A QUANTITATIVE ANALYSIS OF SILURIAN SEDIMENTS IN THE MICHIGAN BASIN

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Wilton Newton Melhorn

1951

This is to certify that the

thesis entitled

"A Quantitative Analysis of Silurian
Sediments in the Michigan Basin"

presented by

Wilton Newton Melhorn

has been accepted towards fulfillment
of the requirements for

Master of Science degree in Geology and Geography

B. T. Sandefur
Major professor

Date Nov., 30, 1951

O-169

# A QUANTITATIVE ANALYSIS OF SILURIAN SEDIMENTS IN THE MICHIGAN BASIN

By

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology and Geography

1951

THESIS

ACKNOWLEDGMENTS

The author wishes to express appreciation to Dr. B. T. Sandefur, who first aroused the writer's interest in sedimentation studies of a quantitative nature and pointed out their possible economic applications. Dr. Sandefur also gave freely of his time and assistance in conduction of the preliminary experiments which are culminated in this paper.

Thanks are due to Mr. George Strait of the Michigan Geological Survey, who aided in selection of samples for analysis and assisted in choosing of formational markers. Dr. W. A. Kelly gave valuable suggestions concerning Silurian stratigraphy. Dr. S. G. Bergquist edited the manuscript, and Mr. J. B. Long aided in sample analysis and offered constructive suggestions on and criticisms of laboratory techniques.

Special thanks are due the writer's mother, Mrs. Pauline Melhorn, for assistance in preparation of the facies maps.

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# INTRODUCTION

## History of Lithofacies Investigations

In the present search for new petroleum reserves, the emphasis on discovery of stratigraphic traps has given steady impetus and increasing importance to studies in sedimentation. Changes in sedimentary facies suitable for the accumulation of oil have focused attention on methods of exploration applicable to this type of trap. The characteristics of sediments partly control the localization of lenses or traps. Methods of quantitative sedimentation afford one means of attacking this problem, because they furnish a more complete picture of sedimentary characters and processes than might otherwise be possible. As Moody (1) recently stated,

> The lateral variations of sedimentary rocks are now of fundamental concern to the practical, front-line exploration geologist. Quantitative petrographic data of regional scope might lift our exploration petrography above its present "sand-shale-lime" level. Can anyone say that this would not be a profitable accomplishment?

In the past two decades, many techniques for the quantitative measurement of sedimentary attributes have been developed, and a large amount of theoretical knowledge has been made available for application to practical geological problems. Many writers, notably Knopf (2), Twenhofel (3), Trask (4), Pettijohn (5), and Levorsen (6) have discussed the place of sedimentation in geology, and have found that the use of quantitative data is increasing in the field of applied sedimentation.

Particle properties, such as size, shape, roundness, surface texture, mineral composition, and orientation have been investigated and quantified by various authors. These properties are, however, all reflected to a greater or lesser degree in the term "lithologic characteristics"; and in turn, the sum total of the lithologic characteristics of a sedimentary rock is its "lithofacies" which may be represented by constructing a lithofacies map. Krumbein (7) has defined a lithofacies map as "an areal representation of sedimentary rock characteristics for a stratigraphic interval."

Lithofacies maps are based on the dominant lithologic characteristics in a certain geological section, which may be either a surface exposure or a subsurface interval. Ver Wiebe (8) in 1930 first recognized the value of contrasting clastic and non-clastic components in the section. In 1945 Krumbein (9) initially suggested use of a map as a method of numerical representation to depict the percentages of various lithologies. Later Read and Wood (10) published a contour-type map based on the ratio of clastic to non-clastic components. More recently Sloss, Krumbein, and Dapples (7) have advanced the idea of construction of lithofacies maps based on the so-called "lithologic triangle." An expansion of this idea is found in a later paper by Krumbein (11), and a summary of this and other methods of construction of lithofacies maps have been described in the most recent publication of Krumbein and Sloss (12).

The preparation of any lithofacies map depends on a knowledge of the thickness and character of the sediments in the geological section under investigation. Work by the previously mentioned authors (chiefly Krumbein and Sloss) was based on data gathered mostly from measured outcrops or exposed sections of considerable vertical extent, and the results expressed in terms of percentage thicknesses of clastic or non-clastic rocks. Only where exposures were not present were well records used to fill in gaps in the general pattern of the lithofacies map. Rittenhouse and Cather (13, 14) did attempt a textural (size) analysis of Paleozoic sandstones and sandy limestones, using both well and outcrop samples from a restricted geographical area. Their analytical procedure involved treating of the samples with hot hydrochloric acid and subsequently washing the samples to remove sand and silt. The percentages of sand and silt were then calculated separately on a basis of 100 per cent. However, their main concern was with the grade sizes of sand grains, and no emphasis was placed on the relative proportions of soluble salts or carbonates, which occurred either as separate particles or as a sand-grain cement.

## Statement of the Problem

In the Michigan basin, where outcrops of any rock type are infrequent, a different approach to lithologic determination is mandatory. Fortunately some 17,000 wells have been drilled in Michigan in the search for oil and gas, and of this great number, a small percentage, perhaps 100 wells in all, have penetrated part or all of the Silurian formations and reached the underlying Ordovician rocks. Initially it was thought that a study of the driller's logs of these wells would be sufficient to establish the general lithologic character of Silurian sediments in the basin; but on further inspection it was discovered that these records were inadequate, frequently incomplete, and sometimes even entirely incorrect as to the types of sediments encountered in the course of drilling operations. The idea was then conceived of analyzing in quantitative fashion the actual sample cuttings from selected wells, and to construct lithofacies maps from the resultant statistics. The present report is based on an investigation conducted along these lines.

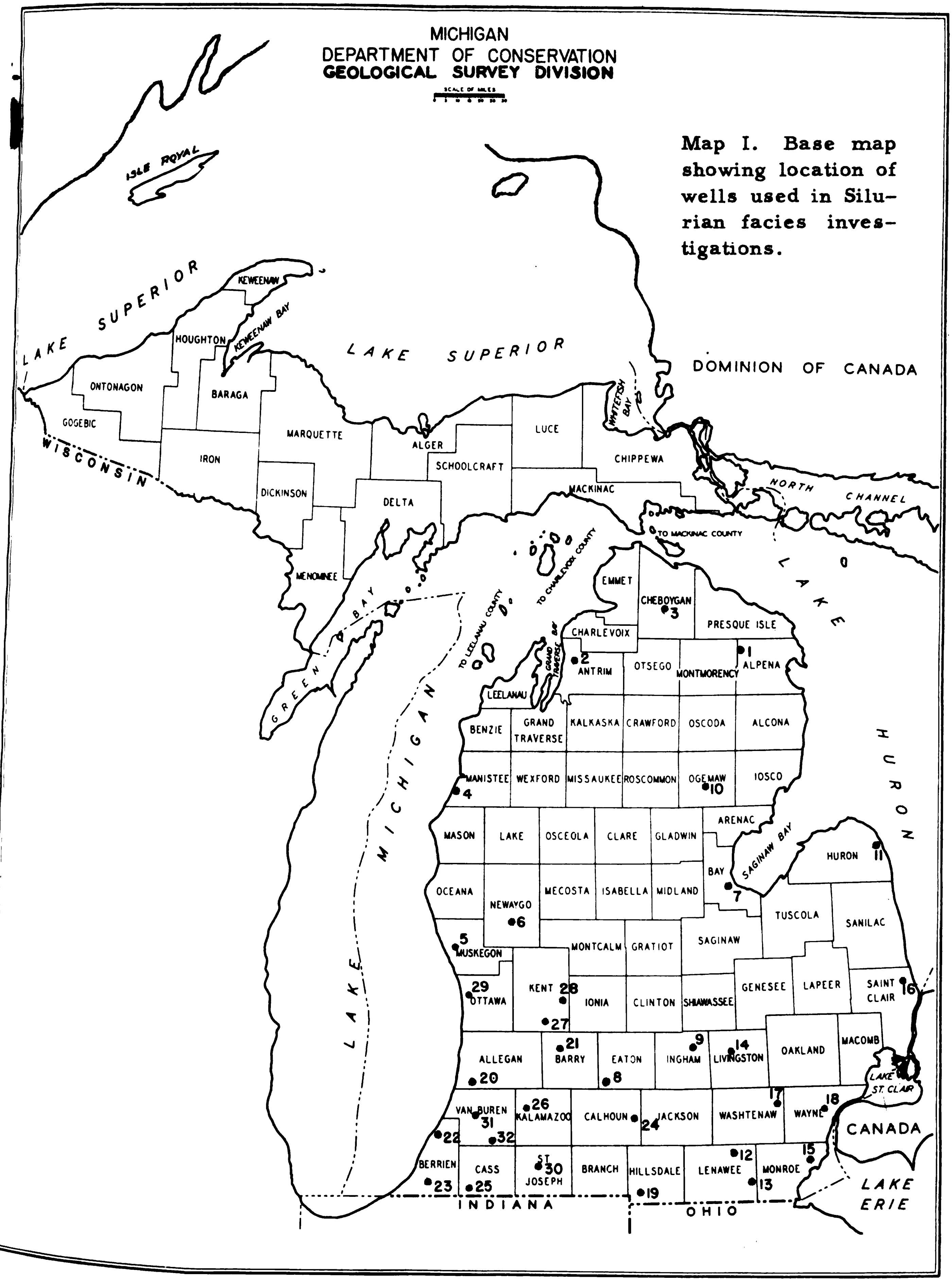
The writer believes that a complete quantitative analysis of well samples for use in the preparation and interpretation of lithofacies maps is the key to a new approach to sedimentary research, and may in time assume economic significance in the prospecting for new petroleum reserves in Michigan.

