (Mackenzie and Geer, 1971) and thus are not diagnostic of pressure solution effects due to burial.

The two clay minerals which occur as pore coatings probably formed at different stages in the history of the Berea. The chlorite (Chamosite, a highly Fe-rich chlorite) clay films occur as flat or slightly curved plates having psuedohexagonal boundaries. These plates are oriented perpendicular to the surfaces of the coated grains. The chemical conditions necessary for chamosite formation are fairly restricted. The presence of organic material, detrital iron and slightly basic pH appear to be the basic chemical environment requirements. There does not appear to be any restriction on salinity conditions as chamosite has been found forming in relatively fresh to saline waters.

Chlorite (in this case chamosite) exists as four structural polytypes in nature depending upon temperature, regardless of the chlorite composition (Hayes, 1970). Chlorite polytypes thus serve as geothermometers, as will be discussed below. Most diagenetic chlorites are of Type I, meaning temperatures of low-grade metamorphism were not reached. The initial stages of chlorite formation take place at low temperatures, probably in a reducing environment. The initial product is a poorly ordered, metastable type Ibd chlorite, in which some expandable layers might persist. Increasing burial with its concomitant increase in temperature should lead to fixation of the remaining expandable layers and an incrase in crystallographic ordering. The proposed sequence (Figure 26.) of crystal polytypes (Hayes, 1970) is:

$$Ib_d \rightarrow Ib\ (\beta = 97°) \rightarrow Ib(\beta = 90°) \rightarrow IIb$$

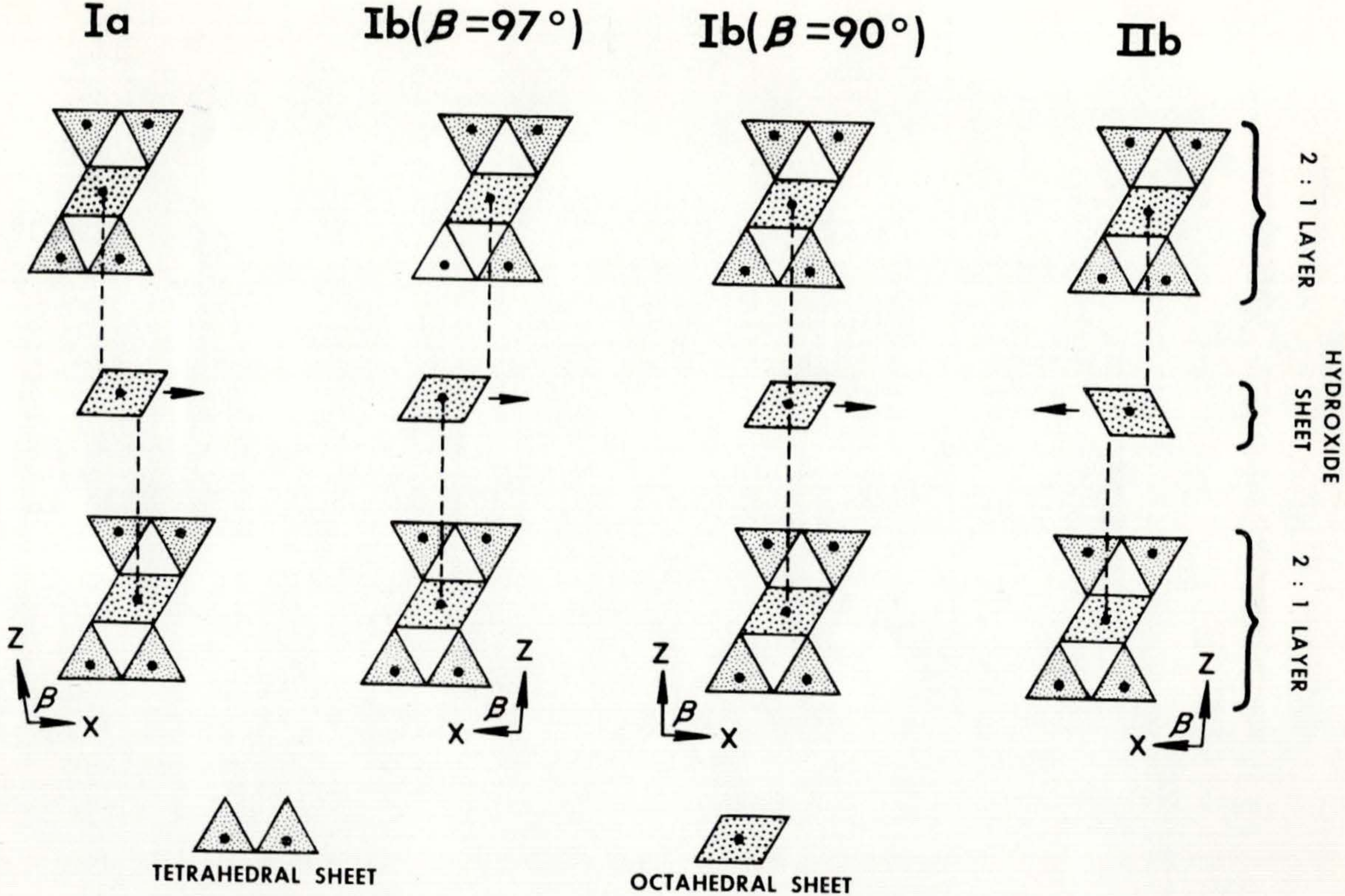


Figure 26. Schematic drawings of four chlorite polytypes in (010) projection (after Hayes, 1970, p. 286). The vertical dashed lines emphasize the differences in stacking sequence. Note the hydroxide sheet of IIβ is rotated 180° with respect to those of type-I structures.

Type Ib(β = 90) is the most stable of the type I polytypes and should persist until enough thermal energy is available to promote conversion to type IIb, the most stable of all polytypes. This conversion should occur in association with low grade metamorphism (260-390° F). Because the driving force for the transition from one chlorite polytype to another is thermal in nature, the polytype present in a sample should represent the highest temperature encountered by the sample. Due to technical difficulties we were unable to determine the chlorite polytype present in this well; however, Hayes (1970) reports Heald determined a chlorite polytype of Ib (β = 90°) for the Pocono Formation (Big Injun Member) in Clay County, West Virginia (temperature $<$ 260-390° F). Thus, the Berea could not have experienced less severe conditions (since it is located nearer the tectonically active Ridge & Valley Province) and has experienced temperature anywhere from less than to $\sim$260-390° F (if the IIb polytype is present).

The period of chamosite formation was succeeded by a period of illite growth and the formation of a second generation of quartz overgrowths and infillings. Illite occur as a secondary pore lining, growing within or on the earlier chlorite (Chamosite) grain coatings (Figures 18 and 21B). The change in mineralogy from chlorite to illite suggests that the formation waters had changed in chemical composition. Figure 17B clearly shows a euhedral quartz growth which has grown around a group of chamosite plates. These second generation quartz overgrowths were extensive enough to completely infill many pores (Figure 19A), and could be derived from tectonic stylolites (R. H. Groshong, Personal Communication). I believe that the second generation of quartz overgrowths was widespread and that hydrocarbon migration occurred prior to the overgrowths and heating up of the formation. Presently there is no data to deny or confirm this hypothesis.

