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STRATIGRAPHY OF THE UPPER DEVONIAN-LOWER MISSISSIPPIAN OF MICHIGAN

Topical Report

By

James H. Fisher
Department of Geology
Michigan State University

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ABSTRACT

A stratigraphic inventory was made of the Devonian-Mississippian black shales of Michigan for their possible future use as a source of oil or gas. Structure contour and isopach maps were made to scales of 1/1,000,000 and 1/250,000. Lithofacies maps were constructed on the 1/1,000,000 scale. An east-west cross-section of central Michigan is included. A portion of eastern Michigan was mapped at the 1/250,000 scale to show bedrock topography, bedrock cover, and drilling depths to the Antrim.

All structure contour and isopach maps were contoured by computer. The remainder were drawn by hand.

The major stratigraphic conclusions are:

1. A minor unconformity is probably present at the top of the Traverse limestone in western Michigan.

2. The Traverse shale has closer affinities to the overlying Antrim than it does to the Traverse limestone.

3. The Antrim should probably be divided into an upper and lower Antrim with a tongue of Ellsworth shale coming in from the west to divide the Antrim.

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INTRODUCTION

Purpose

The overall purpose of the Dow Project is to assess the possiblity of obtaining gas or oil from the black shale of the Antrim Formation of Michigan by means of *in situ* combustion. My portion of the project is a stratigraphic and structural analysis of the interval from the base of the Traverse Formation to the base of the Coldwater Formation in order to establish a resource inventory of these black shales in Michigan.

Area of Study

This study is limited to the major portion of the Michigan Basin which includes the Lower Peninsula of Michigan, northwestern Ohio, and a part of northern Indiana (Fig. 1).

Stratigraphic Section

The stratigraphic section involving the black shales, under consideration for *in situ* processing, extends from the top of the Traverse limestone to the base of Coldwater Formation (Fig. 2). The age determinations of the subsurface formations in the Michigan Basin are still in a rather primitive stage. All of the fossil determinations have been made on the surface formations around the perimeter of the basin. In many cases these surface formations represent a thin, atypical facies of a much thicker subsurface unit and, because of transgressive-regressive relationships, may give an age determination for only a portion of the formation. With the exception of the paleontological work of Ehlers and Kesling

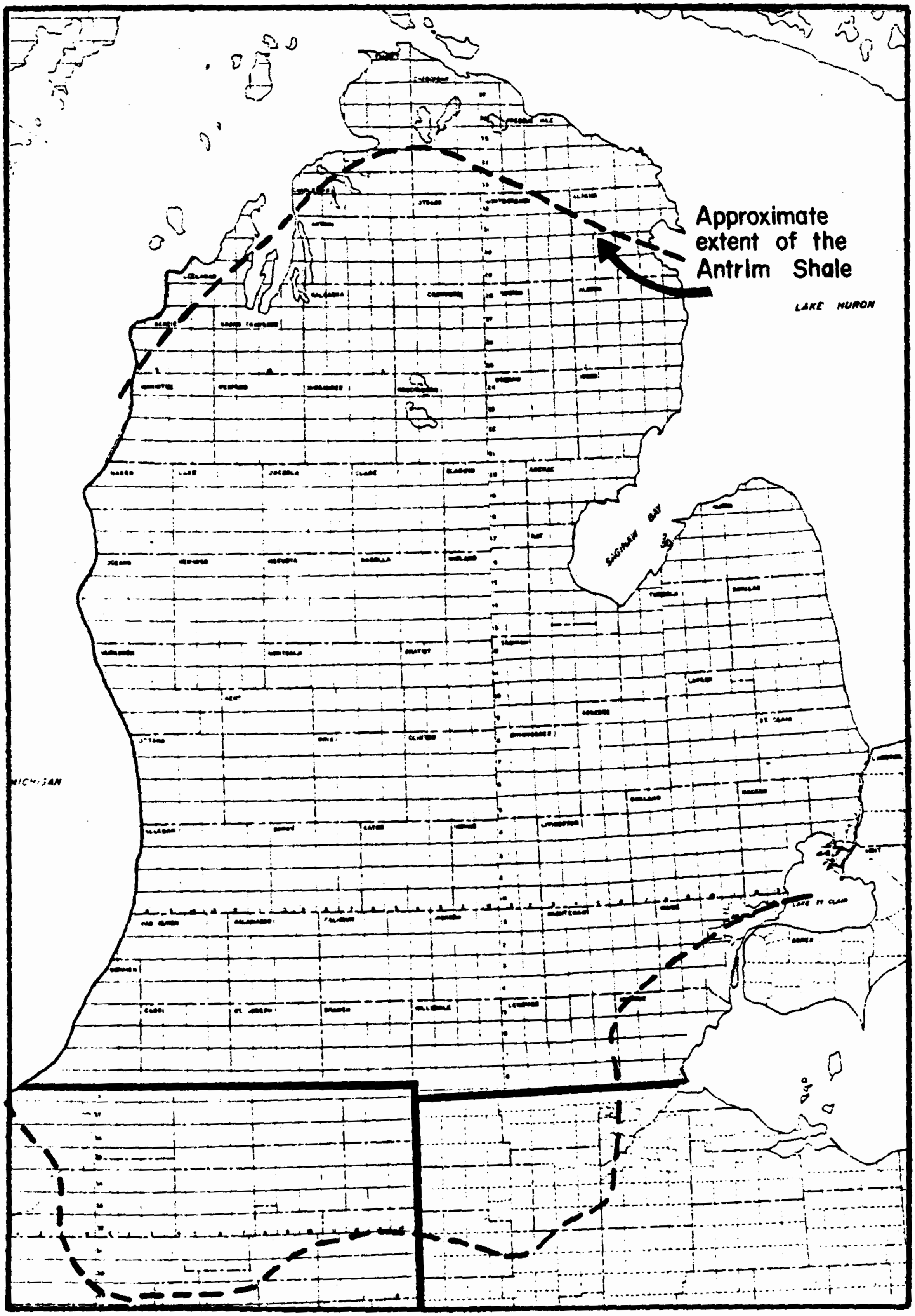

Figure I - Area of Study

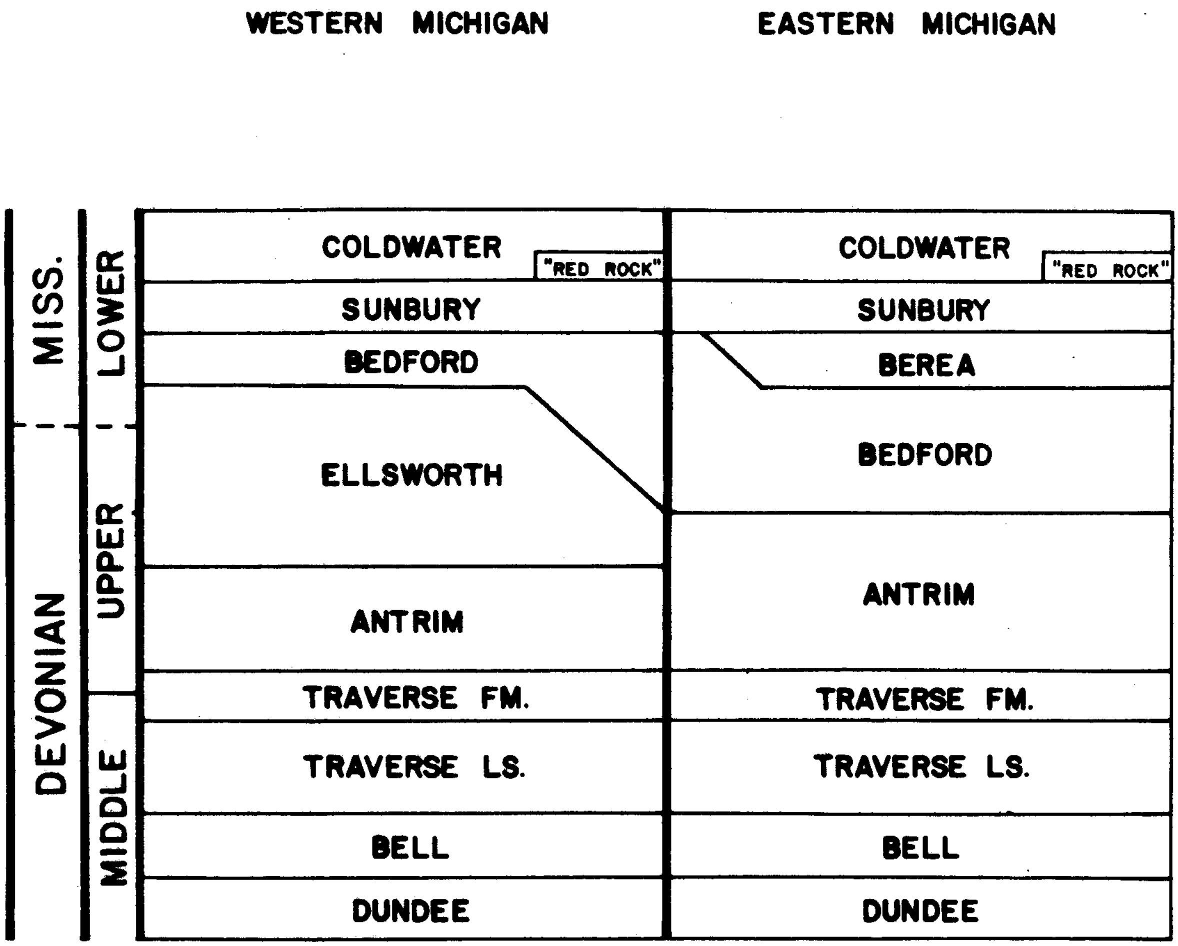

Figure 2 - Stratigraphic section.

(1970) on the Middle Devonian of northeastern Michigan, virtually no microfossil work has been done in the subsurface units of Michigan. As a consequence there is a dichotomy in Michigan nomenclature - a very detailed surface section with many stratigraphic units, most of which cannot be recognized in the subsurface; and a less detailed, simpler subsurface section based primarily on mechanical logs and conforming to the stratigraphic terminology employed by the petroleum industry. The latter system has been used in this study.

Data Sources

The Dow Chemical Company at the beginning of its contract with the DOE, established a data format as follows:

1. All of the isopach and structure contour maps were to be made on the basis of gamma ray logs. Dow asked Petroleum Information Inc., Denver, Colorado, to furnish a list of all of the gamma ray well logs in Michigan that penetrated the complete Antrim shale unit, with the provision that only one well per section be listed. This set of logs was then purchased and formed the basis for the isopach and structure contour maps in this study. It is important to understand that although some 33,000 wells have been drilled in Michigan, most of these were drilled during the period 1925-1945 when it was not customary to mechanically log shallow holes. This early Michigan development was in the center of the basin and since that area has been relatively dormant in recent years, there are very few gamma ray log data points in that region. Conversely, a great number of logs are available in certain areas of concentrated drilling where recent developments have occurred, namely -Albion Scipio (1957), St. Clair County(1960), and the Northern Reef Trend (1969). The great concentration of data in some areas and the

scarcity in others creates problems in computer mapping, and where there is a paucity of data in the center of the basin, the computer can only present a generalization of the true geologic trends.

2. In the matter of the data sources for the lithofacies maps, we were left to our own devices. Sample sets were obtained from the Michigan Geological Survey, Michigan State University, and the University of Michigan. The distribution of these data points is shown in Figure 3. All color determinations of well cuttings were based on the Munsell chart.
3. Data for the bedrock maps were obtained from logs of wells drilled for oil and gas, written well records for oil and gas wells, core hole records (obtained primarily from Dow) and from water well records. The water well records were generally poor and were incorporated in the maps only when supported by better data from surrounding sources.

Base Maps

Two different base maps were employed in this survey. The 1/1,000,00 base is supposedly an Albers-Equal-Area projection. It is an expanded version of a portion of the base map used for the Geologic Map of the United States. The other base used for the 1/250,000 quadrangles is a Transverse Mercator projection employed by the U.S. Geological Survey in most topographic mapping (Greenhood, 1944) (Tau Rho Alpha and Gerin, 1978).

Oil and gas wells are located by a township and range system. The 1/1,000,000 map has no township and range system. The 1/250,000 quadrangles have an incomplete township and range net. In view of this it was decided to locate wells by latitude and longitude. A list of the latitude-longitude locations of all the wells utilized in this program was obtained from Petroleum Information Inc.

Computer map plotting operates on a system of Cartesian coordinates. All geographic map projections are compromises in an attempt to portray a spherical

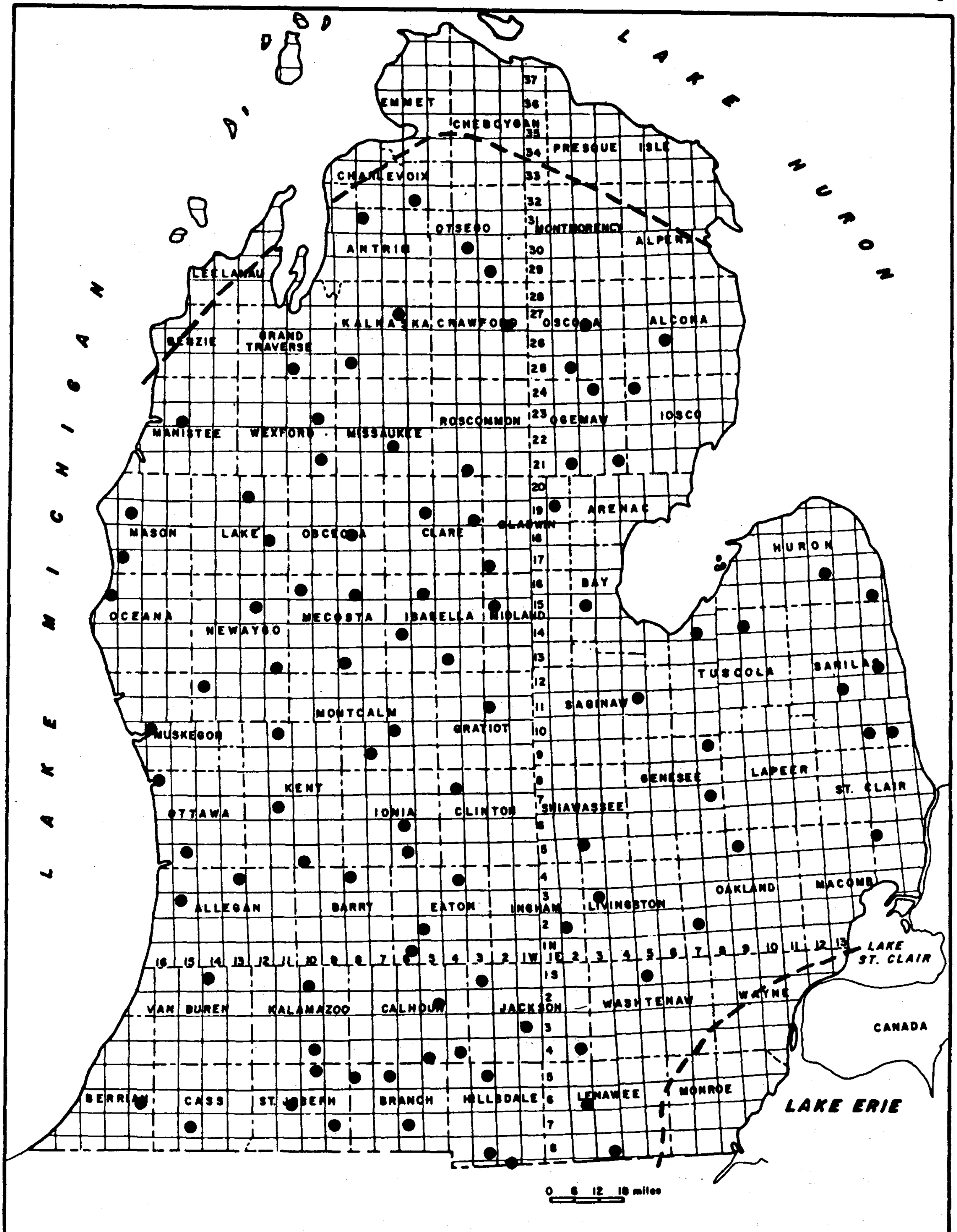

Figure 3 - Data points for lithofacies maps.

surface on a flat piece of paper. When dealing with small areas on either the Albers-Equal-Areas or the Transverse Mercator maps, the distortions are small and can usually be ignored in computer mapping. However, in an area the size of Michigan the convergence of the meridians is considerable and the resulting distortion cannot be ignored. To the naked eye, a 1/250,000 quadrangle sheet appears to be a rectangle. Actually, it is a trapezium and when one attempts to juxtapose a number of these quadrangles, ever-widening gaps appear in a northward direction between adjoining maps. The problem of gridding these maps for computer contouring is a major effort. The computer must sense points across the gap on an adjoining map and construct the contours in such a fashion that they will meet from one map to another.

