

STRATIGRAPHIC CROSS SECTIONS
EXTENDING FROM
DEVONIAN ANTRIM SHALE
TO
MISSISSIPPIAN SUNBURY SHALE
IN
THE MICHIGAN BASIN

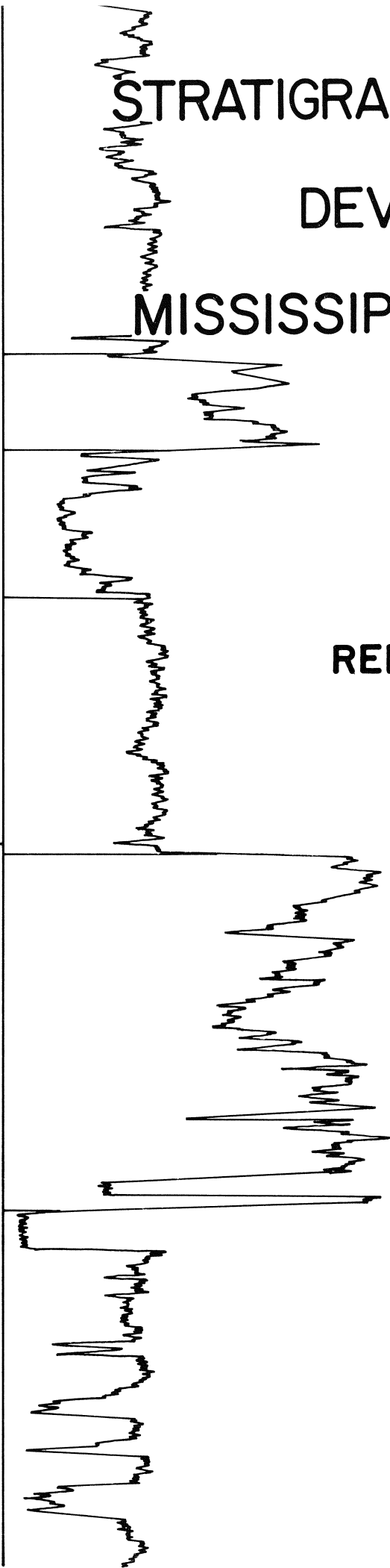
EARLY
MISSISSIPPIAN

REPORT OF INVESTIGATION 22

A TOPICAL REPORT

LATE
DEVONIAN

MIDDLE



MICHIGAN DEPARTMENT
OF
NATURAL RESOURCES

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Report of Investigation 22

STRATIGRAPHIC CROSS SECTIONS EXTENDING
FROM DEVONIAN ANTRIM SHALE TO
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MICHIGAN BASIN

Topical Report

By

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Lansing, Michigan
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PREFACE

This report was originally prepared for The Dow Chemical Company as a part of an oil shale research project of significance to Michigan and the nation. The project, conducted by The Dow Chemical Company under U.S. Department of Energy Contract No. EX-76-C-01-2346, is a program designed to test the feasibility of in situ processing of the Antrim Shale to produce energy values. The report covers one of numerous investigations conducted to help achieve the objectives of the oil shale research program. The Antrim Shale is a definite and useable source of natural gas at the present time, and a potential source of tremendous volumes of liquid hydrocarbons if they can be freed from their rock matrix. Report of Investigation 22 is intended as a useful aid to the understanding of the Antrim Shale to Sunbury Shale sequence as shown by gamma ray log characteristics of this rock interval in the Michigan Basin.

The stratigraphic cross sections which accompanied the original report have been reduced to half size for use in this publication. The vertical scale for the gamma ray log curves is % inch = 100 feet rather than 1 inch = 100 feet as indicated on the individual cross section parts.

Garland D. Ells

ABSTRACT

The Devonian shales of the eastern United States are a potential source for tremendous volumes of liquid and gaseous hydrocarbons. The Antrim Shale of Michigan is a part of this extensive body of rock. The bituminous and combustible nature of lower Antrim Shale beds have been known for over 100 years. In Michigan a program is underway to test the feasibility of in situ processing of Antrim Shale to produce energy values. To help achieve this objective, and as a part of the Shale Characterization Program, stratigraphic cross sections showing the Antrim Shale and associated formations have been constructed for various parts of the Michigan Basin. The cross sections are constructed from gamma ray logs.

The principal formations shown on the stratigraphic sections include the Antrim Shale of Devonian age, the Ellsworth Shale which correlates primarily with the Antrim Shale but whose uppermost part appears to correlate with parts of certain formations of Mississippian age, and the Bedford Shale, Berea Sandstone and Sunbury Shale of eastern Michigan. The Bedford Shale immediately overlies the Antrim in eastern Michigan. Except for the basal few feet of section which may be Devonian, the Bedford is considered as Mississippian in age. Formations superjacent to the Bedford (the Berea Sandstone and Sunbury Shale) are Mississippian in age. Regional cross sections constructed from gamma ray logs offer a more practical and more precise illustration of the stratigraphic associations of these Devonian and Mississippian formations in the Michigan Basin.

Data from gamma ray logs and records of 99 individual wells distributed throughout the Southern Peninsula of Michigan were used to construct six cross sections, Sixteen of the wells are used as common control points where the cross sections intersect. This produces a network of intersecting cross sections which illustrates depths, thicknesses, and the stratigraphic relationship of the subject formations in various sectors of the Basin, and provides a framework for other studies connected with the Shale Characterization Program.

Introduction

The Devonian shales of the eastern United States are a potential source for a tremendous volume of liquid and gaseous hydrocarbons. Upper Devonian shales of special significance are the Ohio Shale, New Albany, Chattanooga and others which can be correlated with the Antrim Shale of Michigan. The bituminous and combustible nature of lower Antrim Shale beds have been known for over 100 years. Antrim Shale gas has been produced in Michigan for many years, and analyses of potential oil content of Antrim shales were published more

than 60 years ago (Smith, 1912, pp. 258-59).

In Michigan a program is underway to test the feasibility of in situ processing of Antrim Shale to produce energy values. To achieve this objective the program consists of four tasks, two of which are principally field investigations and two of which are basic support studies. One of the support studies deals with shale characterization. An important element of this study is to provide stratigraphic cross sections of the Antrim Shale and its equivalent rocks in the Michigan Basin. Over part of the Basin, the black Antrim shales interfinger with a lithologically different shale. The upper part of this Antrim Shale equivalent is thought to be of Mississippian age. The sequence is further complicated in a part of the Basin by lithologically similar black shales of Mississippian age which immediately overlie black Antrim shales. The stratigraphic cross sections, based on gamma ray logs, thus cover several formations ranging in age from Upper Devonian to Lower Mississippian.

The stratigraphic interval encompassing the Devonian black shales includes several formations and extends from the base of the Antrim Shale upward to the top of the black Sunbury Shale considered to be of Mississippian age. The interval involves two depositional regions within the Michigan Basin. In the eastern part of the Basin, the Antrim Shale is overlain, in ascending order, by the Bedford Shale, Berea Sandstone and Sunbury Shale. Traced westward, the upper part of the eastern Antrim merges with the lithologically dissimilar Ellsworth Shale; the Bedford Shale and Berea Sandstone thin westward and merge as a thin unit into the upper part of the Ellsworth Shale. The Sunbury Shale also thins and is absent in some parts of western Michigan. The stratigraphic sequence of formations in the western part of the Basin have thus been defined, in ascending order, as Antrim Shale, Ellsworth Shale and, where recognized, Sunbury Shale. An oil-and-gas bearing interval in the upper part of the Ellsworth Shale has been referred to as "Berea" because it occupies a stratigraphic position similar to the Berea Sandstone of eastern Michigan.

A facies relationship between a part of the Antrim Shale of eastern Michigan and the Ellsworth Shale of western Michigan has long been recognized. In the central part of the Basin where separation of these formations is less certain, the problem is further complicated by similar black shales (Bedford and Sunbury) of Mississippian age which directly overlie black Antrim shales. Subsurface studies, based on well cuttings, have shown the general stratigraphic relationship between these several formations. The stratigraphic sequence of formations as recognized in well cuttings has been related to gamma ray log signatures. Regional cross sections based on gamma ray logs offer more precision in illustrating the stratigraphic relationships of the Devonian-Mississippian black shale formations in the Michigan Basin.

Michigan Basin

The Michigan Basin, as commonly described,

encompasses about 122,000 sq. mi. On the west it is bordered by the Wisconsin Arch and Wisconsin Dome in central Wisconsin, on the south by the Kankakee Arch in northern Indiana, on the east by the Findlay Arch in northwest Ohio and the Algonquin Arch in southern Ontario. On the north it abuts the Precambrian igneous and metamorphic regions of the Canadian Shield. The Basin thus includes the northeastern part of Illinois, part of northern Indiana and northwestern Ohio and a part of southern Ontario, Canada. A large part of the Basin is covered by Lakes Michigan, Huron, St. Clair, and by the western end of Lake Erie (Figure 1).

The Michigan Basin is commonly referred to as a structural basin. It is nearly circular in shape and contains rocks of Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian and Jurassic age. The bedrock, except for thin and isolated outcrops, is covered with Pleistocene glacial deposits up to a 1,000 feet thick in some regions. The deepest part of the Basin is projected to be west of Saginaw Bay in central Michigan. Basal Antrim beds are found at their greatest depth in the basin interior. From this region they rise outwardly toward the Basin margins where they subcrop beneath the glacial drift or the bottom sediments of Lakes Michigan, Huron and St. Clair. Basal beds of the Ellsworth and Antrim outcrop in a number of localities in the northern part of the Southern Peninsula. The overlying Bedford Shale, Berea Sandstone and Sunbury Shale of eastern Michigan are not exposed at the surface. The Bedford, Berea and Sunbury formations, once continuous with correlative rocks in the basins to the south, were eroded and removed from arch areas and are now cut off and isolated within the Michigan Basin. The Antrim, known as Kettle Point Shale in Ontario, extends across Ontario and beneath Lake Erie on into the Appalachian Basin (Sanford, 1969).

Purpose of the Investigation

The purpose of this investigation is to prepare regional and, where necessary, stratigraphic cross sections of the Michigan Basin as a part of the Shale Characteristics Program. The objective of the Shale Characteristics Program is to investigate the mechanism of oil shale failure under confined conditions, to determine the variables affecting the extraction of hydrocarbons from Antrim Shale and to better define those areas in Michigan which are suitable for the in situ processing of Antrim Shale.

The goal of the Shale Characteristics Program is to develop more thorough physical, geochemical, lithological and resource inventory data on the Michigan Basin Antrim Shale deposit in order to permit assessment of Michigan oil shale reserves in terms of energy values. Among the expected results of the program are structural and lithofacies maps of the Antrim including maps of the top, bottom and thickness of the oil shale formations, and an assessment of the chemical and physical properties of the Antrim Shale along with its base and cap rock. The cross

sections provide a regional framework, useful in the achievement of many of the aforementioned objectives.

The cross sections are essentially gamma ray log correlations. In preparing these cross sections, sample cuttings, core, and outcrop descriptions, combined with other existing data, were considered. The cross sections do not show lithologies other than as expressed by gamma ray log signatures associated with the formations. The stratigraphic interval covered in all cross sections includes all designated formations from the top of the Devonian Traverse Group immediately underlying the Antrim Shale upwards to the top of the Sunbury Shale of Mississippian age.

Discussion of Formations

The formations included in the cross sections range in age from Late Devonian to Early Mississippian. Some discussion of the lithologic characteristics of the formations are pertinent to a better understanding of the cross sections.

Traverse Group formations.

The Traverse Group includes rocks which are equivalent to the Hamilton Group of New York, but it also includes beds which are unquestionably Upper Devonian in age (Ehlers and Kesling, 1970, p. 31). The formations are, from base upward: Bell Shale, Rockport Quarry Limestone, Ferron Point Formation, Genshaw Formation, Newton Creek Limestone, Alpena Limestone, Four Mile Dam Formation, Norway Point Formation, Potter Farm Formation, Thunder Bay Limestone, and Squaw Bay Limestone (Figure 2). The formations are fossiliferous marine limestones and shales. In the vicinity of the type localities in Alpena and Presque Isle counties in the northern part of the Southern Peninsula, the group is about 490 feet thick.

The uppermost formation of the Traverse Group, the Squaw Bay Limestone, is overlain by the Antrim Shale. Described as a brown crystalline limestone about 10 feet thick and containing Upper Devonian cephalopods, it may represent the transition bed between the Traverse Group and the Antrim Shale, although the contact between the two formations is not exposed in outcrop. Most shales below the Squaw Bay formation are described as gray, dark gray or blue-gray in color. The relatively low gamma ray log response to these shales is in distinct contrast to the high gamma ray response of the black Antrim Shale. Because it is by no means certain that the Squaw Bay Limestone formation extends throughout the Michigan Basin, the term "Traverse Group" is applied to those beds extending below the Antrim Shale on the cross sections.

In oil field subsurface studies, the gray shales and gray and brown argillaceous limestones and dolomites that immediately underlie the highly radioactive basal black shales of the Antrim are referred to as "Traverse formation" and are assigned to the Traverse Group.

These beds have been described as containing rocks definitely not of the Traverse type, and were recognized as a "transition phase" between the Traverse Group and the Antrim (Hake and Maebius, 1938, p. 45). These investigators did not apply a formal name to the "transitional phase" beds, but did recognize the presence of Squaw Bay Limestone beneath them. The term "Traverse formation" was applied by Riggs (1938, p. 7) to the 50 to 80 feet of shale and shaly limestone below black Antrim shales in Allegan County. He referred to these beds as "Traverse formation" or so-called "Traverse shale" and assigned them to the Traverse Group. Bishop (1940, p. 2159) was of the opinion that the stringers of black shale occurring below the "transitional zone" were more closely related to the Antrim than the Traverse. Cohee (1951, Fig. 10) assigned the "Traverse formation" or "transition zone" beds to the Antrim Shale sequence.

In this report, the "Traverse formation" is assigned to the Traverse Group. For practical reasons, no consideration is given as to whether these beds are transitional between Traverse and Antrim or are, in part, equivalent to the Jordan River Formation or Squaw Bay Limestone.

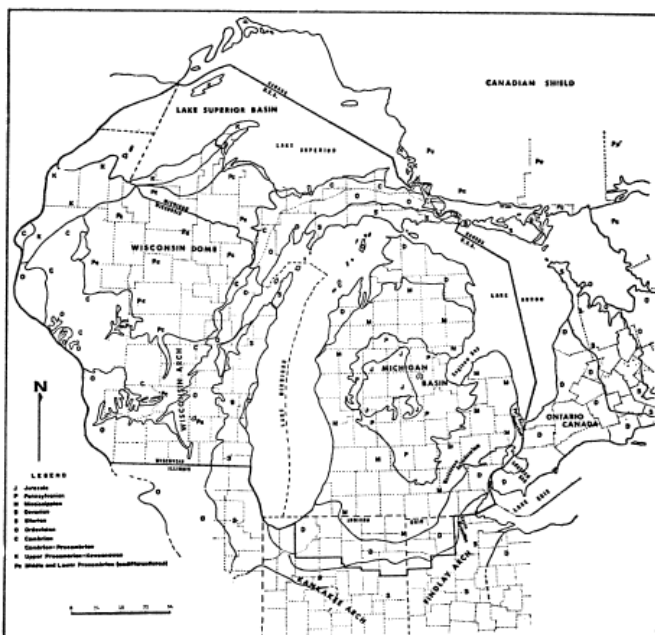


Figure 1. Index map of Michigan Basin and contiguous structural areas. The index map is reproduced by permission of the American Association of Petroleum Geologists and is taken from Memoir 15, Future Oil and Gas Possibilities of Michigan Basin.