The individual who pioneers in a new field of investigation often fails to consider every possible aspect of his problem. This report is admittedly broad in scope, and it is hoped that the reader will give more consideration to the value of the theory involved than to the immediate results. As more deep drilling takes place in the Michigan basin, detailed lithofacies studies on a county or areal basis may become practical. Refinements in laboratory techniques and improvements in the procurement of well samples will also allow for greater analytical accuracy.

## Location of Wells and Selection of Samples

The wells selected for study are shown on Map I. It will be noted that there is a pronounced clustering of wells around the margins of the basin leaving a considerable blank area in the center. This is simply because no wells are available in mid-basin, where drilling depths of 8,000 feet or more would be required to penetrate even the uppermost Silurian formations. No oil tests in mid-basin have been carried deeper than Devonian strata. Therefore, considerable leeway exists for future modifications in the lithofacies analysis as shown in Maps II to V inclusive.

Where possible, an attempt was made to utilize at least one well from each county. Frequently only one well per county was available, and only in the southeastern and southwestern portions of the state was any real selectivity between wells possible. In all, 32 wells distributed over 28 counties were used. Six other wells were studied and discarded, either because too large a percentage of the total section was missing or because removal of the amount of bottled sample requisite to this study would not leave a remainder sufficient for future use.




**Map I. Base map showing location of wells used in Silurian facies investigations.**

Before sample cuts were made from each well, the samples were studied and checked against the records of driller's logs obtained from the Michigan Geological Survey. Sample tops were picked for the various formations and these tops frequently differed from tops as selected by the drillers. It may be appropriate to mention that one of the greatest difficulties in a study of this nature occurs at this point. The selection of formational tops and marker beds in the Silurian are still a matter of controversy among practicing geologists in Michigan, and undoubtedly the selection of limits for the Silurian section as set by the writer would, in certain wells, meet with considerable objection. Therefore the limits as selected for the purpose of sample analysis must be considered as somewhat arbitrary.

Figure 1 is an abbreviated Michigan stratigraphic column. It will be noted that the Bass Island group is now classed as Silurian, but the formations and members of this group are hard to differentiate on a basis of lithology from the overlying Detroit River group and Bois Blanc formation of Devonian age, especially where the Sylvania sandstone is absent or has been replaced by shale or dolomite. Baltrusaitis (15) describes both

| System, Series | Formation, Group | Lithology | Thickness |
| --- | --- | --- | --- |
| Pleistocene | | | |
| "Permo-Carboniferous" | | | |
| Pennsylvanian | | | |
| Mississippian | | | |
| Devonian | Traverse | Limestone, shale | 100-800 |
| | Bell | Shale, limestone | 0-80 |
| | Rogers City-Dundee | Limestone | 0-475 |
| | Detroit River | Dolomite, limestone, salt, anhydrite | 150-1400 |
| | Sylvania | Sandstone, dolomite | 0-550 |
| | Bois Blanc | Dolomite, chert | 0-1000 |
| Silurian | Bass Island | Dolomite | 50-570 |
| | Salina | Salt, dolomite, shale, anhydrite | 50-4000 |
| | Niagaran (Guelph-Lockport-Engadine) (Cataract) | Dolomite, limestone, shale | 150-800 |
| Ordovician | Cincinnatian (Richmond-Maysville-Utica) | Shale, limestone | 250-800 |
| | Trenton-Black River | Limestone, dolomite | 200-1000 |
| | St. Peter | Sandstone | 0-150 |
| Ozarkian | | | |
| Cambrian | | | |
| Algonkian | | | |
| Archean | | | |

Figure 1. Generalized stratigraphic divisions of Michigan.

the Detroit River and Bass Island groups as occurring characteristically in the form of gray, buff, or brown crystalline dolomites. Anhydrite may be found in both groups in certain sections of the state. For purposes of this study, where the Salina salt is present, either the first salt ("F" unit) or gray shale ("G" unit) immediately overlying the salt was used as the top of the measured section. In part of the Southern Peninsula, the salt beds are absent, and again selection of the Salina top is difficult. Sample study showed that frequently a gray shale member underlies the brown dolomite, and the decision was made to use this marker as representing the top of the Salina group.

The separation between the Cataract formation and the underlying Richmond and Utica shales of Ordovician age is made with more facility and assurance. The Cataract contains dolomite (Manitoulin member) and a considerable amount of variegated red, greenish-gray and purple shale, while the Richmond is almost uniformly a light gray shale and the Utica a dark gray or black shale.

Table 1 lists the wells shown on Map I. It gives the formational tops as found in each well, an asterisk indicating

Table 1. List of Wells Used in Silurian Facies Investigation

| Well No. | Cable or Rotary | Detroit River | Sylvania | Bass Island | Salina | Niagara | Clinton |
|---|---|---|---|---|---|---|---|
| 1 | C | 605 | 1400 | 1680 | 2062 | 4115 | 4115(?) |
| 2 | R | 1245 | 2150 | 2435 | 2839 | 4155 | |
| 3 | C | 640(?) | | 1415 | 1665* | 2781 | |
| 4 | C | 2000 | 2345 | 2565 | 2960 | 4195 | |
| 5 | C | 2038 | | 2575 | 2885 | 3600 | 3615(?) |
| 6 | C | 3030 | 3590 | 3615 | 4115 | 5526 | |
| 7 | R | 3079 | 3810(?) | 4810 | 5480 | 8270 | 8353(?) |
| 8 | C | 2030 | 2465(?) | 2585 | 3200* | 3410 | |
| 9 | C | 2643 | 3140 | 3408 | 3566 | 4764 | 4914 |
| 10 | R | 2876 | 3942 | 5117 | 5393 | 8547 | |
| 11 | C | 2074 | 2528 | 3096 | 3432 | 5466 | |
| 12 | C | 1180(?) | 1420 | 1490 | 2085* | 2225 | 2470 |
| 13 | C | | 115(?) | 178 | 365* | 955 | 1150 |
| 14 | C | 937 | 1650 | 1817 | 2331 | 3970 | 4117(?) |
| 15 | C | | | 65 | 205 | 741 | 1135 |
| 16 | C | 1260 | | | 2140 | 3735 | 3835(?) |
| 17 | C | 930 | 1170 | 1405 | 1646 | 2960 | 3057 |
| 18 | C | 215 | 495 | 620 | 990 | 2240 | |
| 19 | C | | 1220* | 1345* | 1465* | 1760* | 2025* |
| 20 | C | 1418 | 1641 | 1650 | 1735 | 2293 | |
| 21 | R | 2180 | 2590(?) | 3070(?) | 3700(?) | 3820(?) | |
| 22 | C | 950 | | | 1073* | 1463 | |
| 23 | C | 630 | | 765 | 870 | 960 | |
| 24 | R | 1800 | | | 2230* | 2845 | |
| 25 | C | 826 | | | 1005* | 1154 | |
| 26 | C | 1575 | 1706 | 1923 | 2080 | 2337* | 2590 |
| 27 | C | 2187 | | 2624 | 3000 | 3820(?) | |
| 28 | C | 2524 | 2865 | 2956 | 3515 | 4522 | 4565 |
| 29 | C | 1940 | 2190(?) | 2220 | 2600* | 3280 | 3233(?) |
| 30 | C | 1157 | | 1325* | 1337* | 1777 | |
| 31 | C | 1315 | 1939(?) | none | 2056* | 2077* | |
| 32 | C | 1160 | | 1275* | 1395* | 1625 | |