In solving this problem for the 1/250,000 quadrangles a Universal Transverse Mercator Grid system (UTM) was used for the initial mapping coordinates. This system, developed following World War II, divides the globe into thirty 6^{o} wide zones. Each zone is then projected independently as a Transverse Mercator map and each linked at the Equator. A meter grid is then laid across the "global" projection (Greenhood, 1944, p. 132-134). We converted the latitude and longitude for each well supplied by Petroleum Information Inc. into UTM northings and eastings with a Fortran IV program (Program number J 380 by Jack Wannan) acquired from the U.S.G.S. Topographic Branch. Unfortunately, because Michigan straddles two zones (numbers 16 and 17), further manipulation was necessary. Because the UTM grid is continuous around the world we simply "tied" zones 16 and 17 together by zeroing zone 17 at 41^{o}lat.-84^{o} long. and adding zone 17 eastings to the 41^{o} lat.-84^{o} long. easting (maximum of zone 16) from zone 16. Now the UTM's could be converted to inches (the plotter is calibrated in inches) and set to an arbitrary origin at 41^{o} lat.-88^{o} long. (the southwest corner of the Chicago quadrangle sheet). The state of Michigan could then be gridded and computer mapped as a unit with each 1/250,000 sheet, defined by latitude and longitude, pulled out and expanded to the proper overlay size.

We also acquired a conversion program for the 1/1,000.000 maps (Program number J 207 by Jack Wannan); however, our data points did not plot properly and we developed serious doubts that the 1/1,000,000 maps were indeed an Albers-Equal-Area projection. We finally plotted it as though it were a Mercator projection and this worked out nicely.

The software utilized in contouring was Calcomp's-General Purpose Contouring Program (GPCP) 1971, revised 1973.

Mapping Methods

The 1/1,000.000 and 1/250,000 isopach and structure contour maps were all constructed by the computer, with the exception of the Ohio and Indiana portions of the basin which were added by hand. All the other maps were hand constructed. When preparing isopach maps via the computer, the computer often has difficulty in placing the zero contour at the wedge edge of a unit, expecially when data points are sparse. To overcome this, we suppressed the zero contour on all isopach maps and drew it in by hand, based on data from our lithofacies maps. This proved to be a more accurate method of contouring.

Previous Studies

Writers who have dealt with the Devonian-Mississippean shales of Michigan or with the structural configuration of the Michigan Basin are listed under references. Particular note should be made of the work of Cohee (1944, 1951, 1965), Ells (1978), and Lilienthal (1978).

STRUCTURE

Regional Setting

The Michigan Basin is an intra-cratonic basin characterized by a round to slightly oval outline, relatively thin sedimentary column, a prevalence of carbonates in the section, low surrounding uplifts, a depocenter rather than a long axis, and relatively mature sediments. In contrast to tectonic basins, where subsidence is usually controlled by several master faults, the sinking of the Michigan Basin is probably related to mass transfers of material in the mantle. The response of the overlying basement is to develop faults or to renew movement along pre-existing faults. However, the displacement along most of these faults is minor -- comparable to the shearing in a deck of cards in which each displacement is small. The result is a series of horst and graben features in the basement which is manifested in the overlying sediments as anticlines and synclines.

The positive features surrounding the Michigan Basin (Fig. 4) have never been high rugged mountains, at least not since the onset of Cambrian time. The Paleozoic section of Michigan is almost totally lacking in arkose, conglomerate, or very coarse sandstones.

The Wisconsin Highland, Canadian Shield, and Algonquin Arch are all Precambrian features. The Kankakee and Findlay Arches are not apparent, as other than margins of a sinking basin, until Middle Devonian time, when they become mildly positive features. The Kankakee structure, while it is called an arch, has more of a platform character. The Findlay Arch has a distinct upward arching. However, by Antrim time, both the Kankakee and Findlay Arches had subsided and in all probability, only the Cincinnati Arch proper was a land area (Fisher, 1953).

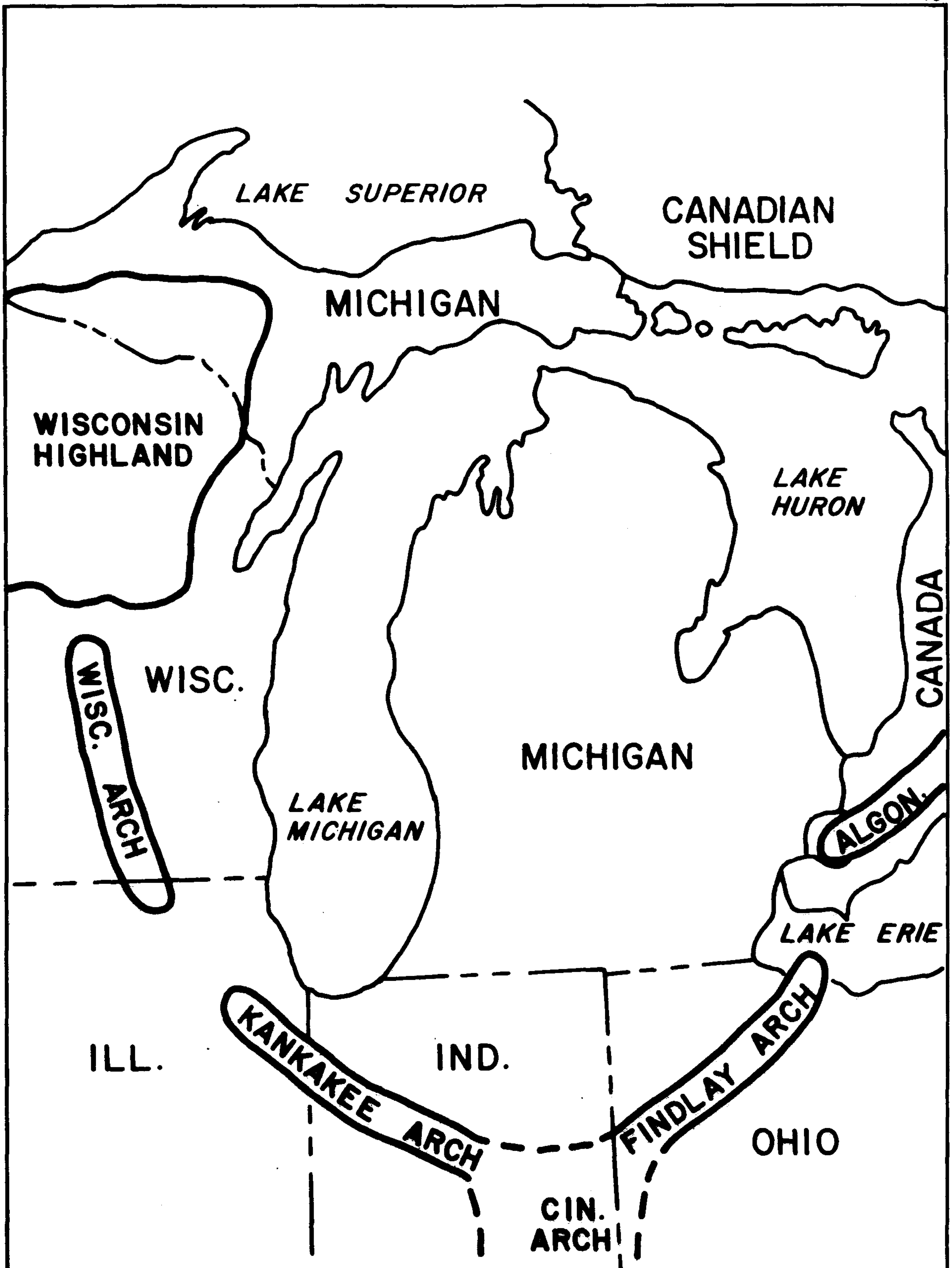

Figure 4 - Structural Elements Surrounding the Michigan Basin.

Michigan Basin

As was previously noted in the discussion of data acquisition, the coverage in the central portion of the Basin is sparse. Under these circumstances, the structure contour maps (Plates 1 through 6) can only be expected to show the general structural trend of the Basin plus a few major features. The Dundee map (Plate 5) is typical of most of the structure maps (save the Antrim and Trenton). The Dundee structure shows a bowl shaped, slightly ovate basin, trending northwest-southeast with a depocenter just west of Saginaw Bay. A major feature, the Howell anticline, is shown trending northwest-southeast through the eastern portion of Livingston County and into the northwest corner of Wayne County. A smaller, parallel feature, the Lucas-Monroe monocline, extends from the western margin of Livingston County, southeast through Washtenaw County and into Monroe County where it turns sharply southward and parallels the Monroe-Lenawee County line. A flexure (or fault) can be observed with an almost north-south trend through Sanilac and St. Clair counties. The high extending from Saginaw Bay, northwesterly through Ogemaw County is the West Branch Anticline. A prominent structural nose is evident in Charlevoix County and a similar feature is seen in Leelanau County. Although the central basin area is depicted as featureless, this is a function of insufficient data. An adequate data net would develop a pattern of many small northwest trending anticlines and synclines.

The Trenton structure (Plate 6) differs in that far fewer data points are available for this relatively deep formation. One can still see the Howell and Lucas-Monroe structures and the Sanilac-St. Clair flexure, although these features appear in subdued form. The West Branch anticline is not shown since only two of the wells in that field reach the Trenton. A single high in Ogemaw County is the only indication of this structure. The irregularities shown in Alpena, Antrim Benzie, and Mason counties are not computer aberrations - these are valid structures. Unfortunately, the anomalies shown, in almost all cases, have been established by a single deep well. A fault is present in the Trenton in Lucas County in northern Ohio. Extensive drilling in the old Trenton field has established that the Lucas-Monroe monocline becomes a fault in the area shown.

The Antrim structure (Plate 3) is comparable to the other structural maps except that there are a series of irregularities extending from northern Kent County, northward to Antrim county. This is false structure and is created by the arbitarary delineation of the Antrim-Ellsworth boundary. This problem is discussed in detail in the section on stratigraphy.

STRATIGRAPHY

Traverse Limestone

The Traverse limestone in western Michigan is primarily a gray to gray-brown, fossiliferous limestone, some 400 to 500 feet thick with minor amounts of gray shale. The contact with the overlying Traverse shale is usually sharp and there is some evidence of erosion. Proceeding eastward to central Michigan and Isabella County (Plate 7), a small shale break appears below the major limestone log marker at the top of the Traverse limestone and increasing amounts of gray shale are evident in the lower part of the formation. Continuing on to Midland County, the shale units near the top and at the bottom have thickened considerably. The shale continues to thicken at the expense of the limestone until in the easternmost section in Sanilac County, the formation is almost all shale with limestone stringers concentrated toward the middle of the unit. Correlations of the top of the Traverse limestone are difficult in this eastern area and many geologists solve the problem by using the term Traverse Group for the first gray shale or limestone encountered below the solid black Antrim shale.

Traverse Formation

The term Traverse Formation or sometimes Traverse shale is utilized extensively in western and northern Michigan for a light-gray, calcareous shale with stringers of limestone that lies between the massive Traverse limestone and the overlying Antrim shale. The term is not used in southeastern Michigan because of the difficulty encountered in separating it from the shaly facies of the Traverse limestone. The Traverse Formation or Traverse shale is in many areas a difficult stratigraphic unit to define. Thin limestone stringers can thicken abruptly and create confusion in determining the contact with the Traverse limestone. The Traverse shale is definitely gradational with the overlying Antrim and has many thin zones of black shale in the upper part of the unit. These black shale stringers are so numerous in some areas that an arbitrary convention must be utilized of picking the base of the Antrim at the first thick, solidly black unit of shale.

Despite the name, Traverse Formation, this unit is gradational with and has far more affinities with the Antrim than it does with the underlying Traverse limestone. Plate 13 shows the highly irregular pattern of thickening and thinning, averaging 50-60 feet, with the thickest zones in southwestern Michigan. I would interpret the Traverse Formation as transitional unit between the shallow environment of the Traverse limestone and the deeper water (perhaps 100 feet) phase of the Antrim.

Antrim

The Antrim shale is generally black, hard, carbonaceous, and thinly bedded. The color ranges from gray to black. Brown Antrim was not observed as a major component of the shale although minor streaks of brown can be seen in some of the strip logs. One strip log from Genesee County appeared to have a substantial section of brown shale but closer examination revealed this to be a brown oxide coating on black shale fragments. The color variations of the shale in the Antrim are shown in Plate 18. Pyrite, spores, fish scales, and fragments of Lingula shells are common throughout the Antrim. Stringers of argillaceous limestone ranging in color from light-gray to brown and black are present throughout the Antrim. Downward in the section, as one approaches the top of the Traverse shale, the limestone stringers become more abundant, thicker, and less argillaceous. Plate 19 shows the percentage of carbonate and the color of the carbonate (not the shale). Where the basal portion of the Antrim contains black and gray shale, the gray shale is the same color as that of the underlying Traverse shale.

The isopach map of the Antrim (Plate 12) has an odd looking anomaly trending northward from Kent County to Emmet County. This is entirely synthetic and is based on a Michigan custom of using the term Antrim in central and eastern Michigan for everything between the Traverse Formation and the Bedford. In western Michigan they describe Antrim overlain by Ellsworth. The problem arises in just how far east do you use the term Ellsworth? The criterion employed is the shape of the gamma ray curve which for typical Ellsworth is fairly uniform (Plate 7, well number 1). Going eastward, black shales appear at the top of the "Ellsworth" section and have a radioactive response high enough to go off scale (Plate 7, well number 3), but would still be identified as Ellsworth. By the time you reach well number 4 in the eastern part of this same county, Mecosta, the highly radioactive shales at the top of the section have thickened to such an extent that most workers would designate the whole section from Bedford to Traverse Formation as Antrim.

These decisions are very subjective and they lead to unusual map configurations such as the anomaly on the Antrim isopach map (Plate 12). My instructions were to use traditional Michigan stratigraphy in constructing the contour maps and this I have done. However, in the east-west cross-section (Plate-7) I have departed from traditional nomenclature and suggested that we designate an upper and a lower Antrim unit. This leads to a much simpler explanation geologically and does not require the physical barriers (structural or topographic) postulated by some writers in an effort to separate Ellsworth lithology from Antrim lithology. In my view, an Antrim black shale sea was present across the entire state. A mild uplift, or perhaps a change in the course of a major river, occurred to the west of the basin, sufficiently distant that only the pro-delta sediments reached Michigan to form the Ellsworth. As the flow of Ellsworth sediment ceased, the black shale sea transgressed to the west and partially covered these deltaic beds. The cross-section (Plate 7) shows the probable extent of the Ellsworth delta and the subsequent transgression of the Antrim facies across a portion of it. The color variation map of the Antrim (Plate 18) shale supports this view - black shale on the east for the whole Antrim section, black shale on the west where we are only dealing with the lower Antrim, and a mixture of gray and black in between which in reality is a dominantly gray Ellsworth tongue between dominantly black Antrim units.

Ellsworth

The Ellsworth is usually a soft, fissle, slightly calcareous, gray shale. Some of the shale might be described as greenish-gray but no definitely green shale, as defined on the Munsell chart, was encountered. Limestone and dolomite stringers are common (Plate 20) and portions of the limestone are oolitic. A minor amount of sandstone was detected in one well in Grand Traverse County. The Ellsworth isopach map (Plate 11) shows the same artificial anomaly, in this case a cut-off, as was previously described in the discussion of the Antrim. The Ellsworth reaches a maximum thickness of approximately 850 feet.

Bedford

The Bedford is generally a gray shale. It is often silty and sandy and in a few areas (Plate 17) is more than 50% sand. Where the Berea overlies the Bedford, the upper Bedford is usually sandy and grades upward into the Berea. There are a few sections of Bedford in which the basal portion is dark-gray to black. This may represent reworked Antrim. The Bedford isopach map shows a general pattern of thinning from east to west; however, there are some notable thickenings of the unit near the distal portion of the delta, namely, Kent and Kalamazoo counties and Steuben County in Indiana. The Bedford is shown as extending to Oceana and

Muskegon Counties on the western edge of Michigan. This is in agreement with Ells (1978) but is a considerable extension beyond the limit set by Cohee(1951). There is a log marker that can be traced from the area of typical Bedford in eastern Michigan, all the way to the western edge of the state.