In the Little Traverse Bay region of northwestern Michigan, outcrops of Traverse Group rocks have been given different stratigraphic names from those which crop out in the Alpena area. An interval of thin bedded limestone and shale immediately beneath black Antrim shales has been given the name Jordan River Formation (Kesling, R. V., et al, 1974, p. 114). The Jordan River Formation correlates approximately (though apparently younger) with the Squaw Bay of northeastern Michigan (Kesling, R. V., et al, 1974, p. 133). In ordinary oil field subsurface studies, both of these formations would be referred to as "Traverse formation" and probably considered as the transitional beds grading upward into the Antrim Shale.

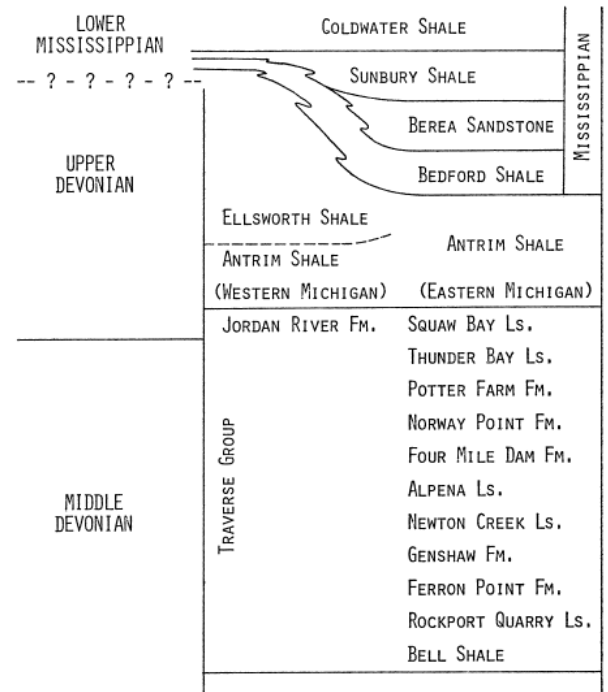


Figure 2. Chart showing the general relationship of western and eastern Upper Devonian and Lower Mississippian formations in Michigan. The Antrim Shale is considered Devonian. The Bedford shale of eastern Michigan is considered essentially Mississippian as are all the superjacent Berea Sandstone and Sunbury Shale. The Upper Devonian and Mississippian time boundary appears to be within the upper part of the Ellsworth Shale in western Michigan.

Antrim Shale.

Black, bituminous shales were recognized at Southern Peninsula localities by Douglass Houghton in 1838 and reported by C. C. Douglass as early as 1841. These shales were subsequently and successively assigned to rock sequences called Portage, Huron, Ohio Black Shales, and St. Clair Shales until 1901 (Martin, 1956). In 1901, A. C. Lane applied the term Antrim as a replacement for the term "St. Clair". Although no definite outcrop locality was indicated, the formation is exposed in the northwestern corner of Antrim County from which it was named, and in Emmet, Charlevoix, Cheboygan, and Alpena counties. In addition, reference was also made to the subsurface section of Antrim Shale in St. Clair County. The Antrim Shale was first discussed under its new name in a 1908 report (Lane, 1908, p. 73). In this discussion the Antrim was said to consist of "dominant shales, black and bituminous at the bottom, then blue sometimes, and at the top where it passes into the Berea Grit, or horizon thereof

red or interstratified with sandstone and gritty". This description, of course, is not in accord with modern views of Antrim lithology.

More modern references to the Antrim Shale derived from subsurface studies describe it as consisting of dark gray to black, hard, thin-bedded, brittle carbonaceous shale interbedded with some gray shale in the lower part. Dark brown bituminous limestone concretions ranging up to five feet in diameter are common near the base of the Antrim (Cohee, 1951).

The Lexicon of Geologic Names of the United States for 1936-1960 (Keroher, 1966) follows Cohee's 1951 description of the Antrim Shale. In addition, the Lexicon provides these statements: "In eastern Michigan, thickens northward from 130 feet in Washtenaw County to 500 feet in Montmorency County; in western (sic) Michigan, underlies Bedford Shale; in western Michigan, grades laterally into Ellsworth Shale. Upper Devonian and Lower Mississippian".

Attempts have been made by biostratigraphers to subdivide the Antrim according to outcrop observations. The basal beds have been referred to as Norwood Shales and the type locality is given as north of Norwood in Section 27, T.33N., R.9W., Charlevoix County (Martin and Straight, 1956, p. 227). The nomenclator for the Norwood Shale appears to be G. E. Ehlers, who first used the term in a 1938 guidebook. The term was applied to the Antrim overlying the Squaw Bay Limestone near Alpena in at least one cross section (in Kesling, R. V., Segall, R. T., and Sorensen, H. O., 1974, p. 116, 132). Historical data and commentary on Antrim outcrops is cited by Kesling and others who have also attempted to revive the term "Norwood Shale". In their 1974 publication they present a map (p. 122) showing black Norwood Shale underlying black Antrim Shale which in turn is overlain by the Ellsworth Shale. Gamma ray logs show the possibility of separating the Antrim Shale into beds or formations and the reranking of the Antrim as a group. At the present time the term "Norwood Shale" is not used in subsurface investigations.

In the northern part of the Southern Peninsula where Traverse Group rocks and Antrim Shale outcrop in numerous localities, the contact between the uppermost Traverse Group formation and the Antrim Shale is not exposed. Drill holes in the floor of the Paxton Quarry (Antrim Shale) in Alpena County offer little solution to the nature of the Squaw Bay-Antrim contact. The top of the Antrim has not been observed in outcrop, and the base has not been definitely determined in outcrop. Subsurface studies based on well cuttings show variable solutions to the separation of Traverse and Antrim rocks and those overlying the Antrim. There are upper Traverse shales which may be dark gray or black, and which may be classified as Antrim, but they do not have the same degree of gamma ray response as most Antrim type shales. Parts of the Bedford Shale are black and difficult to distinguish from the Antrim. On gamma ray logs these Bedford Shales in some areas frequently have the same magnitude of radioactivity as the underlying Antrim. The

increased use of gamma ray logs helped to better differentiate between Traverse, Antrim and overlying lithologies. Therefore the base and top of the Antrim Shale, for the purpose of this study, have been arbitrarily defined on the basis of gamma ray logs used in the several cross sections. The higher degree of radioactivity associated with most black shales classified as Antrim apparently has not been a criterion for helping to define the formation in outcrop, but it is a useful criterion in subsurface studies involving gamma ray logs.

Ellsworth Shale.

The Ellsworth Shale was first described and separated from the Antrim Shale by Newcombe (1932, p. 159) in his study of a test well drilled for oil at Muskegon, Michigan. The formation was later redefined to include an outcrop-quarry exposure as the type locality. The type locality for the Ellsworth was given as the NE 1/4 NE 1/4, Section 26, T.32N., R.8W., Banks Township, Antrim County. Also included in the redefinition was the subsurface section of another well drilled in Section 9, T.10N., R.16W., Muskegon Township, Muskegon County (Newcombe, 1933, pp. 49-51).

Earlier references to Antrim Shale exposures in the Charlevoix County area included green shales now assigned to the Ellsworth Shale formation. The Ellsworth is an apparent western facies of a part of the Antrim Shale as originally defined in the subsurface of eastern Michigan. Parts of the Ellsworth also relate to the Bedford Shale, Berea Sandstone and Sunbury Shale formations stratigraphically above the Antrim Shale of eastern Michigan.

The Lexicon of Geologic Names of the United States for 1936-1960 (Keroher, 1966, p. 1243), citing the work of Cohee (1951) provides this information: "Because upper part of Antrim shale is known to grade laterally westward into lower part of Ellsworth and upper part of Antrim shale is considered to be of lower Mississippian age (Weller and others, 1948, Geol. Soc. America Bull., v. 59, no. 2, chart 5), the Upper Devonian and Mississippian time boundary appears to be within Ellsworth shale in western Michigan and within Antrim in eastern Michigan."

In the subsurface the top of the newly defined Ellsworth Formation was placed at the base of the Coldwater Shale Formation, generally marked by a bed of red limestone traceable over a large area of western Michigan and now referred to as Coldwater Red Rock. The base of the Ellsworth Shale was drawn at the occurrence of the underlying brown or black Antrim Shale. The intervening rocks between the top and base of the Ellsworth were described as blue shale, light and dark gray shale, and greenish-gray shales. As more subsurface data accumulated, it became apparent that beds of limestone and dolomite, some of which were sandy and oolitic, were also common in parts of the Ellsworth extending over several counties in the western and southwestern part of the Basin.

Intertonguing of Ellsworth-Antrim Shales.

Inspection of Antrim Shale well cuttings and cores, taken in regions where Ellsworth Shale is not ordinarily considered a part of the stratigraphic sequence, reveals thin beds and partings of Ellsworth lithology interposed between typical Antrim lithology. On a larger scale, it is known that the Antrim of eastern Michigan merges westward into the greenish-gray Ellsworth Shales. The intertonguing and facies relationship of the Ellsworth-Antrim shales poses problems in correlation and determination of the thickness of the two formations.

Commenting on the Antrim, Newcombe (1933, p. 48) said: "The Antrim beds usually contrast rather sharply with the Traverse below, but in central Michigan they may alternate upward with gray and green shales which grade into either the Bedford or Ellsworth formations". On the same page he also states: "The thickness varies from less than 100 feet to over 450 feet in various parts of Michigan, with the beds thickest in the central area of the Basin and the north Saginaw Bay region. The maximum thickness may be exaggerated by incorrect correlation, as the physical appearance of the overlying Bedford may be very much like the Antrim. The problem of correlating the black shales in Michigan seems to be as perplexing as that which caused the famous Ohio controversy of overlap versus lateral gradation, which Prosser (94) very thoroughly summarized. The possibilities are essentially the same. There is meager subsurface evidence to show (sic) that the Antrim is overlapped (95) by the Bedford in the western part of the State, grades laterally (96) into the Bedford in the north central part of the State, and that the Berea-Bedford pinches out (97) between the Antrim and Sunbury in the south central part of the State."

Hale, in her studies, also recognized the intertonguing or alternation of green Ellsworth and brown Antrim shales. Because drillers found it difficult to pick a good top for the Antrim, the first brown shale coming in with the green shale was usually called "light Antrim" and the true black-to-brown shale was designated as "dark Antrim". The same practice is prevalent today among some drillers and geologists. Occasionally, the upper part of the Ellsworth Shale will be noted as "light Antrim" on some well records. Hale suggested that the alternating green and black Ellsworth-Antrim shales might be called "Eltrim" and that the green shale above be called true Ellsworth (Hale, 1941, p. 716). The term "Eltrim" has little practical application and has been seldom used.

In a study of the Antrim-Ellsworth-Coldwater shales, Tarbell (1941, p. 727) recognized that the Antrim thinned to the west and interfingered with the Ellsworth Shale. An east-west cross section from Bay County to Allegan County, Michigan, showed Antrim Shales merging into Coldwater-type shales which in turn merge into Ellsworth type shales. In this study the lithology of the cuttings were studied microscopically, strip logs were prepared and transferred to two diagrams, and strata were matched and joined in what appeared to be the most probable relationships (Tarbell, 1941, p. 724). The stratigraphic

interpretation, based on the arrangement of the strip logs, was that the great mass of gray shales, dominantly of Coldwater type, is entirely younger than the Antrim but the Ellsworth must be considered in part equivalent to the lower part of the Coldwater of the eastern counties, and in part equivalent to the upper part of the Antrim, also of the eastern counties. A large body of gray shale of "Coldwater type", in Kent County, was said to seem equivalent to the upper part of the Antrim and actually below some Ellsworth type beds, but equivalent to other parts of the Ellsworth (Tarbell, 1941, p. 733).

Another study (Cohee and others, 1951) showed the Antrim Shale of western Michigan to be from 150 to 300 feet thick. In western Michigan the upper part of the black Antrim Shale was said to grade laterally into the lower part of the greenish-gray Ellsworth Shale. Because of this intertonguing of greenish-gray and black shale, it was again confirmed that a boundary between the Antrim and Ellsworth was difficult to establish (Cohee and others, 1951). This study also suggested that along the western boundary of the State the Ellsworth Shale overlying the black Antrim was 400 to 600 feet thick, but toward the east it graded almost entirely into black shale along a north-south line running approximately through the center of the State (Cohee and others, 1951). Cohee's studies also indicated that in central Michigan the Ellsworth grades into the Sunbury Shale which rests directly on the Antrim.

It is evident from the preceding discussions that the general relationship between the Ellsworth and Antrim formations is established, either as an intertonguing, interfingering, lateral transition or facies relationship. On the eastern side of the Basin, Bedford Shale, Berea Sandstone and Sunbury Shale, respectively, lie above the Antrim. Traced to other parts of the Basin, the Bedford Shale appears to thin and merge into the Ellsworth. In other areas, portions of the Bedford are lithologically similar to the Antrim and lie directly upon it. The Berea Sandstone appears to pinch out entirely to the west. The Sunbury Shale also thins westward and pinches out over a large part of western Michigan. However, a black shale, not as radioactive as the Sunbury to the east, is found at the top of the Ellsworth Shale in areas of western Michigan. Thus the entire interval--from basal Antrim upward to the top of the Sunbury Shale--is stratigraphically related in a complicated way.

Bedford Shale.

The Bedford Shale and the overlying Berea Sandstone were first identified in Michigan in a well drilled in the Courthouse Square at Ann Arbor, Washtenaw County (Rominger, 1876, p. 92). Black bituminous shales, 28 feet thick, were logged above the Berea Sandstone, and reference made to their correspondence to the lower black portion of the Cuyahoga shales of Ohio. The Bedford is commonly described as a gray shale. In some areas of central and eastern Michigan, dark-gray to black shale beds may occur above the Antrim. Thin beds of Berea-type sandstone may occur within the Bedford Shale. The upper part of the Bedford may be silty and sandy and

grade upward into the Berea Sandstone. The sandstone of this gradational zone is commonly assigned to the Berea, and the gray shale to the Bedford (Cohee and others, 1951). Where essentially all shale, the Bedford may be as much as 200 feet thick.

The section of strata now called Ellsworth was formerly correlated with the Berea-Bedford of eastern Michigan. Newcombe (1933, p. 51, pp. 78-79) concluded that the beds were not exactly equivalent to these formations, and some of the strata were older than the Berea and Bedford of eastern Michigan. The Bedford Shale does not outcrop in Michigan but can be traced in subcrop beneath Pleistocene glacial drift on the east side of the Southern Peninsula. As noted by Cohee (1951) the Bedford Shale thins in a westerly direction and merges into the upper part of the Ellsworth.

Berea Sandstone.

The Berea Sandstone, identified in Michigan by Rominger (1876, p. 92), is characteristically a light gray, fine grained sandstone which in some areas may contain beds of gray shale similar to the underlying Bedford. The Berea Sandstone has never been observed at the surface in Michigan, but its sub-crop beneath Pleistocene glacial drift can be traced in wells in an uninterrupted arc around the east side of the Southern Peninsula. Studies of well cuttings suggest that the Berea can be divided into several lithologic units.

In a study of the Berea Sandstone in eastern Michigan, Cohee and Underwood (1944) distinguished three lithologic units. The three units supposedly can be related to geographic areas of eastern Michigan. The description of these units were later restated (Cohee and others, 1951). The lower unit was described as light gray sandstone, fine grained, dolomitic, silty and shaley, cemented with silica and dolomite, and micaceous and pyritic. The middle unit is friable, fine grained sandstone composed of angular quartz grains. According to Cohee (1951) thin beds of shale and tightly cemented sandstone are interbedded with the friable sandstone in places. The upper unit is lithologically similar to the lower unit but less shaley and pyritic. While the characteristics of the Berea interval are variable, Cohee's Berea units are rarely distinguished on drilling records.