During(?) and after the growth of these features there occurred a period during which the Berea was tectonically stressed and possibly heated (during the Alleghanian Orogeny) and buried to depths of~4,000 feet. Evidence for this includes undulatary extinction of both the detrital quartz grains and their overgrowths (ie., grain pressure solution) and stylolites formation, such as at 3869.7', (ie., rock tectonic-pressure solution). There are also deformed micas present in the Berea. Some sutured grain contacts occur in which there is a thin clay coating on the sutured surfaces. This indicates that the possible suturing occurred after the formation of the authigenic clay grain coatings.

The chlorite polytype indicates the Berea Sandstone has been affected by moderate to moderately high temperatures in the geologic past; however, the present bottom hole temperature at 4000 feet is only 100° F. A thermal Alteration Index of -4 was obtained from a study of pollen in a shale sample at 3872 feet indicating that temperatures between 220 and $\geq$ 310° F may have occurred. The maximum temperature depends upon the length of time the formation was heated. For 200 m.y. of heat exposure the maximum temperature is 220° F, for 100 m.y. a temperature of 210° F and for $<$100 m.y. temperatures $>$310° F were experienced (W. Meyers, personal communication). If all hydrocarbons had migrated into the Berea reservoir prior to this temperature increase, the Island Creek Coal C-7 area is within a thermal gas province (from Staplin, 1969 and W. Meyers, personal communication). Further data from adjacent areas is necessary to substantiate this.

These higher temperatures may have occurred as a result of burial to a maximum depth of approximately 4,000 feet if the paleo-geothermal gradient was higher in the area, or more likely by tectonic heating during the Alleghanian Orogeny (Pennsylvanian to Permian in age). This well is located near the structural front of the Valley and Ridge Province were significant tectonic activity occurred and, therefore, could have transmitted heat into adjacent portions of the Allegheny Plateau. No igneous intrusive or extrusive rocks occur within the area (Rodgers, 1970).

Further speculation includes the possibility that in addition to heat flow, silica and iron rich solutions (which were the source for the quartz overgrowths and chlorite diagenetic components and do not appear to have been derived in situ) may have also migrated from adjacent shale facies up dip away from the tectonically active Ridge and Valley Province or could have as a source the local stylolites. Since stylolites are common in the Berea (R. Larese, personal commuincation) they appear to be a more likely source if they occurred early in the diagenetic sequence.

The carbonate cements (calcite and siderite) formed as a final stage of diagenesis along with feldspar alteration. The siderite cement may result from the secondary replacement of calcite by the iron rich formation waters.

$$FeCO_3 \text{ (siderite)} + Ca^{++} \rightleftarrows CaCO_3 \text{ (calcite)} + Fe^{+2}$$

$$K = \frac{[Fe^{+2}]}{[Ca^{+2}]} = 0.05$$

For siderite to be stable relative to calcite the concentration of iron must be $>$ 1/20 that of calcium, which is substantiated by analysis of produced Berea Sandstone formation water (see Table 4).

TABLE 4

ANALYSIS OF PRODUCED WATER FROM BEREA SANDSTONE (MISS.)
CSO ISLAND CREEK C-5 MCDOWELL COUNTY, WEST VIRGINIA

	mg/l	me/l
Na^+	24,000	1043
Ca^{++}	7,240	362
Mg^{++}	1,590	133
Ba^{++}	0	0
K^+	1,190	31
Cl^-	63,000	1775
$SO_4^=$	0	0
$CO_3^=$	0	0
HCO_3^-	23	-
TOTAL IRON	1,620	
pH	4.5	

R. Fulford

CONCLUSIONS

1. The cored interval of the Berea Sandstone primarily represents nearshore (upper foreshore) marine deposits, as evidenced by the abundance of slightly inclined reverse graded parallel laminations. These structures are diagnostic of sediment deposition by the swash and backwash of the waves in the "beach" zone (Clifton, 1969).

2. The geometry of the Berea sand body should be linear, narrow in width, (depending upon possible progradation), long (parallel to depositional strike) and relatively thin.

3. The Berea Sandstone is classified as a feldspathic lithic arenite (see Table I), consisting of detrital components (75-80%), diagenetic components (15%), and pore spaces (5-10%). Reduction of porosity and permeability has occurred due to diagenetic alterations.

4. Diagenetic components consist of quartz overgrowths (first generation), chlorite (chamosite) and minor illite clay films, quartz overgrowths and in-fillings (second generation), and carbonate (including siderite) cementation (listed in their order of occurrence). Compaction possible pressure solution, grain suturing and formation of stylolites preceded the second generation of quartz overgrowths.

5. The Berea Sandstone has been: (a) heated to temperatures of between 200 and $\geq$ 310° F (as determined by its thermal alteration index of -4 and by the chlorite polytype) and (b) tectonically heated(?) and stressed (resulting in undulose extinction of quartz grains and overgrowths,

possible grain suturing, deformed mica grains and the formation of styolites). Maximum depth of burial of the Berea in the Island Creek Coal area of McDowell County, West Virginia, was approximately 4,000 feet (its present depth). The present bottom hole temperature is ~ 100° F.

6. Tectonic heat flow and influx of silica and Fe-rich solutions locally from stylolites or from adjacent shale facies during the Alleghanian Orogeny is a working hypotheses to explain the high thermal alteration index, the presence of thermal gas in this well and possibly within other portions of McDowell County and as a source for the diagenetic components . The study area is located in the Allegheny Plateau within 50 miles of the structural front of the Ridge and Valley Province which underwent intense structural deformation during the Alleghanian Orogeny (Pennsylvanian to Permian).

7. Implications of regional extent for McDowell County and the Appalachian Basin have been raised by this study. Tectonic heat flow and thermal maturation of hydrocarbons away from the Ridge and Valley Province into the adjacent Plateau appears possible. More data is required before the validity of this hypothesis can be checked.

8. Stimulation techniques determined by L. P. Brown which do not damage the Berea Formation (i.e., precipitation of ferrous ions) are included in Appendix B. In summary this includes perforating the formation, treating the preforations with acid and a chelating agent which are swabbed back to the surface, and fracturing the sandstone with synthetic or real formation water treated with an oxygen scavanger.

9. Local trends of increasing chlorite percentages with corresponding increases in porosity may be established for the Berea. Superimposed upon other geologic information (*i.e.*, depositional environment, structural setting, etc.) these trends may delineate perspective Berea drill sites.