Berea

Most of the Berea is a light-gray, fine-grained sandstone and siltstone. Interbedded with the sandstones and siltstones are beds of gray shale similar to those in the underlying Bedford. In some areas the shale beds constitute most of the unit (Plate 16). Minor beds of limestone are present in the Washtenaw County area. A three-fold subdivision of the Berea is possible in the area of Michigan southeast of Saginaw Bay. The basal Berea is a light-gray sandstone or siltstone, usually shaly, often micaceous and pyritic. The middle unit is a distinct, friable, fine-grained sandstone. The upper unit is similar to the basal unit except that it lacks pyrite and has a lower percentage of shale. The coarsest grain sizes encountered in the Berea were in Sanilac and Lapeer Counties. The thickest sections of Berea are also in these two counties (Plate 9).

Sunbury

The Sunbury is generally black, carbonaceous, and thinly bedded. The color variation ranges from black to gray (Plate 15). Pyrite is occasionally present. Under low magnification (10X) no spores or other microfossils were observed. The unit consists entirely of shale. In portions of western Michigan where Bedford is absent and Sunbury overlies the Ellsworth, a gradational contact is present. The thickest Sunbury is in Huron and Sanilac Counties (Plate 8) where it reaches 140 feet. Over the remainder of the state it is less than 50 feet with the exception of an anomalous thick in Kent County.

Coldwater Red Rock

At the base of the Coldwater shale there is a distinct red shale unit usually containing thin stringers of reddish limestone or dolomite. It is present over most of Michigan although it is best developed in the western half of the state. It is a distinctive marker on gamma ray logs and is locally known as the "red rock marker." It is quite useful, especially where the Sunbury becomes very thin and Coldwater shales have to be distinguished from the Ellsworth.

CONCLUSIONS

In Middle Devonian time, Michigan was covered by warm shallow seas in which thick, fossiliferous carbonates were deposited, culminating in the Traverse limestone. Apparently somewhat deeper water was present in southeastern Michigan which created the dominant shale facies of the Traverse limestone in that area. A minor unconformity was developed in southwestern Michigan either by a mild uplift or a slight lowering of sea level - it is not possible at this stage to determine whether this was terrestrial or submarine erosion. This is the probable boundary between Middle and Upper Devonian. Following this, the area was either covered again by the sea or the sea became slightly deeper than it had been during the deposition of the Traverse limestone, because now we see mostly shale with occasional stringers of limestone. Further deepening of the sea occurred (to perhaps 100 feet) and a stagnant black shale sea was established.

Two major events created lateral shifts of the black shale environment. The first was the invasion of the Ellsworth delta from the west, which later waned and permitted a partial return of black shale conditions to much of western Michigan. The second event was the invasion of the Berea-Bedford delta from the east. It is interesting to note the re-establishment of black shale conditions above the Berea-Bedford during Sunbury time.

The Devonian-Mississippian boundary apparently lies in the lower part of the Bedford of eastern Michigan (DeWitt, 1970).

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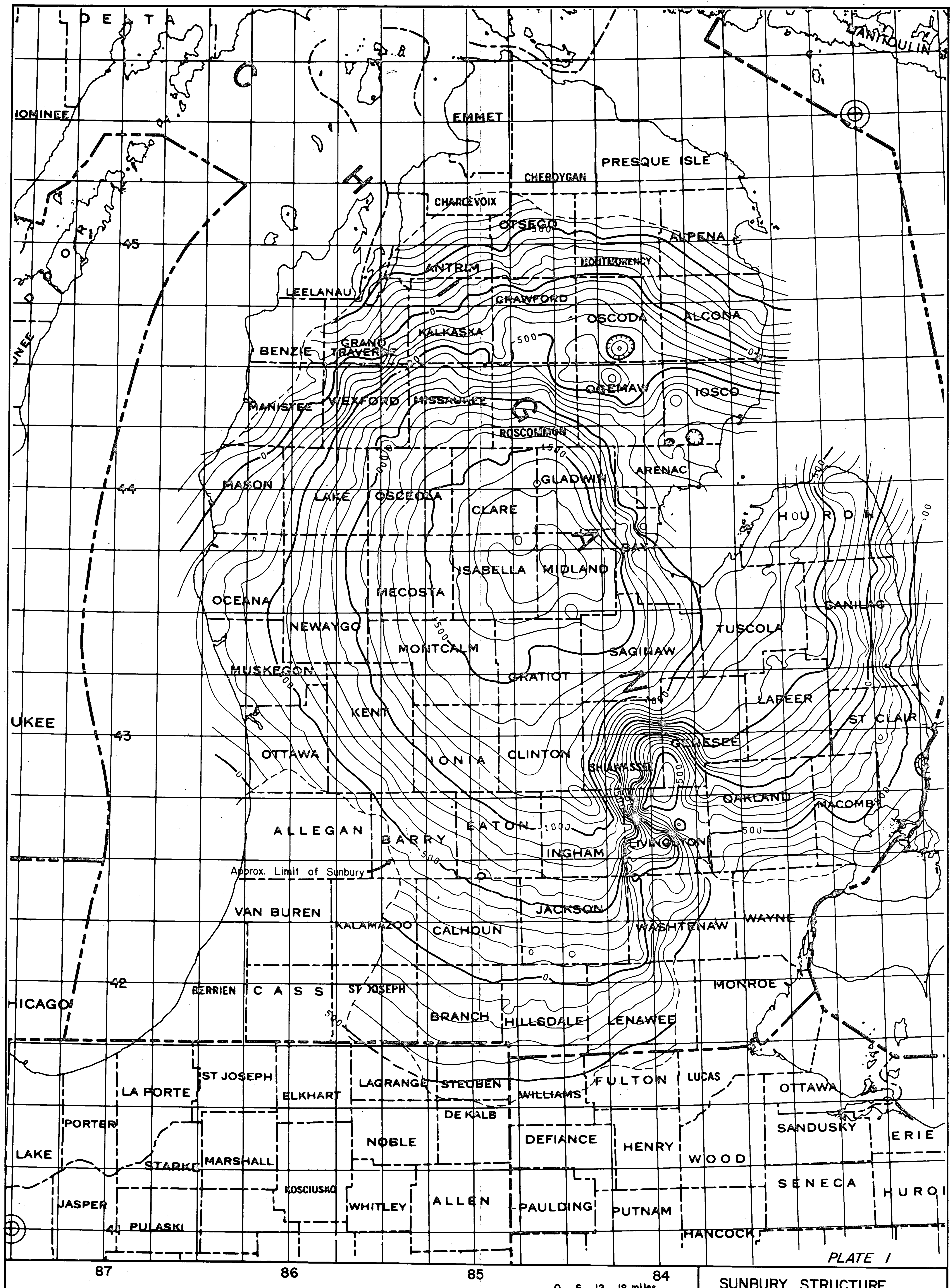

SUNBURY STRUCTURE
Contour interval 100 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

PLATE 2

BEREA STRUCTURE
Contour interval 100 ft.

PREPARED BY:
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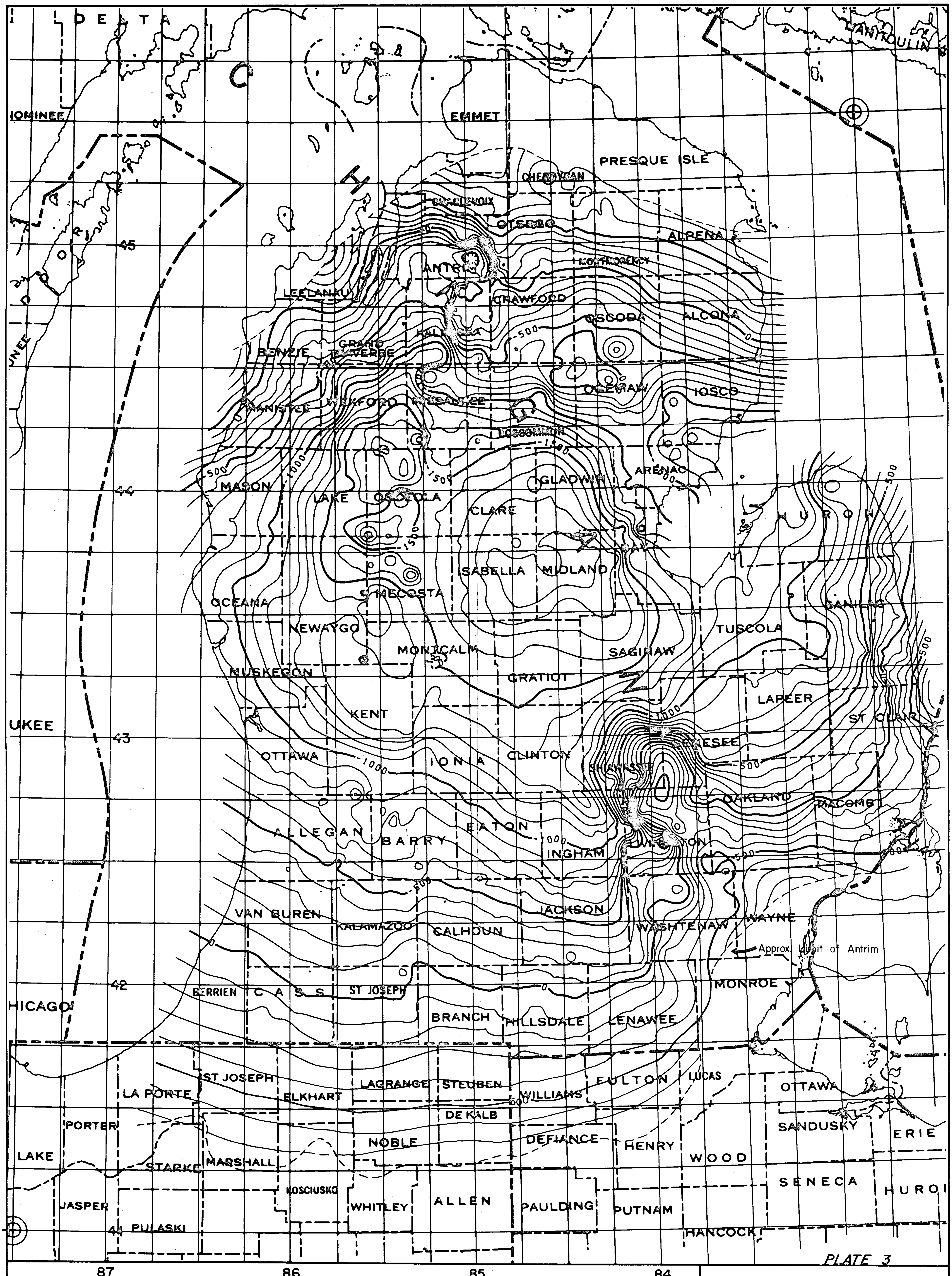

PLATE 3

ANTRIM STRUCTURE
Contour interval 100 ft.

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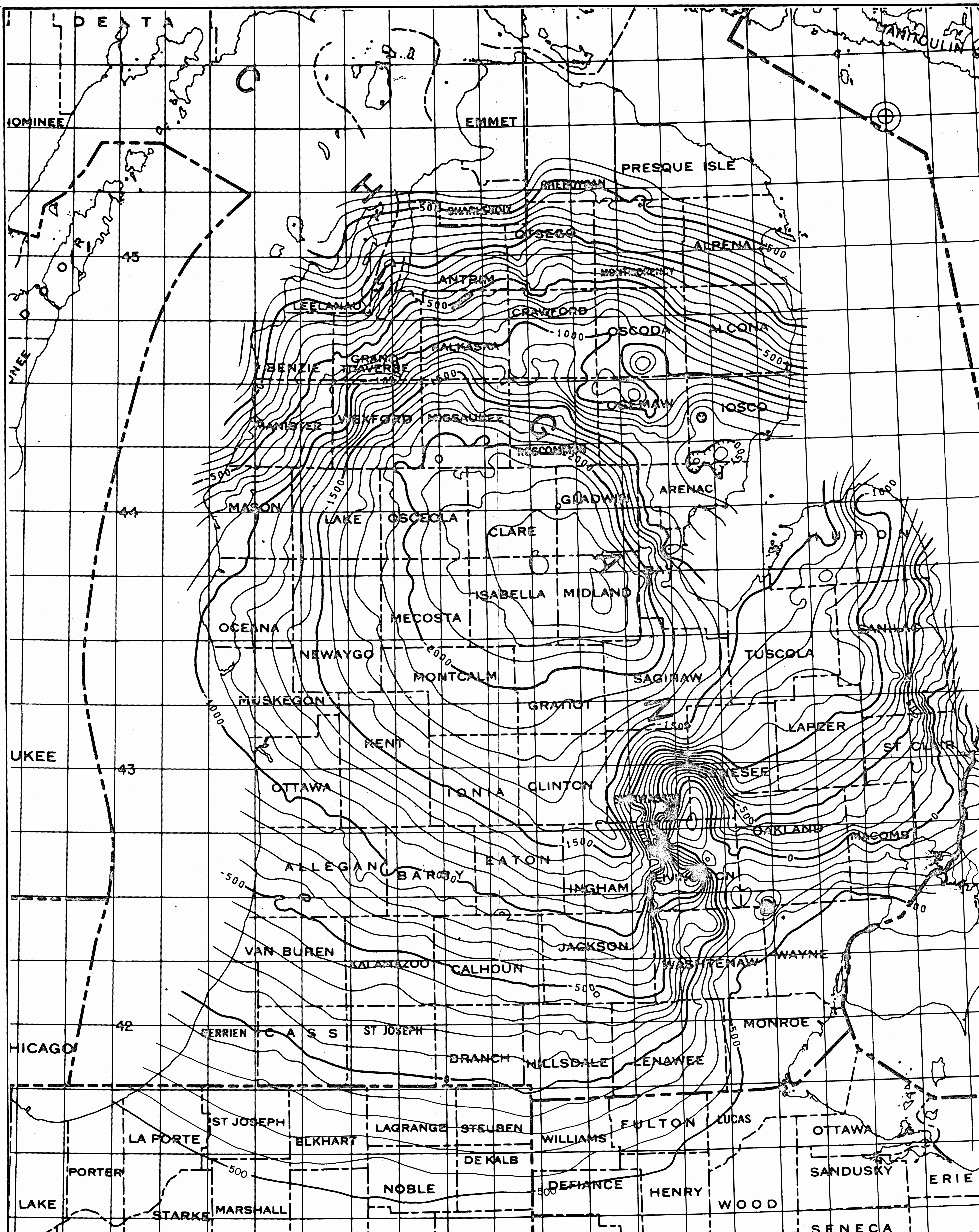
For Dow Chemical Co.
DOE Report No. FE 2346-80