Table 1 (Continued)

| Cabot Head | Mani-toulin | Cincin-natian | Tren-ton | Total Depth | Total Sec-tion | Ele-vation | Year Drilled |
|---|---|---|---|---|---|---|---|
| 4445 | 4575(?) | 4925 | 5145 | 5665 | 2863 | 803' | 1936 |
| 5050 | | 5235 | 5754 | 6150 | 2396 | 738' | 1943 |
| 3707 | | 3848 | 4440 | 4650 | 2183 | 822' | 1949 |
| 4615 | 4685 | 4825 | 5000 | 5280 | 1865 | 591' | 1928 |
| 3820 | 3845 | 3975 | 4315 | 4754 | 1090 | 636' | 1931 |
| | | 6160 | 6385 | 6674 | 2045 | 830' | 1935 |
| 8446 | | 8584 | 9400 | 10447 | 3104 | 599' | 1941 |
| 3650 | 3675 | 3770 | 4263 | 4405 | 570 | 864' | 1929 |
| 5080 | | 5250 | 5752 | 6599 | 1684 | 908' | 1943 |
| 8829 | 8848(?) | 8932 | 9779 | 11021 | 3539 | 903' | 1948 |
| 5640* | (stopped in Cataract) | | | 5702 | | 624' | 1946 |
| 2610 | | 2960 | 3269 | 4060 | 875 | 834' | 1940 |
| | | 1330 | 1985 | 2091 | 965 | 682' | 1940 |
| 4299 | | 4575 | 4983 | 5958 | 2244 | 914' | 1935 |
| 1155 | 1220 | 1269 | 1895 | 2910 | 1064 | 592' | 1949 |
| 3870 | (stopped in Cataract) | | | 3960 | | 729' | ---- |
| 3090 | 3152 | 3205 | | 5692 | 1559 | 818' | 1945 |
| 2355 | 2440 | 2490 | 3065 | 4050 | 1500 | 612' | 1915 |
| 2040* | | 2308* | 2905* | ? | 843 | 1061' | 1948 |
| 2408 | | 2517 | 2843 | 2848 | 782 | 662' | 1950 |
| | | 3930 | 4487 | 5116 | 860 | 857' | 1942 |
| 1721 | | 1808* | 2045 | 2711 | 735 | 667' | 1939 |
| 1270 | | 1345 | 1676 | 1832 | 475 | 746' | 1948 |
| 3215* | | 3515* | 3948 | 4286 | 1285 | 1031' | 1941 |
| | 1525 | 1558 | 1945 | 2029 | 553 | 855' | 1929 |
| 2677 | | 2780 | 3117 | 3209 | 700 | 857' | 1948 |
| | | 3924 | 4550 | 5200 | 924 | 758' | 1945 |
| 4624* | | 4913 | 5325 | 5575 | 1398 | 679' | 1937 |
| 3325(?) | | 3560 | 3783 | 4006 | 960 | 634' | 1939 |
| 2021(?) | | 2330 | 2595 | 2693 | 993 | 886' | 1941 |
| 2263* | | 2420* | 2578* | 2721 | 364 | 771' | 1938 |
| 2150(?) | 2220(?) | 2255 | 2420 | 2523 | 860 | 772' | 1930 |

formation tops as picked by the writer after study of the samples. The "total thickness" column at the right of the table was used in drawing the isopach map (Map V) and represents the thickness of the "measured section." Wells 11 and 16, which did not penetrate the entire Cataract formation, were not employed in constructing the isopach map, but were used in preparation of the lithofacies maps because of their value as key wells in areas where no other control points were available.

## LABORATORY PROCEDURE

### Sample Cutting

The selected wells were numbered from 1 to 32 inclusive. Samples preserved on file at the Michigan Geological Survey offices are contained in glass vials, each vial when full holding seven to eight grams of sample, and 25 vials comprising one tray of samples. It was decided that removal of a one gram sample from each of the vials would permit construction of a composite sample large enough for quantitative analysis, yet at the same time not detract from the future value of the remaining sample. The sample in each vial ordinarily represents the "drilling screw" which is usually a 5 or 10 foot vertical interval. A portion of the sample from each vial was poured onto the pan of a chemical balance until one gram of sample was obtained. All the individual one gram samples from each well were poured together into a composite sample and placed in a 400 ml. beaker of predetermined weight. The beaker and contained sample could then be weighed and recorded to the closest 0.005 gram. A total of 5,457 one gram samples were taken to form the composite samples for the 32 wells.

## Sample Splitting

In cases where the total weight of the composite sample was less than 100 grams, the entire sample was used in analysis. Composites of more than 100 grams weight were split in the Jones sample splitter. A one-half or two-thirds split usually gave a sample of suitable workable weight for analysis. The remainder of the composite sample was saved in glass jars as "seed" for other studies.

## Removal of Soluble Salts

Each composite test sample contained in a beaker of known weight was covered with tap water which had been heated to boiling over a Bunsen flame. The sample was stirred with a glass rod during addition of the water. Weigner (16) has shown that if appreciable amounts of salts are present in sediments, procedures such as boiling increase the agitation of the particles and thus increase the number of collisions between them, thereby aiding in dispersion.

The sample was allowed to boil on an electric plate for one hour, the water decanted, and the process repeated until the soluble salts (probably mostly chlorides of sodium, magnesium and calcium) were removed. Crystalline silver nitrate was used to test for degree of salt removal; this compound has a high order of sensitivity to chlorides and forms a milky precipitate in their presence. As an extremely accurate test was not deemed necessary, the usual procedure involving preparation of a solution of the silver nitrate was not used. When the reaction of a single crystal of silver nitrate in the decanted water from the sample was no greater than that given in a test tube filled with tap water, the significant percentage of the salts was considered to be removed.

The test sample and beaker were dried and weighed, and the weight in grams of salt lost by water immersion computed by taking the difference between the weights before and after boiling.

## Removal of Acid Soluble Compounds

The dried sample was treated at least three times with hydrochloric acid to remove the soluble carbonates, which occurred mostly as calcium carbonate and magnesium carbonate; minor amounts of gypsum and anhydrite ($SO_4$ anions) and ferric chlorides and carbonates will also slowly dissolve in hot acid. In the first two treatments a 50 per cent solution of hydrochloric acid was used. In the third stage of treatment, a 100 per cent acid solution was employed. A few samples required more than three treatments to effect carbonate removal; nine samples gave no reaction to the third treatment. Experiment showed that gentle heating promoted acid action, but boiling of the treated samples was undesirable because of the danger of overflow foaming or cementation of the sample to the beaker if the fluid level was allowed to fall too low. After each treatment, the sample was permitted to settle and the supernatant fluid decanted before the addition of new acid. Though some carbonate in the form of dolomite probably remained even after concentrated acid treatment, this would constitute a relatively minor percentage of the total carbonate present in the original test sample.

## Washing After Acid Treatment

After final acid treatment, the sample was subjected to several washings in clear water. One or two drops of sodium oxalate added to the suspension after each addition of water facilitated rapid settling of the suspended particles.

During each washing, the water was tested with a strip of blue litmus paper to determine whether all acid had been removed; if any significant amount remained in the wash water, the litmus would turn pink. The acid-free sample was then decanted, oven dried and reweighed. The weight of removed carbonates was computed by taking the difference between the preacid and postacid weights.

## Wet Sieving

The next step was to remove grains of sand size or larger from the dried residue. Using Wentworth's system of classification, in which one-sixteenth mm. is taken as the division between grains of sand size and silt size, the remaining sample was again wetted and the resulting suspension poured through a 230 mesh Tyler sieve, which is designed to separate sand size grains from particles of smaller diameter. The residue collected on the sieve was washed with a stream of water, and the liquid passing through the sieve caught in a flat-bottomed pan. Gentle shaking of the sieve or light brushing with the fingertips aided in passing grains less than one-sixteenth mm. in diameter through the sieve. The liquid collected in the pan was then poured into a 1,000 cc. graduated cylinder. During washing, care must be taken so that the total volume of the suspension remains less than 1,000 cc. That portion of the sample remaining on the sieve was returned to the original beaker, dried and weighed. This "sand fraction" was then rebottled in glass vials with a view towards later studies of heavy minerals.

## Pipetting

The method of elutriation used in this experiment is essentially that suggested by Robinson (17). Elutriation by the pipette method is particularly applicable to the silts and clays, though it may be used for fine and medium grained sands. The suspension washed through the sieve and into the graduated cylinder should receive the addition of enough plain water to bring the total volume to 1,000 cc. The liquid suspension in the graduate was then thoroughly mixed by running forced air through a rubber tubing dropped to the bottom of the graduate. After three minutes of agitation the tube was removed and the solution permitted to settle for a period of two hours and three minutes. No dispersing agent was used during the pipetting process.

The pipette method is based on the principle that, in a dilute suspension, the particles fall as individuals according to size. By allowing all grains having a given velocity to settle below a certain level, a sample taken at that level at some critical time will contain the full concentration of all material having a lesser velocity. Stokes' Law (18) states that a sphere will sink in a liquid at a velocity directly proportional to the square of the diameter and the difference in density of the sphere and the liquid, and inversely proportional to the absolute viscosity of the liquid. Since the particles are not spheres it must be assumed that particles with equal diameters will settle with the same velocity. Therefore, given the settling velocities of particles with various diameters, the time which the particles take to settle a given distance may be determined. By taking samples at the determined time intervals, the samples will include the wanted sizes and exclude the unwanted sizes. The period of two hours and three minutes has been computed as the critical time required for all particles of silt size to sink below a 10 cm. level, leaving the clay particles above that level.

Immediately on completion of the settling period, using a 20 cc. pipette, a sample was removed from the graduate and drained into a 50 ml. beaker of known weight. This was oven dried and reweighed. The weight of the evaporite in the beaker represents the weight of the clay in 20 cc. of suspension, which, when multiplied by 50, gives the weight of the clay size particles in the entire 1,000 cc. graduated cylinder. The remainder of the sediment in the graduate was taken to represent the weight in grams of the silt fraction.

