A QUANTITATIVE SEDIMENTARY ANALYSIS OF THE ORDOVICIAN DEPOSITS IN THE MICHIGAN BASIN

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Laurence S. Cooke, Jr.

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A QUANTITATIVE SEDIMENTARY ANALYSIS OF THE ORDOVICIAN DEPOSITS IN THE MICHIGAN BASIN

By

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INTRODUCTION

History of Investigation of the Michigan Basin

Subsurface investigation of the Michigan Basin has been a subject of interest for many years. But, not until the turn of the century was there enough information from deep borings to intensify the study.

The main problem was the extensive cover of Pleistocene glacial deposits. These deposits attain a thickness of nearly 1,300 feet in certain portions of the lower peninsula.

The outcrop pattern of the Paleozoic deposits is elliptical in outline, with the major axes trending northeast-southwest. Map I shows the extent of the outcrops. These sediments are arranged in concentric rings with the Pennsylvanian deposits in the center, and progress towards the outer margin through the Mississippian, Devonian, Silurian, Ordovician, and the Cambrian. Smith (1912) states, "The depth of the Basin is so small in comparison with its diameter that the inclination of its several members is ordinarily between 25 and 50 feet per mile, and rarely exceeds 60 feet."

In describing the areal extent of the Michigan Basin, Newcombe (1933) stated:

> The area comprising the Michigan Basin includes about 106,700 square miles and stretches from Fort Wayne, Indiana, on the south, to Whitefish Point near Sault Ste. Marie, Michigan, on the north, and from west to east about 370 miles.

The deepest portion, or center of the Basin, conforms approximately to the center of the lower peninsula of Michigan. According to Pirtle (1932), the structures bounding the Basin are: the Wisconsin arch in the west, and two limbs of the Cincinnati arch in the south, the Kankakee arch in the southwest, and the Findley arch in the southeast. The northern boundary is the pre-Cambrian complex of the Canadian Shield, and the eastern boundary is the Algonquin arch.

Because of the economic importance attached to the intra-basinal structures, they have been closely studied. Smith (1912) described the six best developed folds which occurred mainly near the margins of the Southern Peninsula and in Western Ontario. He depicts most of these anticlines as being relatively low and short. Some faulting has also occurred in the Basin with displacements generally around 50 to 60 feet. Most of the information for his study was obtained by reconnaissance mapping and from a few well logs.

Pirtle (1932) suggests that the folds within the Basin have a persistent northwest-southeast trend. And this

parallelism of folds is most evident in the central and eastern part of the state. He believes the folds in the southwestern part of the state are different from those in the central and eastern portions. They are much shorter and trend to the northeast. He suggests they are related to the Kankakee arch. In his conclusion, he states; "It is believed that the principle folds now existing in the later sediments are controlled by trends of folding or lines of structural weakness which existed in the old basement rocks." Most of Pirtle's information was obtained from structural contours drawn on the top of the Trenton formation of the Ordovician.

Newcombe (1933) published a thorough report on the sediments and structures in the basin. His conclusions followed very closely those proposed by Pirtle. His findings are based on both structural contour and isopach maps.

Facies Analysis

Moore (1949) defines sedimentary facies as, "Any areally restricted part of a designated stratigraphic unit which exhibits characters significantly different from those of other parts of the unit." The facies analysis method of interpreting structures was used by Sloss, Krumbein, and Dapples (1949) in determining structural relations from a map showing lateral variations of rock

character within a certain stratigraphic interval.

Moore (1949) defines two different types of facies; lithofacies and biofacies. Lithofacies are "groups of strata demonstrably different in lithologic aspect from laterally equivalent rocks." Biofacies are laterally equivalent biotic assemblages differing in their biologic aspect. A third facies is proposed by Sloss, Krumbein, and Dapples (1949) as "tectofacies" where it is defined as, "a group of strata of different tectonic aspect from laterally equivalent strata."

Lithofacies and biofacies maps in general express similar trends and limits. These maps also would show minor variations in sedimentary environment. A tectofacies map, on the other hand, would show the broad tectonic variations.

Purpose

The purpose of this paper is to attempt to determine the structures during Ordovician time in the Michigan Basin by a lithofacies analysis.

Even with the scarcity of samples from wells penetrating the Ordovician, it was felt by this writer that a reasonable interpretation of the tectonic environment of this section could be made. It was necessary that this analysis be conducted on a well defined rock system.

The Ordovician system was chosen for this study because of the small amount of written information available on these formations throughout the Basin. It is hoped that the maps and data obtained from this analysis may add to the information found through earlier research.

WELL SELECTION AND DISTRIBUTION

Stratigraphy of the Section Analyzed

Due to the difficulty in selecting a top and a bottom for the Ordovician system, this analysis contains some lower Silurian deposits and omits the lower Ordovician deposits. Table I describes the section analyzed.

A top and bottom that were reasonably consistent throughout the well samples was chosen. The concensus of opinion among several authors place the top of the Ordovician at the break between the Manitoulin, which is a buff dolomite, and the dark shale of the Queenston. In many of the wells, there is no such break, showing a gradua-tional change instead. For the top, the red shale of the Cabot Head was the best marker bed that could be found. The base of this horizon was chosen instead of a similar red bed in the Cincinnatian to include as much of the Ordovician as possible.

The bottom of the Ordovician is just as difficult to ascertain because of the deep erosion and crustal movement during and following the deposition of the lower Ordovician deposits. There is much ambiguity as to the correlation of some of these sediments, especially the sandstone beds. In some areas, it is very difficult to tell whether the sand is St. Peter, New Richmond or Cambrian. For this reason, the bottom of the Black River Formation was used as the lower limit marker.

It is realized that this is not an analysis of the entire Ordovician system and should not be interpreted as such.

TABLE I

LITHOLOGY AND THICKNESS OF SECTION ANALYZED

Age	Formation		Lithology	Average thickness Western Michigan	Average thickness Eastern Michigan
SILURIAN					
	Cataract				
		Cabot Head	Green, greenish-gray and red shale.		
		Manitoulin	Buff to light brown dolomite with some inter-bedded chert and shale.	40'	70'
ORDOVICIAN					
	Cincinnatian				
		Queenston	Gray and red shale with thin beds of limestone and dolomite.		
		Lorraine	Gray shale with thin beds of lime-stone and dolomite.	400'	805'

TABLE I (Cont.)

Age	Formation	Lithology	Average thickness Western Michigan	Average thickness Eastern Michigan
	Utica	Dark gray to black shale		
	Trenton	Brown and gray crystalline limestone and dolomite with some shale and argillaceous limestone.		405'
	Black River	Brown and gray crystalline limestone and dolomite with some shale, chert and argillaceous limestone.	415'	470'
	St. Peter	Well rounded quartz grains with some chert and conglomerate.	230'	0'
	Prairie Du Chien	Buff dolomite, chert, sandstone and green to greenish-gray shale.		

Requirements for Well Selection

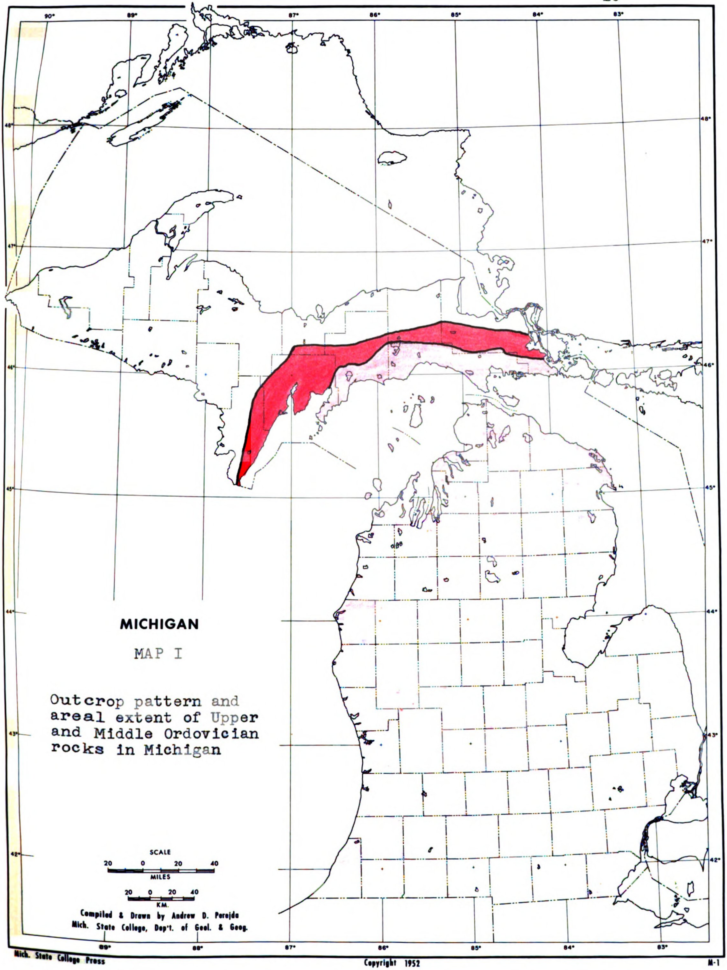
Krumbein and Sloss (1951) compared the cable-tool method of drilling with the rotary-tool method. Rotary-tool samples are contaminated by "the rotation of the drill pipe and each removal and reintroduction of the tools which cause a certain amount of caving from the sides of the bore." On the other hand, cable-tool samples are relatively uncontaminated "with a minor amount of material knocked off uncased portions of the bore by the passage of tools and the bailer." Another comparison of these two methods by Krumbein and Pettijohn (1938), draws the same conclusion; the samples for analysis are the least contaminated if obtained from cable-tool wells.

