DISTRIBUTION AND STRATIGRAPHIC POSITION OF LATE PRECAMBRIAN DIABASE DIKES IN PARTS OF NORTHERN MICHIGAN

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DISTRIBUTION AND STRATIGRAPHIC POSITION OF LATE PRECAMBRIAN DIABASE DIKES IN PARTS OF NORTHERN MICHIGAN

BY

Warren W. Wood

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ABSTRACT

The late Precambrian diabase dikes of northern Michigan outcrop in Gogebic, Iron, Baraga, Marquette and Dickinson counties. They are strikingly similar to one another in field characteristics and composition. Most of the dikes are magnetically reversed to the present geomagnetic dipole and intersect with a definite trend all other rocks in the area. The distribution of these dikes is not fully known but they appear to lie within at least a 50 mile wide belt which appears to parallel the Lake Superior Basin axis.

The dikes probably intersect the post-Animikie granite and are overlain unconformably by a probable Lower Cambrian sandstone. They could therefore be either (1) a post granite pre-Keweenawan intrusive (2) genetically related to the Keweenawan sequence or (3) post-Keweenawan - Precambrian. Structural evidence indicates that the dikes occupy positions probably created by the same stresses that formed the Lake Superior Basin. Chemical similarity between the dikes and the Keweenawan lavas is shown. Reverse polarization is investigated as a possible method of correlation and is rejected.

It is concluded that the dikes are Keweenawan in age.

INTRODUCTION

Purpose and Scope

An extensive amount of field mapping and exploration work, undertaken throughout the older Precambrian areas in the western portions of the Northern Peninsula of Michigan, has shown the presence of grest numbers of basic dikes cutting these older rocks. These dikes vary in direction, size and other characteristics. Some of them appear to be important in iron ore occurrances. Most of these dikes clearly show the effects of metamorphism in that they are now uralitized or chloritized and in some bodies they have apparently altered to clay minerals. Frequently, however, a dike rock is found which in contrast to most of the others, appears surprisingly fresh and unaltered. Where carefully mapped, these dikes cut all lower and middle Precambrian rocks. Other characteristics of these fresh dikes are noteworthy: most are reversely polarized, that is, magnetic readings over them are negative compared to those over adjacent rocks. These diabase dikes have been found in most of the iron bearing districts of the Northern Peninsula either as surface outcrops or intercepted in drill cores. Aeromagnetic surveys have also located some of the larger dikes and these show dominant trends cutting indiscriminantly through all other rocks.

Many geologists have speculated as to the age of these dikes and usually stated that they were probably Keweenawan, but little detail work has been done on them. Most previous investigation has been fragmentary and usually associated with some economic inquiry. Consequently, little has been written about these dikes as a system.

The study of these late Précambrian dikes was undertaken in order to determine their distribution and stratigraphic age. It is held by the writer that a system of dikes, such as exhibited in this area, should be part of a larger orogeny and not a separate entity. The process of fracture and intrusion of dikes on such a large scale should be related to some larger orogenic activity and consequently should bear structural, chemical and/or mineralogical relationships to this activity.

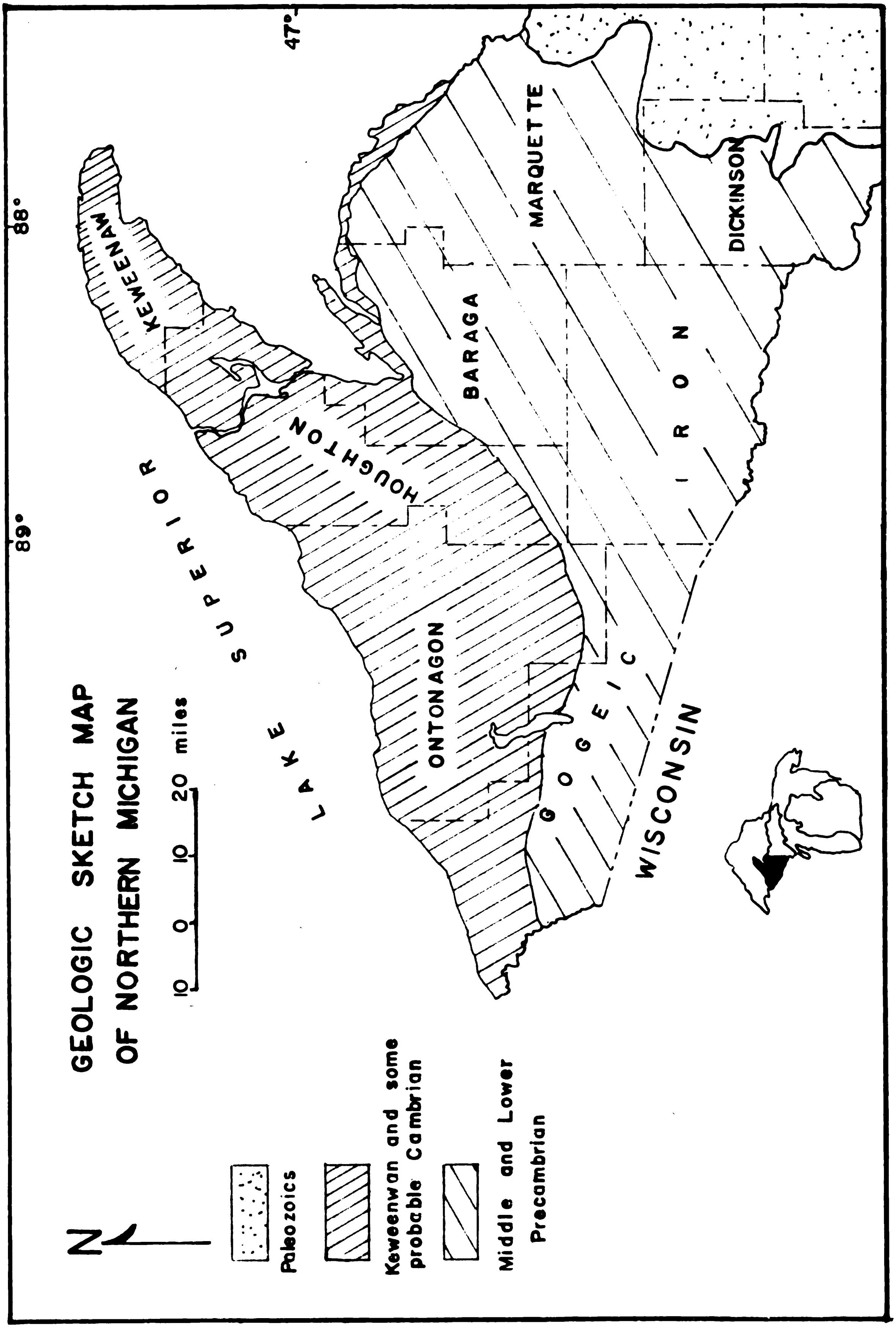
Under the circumstances, comparison and contrast of the chemical composition of the late Precambrian dikes with post-Animikie and Keweenawan intrusions in conjunction with a structural analysis was considered the best method of stratigraphic correlation. This entailed sampling for chemical composition and areal mapping to determine dip, strike and stratigraphic relationship.