TRAVERSE LS STRUCTURE

Contour interval 100 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

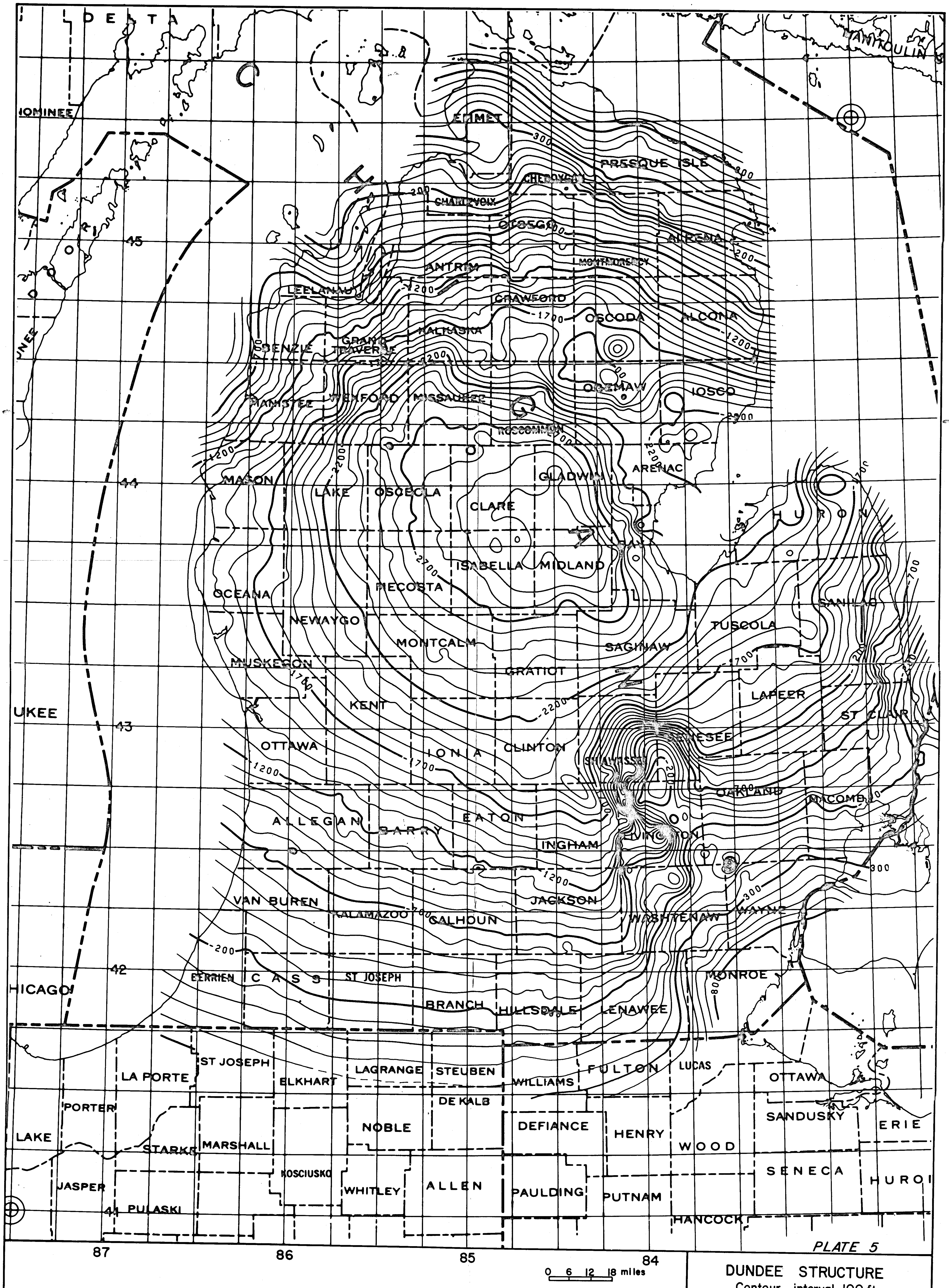
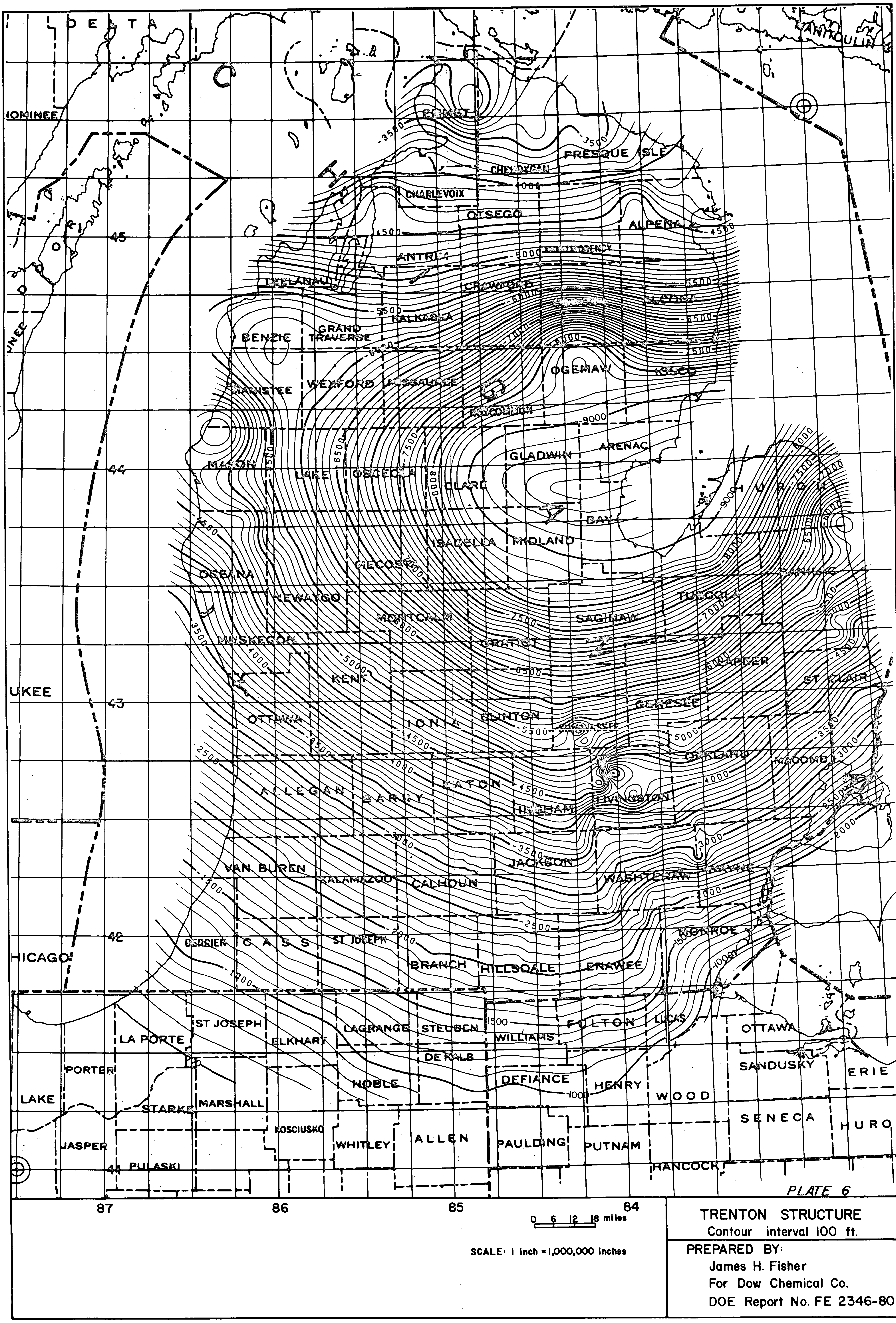


PLATE 5

DUNDEE STRUCTURE
Contour interval 100 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80



TRENTON STRUCTURE
Contour interval 100 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

PLATE 7

EAST-WEST CROSS-SECTION
Horizontal scale - none
Vertical scale - 1/2 inch = 100 foot

PREPARED BY:
James H. Fisher
For Dow Chemical Company
DOE Report No. FE 2346-80

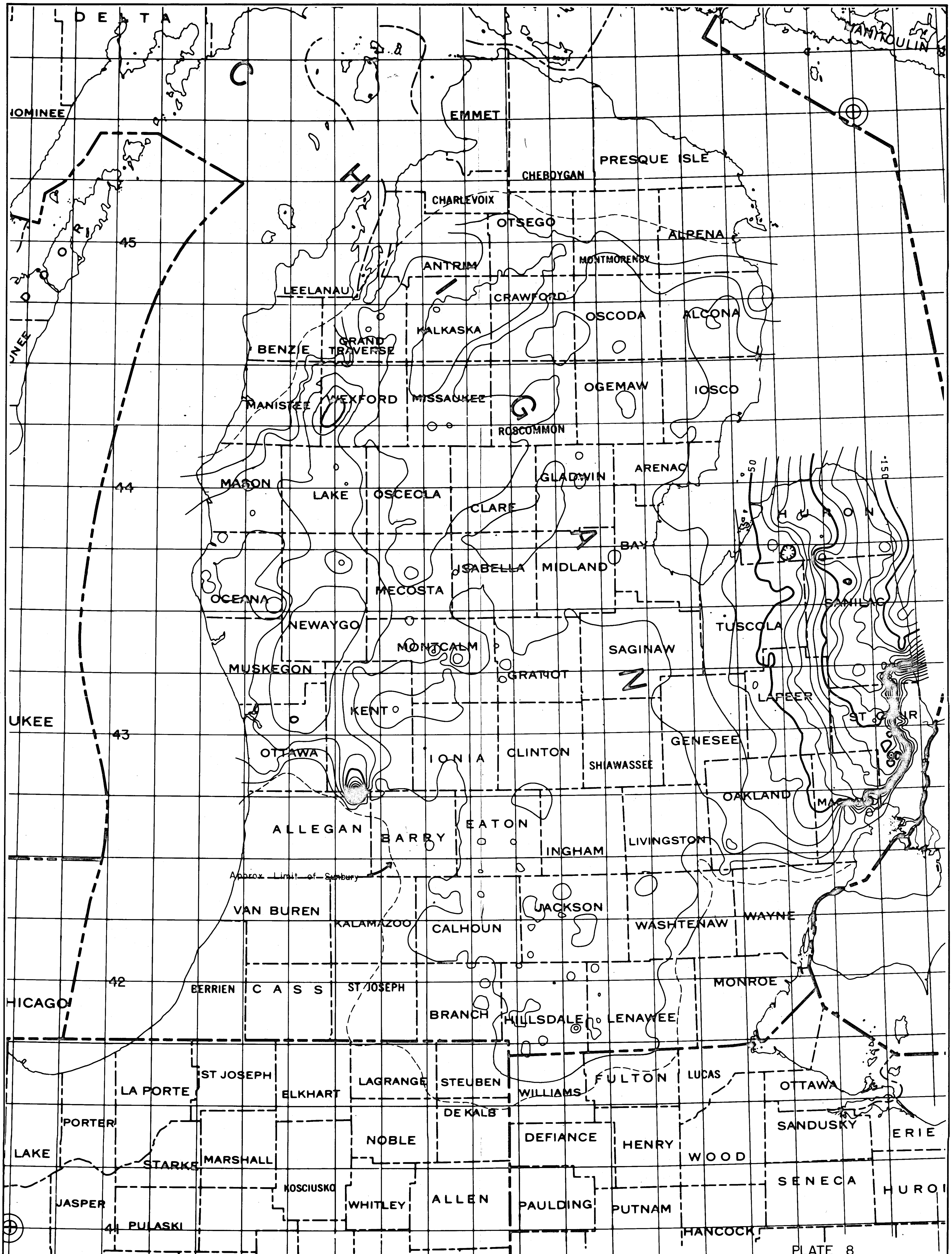


PLATE 8

87 86 85 84

0 6 12 18 miles

SCALE: 1 inch = 1,000,000 inches

SUNBURY ISOPACH
contour interval 10 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

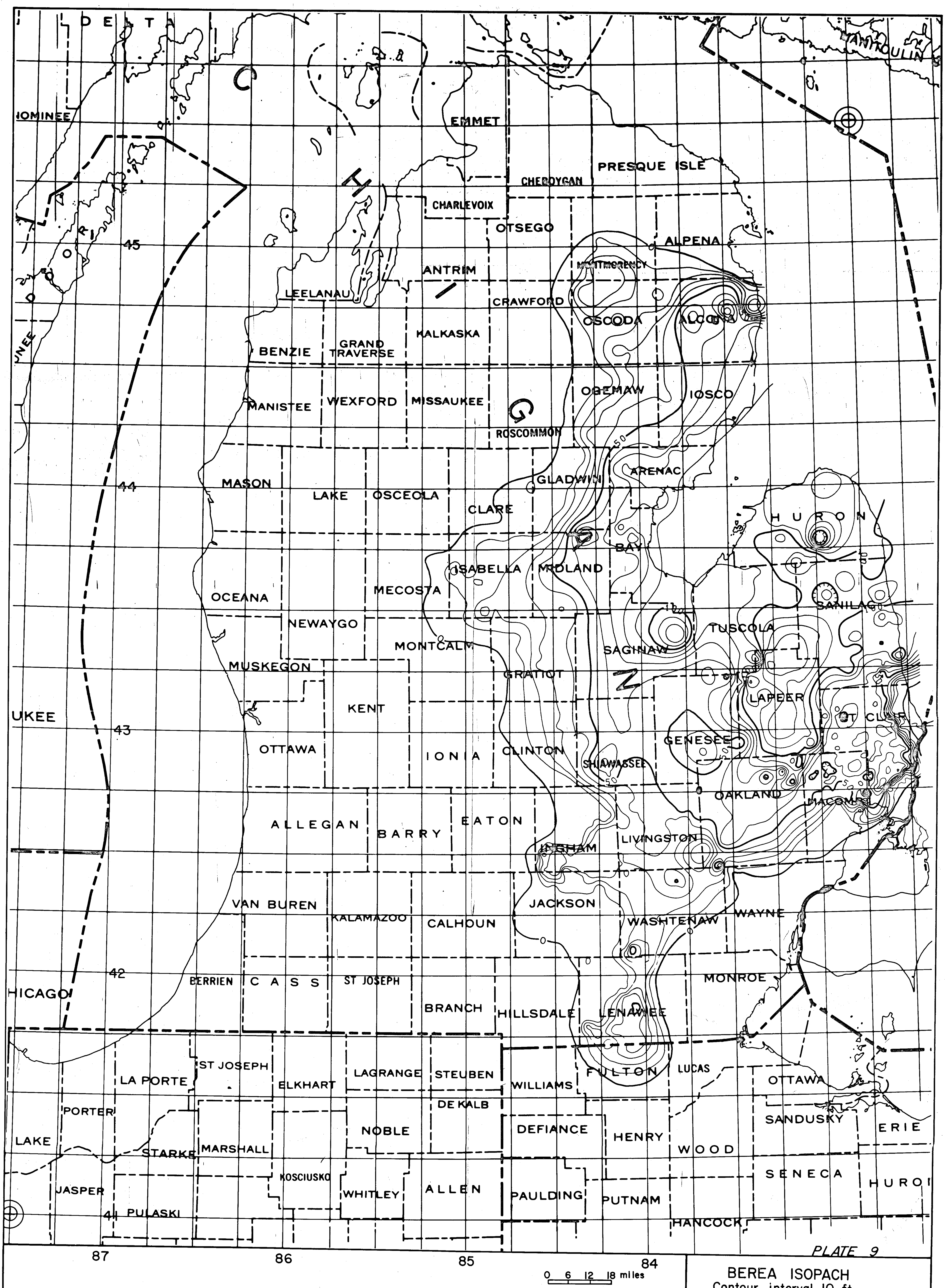
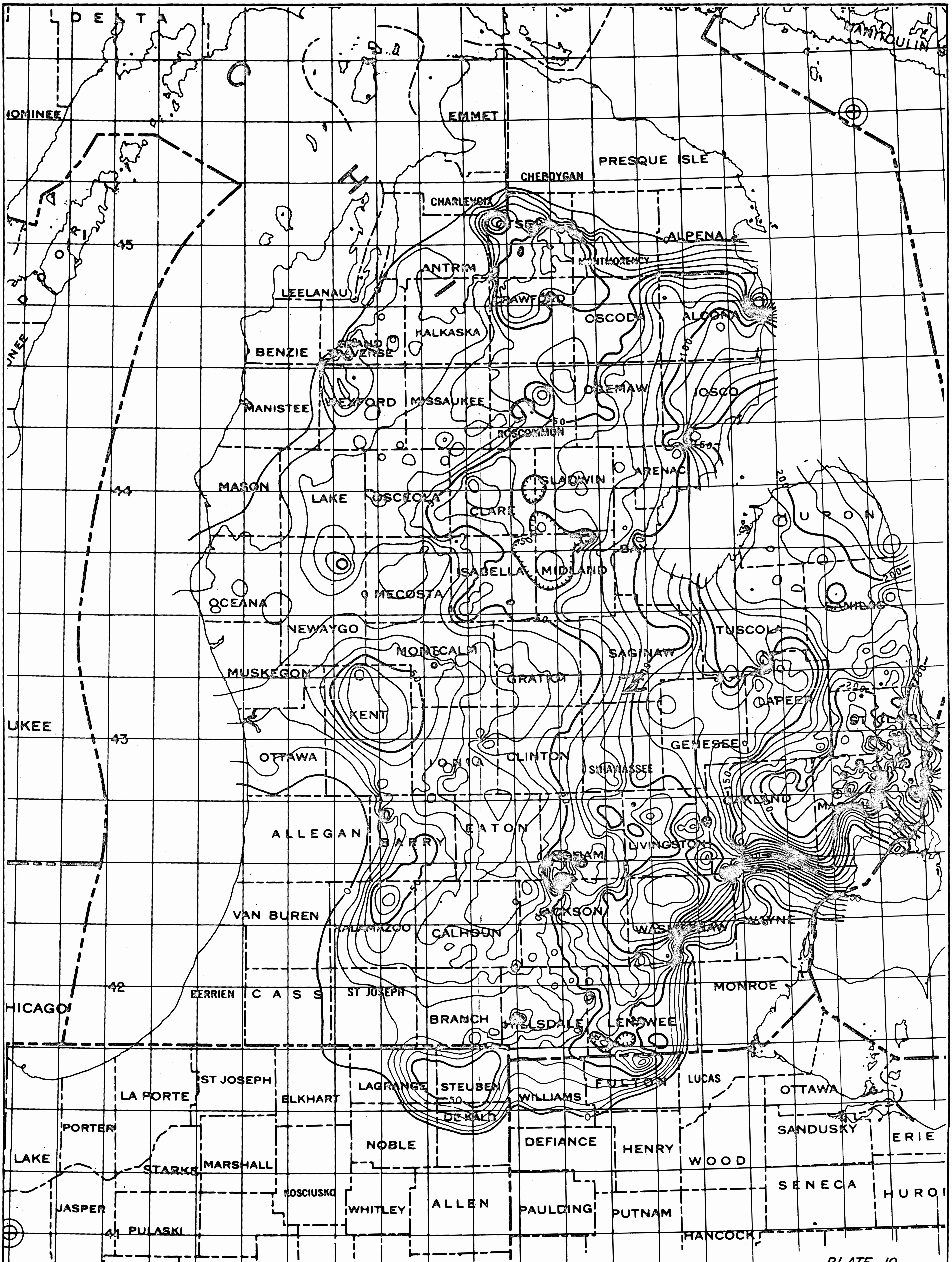


