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A SEDIMENTARY AND CHEMICAL ANALYSIS OF
THE NIAGARA SERIES IN MICHIGAN

Thesis for the Degree of M. S.
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A SEDIMENTARY AND CHEMICAL ANALYSIS OF
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By

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ABSTRACT

A subsurface investigation of the Niagara series in Michigan was conducted by quantitatively and chemically analyzing cuttings from 29 wells distributed throughout the state.

The analyses revealed that the structural development of the Michigan Basin is post Niagaran and dolomitization is secondary and is related to structure in the Niagara series.

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A SEDIMENTARY AND CHEMICAL ANALYSIS OF
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INTRODUCTION

James Hall (1842) is credited with naming the Niagara series. He defined the Niagara series to include the Rochester shale and the Lockport dolomite, and resting on the "Protean" group.

J. G. Dana in his editions of the Textbook of Geology used the "Niagara period" to include the Middle Silurian Niagara group, Clinton group (excluding the Rochester shale member), Medina sandstone and Oneida conglomerate, but excluded the Guelph at the top.

A. W. Grabau (1898) described all rocks between the Devonian Onondaga group and the Upper Ordovician as the Niagara series.

J. M. Clarke and C. Schuchert (1899) included the Guelph dolomite, the Lockport limestone, Rochester shale, and the Clinton beds in the Niagara series. This is the accepted definition of the Niagara series. However, the Rochester shale is now treated as a member of the Clinton formation and the Guelph dolomite is included within the Lockport dolomite by the United States Geological Survey.

The type locality for the Niagara is Niagara County, New York, where all subdivisions of the series are well exposed in the gorge of the Niagara River.

Previous work on the Niagara has been primarily in the field of paleontology by G. M. Ehlers, E. R. Cummings, and R. R. Shrock. Cohee (1948) discussed the structure and thickness of the Niagara group in

his report, U. S. Geological Survey Preliminary Chart Number 33, Oil and Gas Investigations. Melhorn (1958) published an article on the quantitative, stratigraphic analysis of the Silurian rocks in the Michigan Basin. This analysis interpreted the sedimentation and tectonics during Silurian time. This work is a significant contribution to the subsurface geology of the Silurian in Michigan.

STATEMENT OF THE PROBLEM

In June of 1957, the author had an opportunity to participate in a field conference sponsored by the Michigan Basin Geological Society. This field conference was under the guidance of Dr. G. M. Ehlers of the University of Michigan. During the trip, Silurian outcrops of the Upper Peninsula were observed. This conference stimulated the author's interest in Silurian stratigraphy and a thesis of the Niagara series in the Southern Peninsula was undertaken.

A quantitative analysis of the sediments was selected as the best possible approach to the problem. The results of such a study could be expressed and illustrated with lithofacies, structural and isopach maps in order that the sedimentary environment could then be interpreted.

LOCATION OF WELLS

Due to the depth of the Niagara series in the Michigan Basin, the distribution of wells available for this study is not uniform. All wells from the Michigan Geological Survey's List of important deep tests which penetrated the top of the Cataract group were investigated for availability in the Gulf Sample Library at Michigan State University. The amount of available samples proved to be a major factor in the selection of wells.

In order to obtain proper coverage, well locations are at a maximum of 30 miles to the nearest adjacent well where possible. Wells are distributed adequately in the southern part of the state, but are somewhat less evenly spaced in the northern and central sections. As a result of this spacing 29 wells were selected throughout the area.

TABLE I

WELLS USED IN ANALYSIS

Sample Number	Permit Number	Company	Farm	County	Sec.	Twp.	Range
1	2960	C. W. Teater	Nevins #1	Alpena	18	32 N	6 E
2	114936	Roosevelt Oil and Refining Corp.	Ormsbee #1	Cheboygan	1	34 N	2 W
3	10004	Ohio Oil Company	Chamberlin #1	Antrim	14	31 N	8 W
4	17784	Brazos Oil and Gas Company	Genson-Wherton #1	Mason	26	19 N	18 W
5	17549	Carter Oil Co.	Lauber #12	Oceana	6	16 N	17 W
6	411	Newsygo Oil and Gas Company	Bates #1	Newsygo	12	13 W	13 W
7	5689	Voorhees Drilling Co.	Reible #1	Ottawa	36	7 N	16 W
8	11540	Smith Petroleum Co.	Sherk et al. #1	Kent	21	5 N	10 W
9	8274	Seba Oil and Development Company	Zischke #1	Clinton	14	5 N	3 W
10	7873	Sun Oil Company	Kidder #1	Barry	8	3 N	9 W
11	5977	Oil Producers	Jackson #2	Van Buren	29	2 S	16 W
12	6162	Sprenger Bros.	Herwig #1	Berrien	10	4 S	18 W
13	6364	A. Violette	Warren #1	Berrien	8	8 S	20 W

14	8075	Tamblyn Development Company	Good #1	Case	15	8 S	15 W
15	7823	Avery	Dunnsworth #1	St. Joseph	13	6 S	11 W
16	9382	Continental Oil Co.	Bonnett #1	Calhoun	8	2 S	6 W
17	9261	Continental Oil Co.	Turner #1	Calhoun	15	3 S	4 W
18	12307	W. J. Morris	Zeiter #1	Hillsdale	24	8 S	4 W
19	9800	J. L. England	Dunigan #1	Lenawee	7	7 S	1 E
20	10448	W. H. Eckert	Taylor #1	Lenawee	32	8 S	5 E
21	7599	Lenawee Oil and Gas Company	McCarberry #1	Lenawee	36	5 S	5 E
22	18796	W. C. Taggart	Le Master #1	Washtenaw	1	1 S	7 E
23	10011	Colvin and Associates Electric Steel Company	Glaser #1	Ingham	14	3 N	1 E
24	13072	Top of Michigan Development Company	Williams #1	Oakland	22	4 N	8 E
25	11011	Mueller Brass Co.	Van Antwerp #1	St. Clair	9	6 N	17 E
26	18305	W. M. Joy and J. O. Black	Tomczyk #1	Sanilac	35	10 N	16 E
27	11834	Pure Oil Company	Stapleton #1	Huron	22	17 N	15 E
28	5441	Gulf Refining Co.	Bateson #1	Bay	2	14 N	4 E
29	12898	Ohio Oil Company and Pure Oil Company	Reinhart-Consolidated #1	Ogemaw	35	22 N	2 E

A SUMMARY OF NIAGARA STRATIGRAPHY

The Niagara series in Michigan is described by Baltrusaites et al. (1948) as the Clinton formation and the Lockport dolomite. These formations are correlative to the Clinton and Lockport of New York.

The Clinton at places has a gray shale 5 to 10 feet thick at the base, a light brown dolomite from 10 to 15 feet thick and a gray calcareous shale 10 to 15 feet thick of Rochester age at top.

The Lockport dolomite commonly consists of white to buff and light gray dolomite overlain by a light brown dolomite. An argillaceous dolomite is found in the basal portion in the northern part of the peninsula. Certain sections are cherty and in places in the eastern and western parts of the Southern Peninsula pink and red dolomite is common.

In the Northern Peninsula of Michigan, the Niagara series is divided into the Burnt Bluff group, the Manistique group, and the Engadine dolomite.

The stratigraphic column of the Southern Peninsula of Michigan (Martin, 1958) indicates the Niagara as a group and the Clinton and Lockport formation are undifferentiated.

A personal communication from H. M. Martin (1958) stated the latest report from the Committee on Stratigraphic Nomenclature has called the Niagara a series. The series is middle Silurian and rests on the Cataract group and is overlain by the Salina group.

STRATIGRAPHIC COLUMN OF THE SILURIAN OF MICHIGAN*

S I L U R I A N	U P P E R	Bass Island fm. Salina fm	Mackinac Breccia Pt. Aux Chenes
	M I D D L E	Niagara	Lockport dol. Clinton fm. Rochester
	L O W E R	Cateract fm.	Cabot Head sh. mem. Manitculin dol. mem.

*
After Michigan Geological Survey Publication 50.

Figure 1

LABORATORY PROCEDURE

General

A laboratory procedure was utilized by which a sedimentary section could be analyzed quantitatively by weight and this data in turn expressed in a form representing sedimentary facies. This procedure is similar to that followed by previous research workers at Michigan State University. A summary of that procedure follows.

Structure and Thickness

The structure and isopach maps are based upon data from wells analyzed and are supplemented by information obtained from other descriptive logs. These logs were obtained from the Michigan Geological Survey.