Location and Physiography

This study is basically confined to five counties in Northern Michigan: Marquette, Baraga, Gogebic, Dickinson and Iron (Figure #1). The dike system probably extends throughout the Lake Superior Province but time did not permit such an extensive investigation.

The topography of the area depends generally upon the

FIGURE I


GEOLOGIC SKETCH MAP
OF NORTHERN MICHIGAN
10 0 10 20 miles
N
Paleozoics
Keweenwan and some probable Cambrian
Middle and Lower Precambrian
LAKE SUPERIOR
KEWEENAW
HOUGHTON
ONTONAGON
BARAGA
MARQUETTE
IRON
DICKINSON
GOGEBIC
WISCONSIN
47°
88°
89°

resistance of the exposed rocks. In contrast to a series of parallel ranges common to the Keweenaw Peninsula, the five counties exhibit numerous irregular hills, lakes and swamps. In Marquette, Felch and Menominee regions a definite series of east-west trending ridges are prominent. Parallel valleys are formed from less resistant formations.

Field Work and Methods

Exposures of Middle Precambrian rocks in Northern Michigan are spotty and generally lack continuous exposure due to heavy cover of glacial drift and vegetation. This condition in conjunction with the large area of this investigation required extensive motor travel. Fortunately, Northern Michigan has an abundance of good Federal, state and secondary roads which makes the area readily accessible by automobile.

Field work for this problem was conducted in the summer of 1960. The dikes under investigation were recognized by their distinctive brown weathering, their reversed polarization (as observed by dip needle) and their unaltered appearance. Each dike location was examined for dip, strike, post emplacement movement, effects upon country rock (structural and mineralogical) and magnetic anomaly. A representative sample was taken of each occurrance investigated. All laboratory work was conducted at Michigan State University and consisted of thin section study and qualitative chemical analysis.

Previous Work

As early as 1881 Rominger recognized the similarity of the fresh dikes of Northern Michigan with the "Copper bearing Formations" (Keweenawan). Irving and Van Hise (1892) felt that the dikes of the Gogebic district were intimately connected to the Keweenawan lava flows. They state that the dikes were very probably the pipes which fed the lava flows. Van Hise and Bayley (1897) stated they thought the fresh dikes of the Marquette district were intruded during Keweenawan time (p. 218). Clements et al.,(1899 p. 189) called attention to the similarity of the dikes of the Marquette, Gogebic and Crystal Falls areas with each other and with the Keweenawan lava flows. He also warned that chemical similarity was a hazardous method of correlation. Van Hise and Leith (1911) mention that fresh dikes are found in all areas surrounding Lake Superior.

Royce (in Newhouse 1942) studied these dikes in several locations in connection with enrichment of the iron ore. Balsely, James and Wier (1949) commented on the negative magnetic anomaly these dikes produced. Graham (1953) studied the reverse polarization of several dikes in Baraga county.

Many of these workers assigned these dikes to the Keweenawan simply on the basis of lack of metamorphism as compared to the other Precambrian rocks in the area. While this method may be satisfactory it does not allow for the possibility of a post-Animikie, pre-Keweenawan period of intrusion which, on the basis of stratigraphic relationship, the dikes could occupy.

Geology of the Area

The Precambrian geology of Norhtern Michigan is extremely complex and is treated here only as it pertains to the late dikes. The various districts have experienced similar events of sedimentation and diastrophism and only a brief description is given.

Most of the area has at the base of the middle Precambrian a quartzite and dolomite succession overlying unconformably the lower Precambrian. This is followed by a series of quartzite, slate and iron formation, which in turn is overlain by a succession of quartzites, iron formation, volcanics and slates. This last sequence is apparently repeated in some areas. All of these formations are intruded by dikes and sills which are now metadiabase, and folded contemporaneously with intrusions of granite (James et al, 1961). A profound unconformity followed as indicated by the deposition of lower Keweenawan beds upon the folded and plained older rocks as shown in the Gogebic district. Radiometric methods of dating, indicated about 300 million years between the ages of the post-Animikie granite 1.4×10^9 and the Duluth Gabbro 1.1×10^9 (probable Keweenawan) (James 1958). The dikes of this study intruded the Animikie series and granite, and in the Gogebic range some of the lower Keweenawan flows.

In Michigan, the Keweenawan series (upper Precambrian) is represented by basic lava flows interbedded with felsic conglomerates. The series is generally divided into 3 units on the basis of lithology: lower, middle and upper. The lower and upper units are primarily sedimentary with some basic flows in the lower and more feldspathic flows in the upper. The middle unit is composed mainly of basic lava flows which extend 15,000 feet in some areas. The extrusions and sediments are confined mainly to Keweenaw, Houghton and Ontonagon counties and form the Keweenaw Peninsula.

Unconformably above the Keweenawan, lies a probable Cambrian sandstone (Hamblin 1958) upon which, unconformably, till and outwash of the Pleistocene epoch is deposited. A generalized geologic column is given for the middle Precambrian. A more detailed description of the upper Precambrian is also included (Column 1).

GENERALIZED GEOLOGIC COLUMN FOR PARTS OF NORTHERN MICHIGAN

Cenozoic	Quartenary	Pleistocene outwash and till	
Paleozoic	Cambrian	Jacobsville sandstone	
Upper Precambrian	Keweenawan series	Upper	Freda sandstone Nonsuch shale
		Middle	Copper Harbor group Eagle River group Ash Bed group Central Mine group
		Lower	Bohemian Range group
	Granite (Intrusive contact) Metadiabase (Intrusive contact)		
Middle Precambrian	Animikie series	Upper	
		Middle	
		Lower	
Lower Precambrian	Granite, Syenite, Peridotite, Gneiss, Metasediments		

DISTRIBUTION

The system of late Precambrian dikes under study (Plate #1), apparently represented by two varieties, probably exists throughout the Lake Superior province. In Michigan, middle and lower Precambrian exposure areas afford the only opportunity for open examination due to the overlap of Paleozoic sediments from the southeast and Keweenawan-Cambrian sediments from the northwest, wherein dikes can be found.