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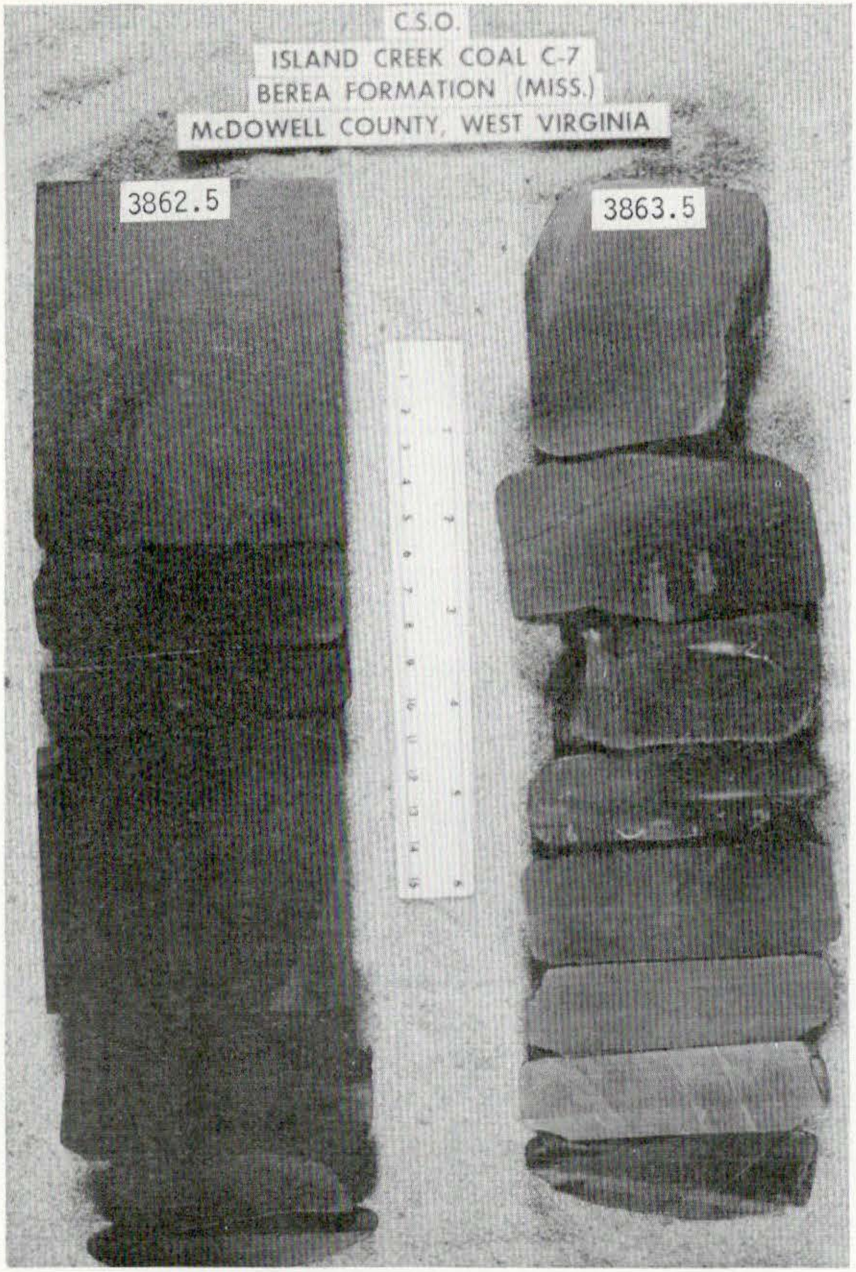
APPENDIX A