Sample Composition

The sample well cuttings were obtained from the Gulf Sample Library at Michigan State University. The cuttings are stored in glass vials and each vial represents a drilled interval. A sample cut by weight per foot was taken from each vial in the Niagara series. These sample cuts from a single well were combined to form a composite sample which represents the Niagara section of that particular well location.

"Junk iron" which contaminated the sample was removed with an electro magnet.

Selection of Tops and Bottoms

The marker horizon for the top of the Niagara series is the base of the Salina formation. The Salina salt is underlain by a brown dolomite. In the southern section of Michigan the salt beds may be missing. A brown dolomite which correlates with the Greenfield dolomite of northern Ohio was selected as the marker horizon where the salt was missing.

The Cabot Head shale is a marker horizon for the base of the Niagara series. The shale is a very distinct greenish shale and some interbedded red shale. Where the Cabot Head shale is not present the Manitoulin dolomite is the bottom marker horizon.

Analysis for Water Soluble Salts

The sample was placed in a weighed 400 milliliter beaker and weighed. Distilled water was added to the sample and the mixture boiled and decanted. This procedure was continued until a test of the supernatant liquid using a silver nitrate test revealed no significant amount of soluble salts in solution.

Distilled water was necessary because the hardness of the tap water at East Lansing would contaminate the sample for the magnesium/calcium ratio study.

The sample was then dried and weighed. Loss of weight in the sample was the amount of water soluble salts. The weight of water

soluble salts divided by the original sample weight multiplied by one hundred is the per cent water soluble salt.

Analysis for Carbonates

The sample after treatment for water soluble salts was dissolved in hydrochloric acid. Three normal, six normal, and concentrated acid were added, heated, decanted, and filtered in three successive stages respectively. Filtering was necessary to avoid loss of fine clastics in the decanting. Ashless filter paper was used in order that the filter paper could be ignited in an igniting dish and the residue returned to the sample. Average ash content of the filter used was 0.0005 grams. Since all weighing was conducted to the nearest 0.001 gram, the weight of the ash would not affect the sample to any significant degree.

The sample was washed to remove all calcium chloride and magnesium chloride. The loss of weight in the sample after acid treatment is equal to the amount of carbonates. The weight of carbonates divided by the original sample weight times a hundred is the per cent carbonate in the sample.

Analysis for Shale and Silica

The residue remaining after the acid treatment consisted of chert and clastics. It was disaggregated by boiling in a one normal solution hydrochloric acid. This procedure was all that was necessary because

any shales or sands bound together by a calcareous matrix were disaggregated in the analysis for carbonates. This material was then wet sieved through a 230 mesh sieve (0.062 mm. opening). The material remaining on the sieve was then dried and weighed. The loss of weight due to fine clastics, silt size and smaller which passed through the 230 mesh sieve was called shale by this author. The weight of shale divided by the original sample weight times one hundred equals the per cent shale.

The material remaining on the sieve was dried and weighed. The residue was then examined with a binocular microscope. This material consisted mostly of chert; quartz sand was noted where present. The size sample remaining was not large enough to permit any satisfactory separation of the quartz and chert. This residue was called silica and the weight of silica divided by the original sample weight times one hundred equals the per cent silica.

Magnesium/Calcium Ratio

The versenate method (EDTA, TitraVer) was used to determine the magnesium/calcium ratio. Jodry (1954) and Young (1955) have used this method and it has proved to be very accurate and rapid (average time necessary to titrate a sample was 10 minutes). A brief description of this method follows.

Reagents and Solution

Sample Solution. One gram of sample is dissolved in 10 milliliters of 6 normal hydrochloric acid and then diluted to 250 milliliters with distilled water.

Versonate Solution. Dissolve 4.00 grams of disodium dihydrogen ethylenediaminetetraacetate dihydrate (versonate) in about 100 milliliters of distilled water and then dilute to one liter.

Potassium Hydroxide Solution. Dissolve 21.4 grams of reagent grade potassium hydroxide crystals in about 100 milliliters of distilled water. This basic solution is used to adjust the pH value of the sample being titrated.

Calcium Indicator Powder. Thoroughly mix 99 grams of potassium sulfate and one gram of murexide (ammonium purpurate). This indicator is also available in the prepared form from the Hach Chemical Company, Ames, Iowa, under the trade name of "CalVer". This indicator is unstable and it should be used in the powder form.

Buffer Solution. Dissolve 67.5 grams of ammonium chloride and 5 grams magnesium salt of TitraVer in about 200 milliliters of distilled water. Add 570 milliliters of concentrated ammonium hydroxide and dilute to one liter.

Potassium Cyanide. Prepare a 10 per cent aqueous solution. This solution overcomes any interference caused by iron, copper, cobalt, or nickel that may be present in the sample.

F-241 Indicator. Dissolve 0.15 grams of Eriochrome Black T (called F-241 and available from the Hach Chemical Company) and 0.50 gram of sodium borate in 25 milliliters of methanol. This indicator solution is stable for approximately one month.

Titration

Calcium. Pipette 10 milliliters of solution to be analyzed into a 200 milliliter porcelain dish (white background of the porcelain dish aids in identifying the end point), then add about 20 milliliters of distilled water, one milliliter of potassium hydroxide solution, and approximately 0.10 gram of calcium indicator powder. Stir, and titrate with the versenate solution. The end point is reached when the color changes from pink to violet. Due to the instability of the indicator, any samples not titrated to the end point in ten minutes after adding the indicator should be discarded.

Total Calcium and Magnesium. Pipette 10 milliliters of sample solution to be analyzed into a 100 milliliter beaker, add 25 milliliters of distilled water, 2 milliliters of buffer solution, several drops of potassium cyanide solution, and 3 drops of indicator solution (depending on strength of indicator solution). Care must be taken to add reagents in the above named order. Stir, and titrate with the versenate solution. The end point is reached when the color changes from wine-red to clear blue.

Calculations

Given:

A = milliliters of versenate required to titrate calcium to the end point

B = milliliters of versenate required to titrate total magnesium and calcium to the end point

$$0.607 = \frac{\text{atomic weight of magnesium}}{\text{atomic weight of calcium}}$$

Therefore:

$$\text{Mg/Ca} = 0.607 \times (B-A)/A$$

RESULTS OF LABORATORY ANALYSIS

Structure

The structure of the Niagara series in the southern peninsula of Michigan is a basin. The deepest portion of the basin is in the general locality of Gladwin County and is estimated to be over 8000 feet below sea level. The Niagara series crops out in the extreme southeast corner of the state in Monroe County.

An anticlinal structure is present near Howell, Michigan, and gas is produced in that locality from the top of the Niagara series and the bottom of the Salina group. Other minor structures are present locally due to the numerous reefs in the Niagara series.

Thickness

The Niagara series thickens in the northern part of the state but thins within a belt extending from the "Thumb" area on the east to South Haven on the west. The thinnest section recorded by the author is in Caledonia Township in Kent County. The recorded thickness is 65 feet. The series gradually thickens south of the thin zone to over 400 feet in the extreme southern portion of the state.

Evaporites

The percentage of evaporite in the analysis of the samples remained relatively low (less than 3 per cent). There are two areas where the

percentage is above two per cent, one in the northwest part of the state and the other extends from the "Thumb" area south along the eastern edge of Michigan. Two locations, one in each area had more than two per cent (samples 6 and 27). The remaining part of the state had less than one per cent evaporites in the Niagara.

Carbonates

The dominant lithologic elements of the Niagara series are carbonates. The carbonates generally decrease toward the center of the structural basin. The lowest percentage of carbonate recorded was sample 9 with 77.4 per cent and the highest percentage was sample 18 in Hillsdale County (97.3 per cent). The percentage of carbonates is higher in the southern portion of the state and less on the north and east.

Shale

The percentage of shale and silt size particles (less than 0.062 mm.) was highest in the "Thumb" area and drops off rapidly to the south. The percentage lessens gradually to the west and to the south of this high area.

Silica

The analysis did not divide the chert from the sand. However, a visual examination of the residue determined the areal distribution of

sand. The sand is composed of quartz, well rounded, frosted, and poorly sorted. Sand was found in samples 11 through 21 or in the southern quarter of the state.

Silica concentration is the highest in sample 9 in Clinton County. Here the amount exceeded 13 per cent. The silica content remains above 5 per cent over most of the northwestern part of the state. In the "Thumb" area and the extreme south central area, the percentage was less than one. The Niagara from other areas contained between one and five per cent silica.

Magnesium/Calcium Ratio

Results of the magnesium/calcium ratio analysis yielded a simple pattern of low magnesium in the center and east central sections of the state. The magnesium content gradually increases to the south until it reaches a mean magnesium/calcium ratio of about 0.62 and remains near this value. To the north and west the ratio constantly increases until a maximum ratio of 0.707 is reached in Manistee County.