Both reversely and normally polarized fresh dikes are observed in Northern Michigan. Whether the two types truly represent two different times, different swarms, or different composition, is not known; it is not intended to imply similarity of intrusion for all reversely polarized rocks. This feature is used for comparison purposes like any physical property and may not have a time significance. Both types of dikes intersect the post-Animikie pre-Keweenawan granite, but no normally polarized dikes have been observed truncated by the Jacobsville sandstone. The reversely polarized dikes appear to be much more abundant, however, this may be due in part to their reverse polarization which makes them immediately recognizable.

In the Gogebic district of Michigan, late Precambrian dikes are extremely numerous, occurring in all of the mines of the areas, occasionally 3 or 4 in a mine. The dikes found here are generally altered by the fluids that concentrated the iron ore. Fresh exposures, which are similar to late dikes in other areas, are found only away from the ore. It is probable that the original magnetism in the altered areas, regardless of its orientation, was destroyed by the ore concentrating fluids. There are no published aeromagnetic maps of the region in which to check for reversals of polarization, and the writer was unable to find any outcrops to check this feature; however, dip needle traverses, run in 1926 by the Michigan Department of Conservation, indicate some negative reading over diabase outcrops. These are interpreted by the writer to be an expression of the same dike system as observed in the other areas of Northern Michigan.

Graham (1953) indicated 25 probable reversely polarized dikes in a 18 X 18 mile square in Baraga county. An aeromagnetic survey (Balsley, James and Wier 1949) on parts of Houghton, Baraga and Iron counties, covering additional area to Graham's report, shows a prominent belt of negative magnetic anomalies between Township 47 North and Township 49 North. When correlated with the geology, these negative anomalies are found to be associated with fresh diabase dikes. The dikes appear to start abruptly at Township 49 North and to decrease southward from Township 46 North (Plate 1).

In Marquette county there are at least 10 reversely polarized dikes and probably several times that many, but the aeromagnetic surveys which have been flown by the United States Geological Survey and would have disclosed these reversely polarized dikes, have not been released. The area of intrusion could be predicted for Marquette county on the basis of the intrusions in Baraga county and investigation by the author. The largest number of dikes would be expected to lie between Township 46 North and Township 49 North and strike E-W with little variance. All of the samples collected by the writer in Marquette county (Figure #2) are within this belt; in addition, a fresh olivine diabase dike of unknown magnetism and age occurrs on Green Island in Lake Michigamme (Van Hise and Bayley 1897).

Dikes south of Township 46 North might be expected to strike N 70 E, if they follow the basic fault pattern of the Marquette synclinorium (Empire, Volunteer and Palmer faults). Three reversely polarized dikes have been observed striking N 70 E in the southern area. The dike at the abandoned Isabella mine (Sample #7), is in a fault plane parallel to the main faults of the area. This dike exhibits minor slickensides which are attributed to post emplacement readjustment. Buzas (1960) found 2 negative anomalies (R 24-25 W., T 47 N and R 23-27 W., T 43 N) (Plate #1), which he attributed to reversely polarized dikes. These dikes parallel probable faults (Allen 1914). While Buzas did not intimate that the dikes were intruded into fault zones, it is possible that the strong negative anomaly produced by the dikes masked the magnetic break generally exhibited by a fault. If the strike of the dike in R 23-27 W., T 43-44 N, is projected into Dickinson county it coincides with a series of faults north of the Felch trough in R 28-30 W., T 42 N.

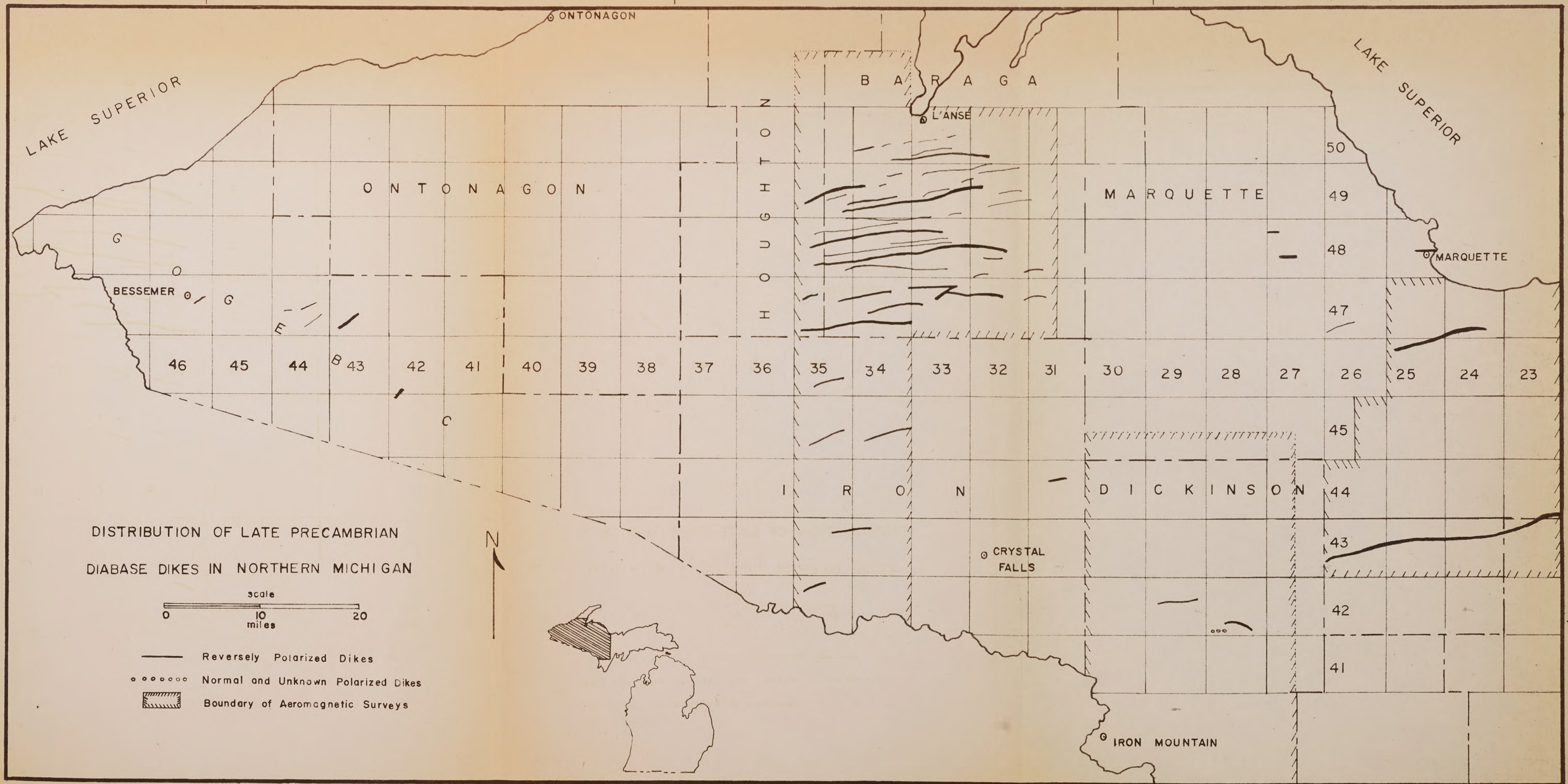
In the Mineral Hills area of Iron county there are a few fresh dikes, one of which is reversely polarized and fault controlled (James and Dutton 1951). Gair and Wier (1956) found one reversely polarized fresh dike in the Kiernan Quadrangle (T 43 N., R 31 W.). Bayley (1959) found only a few fresh stringers a few inches to 3 feet wide in the Lake Mary Quadrangle, south of the above area (T 42 N., R 31 W.). None of these fresh intrusions were reversely polarized. An aeromagnetic survey (Balsely, James and Wier 1949) disclosed the presence of several reversely polarized dikes in T 45 N., R 34-35 W., and also one in T 42 N., R 35 W., in addition to the previously mentioned dike at Mineral Hills.