PLATE 9

BEREA ISOPACH
Contour interval 10 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80



BEDFORD ISOPACH
Contour interval 10 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

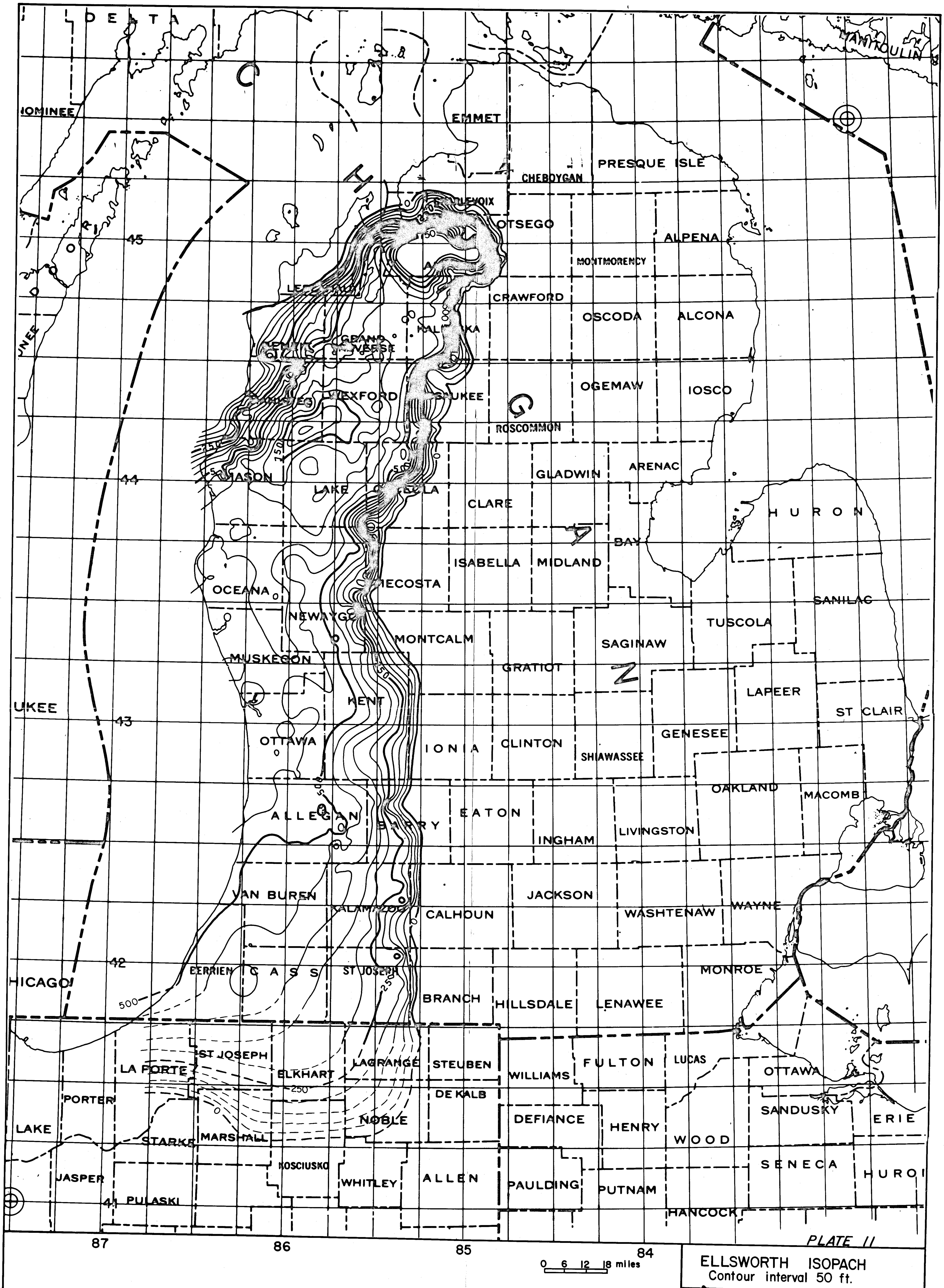


PLATE II

ELLSWORTH ISOPACH
Contour interval 50 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

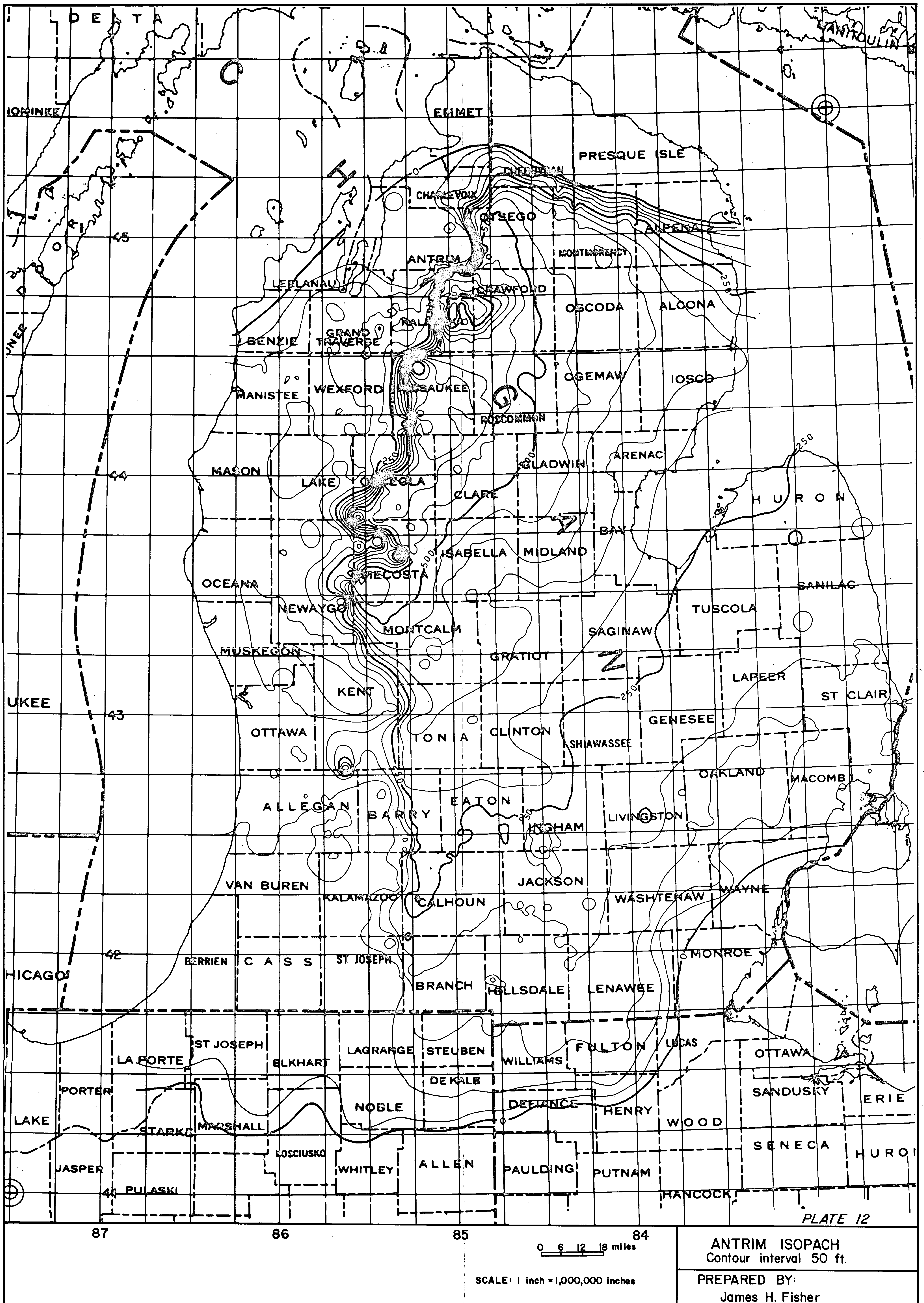


PLATE 12

ANTRIM ISOPACH
Contour interval 50 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

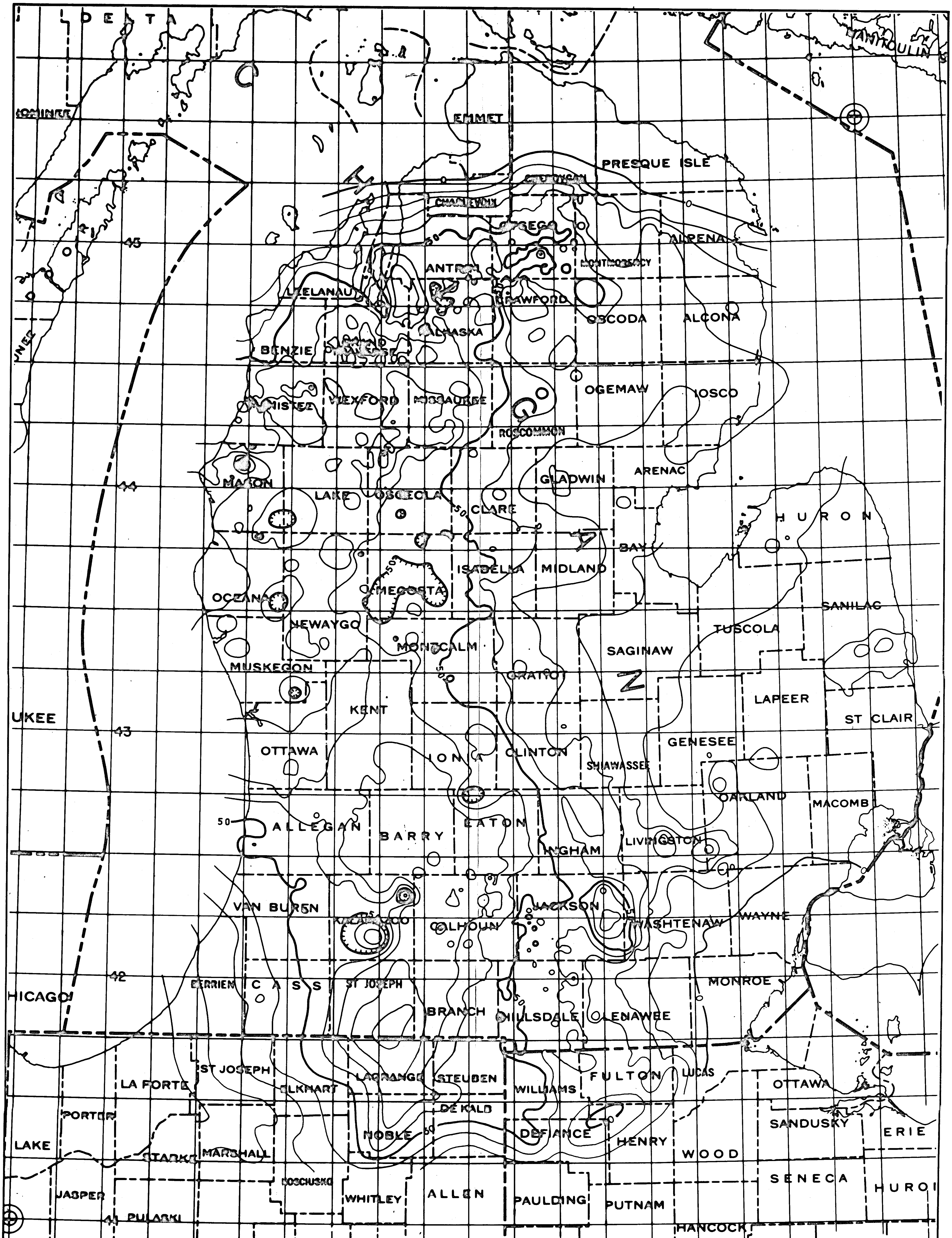


PLATE 13

TRAVERSE FM. ISOPACH

Contour interval 10 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

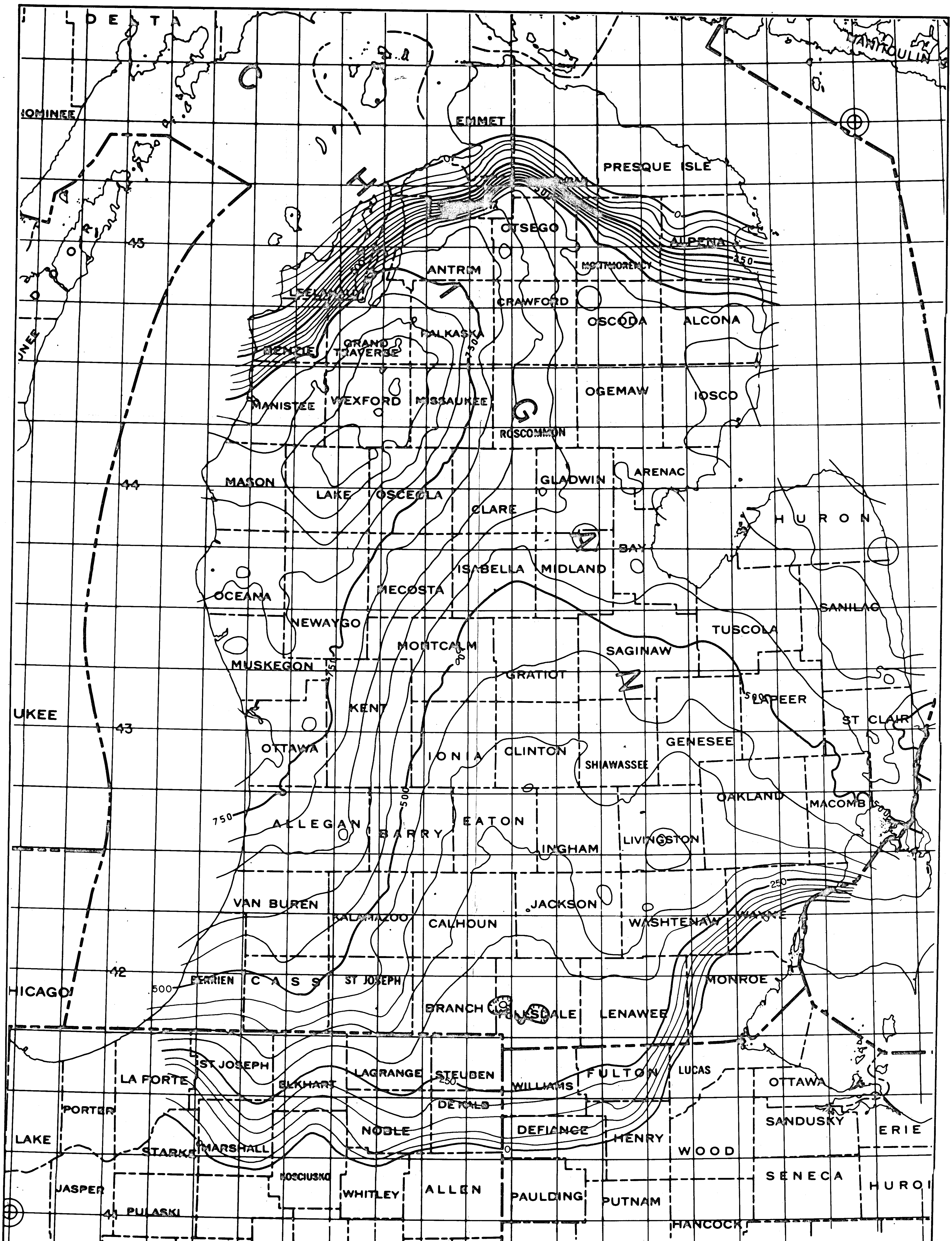


PLATE 14

TOTAL ISOPACH
Contour interval 50 ft.