Errors in Laboratory Analysis

The largest error in the analysis is in the sample itself. Error is the impossibility of taking an uncontaminated sample to the top and to the bottom of the series. In certain areas the picking of tops and bottoms of the section was difficult.

Contamination from cavings is to be expected even if great care is taken to remove the larger pieces of caved material from the sample. Some minute pieces of iron from the drilling equipment also create a source of error.

The initial washing of the sample to remove the drilling mud probably reduced the soluble salt content of the samples. In a like manner, the fines (shale and silt) were also quantitatively reduced.

It is believed that in a study of this type with its regional aspects that these errors, which were kept at a minimum, have not lowered to any great degree the significance of the results.

TABLE II
QUANTITATIVE AND CHEMICAL DATA

Sample Number	Per Cent Evaporites	Per Cent Carbonates	Per Cent Shale	Per Cent Silica	Mg/Ca Ratio
1	0.620	84.075	5.958	9.346	0.263
2	0.674	89.559	3.128	6.638	0.620
3	1.040	83.190	8.412	7.356	0.611
4	0.480	87.109	4.591	7.821	0.707
5	0.529	85.560	9.549	4.373	0.645
6	2.181	80.693	8.653	8.471	0.175
7	0.325	86.861	7.658	5.128	0.275
8	0.821	89.987	8.295	0.899	0.101
9	0.288	77.364	8.388	13.960	0.576
10	0.985	92.943	5.835	0.235	0.208
11	0.790	88.796	7.425	2.988	0.631
12	0.139	89.079	7.893	2.889	0.654
13	0.648	90.871	4.735	3.746	0.646
14	0.182	95.149	3.280	1.388	0.624
15	1.227	96.468	2.092	0.210	0.634
16	0.429	93.631	4.850	1.090	0.626
17	0.139	96.684	2.215	0.804	0.631
18	0.131	97.343	1.831	0.703	0.598
19	0.247	96.757	1.784	1.211	0.634
20	0.219	96.737	1.490	1.552	0.626
21	0.300	95.024	3.327	1.349	0.631
22	1.033	88.327	9.111	1.522	0.598
23	0.277	91.315	6.534	1.873	0.612
24	0.451	87.043	12.303	0.202	0.306
25	0.704	87.868	10.907	0.521	0.592
26	1.066	84.981	13.747	0.204	0.095
27	2.580	81.333	15.662	0.402	0.058
28	0.297	89.149	9.861	0.693	0.057
29	0.333	87.021	9.407	3.239	0.064

TABLE III
STRUCTURAL DATA

Sample Number	Elevation of Top of Niagara	Thickness
1	-3227	415
2	-1959	926
3	-3422	875
4	-3673	348
5	-3592	270
6	-4705	245
7	-2546	145
8	-3073	65
9	-4376	131
10	-2857	97
11	-1261	301
12	-699	355
13	+24	452
14	-536	360
15	-911	244
16	-1942	343
17	-1814	385
18	-699	250
19	-782	492
20	-465	210
21	-801	302
22	-2413	160
23	-3852	103
24	-3578	134
25	-2391	109
26	-3402	111
27	-4881	119
28	-7675	166
29	-7642	275

INTERPRETATION OF LABORATORY RESULTS

Eardley (1951) places the Michigan Basin in the central stable tectonic region, which consists of a foundation of Precambrian crystalline rock covered by a thin veneer of sediments. In general, the strata in this tectonic region dip gently except where slow and prolonged movements during Paleozoic time created domes, arches, and basins.

Schuchert (1955) shows the Niagara Sea extending over most of Michigan during the Niagaran epoch. In early Clinton time, the southern part of the Southern Peninsula of Michigan was exposed but by late Clinton time the entire peninsula was covered by an epeiric sea, which was confluent with the waters of the Appalachian geosyncline until late Lockport time. The Basin probably was not isolated until Salina time. A comparison of the isopach maps of the Niagara series and the entire Silurian section as mapped by Melhorn (1958) indicates that the Michigan Basin developed in the Upper Silurian.

Melhorn (1958) states:

... isopach maps of Cohee (1948) indicate a center of the Middle Silurian Niagaran basin located in western Gladwin County. Eardley (1951, p. 29) locates the center of the early Paleozoic Michigan basin in the general area where Clare, Gladwin, Midland, and Isabella counties adjoin.

... in the early and middle Silurian time the center of the Michigan basin was farther northwest than shown by Cohee and Eardley, probably being located in southeastern Missaukee County.

Isopach maps constructed by Cohee (1948) and the author do not indicate a basin development in Michigan in the Middle Silurian, certainly

not centered in Missaukee County. Eardley (1951) indicates only the present day structural configuration which is unlike the basin of the Middle Silurian time.

If the basin had developed in Niagara time, the thickest sediments may have been in the vicinity of Clare county. The thickness of these sediments should decrease concentrically from this center. This is not the result obtained in the analysis. The series thickens to the north from the central part of the state and it also thickens to the south.

This thinning of sediments on the structure extending through south Kent and north Barry counties is an interesting feature. Was it due to uplift and erosion or was it a high on the sea floor resulting in an area with less deposition? The author believes this area was a high in the sea floor caused by a delay in the subsidence in the forming of the Michigan Basin. It is interesting to note that the presence of sand in the Niagara series does not extend northward beyond or across this high on the sea floor. Possibly the currents were unable to carry the sand beyond this high.

The series thins slightly in the extreme south section of Michigan and may reflect the development of the Cincinnati Dome. The continued thinning to the east may indicate the early development of the Findlay Arch. The percentage of clay size material in the "Thumb" area could indicate a facies change from the source of clastic sediments from the Cincinnati Dome area.

According to the criteria set forth by Sloss (1947), the Niagara series was deposited in a platform-type environment. The platform limestones are deposited under marine conditions in tectonically neutral areas of the continental interior. Adjacent positive areas are either peneplaned, submerged, or are too far removed from the site of deposition to contribute any clastics.

Chert is common in platform limestones (Sloss, 1947). Results of the laboratory analysis of the Niagara samples show significant quantities of chert. The higher percentages of chert are concentrated in the northwestern part of the state. It is noticeable that the tectonic high which existed during Niagara time in the central section of the state separates the chert concentrated in the north from the lesser amounts in the south.

The small amount of evaporites indicate that the areas of high evaporite percentages were not isolated for any length of time. At times these areas were possibly isolated from a supply of fresh marine water and in this manner the concentration of salts became high enough to precipitate.

The calcium/magnesium ratio is not influenced by thickness but seems related to structure. The amount of magnesium increases toward the margin of the structural basin. For this reason, the author believes that dolomitization is secondary and is related to the regional structure of the Niagara series,

Jodry (1954) believed that dolomitization was related to structure and found this relationship to be true in a study of structure and porosity in Michigan. Young (1955) in a study of the Stony Lake Oil Field in Michigan found this relationship was not true. Apparently for small, local, detailed studies, or where the structure is not well developed, this relationship of dolomitization to structure does not always hold true.

Tinklepaugh (1957) in conducting a detailed study involving three oil fields covering an area of six townships found a significant statistical relationship between high dolomite and structural high.

The process of dolomitization has lead to a great deal of speculation. The theory of marine alteration may come close to being the answer. Marine alteration is the modification of limestone by sea water before emergence. The magnesium is supplied by the sea water.

In summarizing it may be said that whatever the process causing dolomitization in the Niagara series, the dolomite is secondary and is related to structure; and secondly, the structural development of the Michigan Basin is post Niagaran.

SUGGESTIONS FOR FURTHER STUDY

The research of Jodry (1954), Young (1955), Tinklepaugh (1957), and the author have but scratched the surface of the possible relationship between dolomitization and structure. Further studies of the Traverse group are recommended to investigate this problem since wells into the younger group would be available in greater quantity than from the Niagara at the present time and a better regional study of this relationship would be possible. As more and more wells are drilled in the Niagara group a study in more detail could be conducted for a comparison to the dolomite-structure relationship of the Traverse.