It has been recognized for many years that the Berea, as a sandstone or siltstone, does not extend into the western part of the Southern Peninsula. Previous investigations have shown that the Berea, like the underlying Bedford Shale, thins in a westerly direction and pinches out or merges with a thin section of Bedford which in turn merges into the upper part of the Ellsworth Shale of western Michigan. In western Michigan the upper part of the Ellsworth contains dolomite and limestone beds which contain gas and oil. These strata, which may be sandy or silty in places, have been called Berea by some subsurface workers because it occupies approximately the same stratigraphic position as the Berea Sandstone of the eastern part of the State. It has been suggested that this

interval is possibly the time equivalent of the Berea Sandstone in eastern Michigan but was deposited in a sea receiving little clastic material (Cohee and Underwood, 1944).

Sunbury Shale.

Although black, bituminous shales were logged in the same well in which the Bedford and Berea formations were first identified (Rominger, 1876, p. 92) the name Sunbury was first applied to similar black shales found in a well drilled on the Campus of the University of Michigan, Ann Arbor, in 1900. The Sunbury Shale is thickest in eastern Michigan, exceeding 100 feet in some places in the vicinity of Saginaw Bay. It extends over most of the Southern Peninsula but thins westward from eastern Michigan. In some parts of western Michigan the Sunbury is absent, but in other parts of western Michigan it grades into gray and greenish-gray shales of the Ellsworth Shale.

Bedford Shale, Berea Sandstone and Sunbury Shale.

These formations are correlated with the Bedford, Berea and Sunbury formations of Ohio (Cohee and others, 1951) and the Appalachian Basin (DeWitt, 1970) on the basis of lithology and stratigraphy. The formations do not extend from the Michigan Basin into the Appalachian Basin, having been eroded from the Findlay Arch in northwestern Ohio and the Algonquin Arch of southwestern Ontario, Canada. According to DeWitt (1970, p. G10), the ages assigned to the Bedford Shale, Berea Sandstone, and Sunbury Shale of the Appalachian Basin can be projected into the Michigan Basin with confidence. In the absence of evidence to the contrary, much of the Bedford Shale, all the superjacent Berea Sandstone, and the Sunbury Shale of the Michigan Basin were stated to be of Early Mississippian age and make up the Kinderhook Series in the Michigan Basin. The basal few feet of the Bedford Shale in the vicinity of Cleveland, Cuyahoga County, Ohio, is apparently Devonian in age (DeWitt, 1970, p. G5). Whether the basal part of the Bedford Shale in the Michigan Basin is of Devonian or Mississippian age is a moot point according to DeWitt (1970, p. G10).

Coldwater Red Rock.

The youngest stratigraphic interval dealt with in the cross sections is the Coldwater Red Rock, considered to be the basal beds of the Coldwater Shale formation. Thin red shales and limestones near the base of what is now considered the Coldwater Shale have been recognized by drillers for many years. Well records published in 1912 (Smith, 1912, pp. 152, 154, 155, 157) note these red sediments, which were variously assigned to the Coldwater Shale and sometimes to the Berea horizon. In a well drilled at Charlotte, Eaton County, many years prior to 1912, the Berea "Horizon" was said to be represented by gritty red shales. It was further stated that the Berea formation existed as a sandstone only on the eastern side of the Basin, being generally represented by red shales in

the western half of the State (Smith, 1912, pp. 154-155). Thus in earlier years these red sediments were variously assigned, sometimes to the Coldwater, but generally to the then-called Berea horizon and Bedford Shale on the west side of the Basin. Rocks in western Michigan which were once assigned to the Bedford are, of course, now called Ellsworth.

Eventually these red shales and limestones became significant as marker-beds. In a 1928 paper, (Newcombe, 1928, p. 207) it was pointed out that the red shale which replaces part of the Berea in the southwestern part of the State may be used as a marker in a few limited localities, but the stability of its position is not certain. In the same paper, a red calcareous shale in the Coldwater formation was said to serve as an aid to delineate structural trend at Muskegon. In a later paper (Newcombe, 1932, p. 156) dealing with the Muskegon oil field, reference is made to a bed of red, shaley fossiliferous limestone in the lower part of the Coldwater which can be so "easily recognized that it is the most useful horizon marker in the field." The term Coldwater Red Rock probably stems from this reference.

The red limestone and shale bed, which overlies the Sunbury Shale or its equivalent, may be equivalent to the Rockford Limestone which overlies the New Albany Shale in northern Indiana and Illinois (Cohee and others, 1951). According to Lineback (1970, p. 35) the Rockford Limestone is not recognized in the Michigan Basin, but as the Jacobs Chapel Bed probably occupies a position above the Sunbury Shale, the Jacobs Chapel may correlate with the basal part of the Coldwater in northeastern Indiana. The Jacobs Chapel Bed may equate with the red rock horizon.

In parts of western Michigan the Coldwater Red Rock consists, in drillers terms, of two "streaks" which may cover an interval as much as 20 feet thick. In parts of the Basin, red sediments may not be recognized either due to depositional pinch out, lateral facies change, or erosion. A thin non-red facies of the red unit may occur immediately above the Sunbury Shale in the eastern part of the Basin. A reddish shale in the lower part of the Coldwater in some areas of this region but well above the Sunbury does not seem to be correlative with the Coldwater Red Rock as generally identified.

Oil and Gas Zones

Oil and gas "shows" have been logged in porous intervals found in parts of most stratigraphic units discussed and illustrated in this report. Commercial oil and gas production has been established in some of them.

Antrim-Ellsworth.

Because of the intertonguing or facies relationship between these two lithologically different shale formations, their oil and gas aspects are discussed under one heading. The Antrim Shale has long been known for its oil shale possibilities (Smith, 1912, p. 258-59) and for its

bituminous, and carbonaceous characteristics, distributed unevenly vertically and perhaps laterally throughout its areal extent. Liquid hydrocarbons have not been produced from the Antrim, and shows of oil have rarely been recorded from wells that have been drilled completely through the formation. In western Michigan where Ellsworth shales are interbedded with shales of the Antrim type, oil and gas shows have been found at several levels within the Ellsworth. It has been suggested that gas and possibly oil from the Antrim formation may have found its way from the Antrim into the overlying or contemporaneous rocks (Hake, 1938, p. 405). The record of an oil and gas test well drilled in Manistee County, western Michigan, in 1977, indicated shows of oil in the basal part of the Antrim, described elsewhere in this report as Unit 1 B.

Shows of gas are common in the black Antrim and in that part of the Ellsworth which is contemporaneous or interbedded with the Antrim. Most producing Antrim gas reservoirs are located in the lower part of the shale sequence, and most Ellsworth gas reservoirs have been found in dolomite beds in the uppermost 100 feet of the formation. Ellsworth oil pays are located in dolomite or limestone lentils found near the top of the formation. Other oil bearing zones occur at greater depths within the formation. The uppermost Ellsworth reservoir rocks of western Michigan have been called Berea by some subsurface geologists because they occupy approximately the same stratigraphic position as the Berea Sandstone of eastern Michigan.

Berea Sandstone.

The Berea Sandstone of eastern Michigan has produced oil and gas in commercial quantities from numerous fields since 1925. Pay zones are generally in the finer, less porous sandstones of the upper most beds. Saltwater is found in the more friable sandstones beneath. So-called "Berea" pay zones of western Michigan are in the Ellsworth Shale facies of the eastern Antrim Shale and Bedford Shale.

Coldwater Red Rock.

Although there is no evidence that the Coldwater Red Rock is a potential oil reservoir, or that oil has actually been produced from this interval, oil and gas shows have been found associated with this marker bed. In describing the geology of the Muskegon oil field, Newcombe (1932, p. 156) mentions that oil and gas are found in considerable quantities at this horizon in some parts of the producing area.

Scope of the Investigation

The stratigraphic interval important to the Shale Characterization Program extends from the top of the Traverse Group of Middle Devonian age and includes, in ascending order, the Antrim Shale, the Ellsworth Shale,

Bedford Shale, Berea Sandstone, Sunbury Shale, and the basal bed of the Coldwater Shale. The interval includes formations of Devonian and Mississippian age.

The scope of this investigation is essentially limited to the construction of stratigraphic cross sections covering the aforementioned formations, and the reporting of background data necessary to the understanding of the geologic interval and the cross sections. The cross sections have been generated from gamma ray logs but do not graphically show the lithologies other than as reflected by the gamma ray log signatures. By establishing a stratigraphic framework based on gamma ray logs, a better basis for detailed mapping and geologic analyses of black shales may result.

Previous Investigations

Many studies have been made and published on one or more of the stratigraphic divisions covered in this report. Some of the more pertinent information gleaned from these studies has been previously cited to provide historical perspective and contrasting views leading to the present understanding of these rock divisions. Numerous graphic cross sections have been published showing the stratigraphic relationship of these rock divisions covered in the Traverse Group to Sunbury Shale interval in the Michigan Basin. Nearly all the cross section presentations have been based on studies of well cuttings, descriptive well logs, or some combination of the two. Few of the cross section presentations utilize geophysical logs of the various types such as the gamma ray-neutron.

Graphic cross sections of the Bedford-Berea formations of eastern Michigan were published by Cohee and Underwood in 1944. These sections, based on well cuttings, showed the stratigraphic relationship and lithologies of the Bedford Shale and Berea Sandstone throughout their extent in the eastern part of the Basin. Additional and expanded studies were published by Cohee and others in 1951. The graphic cross sections presented in the 1951 study showed the stratigraphic relationship between the Antrim, Bedford, Berea, and Sunbury formations of eastern Michigan and the Antrim, Ellsworth, and Sunbury shales of western Michigan. These studies did not relate the stratigraphy and lithology to geophysical logs. Presumably the Cohee studies influenced the stratigraphic concepts now currently applied to the Antrim-Sunbury interval. About 16,000 new wells have been drilled in the Basin since the studies of Cohee, so a large amount of new data is available. The increased use of geophysical logs, particularly of gamma ray type, provided an additional means of correlation and delineation of formation boundaries. At least one later study involves gamma ray log correlations.

Lemone (1964, unpublished Ph.D. Thesis) in a comprehensive study of Upper Devonian and Lower Mississippian sediments in the Michigan Basin, confirmed by means of gamma ray log cross sections several previously noted stratigraphic associations reported by earlier investigators. By means of gamma ray logs, it was

possible to divide the eastern Antrim into an upper and lower unit. These log divisions were extended into western Michigan and related to the Antrim-Ellsworth shales of that region. The lower Antrim, as defined by Lemone, is said to be extended over the entire Basin. The upper unit is restricted to the area east of a narrow region which he called the "B" barrier (p. 76). Seven gamma ray log cross sections covering several parts of the Basin show correlations of the Antrim to Sunbury interval. According to Lemone (1964, p. 76) the Ellsworth Shale is equivalent to the upper Antrim-Bedford-Berea sequence in the southwest, to the upper Antrim-lower Berea-Bedford equivalent in west-central Michigan, and is older than the Berea but equivalent to the lower Bedford-upper Antrim in northwest Michigan.

In another study of Lower Mississippian sediments in the Michigan Basin, Asseez (1967, unpublished Ph.D. Thesis, p. 18) attempted to see if there was a significant correlation between color variation in the sediments and radioactive and electric log kicks. Color variation standards were based on the Rock Color Chart (National Research Council, 1948). As many as nine variations were determined for the Antrim Shale. After studying about 40 wells he was convinced that no such correlation exists. The logs were used, when available, to check contacts of two formations when the boundary was difficult to delimit on lithologic basis alone (Asseez, 1967, p. 18). Computer-derived well sections showing the vertical color variations within the individual well were formed into 10 graphic cross sections. Color variations were shown by an individual symbol which was keyed to a selected color standard. Correlation lines showed the stratigraphic relationship of the several formations and the lateral color variation from well to well. The age relation of the Berea-Bedford and the Ellsworth Shale was judged to be uncertain. According to Asseez (1967, pp. 78-79), their gradational contact with the Antrim showed that each is a lateral equivalent of some part of the Antrim Shale. Electric log cross sections were not presented in his 1967 thesis or 1969 published report.

Gamma ray-neutron log cross sections of the stratigraphic sequence in the Michigan Basin have been published (Michigan Basin Geological Society, 1969). The Antrim Shale-to-Coldwater Shale interval is generalized on these cross sections. The lithologies and stratigraphic relationships of the formations are discussed in an accompanying report.

A gamma ray log cross section has been published for Barry County, Michigan. This stratigraphic cross section is more definitive and shows the Antrim Shale-to-Coldwater Shale interval in greater detail (Lilienthal, 1974, p. 8, p. 12).

Use of Gamma Ray Logs in Stratigraphic Cross Sections

Gamma Ray-Neutron Logs.

Gamma ray-neutron logs, many of which are commercially available, have been used in Michigan for over 25 years. Because they can be run in fluid-filled or empty holes, open or cased, and are primarily lithology measuring logs, they are particularly useful in differentiating formations of varying lithologies. Gamma ray logs measure the natural radioactivity of the rocks. The gamma rays result from the decay of radioactive elements, primarily of radioactive potassium (K^{40}) and the radioactive elements of the uranium and thorium series (Schlumberger, 1972, p. 57). Different rock types emit gamma rays in proportion to the concentration of radioactive elements present in the rocks. Shales, which have high concentrations of potassium, are strong emitters of gamma rays; clean sandstones composed of quartz (SiO_2) and clean limestone composed mostly of calcite ($CaCO_3$) are ordinarily poor emitters of gamma rays (Kelley, 1969, p. 10).

Except for the Berea Sandstone of eastern Michigan, the formations involved in this investigation are essentially classified as shales. Thin limestone, dolomite, sandstone, and siltstone beds have been identified at various levels in well cuttings from some shale sections. Such thin beds may not be recognized in the gamma ray deflections of a typical shale section. A characteristic of the Devonian black Antrim Shale and the black, Mississippian age, Sunbury Shale is an exceptionally high gamma ray response relative to all other shale intervals found in the Paleozoic sequence in the Michigan Basin. The gamma ray deflections, or signatures, associated with the Antrim and Sunbury formations contrast with those of the intervening formations, the Bedford Shale and Berea Sandstone.

Orientation of cross sections.

The distribution and geographic orientation of the cross sections was selected to best show the variation in stratigraphic relationships and character of the Antrim Shale, Ellsworth Shale, Bedford Shale, Berea Sandstone, and Sunbury Shale in different sectors of the Michigan Basin. There are six cross sections involving portions of 99 gamma ray logs of individual wells. Sixteen of the gamma ray logs are used as common control points where cross sections intersect. The network of intersecting cross sections is shown in Figure 3.

When the name Antrim was proposed by A. C. Lane in 1901 for the black shale formation which was then called St. Clair, he also designated St. Clair County as a region which was underlain in the subsurface by Antrim Shale. First references to the Bedford Shale, Berea Sandstone, and Sunbury Shale in Michigan were made from wells drilled in the southeastern part of the State. Although the type localities for these three formations are not located in Michigan, they are considered, along with the Antrim Shale, as "type" formations of eastern Michigan. Correlations with their western Michigan counterparts or facies are in reference to the eastern "type" formation.

The most easterly cross section, Cross Section C (Figure 7), begins in the northeastern corner of Indiana, extends into Michigan in a northeasterly direction and then trends northerly along the eastern edge of the Southern Peninsula until it terminates in Alpena County. The northern terminus of this cross section is near the erosional edge of the Antrim Shale and about 12 miles west of the Paxton quarry where beds in the lower part of the Antrim are exposed. The geographic orientation of this cross section is arranged to show the characteristics of the "type" Antrim, Bedford, Berea, and Sunbury formations as reflected by their gamma ray log signatures on the eastern side of the Southern Peninsula.