Core Photographs
(Core Depths are corrected to log footages)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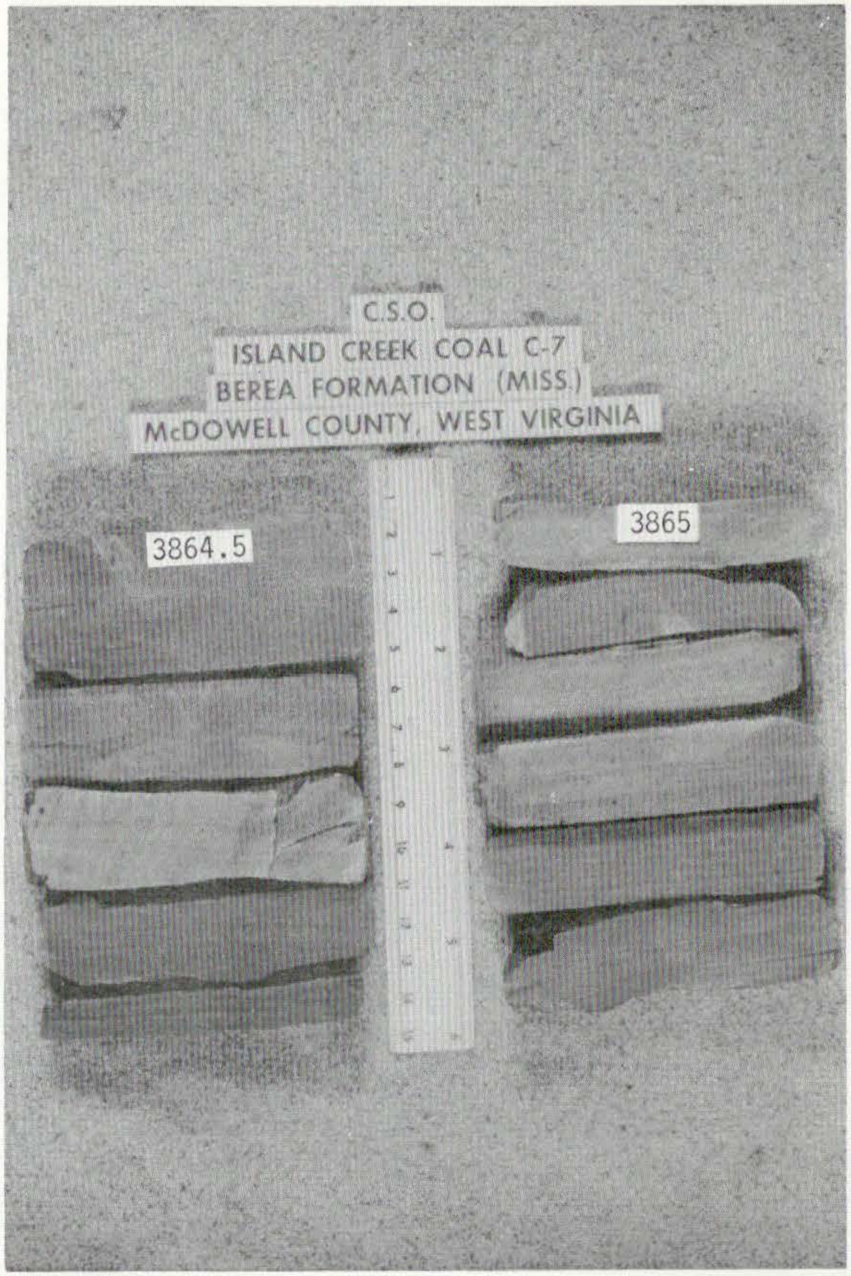
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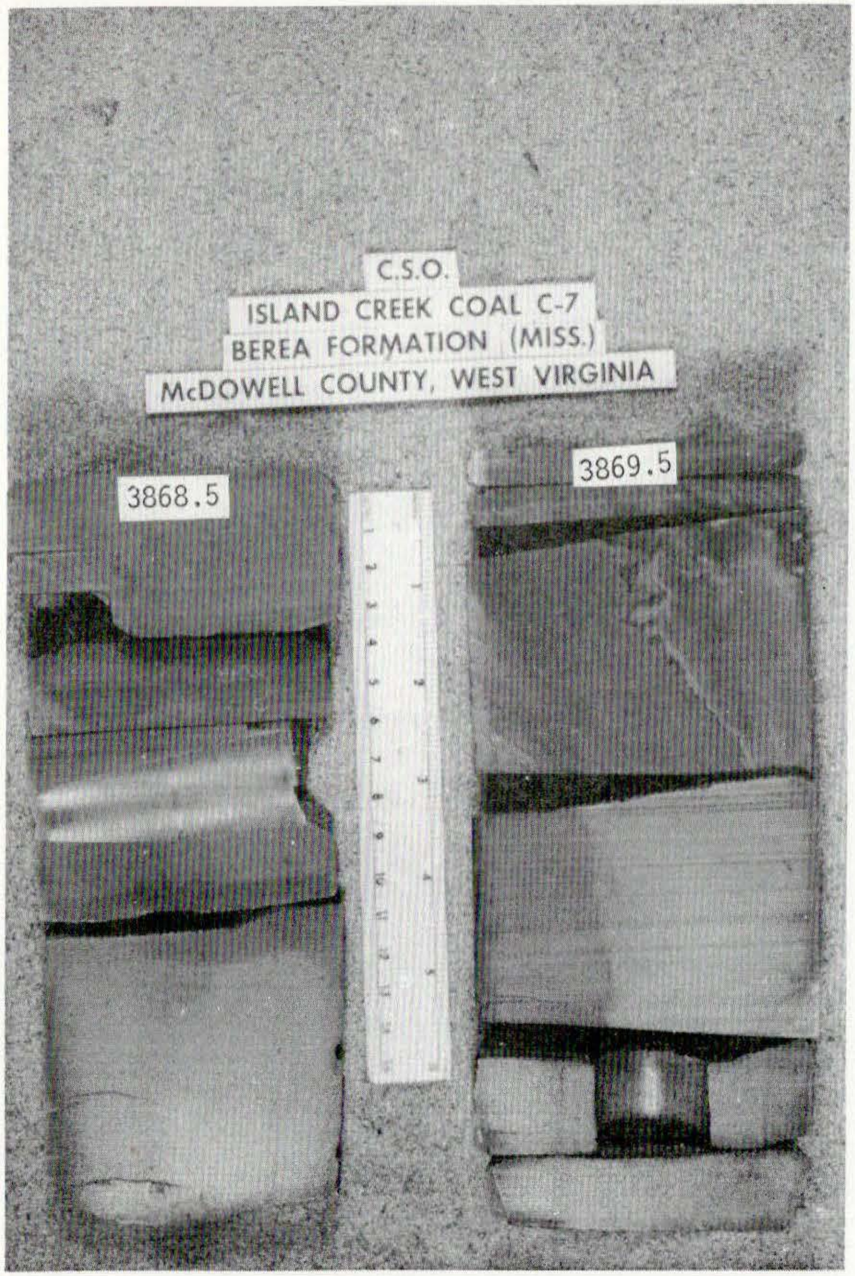
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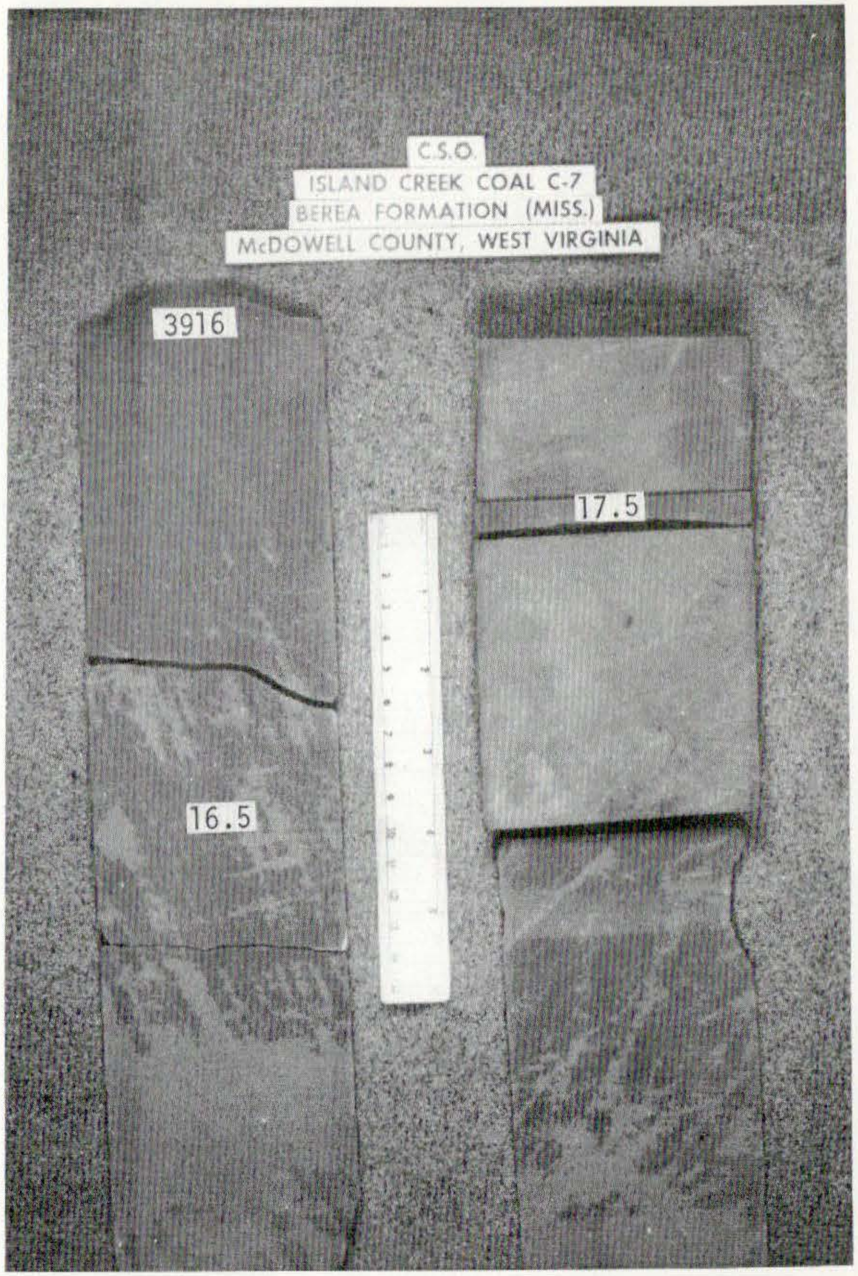