Because of the scarcity of wells that penetrate the Ordovician, all of those available were used. For this reason, there was little problem in the spacing of the wells.

The wells selected in the Upper Peninsula were those where most of the lower Silurian sediments were present. Along the eastern margin of the state, from Alpena County to Claire County and in the middle of the basin, there were no wells selected. Map I gives the outcrop pattern and the areal extent of the Ordovician deposits within the state of Michigan.

Selection of Wells

Half the wells selected for this study were cable-tool wells. Because of the depth at which the Ordovician is found, most of the wells are located towards the periphery of the state. For each well, the section analyzed


90°
89°
87°
86°
85°
84°
83°
48°
47°
46°
45°
44°
43°
42°
MICHIGAN
MAP I
Outcrop pattern and
areal extent of Upper
and Middle Ordovician
rocks in Michigan
SCALE
20 0 20 40
MILES
20 0 20 40
KM.
Compiled & Drawn by Andrew D. Perejda
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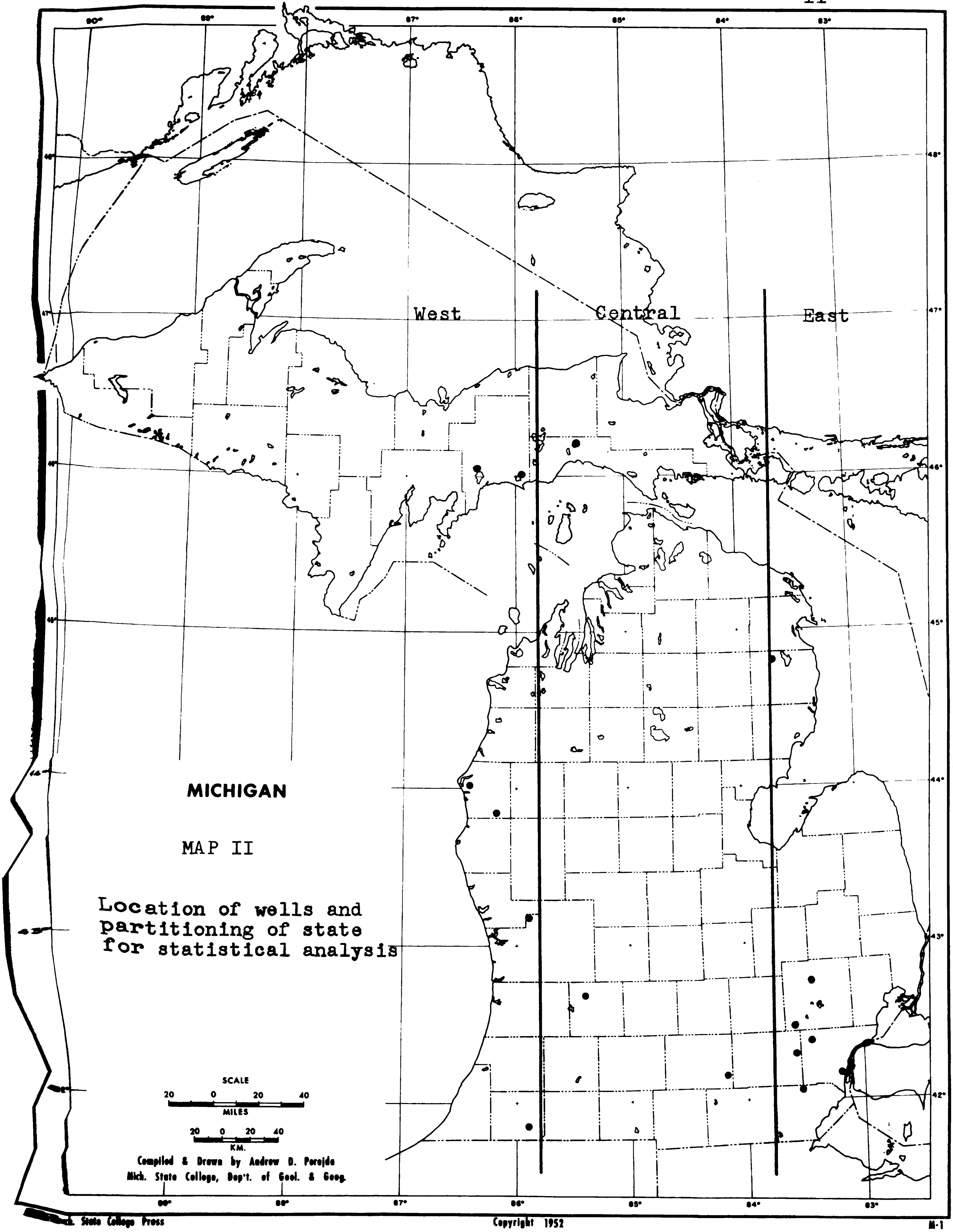

West
Central
East
MICHIGAN
MAP II
Location of wells and partitioning of state for statistical analysis
SCALE
20 0 20 40
MILES
20 0 20 40
KM.
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was obtained from the Michigan Geological Survey.

Map II shows the location of the wells and Table II defines the wells used in this study. Included in the table are the county and township, company and farm, location, and the thickness of the section studied for each well.

TABLE II

WELLS USED IN ANALYSIS

Well Number	County and Township	Company and Farm	Sec.	Twp.	Rg.	Thickness Of Section
1	Alpena Long Rapids	Charles W. Teater Nevins #1	18	32N	6E	1121'
2	Jackson Norvell	The Taggert Co. Watkins Farm Inc. #1	13	4S	2E	1412'
3	Monroe London	Dow Chemical Co. Loyal Grassey #1	7	5S	7E	1407'
4	Barry Rutland	Rex Oil and Gas Co. J. and J. Robertson #1	4	3N	9W	1139'
5	Cass Calvin	D. B. K. Van Raalte Wm. Gemberling #1	36	7S	14W	923'
6	Schoolcraft Hiawatha	B. P. Pettison Alphonse Verschure #1	14	42N	16W	577'
7	Schoolcraft Seul Choix	Schoolcraft Dev. Synd. Schoolcraft Dev. Synd. #2	31	41N	13W	854'
8	Washtenaw Superior	Calvin and Assoc.	12	2S	7E	1579'

TABLE II (Cont.)

Well Number	County and Township	Company and Farm	Sec.	Twp.	Rg.	Thickness Of Section
9	Mason Hamlin	Dow-Brazos-Taggert Dow-Brazos-Taggert	27	19N	18W	684'
10	Wayne Monguagon	Penna. Salt Mfg. Co. Penna. Salt Mfg. Co. #14	5	4S	11E	1461'
11	Ottawa Chester	Mich. Petroleum Co. Charley Moe #1	6	9N	13W	805'
12	Mason Eden	Superior Oil Co. M. Sippy <u>et</u> <u>al</u>. #17	25	17N	16W	803'
13	Wayne Northville	Woodson Oil Co. Det. H. of C. #3	17	1S	8E	1786'
14	Mackinaw Garfield	C. Van Keuren Hiawatha Sportsman Club <u>et</u> <u>al</u>. #1	17	44N	9W	766'
15	Oakland Springfield	Top O' Mich. Dev. Co. Williams #1	22	4N	8E	1659'
16	Oakland Lyon	C. W. Collin Gowans <u>et</u> <u>al</u>. #1	35	1N	7E	1553'

LABORATORY PROCEDURE

Sampling Method

Samples for each well were obtained from the Michigan Geological Survey. The Ordovician section of the wells was represented by seven to twelve trays, each containing about 25 vials. Each vial contained a sample of five to ten feet of the drilled section.

In order to obtain the best results in a mechanical analysis, approximately one hundred and twenty-five grams of sample are necessary (Wentworth 1926). The vertical section studied ranged from about 800 feet to 1500 feet. At one gram of sample for every ten feet, the composite approaches Wentworth's figure.

There were from eight to ten grams of sample in each vial. The selection of one-half to one and one-half gram would be a sufficient sample for analysis and would not detract from the value of the original sample.

A 400 ml. beaker was weighed and labeled for each well. As the sample from each vial was weighed, it was placed in the beaker to form a composite sample for the well. A small magnet was used on the composite sample to remove the small pieces of drill bit. If obvious contamination were present in the two rotary tool wells, it was removed. To check the weighing accuracy, the net weight of the composite sample was divided by one-tenth. This should equal the number of feet sampled.

None of the wells showed an error of more than one-half gram, which is not considered significant enough to alter the results.

Removal of Water Solubles

Very little of the Ordovician in Michigan is composed of water soluble material. But it was necessary to include these minor amounts of electrolytes in the analysis.

Weigner (1927) found that by boiling the sample in water the ionic particles will go into solution and may be removed by filtering or siphoning. Because of the small amount of electrolytes present, they caused no apparent flocculation of the fine clastics during the treatments.