## List of Laboratory Equipment

The equipment needed for sample analysis includes the following:

1 composite sample of known weight
1 230 mesh Tyler sieve
1 chemical balance and weights to 0.005 gram
1 graduated cylinder, 1,000 cc.
1 glass stirring rod

2 lengths 1/4-inch rubber tubing
1 pipette, 20 cc.
1 beaker, 400 ml.
1 beaker, 50 ml.
1 electric oven
1 Bunsen burner
2 Flat-bottomed pans

## Error in Sampling and Treatment

Prewashing of the samples during drilling, sacking, and bottling has undoubtedly removed much of the clay and silt. The remaining subsand size grains remain as siltstone aggregates or shale fragments. It is necessary, therefore, to assume that the amount of fines lost has occurred on the same percentage basis in each well. As a greater proportion of fine grained sediment is probably lost during rotary drilling than in cable tool operations, cable tool samples were used where possible, but a few rotary well samples had to be used for purposes of control.

Minor errors may also enter when, in changing the sample from one container to another, some of the fine material is floated away in the air as dust. Some fines may also be lost during decantation.

## Summary of Laboratory Procedures

The following summary may be useful to those wishing to duplicate the techniques described in the foregoing sections:

1. Weigh out a one gram sample from each vial.

2. Make a composite sample population for each well from the individual one gram samples.

3. Divide the composite into a workable portion using the Jones sample splitter. The weight of the workable portion will vary with the number of samples and thickness of the measured section, but to facilitate analysis composite samples should, after splitting, approximate 100 grams.

4. Weigh a clean empty 400 ml. beaker to the nearest 0.005 gram. Pour the composite sample into the beaker, add boiling water, and continue to heat on an electric hot plate until about half of the water evaporates. Decant the remainder of the water, and repeat the process until reaction of the decanted fluid to silver nitrate is not more than the reaction in ordinary tap water.

5. After final decantation, dry and weigh the sample to determine the weight loss of soluble salts.

6. Add a 50 per cent solution of hydrochloric acid to the sample, slowly, in order to minimize the danger of overflow by excessive effervescence. Continue this treatment, increasing the acid concentration, until effervescence ceases. A gently heated 100 per cent acid solution in the final stage of treatment should remove most of the remaining less soluble carbonates. To be most effective, decantation of the supernatant liquid is made after each stage in treatment.

7. After final acidization, continue to wash the sample with plain water until a blue litmus test shows it to be acid free. Dry the residue and reweigh to determine the amount of carbonate loss.

8. Wash the dried residue through a 230 mesh Tyler sieve into a flat-bottomed pan, keeping the volume of suspension passing through the sieve less than 1,000 cc.

9. Dry, weigh and bottle the material retained on the Tyler sieve. This is the sand fraction from the composite sample.

10. Pour the suspension in the pan into a 1,000 cc. graduated cylinder, adding any necessary amount of water to bring the level to exactly 1,000 cc.

11. Agitate the suspension for three minutes and then allow to settle for two hours and three minutes. Pipette a 20 cc. sample from a depth of 10 cm. in the graduated cylinder.

12. Drain the pipette into a 50 ml. beaker of known weight. Dry in oven and reweigh. This weight, multiplied by 50, represents the weight of the clay fraction in the graduate. The sum of the clay and sand fractions subtracted from the total sample weight before wet sieving will give the weight of the silt fraction.

## Results of Quantitative Analysis

A statistical summary of quantitative analysis of the 32 wells made in accordance with the foregoing procedures, is contained in Table 2. The data for each well in this table were used in computing the various lithologic ratios as summarized

Table 2. Statistical Summary of Quantitative Analysis



| Well Number | Permit, Operator, Farm, County and Township | Land Survey Description | Sample Wt., (Grams) | Weight Loss, Water Solubles (Grams) | Weight Loss, Acid Solubles (Grams) | Sand Fraction (Grams) | Silt Fraction (Grams) | Clay Fraction (Grams) | Totals (Grams) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2960, C.W.Teater, Nevins#1, Alpena Co. Long Rapids Tp. | 18-T32N-R6E | 120.575 | 48.195 | 51.795 | 7.605 | 11.480 | 1.500 | 120.575 |
| 2 | 10004, Ohio Oil, Chamberlain #1, Antrim Co. Central Lake Tp. | 14-T31N-R8W | 72.945 | 13.000 | 46.575 | 3.735 | 9.135 | .500 | 72.945 |
| 3 | 14936, Roosevelt Oil, Ormsbee #1, Cheboygan Co. Ellis Tp. | 1-T34N-R2W | 93.585 | 10.100 | 54.900 | 13.895 | 13.690 | 1.000 | 93.585 |
| 4 | 14, Ruggles & Rademacher, Fee #24, Manistee Co. Filer Tp. | 12-T21N-R17W | 104.675 | 27.910 | 54.655 | 7.205 | 14.305 | .600 | 104.675 |
| 5 | 309, Muskegon Oil, H.Heinz#5, Muskegon Co. Muskegon Tp. | 8-T10N-R16W | 117.515 | 37.940 | 63.970 | 4.175 | 10.880 | .550 | 117.515 |
| 6 | 411, Newaygo Oil, Bates #1, Newaygo Co. Sherman Tp. | 12-T13N-R13W | 96.005 | 37.820 | 42.945 | 4.195 | 10.195 | .850 | 96.005 |
| 7 | 5441, Gulf Oil, Bateson #1, Bay Co. Monitor Tp. | 2-T14N-R4E | 114.065 | 28.990 | 41.565 | 15.985 | 26.025 | 1.500 | 114.065 |
| 8 | 429, Wittmer Oil, Alpha Portland#1, Eaton Co. Bellevue Tp. | 28-T1N-R6W | 52.670 | 6.530 | 41.030 | .475 | 4.235 | .400 | 52.670 |
| 9 | 10011, W.H.Colvin, Glaser #1, Ingham Co. Wheatfield Tp. | 14- T3N-R1E | 101.070 | 17.665 | 44.170 | 18.005 | 19.980 | 1.250 | 101.070 |
| 10 | 12898, Ohio Oil, Reinhardt #1, Ogemaw Co. West Branch Tp. | 35-T22N-R2E | 93.915 | 51.615 | 30.975 | 3.385 | 7.240 | .700 | 93.915 |
| 11 | 11834, Pure Oil, Stapleton #1, Huron Co. Rubicon Tp. | 22-T17N-R15E | 86.810 | 33.505 | 32.840 | 3.645 | 15.720 | 1.100 | 86.810 |
| 12 | 7598, Voorhees Drlg., Gove #1, Lenawee Co. Clinton Tp. | 8- T5S-R4E | 101.155 | .100 | 60.460 | 25.475 | 14.270 | .850 | 101.155 |
| 13 | 7870, N.J.Berston, Heath #1, Lenawee Co. Deerfield Tp. | 13- T7S-R5E | 106.430 | .830 | 47.670 | 36.020 | 21.010 | .900 | 106.430 |
| 14 | 2179, Talbot Oil, McPherson #1, Livingston Co. Howell Tp. | 35- T3N-R4E | 139.595 | 35.295 | 60.985 | 16.860 | 25.455 | 1.000 | 139.595 |
| 15 | 13867, F.T.Canon, Campau #1, Monroe Co. Frenchtown Tp. | 12- T6S-R9E | 97.070 | .215 | 52.865 | 28.515 | 14.525 | .950 | 97.070 |
| 16 | -----, Michigan Pet., Richardson#2, St.Clair Co., Grant Tp. | 27- T8N-R16E | 95.285 | 38.455 | 34.110 | 6.210 | 14.810 | 1.700 | 95.285 |