The Ellsworth Shale, which overlies the black Antrim Shale, is best developed and more clearly defined on gamma ray logs of wells drilled in western Michigan. The most westerly cross section, Cross Section A (Figure 10), begins in the northeastern corner of Indiana and trends northwesterly into Michigan and then essentially north into



Figure 3. Index map showing network of Cross Sections A, B, C, D, E, and F. The orientation and trend of individual cross sections are shown on Figures 5, 6, 7, 8, 9, and 10.

In sedimentary formations, the gamma ray log normally reflects the shale content of the formation because the radioactive elements tend to concentrate in the clays and shales. Clean formations usually have a very low level of radioactivity, unless radioactive contaminants such as volcanic ash or granite wash are present, or when the formation waters contain dissolved potassium salts (Schlumberger, 1972, p. 57).

Antrim County. The northern terminus of this cross section is about three miles to the west of an Ellsworth outcrop-quarry section designated as the type locality for the Ellsworth Shale (Newcombe, 1933, pp. 49-51). The geographic orientation of this cross section is arranged to show a relatively rapid transition from Antrim-type shale into Ellsworth type as reflected by gamma ray log signatures, and to show the increase in thickness from the top of the Traverse Group to the top of the Sunbury Shale.

Cross Sections A and C illustrate the difference in the stratigraphic sequence from the top of the Traverse Group to the top of the Sunbury Shale in the western and eastern parts of the Basin. Cross Section E (Figure 9) and Cross Section D (Figure 8) are oriented mainly in a general south-to-north direction to show the changes that occur between the eastern and western parts of the Basin.

Cross Section B (Figure 5) and Cross Section F (Figure 6) trend in general northeast to southwest directions. They are oriented to show the merging of a part of the Antrim Shale into Ellsworth Shale, the westward thinning of the Bedford Shale, the pinch out of the Berea Sandstone, and the westward thinning of the Sunbury Shale.

Construction of cross sections.

Six stratigraphic cross sections were prepared to show the relationship and gamma ray log characteristics of the subject formations in the different parts of the Michigan Basin. The general format of the cross sections is designed to be illustrative and to best show, by gamma ray logs, the stratigraphy of the several formations. Therefore they differ somewhat from conventional stratigraphic cross sections. In order to make cross sections of manageable size, they have not been constructed in natural horizontal scale. Individual cross sections have been divided into parts, or segments, designed so that they can be used individually or joined together to form a continuous cross section.

The wells shown on the cross sections are more or less equally spaced. Approximate distances between wells are shown on the structure section immediately below the stratigraphic section. The distances between wells were determined by plotting each well location as close as possible on a sectionized, paper base map (DNR Map No. 03523, Scale 1:500,000). Straight-line measurements were then made between control points and then converted to approximate distances in miles. The structure section is intended to graphically show the relative difference in sea level datums of the various formations at the specific well location. Datums for the individual formations are found in the Appendix.

Gamma ray logs used in the cross sections have been marketed under several different logging company names. The logging methods and resulting logs are essentially the same. Data covering the various logs are found in the Appendix. With one exception, all gamma ray log curves were hand-traced on vellum tracing paper from the 2 inch = 100 feet scale. The single exception was photographically reduced from the detail log (5 inches =

100 feet) to the 2 inch = 100 feet scale, and then traced from the photograph onto the cross section draftings.

The gamma ray calibrations commonly used in Michigan most frequently result in the gamma ray curve going off scale adjacent to the Antrim and Sunbury shales. When the gamma ray deflection exceeds the 10 divisions to the right of the zero line on the standard API log heading, the deflection is again picked up on the left margin and continued. In a number of cases the entire gamma ray response to the Antrim Shale section is incomplete in that the maximum deflection has not been traced on the log. So that the character and shape of the gamma ray deflection will be more evident than shown on the original log, the curves have been traced to show the "offset" deflections as continuous segments. In those cases where the maximum deflection was not recorded on the original log, the gamma ray curve is open and does not extend beyond the API Unit scale shown at the top of the log tracing.

The top of the Traverse Group (or base of the Antrim Shale) is used as the reference plane for all six stratigraphic cross sections. The base of the Antrim Shale is arbitrarily defined by gamma ray logs and corresponds to the base of the lowest Antrim beds showing the greatest deflection to the right on the gamma ray curve. The lowest Antrim bed shown in the cross sections is labeled as Unit 1 C and in a few wells, Unit 1-A, B, C. On gamma ray logs this lowest unit consists of several gamma ray deflections. The top of the Traverse Group is given in the Appendix for each well used in the cross sections. All shale or shaley limestone intervals below the reference plane are assigned to the Traverse Group. Some of the shale beds at the top of the Traverse Group and immediately below the Antrim Shale are described as gray, brown, and black, but they do not have the same degree of gamma ray deflection.

All major lithologic units depicted on the cross sections are identified by their most widely recognized stratigraphic name. Unofficial subunits, devised solely for correlation of parts of gamma ray curves, are labeled and identified within the Antrim Shale and Bedford Shale and their correlative parts within the Ellsworth Shale. Not all subunits can be identified within the Ellsworth.

Correlations

Part of the data incorporated in this report and used in the cross sections are a continuation of investigations begun about a decade ago in an attempt to gain better insight into the stratigraphic relationship of the eastern Antrim, the Bedford, Berea, and Sunbury formations, and their corresponding intervals in different parts of the Basin.

An inspection of hundreds of gamma ray logs covering the Traverse Group to Sunbury Shale interval in eastern Michigan led to the conclusion that individual formation signatures could be further subdivided into units which apparently relate to the lithologic character of the specific interval and not to statistical fluctuations in gamma ray

count. In a given area of the Basin the characteristics of the gamma ray signatures and those of the smaller units are consistent but they gradually change from region to region. By dividing the larger signatures into smaller units, it is possible to trace individual formation beds for long distances and into other parts of the Basin.

In the original study, the Antrim Shale of eastern Michigan was divided into six units based on the relative amount of radioactivity as reflected by the gamma ray curve. The lowermost unit was designated as Unit 1 and later subdivided, in ascending order, into Unit 1 C, Unit 1 B, and Unit 1 A. The five additional Units, in ascending order, are: Unit 2, Unit 3, Unit 4, Unit 5, and Unit 6. The overlying Bedford Shale was subdivided into Unit 7 and Unit 8. The Berea Sandstone was labeled Unit 9. The designated units have no formal status as smaller divisions of the Antrim, Bedford, or Berea formations. They appear to be useful as aids in helping to decipher the regional stratigraphy of the Basin. Insofar as they are based on apparent relative amounts of natural radioactivity inherent in the rocks, in this sense they may be regarded as beds of the formally defined formations.

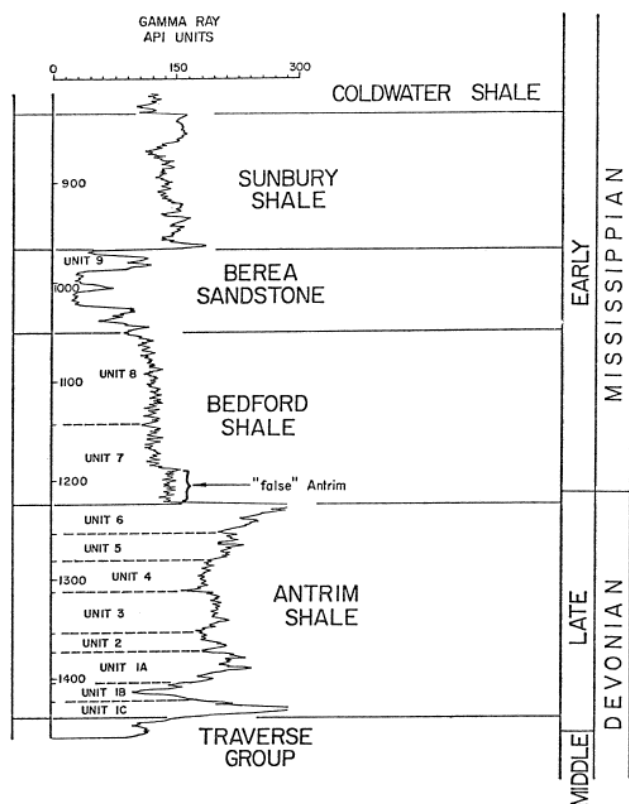


Figure 4. Portion of gamma ray log curve from The Dow Chemical Company No. 1 Rhoburn well, Sanilac County, Well C 12, Cross Section C (Part 3). The entire sequence shown above was cored. Depths to informal Antrim, Bedford and Berea Sandstone units are shown on the core description in Appendix H. Lower strata of the Bedford are sometimes dark gray in color and may be mistaken for the Antrim.

Because the Shale Characteristics Program includes subtasks such as geochemical, lithological, and physical

characterization of the Antrim Shale and presumably its Ellsworth Shale component, the informal Antrim units may be of stratigraphic value in these studies. Geochemical, lithological, physical, and paleontological data derived from Antrim or Antrim-Ellsworth cores can be related to gamma ray log signatures, and it may then be possible to further associate these data with the smaller Antrim units. For these reasons, and as a requirement of this investigation, the informal Antrim units have been included on the cross sections.

Correlation of these informal Antrim and Bedford units from well to well was made by visual inspection of the total gamma ray signature and noting the increase or decrease in deflections relative to the unit above or below, or by direct overlay and comparison of the gamma ray log. In those areas where certain units were less distinct, thickness measurements were applied to determine the upper or lower boundary of the unit in question.

For the purpose of this investigation the contact between rocks of the Traverse Group and rocks of the Antrim Shale is arbitrarily defined by their gamma ray characteristics. The contact between the Antrim Shale and the Ellsworth Shale is also based on abrupt differences in gamma ray characteristics in those parts of the Basin where the Ellsworth appears to be a distinctive formation. In certain parts of the Basin, the Bedford Shale has gamma ray characteristics similar to the Antrim. Because of this similarity, the shales would ordinarily be classified as Antrim. These investigations suggest that they should be assigned to the Bedford Shale and have thus been classified as Bedford.

The Antrim Shale of eastern Michigan, as commonly defined by its gamma ray signature, exhibits an overall high degree of gamma ray emission. The degree of deflection or increase to the right on the API scale varies, however, from the bottom to the top of the sequence. These changes in deflection are caused by the relative amount of natural radioactivity in the beds that make up the Antrim Shale sequence. Because of this variation the Antrim can be conveniently divided into divisions, or units.

The variation in gamma ray emission from the Antrim Shale is shown in Figure 4 by a partial gamma ray log section of a well drilled in Sanilac County in eastern Michigan. This well, the Rhoburn No. 1, was one of the early wells drilled by The Dow Chemical Company on their experimental test site in Sanilac County. The well was cored through the Sunbury Shale to Traverse Group interval. The detailed core description (see Appendix H) shows depths to formations, boundary depths between informal Antrim and Bedford units as determined by inspection of the gamma ray log, and the lithology as described from the cores.

The Antrim Shale sequence has been divided into six divisions. The lowermost division, Unit 1, has been further subdivided; the uppermost division is labeled Unit 6. Traced from well to well, certain of these gamma ray-based units maintain their general identity while others decrease or increase in radioactivity relative to the unit

above or below. In some areas, generally on the edge of the Basin, the uppermost units are not identified. They may be absent because of nondeposition or erosion, or because they have thinned and merged with other Antrim units and have been misidentified.

In viewing the six cross sections it is important to note that in many Antrim sections, Units 1 and 2 and Units 5 and 6 exhibit, in a general but readily apparent way, a higher magnitude of gamma ray deflection than the middle Units 3 and 4. This overall gamma ray curve configuration changes as the Antrim Shale of eastern Michigan is traced with gamma ray logs into western Michigan. Traced westward, it is seen that the upper part of the Antrim, Units 5 and 6, become less radioactive relative to Units 4, 3, 2 and 1. Finally, as the middle and upper parts of the Antrim pass into Ellsworth-type lithology, the only "Antrim-type" gamma ray deflection (or curve) is that of Units 1, 2, and 3. Unit 3 in western Michigan contains transitional beds between the black, highly radioactive Antrim and the overlying Ellsworth Shale. This transitional unit is sometimes called "light Antrim."

(Antrim-Ellsworth-Sunbury) traditionally appears to have been correlated with reference to the eastern Antrim, Bedford, Berea, and Sunbury intervals. To that extent, these eastern formations are considered as "type" or standard reference formations although no particular well has ever been designated as the "type" well. The wells used in the cross sections in the studies by Cohee and Underwood (1944) and Cohee and others (1951) might be considered, although these studies of well cuttings were not reconciled to electric or gamma ray logs. Extensive and comprehensive studies have been made of Antrim cores taken from wells drilled at The Dow Chemical Company experimental site in Sanilac County. A gamma ray log of the previously mentioned Rhoburn No. 1, a well drilled on this site, is included on one of the cross sections. Although the Rhoburn log has a characteristic gamma ray response for the Antrim through Sunbury interval for this part of Sanilac County, it is not considered the "type" or standard to which all other gamma ray logs used in the cross sections have been keyed. The east-to-west stratigraphic relationships are discussed, starting with Cross Section B and then Cross Section F. General north-to-south Cross Sections C, D, E, and A are discussed in that order.

Cross Section B.

Cross Section B consists of four parts. It shows appropriate portions of 21 gamma ray logs of wells drilled into or through the Traverse Group of rocks. The section begins in Sanilac County where "type" or characteristic Antrim, Bedford, Berea, and Sunbury formations occur. The section trends west through the central part of the Basin and then southwest to Cass County. The wells are distributed over a distance of approximately 300 miles (Figure 5). See Appendix B for individual well data.

Antrim Unit 1 has been subdivided into three divisions: Unit 1 C, Unit 1 B, and Unit 1 A. The lowermost division, Unit 1 C, is stratigraphically the oldest basal Antrim. Starting with well B 21, Sanilac County, the entire Antrim Unit 1 is about 80 feet thick and attains a thickness of over 100 feet in the central basin wells (wells B 16, B 15, B 14). From this region, Unit 1 and its subdivisions thin in a southwesterly direction and loose identity between wells B 4 and B 3 in Van Buren County, where Unit 1 is overlapped by Unit 2 which then becomes the oldest Antrim above the Traverse Group.

Antrim Unit 1 is characterized by its middle division, Unit 1 B. This subdivision is distinctive and has a different lithology than 1 C below and 1 A above. Generally described as a gray or greenish-gray dolomitic shale which may contain shaly carbonate beds, the magnitude of its gamma ray deflection is similar to that of shales in the Traverse Group, or the Ellsworth Shale and Bedford Shale. In some parts of the Basin, Unit 1 B may contain stringers of Antrim-type shale which have gamma ray deflections similar to the Antrim, Unit 1 B is variable in thickness and may be traced over many parts of the Michigan Basin. In those regions of the Basin where all three divisions of Unit 1 converge to form a thin section,



Figure 5. Orientation and trend of Cross Section B. Cross Section B consists of four parts or segments. Numbers 1, 2, 3, and B 21 indicate terminus of individual cross section segments.

General Discussion of Cross Sections

The stratigraphic relationship of the formations within the Antrim to Sunbury interval of eastern Michigan and the Antrim to Sunbury interval of western Michigan is not easily portrayed. No single straight-line cross section is ideal for showing the various stratigraphic situations within the Basin. In subsurface studies, the western interval

Unit 1 is labeled 1-A, B, C. A similar gray shale interval, near the base of the Antrim, has been figured by Cohee and others (1951, Fig. 10). Unit 1 B should not be confused with the "Traverse formation" of current usage.

Antrim Unit 2 in well B 21 is about 30 feet thick, thins in several wells and then gradually increases up to about 90 feet in thickness in the last few wells of Cross Section B. The gamma ray characteristics of Unit 2 gradually change in an east-to-west direction and finally overlaps Unit 1 at some point between wells B 4 and B 3. In wells B 8 through B 1 the Antrim Shale is arbitrarily designated as Unit 1 and Unit 2, the section above these units as Ellsworth Shale.