An aeromagnetic survey of Dickinson county (Wier, Balsely and Pratt 1953) disclosed only two magnetic anomalies which could be interpreted as reversely polarized dikes. In central Dickinson county, extremely detailed mapping disclosed one large reversely polarized dike (mentioned above) and several small fresh normally polarized dikes (James et. al., 1961). There is no mention by Bayley (1904) of fresh dikes or intrusives in the Menominee district, nor did the aeromagnetic survey of Dickinson county disclose any reversely polarized dikes in that area.

It can be seen that the dikes were intruded in a belt at least 50 miles wide, with the main belt of intrusion

25 miles wide (Plate #1). Most of the area of intrusion is occupied by folded Animikie sediments. To what extent these folded sediments may have controlled intrusion is unknown but it appears that many dikes away from the main intrusion belt are controlled by preexisting faults and should be considered in this light.

It would be expected that the belt of dikes in Baraga county is an extension of those in the Gogebic district. Whether an aeromagnetic survey could confirm this under a cover of Cambrian sediments and Keweenawan traps is doubtful. This belt undoubtedly extends through Marquette county and eastward into Lake Superior. Final evidence rests on the release of the aeromagnetic data from the United States Government.



90°
89°
88°
-46°
ONTONAGON
LAKE SUPERIOR
LAKE SUPERIOR
B A R A G A
L'ANSE
O N T O N A G O N
H O U G H T O N
M A R Q U E T T E
MARQUETTE
BESSEMER
G O G E B I C
I R O N
D I C K I N S O N
CRYSTAL FALLS
IRON MOUNTAIN
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
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43
42
41
N
DISTRIBUTION OF LATE PRECAMBRIAN
DIABASE DIKES IN NORTHERN MICHIGAN
scale
0
10
20
miles
Reversely Polarized Dikes
Normal and Unknown Polarized Dikes
Boundary of Aeromagnetic Surveys

DESCRIPTION OF SAMPLES

Petrography

The use of the integrating stage with calculation of modal percentages was considered adequate for the purpose of this study, allowing both a petrographic and semiquantitative chemical analysis. Over 300 equalgranular crystals were counted in a typical mode, thereby indicating a standard deviation of about one percent of that represented by the slide (Niggli 1954). Moorhouse (1959) believes that when optical properties are known with sufficient accuracy, the volume percentage method is more accurate than conventional chemical analysis. Correlation of optical properties with chemical composition was accomplished by the use of the findings of Hess (1949), Larsan and Berman (1934), Moorhouse (1959) and Johannsen (1939), the latter work being used in converting species composition to oxides. Conventional petrographic techniques were used in obtaining the optical data.

When altered minerals were encountered in a modal traverse, the original mineral was recorded if its identification was positive. In instances where there was insufficient evidence as to the character of the original mineral, the altered mineral was included in a separate category but not included in the conversion to oxides, as the original composition was the primary interest. In most instances the degree of alteration was minor, thereby minimizing the danger of selective alteration changing the percentages of any particular mineral.

The fresh reversely polarized dikes (Sample Locations Figure #2) have a megascopic texture varying from near glass at the contact edges to a courseness of grain size in the center that is dependent upon the width of the dike. This clearly indicated that cooling proceeded from the contact edge. The major mineral constituents in these dikes are plagoclase, pyroxene, olivine and magnetite. A light rusty brown color is characteristic of the weathered surface. On fresh unweathered surfaces the rock is a grey-green to black.

Microscopically, the fresh holocrystalline diabase dike (Figure #3) consists of 50 to 60% idiomorphic, carlsbad and albite twinned, labradorite laths (Ab 44-46), 30 to 35% hypidiomorphic clinopyroxene (species pigeonite), 0 to 5% olivine (Fa 10-30), and 5 to 10% titaniferous magnetite. The latter three minerals are interstitually deposited. The minerals are generally fresh and unaltered; only the olivine suffers minor alterations on its periphery and in irregular cracks throughout the crystals. The average grain size of the samples taken is 0.4mm, if the long dimension (0.5mm-2.5mm) of the labradorite can be neglected.