| Well Number | Permit, Operator, Farm, County and Township | Land Survey Description | Sample Wt., (Grams) | Weight Loss, Water Solubles (Grams) | Weight Loss, Acid Solubles (Grams) | Sand Fraction (Grams) | Silt Fraction (Grams) | Clay Fraction (Grams) | Totals (Grams) |
|---|---|---|---|---|---|---|---|---|---|
| 17 | 11341,W.H.Colvin,Meinzinger#1,Washtenaw Co.Superior Tp. | 12- T2S-R7E | 118.910 | 36.845 | 55.810 | 11.300 | 13.705 | 1.250 | 118.910 |
| 18 | ----H.R.Ford Well,Dearborn Wayne Co. Dearborn Tp. | 22- T2S-R10E | 120.300 | 48.135 | 46.825 | 7.880 | 16.060 | 1.400 | 120.300 |
| 19 | 12307,Hugh Rogers,Zeiter #1, Hillsdale Co. Camden Tp. | 24- T8S-R4W | 98.185 | .790 | 87.375 | 4.670 | 4.850 | .500 | 98.185 |
| 20 | 15327,N.L.Stevens,Starbakck #1,Allegan Co. Lee Tp. | 29- T1N-R15W | 105.400 | 2.100 | 57.225 | 27.870 | 17.305 | .900 | 105.400 |
| 21 | 9618,Sun Oil Co, Mead #1 Barry Co. Rutland Tp. | 10- T3N-R9W | 68.250 | .895 | 40.620 | 16.755 | 9.080 | .900 | 68.250 |
| 22 | 6126,Sprenger Bros.,Herwig #1,Berrien Co. Benton Tp. | 10- T4S-R18W | 79.360 | 1.320 | 43.330 | 20.895 | 12.965 | .850 | 79.360 |
| 23 | 13779,Norman Nelson,Speckine #1,Berrien Co. Buchanan Tp. | 32- T7S-R18W | 75.315 | 1.920 | 48.875 | 14.450 | 9.670 | .400 | 75.315 |
| 24 | 9261, Conoco Oil, Turner#1, Calhoun Co. Albion Tp. | 15- T3S-R4W | 99.250 | .720 | 47.320 | 31.700 | 18.860 | .650 | 99.250 |
| 25 | 579,Blair & Miller,Knowlton #1,Cass Co. Milton Tp. | 2- T8S-R16W | 75.375 | 1.330 | 48.640 | 16.345 | 8.710 | .350 | 75.375 |
| 26 | 13483,Chas.L.Hook, Fee #1, Kalamazoo Co. Oshtemo Tp. | 31- T2S-R12W | 73.920 | 2.340 | 44.690 | 14.670 | 11.620 | .600 | 73.920 |
| 27 | 11540,Smith Pet.Co.,Sherk #1,Kent Co. Caledonia Tp. | 21- T5N-R10W | 67.280 | 22.820 | 37.065 | 3.530 | 3.415 | .450 | 67.280 |
| 28 | 3090,J.E.Flanigan, Croft #1,Kent Co. Vergennes Tp. | 35- T7N-R9W | 107.075 | 47.995 | 45.545 | 1.680 | 11.105 | .750 | 107.075 |
| 29 | 5689,Voorhees Drlg.,Reible #1,Ottawa Co.Grand Haven Tp. | 36- T7N-R16W | 80.225 | 2.225 | 54.315 | 12.145 | 10.790 | .750 | 80.225 |
| 30 | 7823,Ora Avery,Dunnworth#1, St.Joseph Co. Lockport Tp. | 13- T6S-R11W | 91.540 | 1.185 | 45.685 | 25.185 | 18.785 | .600 | 91.540 |
| 31 | 5229,Whitehill-Drury,Ament & Webster#1,Van Buren Co., Bangor Tp. | 35- T2S-R16W | 38.380 | .545 | 30.485 | 1.770 | 5.180 | .400 | 38.380 |
| 32 | 449,Wolverine Oil,Vought #3, Van Buren Co. Decatur Tp. | 32- T4S-R14W | 103.685 | 1.670 | 64.740 | 23.565 | 13.310 | .400 | 103.685 |

in Table 3. The processes used in computing these ratios are described under the heading "Lithologic Ratios" in the following section.

Table 3. Statistical properties of 32 wells, computed by procedures contained in the text, and summarized from Table 2.

| Well | Clastic ratio | Sand-shale ratio | Evaporite ratio |
|---|---|---|---|
| 1 | .206 | .586 | .931 |
| 2 | .224 | .388 | .279 |
| 3 | .440 | .946 | .184 |
| 4 | .268 | .483 | .571 |
| 5 | .153 | .365 | .593 |
| 6 | .189 | .380 | .881 |
| 7 | .617 | .581 | .697 |
| 8 | .108 | .102 | .159 |
| 9 | .635 | .848 | .399 |
| 10 | .137 | .426 | 1.666 |
| 11 | .309 | .217 | 1.020 |
| 12 | .670 | 1.685 | .002 |
| 13 | 1.194 | 1.644 | .017 |
| 14 | .453 | .635 | .579 |
| 15 | .829 | 1.843 | .004 |
| 16 | .313 | .376 | 1.127 |
| 17 | .283 | .756 | .660 |
| 18 | .256 | .451 | 1.028 |
| 19 | .114 | .873 | .009 |
| 20 | .777 | 1.531 | .038 |
| 21 | .644 | 1.678 | .022 |
| 22 | .777 | 1.513 | .031 |
| 23 | .483 | 1.435 | .039 |
| 24 | 1.066 | 1.625 | .015 |
| 25 | .508 | 1.804 | .027 |
| 26 | .572 | 1.200 | .052 |
| 27 | .123 | .913 | .616 |
| 28 | .252 | .142 | 1.050 |
| 29 | .419 | 1.053 | .041 |
| 30 | .949 | 1.299 | .026 |
| 31 | .237 | .317 | .018 |
| 32 | .561 | 1.719 | .026 |

## LITHOFACIES

### Definitions of Facies

According to Moore (21), "facies are areally segregated parts of differing nature belonging to any genetically related body of sedimentary deposits." He emphasizes that facies are "variants or aspects of stratigraphic units having mutually exclusive space distribution," and clarifies the relationship between lithofacies and lithotopes. Sloss, Krumbein and Dapples (11) believe facies may be considered as the resultant of any set of factors which permit an areal differentiation of varying aspects of a stratigraphic unit.

### Lithotopes and Lithofacies

Wells (22) has established the term "lithotope," meaning "rock environment," to include all the environmentally significant characteristics of a sedimentary deposit from which environmental conditions may be interpreted. Each recognizable rock environment in a succession is a lithotope.

"Lithofacies" are groups of strata demonstrably different in lithologic aspect from laterally equivalent rocks, the aspect being controlled by the lithotopes of which the lithofacies are composed. Thus a lithofacies may contain a number of lithotopes, the designation of the lithofacies being derived from the gross aspect of the lithology (11).

## Lithologic Ratios

The over-all lithologic character, or gross aspect, of a measured subsurface section may be determined by grouping the rocks into clastic components (conglomerate, siltstone, sandstone, shale) and non-clastic components (limestone, dolomite, evaporites), and then be used in development of a lithofacies map. Table 2 expresses the amount, by weight, of evaporites, limestone-dolomite, sand, silt and clay (shale) in a composite sample taken from the measured section of a number of wells. The weight of each of these components can be converted into a percentage of the total weight. The percentages of the clastics are then added together and divided by the sum of the percentages of the non-clastics. The resulting decimal number is the "Clastic ratio." This may be augmented by a "Sand-shale ratio," which is the ratio of sandstone and conglomerate to siltstone and shale in the section, regardless of the amount of non-clastics present. The two ratios may be expressed as follows:

$$\text{Clastic ratio} = \frac{\text{Conglomerate} + \text{Sandstone} + \text{Shale}}{\text{Limestone} + \text{Dolomite} + \text{Evaporite}}$$

$$\text{Sand-shale ratio} = \frac{\text{Conglomerate} + \text{Sandstone}}{\text{Siltstone} + \text{Shale}}$$

## The Lithologic Aspect Triangle

Clastic ratio and sand-shale ratio aspects of lithology can be referred to a triangle diagram (Fig. 2) on which both appear as parameters. A discussion of the fundamentals of construction of the lithologic triangle may be found in "Stratigraphy and Sedimentation" (12). Each corner of the triangle represents 100 per cent of the non-clastics, sand, and shale respectively. Thus, for example, 100 per cent non-clastics at the triangle apex represents a clastic ratio of zero, while the base line directly opposite represents a clastic ratio of infinity. Intermediate values can be plotted at points between these extremes. In similar fashion the base line of the triangle represents a sand-shale ratio ranging from zero to infinity.

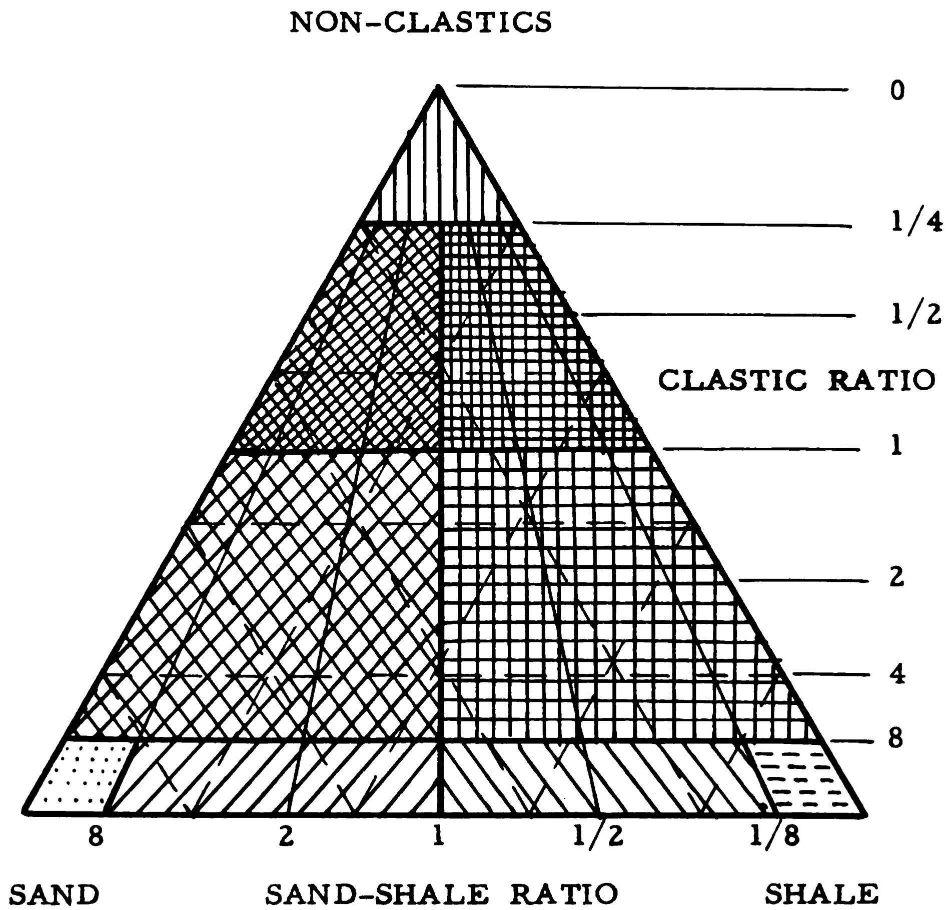



Figure 2. Clastic ratio and sand-shale ratio superimposed on percentage triangle. The patterns illustrate nine statistical groupings of lithology.