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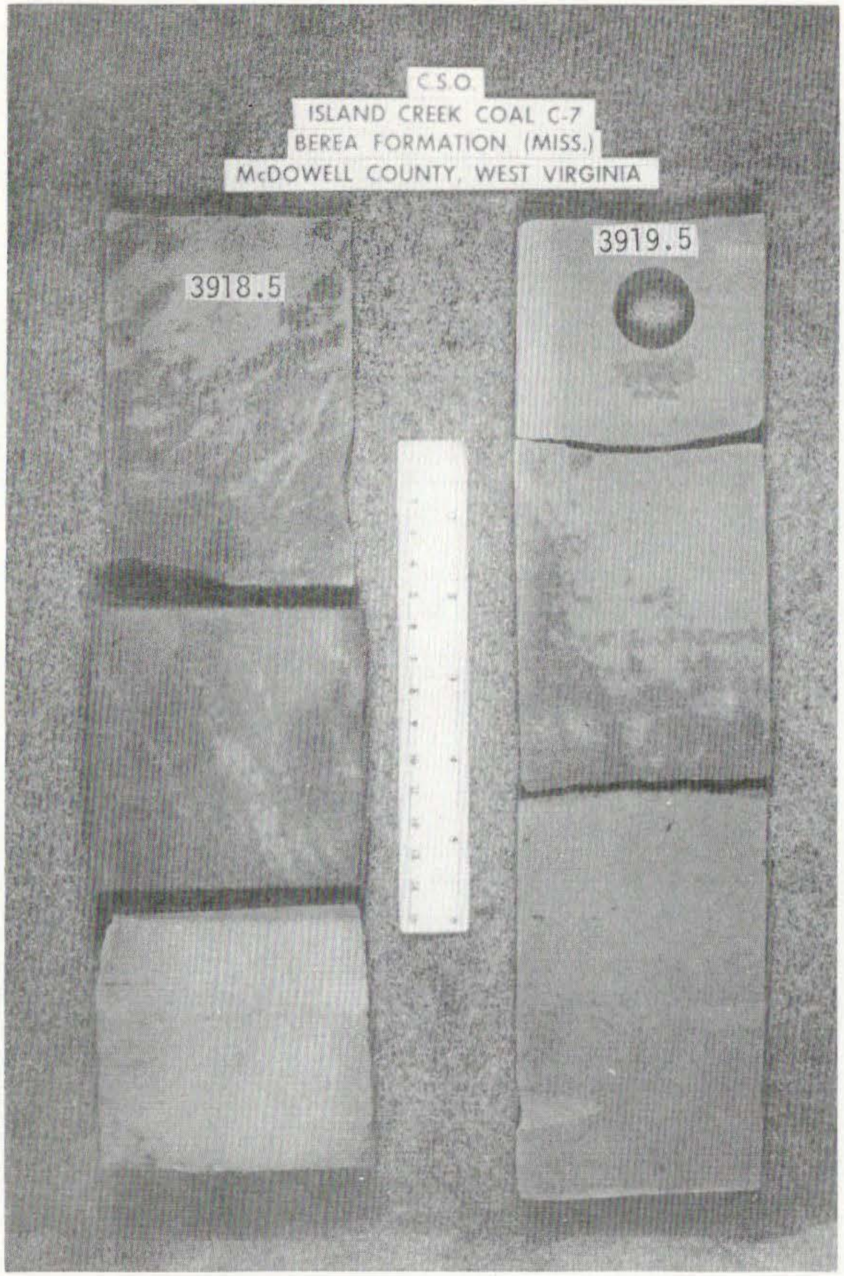
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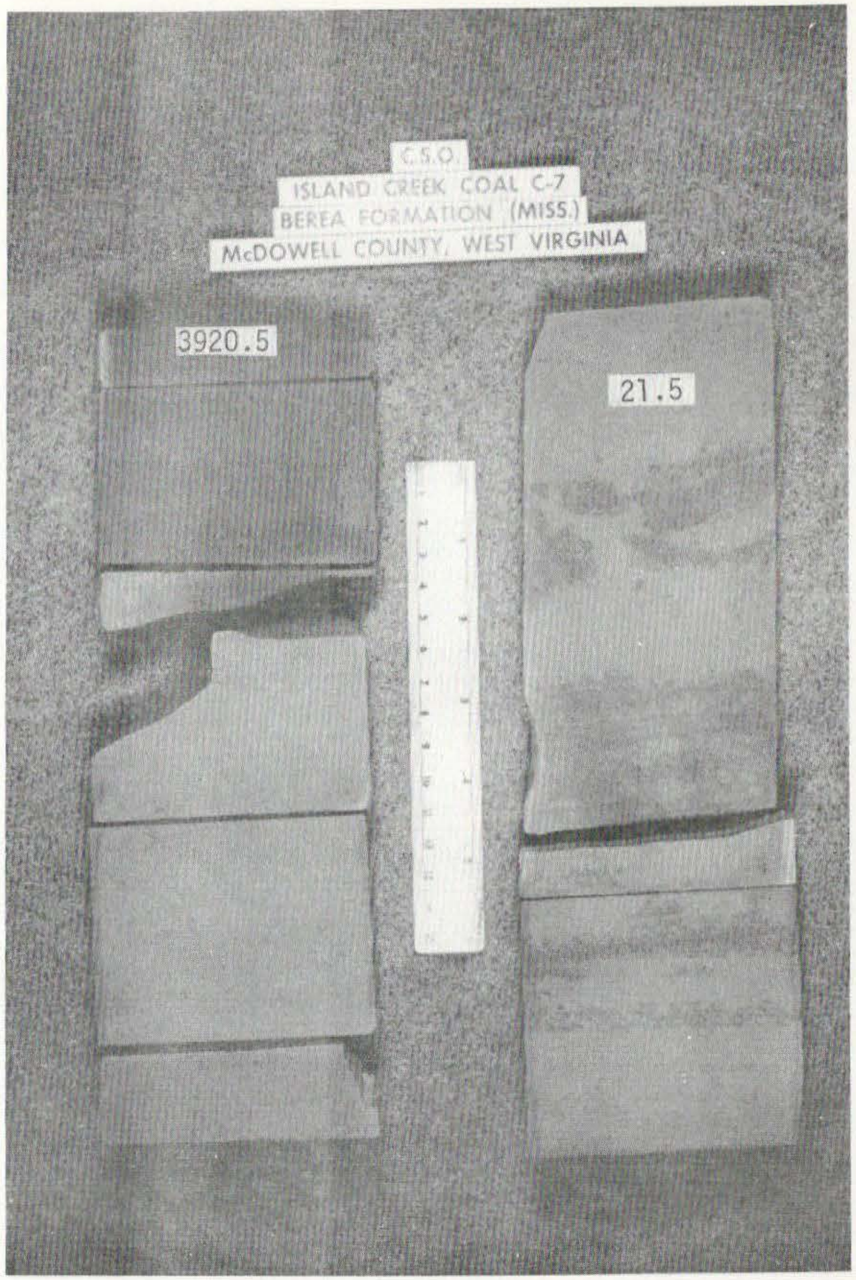
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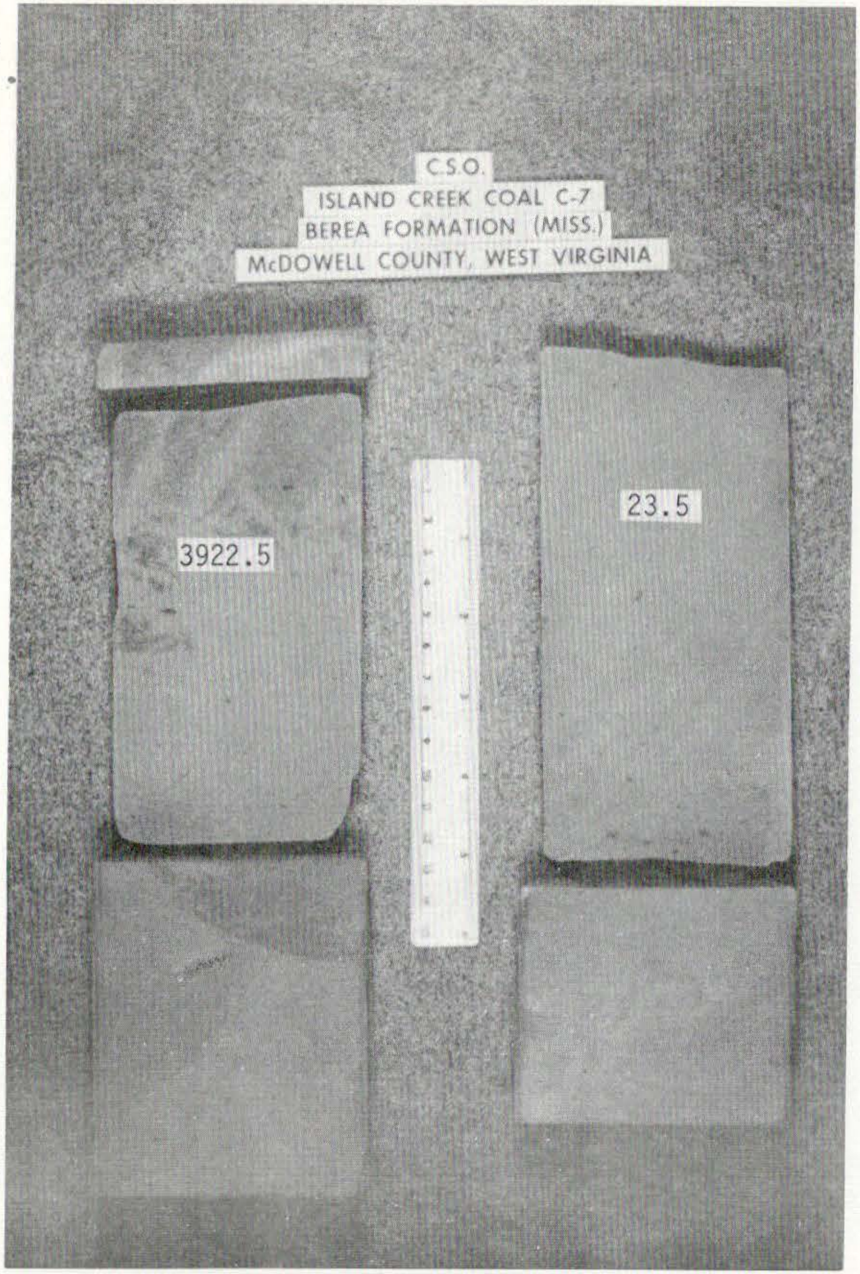