Antrim Units 3 and 4 in well B 21 have a combined thickness of about 60 feet and exhibit a lesser magnitude of radioactivity than Units 2 and 1 below, and Units 5 and 6 above. Unit 3 gradually increases in thickness, and maintains its relative radioactive characteristic as it passes into the lower part of the Ellsworth Shale in well B 8. In wells B 8 through B 1 in Cass County, it becomes the "light Antrim" or transitional beds between the Antrim and the overlying Ellsworth Shale. In well B 8, the combined thickness of Units 3 and 4 is about 170 feet, of which 150 feet is assigned to Unit 4. In wells B 7 through B 1, Unit 4 loses its Antrim-type radioactive characteristics and cannot be recognized within the Ellsworth Shale.

Antrim Units 5 and 6 in well B 21 have a combined thickness of about 60 feet, and a higher magnitude of radioactivity relative to the underlying Units 4 and 3. Both Units 5 and 6 gradually increase in thickness to about 130 feet in well B 15, Midland County, and then begin to decrease. The Antrim-type radioactive characteristics of Units 5 and 6 begin to diminish in well B 9 as these units pass into Ellsworth Shale lithology. In wells B 7 through B 1, Units 5 and 6 cannot be recognized.

The Bedford Shale above the Antrim has been separated into two divisions: Unit 7 and Unit 8. Locally, in areas of abundant well control, there is good correlation of these units from well to well. In other areas, correlation is less secure. The gamma ray signature of the entire Bedford interval is readily recognized where the formation is best developed. It is not so readily recognized in those areas where it and the overlying Berea Sandstone start to thin and merge together, because the Berea may have shale stringers and the Bedford may have Berea-type sandstone beds in the upper part.

In well B 21, Sanilac County, the Bedford Shale is about 220 feet thick, and shows an abrupt contact with the overlying Berea Sandstone. The next well (B 20), located about 18 miles west, shows an anomalous Bedford Shale section with regards to lithology and gamma ray log signature. The top of the Bedford was logged at a depth of 1,513 feet. The drilling records indicate that the first 47 feet of shale was recorded as dark brown to black, and carbonaceous. The gamma ray signature covering the 47 foot interval exceeds 300 API gamma ray units and is similar to the gamma ray response of the Antrim Shale. The next 194 feet of section down to the top of the Antrim

is described as fine-grained gray shale grading into fine-grained white sandstone with calcareous cement. The gamma ray signature of this interval appears to confirm the lithologic description. Because there is no evidence to the contrary, such as a faulty or miscalibrated gamma ray log, it is assumed that the drilling record (see Appendix I) and log are valid.

In wells B 19 and B 18, the gamma ray signature of the Bedford Shale is similar to well B 21, but the section in both wells has thinned to 180 feet and 190 feet, respectively. From well B 18 westward, both units of the Bedford thin and appear to increase in sand or silt content. In well B 12, Montcalm County, Unit 8 is absent and Unit 7 has thinned to about 10 feet in thickness and appears to be entirely shale. In this well the Berea Sandstone is absent and Unit 7 of the Bedford Shale lies between the Sunbury and Antrim shales. From well B 12 the Bedford again thickens and merges laterally into the upper part of the Ellsworth Shale in wells B 9 and B 8. The thickness of the Bedford Shale equivalent, projected from well B 9 to well B 8, amounts to about 100 feet. In the remaining wells, B 7 through B 1, the Bedford Shale equivalent cannot be recognized as a distinctive gamma ray signature.

The Berea Sandstone, Unit 9, contains shale beds similar to those in the underlying Bedford Shale. Gamma ray logs of wells drilled in eastern Michigan generally show one or more beds of shale in an otherwise sand section. In well B 21, Sanilac County, most of the shale is concentrated in the upper part of the Berea. In well B 20, located 18 miles to the west, most of the shale is concentrated in the lower part and represents an anomalous section as does the Bedford Shale below. According to the drilling record for this well, the lower 63 feet of the Berea Sandstone is described as containing sandstone; some light gray and green shale; and gray, arenaceous and micaceous siltstone. The gamma ray signature of this interval appears to substantiate the description. From well B 21 through well B 13 the Berea gradually thins and becomes more silty and shaley, and finally pinches out between wells B 13 and B 12.

The Sunbury Shale which overlies the Berea Sandstone in eastern Michigan is about 125 feet thick in well B 21, Sanilac County. It is readily recognized on gamma ray logs by its high level of gamma ray emission, except in those areas where it is associated with the Ellsworth Shale. Where the Sunbury is comparatively thick, the overall gamma ray configuration is similar to that of the Antrim Shale; that is—the middle part of the signature exhibits less radioactivity than the lower and upper parts. This "two-prong" configuration persists in Sunbury sections that are as thin as 15 feet. On Cross Section B the Sunbury decreases in thickness from 125 feet in well B 21 to about 10 feet in well B 9, Barry County. In the next well (B 8) 9 miles to the southwest, the Sunbury Shale is absent. In this well the formation beneath the Coldwater Red Rock is classified as Bedford Shale equivalent and is included as a part of the Ellsworth Shale. However, in the next well (B 7) a very thin section of

Sunbury Shale appears to be present between the Coldwater Red Rock and the underlying Ellsworth Shale. In wells B 6 through B 1, the Sunbury Shale cannot be identified on gamma ray logs.

The Coldwater Red Rock is a distinctive marker-bed at the base of the Coldwater Shale formation and above the Ellsworth Shale in western Michigan. Its gamma ray log characteristic on the east side of the Basin (well B 21) is a thin gamma ray deflection to the left and immediately above the Sunbury Shale. In this part of the Basin there is no red sediment associated with this thin interval which is about 3-4 feet thick. Traced westward above the Sunbury Shale the interval persists, eventually thickens to as much as 15 feet, and is associated with red sediments where it directly overlies the Ellsworth Shale in wells B 8 through B 1.



Figure 6. Orientation and trend of Cross Section F. Cross Section F consists of two parts or segments. Numbers 1 and F 1 indicate terminus of individual cross section segments.

Cross Section F.

Cross Section F consists of two parts. It shows appropriate portions of 10 gamma ray logs of wells drilled into or through the Traverse Group of rocks. The section begins in Alcona County where "type" or characteristic Antrim, Bedford, Berea, and Sunbury formations occur, and trends southwest into Muskegon County in Western Michigan where "type" Ellsworth Shale occurs in the subsurface. Eight of the ten wells used in this section also occur in cross sections oriented in general south to north directions. The wells are distributed over a distance of approximately 187 miles (Figure 6). See Appendix F for individual well data.

The overall gamma ray signatures of the Antrim Shale shown on Cross Section F are similar to most of those in Cross Section B. Antrim Units 1 and 2 and 5 and 6 have a higher magnitude of gamma ray deflection than middle Units 3 and 4.

The Antrim Shale is about 300 feet thick in well F 10, Alcona County, and gradually increases to about 585 feet in well F 5, Osceola County. Well F 5 is located in an area of the Basin where difficulty is encountered in differentiating Antrim Shale from overlying Sunbury Shale in well cuttings (Cohee and others, 1951, Figs. 2 and 3). In well F 5 the top of the Antrim is placed at the top of Unit 6. Well F 5 is located in a part of the Basin where transition between Antrim and Ellsworth lithology occurs, thus the middle Antrim units have gamma ray characteristics similar to the Ellsworth.

Antrim Unit 1 in well F 10 has been subdivided into three divisions: Unit 1 C, Unit 1 B, and Unit 1 A. The lowermost division, Unit 1 C (or Unit 1-A, B, C) is stratigraphically the oldest basal Antrim shown in Cross Section F. Starting with well F 103 Alcona County, the entire Antrim Unit 1 is about 90 feet thick and gradually attains a thickness of about 150 feet in well F 7 located approximately 83 miles to the southwest in Clare County. All three subdivisions of Unit 1 increase in thickness; the greater increase occurring in Unit 1 B which thickens from 25 feet in well F 10 to 65 feet in well F 7. From well F 7, Unit 1 gradually thins to 40 feet in thickness in well F 1 in Muskegon County. Unit 1 B decreases in thickness to about 25 feet in well F 4 and, though probably present as a lithological unit similar to the Antrim, it cannot be confidently identified in the remaining wells of the cross section. In those wells where Unit 1 B cannot be recognized, Unit 1 is labeled Unit 1-A, B, C.

Antrim Unit 2 is about 20 feet thick in well F 10 and increases to about 90 feet in well F 1 in Muskegon County. The gamma ray characteristics of this unit stays fairly consistent to well F 4 where it begins to change and reaches a thickness of about 45 feet. In this well it is overlain by the transitional Antrim beds (Unit 3) which grade upward into Ellsworth Shale. In the areas where characteristic Antrim is overlain by Ellsworth Shale, the top of the Antrim Shale is placed at the top of Unit 2. However, in wells F 4 and F 3 the top of the Antrim Shale is placed about 10 feet higher so as to be in better agreement with wells F 2 and F 1.

Antrim Units 3 and 4 have a combined thickness of about 80 feet in well F 10. Southwestward they increase to about 330 feet in thickness in well F 5. The greatest increase is found in Unit 4 which amounts to 260 feet in well F 5. At the start of the cross section in wells F 10 and F 9, Units 3 and 4 are less radioactive than the two units below and above. As these middle units are traced through following wells, the lower part of Unit 5 becomes less radioactive. Unit 3 gradually changes as it merges with the lower part of the Ellsworth Shale in wells F 4 through F 1. In these wells this unit is regarded as transitional between the Antrim Shale and the overlying Ellsworth Shale.

Antrim Units 5 and 6 have a combined thickness of about 105 feet in well F 10 and about 115 feet in well F 5. Unit 6 has a higher magnitude of radioactivity than Unit 5 which tends to become less radioactive from well to well. In well F 4, Antrim Units 4, 5, and 6 cannot be detected in the Ellsworth Shale section. However, the thin gamma ray deflection in the Ellsworth Shale beneath the base of Unit 7 in well F 4 is considered to be correlative with a part of the maximum gamma ray deflection in Unit 6, well F 5. In well F 5 through F 1, Antrim Units 4, 5, and 6 merge into the Ellsworth Shale and cannot be recognized by gamma ray characteristics.

The Bedford Shale above the Antrim has been separated into two divisions: Unit 7 and Unit 8. The combined thickness of the units amounts to about 125 feet in well F 10. Unit 8 appears to be more sandy or silty and grades downward into Unit 7. In well F 8 in Ogemaw County, the approximate lower half of Unit 7 is a black shale with radioactive characteristics similar to the Antrim. The radioactive lower half of Bedford Unit 7 thins in well F 7 and the upper part becomes more radioactive than in the preceding well F 8. A similar gamma ray response occurs in wells F 6 and F 5. In well F 4 the Bedford Unit 7 has thinned to about 35 feet thick. Although the gamma ray log configuration of this unit appears similar to that in well F 55 it is less radioactive than the overlying Sunbury and the underlying Ellsworth Shale. From well F 4, Unit 7 thins to about 15 feet in well F 1. The unit is within the Ellsworth Shale and is labeled "Bedford Shale equivalent."

The Berea Sandstone, labeled as Unit 9, is a variable formation consisting of siltstones, sandstones, and shales. In some areas of Berea deposition it is difficult to draw a logical boundary between Berea Sandstone and underlying Bedford Shale because of the alternation of sandstone and shale beds. In well F 10, Alcona County, the section assigned to the Berea is about 75 feet thick. The Berea thins to mainly shale in well F 9 located 32 miles southwest. In the next well, F 8, it has thinned to about 25 feet, is still mainly shale, and is gradational with the underlying Bedford interval designated as Unit 8. Between wells F 8 and F 7, the Berea Sandstone, identified as Unit 9, pinches out and is not recognized in wells F 6 through F 1.

The Sunbury Shale is about 20 feet thick in well F 10 and thins to about 15 feet in well F 6 about 100 miles southwest in Clare County. The Sunbury Shale in well F 10 appears less radioactive relative to the gamma ray signatures of the Antrim Shale. The radioactivity increases in well F 9 and remains essentially constant and similar to that of the Antrim in wells through F 5. In well F 4, a black shale occurs at the top of the Ellsworth and below the Coldwater Red Rock. The gamma ray signature of this shale shows a large decrease in radioactivity relative to the Sunbury Shale in the preceding well, F 5. Traced from well F 4 to well F 1, the gamma ray signature decreases and becomes similar to that of the Ellsworth Shale. This interval is correlated with the Sunbury Shale of eastern Michigan and is labeled as "Sunbury Shale equivalent." It is included as a part of the

Ellsworth Shale.

A Coldwater Red Rock interval is not evident on the gamma ray log of well F 10. A characteristic gamma ray signature appears above the Sunbury Shale and its equivalent in wells F 9 through F 1. The interval increases in thickness and becomes associated with red shale and limestone toward the western part of the Basin. In western Michigan wells, (F 4 through F 1) the gamma ray signature frequently shows a shale bed interposed between two presumably carbonate beds.



Figure 7. Orientation and trend of Cross Section C. Cross Section C consists of five parts or segments. Numbers 1, 2, 3, 4, and C 25 indicate terminus of individual cross section segments.

Cross Section C.

Cross Section C consists of five parts. It shows appropriate portions of 25 gamma ray logs of wells drilled into or through the Traverse Group of rocks. The section begins a few miles south of the Michigan-Indiana State boundary in Steuben County, Indiana, extends into Michigan and then northeasterly to Sanilac County where the trend is generally to the north, finally ending in Alpena County. Most of the cross section traverses the eastern part of the Michigan Basin where "type" or characteristic Antrim, Bedford, Berea, and Sunbury formations occur, and finally ends in an area where basal Antrim beds subcrop beneath glacial drift or are exposed at the surface. The 25 wells shown on the cross section are distributed over a distance of about 370 miles (Figure 7). See Appendix C for individual well data.

The Antrim Shale in well C 1, Steuben County, Indiana, is about 160 feet thick. Antrim Unit 1 and its subdivisions, and Antrim Units 2, 3, and 4 are recognized in the first 10 wells. In well C 11, a part of Unit 5 appears to be present,

and in wells C 12 through C 14 where the Antrim section has increased to about 240 feet, all six units are present. In well C 15, the gamma ray log shows the entire Antrim section to be about 155 feet thick, and only units 1, 2, 3, and 4 present. This is an anomalous Antrim section similar to well B 20 in Cross Section B. From well C 15, the Antrim section thickens to as much as 380 feet in well C 19, Iosco County. The Antrim section thins from well C 19 to well C 20, is partially eroded and lies immediately below the glacial drift in well C 21, and then thickens again in wells C 22 through C 24. In well C 25, the upper part of the Antrim, Unit 6, has been removed by pre-Pleistocene erosion. It should be noted in Cross Section C that the middle part of the Antrim, generally Units 3 and 4, tend to be less radioactive than the lower and upper two units.

In Cross Section C, Antrim Unit 1 is also characterized by its middle division, Unit 1 B. This widespread and easily recognized unit is present in all 25 wells. In well C 1, Steuben County, Indiana, Unit 1 B is 20 feet thick. In this well, the greenish-gray shale beds of Unit 1 B are separated by a thin bed of Antrim type shale with Antrim type radioactive characteristics. In the next well, C 2, the Antrim type shale is not present. Unit 1 B in well C 1 may be the Selmier Member of the New Albany Shale of Indiana. According to Lineback (1970, p. 41) rocks equivalent to the Selmier Member are included in the Antrim Shale in the Michigan Basin.