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

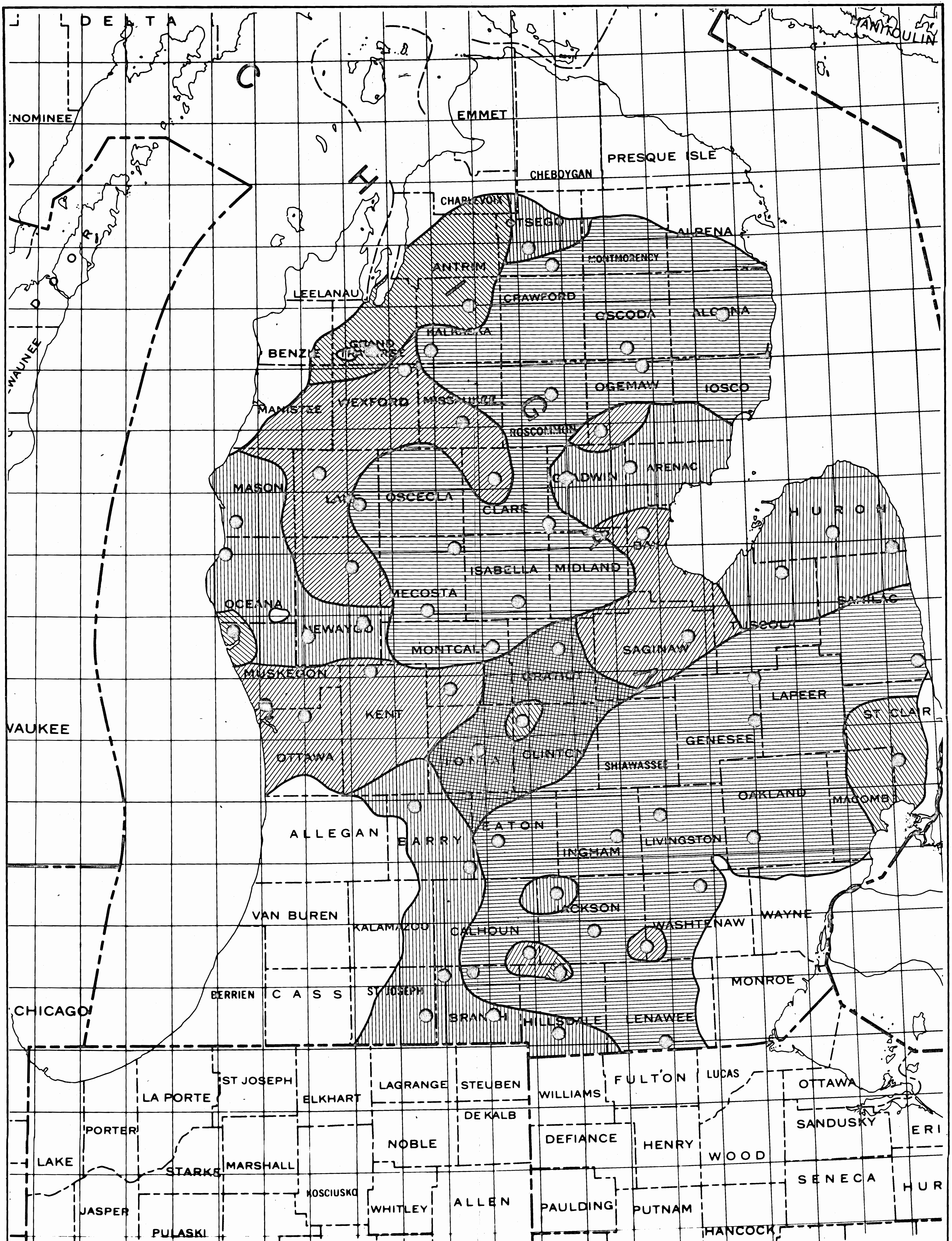


PLATE 15

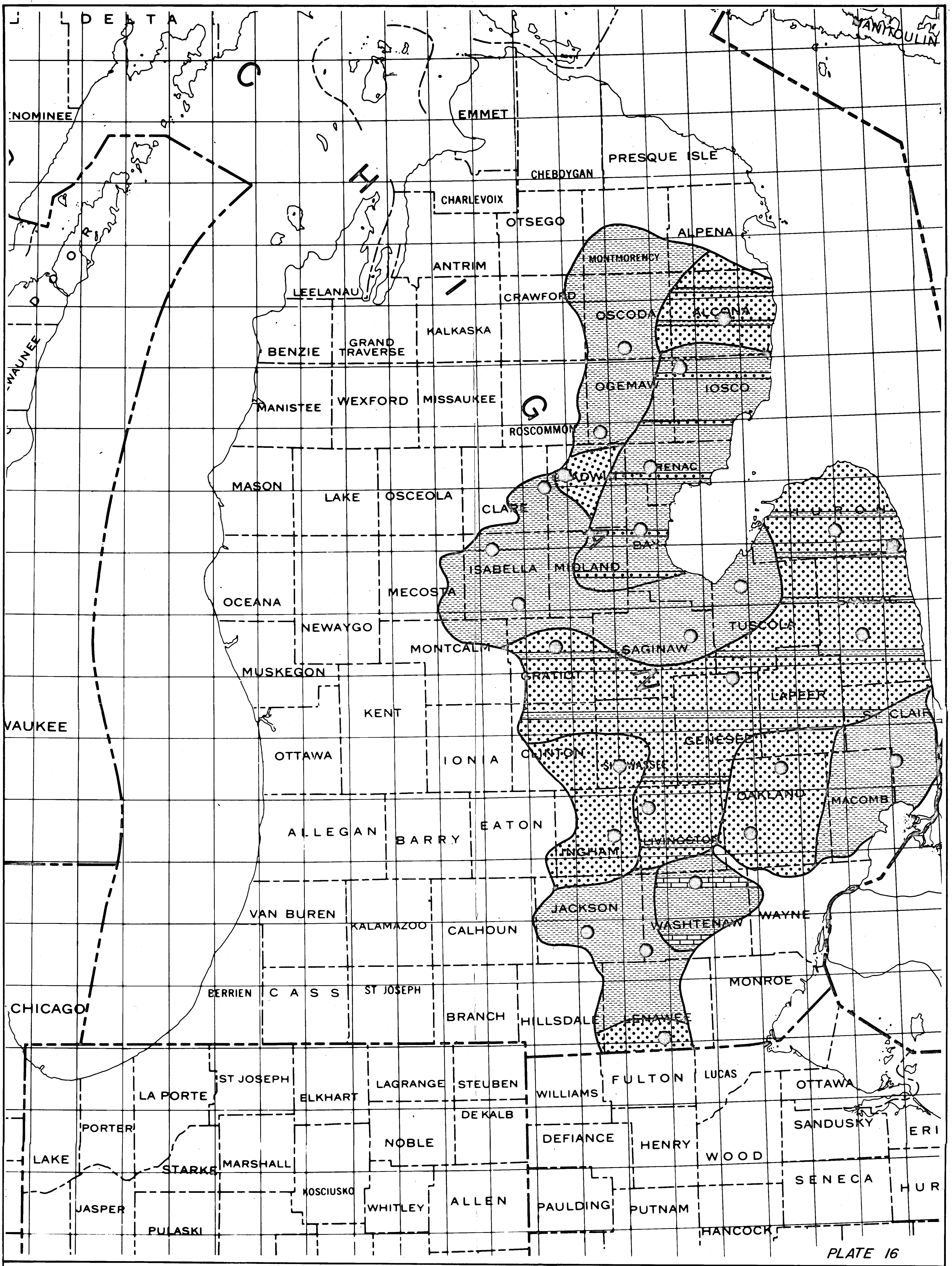
- BLACK
- VERY DARK GRAY
- DARK GRAY
- GRAY
- DARK GRAY & GRAY
- SAMPLE LOCATION

0 6 12 18 miles

SCALE 1 inch = 1,000,000 inches

SUNBURY LITHOFACIES
(color variation)

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80



100% SANDSTONE

> 50% SANDSTONE AND SILTSTONE

< 50% SANDSTONE AND SILTSTONE

100% SHALE

SHALE WITH MINOR LIMESTONE

SAMPLE LOCATION

0 6 12 18 miles

SCALE: 1 inch = 1,000,000 inches

BEREA LITHOFACIES
(lithologic variation)

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

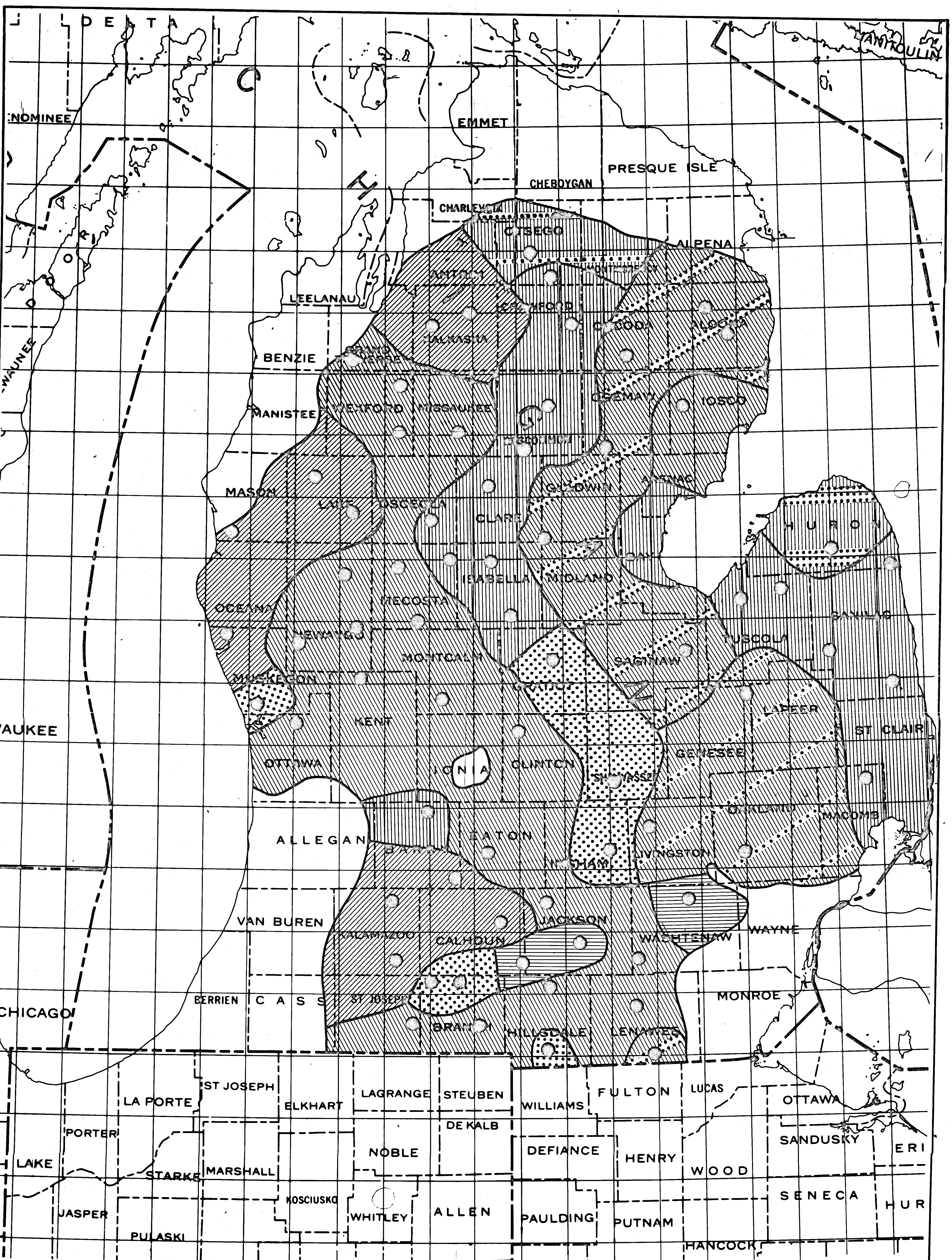


PLATE 17

100% SANDSTONE & SILTSTONE

BLACK SHALE

VERY DARK GRAY SHALE

DARK GRAY SHALE

GRAY SHALE

SAMPLE LOCATION

0 6 12 18 miles

SCALE: 1 inch = 1,000,000 inches

1-25% SANDSTONE | 25-50% SANDSTONE | >50% SANDSTONE

BEDFORD LITHOFACIES
(Dominant Color & Lithologic Variation)

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

PLATE 18

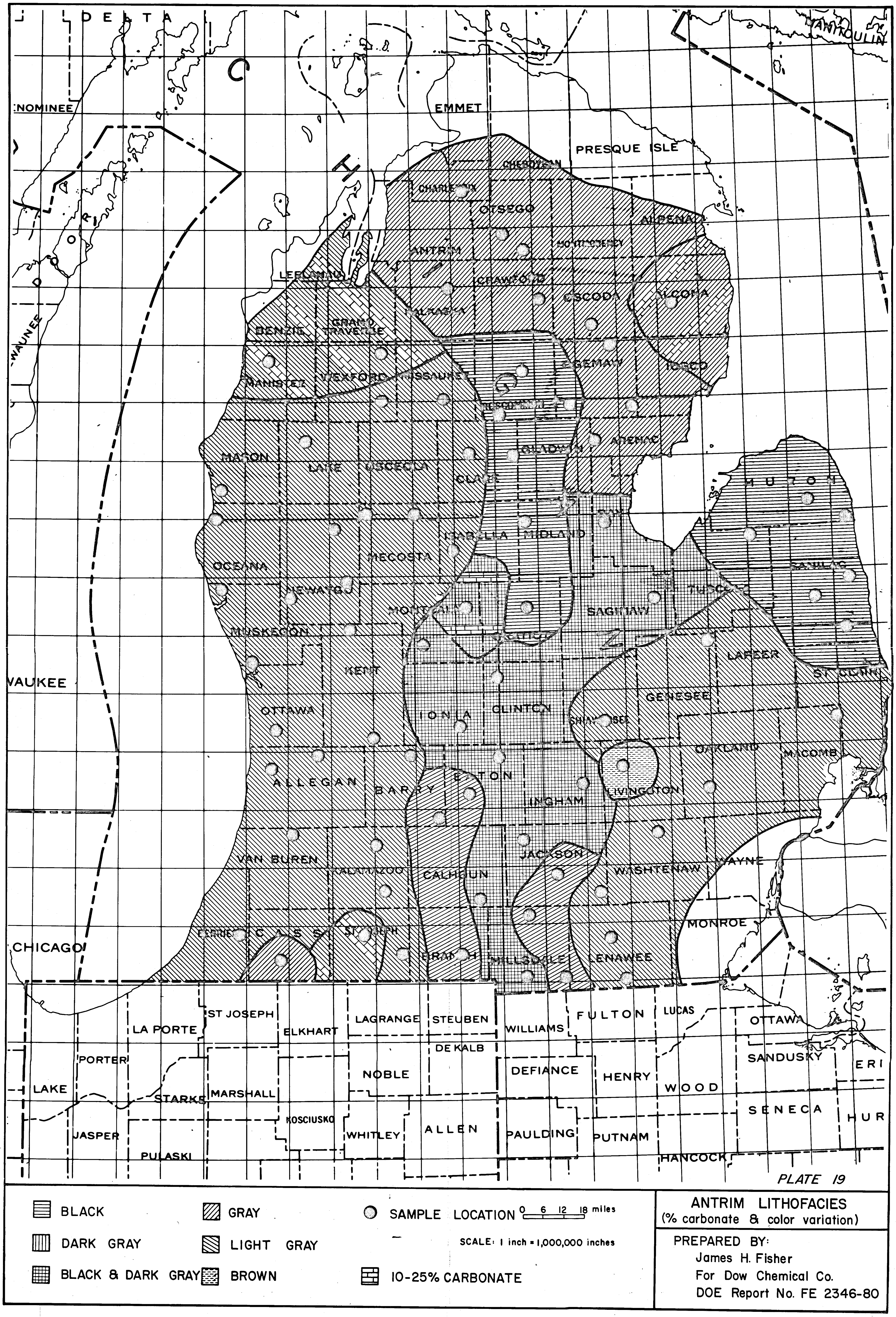
- BLACK
- VERY DARK GRAY
- BLACK & VERY DARK GRAY
- VARIABLE; BLACK, VERY DARK GRAY & DARK GRAY
- VARIABLE; DARK GRAY & GRAY
- SAMPLE LOCATION