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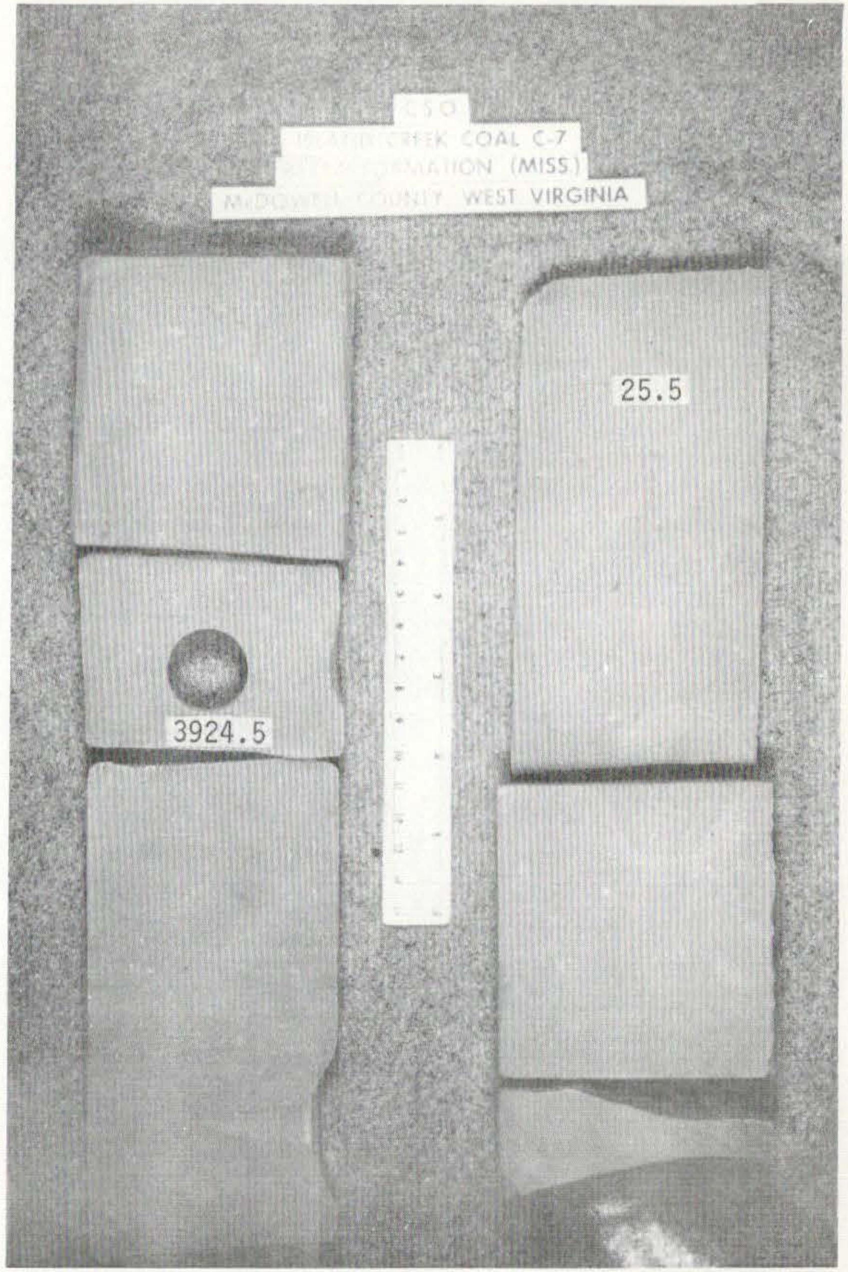
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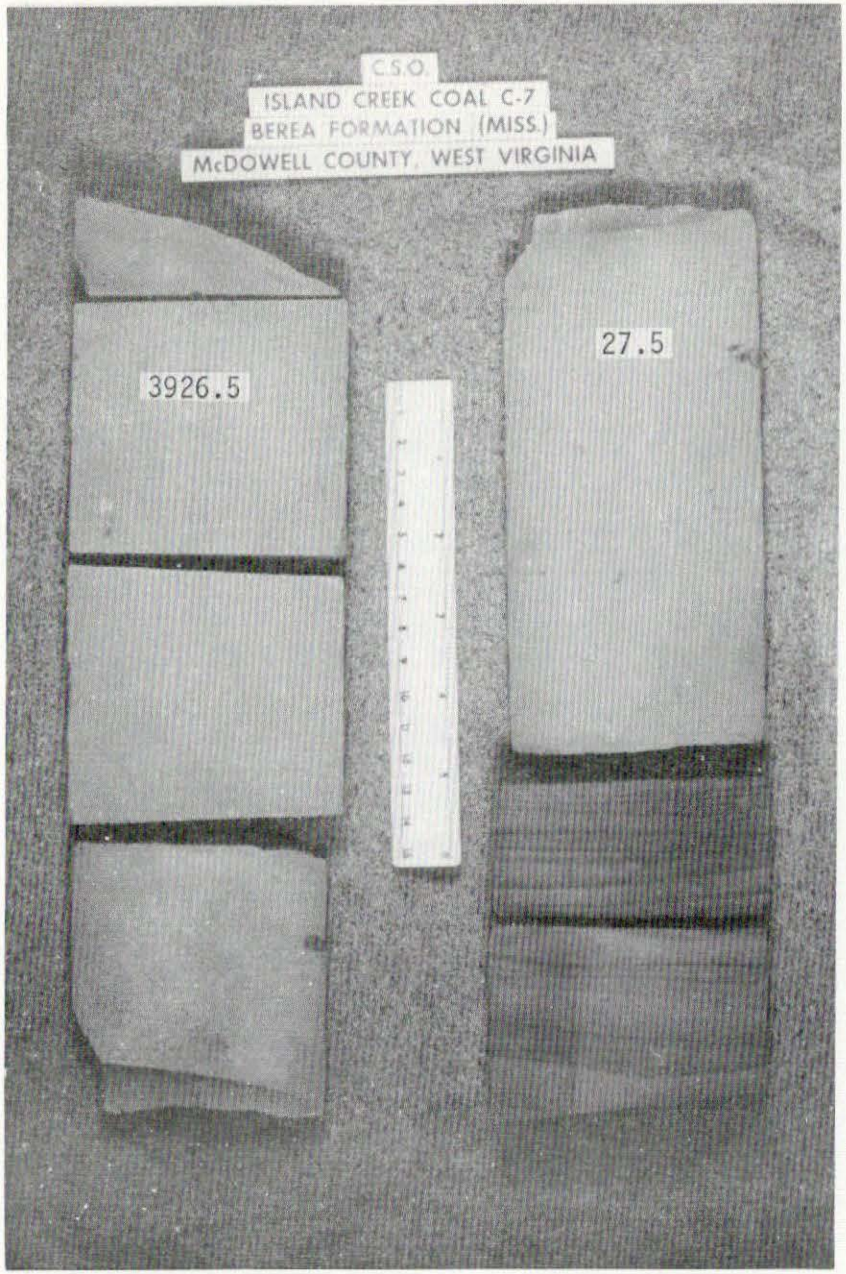
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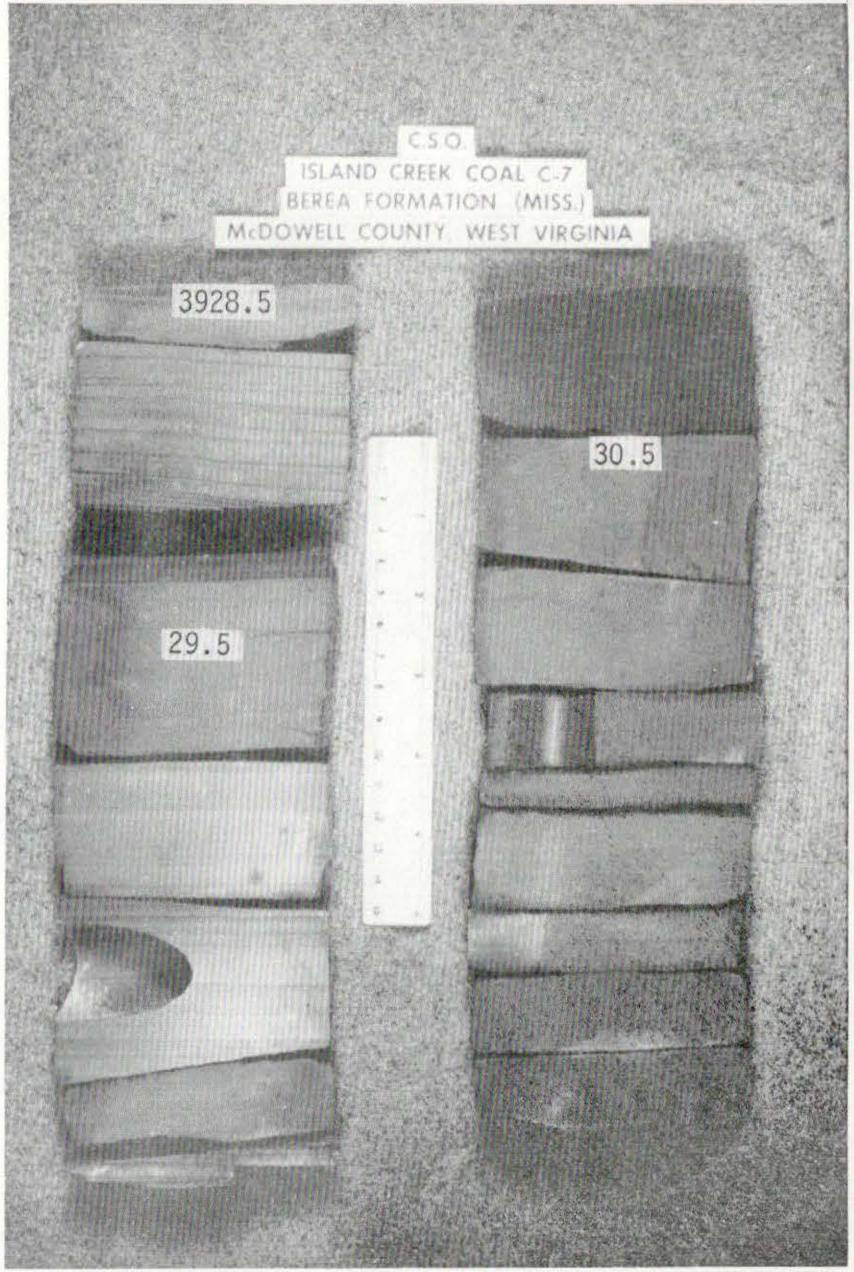
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BEREA FORMATION (MISS.)