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APPENDIX

SOUTHERN PENINSULA
OF
MICHIGAN

STRUCTURE CONTOUR MAP

Top of Niagara Series

Contour Interval: 1000 feet



SCALE
0 10 20
Miles

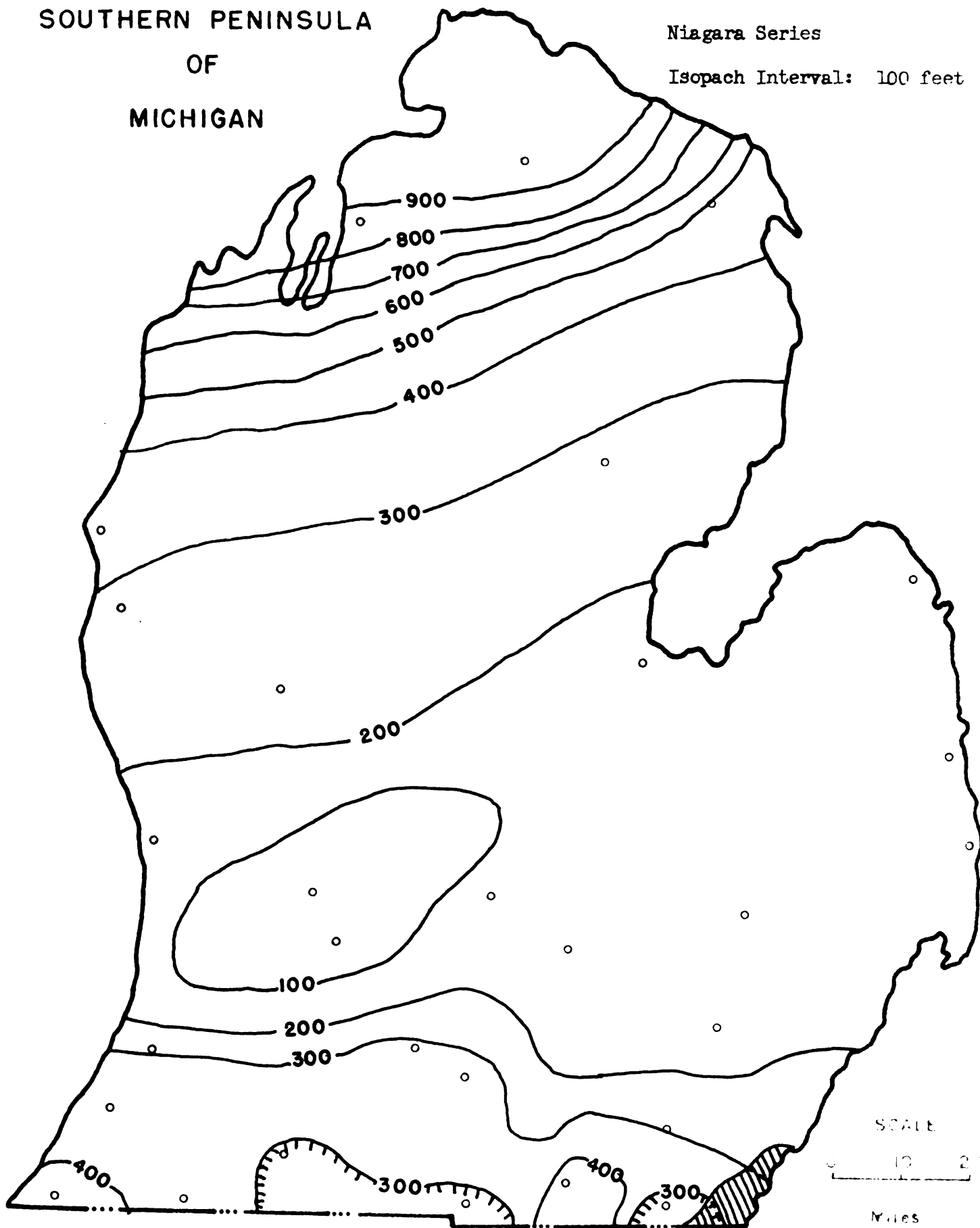
○ Well Location

SOUTHERN PENINSULA
OF
MICHIGAN

ISOPACH MAP

Niagara Series

Isopach Interval: 100 feet