0 6 12 18 miles

SCALE: 1 inch = 1,000,000 inches

ANTRIM LITHOFACIES
(color variation)

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80


DELTA
MANITOULIN
MENOMINEE
EMMET
PRESQUE ISLE
CHEBOYGAN
CHARLEVOIX
OTSEGO
ALPENA
MONTMORENCY
ANTRIM
LEELANAU
CRAWFORD
OSCODA
ALCONA
KALKASKA
BENZIE
GRAND TRAVERSE
OGEMAW
IOSCO
MANISTEE
WEXFORD
MISSAUKEE
ROSCOMMON
GLADWIN
ARENAC
MASON
LAKE
OSCEOLA
CLARE
HURON
ISABELLA
MIDLAND
OCEANA
MECOSTA
SANILAC
NEWAYGO
MONTCALM
SAGINAW
TUSCOLA
MUSKEGON
KENT
LAPEER
ST CLAIR
WAUKEE
GENESEE
OTTAWA
IONIA
CLINTON
SHIAWASSEE
OAKLAND
MACOMB
ALLEGAN
BARRY
EATON
INGHAM
LIVINGSTON
VAN BUREN
KALAMAZOO
CALHOUN
JACKSON
WASHTENAW
WAYNE
MONROE
CASS
ST JOSEPH
BRANCH
HILLSDALE
LENAWEE
CHICAGO
ST JOSEPH
LA PORTE
ELKHART
LAGRANGE
STEUBEN
WILLIAMS
FULTON
LUCAS
OTTAWA
DE KALB
PORTER
NOBLE
DEFIANCE
HENRY
SANDUSKY
LAKE
STARKE
MARSHALL
WOOD
SENECA
KOSCIUSKO
WHITLEY
ALLEN
PAULDING
PUTNAM
JASPER
PULASKI
HANCOCK
PLATE 19
BLACK
DARK GRAY
BLACK & DARK GRAY
GRAY
LIGHT GRAY
BROWN
SAMPLE LOCATION
0 6 12 18 miles
SCALE: 1 inch = 1,000,000 inches
10-25% CARBONATE
ANTRIM LITHOFACIES
(% carbonate & color variation)
PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80

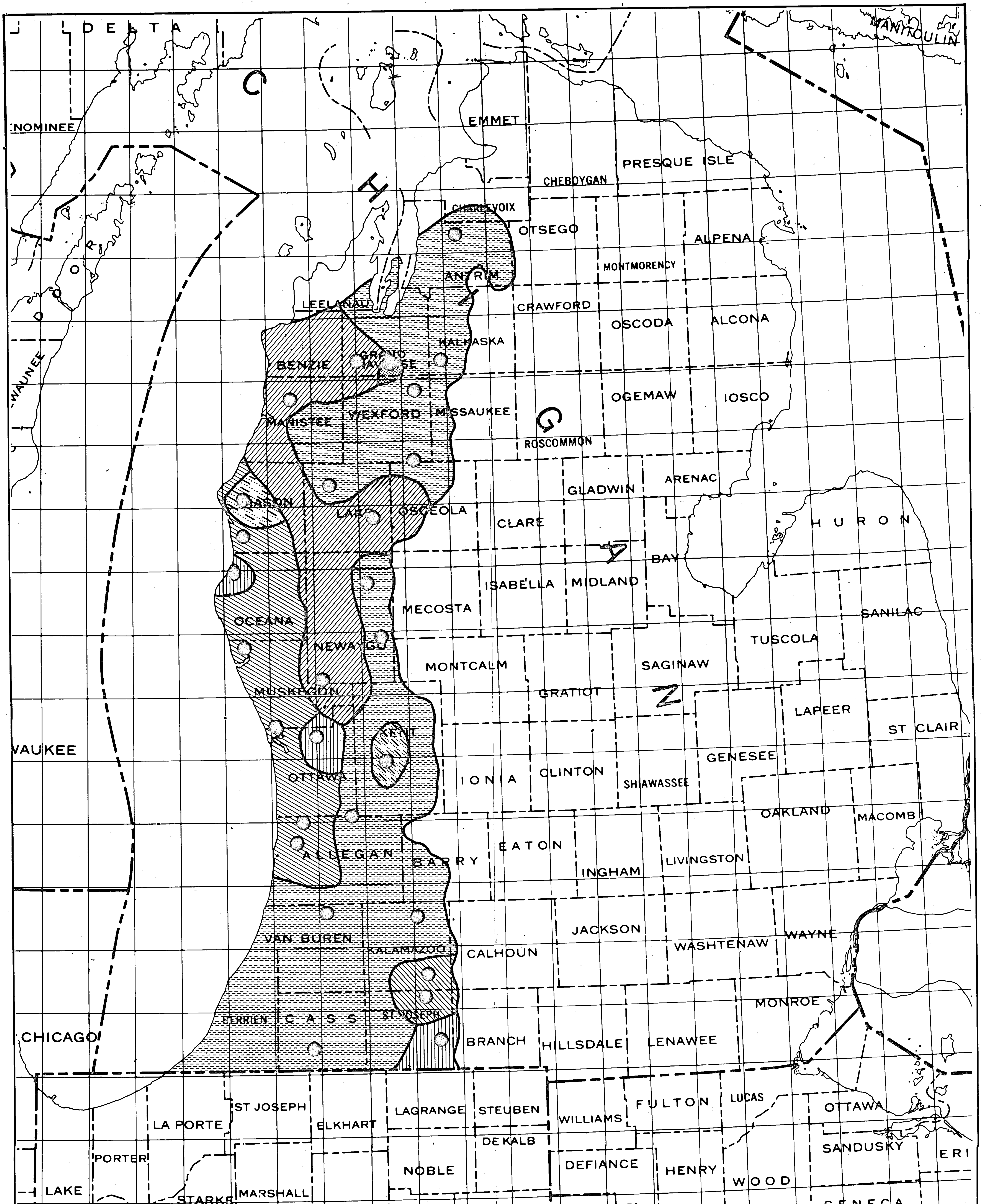


PLATE 20

SHALE, WEAKLY TO MODERATELY CALCAREOUS	SHALE, CALCAREOUS, INTERBEDDED LIMESTONE AND MINOR DOLOMITE
SHALE, CALCAREOUS, INTERBEDDED DOLOMITE AND MINOR LIMESTONE	SHALE, CALCAREOUS, WITH MINOR QUARTZ SANDSTONE
SHALE, CALCAREOUS, AND INTERBEDDED LIMESTONE, OFTEN OOLITIC	SHALE, NON CALCAREOUS

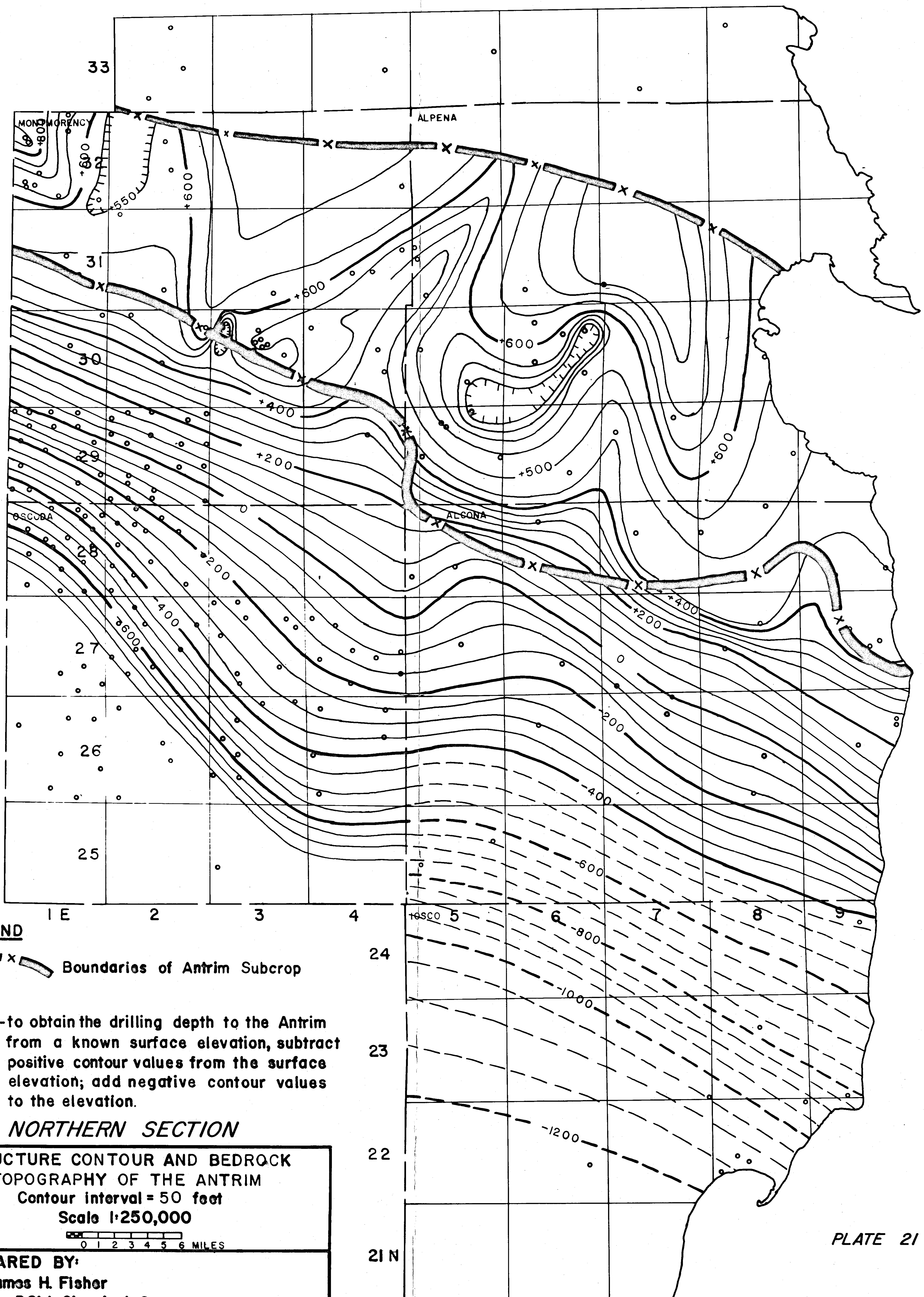
0 6 12 18 miles

SCALE: 1 inch = 1,000,000 inches

SAMPLE LOCATION ○

ELLSWORTH LITHOFACIES
(lithologic variation)

PREPARED BY:
James H. Fisher
For Dow Chemical Co.
DOE Report No. FE 2346-80



LEGEND

Boundaries of Antrim Subcrop

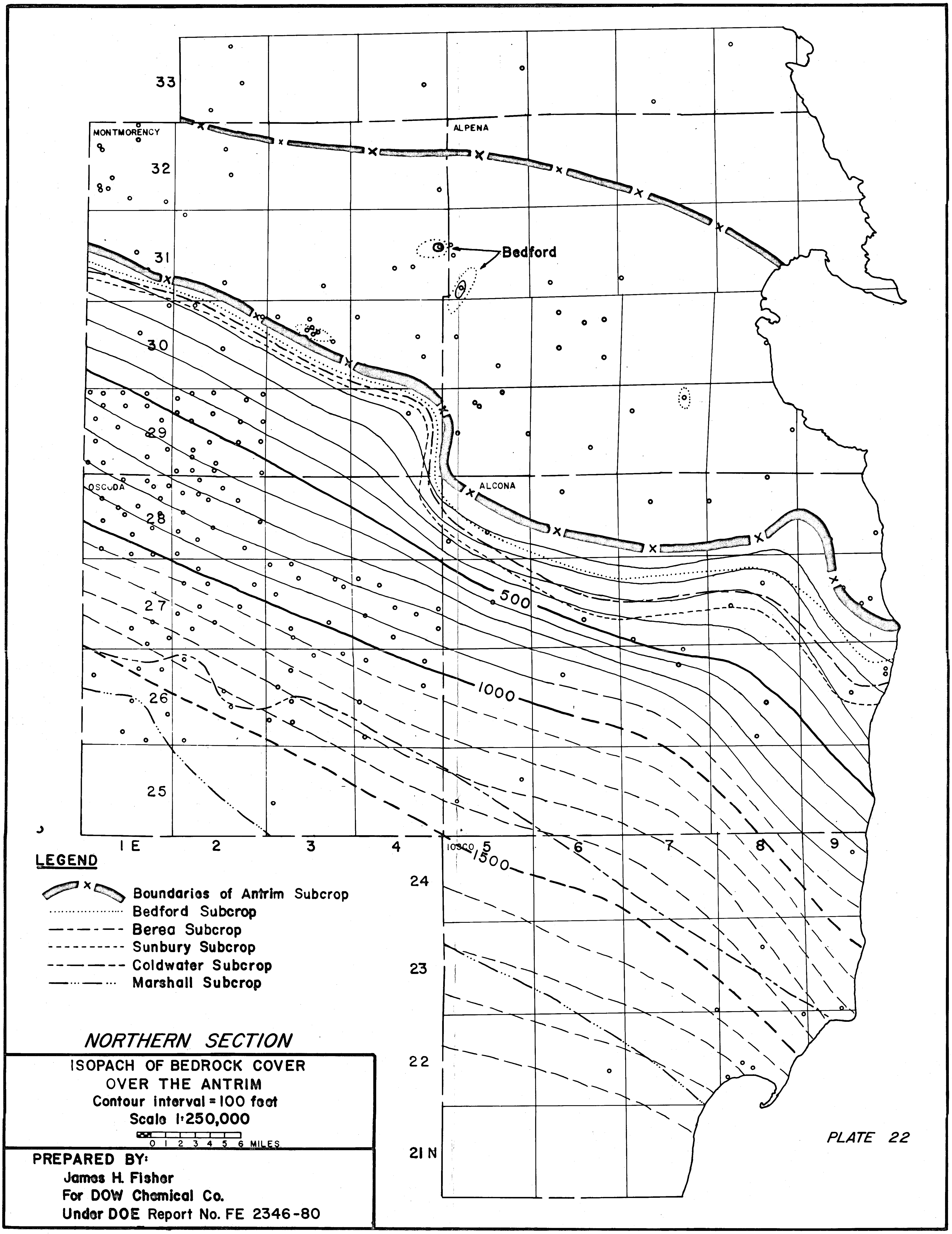
Note–to obtain the drilling depth to the Antrim from a known surface elevation, subtract positive contour values from the surface elevation; add negative contour values to the elevation.