FIGURE 2

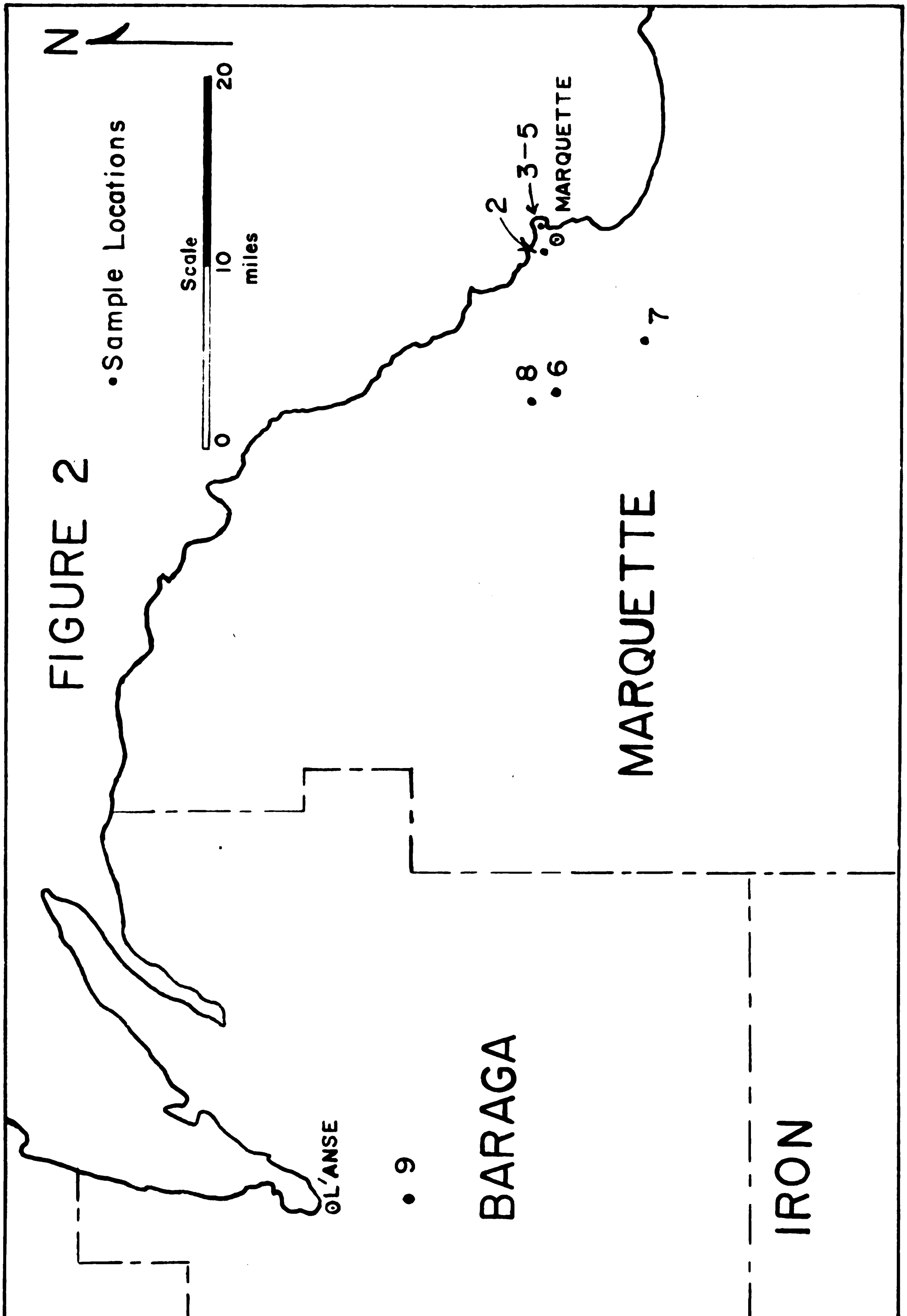


FIGURE 2
N
•Sample Locations
Scale
0
10
20
miles
2
3-5
MARQUETTE
6
7
8
MARQUETTE
L'ANSE
9
BARAGA
IRON

Location and Field Relationship

Sample 1

Location: Lot 6, Con. 5, Township of Mckim, District of Sudbury, Ontario, Canada. The dikes of this type are vertical and trend NW in the Sudbury Basin. They are the last intrusives in the area and only rarely are they cut by faults. They are observed intersecting the Murrey Granite (Thomson 1956) and the Killarny Granite (Cooke 1946). The sample was taken from a dike that was exposed intermittently over ½ mile. The width, about 75 feet, did not vary much in that distance. These dikes in the Sudbury Basin have a positive magnetic inclination and only when they pass through a magnetic formation are they reversed (Zurbrigg 1961). This sample was collected for the comparison of late intrusives in other Precambrian areas.

Volume Percentage of Mineral Species

Pigeonite-------	15.75	Olivine-------	3.91
Magnetite-------	6.70	Labradorite---	73.63

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O
50.14	20.21	4.89	6.45	4.23	8.44	4.12

Sample 2

Location: NE¼, NW¼ of sec. 24, T. 48 N., R. 25 W, Corner of Pine St. and East Michigan St., Marquette, Michigan. This outcrop is a western extension of Sample 5 as traced

Figure 3

Sample 5, X-Nicols 20 power. Typical fresh diabase as exhibited by most examined dikes. Lath shaped Carlsbad and Albite twinned feldspar, hypidiomorphic clinopyroxene (pigeonite), olivine (minor in this photomicrograph) and magnetite.

Figure 4

Sample 4, 50 power plane light. Fine grained border of Sample 5. This illustrates border chilling and feldspar development.

Figure 3

Figure 4

by dip needle. The 25 foot wide outcrop, dipping 60° north, was sampled in the center. No contact edge was visible to ascertain the metamorphic effects upon the surrounding Mona schist.

Volume Percentage of Mineral Species

Pigeonite	34.89	Olivine (Fa 20)	1.17
Magnetite	4.19	Labradorite (Ab 45)	59.74

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O
50.42	17.62	3.49	11.48	3.78	7.93	3.25

Sample 3 and 4

Location: NE¼, NW¼, of sec. 24, T. 48 N., R. 25 W, at Lighthouse Point in the city of Marquette, Michigan.

These samples were originally collected to determine if there is a change in composition with respect to the contact edge. The samples were collected 1 and 8 inches respectively from the contact edge. The crystals, upon examination, were too fine grained for consistent optical identification (Figure #4). The plagoclase however, had albite extinction angles comparable to the sample obtained in the middle of the dike (Sample #5).