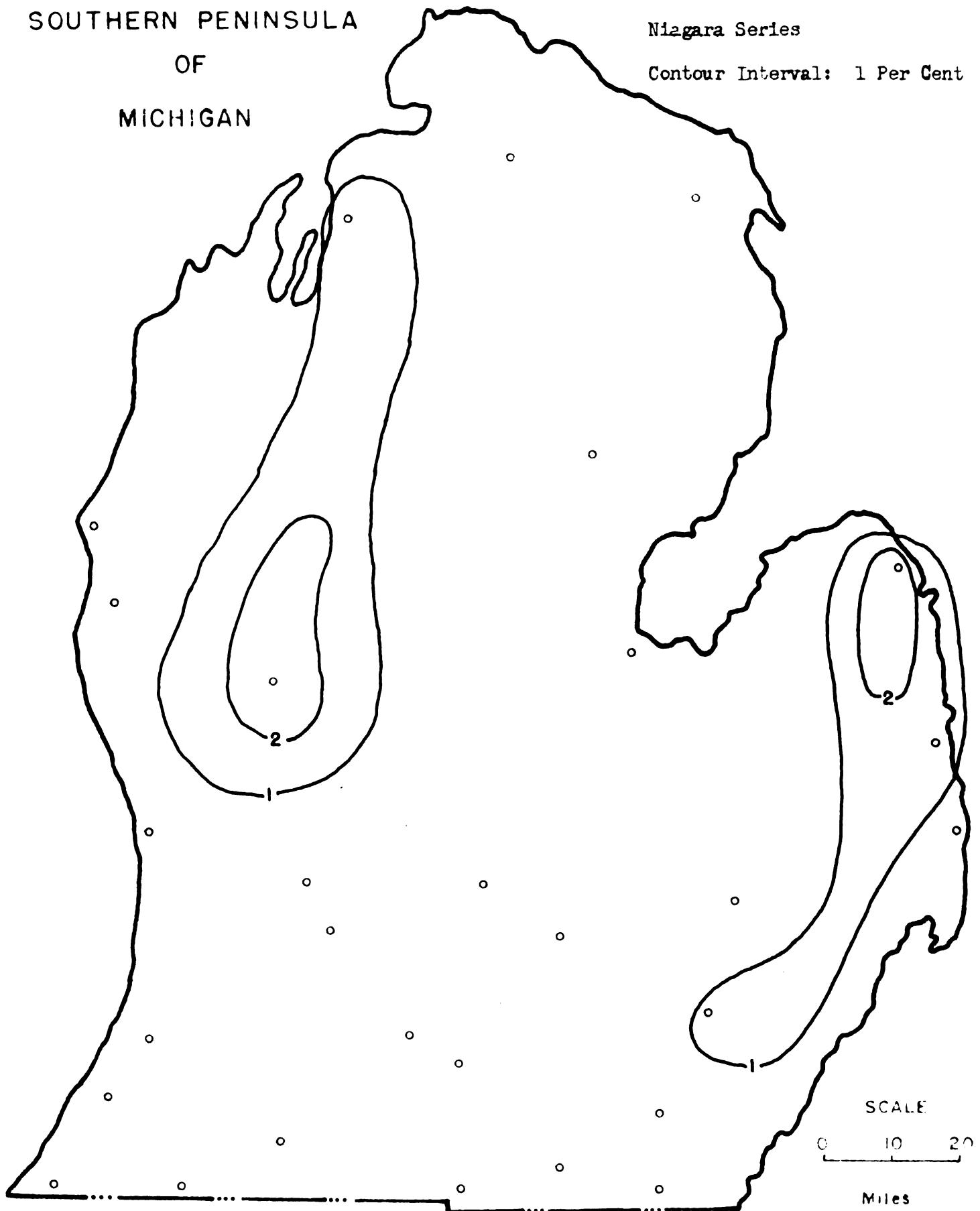


SOUTHERN PENINSULA
OF
MICHIGAN

WATER SOLUBLE SALTS

Niagara Series

Contour Interval: 1 Per Cent



SCALE

0 10 20

Miles

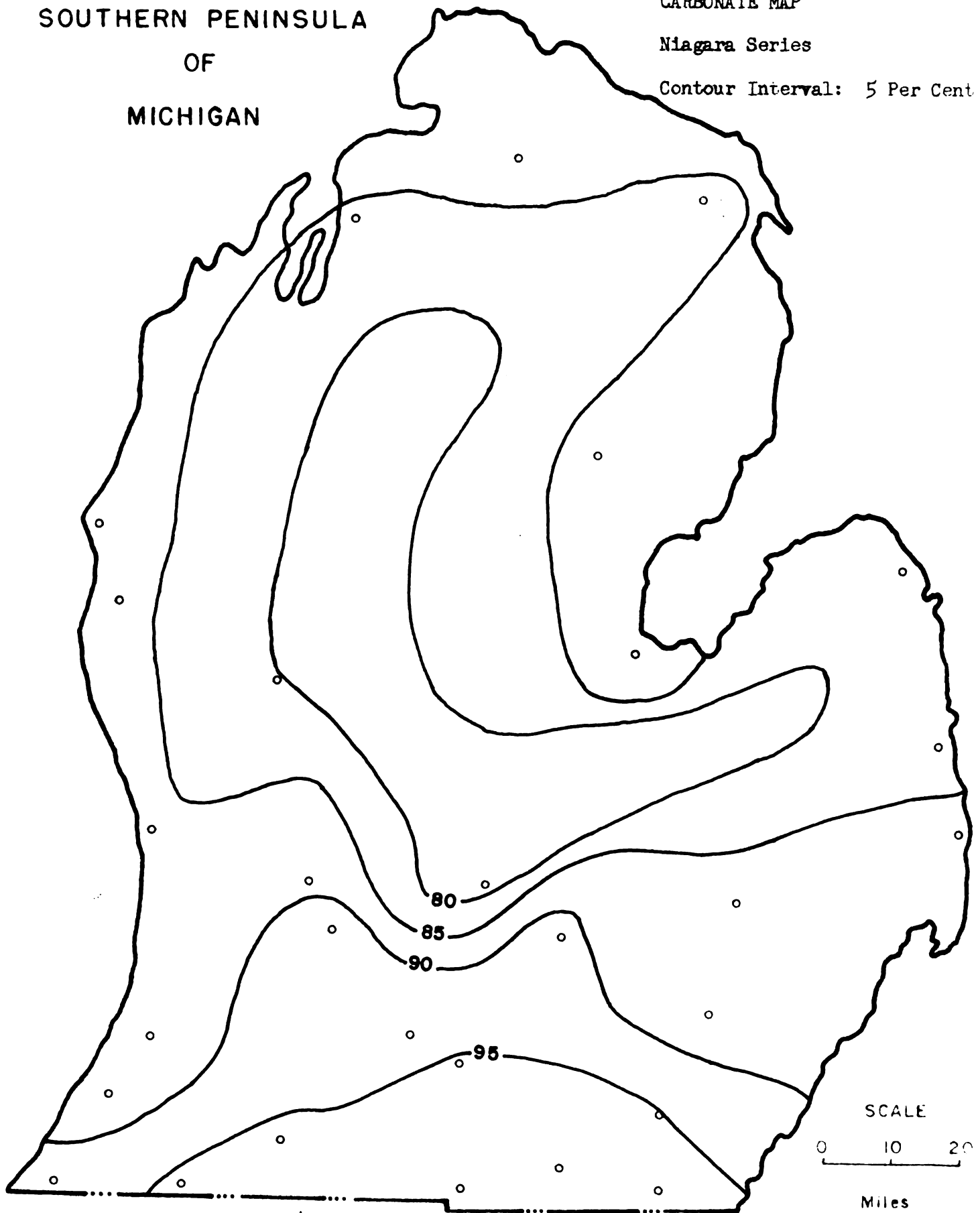
o Well Location

SOUTHERN PENINSULA
OF
MICHIGAN

CARBONATE MAP

Niagara Series

Contour Interval: 5 Per Cent

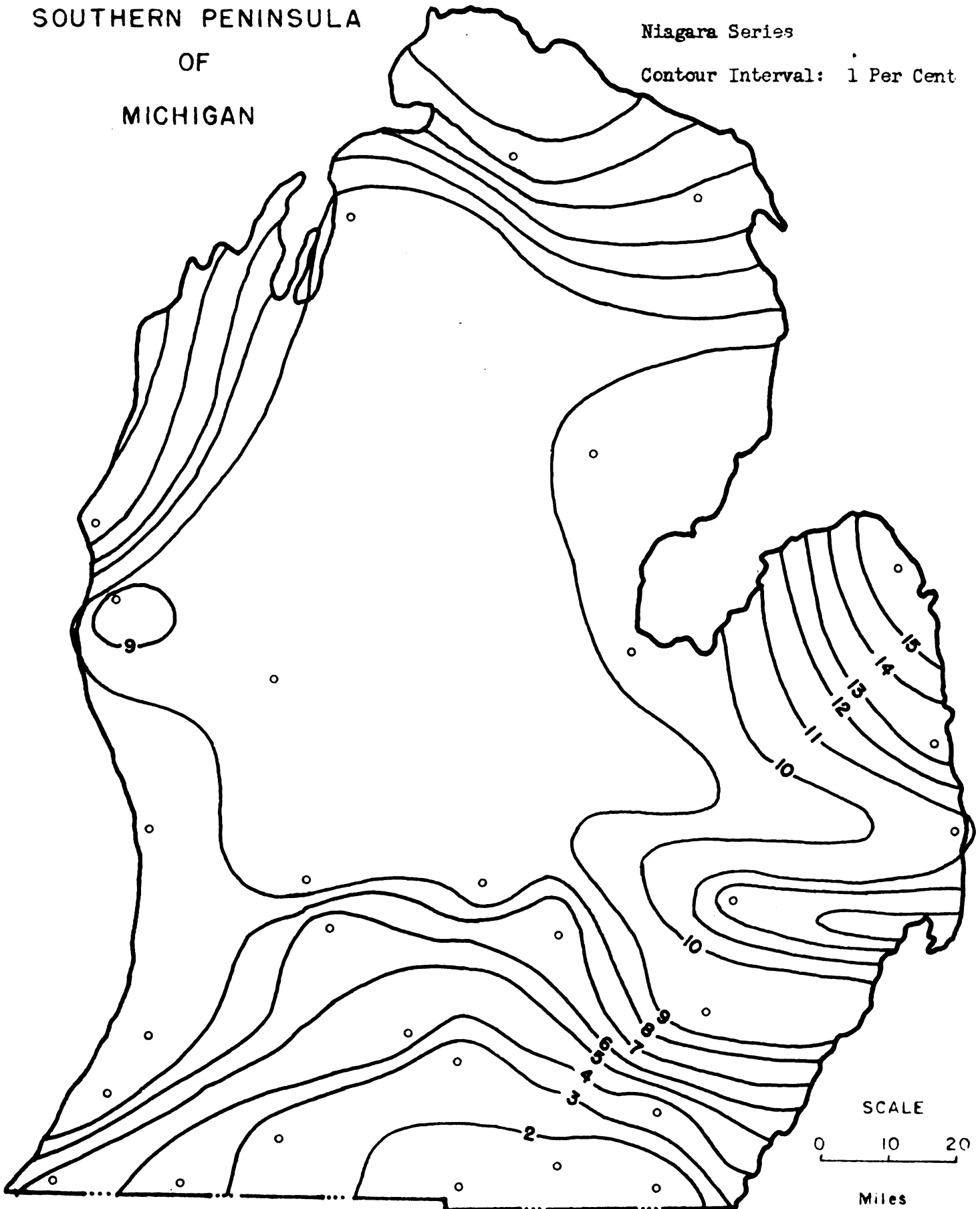