NORTHERN SECTION

STRUCTURE CONTOUR AND BEDROCK TOPOGRAPHY OF THE ANTRIM
Contour interval = 50 feet
Scale 1:250,000
0 1 2 3 4 5 6 MILES

PREPARED BY:
James H. Fisher
For DOW Chemical Co.
Under DOE Report No. FE 2346-80

PLATE 21



NORTHERN SECTION

ISOPACH OF BEDROCK COVER
OVER THE ANTRIM
Contour interval = 100 feet
Scale 1:250,000

PREPARED BY:
James H. Fisher
For DOW Chemical Co.
Under DOE Report No. FE 2346-80

PLATE 22

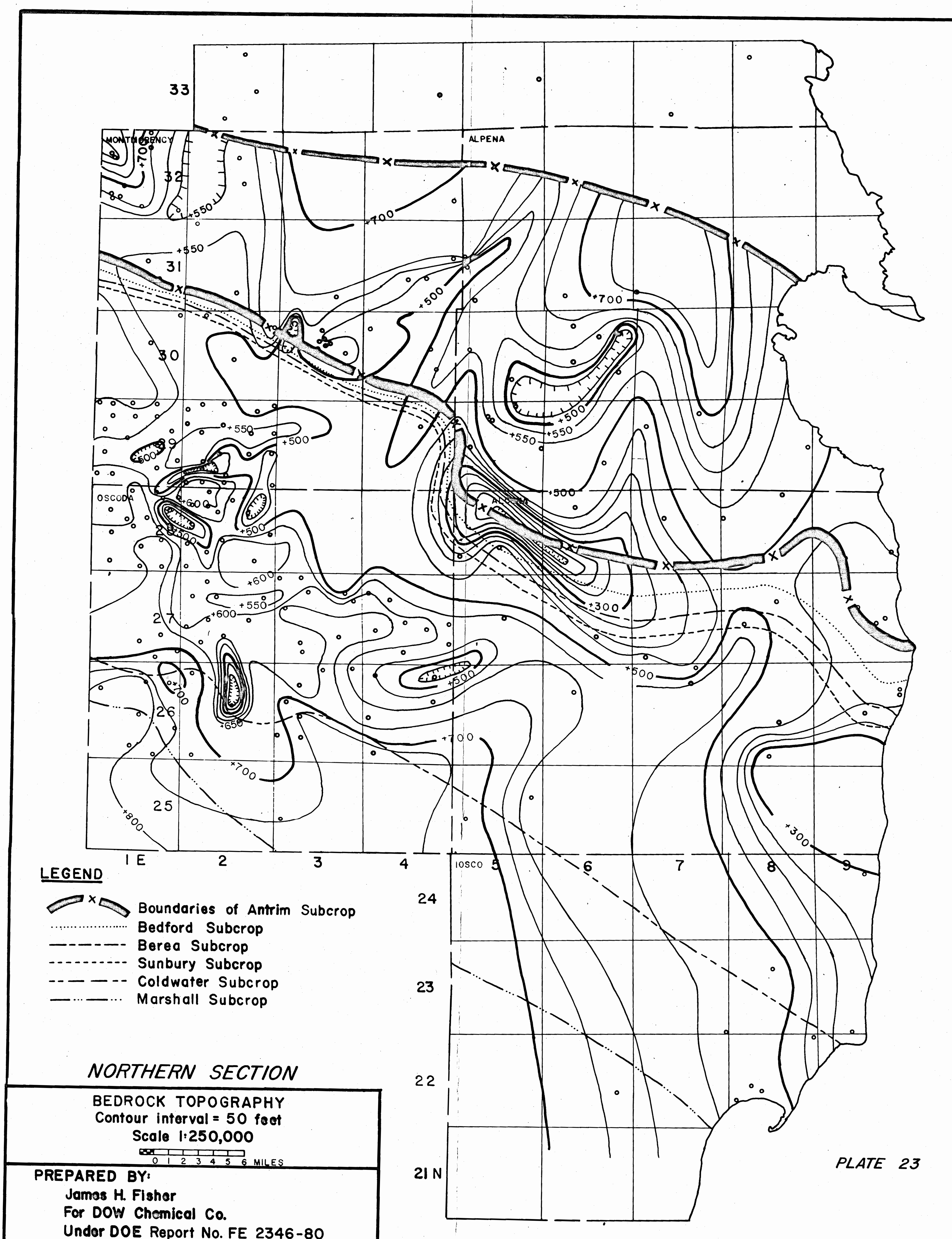

MONTMORENCY
ALPENA
OSCODA
IOSCO
33
32
31
30
29
28
27
26
25
24
23
22
21 N
1 E
2
3
4
5
6
7
8
9
+700
+550
+500
+600
+650
+800
+300
LEGEND
Boundaries of Antrim Subcrop
Bedford Subcrop
Berea Subcrop
Sunbury Subcrop
Coldwater Subcrop
Marshall Subcrop
NORTHERN SECTION
BEDROCK TOPOGRAPHY
Contour interval = 50 feet
Scale 1:250,000
0 1 2 3 4 5 6 MILES
PREPARED BY:
James H. Fisher
For DOW Chemical Co.
Under DOE Report No. FE 2346-80

PLATE 23

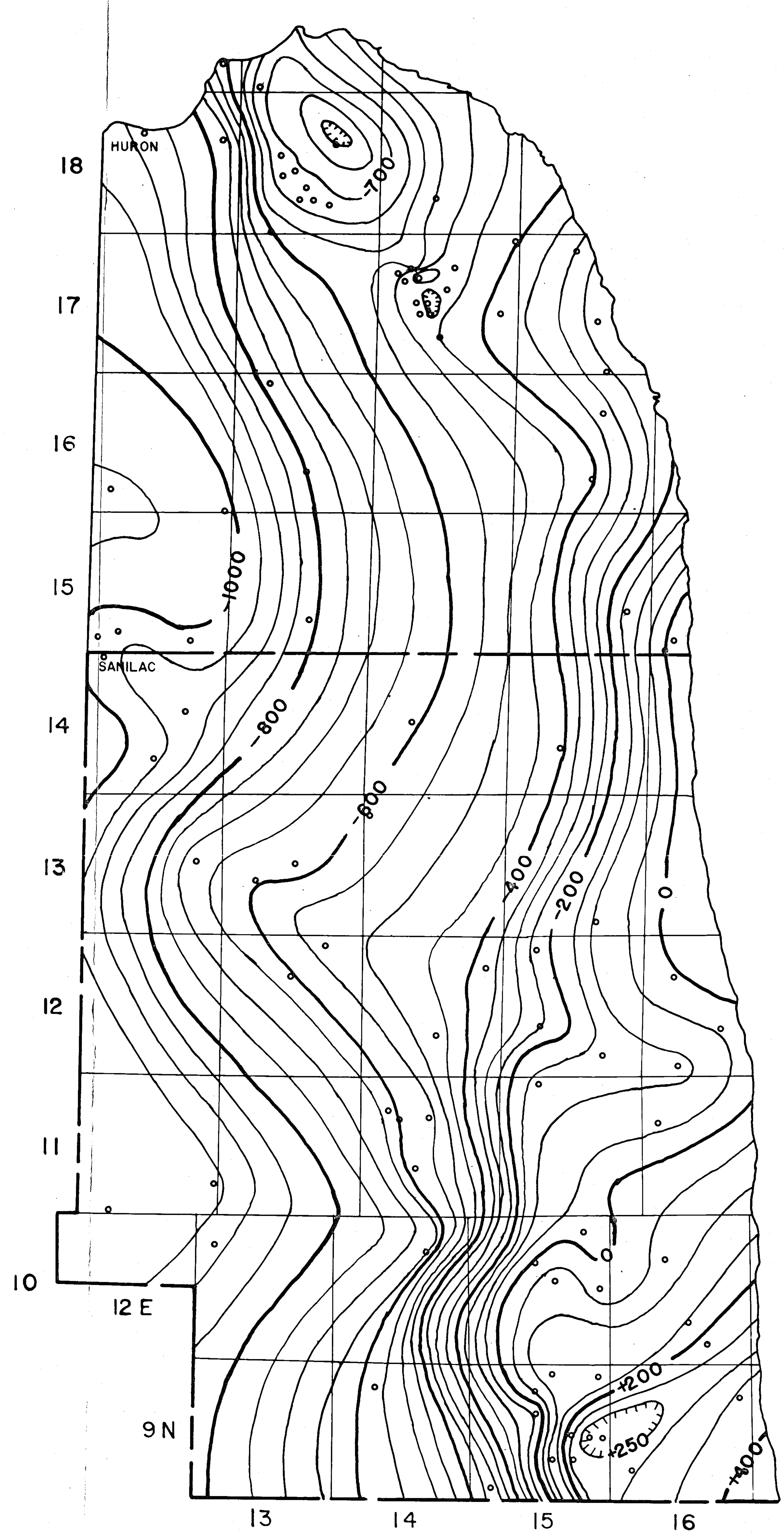


PLATE 24

Note–to obtain the drilling depth to the Antrim from a known surface elevation, subtract positive contour values from the surface elevation; add negative contour values to the elevation.

SOUTHERN SECTION

STRUCTURE CONTOUR OF THE ANTRIM

Contour interval = 50 feet

Scale 1:250,000

0 1 2 3 4 5 6 MILES

PREPARED BY:

James H. Fisher

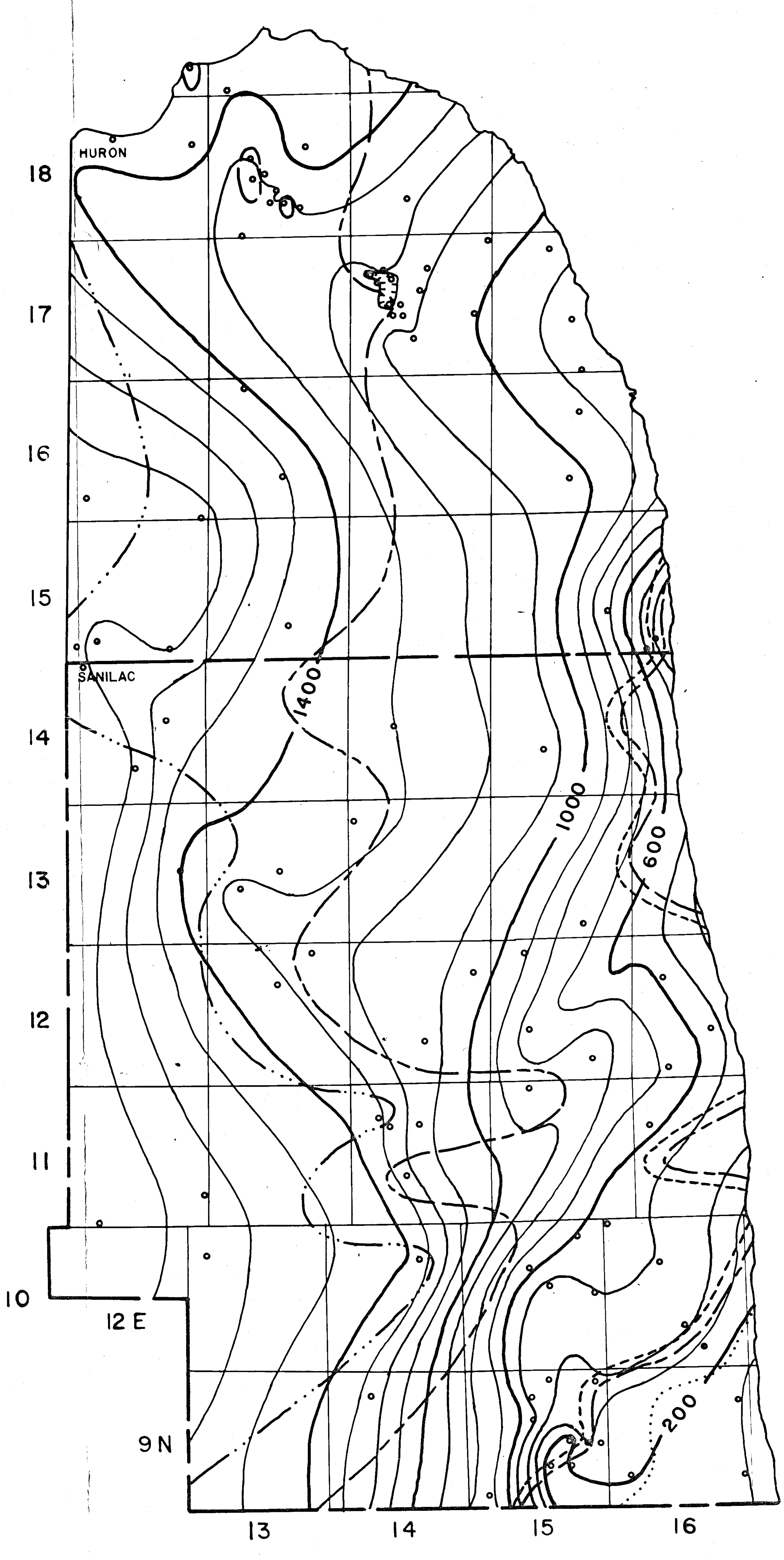
For DOW Chemical Co

DOE Report FE 2346-80

PLATE 25

LEGEND

- ·············· Bedford Subcrop
- ———— Berea Subcrop
- - - - - - - Sunbury Subcrop
- — — — — Coldwater Subcrop
- —··—··— Marshall Subcrop



SOUTHERN SECTION

ISOPACH OF BEDROCK COVER OVER THE ANTRIM

Contour interval = 100 feet

Scale 1:250,000

0 1 2 3 4 5 6 MILES

PREPARED BY:

James H. Fisher

For DOW Chemical Co

DOE Report FE 2346-80

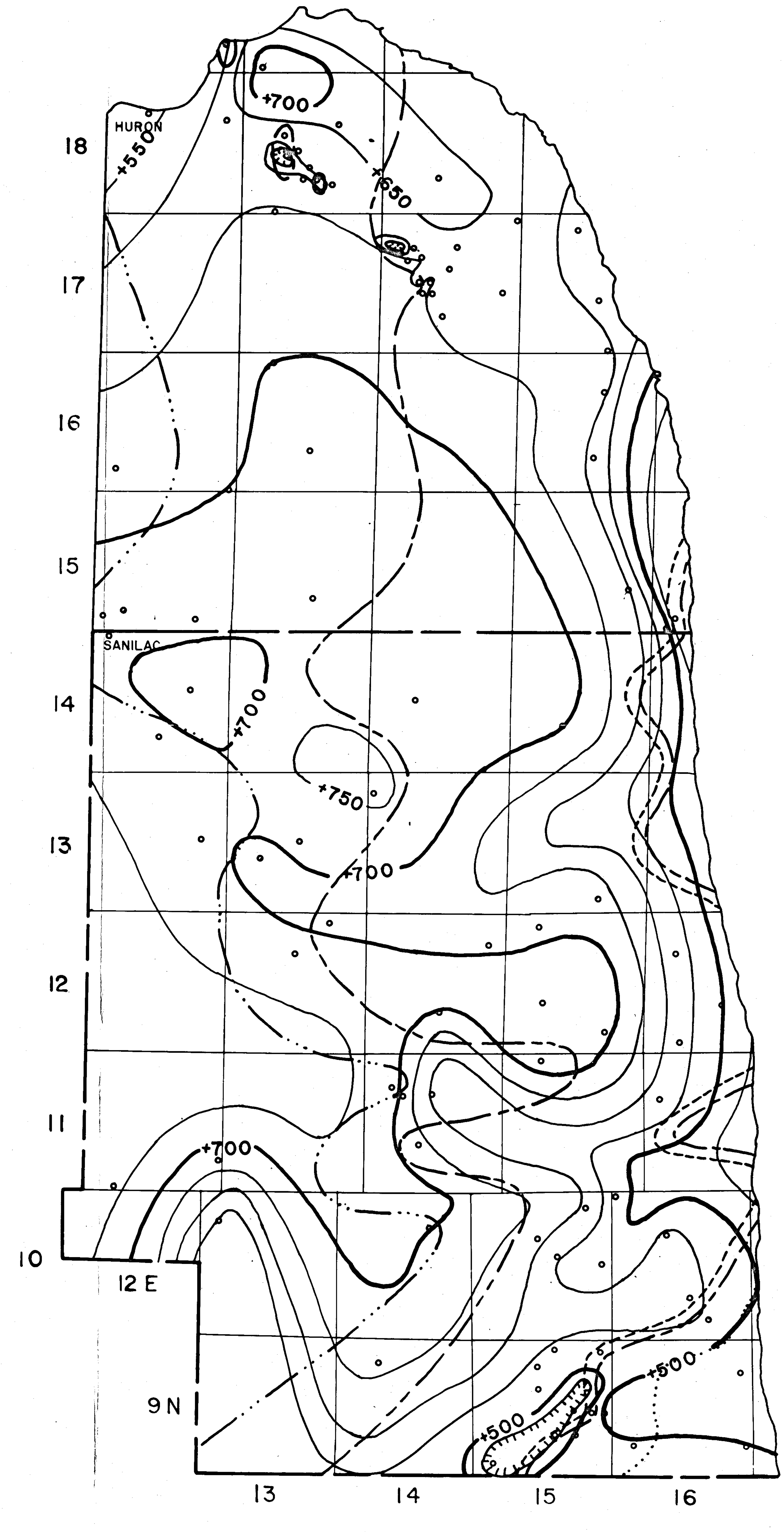


PLATE 26

LEGEND

- Bedford Subcrop
- Berea Subcrop
- Sunbury Subcrop
- Coldwater Subcrop
- Marshall Subcrop

SOUTHERN SECTION

BEDROCK TOPOGRAPHY
Contour interval = 50 feet
Scale 1:250,000
0 1 2 3 4 5 6 MILES

PREPARED BY:
James H. Fisher
For DOW Chemical Co
DOE Report FE 2346-80