Unit 1 B was cored in well C 12, Sanilac County. Well C 12 is the previously mentioned Dow Chemical Company, Rhoburn No. 1 (See Figure 4 and Appendix H). The core description of Unit 1 B shows a variable lithology which was described as follows:

1405.0 - 1405.8	Limestone, white and green gray, mottled, some dark shale
1405.8 - 1406.5	Black shale, reddish, as before
1406.5 - 1407.6	Shale, gray and lt. green-gray, the greener shale is very limy
1407.6 - 1409.0	Limestone, white to lt. greenish
1409.0 - 1411.5	Shale, black, minor green-gray
1411.5 - 1413.0	Shale as above with white lime
1412.0 (6"), 1412.8 (1"), 1412.9 (1")	and calcareous greenish shale, 1411.5 (2")
1413.0 - 1422.5	Shale, black, minor greenish calcareous, shale in thin beds throughout-beds below 1420 are cyclic grading up into lighter color and ending at top in abrupt change to dark above. Considerable pyrite.
1422.5 - 1423.8	Limestone, white and light gray, brecciated with much calcite.

The gamma ray signature of Unit 1 B in well C 12 is not as prominent as in most wells. Whether the described lithology is characteristic of the unit wherever it occurs is unknown. Generally it is described from well cuttings as a gray or greenish-gray dolomitic shale which may contain shaley carbonate beds.

The Bedford Shale in well C 1, Steuben County, Indiana,

is identified as Bedford Unit 7, the overlying Unit 8 not being identified on gamma ray logs until well C 4. According to Lineback (1970, p. 33, Fig. 14) a similar shale interval found in a well drilled in Section 16, T.38N., R.13E., Steuben County, Indiana, is assigned to the upper part of the Ellsworth Shale. It has been shown in this report that a part of the Bedford Shale of eastern Michigan grades into the upper part of the Ellsworth Shale of western Michigan.

Bedford Shale Unit 7 is about 40 feet thick in well C 1. Bedford Unit 8 is first recognized on gamma ray logs in well C 4 and on successive gamma ray logs through well C 24. From well C 4 through well C 8, Units 7 and 8 appear to contain numerous silt or sandstone beds which appear to decrease in frequency from well C 9 through well C 25. The Bedford Shale interval increases in thickness from well C 1 to well C 15 in Huron County where it is interpreted to be about 385 feet thick. From well C 15 the Bedford Shale interval decreases to about 100 feet in well C 24. In well C 25, the Bedford has been removed by pre-Pleistocene erosion.

The gamma ray log of well C 15 suggests an anomalous Berea-Bedford interval compared with the logs of adjacent wells. According to the sample description provided by the company (see Appendix J), the top of the Berea was picked at 1,358 feet and the section described as white sandstone, fine to medium grained, with fair sortings. The sandstone interval was 29 feet thick. The next intervals 42 feet thick, is described as black shale with some spore cases. The next lower bed, 18 feet thick, is described as gray, micaceous shale. The next interval, 111 feet thick, is described as gray to black, micaceous shale with some spore cases. The lowermost interval, 216 feet thick and extending from 1,558 feet to the top of the Antrim Shale at 1,774 feet, is described as light gray to white sandstone, tan in upper part, fine grained, slightly friable with trace of calcareous cement; some interbedded, dark gray to black, and gray to green, and light gray shales. An appraisal of the gamma ray signature of the anomalous Berea-Bedford interval appears to confirm the general rock types. Because there is no evidence to the contrary, such as a faulty or miscalibrated gamma ray log, it is assumed that the drilling record and log are valid. A similar anomalous Berea-Bedford interval and gamma ray log section is shown in well B 20 on Cross Section B.

The Bedford Shale interval in well C 15 combines Units 7 and 8 since the boundary between the two is indeterminate. The combined thickness of Bedford Units 7 and 8 in well C 14 amounts to about 215 feet and is about equal to the thickness of the last described Bedford interval (1,558 to 1,774 feet) in well C 15. There are gamma ray log characteristics in well C 15 which suggest that the lower interval could be correlated with Units 7 and 8 in well C 14, but this would then place an anomalous lithological section within the Berea Sandstone interval. Although such a correlation may be possible, and the Berea-Bedford interval may have this anomalous relationship in the vicinity and beneath Saginaw Bay, the preferred correlation as shown on well C 15 seems the

most reasonable.

On Cross Section C the Berea Sandstone, identified as Unit 9, first appears as a thin sandstone in well C 5. In well C 5 it is about 15 feet thick, increases to about 90 feet in some eastern Michigan wells, and then thins to about 35 feet in well C 24 in Alcona County. In well C 25, the Berea is absent because of pre-Pleistocene erosion.

The Sunbury Shale is readily recognized in well C 1, Steuben County, Indiana, and in all wells in Cross Section C with the exception of those where the formation has been removed by erosion. In the first six wells of Cross Section C, the Sunbury averages about 10-15 feet thick and then starts to increase in thickness at well C 7 where its gamma ray signature begins to reflect a "two-prong" configuration. In Sanilac County in well 12 the Sunbury is 135 feet thick, decreases to 65 feet in well C 13, and increases again to 125 feet thick in well C 14. In the next three wells, C 15, C 16, and C 17, all in Huron county, the Sunbury reflects its regional thickening in the vicinity of Saginaw Bay. From well C 17 in Huron County where the Sunbury is about 125 feet thick to well C 18 across Saginaw Bay in Iosco County, the Sunbury decreases to a thickness of about 30 feet. From this well the thickness interval gradually decreases to at least 20 feet in well C 24. In well C 25 the Sunbury is absent because of pre-Pleistocene erosion.

The Coldwater Red Rock gamma ray signature, a thin gamma ray deflection to the left, is apparent on most logs of wells used in Cross Section C. The interval is about 3-4 feet thick and lies immediately above the Sunbury Shale. Red sediments are not associated with the interval in the eastern part of the Basin.



Figure 8. Orientation and trend of Cross Section D. Cross

Section D consists of three parts or segments. Numbers 1, 2, and D 15 indicate terminus of individual cross section segments.

Cross Section D.

Cross Section D consists of three parts. It shows appropriate portions of 15 gamma ray logs of wells drilled into or through the Traverse Group of rocks. The section begins in northeastern Washtenaw County and trends north-northwest to about the mid-Basin region where it then trends in a general northeasterly direction to its terminus in Alpena County. This cross section shows characteristic gamma ray response of "type" Antrim, Bedford, Berea, and Sunbury formations in the southeast part of the Basin, the central part, and the northeast part. The 15 wells shown on the cross section are distributed over a distance of about 260 miles (Figure 8). See Appendix D for individual well data.

In well D 1 (well C 7 in Cross Section C), Washtenaw County, the Antrim Shale is about 125 feet thick and consists of Antrim Units 1 through 4. Traced basinward from Washtenaw County into Livingston County, the Antrim section increases in thickness and Units 5 and 6 are recognized on the gamma ray curve. Unit 6 has gamma ray log characteristics similar to the overlying Bedford Shale and does not exhibit typical Antrim Shale radioactive characteristics until well D 6, located in Saginaw County. The Antrim continues to increase along the line of section and is about 505 feet thick in well D 9, Clare County. From well D 9, the Antrim begins to decrease in thickness toward its subcrop region where in well D 15 it is about 280 feet thick, the upper part having been removed by pre-Pleistocene erosion.

As in the previous cross section, the upper and lower parts of the Antrim are more radioactive than the middle part. Generally the middle Units 3 and 4 show the lesser degree of radioactivity. But in basin regions where the Antrim is thicker, parts of Units 2 and 5 may be involved. The gamma ray logs which show this configuration are those of wells D 7 through D 15.

The middle division of Antrim Unit 1 (Unit 1 B) is present in all 15 wells of Cross Section D. In well D 1, Washtenaw County, Unit 1 B is about 15 feet thick. The maximum thickness recorded in Cross Section D is 65 feet in well D 9, Clare County.

The Bedford Shale in well D 1, Washtenaw County, is about 170 feet thick. It has been divided into a Unit 7 and an overlying Unit 8. The gamma ray response of Unit 7 is characteristically that of the gray Bedford Shale. Unit 8, about 100 feet thick, is similar to a shale-bearing Berea Sandstone section. Traced basinward to well D 4 in Shiawassee County, Units 7 and 8 become increasingly shaley and decrease in thickness to about 65 feet, of which 20 feet is assigned to Unit 8. In well D 5, also in Shiawassee County, Unit 8 has become sandy and has increased in thickness to about 85 feet; the combined thickness of Units 7 and 8 amounting to about 140 feet. In the next well, D 6 in Saginaw County, the combined thickness of Units 7 and 8 has decreased to about 85 feet.

From well D 6 to well D 7 the amount of sand appears to decrease and the gamma ray response is more characteristically that of the Bedford Shale. From well D 7 to well D 9 in Clare County, Units 7 and 8 appear to have become more radioactive. The gamma ray response of Bedford Units 7 and 8 in wells D 7 through D 9 is similar in magnitude to the underlying Antrim Shale. In wells D 10 through D 12, however, a change in radioactive characteristics occurs in Units 7 and 8, so that only the approximate lower half of Unit 7 has a gamma ray response similar to the underlying Antrim Shale. The upper half of Unit 7, and all of Unit 8, in wells D 10 through D 12, have gamma ray characteristics similar to the gray Bedford Shale and the Coldwater Shale above the Sunbury. In contrast to well D 12, Oscoda County, where the just mentioned situation occurs, the next well in Oscoda County (D 13) shows that Units 7 and 8 have radioactive characteristics similar to the Antrim Shale. The Bedford Shale and younger formations are absent in the next two wells because of pre-Pleistocene erosion.

The Berea Sandstone, identified as Unit 9, is about 70 feet thick in well D 1, Washtenaw County. The gamma ray log response in this well is one of shale indispersed with silt or sandstone beds, and is similar in appearance to the underlying Bedford Shale sequence. In successive basinward wells in Cross Section D, the Berea tends to thin but retains its shaley character until well D 5 where it appears to be largely sandstone. In well D 6, the Berea again becomes shaley and at well D 8, Isabella County, it has become significantly radioactive. In this well, D 8, the approximate lower half of Unit 8 has a gamma ray response similar in magnitude to the underlying Antrim Shale. The upper part of Unit 8 in this well has a gamma ray response similar to the Bedford Shale, or the shale beds found within the Berea Sandstone interval. Berea Unit 9 is judged to be absent in well D 9. In wells D 10 through D 12, Unit 9 is present but does not have radioactive characteristics similar to well D 8. In well D 13, Unit 9 may be present and is characterized, in part, by a thin section of shale having a gamma ray response similar to part of the Antrim Shale. The Berea is absent in the last two wells of Cross Section D because of pre-Pleistocene erosion.

The Sunbury Shale in the 15 wells shown on Cross Section D remains fairly consistent in thickness, ranging from about 15 to 20 feet in most wells but as much as 30 feet in wells D 8 and D 12. Cross Section D trends in a general south to north direction and reflects the thinning of the Sunbury in a westerly direction. As on previously discussed cross sections, the Sunbury is characterized on most gamma ray logs by a "two-prong" gamma ray configuration. The Sunbury is absent in wells D 14 and D 15 because of pre-Pleistocene erosion.

The Coldwater Red Rock gamma ray deflection to the left and immediately above the Sunbury Shale is not prominent in wells D 1 through D 7. A typical gamma ray deflection occurs in wells D 8 through D 13. Red sediments are not generally associated with the eastern basin Red Rock interval.

Cross Section E.

Cross Section E consists of four parts. It shows appropriate portions of 22 gamma ray logs of wells drilled into or through the Traverse Group of rocks. The section begins a few miles south of the Michigan-Ohio State boundary in Fulton County, northwestern Ohio. It extends into Michigan and continues north westerly to Kent County and then trends northerly into Wexford County where it then trends in a northeasterly direction into Otsego County. Cross Section E shows a characteristic gamma ray response of "type" Antrim, Bedford, Berea, and Sunbury formations in the Ohio part of the Michigan Basin, and the change in character of these formations as they merge northwesterly with the Ellsworth Shale of western Michigan. The 22 wells shown on the cross section are distributed over a distance of approximately 308 miles (Figure 9). See Appendix E for individual well data.



Figure 9. Orientation and trend of Cross Section E. Cross Section E consists of four parts or segments. Numbers 1, 2, 3, and E 22 indicate terminus of individual cross section segments.

The Antrim Shale in well E 1, Fulton County, Ohio, is about 170 feet thick. In wells E 1 through E 3 only Antrim Units 1 through 4 are recognized on the gamma ray logs. In well E 4 the section has significantly increased in thickness to 205 feet, and all six units are recognized. The Antrim continues to increase in thickness and is 575 feet thick in well E 12 in Osceola County. In the next well, E 13, also in Osceola County, Antrim Units 4, 5, and 6 cannot be recognized on the gamma ray log which shows a characteristic Ellsworth Shale gamma ray response where these units should occur. A similar Ellsworth Shale

gamma ray response occurs above Antrim Units 4, 5, and 6 in wells 14 and 15. It is apparent that Antrim Units 4, 55 and 6 merge laterally into the Ellsworth Shale. Unit numbers 4, 5, and 6 are shown on wells E 13 through E 15 but the boundaries between the units have not been drawn. The total Antrim thickness in well E 12 is 575 feet; the equivalent thickness (including Ellsworth Shale) in wells E 13, E 14, and E 15 is 750 feet, 750 feet, and 740 feet, respectively. From well E 15 in Wexford County, the cross section trends due east into Missaukee County. Here the gamma ray log characteristics of well 16 are very similar to that of well E 12 in Osceola County. The gamma ray configuration in both wells has similarities of the Ellsworth and Antrim Shale gamma ray response. In wells E 17 through E 22 the gamma ray response of Antrim Units 1 through 6 are characteristically Antrim in configuration.

As shown in the other cross sections, the Antrim Shale in Cross Section E is characterized by a higher magnitude of radioactivity in the lower and upper units. As the Antrim merges into the Ellsworth Shale, upper Antrim Units 5 and 6 lose their radioactive characteristics relative to Units 1 and 2 and become similar to the middle units.

In Cross Section E, Antrim Unit 1 is characterized by its middle division, Unit 1 B. This widespread and easily recognized unit is present in all 22 wells. It is thinnest in wells E 8 and E 10, and thickest in well E 15 where it is about 75 feet thick.

The Bedford Shale-Berea Sandstone interval in wells E 1 through E 3 of Cross Section E has gamma ray characteristics typical of the Bedford Shale formation. Though mainly shale, thin siltstone and sandstone beds appear evident on the gamma ray logs. Bedford Units 7 and 8, and Berea Unit 9, have been identified in wells E 1 through E 3. The thickness of the Bedford-Berea interval in wells E 1 through E 3 is 80 feet, 90 feet, and 90 feet, respectively. Berea Unit 9 is not identified on gamma ray log of well E 4 which has a combined Bedford Unit 7 and Unit 8 thickness of 30 feet. The Bedford interval thins and is judged to be entirely absent in well E 7, Ionia County. In the next well, E 8, 12 miles distant and also in Ionia County, only Bedford Unit 7 is identified and it is 30 feet thick. Bedford Unit 7 continues to well E 12 in Osceola County. In well E 12 it has radioactive characteristics similar in magnitude to the lower and upper units of the Antrim Shale. In the next well, E 13, 16 miles distant and also in Osceola County, the gamma ray log characteristics above Antrim Units 1, 2, and 3 are typically those of the Ellsworth Shale. Bedford Units 7 and 8 are identified in the upper part of the Ellsworth immediately below the Sunbury Shale in well E 13 and are labeled Bedford Shale equivalents. In the next well, E 14, the gamma ray response in the uppermost part of Unit 7 shows a slight increase in radioactivity. In the next well, E 15, the gamma ray response of Unit 7 has increased in magnitude and the interval has become thicker, finally reaching a magnitude similar to the Antrim in well E 16. The overlying Unit 8 is distinctive in wells E 15 through E 18 but in well E 19 it, too, becomes increasingly radioactive

and has a gamma ray log response similar to the underlying Unit 7 and the Antrim Shale. From well E 19 through well E 21, Bedford Units 7 and 8 have gamma ray log responses similar in magnitude to the Antrim Shale. In the last well of the cross section, E 22, Unit 8 has become less radioactive and has gamma ray characteristics similar to the "normal" gray Bedford Shale.