Lane (1911) describes chemical analyses made from samples at Lighthouse Point. The contact, .616mm, 4.115mm and 7.6mm are reproduced in Table #1. A comparison of chemical versus thin section analysis is included. The

Table 1

	(1)	(2)	(3)	(4)	(5)
SiO_2	46.98	47.67	47.25	47.10	49.09
Al_2O_3	17.85	17.55	18.00	17.47	17.40
Fe_2O_3	3.13	2.51	2.21	2.66	5.08
FeO	10.36	12.69	12.42	12.93	10.86
MgO	7.16	5.65	6.35	6.88	5.69
CaO	8.47	10.75	11.45	10.27	7.71
Na_2O	2.04	2.21	1.96	1.91	3.21
K_2O	.60	.65	.66	.59	
H_2O	4.47	2.07	----	----	
TiO_2	----	----	----	----	
P_2O_5	.14	.17	.16	.16	
CO_2	----	----	-----	----	
S	.09	.18	.08	.11	
SO_3	----	-----	-----	-----	
MnO	.26	.19	.18	.15	
Cl	.07	.05	.02	.09	

Dike at Lighthouse Point (Lane 1911)

(1) Contact

(2) 0.616 mm from margin

(3) 4.115 mm " "

(4) 7.6 mm " "

(5) Thin Section Analysis 4 meters from margin (Sample#5)

results are so nearly the same that the use of thin section analysis for comparative purposes is justified. Lack of mineralogical variation along strike is afforded by comparing Sample #2 and #5.

Sample 5

Location: NE¼, NW¼ of sec. 24, T. 48 N., R. 25 W, at Lighthouse Point in the city of Marquette, Michigan.

The 25 foot wide outcrop is well exposed at this location where it intersects the Mona schist and other dikes cutting this schist. This is the only observed dike that deviates from vertical by dipping 72° north.

Volume Percentage of Mineral Species

Pigeonite -------	30.87	Olivine (Fa 10) -----	3.43
Magnetite -------	6.59	Labradorite (Ab 45) -	59.12

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O_3
49.09	17.40	5.08	10.86	5.69	7.71	3.21

Sample 6

Location: SW¼, sec. 21, T. 48 N., R. 27 W, 1.1 miles north of Deer Lake in Marquette county.

The vertical east west dike intersects the Kitchi schist at this location. Slight baking of contact was observed. The high percentage of alteration in this sample is probably due to surface weathering. The hand specimen shows a definite increase in weathering toward the surface.

The high percentage of magnetite may be due to alteration of iron rich olivine but most of the magnetite is primary.

Volume Pèrcentage of Mineral Species

Pigeonite -------	29.96	Olivine (Fa ?) -------	.44
Magnetite -------	9.84	Labradorite (Ab 45) --	52.37

Alteration ---- 7.39

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O_3
47.45	15.68	7.82	12.51	4.29	7.49	3.07

Sample 7

Location: SE¼, SW¼ of sec. 29, T. 47 N., R. 26 W, at the abandoned Isabella Iron Mine.

A vertical dike, striking north of east, intersects the Negaunee Iron formation at this location. The sample appeared to have slickensides on it but no microscopic evidence of brecciation was found.

Volume Percentage of Mineral Species

Pigeonite -------	34.29	Olivine (Fa 25) ------	6.73
Magnetite -------	7.54	Labradorite (Ab 45) --	51.41

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O_3
47.81	15.11	5.78	13.76	6.65	6.88	2.87

Sample 7 (a)

This sample was obtained from the Isabella mine dump and thought to be the altered equivalent of Sample 7. The rock is completely altered with only relic fabric and some plagoclase remaining (Figure #5).

Sample 8

Location: SE¼, NE¼, NE¼ of sec. 7, T. 48 N., R. 27 W, north of Ishpeming, Michigan.

The steeply dipping (by dip needle) east-west striking dike probably intersects the Michigamme slates, although the surrounding rocks were not exposed for identification.

Volume Percentage of Mineral Species

Pigeonite -------	30.14	Olivine (Fa 30) -------	5.10
Magnetite -------	6.97	Labradorite (Ab 43) ---	57.67

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O_3
47.93	17.19	5.43	13.77	4.11	7.77	3.00

Sample 9

Location: NE¼, NW¼, NW¼ of sec. 18, T. 49 N., R. 33 W, near the town of Alberta, Michigan.

The vertical, south of east trending dike, 25 meters wide, intersects the Michigamme formation at this location. The sample was taken 4 meters from a contact edge. The development of large plagoclase crystals gave the dike an

Figure 5

Sample 7a, 40 power plane light. An example of a dike altered by iron ore concentrating fluids. Only relic fabric and some magnetite is visible.

Figure 6

Sample 10, 40 power X-Nicols. Typical ophitic texture displayed by the more basic Keweenawan lava flows.

Figure 5

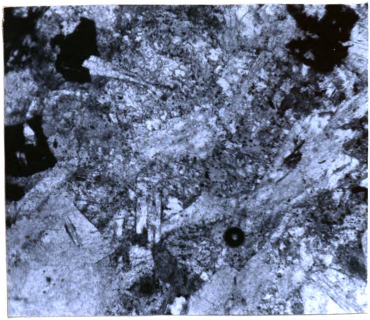
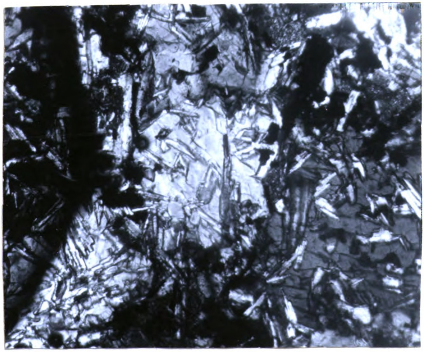


Figure 6



"Oatmeal" look, however, the dike was not porphyritic.

Volume Percentage of Mineral Species

Pigeonite -------	19.60	Olivine (Fa 25) -------	2.36
Magnetite -------	5.38	Labradorite (Ab 46) ---	72.65

Mineral Species Converted to Oxides

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O
50.22	21.20	4.05	7.99	3.02	6.78	4.15

The variation of mineral percentage, compared to that of other dikes examined, can be explained without postulating a change in the composition of the dike. The statistical validity of this thin section was invalidated by the development of large feldspar crystals. Consequently, this dike is not included in the average.

Sample 10

Location: SE¼, SW¼, NE¼ of sec. 1, T. 54 N., R. 34 W, a Keweenawan lava flow near the geology building at the Michigan School of Mines at Houghton, Michigan.