Each well was treated with about 200 ml. of tap water and boiled for two hours. All the fine material in the beaker was allowed to settle. Then the water was filtered and 10 ml. of the filtrate was added to a test tube. Another test tube was filled with 10 ml. of tap water. Into each, was placed about one-half gram of silver nitrate crystals. If the filtrate gave more white precipitate than the tap water, another treatment was necessary.

The samples were stirred several times during each

treatment to insure better access of the sample to the water. Three or four treatments were sufficient to remove all the water solubles. The weight of the fine material left on the filter paper was obtained by weighing the filter paper before and after filtration. This residue was later added to the clay fraction. The sample was then dried on a hot plate and weighed.

Removal of Acid Soluble

The remaining portion of the non-clastic material was composed mostly of limestone and dolomite.

Because of the great effervescence of limestone, the first treatment was a 25 percent solution of hydrochloric acid. About 100 ml. of the solution was added to the sample very slowly. The sample was then stirred until all effervescence ceased. Most of the fine material was allowed to settle from the liquid before filtering.

A 50 percent solution was used for the second treatment and a 100 percent acid solution was used for the final treatment. After effervescence stopped in the last treatment, the beaker was placed in a warm sand bath and stirred intermittantly until all action ceased. Because of the large amount of dolomite present, the solution was heated for several hours. Contrary to the opinion of some, gentle boiling did not bring about cementation.

Because of the hydrochloric acid content of the liquid, the fine material in suspension flocculated very rapidly. After the liquid was cooled and the finer material settled out, the liquid was filtered. The sample was then washed with tap water until blue litmus paper showed no change. Each filter paper was washed several times to remove as much acid as possible. The acid caused a great increase in weight if it were not removed. Again the change in weight of the filter paper was added to the clay fraction. The sample was allowed to dry and the weight loss due to the acid solubles was recorded.

Disaggregation

Most of the shale was broken down in treating the sample for the water solubles and the acid solubles. But some black carbonaceous bits, probably from the Utica formation, still remained.

Krumbein and Pettijohn (1938) define disaggregation as "the breaking down of aggregates into smaller clusters or into individual grains." They also state; "avoid the use of harsh chemicals", although they advocate their use in some instances.

Before disaggregation, the large pieces of shale were crushed with a mortar and pestle to about a 30 mesh seive size to facilitate the treatments.

The techniques used in disaggregation are as follows:

1. Tolmachoff (1932) suggested soaking the shale in a hot solution of "hypo" (sodium hyposulfite). Upon cooling the supersaturated solution, crystallization starts and is accompanied by the disintegration of the shale. This method seemed to have little effect.

Krumbein and Pettijohn suggest the use of an alkaline digest, either a KOH or NaOH solution.

2. A supersaturated solution of NaOH was first tried. 100 ml. of solution was mixed with the sample in a 250 ml. beaker. The sample was boiled for three days and water was added when needed. Some disaggregation was noted, but the process was too slow to be acceptable.

3. KOH was the best compound used for disaggregation. The solution was prepared in boiling water and was extremely supersaturated. Care was taken not to add the KOH too rapidly to the water as a violent reaction would result. After boiling the solution ten or twelve hours a day for two days, the shale was almost completely disaggregated. The disaggregated material was siphoned off into a 600 ml. beaker and the remaining particles were again subjected to the KOH treatment. Three treatments were sufficient to disaggregate all the shale in 14 of the wells.

The small amount of shale remaining in the other two wells was removed as explained later in this chapter.

Prior to dispersion, it was necessary to remove the KOH from the sample. Four to six washings of tap water were necessary. Red litmus paper was used to determine when the sample was neutral. After each washing, the fine materials were allowed to settle before the liquid was filtered. Each filter paper was then washed with tap water to remove the KOH. The difference in weight of the filter was added to the clay fraction.

The purpose of disaggregation was to separate any sand that may be present from the shale. Also to insure the material left on the sieve in the sieving process (explained later) will be only sand.

Dispersion

Clay and silt size particles tend to flocculate even in a neutral solution unless the potential of the electrically charged particles is increased. Krumbein and Pettijohn (1938) suggest several different peptizing agents. A .01 N sodium oxalate was found by them to be the most effective. The solution was prepared by adding .67 gram of dry sodium oxalate to one liter of water. Before dispersion, the residue was completely dried so as much of the peptizing agent as possible could be used.

Sieving

Prior to removing the sand size particles, approximately 200 ml. of the sodium oxalate solution was added to the dry residue. This was allowed to stand for several minutes until a mud formed.

This mud was then washed through a 230 mesh Tyler sieve. Wentworth (1922) suggested this sieve as the division between the silt and the sand size particles. The material and solution passing through the sieve was caught in a flat bottomed pan. It was imperative, that not more than 800 ml. of the sodium oxalate solution be used in this process. About 500 ml. or 600 ml. of the solution was usually necessary to remove all the silt and clay from the sieve. The suspension in the pan was then funneled into a 1000 ml. graduated cylinder and saved for the pipette analysis. The sand left on the sieve was allowed to dry and the weight was recorded. For each well, a small vial was labeled into which the sand was poured and saved for the quartz-chert analysis.

Under microscopic inspection, four of the wells showed some shale particles left on the sieve. Before these sands were placed in the vials, a separation was performed to remove the shale.

A bromoform alcohol solution was prepared in a large funnel which was closed at the bottom by a rubber tube and a clamp. The correct solution was determined by placing a piece of quartz and a piece of shale into the funnel containing bromoform and adding alcohol until the quartz sank and the shale remained on top. The sand was then poured into the solution and allowed to settle. The clamp was opened to allow the sand and some of the liquid to pass onto a filter paper in a lower funnel. The difference in weight of the filter paper was recorded as the sand fraction. The remaining shale was then washed with alcohol from the first funnel and onto another filter paper. The weight of the small amount of shale for each of the four wells was divided into percentages and added to the silt and clay fractions. These percentages were computed from the pipette analysis of each well. Less than one gram of shale residue was present in each case.

Pipetting

Robinson (1922) devised a method of separating fine clastic material using the ordinary pipette. In theory, the pipette method is based on Stoke's law of settling velocities, where the method actually determines the density of the suspension at a fixed depth as a function of time (Krumbein and Pettijohn, 1938). By using a 1000 ml. graduated cylinder, they also found that after two hours and three

minutes all the suspended particles ten cm. or less from the surface of the liquid will be clay. The amount sampled is representative of the total amount of material in the cylinder having smaller settling velocities. Wentworth (1922) suggested 1/256 mm. in diameter as the dividing line between clay and silt size particles, of which clay is the smallest.

To the 1000 ml. graduated cylinder prepared during the sieve analysis, is added enough sodium oxalate solution to bring the level the liquid to 1000 ml.

The material was agitated by inserting a glass tube attached to a rubber hose to the bottom of the graduate. Air from an air jet was forced slowly through the hose. Care has to be taken to prevent excessive bubbling which might result in losing some of the material. The material was allowed to settle for two hours and three minutes. After which, a twenty ml. pipette was inserted to a depth of ten cm. and twenty ml. of solution was withdrawn. Inserting the pipette and withdrawing the material must be done rather slowly to avoid excess agitation. This material was placed in a 50 ml. beaker and dried in a warm sand bath. The difference in weight of the beaker represented 1/50 of the weight of the clay in the 1000 ml. graduate and of this weight, .013 g. represented 1/50 the weight of the sodium oxalate. To obtain the weight of all the clay in the graduate, the proportionality factor for the sodium oxalate (0.013 g.) was subtracted from tho weight of the clay sample. The resultant weight was then multiplied by fifty.

To this weight was added the filter paper residue obtained from the previous analyses plus the percentages of the undisaggregated shale. This weight represents the total amount of clay present in the well.

The silt fraction was obtained by subtraction of the non-clastics, sand, and clay from the weight of the original sample.

Mounting and Analyzing the Sand Grains

A hot plate and Bunsen burner were used to heat a clean glass slide. After the slide was hot, a small amount of canada balsam was placed on it and allowed to cook for several minutes. Meanwhile, the sand saved from the sieve analysis was sieved through a 60 mesh Tyler sieve to facilitate mounting on the slide. Most of this sand was then sprinkled on the melted canada balsam and a cover glass was placed over it.

Under the microscope, only the percentages of quartz and chert were estimated. But it was discovered that in all cases more than fifty percent of the sand was composed of pyrite crystals. Each slide was considered representative of the entire sand in the well.

Laboratory Equipment

For the quantitative analysis of one well, the following laboratory equipment was used:

1 50 ml. beaker
1 250 ml. beaker
1 400 ml. beaker
1 600 ml. beaker
1 30 mesh Tyler sieve
1 60 mesh Tyler sieve
1 230 mesh Tyler sieve
1 flat bottom pan
2 large funnels
1 2 foot glass tube
1 3 foot rubber hose
1 glass stirring rod
1 20 cc. pipette
1 1000 ml. graduated cylinder
1 sample vial and cork
1 glass slide
1 cover glass
1 electric hot plate
1 sand bath
1 chainomatic balance and weights
1 polarizing microscope
1 Bunsen burner
1 hot plate
15 cm. #1 filter paper

Errors in the Analyses

Some error did exist in forming the composite sample. This may be due in part to loss as dust or to some accumulative error in weighing. After boiling in the KOH solution, it was impossible to remove some of the material stuck to the sides of the beaker. This amount was determined to be less than 1/10 g. in all instances and was added to the clay fraction. Some error would have occurred in washing the material through the sieve in the sieve analysis. This error, however, was undeterminable.