SOUTHERN PENINSULA
OF
MICHIGAN

SHALE MAP

Niagara Series

Contour Interval: 1 Per Cent



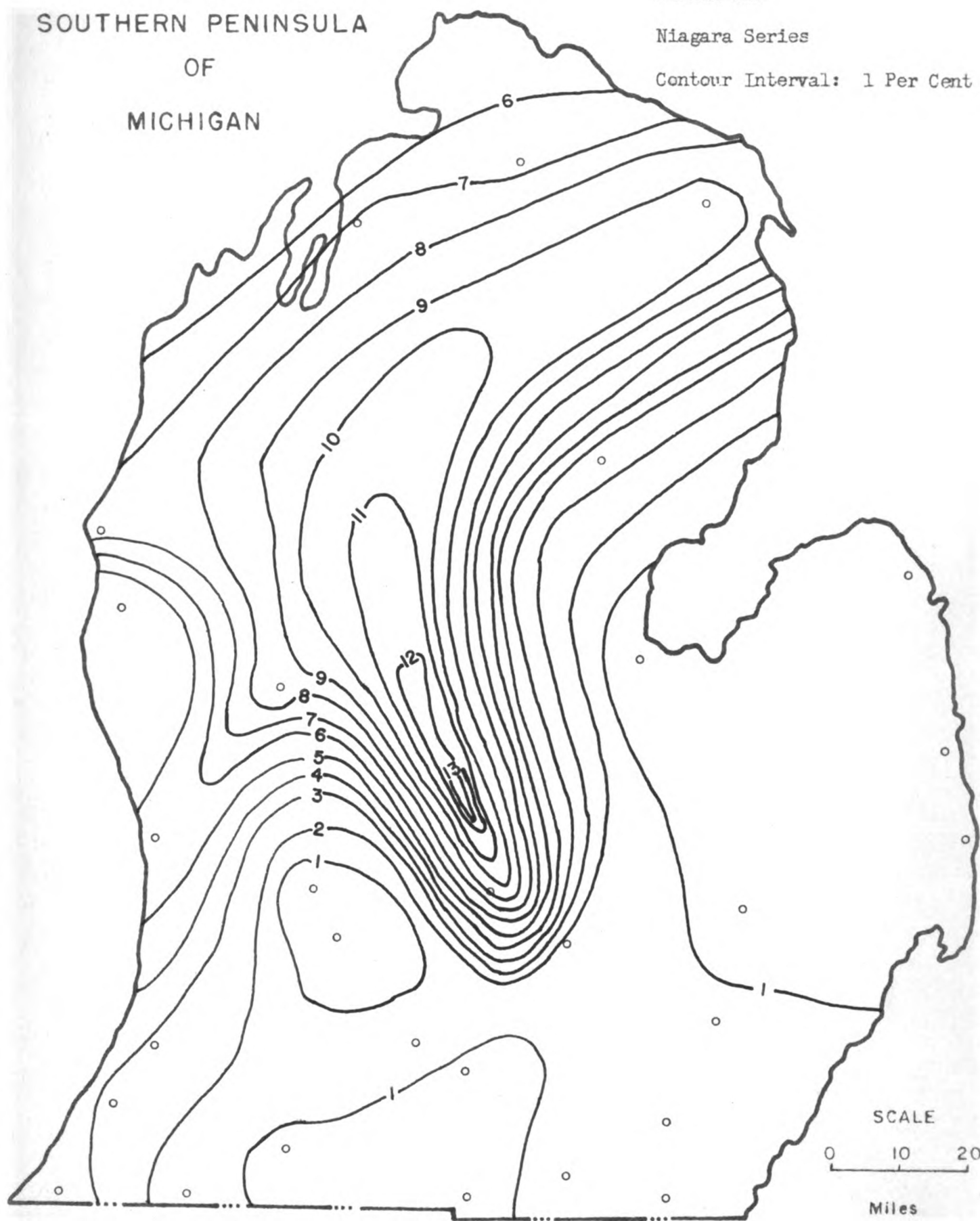
o Well Locations

SOUTHERN PENINSULA
OF
MICHIGAN

SILICA MAP

Niagara Series

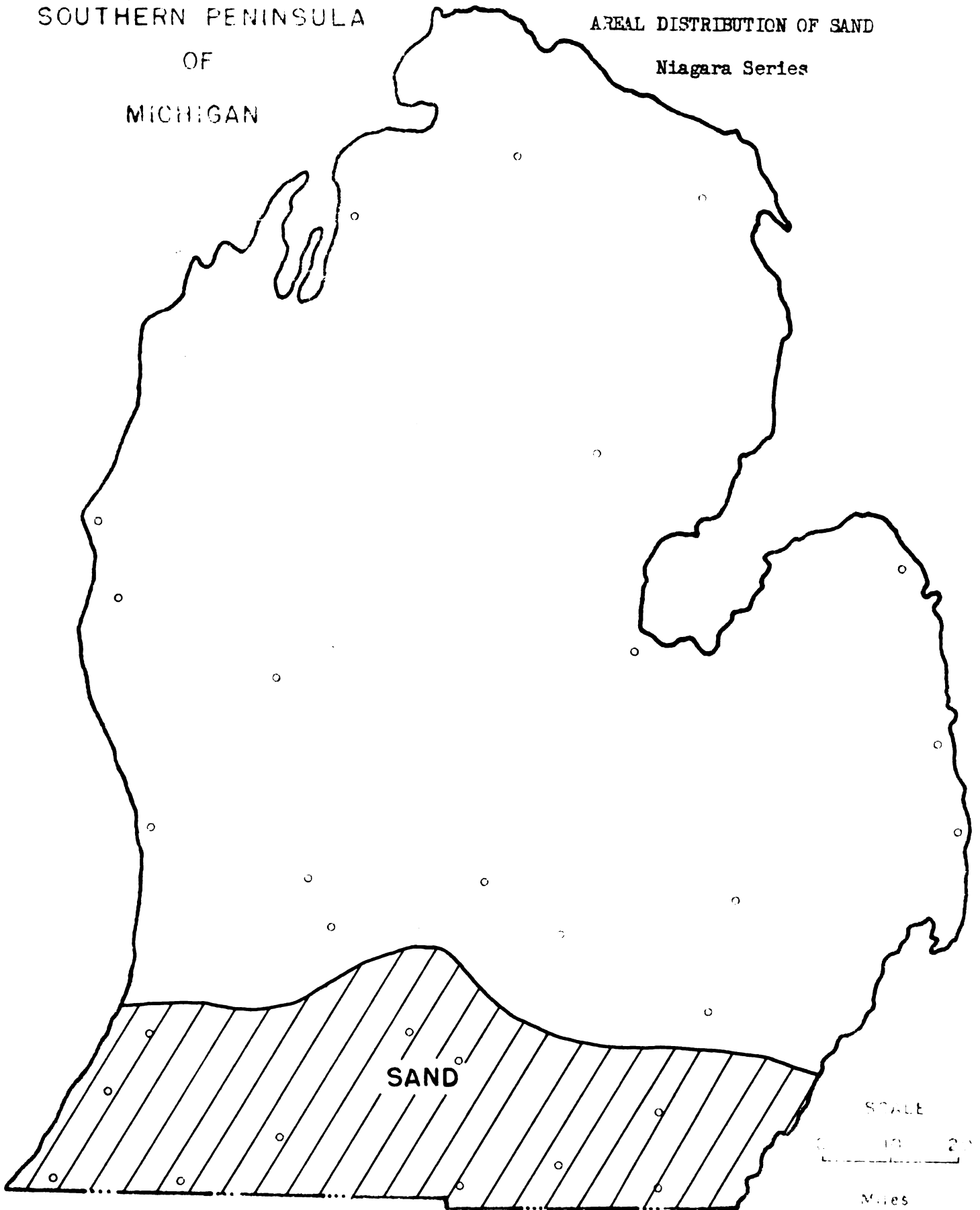
Contour Interval: 1 Per Cent



o Well Locations

SOUTHERN PENINSULA