The Sunbury Shale is readily recognized on all gamma ray logs of wells used in Cross Section E. Ranging in thickness from 10 to 18 feet in wells E 1 through E 5, it has radioactive characteristics of about the same or greater magnitude than the Antrim Shale, and is separated from the Antrim Shale by the Bedford-Berea interval. In well E 6 the Sunbury lies on a thin Bedford Shale (Units 7 and 8) interval which is similar to the Antrim, and in well E 7 it lies directly on the Antrim. A similar situation occurs in wells E 12, E 19, E 20, and E 21. In well cuttings it would be difficult to separate Sunbury Shale from Antrim Shale in these wells. Though the Sunbury is a relatively thin formation in the wells shown on Cross Section E, it does reach a thickness of 30 feet in well E 13. It thins to about 10 feet thick in wells E 19 through E 22, the terminal well of the cross section.

The Coldwater Red Rock gamma ray deflection to the left and immediately above the Sunbury Shale is not prominent in wells E 1 through E 5 but becomes more apparent in the more basinward wells. Red sediments may be associated with the thicker Red Rock intervals in western Michigan.



Figure 10. Orientation and trend of Cross Section A. Cross Section A consists of four parts or segments. Numbers 1, 2, 3, and A 22 indicate terminus of individual cross section segments.

Cross Section A.

Cross Section A consists of four parts. It shows appropriate portions of 22 gamma ray logs of wells drilled into or through the Traverse Group of rocks. The section begins a few miles south of the Michigan-Indiana State boundary in Steuben County, Indiana. The first well of Cross Section A is also the first well of Cross Section C which trends northeast to the eastern part of the State. Cross Section A trends northwest into Van Buren County, Michigan, and then northward along the west side of the state to its terminus in Antrim County. Most of the cross section traverses the far western part of the State where the "type" subsurface Ellsworth Shale overlies the Antrim Shale as generally described in western Michigan. A thin but well defined, highly radioactive Sunbury Shale is evident in several wells of Part 1, Cross Section A, but absent in others. About midway in Part 2 of the cross section, a Sunbury-type shale appears in the uppermost part of the Ellsworth Shale and immediately below the Coldwater Red Rock. The gamma ray curve of this Sunbury equivalent does not show a high degree of radioactivity, yet as it is traced northward there appears to be little question that it is correlative with the Sunbury of eastern Michigan. The 22 wells shown on the cross section are distributed over a distance of about 355 miles (Figure 10), See Appendix A for individual well data.

The Antrim Shale in well A 1 (same as C 1 in Cross Section C) in Steuben County, Indiana, is about 160 feet thick. Antrim Unit 1 and its subdivisions, and Antrim Units 2, 3, and 4 are recognized. In well 2 A the Antrim has increased to about 210 feet thick and, with respect to gamma ray characteristics, has begun to assume elements of the Ellsworth Shale. In the next well (A 3), 13 miles west, the section has expanded to about 330 feet thick. The gamma ray log exhibits a characteristic Ellsworth Shale overlying the Antrim Shale. Antrim Units 1 through 4 were recognized in well A 1, and Antrim Unit 5 in well A 2. Although an attempt has been made to show where Units 3, 4, and 5 should fall in wells A 3 through A 6, the boundaries are questionable and by no means certain. In wells A 7 through A 22, Antrim Units 4, 5, and 6 cannot be identified. Antrim Units 1 and 2, and in most of the wells Unit 3, can be identified by their radioactive signatures. In those wells where gamma ray logs show definite Ellsworth Shale-signatures, the top of the Antrim is defined as the top of Unit 2.

Antrim Unit 1 is characterized by its middle division, Unit 1 B, which is, however, not well defined in all wells of Cross Section A. Unit 1 B appears to be absent or poorly defined in wells A 4 through A 14. The unit may be present in these wells but obscured by the Antrim Shale stringers which are found in the unit at its depositional margin on the edges of the Basin.

In well A 1 (same as well C 1 in Cross Section C) the Bedford Shale, designated as Unit 7, is about 40 feet thick. It is recognized in well A 2 and in well A 3, St. Joseph County, where it immediately underlies a thin Sunbury Shale and would normally be considered as a

part of the Ellsworth Shale. In wells A 3, A 4, and A 5, the gamma ray log signatures suggest that the interval is present but has a slightly less radioactive response than the underlying shales of the Ellsworth. The gamma ray logs of wells A 6 through A 9 do not show gamma ray signatures that can be related to the Bedford, though it is likely that an equivalent interval is present in the uppermost part of the Ellsworth Shale. In these same wells, A 6 through A 9, the Sunbury Shale or its equivalent cannot be identified on the gamma ray logs. However, in wells A 10 through A 21, a Sunbury-type shale appears immediately below the Coldwater Red Rock gamma ray deflection. Beneath this Sunbury Shale equivalent is a thin interval which is correlated with Bedford Shale Unit 7. This unit is readily correlated with the Bedford Shale in the eastern part of the Basin.

There is little question that the thin Sunbury Shale shown on the gamma ray logs of wells A 1, A 2, and A 3 correlates with the Sunbury Shale of eastern Michigan. In most of the wells on Parts 2, 3, and 4 of Cross Section A, the Sunbury or its equivalent does not exhibit similar gamma ray characteristics showing a high degree of gamma ray response. In wells A 6 through A 9, the Sunbury is not recognized on the gamma ray logs of these wells.

The Coldwater Red Rock gamma ray signature, a gamma ray deflection to the left, is found on most logs of wells used in Cross Section A. The signature is well defined in wells A 6 through A 20. Red sediments are associated with most of the interval.

Summary

The sequence of formations important to the in situ processing of Antrim Shale to produce energy values are, in ascending order: Antrim Shale, Bedford Shale, Berea Sandstone, and Sunbury Shale. This sequence occurs in the eastern half of the Michigan Basin. On the western side of the Basin the sequence is Antrim Shale overlain by Ellsworth Shale which, in turn, is overlain by Sunbury Shale in some areas. The east to west stratigraphic relationship is explained by a facies relationship between a part of the Antrim and Ellsworth, the Bedford and Ellsworth, a pinch out of the Berea Sandstone, and a thinning of the Sunbury Shale in some areas and a merging of the Sunbury into the uppermost Ellsworth in other areas. The stratigraphic association between these two dissimilar parts of the Basin has been demonstrated by several subsurface studies involving well cuttings or by a combination of well cuttings and electric logs.

The black carbonaceous and partially bituminous shales now called Antrim have been studied from time-to-time since their discovery over 140 years ago. In the Antrim outcrop areas in Emmet, Charlevoix, Cheboygan, and Alpena counties, the amount of vertical section exposed in a given outcrop is very small compared with measured Antrim sections which may exceed 650 feet in thickness in the subsurface. The Antrim Shale in outcrop, and with fresh nonweathered surfaces, is invariably described as

black in color. In the subsurface it is described as dark gray to black with some gray shale in the lower part. In the western part of the Basin, basal beds of the Antrim grade upward from black shale into grayish black shale and then into the greenish gray shales of the Ellsworth. Some shale beds in this transitional phase have a brown color. From west to east, the shales of the Ellsworth grade laterally into grayish black shales and then black shales of the upper portion of the Antrim. In the eastern part of the Basin, the Antrim is not always readily distinguished from the overlying Bedford Shale if color is to be the sole criterion, because some basal Bedford shales are dark gray or black in color.

The contact between the Antrim and the overlying Bedford Shale of eastern Michigan is not exposed in outcrop and is known only from subsurface studies. The Bedford Shale in parts of the Basin has color characteristics (gray, dark gray and black) similar to the Antrim, thus making the contact between the two formations less readily determined.

The Berea Sandstone of eastern Michigan cannot always be accurately separated from the underlying Bedford Shale. Some geologists consider both formations as a single rock division. The Bedford thins in a westerly direction and merges into the upper part of the Ellsworth Shale. The Berea, as a sandstone or silt-stone formation, thins in a westerly direction and finally pinches out, probably by nondeposition.

The Sunbury Shale is thickest in eastern Michigan. It thins in a westerly direction; is absent in some parts of western Michigan, and merges into the top part of the Ellsworth Shale in other parts of western Michigan. The contacts between the Bedford-Berea, Berea-Sunbury, and Sunbury-Coldwater formations are not exposed in outcrop and are known only from subsurface studies. In parts of the Basin the black Sunbury Shale lies almost in contact with black Antrim Shale, the intervening formation being a thin interval of gray Bedford Shale.

It is believed that gamma ray logs can be used to more successfully differentiate the boundaries between the Antrim, Bedford, Berea, and Sunbury formations of eastern Michigan and the Antrim, Ellsworth, and Sunbury formations of western Michigan than is possible by well-cutting examinations alone. Subsurface studies show that the aforementioned formations can be related to gamma ray logs and that two of the formations, the Antrim and Sunbury, normally exhibit greater gamma ray response than the rocks of the Bedford Shale, Berea Sandstone, and Ellsworth Shale. It is also pointed out that in a part of the Basin, a portion of the Bedford Shale is grayish black to black in color and has radioactive characteristics similar to the underlying Antrim and to the Sunbury Shale which overlies the Bedford. In some areas of eastern Michigan the basal part of the Bedford contains grayish black shale strata referred to as "false Antrim" (R. D. Matthews, oral comm.) but the gamma ray response amounts to only a few API Units more than the normal Bedford Shale response. In ordinary well-cutting examinations, black or dark colored Bedford shales would ordinarily be classified

as Antrim. In eastern Michigan the top of the Antrim has been related to that portion of the gamma ray curve having the greatest degree of deflection to the right in terms of standard API gamma ray units.

In eastern Michigan gamma ray-emitting elements are not distributed evenly throughout the vertical succession of Antrim strata. Thus it is possible to divide the Antrim into units based on the relative gamma ray response of the beds that make up the vertical succession. These units can be used to define the lower and upper limits of the Antrim in the subsurface; to separate the grayish black or black shale of the Bedford from that of the Antrim; and to show the facies association of the eastern Antrim to the lithologically differ-Ellsworth Shale of western Michigan.

Antrim correlations based on the six radioactive divisions, or units, of the eastern Antrim are shown on the six cross sections. Where possible, the units have been traced into the Ellsworth Shale. In western Michigan the top of the Antrim is arbitrarily defined on the gamma ray logs, for the purpose of this study, as the top of Antrim Unit 2. There appears to be no practical lateral separation between Antrim and Ellsworth facies above Unit 2, since the gamma ray logs show lateral gradation. On the basis of the Antrim correlations, most of the Ellsworth appears to be of Devonian age. The Bedford Shale and Berea Sandstone, both of which are considered to be Mississippian age, are younger than the Antrim. In relationship to the Ellsworth Shale, a part of the Bedford Shale extends into the upper part of the Ellsworth Shale. The Sunbury Shale, also of Mississippian age, merges into the uppermost interval of the Ellsworth Shale.

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APPENDIX G

A total of 99 gamma ray well logs were used to construct six stratigraphic cross sections covering the Antrim Shale to Sunbury Shale interval. Certain cross sections intersect or connect, thus forming a network. Certain wells appear on one or more cross sections. Wells that are common to one or more cross sections, and the cross section intersected, are as follows:

Cross Section A, 4 Parts; total of 22 wells.

Well A 1 same as Well C 1, Cross Section C
 Well A 6 same as Well B 5, Cross Section B
 Well A 11 same as Well F 1, Cross Section F
 Well A 12 same as Well F 2, Cross Section F
 Well A 13 same as Well F 3, Cross Section F

Cross Section B, 4 Parts; total of 21 wells.

Well B 5 same as Well A 6, Cross Section A
 Well B 11 same as Well E 8, Cross Section E
 Well B 14 same as Well D 7, Cross Section D
 Well B 21 same as Well C 14, Cross Section C

Cross Section C, 5 Parts; total of 25 wells.

Well C 1 same as Well A 1, Cross Section A
 Well C 4 same as Well E 3, Cross Section E
 Well C 7 same as Well D 1, Cross Section D
 Well C 14 same as Well B 12, Cross Section B
 Well C 19 same as Well F 9, Cross Section F
 Well C 20 same as Well F 10, Cross Section F
 Well C 25 same as Well D 15, Cross Section D

Cross Section D, 3 Parts; total of 15 wells.

Well D 1 same as Well C 7, Cross Section C
 Well D 7 same as Well B 14, Cross Section B
 Well D 9 same as Well F 7, Cross Section F
 Well D 10 same as Well F 8, Cross Section F
 Well D 15 same as Well C 25, Cross Section C

Cross Section E, 4 Parts; total of 22 wells.

Well E 3 same as Well C 4, Cross Section C
 Well E 8 same as Well B 11, Cross Section B
 Well E 12 same as Well F 5, Cross Section F

Cross Section F, 2 Parts; total of 10 wells.

Well F 1 same as Well A 11, Cross Section A
 Well F 2 same as Well A 12, Cross Section A
 Well F 3 same as Well A 13, Cross Section A
 Well F 5 same as Well E 12, Cross Section E
 Well F 7 same as Well D 9, Cross Section D
 Well F 8 same as Well D 10, Cross Section D
 Well F 9 same as Well C 19, Cross Section C
 Well F 10 same as Well C 20, Cross Section C

APPENDIX H

The Dow Chemical Company Rhoburn No. 1 Well Core and Sample Description

Section 8, T9N, R15E, Fremont Twp., Sanilac County

Kelly Bushing Elevation: Estimate 798' above sea level

The Interval covered in this description extends from 816.5 feet in the Coldwater Shale to total depth. The cores were described by R. D. Matthews of The Dow Chemical Company. The original description format has been modified to show depths of Antrim, Bedford, and Berea informal units according to the gamma ray log (GR-N) and position within the cored or sampled interval. Reference should be made to figure 4 and Well C 12, Cross Section C, Part 3. Also see Appendix C, Well C 12.