In most instances, clastic ratio, sand-shale ratio, and lithologic triangle form the basis for mapping nonspecific lithofacies. However, each of the end-member corners of the basic triangle either is subdivisible into other ratios or capable of expansion into other triangles. In this problem it is useful to differentiate the non-clastics by application of an "Evaporite ratio," which is the ratio between evaporites and carbonates in the measured section.

Thus:

$$\text{Evaporite ratio} = \frac{\text{Evaporites}}{\text{Limestone + Dolomite}}$$

# LITHOFACIES MAPS

## Construction

Plotted on a base map, the values of the clastic ratio and sand-shale ratio may be contoured. Krumbein (7) superposed these contoured ratios on an isopach base map, but the expression of so many features on one map makes it cumbersome and difficult to interpret. Therefore, in this report the isopach map is prepared on a base separate from that of the ratio maps.

Since the lithologic triangle as set up by Krumbein (Fig. 2) is subdivided geometrically into nine types of lithology, the values obtained for the various ratios in each well determine its place relative to the network of lithofacies lines. The 32 wells are thus shown as a scatter-diagram (Fig. 3).

The values used in construction of the triangle which limit the nine lithologic associations statistically are designated by different colors (Fig. 4). General stratigraphic procedure is used herein, the colors changing from yellow in the sand-dominated section to green in the shale-dominated section and

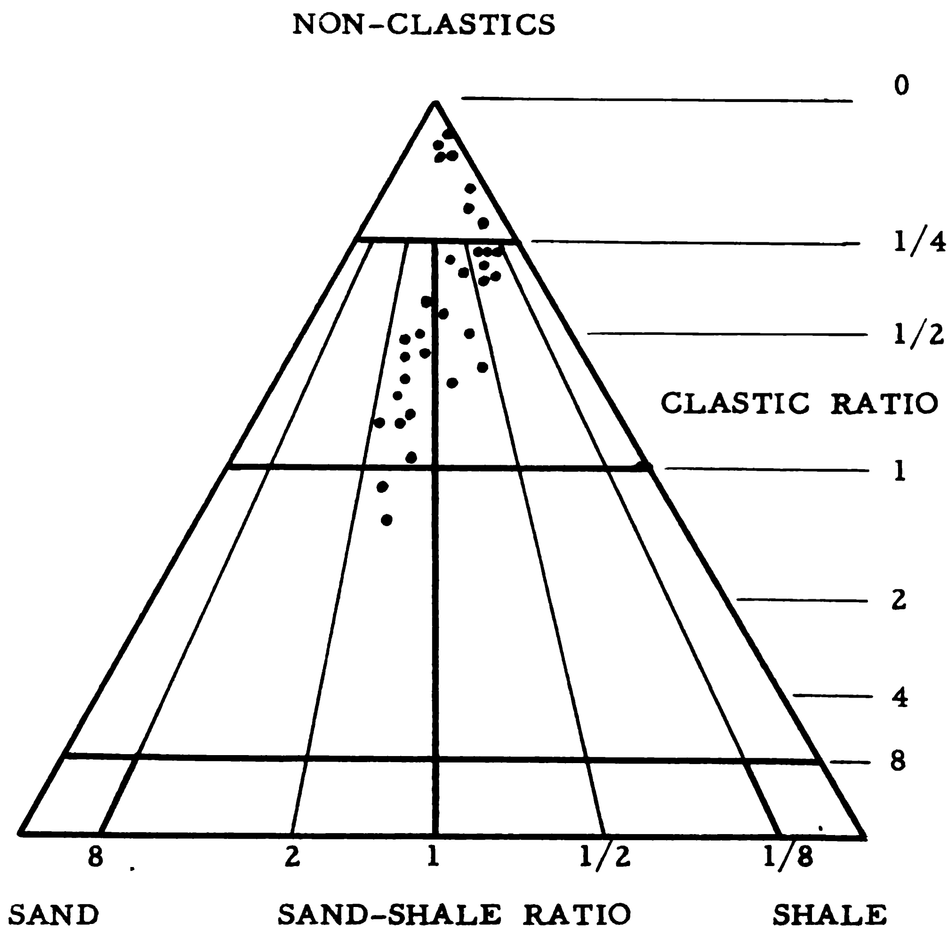



Figure 3. Use of the lithologic triangle as a scatter-diagram. The 32 wells are plotted relative to the lithofacies lines. Values of the various ratios determine the position of each well relative to the network of lines.

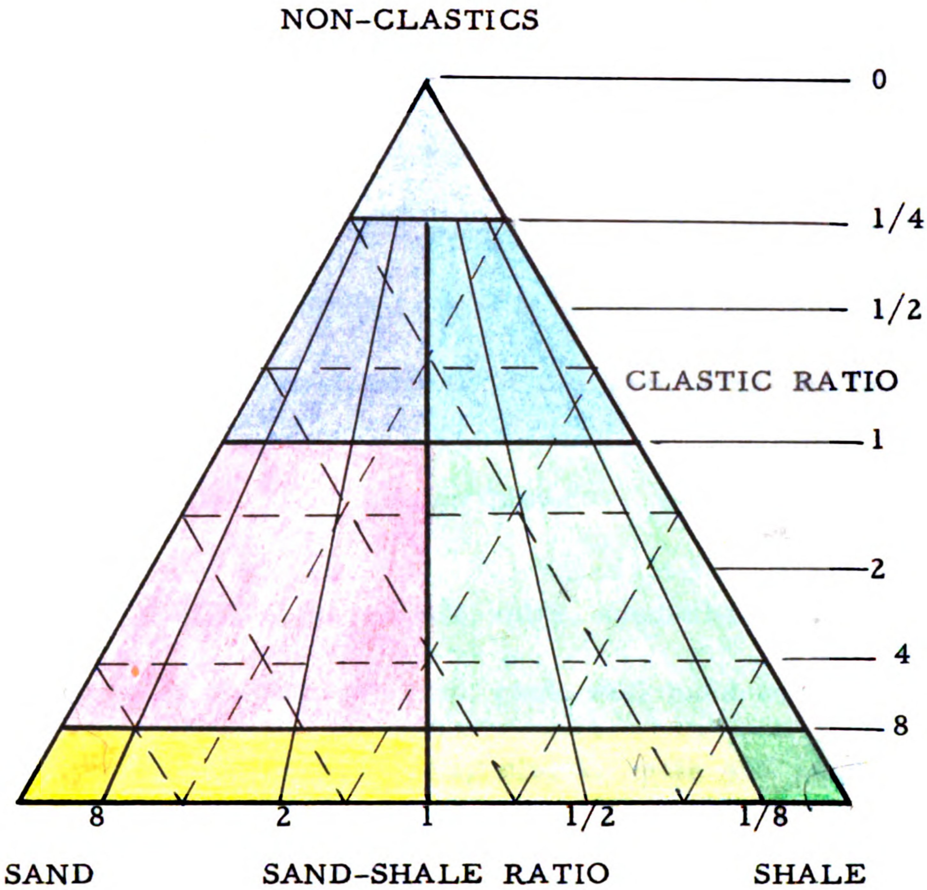



Figure 4. Clastic ratio and sand-shale ratio superimposed on percentage triangle. Same as Fig. 2 except statistical groupings are illustrated in color rather than in patterns. This coloration is used in the lithofacies maps.

blue in the limestone-dominated section. In accordance with the triangle, as constructed and colored, the lithofacies maps show the average statistical properties of the measured interval, so that it is possible to see at a glance whether sand, shale, or non-clastics dominate in the particular section.

## Facies Maps

Table 3 lists the clastic ratio, sand-shale ratio, and evaporite ratio as computed for each well used in this study. Maps II and III are respectively clastic ratio and sand-shale ratio maps drawn and colored in accordance with Figure 4. Map IV is an evaporite ratio map, and Map V is an isopach map of the measured Silurian section.

# SEDIMENTARY FACIES AND TECTONICS

## Interpretation and Synthesis of Facies Analysis

One approach to a study of facies and their distribution patterns attempts a reconstruction of ancient source areas and depositional environments and their distribution in past geographic patterns. However, many attributes of ancient environments are not preserved and a strictly environmental approach is necessarily incomplete and may be dependent on difficultly substantiated inference.