OF
MICHIGAN

AREAL DISTRIBUTION OF SAND
Niagara Series

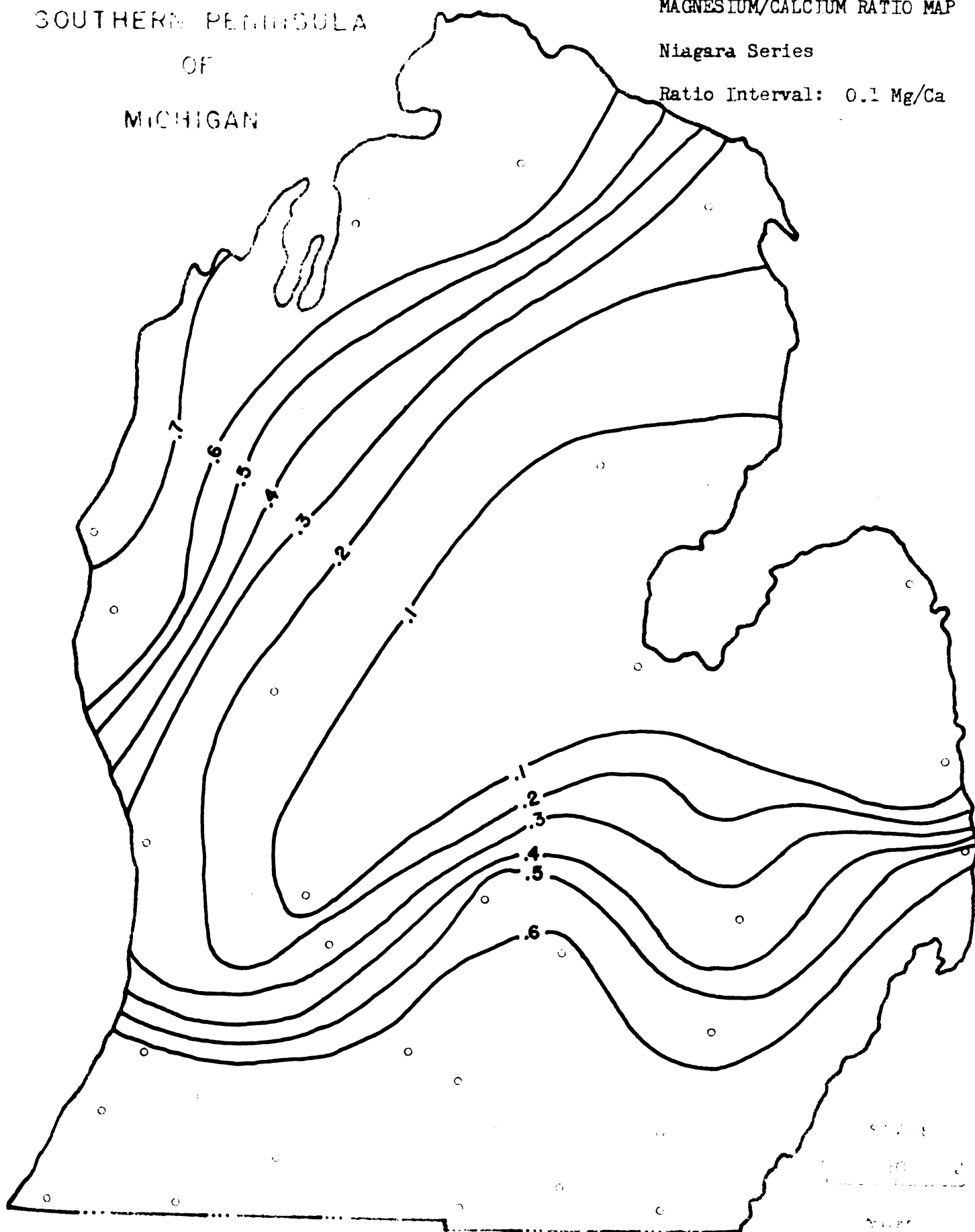


SOUTHERN PENINSULA
OF
MICHIGAN

MAGNESIUM/CALCIUM RATIO MAP

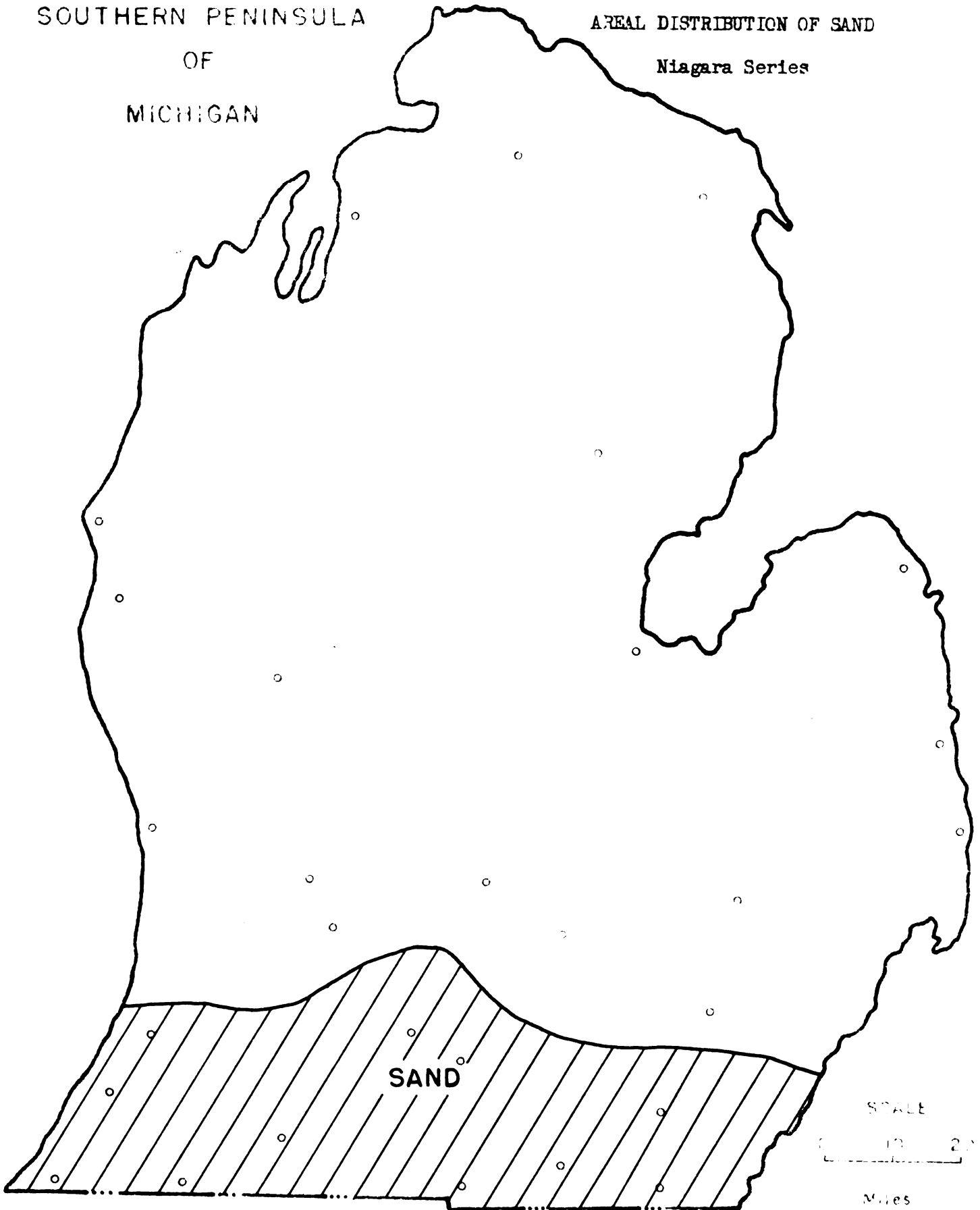
Niagara Series

Ratio Interval: 0.1 Mg/Ca



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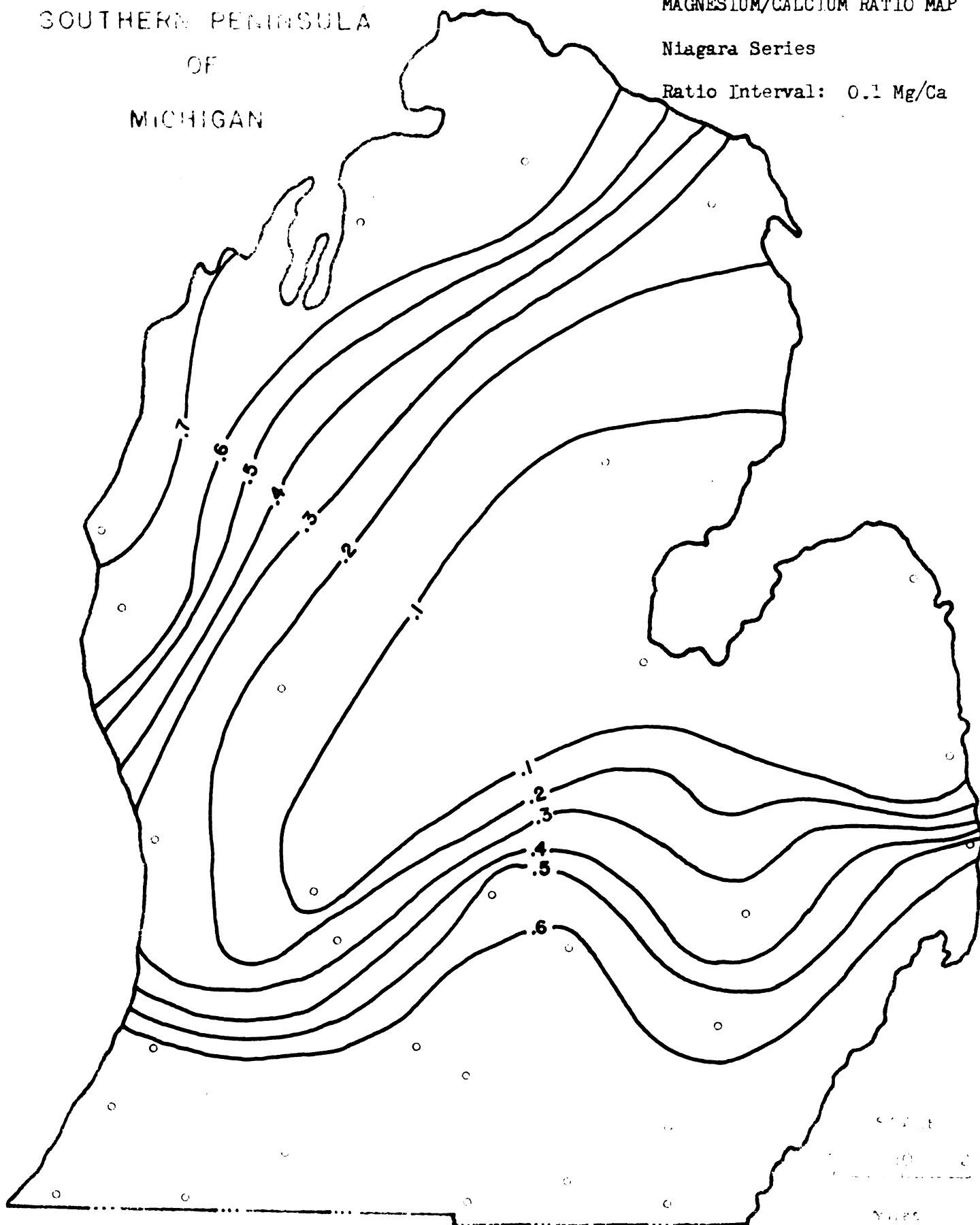