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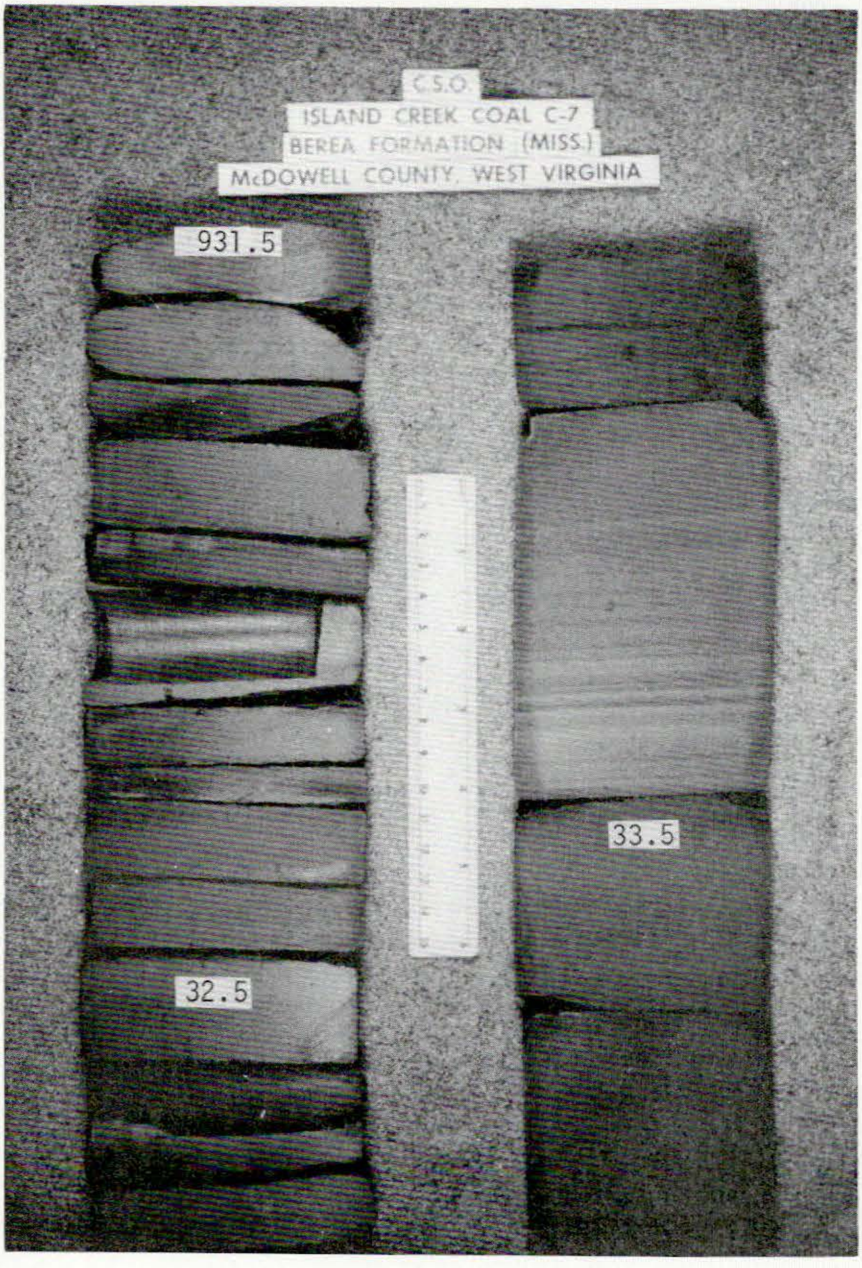
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ISLAND CREEK COAL C-7
BEREA FORMATION (MISS.)
McDOWELL COUNTY, WEST VIRGINIA
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APPENDIX B