This section exhibits the ophitic texture which is typical of the less feldspathic Isle Royal flows (Figure #6). No species percentage was taken on this sample, as the statistical condition of granular equality was not kept. The minerals are augite, labradorite, olivine and magnetite. This section has not suffered from the mineralization as have other flows.

Sample 11

This sample was taken from an unknown flow in a quary outside Houghton, Michigan. The sample is completely altered; not even the texture is discernible.

Possible Sources of Error in Modal Conversion

There are several possible sources of error in converting the modal analysis to oxides, even when the optical properties are known. The optical data of olivine was derived from the center of the crystal which is probablt richer in magnesium than the periphery of the crystals due to the sequence of crystallization. The data derived from examination of the feldspars may not represent the true composition due to some zoning on large crystals. This would tend to increase the total SiO_2 and Na_2O and decrease CaO and Al_2O_3 from the true composition. Thirdly, the ilmenite included in the magnetite was computed as FeO and Fe_2O_3 in conversion to oxides. The extent of ilmenite can be seen in Figures #7 and 8 which show the skeletal magnetite crystals after removal of the less resistant ilmenite. The excess of computed iron in the magnetite overcompensates for the lack of computed iron in olivine, probably giving a higher total iron than actually exists, and the titanium content is not computed.

Figure 7

Sample 6, 40 power plane light. Magnetite with ilmenite weathered out, leaving skeletal structure.

Figure 8

Sample 6, 40 power plane light. Same as photomicrograph 5.

Figure 7

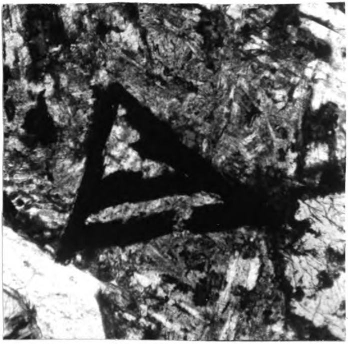


Figure 8

COMPOSITIONAL SIMILARITY OF KEWEENAWAN FLOWS AND THE LATE DIKES

Several late normally polarized dikes have been observed intersecting the post-Animikie - pre-Keweenawan granite in northern Michigan. There is no known instance of reversely polarized dikes intersecting this granite, however, one such dike was observed (sec. 29, T.42N., R.28W.) a few hundred yards from the late granite, and had suffered no thermal metamorphism. None of the examined dikes indicated thermal metamorphism that James (1955) has shown to be associated with the late granite. All of the late dikes in northern Michigan are therefore inferred to be younger than the post-Animikie - pre-Keweenawan granite.

As to stratigraphic position, these dikes could be either (1) a post granite-pre-Keweenawan age (2) genetically related to the Keweenawan volcanic series, and therefore of Keweenawan age, or (3) post-Keweenawan - pre-Jacobsville in age. A chemical comparison is included to help resolve this situation.

Clements et al., (1899) mention the similarity of the fresh diabase dikes in different sections of northern Michigan with one another. By observing these dikes in the field it is easy to see how this conclusion was reached. The dikes weather to a distinctive rusty brown that appears to be diagnostic of these dikes. They occupy the same stratigraphic position in all the areas and their strike is generally constant for a given area. These and other characteristics give the impression of similarity of intrusion among the areas.

Table #2 compares the composition of the samples collected, all of which are extremely similar. Analysis X and Y are taken respectively from a normal and a reversely polarized dike located in central Dickinson county (James et al., 1961). They are left in the volume percentage figures due to a lack of optical information on the minerals. However, if the augite is pigeonite, as it is in the examined dikes, the composition would be similar. Sample #9, from Alberta, Michigan, is statistically unacceptable due to the development of large feldspar crystals and is not included in the dike average composition, as it was included in the study for comparison of late Precambrian dikes in other areas.

Table #3 gives a chemical analysis from a dike in the Gogebic district (Irving and Van Hise 1892) and is compared with an average of the analyses of the Lighthouse Point dike given previously in Table #1. The Gogebic dike is apparently more basic, however, the similarity between the two dikes is striking. The similarity of composition of the dikes of the Gogebic district with those of the Marquette and Iron River districts is important. If a similar magma source can be postulated for both of these locations, thereby inferring a similar time of intrusion, the dikes can be restricted to a limited time interval.

In the Gogebic district the olivine diabase dikes intersect the Lower Keweenawan sequence (Irving and Van Hise 1892) and are therefore younger than Lower Keweenawan in age.

Clements et al., (1899), while acknowledging the similarity of these dikes, warned of correlation by chemical composition over extended distances. Comparison of the analyses (Table #3) may not establish a true correlation; they are intended only to show the possibility of the same or a similar magma source.

Similarity of composition between the fresh dikes and the Keweenawan lava flows first led Rominger (1881) to the conclusion of equivilance of the two. This similarity is illustrated in Table #3 which compares several flows with the analyses from the Gogebic dikes; the average of analyses from the Lighthouse Point dike and the dike averages as determined by thin section analysis. This comparison, allowing for small variations caused by different analyzing techniques, illustrates similarity of percentages of all important oxides. The difference between the individual flows is greater than the difference between the dikes and the flows.

These dikes, if they are Keweenawan in age, may not have intruded at the same time in all areas. If the Lake Superior Basin was sinking throughout the deposition of the Keweenawan sequence (Hotchkiss 1923) fractures would form progressively away from the basin axis as it subsided, consequently, dikes further away would be younger. A dike system which represents a certain arbitrary unit of time, may actually have been intruded throughout a period of many thousands of years.

If Butler and Burbank's (1929) conclusions, that the flows become more feldspathic higher in the series, is correct, then, additional evidence of a Keweenawan age of the dikes might be obtained if the dikes were more feldspathic progressively away from the basin axis. Evidence for this change is at the present time inconclusive.

As these dikes intersect the younger granite they are obviously younger than this intrusive. If the dikes are considered to be genetically connected to the late granite, it is difficult to account for their distribution, which is unrelated to the outcrop area or zones of metamorphism caused by the granite. Additionally, it is not probable that this acidic magma (Table #3) of limited extent, would have associated with it the large quantities of basic magma now incorporated in the dikes. The comparison between the Keweenawan lava flows and the late dikes offers nothing which would prevent the conclusion that the flows and the dikes could be from the same magma source. It, however, does not prove their equivalence. In addition, the intrusion pattern of the dikes, covered in detail in the section on structure, indicates a Keweenawan stress pattern and therefore presumably a Keweenawan age.