Coldwater Shale Footage	Interval	Core #6 819-877' Cut 58' Rec 22.05'
(2.5)	816.5-819.0	Shale, dk gray; broken core 818.2-818.8'. (End Core #5)
(6.6)	819.0-825.6	Shale, dk gray, as above
(2.0)	825.6-827.6	Shale, lt gray and gray-green, calcareous and thin shaley limestone beds, the limestone beds are gray-brown (827.6 Core = 827 GR-N)
Sunbury: (10.3)	827.6-837.9	Shale, black, hard, brittle, less dense than shale above; core splits vertically and along sides; top of Sunbury show sharp color change but is gradational over one inch with "worm trails" of green-gray shale interspersed in the block. Some broken core at 827.7. Loss of core assumed at bottom left in hole. Catchers are not working as well on the Sunbury as they did on the gray shale of Coldwater.
(0.6)	837.9-838.5	Concretion, lt gray dolomite, cemented breccia in part. <u>Core #7 877-898' Cut 21' Rec 38'</u> (Rec 36' of Core #6 and 2' Core #7; 19' of Core #7 was left in the hole and was felt when going into cut #8)
(37.6)	841.0-878.6	Entire core shale, black, fine grained, flat thin beds, splinters easily, breaks flat along bedding, no spores, little pyrite. <u>Core #8 898-907' Cut 9' Rec 9', plus rubble.</u>
(20.4)	878.6-899	Black shale rubble – a large pail of broken core is all that is left of this footage.
(8.5)	899.0-907.5	Black shale as in Core #7 <u>Core #9 907-966' Cut 59.5' Rec 59.0'</u>
(56.3)	907-963.3	Shale, black, as above
Berea (Unit 9) (2.7)	963.3-966.0	(966 Core = 964 GR-N) Sandstone, lt gray, fine to med. grain. <u>Core #10 966-1017' Cut 51' Rec 51'</u>
(2.5)	966-968.5	Sand, lt gray
(13.8)	968.5-982.3	Shale, gray and sandy lt gray shale in thin wavy beds; occasional sandstone bed 974.8-975.1, 976.0-976.4, 982.3-984.5. The sandstone is lt gray, med. to fine grained, with some cross-bedding or slumping.
(12.8)	984.5-997.3	Sandstone, gray, medium xlyn, sucrosic, some nearly white, some spotted, generally massive.
(3.7)	997.3-1001.0	Sandstone, med to fine grained, thin bedded, lt gray
(1.1)	1001.0-1002.1	Shale, dk gray, thin bedded and minor sandstone, as above
(14.9)	1002.1-1017	Remainder of core badly broken. Chunks and pieces of sandstone, med. to fine,

		sucrosic, soft, appears permeable, slight oil stain near bottom end.	(0.6)	1287.7-1288.3	top and base Shale, black	
(3.6)	1017-1020.6	<u>Core #11 1017-1077' Cut 60' Rec 59.6'</u> Sandstone, lt gray med to fine grain, xlyn sucrosic	(18.4)	1288.0-1306.4	<u>Core #16 1288-1328' Cut 40' Rec 34.66'</u> Shale, black; green shale (4") at 1292.1-1292.4 and 16 gray green (1") at 1299.2; shale above 1292 is slightly blacker.	
(7.3)	1020.6-1027.9	(1,020.6 Core = 1,022 GR-N) Shale, dark gray, minor lt shale banding in upper half. Poss. Bedford top 1020.6'	(1.5)	1306.4-1307.9	Limestone, gray, brecciated, fractures healed with calcite, hard brittle.	
(0.9)	1027.9-1028.8	Sandstone, lt tan, f.g; minor dk shale bands, irregular	Antrim Unit 3 @ 1314 GR-N	(14.7)	1307.9-1322.6	Shale, black, slightly brownish cast on outside, pyrite in small (1/4" - 1/2") nodules very common.
(3.2)	1028.8-1032.0	Shale and sandstone in irregular masses.				
(6.9)	1032.0-1038.9	Shale and carbonaceous sandstone in irregular masses, the sands are lt gray and fine grained.	(14.0)	1328-1342	<u>Core #17 1328-1378' Cut 50' Rec 16'</u> Shale, black pyrite	
(3.9)	1038.9-1042.8	Shale, dark gray; minor banding 1040-41'.	(2.0)	1342-1344?	Shale black and reddish brown cast, badly broken, minor (1") green gray shale at 1343.5'.	
(9.8)	1042.8-1052.6	Shale dark gray and lt gray with about 20% lt gray sandstone in thin irregular, contorted interrupted beds.	Antrim Unit 2 @ 1353 GR-N		(Lost core about 1344-1379')	
Bedford Shale (Unit 8)			Antrim Unit 1A @ 1375 GR-N		<u>Core #18 1379-1430' Cut 51' Rec 52.85'</u>	
(9.1)	1052.6-1061.7	Shale, dark and light gray banded with 10-15% light tan shaly sandstone in thin beds generally less than 1" thick and often slightly contorted.	(12.5)	1379-1391.5	Shale very black, having a slight reddish-brown cast on the outside and when crushed or powdered, and 5% green shale in thin bands, paper-thin to 4" thick; green shale at 1380.0' (2"), 1380.4 (2"), 1380.7' (2" mottled), 1381.0' (1"), 1381.8 (1"), 1382.0' (4"), 1387.0 (1").	
(5.3)	1061.7-1067.0	Shale, dk gray; minor sandy beds as above 1065-1066.				
(6.0)	1067.0-1073.0	Shale as above with thin lt gray and tan sandy beds	(6.5)	1391.5-1398.0	Shale very black as above with much thin banding of green shale, and paper thin white limestone or calcite.	
(3.6)	1073.0-1076.6	Shale, dark gray <u>Core #12 1077-1137' Cut 60' Rec 60'</u>				
(6.2)	1077.0-1083.2	Shale, dark gray	(0.2)	1398.0-1398.2	Limestone, white mottled with green gray shale.	
(14.5)	1083.2-1097.7	Shale, dark gray and lt gray banded in thin bands with minor thin light tan sandy zones.	(4.5)	1398.2-1402.7	Shale, green-gray, subordinate black shale as above	
(1.8)	1097.7-1099.5	Shale, dark gray	(2.3)	1402.7-1405.0	Shale, black and green-gray, 50-50 the green-gray is calcareous.	
(3.1)	1099.5-1102.6	Shale, broken core, largely dark gray shale				
(15.9)	1102.6-1118.5	Shale, dark gray; broken core 1106.0-1109.9, core in rubble, splits vertically and in thin tablets	Antrim Unit 1B @ 1405 GR-N	(0.8)	1405.0-1405.8	Limestone white and green gray, mottled, some dark shale.
(18.7)	1118.5-1137.2	Shale, dark gray and light gray in thin wavy bands with occasional thin sandy zones.	(0.7)	1405.8-1406.5	Black shale, reddish, as before	
Bedford Shale (Unit 7) @ 1144			(1.1)	1406.5-1407.6	Shale, gray and lt green-gray, the greener shale is very limy.	
(42.1)	1137.0-1179.1	<u>Core #13 1137-1196' Cut 59' Rec 59'</u> Shale, dark gray, with 5% minor lt gray shale and lt tan sandy zones, interbedded; a few sandy beds are over 1" thick, most are 1/4" or less in thickness.	(1.4)	1407.6-1409-0	Limestone, white to lt greenish	
(6.4)	1179.1-1185.5	Shale dark gray	(2.5)	1409.0-1411.5	Shale black, minor green-gray	
(10.7)	1185.5-1196.2*	Shale, black (1,185.5 Core = 1,185 GR-N) *Note: "False Antrim" at 1185.5. A dark gray, nearly black satiny smooth (micaceous?) shale very brittle, soft, and relatively non-radioactive compared to true Antrim, in the base of the Bedford Shale.	(1.5)	1411.5-1413.0	Shale as above with white lime 1412.0 (6"), and calcareous greenish shale, 1411.5 (2"), 1412.8 (1"), 1412.9 (1").	
(20.6)	1196.0-1216.6	<u>Core #14 1196-1256' Cut 60' Rec 25.0'</u> Shale, black, v.f.grained, slippery smooth on bedding plane breaks, breaks into biscuits and thin tablets, poss. micaceous.	(9.5)	1413.0-1422.5	Shale, black, minor greenish calcareous, shale in thin beds throughout – beds below 1420 are cyclic grading up into lighter color and ending at top in abrupt change to dark above. Considerable pyrite.	
(1.5)	1216.6-1218.1	Shale, black and dark gray in thin interbeds.	(1.3)	1422.5-1423.8	Limestone white and light gray, brecciated with much calcite.	
(1.0)	1218.1-1219.1	Shale, dark gray to lt gray to gray green and green in descending gradation the last 1" is glauconitic and slightly calcareous.	(8.0)	1423.8-1431.8	Shale, black, as before, minor greenish, calcareous shale.	
DEVONIAN			Antrim Unit 1 C @ 1423			
Antrim Unit 6 @ 1224 GR-N			(2.0)	1430.0-1432.0	<u>Core #19 1430-1463' Cut 33' Rec 32'</u> Shale black, "reddish-streak" type pyritic	
Antrim			(1.6)	1432.0-1433.6	Shale, black, and green-gray	
(1.9)	1219.1-1221.0	(1,219.1 Core = 1,222 GR-N) Shale, black; top of zone is abrupt and sharp. (Core lost 1221-1256. Drilled up. Circulating samples after drilling 1256-1259 all chunks of black shale) <u>Core #15 1259-1289' Cut 30' Rec 29.2'</u>	(0.7)	1433.6-1434.3	Limestone, gray-green to dark gray, argillaceous, fossiliferous, carbonaceous parting, paper-thin common.	
Antrim Unit 5 @ 1254 GR-N			(4.2)	1434.3-1438.5	Shale black and dark reddish tan with pyrite and thin limestone or calcite.	
(28.5)	1259.0-1287.5	Shale, black, outside of core has a brownish cast, the shale is not as fine grained as black shale above; a limestone bed 1/2" thick with pyrite at 1265.5'.	(1.4)	1438.5-1439.9	Shale black and reddish-tan, banded, pyritic	
Antrim Unit 4 @ 1282 GR-N			DEVONIAN			
(0.2)	1287.5-1287.7	Shale, green gray calcareous, gradational	Traverse Group	(0.9)	1439.9-1440.8	(1,439.9 Core = 1,444 GR-N) Shale, green gray calcareous
			(1.7)	1440.8-1442.5	Limestone lt gray and dark gray, argillaceous	
			(3.9)	1442.5-1446.4	Shale, gray, limy; occasionally thin calcite bed	
			(4.1)	1446.4-1450.5	Shale, gray, very calcareous	
			(1.6)	1450.5-1452.1	Lime, gray, shaly	
			(2.7)	1452.1-1454.8	Lime, white and gray, finely xlyn variegated,	

		uneven wavy bedding.
(4.2)	1454.8-1459.0	Limestone, lt gray to white
(0.2)	1459.0-1459.2	Shale, dark gray
(0.5)	1459.2-1459.7	Limestone, tan and light gray
(2.3)	1459.7-1462.0	Dolomite, lt gray, vugular with chert, white in irregular masses. 4" vug, xly. lined 1460.51. T.D. Core 1462.0'
	T.D. Birdwell 1470.	= 1463 Geolograph = 1,462.0 Core measurement

APPENDIX I

C. J. Simpson, Lindeman No. 1, Permit No. 23583

Section 28, T14N, R12E, Greenleaf Twp., Sanilac County

Rotary Bushing Elevation: 789.0 feet above sea level

The following lithologic description covering basal Coldwater Shale beds downward into the top part of the Traverse Group was compiled by Geological Survey personnel from records and geophysical logs submitted by the company. Refer to Cross Section B, Well B 20, Part 4, and Appendix B, Well B 20.

	Thickness (feet)	Depth (feet)
MISSISSIPPIAN:		
Coldwater Shale:		
Shale as above; some limestone, brown, with vugular porosity; no shows	49 (723)	1329 RA.
Sunbury:		
Shale, dark brown to black, carbonaceous	62	1391 RA.
Berea:		
Sandstone, light gray, loosely cemented, fine grained, angular to subrounded	29	1420
Sandstone as above; some shale, light green	10	1430
Sandstone as above	20	1450
Sandstone as above; some shale, light gray and green; siltstone, gray, micaceous, arenaceous	63 (122)	1513 RA.
Bedford:		
Shale, dark brown to black, carbonaceous	47	1560
Shale, gray, fine grained, grading into sandstone, white, fine grained with calcareous cement	194 (241)	1754 RA.
MISSISSIPPIAN-DEVONIAN		
Antrim:		
Shale, dark brown, pyritic	16	1770
Shale, dark brown to black, carbonaceous, pyritic	150	1920
Shale as above, some limestone, white, coarse to medium grained; some shale, gray	10	1930
Shale as above; some limestone, brown, medium grained, very argillaceous	32 (208)	1962 RA.
DEVONIAN		
Traverse Group:		
Limestone, tan, fine grained; shale, gray, becoming calcareous	8	1970
Limestone, tan, crystalline; shale, gray, calcareous, smooth; some limestone, crinoidal, detrital	20	1990
TOTAL DEPTH		3357

APPENDIX J

Texaco, Inc., C. P. Scott No. 1, Permit No. 24789 Section 36, T16N, R12E, Col fax Twp., Huron County Rotary Bushing Elevation: 763 feet above sea level

The following lithologic description covering the Coldwater Shale beds downward into the Traverse Group was compiled by Geological Survey personnel from records and geophysical logs submitted by the company. Refer to Cross Section C, Well C 15, Part 3, and Appendix C, Well C 15.

	Thickness (feet)	Depth (feet)
MISSISSIPPIAN:		
Coldwater (?):		
Interbedded gray shales and siltstones	916	1280 Schj
Sunbury:		
Shale, dark gray to black (¾° Deviation @ 1378)	78	1358 Schj
Berea-Bedford:		
Sandstone, white, fine to medium grained, fair sortings	29	1387
Shale, black with some spore cases (DST #1 1360-1415 (Shut in 30 minutes, open 1 hour) recovered 660' Salt Water IHMP 731#; ICIP 616#; IFP 44#; FFP 359#; FCIP 600#; FHMP 715#)	42	1429
Shale, gray, micaceous	18	1447
Shale, gray to black, micaceous; some spore cases	111	1558
Sandstone, light gray to white, tan in upper part, fine grained slightly friable with trace calcareous cement: some interbedded Shales, dark gray to black, gray to green and light gray	216 (416)	1774 Schj
MISSISSIPPIAN-DEVONIAN:		
Antrim:		
Shale, black	29	1803
Limestone, black, shaly	5	1808
Shale, black	67	1875
Shale, gray	25	1900
Shale, black and gray	39 (165)	1939 Schj
DEVONIAN:		
Traverse:		
Limestone and Dolomite, gray to gray brown, fine to medium crystalline, interbedded with Shales, gray, gray green, dark gray, calcareous	341	2280
TOTAL DEPTH		7260

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Factors for converting from METRIC to U. S. Customary and U. S. CUSTOMARY					
When You Know	(Symbol)		Multiply By	To Find	(Symbol)
LENGTH					
millimeters	(mm)	X	0.039	inches	(in.)
centimeters	(cm)	X	0.394	inches	(in.)
meters	(m)	X	3.281	feet	(ft.)
meters	(m)	X	1.094	yards	(yd.)
kilometers	(km)	X	0.621	miles	(mi.)
inches	(in.)	X	2.540	centimeter	(cm)
feet	(ft.)	X	30.480	centimeter	(cm)
yards	(yd.)	X	0.914	meters	(m)
miles	(mi.)	X	1.609	kilometers	(km)
AREA					
square centimeters	(cm ²)	X	0.155	square inches	(in. ²)
square meters	(m ²)	X	10.764	square feet	(ft. ²)
square meters	(m ²)	X	1.196	square yards	(yd. ²)
square kilometers	(km ²)	X	0.386	square miles	(mi. ²)
square inches	(in. ²)	X	6.452	square centimeters	(cm ²)
square feet	(ft. ²)	X	0.093	square meters	(m ²)
square yards	(yd. ²)	X	0.836	square meters	(m ²)
square miles	(mi. ²)	X	2.590	square kilometers	(km ²)
MASS (weight)					
grams	(g)	X	0.035	ounces	(oz.)
kilograms	(kg)	X	2.210	pounds	(lb.)
ounces	(oz.)	X	28.350	grams	(g)
pounds	(lb.)	X	0.454	kilograms	(kg)
VOLUME					
milliliters	(ml)	X	0.352	fluid ounces	(fl.oz.)
liters	(l)	X	2.113	pints	(pt.)
liters	(l)	X	1.057	quarts	(qt.)
liters	(l)	X	0.264	gallons	(gal.)
cubic meters	(m ³)	X	35.314	cubic feet	(ft. ³)
fluid ounces	(fl. oz.)	X	28.383	milliliters	(ml)
pints	(pt.)	X	0.473	liters	(l)
quarts	(qt.)	X	0.946	liters	(l)
gallons	(gal.)	X	3.785	liters	(l)
gallons	(gal.)	X	0.0283	cubic meters	(m ³)
TEMPERATURE					
Fahrenheit	(°F)	X	(°F-32)/1.8	Centigrade	(°C)
Centigrade	(°C)	X	(1.8°C+32)	Fahrenheit	(°F)