Results of the Laboratory Analyses

Table III represents the data obtained from the quantitative analyses of the 16 wells. This data was used to compute the first three ratios of Table IV. The quartz-chert ratio data was determined from a microscopic examination of the sand grains.

TABLE III

QUANTITATIVE ANALYSIS

Well Number	Sample Weight	Water Solubles	Acid Solubles	Sand Fraction	Silt Fraction	Clay Fraction
1	112.17g.	0.47g.	76.48g.	0.68g.	20.69g.	13.85g.
2	141.24	0.88	94.85	0.48	25.75	19.31
3	140.72	0.35	80.48	0.15	29.95	25.23
4	113.94	0.61	84.44	0.18	15.73	12.98
5	92.35	1.31	57.43	0.10	18.51	15.98
6	57.93	0.03	38.17	0.07	6.97	12.49
7	85.41	0.49	58.17	0.20	12.63	13.90
8	157.96	0.29	110.24	0.34	21.84	25.25

TABLE III (Cont.)

Well Number	Sample Weight	Water Solubles	Acid Solubles	Sand Fraction	Silt Fraction	Clay Fraction
9	68.45	0.19	48.92	0.14	8.15	11.05
10	146.16	0.42	96.28	0.22	25.20	24.04
11	80.58	0.24	53.23	0.03	16.32	10.75
12	80.30	0.64	56.95	0.26	9.42	13.03
13	178.67	1.28	123.03	3.09	27.43	23.83
14	76.63	0.66	54.77	0.46	8.70	12.05
15	165.95	0.34	118.70	0.14	21.56	25.21
16	155.37	0.88	112.49	0.15	17.15	24.70

LITHOLOGIC VARIATION

Lithologic Ratios

Because of the growing abundance of subsurface exploration in recent years, samples for analysis and mapping have become more abundant. Krumbein (1948) devised a system of ratios for mapping purposes.

> "The thickness (or percentage) of clastics are added together and divided by the sum of the thicknesses (or percentages) of the non-clastics. The resulting number is defined as the "clastic ratio". The clastic ratio is augmented by a "sand-shale ratio" which is the ratio of sandstone (plus conglomerate) to shale in the section, regardless of the amount of non-clastics present:
>
> $$\text{clastic ratio} = \frac{\text{conglomerate + sandstone + shale}}{\text{limestone + dolomite + evaporite}}$$
>
> $$\text{sand-shale ratio} = \frac{\text{conglomerate + sandstone}}{\text{shale}}$$
>
> A clastic ratio of 2, for example, means that on the average 2 feet of clastic material were deposited per foot of non-clastics."

Another ratio that is very widely used is the evaporite ratio where:

$$\text{evaporite ratio} = \frac{\text{evaporites}}{\text{limestone + dolomite}}$$

A quartz-chert ratio where:

$$\text{quartz-chert ratio} = \frac{\text{\% quartz}}{\text{\% chert}}$$

was devised to determine statistically whether there is a significant trend in chert content from the eastern to the western part of the state.

A pyrite to sand or a pyrite to chert-quartz ratio may be feasible in this paper. But, for lack of time, this analysis was not attempted.

The analysis showed very little evaporite (water soluble) material present. For this reason, it is questionable whether the ratio is significant. Any small errors that may occur in the analysis are apt to show here. This is also true for the sand. Of the four ratios, the clastic ratio and the quartz-chert ratio will be the most significant.

Table IV shows the lithologic ratios for each well. These ratios were obtained from the data on Table III.

TABLE IV

LITHOLOGIC RATIOS

Well Number	Clastic Ratio	Sand-Shale Ratio	Evaporite Ratio	Quartz-Chert Ratio
1	0.46	0.019	0.006	2.08
2	0.48	0.011	0.009	2.00
3	0.68	0.002	0.003	0.33

TABLE IV (Cont.)

Well Number	Clastic Ratio	Sand-Shale Ratio	Evaporite Ratio	Quartz-Chert Ratio
4	0.34	0.007	0.007	1.40
5	0.58	0.003	0.023	0.50
6	0.51	0.003	0.001	3.00
7	0.46	0.008	0.008	0.24
8	0.43	0.007	0.003	1.20
9	0.39	0.007	0.004	2.50
10	0.51	0.004	0.005	3.00
11	0.51	0.001	0.005	1.00
12	0.39	0.011	0.011	1.33
13	0.44	0.060	0.010	3.00
14	0.38	0.022	0.012	9.00
15	0.39	0.003	0.003	2.50
16	0.28	0.004	0.008	0.20

Facies Map Construction

In constructing the facies maps, it was first necessary to obtain a good base map. The ratios were then plotted in their respective positions on the map. Contour lines of equal ratio were constructed from this data.

These lines were plotted with an arithmetic rather than a geometric interval (krumbein 1952).

To facilitate interpretation of the maps, rather than constructing isopach lines over the ratio contours, a separate isopach map was made on semi-transparent paper. The ratio maps were constructed on opaque paper. Therefore, the isopach map may be placed over any of the ratio maps to aid in interpretation.

Maps III, IV, and V are the clastic ratio, sand-shale ratio, and evaporite ratio maps respectively. Map VI is the isopach map. Each was constructed using the data obtained from the analyses of the 16 wells.

INTERPRETATION OF FACIES MAPS

Methods of Geological Interpretation

Krumbein (1952) devised a unique classification of relationships between the lines of an isopach map and the contours of a lithofacies map. By superimposing the isopach on the lithofacies map, certain angles are formed by the contour lines. He defines six relations that can be found between any set of isopachs and lithofacies lines. Some of the illustrations he gives for these patterns are as follows: "The linear sub-parallel pattern may occur under conditions where clastic sediments are spread over a subsiding area in decreasing amount away from the source, so that the clastic ratio lines tend to decrease as the isopachs increase ...", and the "curvilinear-discordant pattern may arise when a local concentration of clastics is poured into a subsiding area, as a delta."

Three patterns are especially suited to an intracratonic basin such as the Michigan Basin (Krumbein 1952).

The discordant-ovate pattern would indicate either a nearby organic source or a nearby epeirogenic source.

A concentric-ovate pattern could indicate either a nearby orogenic source, a nearby epeirogenic source, or a distant source.

A curvilinear pattern usually shows a nearby orogenic source.

These relationships should give a good basis for interpreting the source areas and their relative distance. Figure I illustrates the relations.

Methods of Statistical Interpretation

Krumbein (1955) suggests the use of analysis of variance to stratigraphic or lithologic variations. In the discussion of stratigraphic populations, he states:

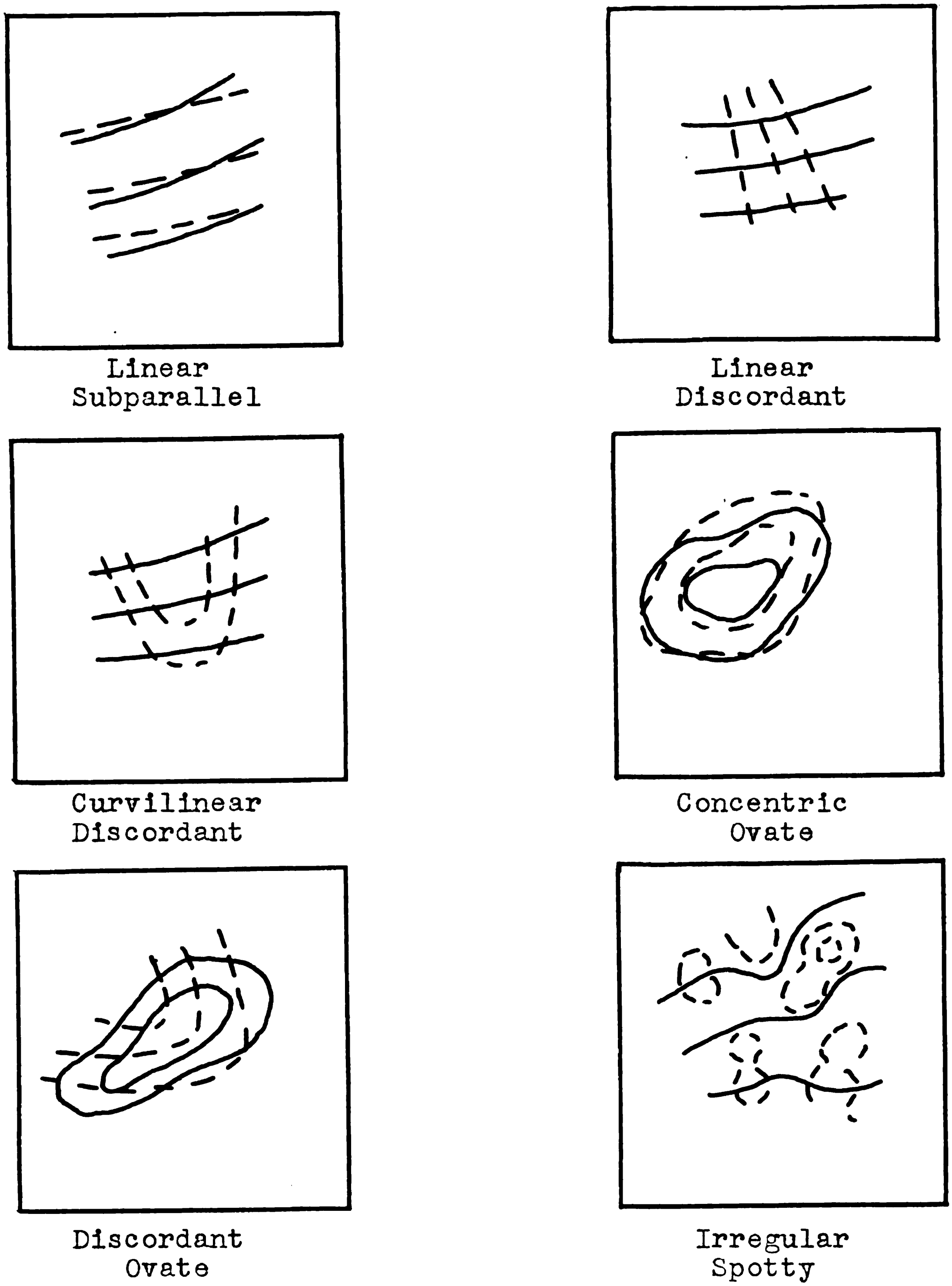
> "A stratigraphic unit has certain statistical properties when it is thought of as a population of attributes. Some of these properties can be translated into geological terms, and they provide useful concepts in the study of facies maps. For example, the total population may be homogeneous, so that samples drawn from any one subarea are similar to those drawn elsewhere; or the population may have a gradient, so that the measured properties vary systematically in some direction over the map."