Lithofacies are subject to interpretation in respect to their dominant sedimentary environment. From a combination of environmental and tectonic data, a broad view of the paleogeography of an area can be derived. The geographic reconstruction includes distribution of ancient lands and seas, of source areas and sites of deposition, the shifting pattern of environments, and the contemporaneous tectonic activity of the area during a particular time span of deposition. Studies of large stratigraphic units, such as the Silurian in the Michigan Basin, yield more or less broad aspects of paleogeography in which a number of short-lived events and conditions may be obscured. A reduction in the vertical limits of the units studied will change an over-all synthetic product into a more closely knit representation of actual conditions at any particular time.

## Sedimentary Tectonics

The term "tectonics" refers to earth movements and rock structures in general. The multitude of information now available shows that a wide range of environmental conditions may occur. In sedimentary basins such as that in Michigan thick deposits with few stratigraphic breaks imply nearly continuous sedimentation and subsidence. Hence the very lack of discontinuity hinders facies analysis in a quantitative fashion.

Schuchert (23) was the first to classify tectonic elements, especially geosynclines. A great number of concepts of tectonism have been advanced, and there are as many different terminologies applied as there are concepts. The term "craton" is one of the more recent nomenclatural innovations to appear in print. Kay (24) defined the craton as "the consolidated, relatively neutral area which comprises the main part of the continent or of oceanic basins.'' H. Stille in 1936 had used the term ''parageosyncline'' to denote an area of subsidence within the craton itself, receiving thick sediments as compared to the cratonic areas intervening between themselves and the major geosynclines. Kay followed Stille in classifying geosynclines, but expanded the parageosynclines to include varying types of subsidence within the craton. Among these types he lists the ''autogeosyncline'' possessing the following characteristics: [1] isolated depositional area within a craton and [2] detritus gained from distant cratonic sources. The Michigan Basin is listed as a type example of an autogeosyncline. He also believed that the craton is not always a relatively stable and rigid mass, but displays local subsidence and uplift, giving rise to markedly greater thicknesses of sediment in the intracratonic basins.

Krumbein and Sloss (12) imply that the Michigan Basin typifies a condition of rapid subsidence and slow deposition. Under such conditions, when the rate of subsidence exceeds the rate of sedimentation, bathyal or abyssal depths will be dominant; the detrital sediments will be fine-grained and the deposition predominantly non-clastic components. They further state:

> The Michigan Basin, during part of its history, was a subsiding basin without complementary uplift in nearby cratonic areas. There is no evidence in the sediments that bathyal or abyssal depths were attained, but the presence of thick, non-clastic sequences attests to the lack of appreciable land-derived debris.

## Intracratonic Basins

These are Kay's intracratonic geosynclines, the term "basin" being appropriate for isolated, ovate areas. The basin lies within the craton and relatively distant from uplifted source areas of sediment. The sedimentary deposits may include fine clastics derived from distant sources, and abundant carbonates and associated evaporites. Kay considers the Michigan Basin to have been isolated during all or part of the Silurian.

Krumbein and Sloss (12) show Michigan as a subsiding basin surrounded by a wide expanse of unstable shelf during Niagaran time. Whether this shelf was low-lying dry land or covered by a shallow sea is difficult to determine. Possibly dry land prevailed during the Salina interval. During Niagaran time there existed either dry land or a "barred basin" formed by biohermal reefing in the shallow epicontinental seas on the surrounding shelf.

Krynine (20) discusses the evolution of sediments in synclinal basins, stating that:

> First cycle carbonates and especially soluble salts are generally connected with low relief and weak tectonic activity and show strong affinities with shallow barred and semi-barred basins, frequently under arid conditions. . . .
>
> "Normal" primary cherts produced by supersaturation of leached silica are related to very low relief, frequently under conditions approaching peneplanation. . . .

A considerable amount of chert is present in the residues from the wells used in this study.

## Lithologic Associations in Intracratonic Basins

The idea of lithologic associations was derived from the principle that sedimentary properties are related to the tectonic intensity which prevails during their deposition.

Krumbein, Sloss and Dapples (26) outlined the relation between sedimentary tectonics and sedimentary environments. The succeeding list of sedimentary attributes in intracratonic basins should therefore apply to the Michigan Basin, and appear on the lithofacies maps prepared for this study.

Intracratonic basin associations are:

1. An intracratonic basin develops when concentric subsidence at a point on the craton results in a circular or elliptical area with rates of subsidence varying from slight at the margin to moderate in the center of the basin.

2. Intracratonic basins show greatest rate of deposition in the center, relatively slower at the margins.

3. They may have open or restricted circulation. Occurrence of evaporites is characteristic of intracratonic basins.

4. The relation between rates of subsidence and of sedimentation is partly a matter of associated source areas. If adjacent uplifts are absent, subsidence may exceed deposition and non-clastics may dominate the section. If uplifts are nearby and active, clastic sediments may fill the basin.

# LITHOFACIES MAPS AND APPLIED PROBLEMS

## Interpretation and Value of Facies Maps

The interpretation of facies maps designed to give an over-all picture, such as the ratio maps contained in this report, cannot show details on types or thicknesses of individual beds. Preparation of all specific aspects of facies variation would require an entire sequence of maps. The chief value of a regional study, such as this of Silurian sediments in the Michigan Basin, may lie only in its historical reconstruction of a major geological feature. In oil exploration, emphasis must be placed on all the possible relations between the specific and gross aspects. Among specific aspects could be included the study and preparation of maps showing the types and distribution of heavy minerals, and the nature of the microfauna. It has occurred to the writer that a pursuit of studies along these lines would be of great complimentary value to the present report. The insoluble residues remaining from the current study were saved in glass vials, and could be used directly for heavy mineral studies. Microfossil studies could be made of

the samples from the same measured sections in the wells and biofacies maps constructed from the data obtained.

Maps based on strictly numerical data, such as these ratio maps, are limited in interpretation. They do have an advantage over more qualitative maps in that lines of equal value on the maps are related to their neighboring lines by some constant quantity or ratio. On each map the lines are inversely proportional to the degree of slope, and the closeness of the linear spacing indicates the rapidity of facies changes.

## Properties of Contour-type Facies Maps

Kay (27) has classified maps for stratigraphic and structural studies. He contends that a map is geographic if it portrays conditions at a single time, stratigraphic if it covers a span of time. When characteristics of sediments are converted to numbers, or ratios, they can be used to construct contour-type maps whose lines connect points of equal magnitude. These he calls "isopleth" maps, and the lines are referred to as "isoliths."

The maps of this report cut across all groupings to some extent. Strictly speaking, they are both geographic and stratigraphic. They are both isopleth and isolith maps, and the contour lines themselves can certainly be called isoliths. In a sense they are also isopach maps, inasmuch as they are contoured through points of equal properties.

## CONCLUSIONS

Can lithofacies maps be interpreted in terms of regional structure and tectonics? If we take a positive attitude and assume that such interpretations are possible, then an observation of the lithofacies maps leads to some interesting conclusions.

Maps II and III (Clastic ratio and Sand-shale ratio Maps respectively) can be studied almost as a unit. Their general degree of symmetry is quite remarkable. Cohee (28) has shown the center of the Michigan Basin during Niagaran time to be located in western Gladwin County. Other writers, including Eardley (19) have shown the approximate center of the early Paleozoic basins to be in the four-corner area where Clare, Gladwin, Midland and Isabella Counties meet. But both ratio maps prepared from evidence gathered in this study show the Silurian basin as wider, and elongated in a general northeast-southwest direction with the approximate center somewhat farther north and west, probably near the confluence of the Clare, Osceola and Missaukee County lines. Map V (Isopach Map) shows the greatest vertical thickness of Silurian sediments

(3,539 feet) in well 10 (Ogemaw County). However, there is no reason to believe, lacking evidence to the contrary, that any wells drilled to the west of well 10 would not encounter an equal or greater thickness of Silurian sediments.

The Findlay arch, an extension of the Cincinnati arch, appears on both ratio maps. From southern Monroe County it seems to turn abruptly eastward into Ontario before again swinging northward. Wells 12 and 24 indicate either a flattening and westward extension of the Findlay arch as far as Calhoun County, or the presence of a cross-arch which bisected the Findlay feature and gradually died out to the northwest. Though the ratios for well 24, a rotary well, may be too high, ratios for cable tool wells 9 and 14 tend to show that some feature of this nature persisted throughout at least a part of the Silurian.

Eardley states:

> In pre-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.

The ratio maps show a deep trough containing non-clastic sediments swinging south by southeast from southern Eaton County through western Hillsdale and Calhoun counties, and then southward into northeastern Indiana. But the wells in southwestern Michigan show that complimentary arch was present to the west of this trough, being especially prominent in Cass, St. Joseph, Van Buren and Kalamazoo Counties. Its influence on sedimentary deposition must, at times, have prevailed as far north as southern Muskegon and Kent Counties. This ridge may have been either an offshoot from, or the forerunner of, the Kankakee arch. If Eardley is correct, the trough through Eaton, Calhoun, and Hillsdale Counties may have connected the Michigan and Indiana-Illinois Basins throughout middle Silurian time, disappearing prior to the deposition of the Salina salt. The writer wishes to suggest the name "Battle Creek trough" for this connection of the Michigan and Indiana-Illinois Basins.