SOUTHERN PENINSULA
OF
MICHIGAN

MAGNESIUM/CALCIUM RATIO MAP

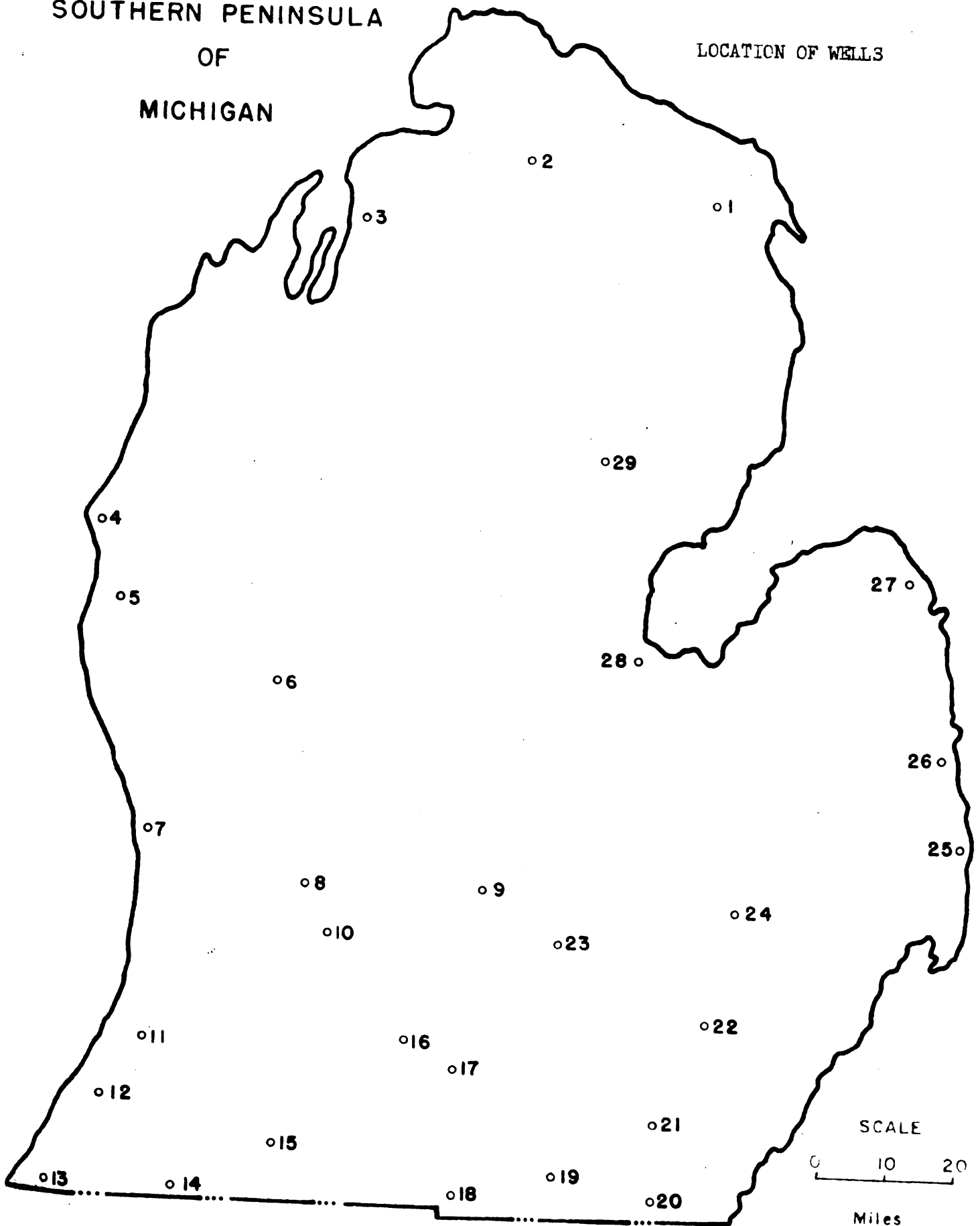
Niagara Series

Ratio Interval: 0.1 Mg/Ca



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OF
MICHIGAN

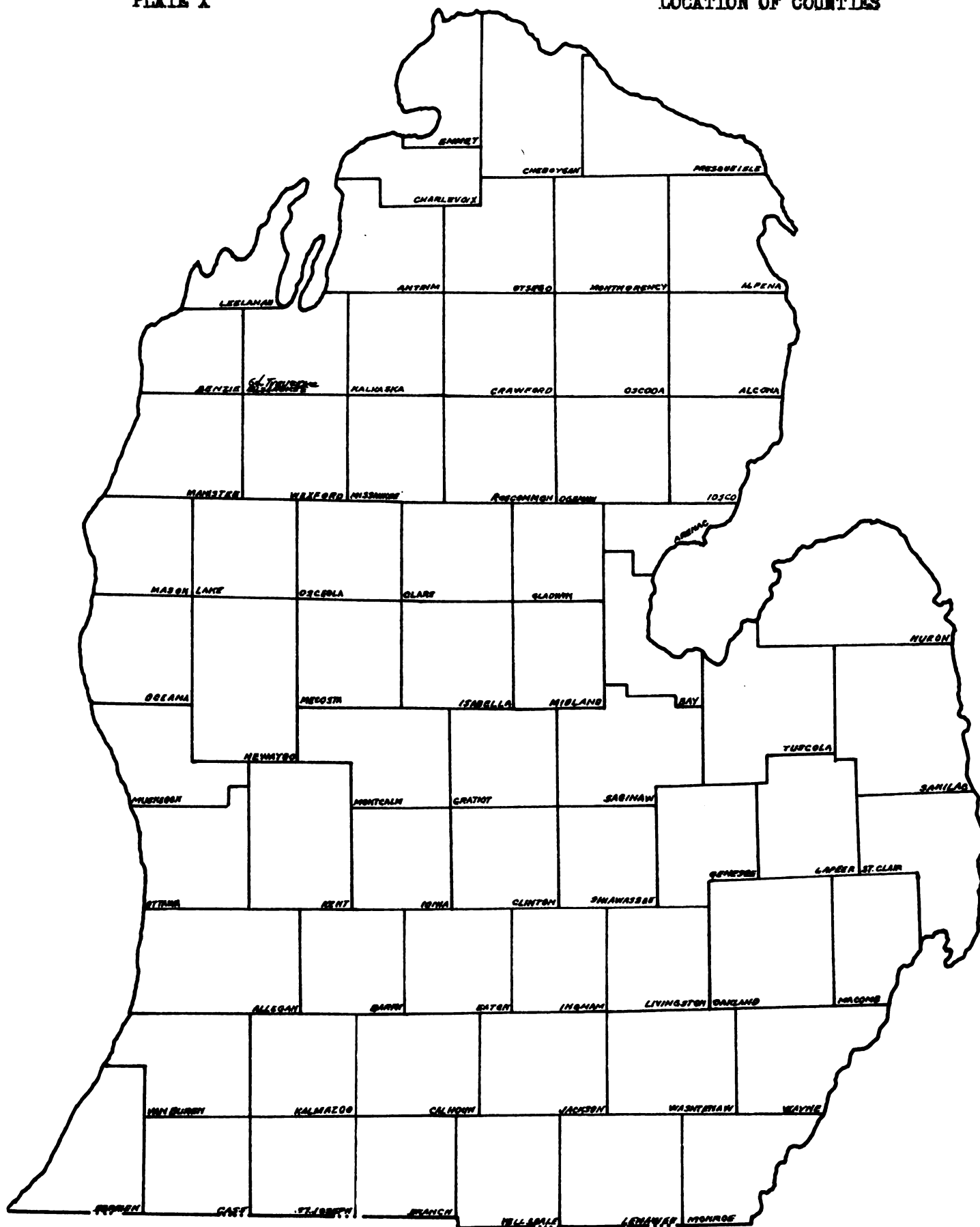
LOCATION OF WELLS



SCALE
0 10 20
Miles

o Well Location

LOCATION OF COUNTIES



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