This type of statistical analysis of facies maps is relatively new. It is designed primarily to test facies patterns that are spotty and give no indication of trending in any particular direction.

In testing data by analysis of variance, a hypothesis is chosen which in this problem states, there is no significant difference between the position means.

FIGURE I

Relationships Between Isopachs (Solid) and
Facies Lines (After Krumbein, 1952)



The sum of squares for positions was obtained by summing each column of data. Each of these figures was then squared and divided by the number of observations for each position. These three values were then added together. From this number, is subtracted a figure computed as follows; each observation is squared and summed, then divided by the total number of observations. The resultant value from the subtraction is the sum of squares for positions.

The total sum of squares was calculate by summing the square of each observation and subtracting the same value as above.

The error sum of squares was obtained by subtracting the position value from the total.

Degrees of freedom were determined by subtracting the number one from the number of values used in the calculations. For example, there are three values for positions so the degrees of freedom for positions are two. The total degrees of freedom are the total number of observations minus one or 16 minus one equals 15. The error term was obtained by subtraction.

To determine the mean square value for positions, divide the sum of squares by the degrees of freedom. This was also the method of calculating the error mean square.

The F ratio was obtained by dividing the position mean square by the error mean square. The F tables were

found in Goulden (1952). The degrees of freedom for the numerator in the F ratio are the horizontal values in the tables. The degrees of freedom for the denominator are the vertical values. If the calculated value for the F ratio is greater than the table value, the means of the positions are considered significantly different at the five percent level. The light numerals in the table constitute the five percent level.

A significant difference in means suggests a definite gradient in the values. In this analysis, no significant difference was evident.

Map VII is the facies map for the quartz-chert ratio. Map II illustrates the breakdown of the state into the three positions; eastern, central, and western. These positions are of equal length and constitute the columns in the analysis of variance. The analysis is shown in Table V.

TABLE V

ANALYSIS OF VARIANCE OF QUARTZ-CHERT RATIOS IN THE MICHIGAN BASIN

Raw Data		
West Section	Central Section	East Section
3.00	9.00	2.08
0.24	1.40	2.50

TABLE V (Cont.)

Raw Data

West Section	Central Section	East Section
2.54	2.00	0.20
1.33	1.20	3.00
1.00		3.00
0.50		0.33

Analysis of Variance

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Positions	2.12	2	1.06	< 1 NS
Within positions ..	43.38	13	3.36	
Total	45.50	15		

$F_{(0.95)}$ (2, 13) = 3.80

Errors Involved in Interpretation

Many errors are involved in analyzing and interpreting the section used in this study. The most obvious is the great amount of interpolation necessary in constructing the

maps. Some large and some small structures are undoubtedly omitted. However, most of the large irregularities are brought out in the analysis. These structures are broad and persistent and in some cases tend to be accentuated by this composite study.

Very little erosion has occurred during or after the deposition of these sediments. So the isopach and lithofacies maps should be very conclusive.

It was difficult to construct and interpretate the quartz-chert ratio map because of the limited number of wells and the spotty pattern of deposition of the chert. The statistical analysis was much more significant for this type of deposit. The analysis was used to measure an east-west trend.

Interpretations

Geological Interpretation

The facies maps were interpreted separately, by placing the isopach over each one. It was thought necessary to use counties as a basis for interpreting the structures. It would be helpful to have a county map of Michigan to refer to during the following discussion.

The clastic ratio map. This type of map is considered to be the most accurate of the facies maps. For this reason, the results from this map should take preference over most differences brought out on the other maps.

In the northern peninsula, a curvilinear discordant pattern is found in Mackinac, Luce, and Chippewa counties. The nose of the clastic ratio contours points away from the basin indicating a possible subsidence or trough present in the area. These ratio contours continue beyond the scope of the isopach map. This trough seems to have affected the whole northern section of the state.

Applying Krumbein's (1952) theory of the tectonic factors controlling deposition in an intracratonic basin, a curvilinear discordant pattern of this type would indicate a relatively distant orogenic source. This could be called an "inverted" curvilinear discordant pattern.

The western part of the state is characterized generally by a linear subparallel pattern. However, there is some evidence of another inverted curvilinear discordant pattern in Mason and Manistee counties; in fact, the isopach shows some thickening of sediments in this area, while the clastic ratios decrease, indicating some degree of subsidence.

South of this area, between Mason and Ottawa counties, there is a definite linear subparallel relation. Krumbein (1952), referring to this pattern, states, "clastic sediments are spread over a subsiding area in decreasing amount

away from the source, so that the clastic ratio lines tend to decrease as the isopachs increase because of increasing lime deposition."

In the southwest, the relationship between the isopach lines and the ratio contours range from a slightly curvilinear discordant and linear subparallel pattern to a relatively strong curvilinear discordant pattern. This indicates a strong regional subsidence or trough effect to the southwest. This effect is evident from Ottawa to Hillsdale County.

A rather intricate pattern is found in the southeastern section of the state. In Oakland and Macomb counties, there is a strong discordant ovate pattern. But, farther to the southeast, in Monroe, Wayne, and Washtenaw counties and into southwest Ontario, the pattern changes to an inverted curvilinear discordant relationship. This is suggestive of a nearby orogenic or epeirogenic source in Oakland and Macomb counties as against an area of subsidence to the south and southeast.

The ovate pattern on the isopach in Wayne and Oakland counties indicates the thickest accumulation of sediments. However, the clastic ratio map places the greatest deep water deposits farther to the northwest.

Relatively little information is available in the

east, but the pattern seems to be linear subparallel. Because of the large area covered by this pattern, it is postulated that the material came from a distant source.

The following is a summary of the major structural trends determined from the clastic ratio map.

1. An area of subsidence in Mackinac, Luce, and Chippewa counties trending to the north into the Lake Superior Basin.

2. A widespread general subsidence in the southwestern section of the state. This structure trends to the southwest.

3. In Wayne and Livingston counties, there is a narrow deep trough indicated with source material nearby both to the northeast and southwest.

<u>The sand-shale ratio map</u>. Because of the exclusion of the lower Ordovician sediments, which contain most of the sand, the sand-shale ratio is extremely small.

In Schoolcraft and western Mackinac counties, there is a relatively weak curvilinear discordant pattern. This indicates a slight increase in sand content. Both to the west and east of this structure, there are slight indications of subsidence. The trough to the southeast corresponds to the conclusions drawn in the clastic ratio interpretation of this area.

There are two ridge-like structures. One trends to the northeast through Oceana, Mason, and Lake counties, and the other east through Allegan, Kent, Barry, and Ionia counties. The isopach through both of these areas indicates the exactly opposite structure. This may be due to the error introduced by the relatively small amount of sand, but the writer thinks not.

The southwest corner of the state shows a strong low in the sand-shale ratio and illustrates an excellent inverse curvilinear discordant pattern. This low extends to the southwest and corresponds to the clastic ratio interpretation.

In the southeast, a distinct inverse curvilinear discordant pattern exists, trending southeast through Washtenaw, Wayne, and Monroe counties. The northwestern corner of Wayne County shows an extremely high sand-shale ratio. This is possibly a good example of error due to contamination in sampling or a small increase in sand content in the section. The high is represented by a ratio of .060.

To the west of this area, passing through Lenawee County is a rather small structure indicated by an increase in sand content. The contour relations show a linear discordant pattern.

The east is represented by a linear subparallel pattern, as it was on the clastic ratio map, indicating a distant source of material.

The major structural features represented on the sand-shale ratio map are as follows:

1. Two trough-like structures in the Upper Peninsula. One passing northward through Schoolcraft county and the other trending northward through Mackinac and Luce counties.