Along the northern borders of the Findlay and pre-Kankakee (?) arches there is a rapid change to the non-clastic deposition in the central Michigan Basin. Another depositional trough of non-clastic sediments paralleled the western flank of the Findlay arch through Sanilac, Lapeer, and eastern Oakland Counties. This trough will hereafter be referred to as the "East Michigan trough." In the Saginaw Bay area another ridge or arch, whose northeastward extent cannot be determined, separated the East Michigan trough from the major basin in the central part of the state.

In the northern part of the Southern Peninsula there is again a gradual transition from non-clastic to clastic sediments as progression is made toward the pre-Cambrian rocks of Ontario north of Lake Huron. Western Michigan seems to have been far distant from any land-derived sediment. There is only a gradual westward increase in clastic components progressing outward from the center of the basin.

In general, it may be inferred that the Southern Peninsula of Michigan was an area of oscillating shallow seas, with occasional emergences of dry land along the Findlay and pre-Kankakee (?) arches, so that clastic deposition at times dominated. The central part of the state remained as a subsiding basin of moderate depth, as did the East Michigan trough paralleling the Findlay arch. The presence of non-clastic deposition in these basins attests to the lack of appreciable land-derived debris.

Map IV (Evaporite ratio Map) shows the thickest evaporite sequence to be in Ogemaw County, but significant ratios of salt are present as far south as Kent, Ionia, and Clinton

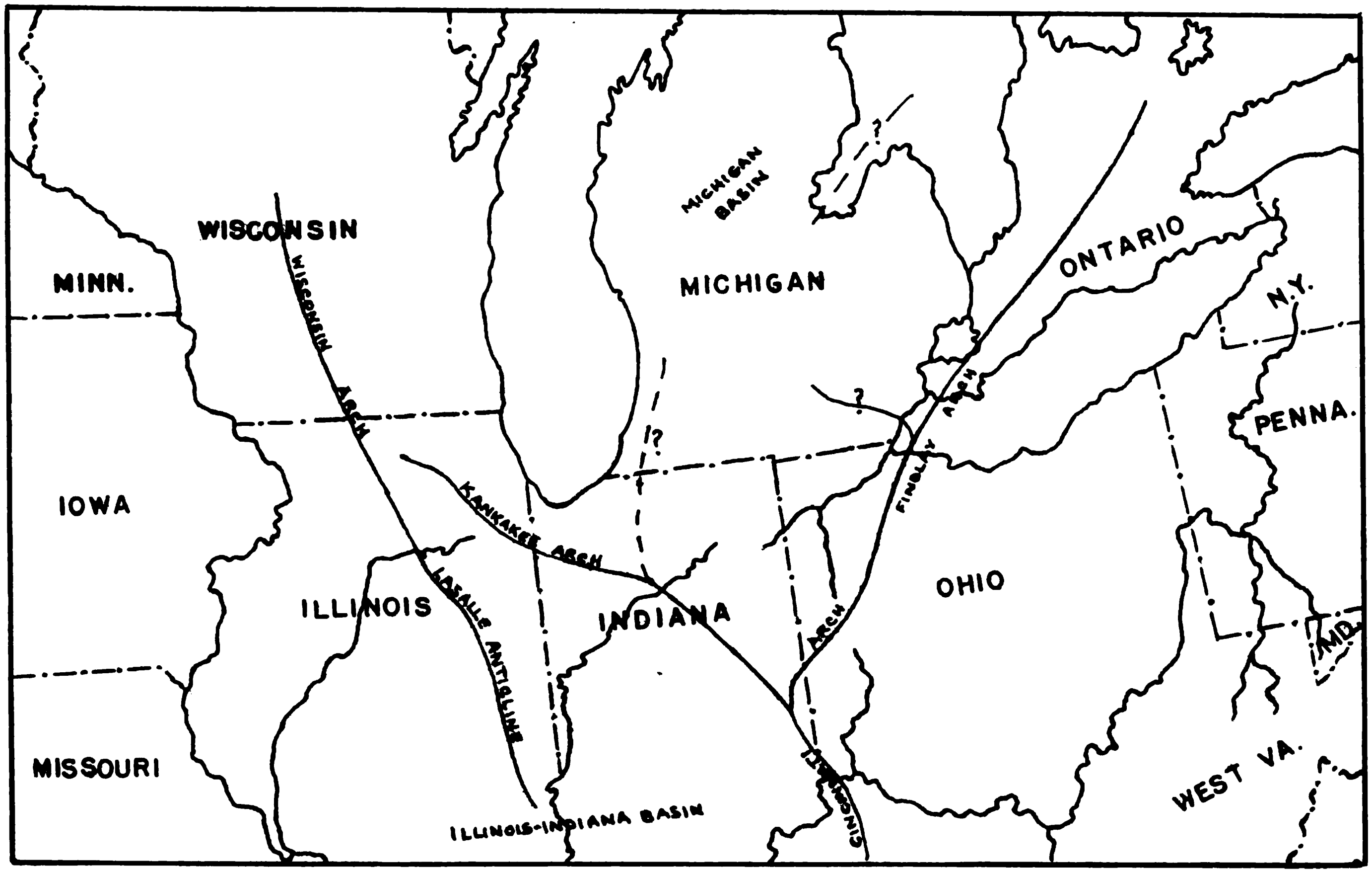



Figure 5. Regional structure of the Michigan Basin and adjacent areas.

Counties, where the evaporite series abruptly disappears. The salt basin assumes the same general northeast-southwest configuration displayed by the other ratio maps. The East Michigan trough must have shifted farther eastward during the Salina so as to lie in eastern Macomb and St. Clair Counties and beneath Lake St. Clair and Lake Huron.

If the Findlay and pre-Kankakee (?) arches were joined as a broad unstable shelf, and the Battle Creek trough was closed, separation of the Michigan and Indiana-Illinois Basins was accomplished at the beginning of Salina deposition. The abrupt rise out of the salt basin in south-central Michigan tends to show that the subsiding basin of the central part of the state was being counteracted by a continuous slow rising of the unstable shelf area to the south.

This rapid interplay and change from a predominant evaporite sequence to a sequence of another type may be significant from an economic standpoint. Eardley (19) says:

> Significant units in the Michigan basin are the evaporite series of the Silurian and Devonian. . . . Porous dolomites in these evaporite series are reservoir rocks for oil and gas, and many oil fields have been developed in the basin. Very gentle folds or "highs" ripple the basin beds and take an irregular northwest-southeast direction. They have served to trap the oil.

More than 200 wells have been drilled into or through the Niagaran formation, and oil shows have been reported in at least 20 wells distributed over 13 counties. The only productive Niagaran field in Michigan is the Howell gas field in Livingston County, which produces from the lower basal Salina and the top 40 feet of the Lockport (Niagaran) dolomite (28).

Boyd (28) states the structural high on top of the Niagaran structure at Howell does not conform to the Dundee (middle Devonian) high, but is about 1-1/2 miles to the southwest. Evans (29) reports similar conditions of structure in southwestern Ontario where the Niagaran top is structurally high and the Devonian rocks are structurally low. The variation in thickness of the salt beds, dolomites, and shales of the rocks of the upper Silurian (Salina) account largely for the structural variation between the shallower beds and the top of the Niagaran. Most of the deep Silurian oil tests have been drilled at or near the axes of known Devonian structures. Is there not reason to believe that this theory of exploration is in error? Perhaps facies analyses combined with detailed stratigraphic studies will open the way to another method of location for

future Silurian oil tests in Michigan. A statement by Krumbein (9) may be the key to a new line of thinking:

> Where rapid changes in sedimentary attributes result in closer spacing of the lines, they may indicate that other features are changing rapidly also. In short, it may be the steeper slopes or the margins of the steeper slopes which may be significant in the search for sedimentary-stratigraphic oil. Moreover, these areas of rapid change may show typical closure, so that "attribute highs" instead of structural highs may afford the magic closed contour for sedimentary-stratigraphic exploration.

The facies maps, and the interpretations therefrom, satisfy the criteria necessary for classification of Michigan as an intracratonic basin. The lithofacies maps of the Michigan Basin during the Silurian display these characteristics: [1] Michigan is an elliptical basin with moderate subsidence in the center, slight subsidence at the margins; [2] the greatest deposition is in the center of the basin; [3] it shows evidence of both restricted and open circulation, and contains evaporites; and [4] shows evidence of slow and relatively minor adjacent uplifts, with subsidence exceeding deposition so that non-clastic components dominate in the section.

In conclusion, the writer wishes to reiterate that the lithofacies maps are subject to correction or change in light of new evidence gained from future drilling. If similar lithofacies studies were made using well samples from northern Ohio, Indiana, and western Ontario, a broader regional picture would become available. The present interpretations of Silurian litho-facies and tectonics could then be modified in accordance with any new evidence gained through these studies.

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