Summary of Investigations on Berea Cores

by

L. P. Brown

INTER-OFFICE LETTER

TULSA LABORATORY

July 12, 1974

TO: Mr. Verlin Meier

FROM: Larry P. Brown

SUBJECT: Summary of Investigations on Berea Cores. Island Creek "C" #7 Well, McDowell Co., West Virginia

A program to determine optimum stimulation procedures for the tight Berea sandstone on the Island Creek Coal Co. "C" lease was conducted by the Tulsa E & P Research Laboratory and Dowell Laboratory in Tulsa. A description of the various tests and conclusions are given below.

CONCLUSIONS:

1. Fresh water can cause permeability damage in the sand.

2. A solution containing 2% KCI has been shown to be non-damaging.

3. Iron compound precipitation in the formation or in produced water appears to be caused by the interaction of the clay mineral chlorite, acid, and oxygen.

4. The sequence of events which causes iron compound precipitation in the formation is:
   (a) Acid releases ferrous ions into solution from clay minerals.
   (b) The ferrous ions are oxidized to ferric ions.
   (c) The ferric ions form ferric hydroxide, an insoluble precipate in solutions having a ph greater than three.

5. The treatment recommended by Dowell is intended to minimize the possibility of iron compound precipitation in the formation. The specific procedure to accomplish this is:
   (a) After the perforations are broken down by acid, the acid should be swabbed back to the surface.

This eliminates the possibility of release of ferrous ions far out in the formation by acid ahead of the fracture fluid. A chelating agent will be used in the acid to tie up any iron ions released in the vicinity of the wellbore to prevent any near-wellbore precipitation.

(b) The fracture water should be treated with an oxygen scavenger prior to mixing. This step keeps any oxidation from occuring in the formation.

(c) Dowell may recommend an enzyme breaker in the frac fluid. This breaker replaces the more generally used oxidizing breaker. Oxidizing breakers may cause the same type of problem solved in (b) above.

6. This investigation has been a learning experience for both Dowell and the E & P Research Lab. We feel that more study should be given to the complex chemistry of water, hydrocarbon, rock, and stimulation fluid interactions in the design of fracture treatments for specific wells and fields. In order to perform a good study, at least cuttings should be available for determination of composition, solubility tests, and fluid compatibility.

LABORATORY TESTS:

Tests and analyses performed by the E & P Lab and by Dowell are listed below:

1. X-ray diffraction - determination of rock composition
2. Thin sections - determination of rock composition
3. Dry core gas permeability
4. Gas permeability for various water saturations
5. Sensitivity to fresh water
6. Sensitivity to brine
7. Sensitivity to brine-base fracture fluids
8. Solubility to HCl and Mud Acid
9. Ionic analysis of "spent" acid
10. Iron leaching capabilities of acid and water on pure chlorite.

Additional tests are planned to analyze the iron content of the load water after the frac job, as well as ph and iron content of the returned acid.

In addition, pressure buildup data taken subsequent to clean-up will be analyzed for comparison with pressure buildup data taken prior to the frac treatment in order to evaluate the treatment.

Dowell's Laboratory report summarizes the results of this study. A copy of this report has been sent to your office. Dowell people in Charleston will use the Lab report to make a specific treatment recommendation.

If you have any questions concerning the report or this letter, please call me.

cc: Messrs. V. W. Rhoades
L. P. Davis
G. Kellerhals
G. Flesch

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