2. In the west, two ridge-like structures. Both, however, are contrary to the interpretations of the isopach map.

3. The southwest shows a trough trending to the southwest with relative highs on both sides.

4. Another trough is represented in the southeast trending east through Washtenaw and Wayne counties.

5. An exceptionally high area is present in northwest Wayne county. This is probably due to the error previously discussed.

The evaporite ratio map. "The concentric ovate pattern is characteristic of evaporites in an intracratonic basin" (Krumbein 1952). This pattern is especially obvious in the Oakland and Wayne county area.

Another ovate pattern is formed in the southwest in St. Joseph, Kalamazoo, Calhoun, and Branch counties. This structure conforms to the southwest trending trough already discussed.

Just to the north of this structure, there is a strong high shown on the lithofacies map. This high is accompanied by a thickening of sediments shown on the isopach. However, this structure is probably part of the trough to the south. The nose of the contour trends to the southeast through Allegan, Ottawa, and Barry counties.

Along the western edge of the state, the isopach and evaporite contours closely parallel each other. This suggests a distant source of material.

A distinct relationship between the isopach lines and facies contours is represented in the Upper Peninsula. The isopach lines show thinning to the northwest as the facies lines thicken toward the basin. A trough-like structure trending northwest is suggested. This structure is located in Schoolcraft, Luce, and Western Mackinac counties.

Interpolation in the eastern part of the state indicates much the same type of deposition as was suggested from the other facies maps.

The following is a summary of the prominent structures indicated by the evaporite lithofacies map:

1. A small area of basinal deposition in Wayne and Oakland counties.

2. Another area of basinal deposition is elongated to the southwest. The width of this structure stretches from Allegan County southeast to Hillsdale County.

3. A small trough is indicated in the Upper Peninsula, trending northwest through Schoolcraft, Luce, and Western Mackinac counties.

The quartz-chert ratio map. This map generally has an irregular spotty pattern which, according to Krumbein (1952), is indicative of either a nearby epeirogenic source or a distant source.

There are extreme differences in the ratios between southwestern Schoolcraft County and northwestern Mackinac County, which indicates to some extent a random type of deposition.

In the southwest corner of the state, however, there is an inverted curvilinear discordant pattern that is rather pronounced. This shows some increase in the relative quantity of chert which indicates subsidence. This structure trends to the southwest.

In Wayne, Washtenaw, Livingston, and Oakland counties there is a concentric ovate relation which is characteristic of evaporite deposition in an intracratonic basin. This structure indicates deep water deposition which conforms to the isopach interpretation of this area.

The major structures indicated by the quartz-chert ratio map are as follows:

1. A random type of deposition in the Upper Peninsula.

2. A trough through Kalamazoo, Cass, and St. Joseph counties trending southwest.

3. A deep water intracratonic basin deposit in Livingston, Oakland, Washtenaw, and Wayne counties.

Statistical Interpretation

Only the quartz-chert ratio map was analyzed statistically. This was done because of the irregular spotty type of deposition. The other ratio maps showed strong trends and needed no statistical interpretation.

Before the analysis, there was presumed to be some variation from east to west in the chert content. The analysis showed, however, no trend whatsoever. There could be some local trends, but on this regional scale they would tend to cancel each other.

REGIONAL TECTONICS

Structural Relations of the Michigan Basin

The greatest Paleozoic unconformity in the Michigan Basin is found at the break between the St. Peter sandstone and the Trenton and Black River limestones. The St. Peter marks the time of uplift and erosion. From west to east, the lower and middle Ordovician deposits successively rest on the upper Cambrian to the pre-Cambrian crystalline rocks (Eardley 1951).

Prior to Devonian time, the Michigan and Illinois-Indiana-Kentucky basins were continuous; "But beginning in the Devonian, the Kankakee arch began to form, and the two basins became increasingly individualistic thereafter" (Eardley 1951). The Kankakee arch is the southern and southwestern boundary of the Michigan Basin.

Early in the Ordovician, the northeastern branch of the Cincinnati arch, the Findlay arch, began to form (Cohee 1948). The Wisconsin arch, which bounds the basin on the west, began to form in early Cambrian but the major movement was post-Cambrian. According to Ekblaw (1938), the major movement of the Wisconsin arch occurred after the Lower Ordovician.

Cohee (1948) suggests the basin continues in the north as a narrow trough between pre-Cambrian crystalline and metamorphic rocks. The basin was possibly continuous with the Lake Superior geosyncline which follows the present lake in a half-moon shape around the upper peninsula. The connection was near the north tip of the Lower Peninsula (Pirtle 1932).

Now, let's consider the relationships of the facies maps with the regional structure during Ordovician time.

Structural Interpretations in Relation to Tectonics

Most of the major intrabasinal structures are represented in the facies maps. The evaporite ratio and quartz-chert ratio maps indicate the deep areas of deposition. On the other hand, the sand-shale and clastic ratio maps magnify the marginal areas and areas of uplift.

Cohee (1948) made an extensive study of the Cambrian and Ordovician rocks in the Michigan Basin. Using well logs for data, he constructed two maps showing the thicknesses of both the Upper and Middle Ordovician sediments. The center of the basin is shown on these maps as a trough extending from Saginaw County southeast to Oakland County. A similar structure was shown on the maps in this analysis.

The clastic ratio and sand-shale ratio maps indicate a possible extension of this trough to the east and southeast. In referring to this depression, Cohee (1948) states, "This sag probably served as a connection between the Michigan and the Appalachian Basins at various times." Both to the north and south of the depression, are located structural highs. During the lower Ordovician, the Findlay arch was beginning to form. Intermittant linking with the Appalachian Basin due to fluctuations during the formation of the arch, is probably a more accurate interpretation of this trough than the presence of a continuous connection.

In the southwest section of the state, a broad continuous depression which connected the Michigan Basin to the Illinois-Indiana-Kentucky Basin existed. This interpretation corresponds to the conclusions of both Eardley (1951) and Cohee (1948). According to Eardley (1951), the Kankakee arch began to form in the Devonian. This statement is partially supported by the great amount of faulting exhibited in the Trenton Limestone in Northern Ohio, which indicates post-Trenton movement (Cohee, 1948).

The Wisconsin arch is a broad fold trending northwest (Pirtle, 1932). Most of the movement of this arch occurred in post-Cambrian time. This would indicate that during the Ordovician it was not a very prominent feature.

The type of deposition in the western part of the state indicates the existence of this kind of structure.

Cohee (1948) suggests the possibility of a connection between the Michigan Basin and the Lake Superior Basin. The Lake Superior Basin was postulated to be present during Ordovician time. All the maps, with the exception of the quartz-chert ratio map, show the presence of a shallow trough, trending northwest, through Mackinac, Luce, and Schoolcraft counties.

Because of the scarcity of information in the eastern part of the state, the conclusions drawn are rather inconclusive. But the material for deposition seems to be from a rather distant source. The Findlay arch, because of its low attitude did not affect deposition in this area to any extent.

Tectonic Aspect

The interpretation of the facies maps indicates the Michigan Basin as a relatively broad depression. Because of the relatively small amount of evaporites present, it is inferred that the basin was rather stable and continually below water. Most of the highlands surrounding the basin were eroded to relatively low positive structures during the period between the St. Peter and Black River depositions.

This environment may also account for the small amount of sand in the analysis. The lithologic change from the limestones and dolomites of the middle Ordovician to the shales of the upper Ordovician indicate some uplift on the periphery of the basin.

CONCLUSIONS

Most of the structures interpreted from this analysis are not shown in the present structure of the Michigan Basin. These structures represent the beginning of the formation of the basin and have changed considerably since deposition of the Ordovician sediments. One of the most marked changes is the shift in the position of the center of the basin from Oakland County, northwest, to the vicinity of Clare County. The presence of some of these structures was extremely valuable in the interpretation of the tectonic activity during the deposition of the Ordovician sediments.

In recent years at Michigan State University, this type of analysis has been performed on most of the Paleozoic sediments. With the completion of the remaining systems, a great deal of information will be available concerning the Michigan Basin.

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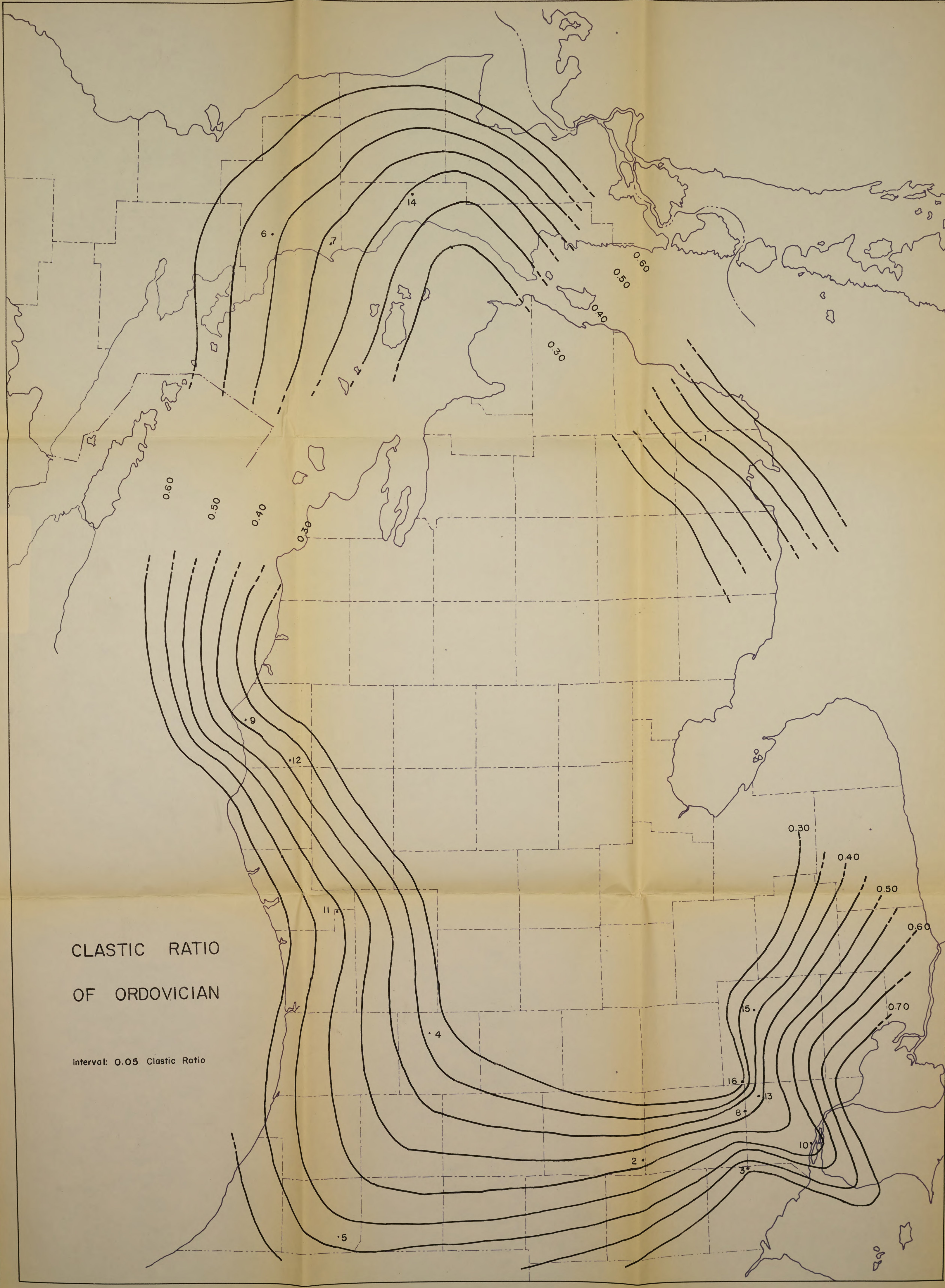

CLASTIC RATIO

OF ORDOVICIAN

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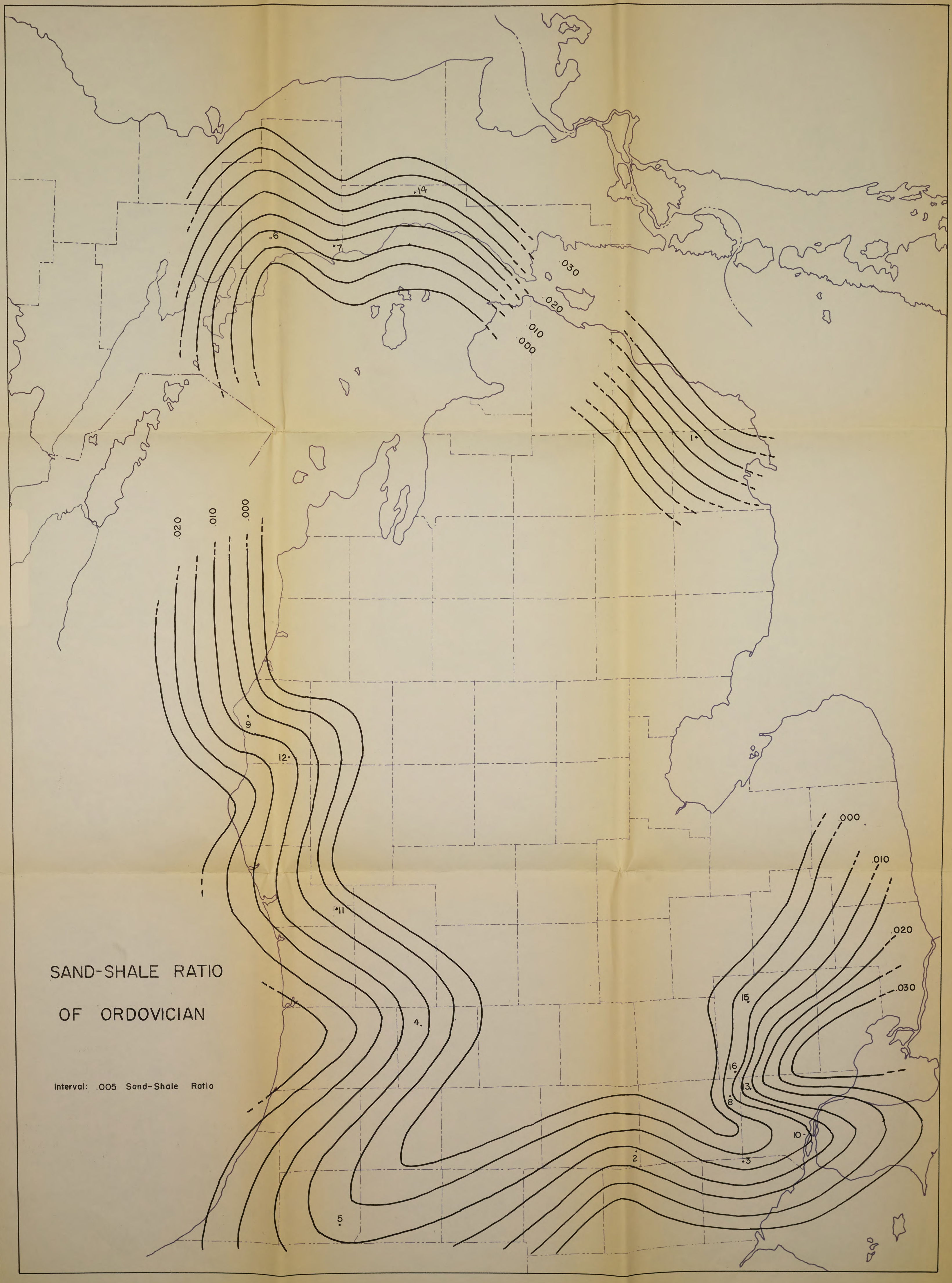
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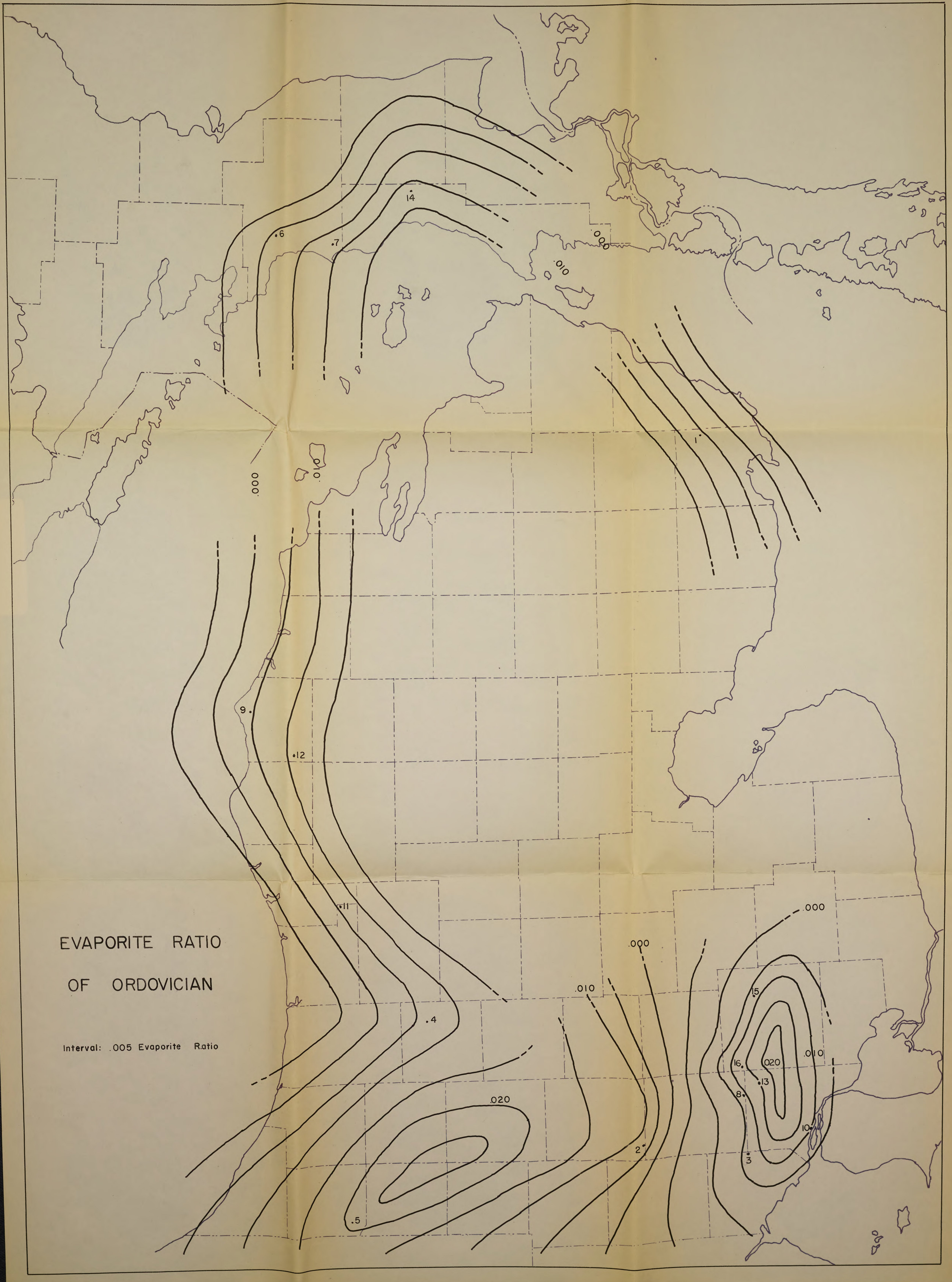
SAND-SHALE RATIO
OF ORDOVICIAN
Interval: .005 Sand-Shale Ratio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OF ORDOVICIAN
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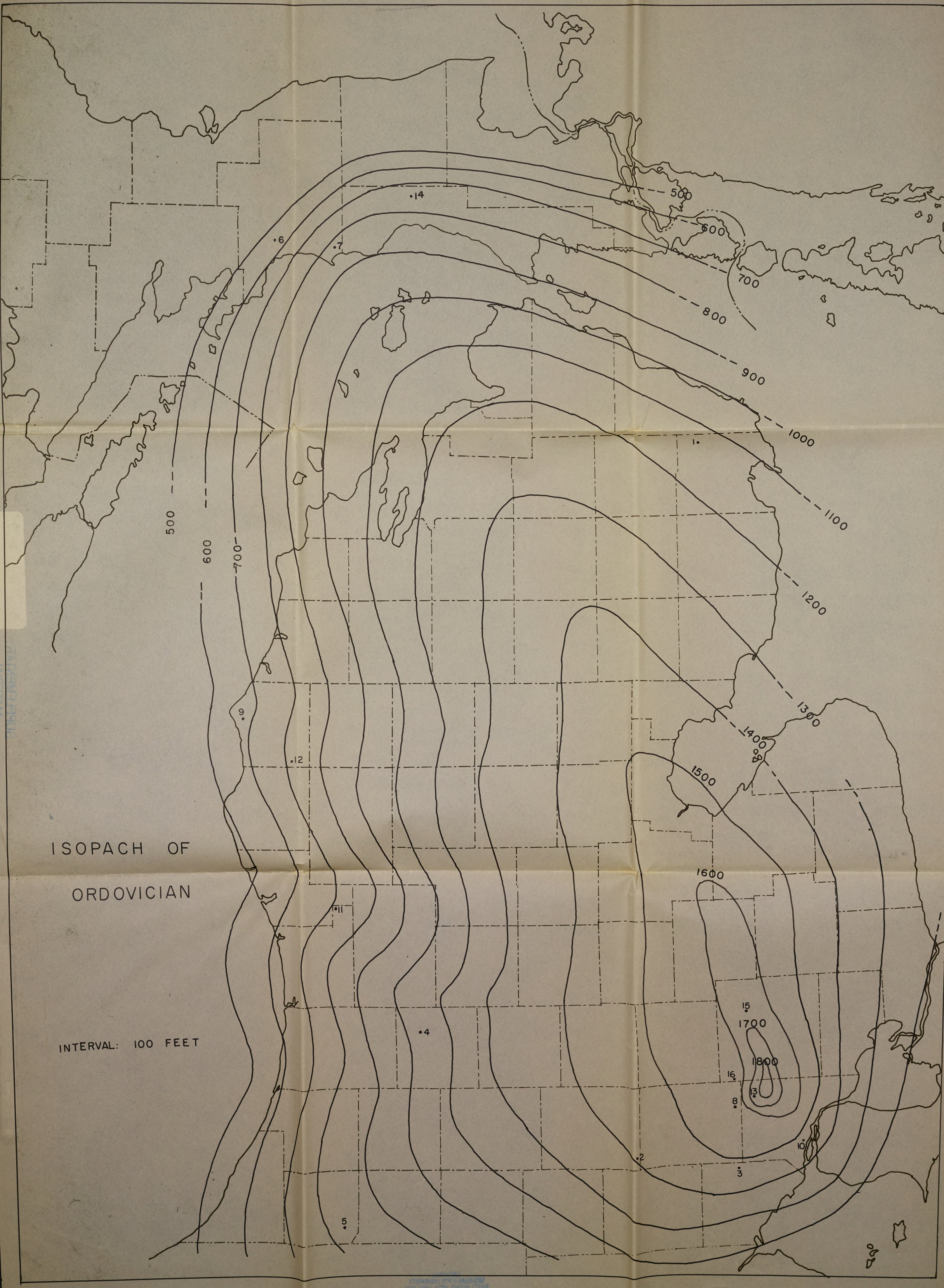
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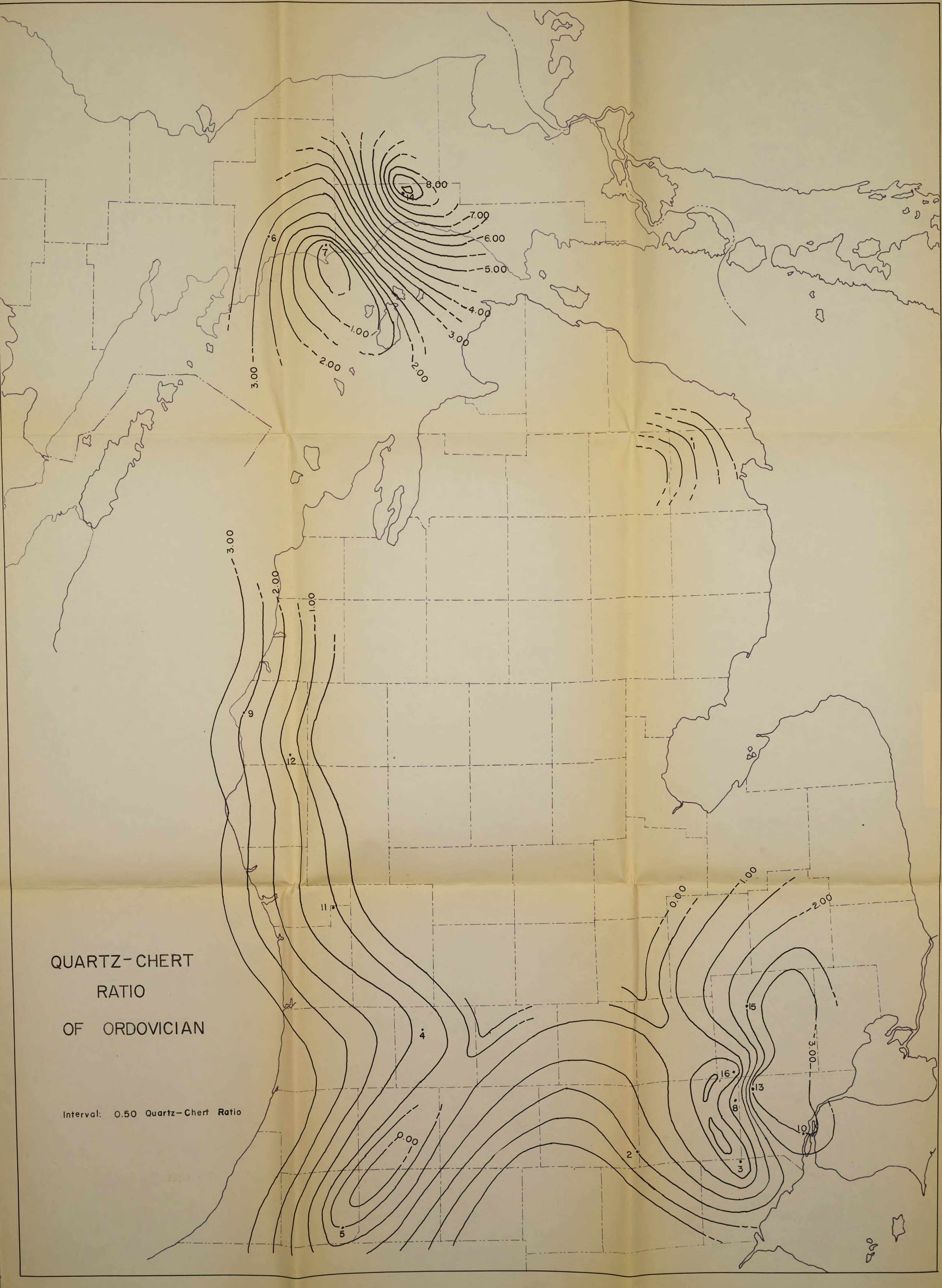
QUARTZ-CHERT
RATIO
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