TABLE 2

	1	2	5	6	7	8	9	Average 2 -8
SiO_2	50.14	50.42	49.09	47.45	47.81	47.93	50.22	48.54
Al_2O_3	20.21	17.62	17.40	15.68	15.11	17.19	21.20	16.60
Fe_2O_3	4.89	3.49	5.08	7.82	5.78	5.43	4.05	5.52
FeO	6.45	11.48	10.86	12.51	13.76	13.77	7.99	12.47
MgO	4.23	3.87	5.69	4.29	6.65	4.11	3.02	4.90
CaO	8.44	7.93	7.71	7.49	6.88	7.77	6.78	7.55
Na_2O	4.12	3.25	3.21	3.07	2.87	3.00	4.15	3.08

Analysis X

Plagoclase	53.7	(an 54)
Augite	41.0	
Magnetite	5.3	

Analysis Y

Plagoclase	52.8	(an 54)
Augite	41.8	
Magnetite	3.1	

(1) Sudbury Ontario, Canada. Thin section analysis

(2) Pine St. Marquette Michigan. Thin section analysis

(5) Lighthouse point. Thin section analysis

(6) Deer Lake Marquette County. Thin section analysis

(7) Isabella mine. Thin section analysis

(8) North of Ishpeming. Thin section analysis

(9) Alberta dike. Thin section analysis.

Analysis X Normally polarized dike north of Felch Mich.

Analysis Y Reversely polarized dike north of Felch Mich.

TABLE 3

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO_2	47.90	47.25	48.54	48.57	47.39	50.07	48.80	70.09
Al_2O_3	15.60	17.71	16.60	16.34	16.82	12.63	13.98	15.46
Fe_2O_3	3.69	2.63	5.52	4.73	3.09	3.84	3.59	1.92
FeO	8.41	12.10	12.47	6.13	7.91	10.30	9.87	2.46
MgO	8.11	6.51	4.90	6.43	6.65	5.23	6.70	.31
CaO	9.99	10.24	7.55	9.68	9.87	6.55	9.38	2.26
Na_2O	2.05	2.03	3.08	2.68	2.63	3.53	2.59	4.10
K_2O	.23	.62		.55	.48	1.90	.69	2.20
$H_2O\pm$	2.49			2.98	1.48	2.82	1.80	.42
CO_2	.38			.19	.08			.26
TiO_2	.82			1.47	1.53	2.50	2.19	.28
P_2O_5	.13	.16		.18	.18	.22	.32	.13
S		.12		.01	.02			
Cu				.009	.01			
MnO	.17	.20		.16	.16			

(1) Gogebic diabase dikes (Lane 1911)

(2) Average of analyses of Lighthouse Point dike (Lane 1911)

(3) Average composition of late dikes (thin section analyses)

(4) Kearsarge flow group (average of 7 analyses) (Broderick 1935)

(5) Greenstone flow group (average of 12 analyses) (Broderick 1935)

(6) Bed #65 Eagle River, Keweenaw Point, Mich. (Lane 1911)

(7) Daly's average for plateau basalt

(8) Post-Animikie, pre-Keweenawan granite (James et al., 1961)

STRUCTURAL ANALYSIS

In attempting to date the fresh diabase dikes of the western part of the Northern Peninsula of Michigan, these facts have been noted: these dikes are truncated by the Jacobsville sandstone of probable Cambrian age; they intersect the folded Michigamme slate and probably the post-Animikie granite. A structural analysis, to further define their age will be attempted. Such an analysis will present several hypotheses since it involves comparing the probable stress patterns of the Animikie and Keweenawan and seeing which fits the dike intrusion pattern more accurately.

The intrusion pattern should be explained in terms of stress and forces responsible for the observed relationships. Fractures bear a definite geometric relation to the state of stress at failure. If the relation between stress and fracture is known, then the probable fracture system resulting from a given stress distribution can be predicted (Hafner 1951, Sanford 1959). Conversely, given a systematic fracture system it may be possible to determine the distribution of stress that produced it. The dikes may not occupy fracture positions but it is assumed that zones of weakness would occupy the same geometric relationship with the stress axes.

The dikes in eastern Marquette county strike east-west with a variance of 5°- 10° north or south. In western Marquette county and eastern Baraga county the dikes are consistently a few degrees north of east as are the reversely polarized dikes in Iron county. A geologic map interpreted from aeromagnetic data (Balsley, James and Wier 1949) indicates that this change continues through western Baraga county where the strike approximates 10^{o}- 15^{o} north of east. In the Gogebic district, dikes thought to be of the same group, when rotated to the vertical, strike northeast.

The dips of the observed dikes are approximately vertical with the exception of Lighthouse Point, Pine St. dike which dips 62^{o}- 72^{o} north. Aeromagnetic data from parts of Houghton, Baraga and Iron counties (Balsley, James and Wier 1949) indicates that the reversely polarized dikes are nearly vertical in these areas. In parts of Marquette county, magnetic interpretation by Buzas (1960) indicates that the reversely polarized dikes were vertical. In the Kiernan Quadrangle, Gier and Wier (1956) indicate that a reversely polarized dike was steeply dipping. In the northern part of the Iron River district, James and Dutton (1951) found a fresh unaltered late Precambrian reversely polarized dike that dipped 60^{o}- 80^{o} south, over a distance of a mile and a half.

In the examined samples, the olivine diabase dikes are vertical or nearly so, and the country rock shows no apparent strike-slip or vertical displacement. There is only one observed instant of shattering which might be interpreted as the result of shearing. From this evidence it is inferred that the intrusion pattern of the olivine diabase dikes was apparently controlled by horizontal tension. It would appear that the dikes intruded in a wedging manner such as described by Anderson (1942): the magma actually propagating the displacement into which it flowed. The Isabella dike with its N. 70° E. strike is probably fault controlled (Royce in Newhouse 1942) as is the reversely polarized dike in the Mineral Hills area (Balsley, James and Wier 1949). The strike of the dikes located by Buzas (1960) indicates that they probably follow a fault pattern (Plate #1).

A case could be made for the proposition that the strike of the olivine diabase dikes in the Marquette district resulted from release of the thrusts from the north or northeast that are believed to have folded the Marquette Synclinorium at the end of Animikie time. Such thrusts would give the synclinorium the observed, nearly east-west strike. Release zones of weakness could then form parallel to the axis of the Marquette structure in an east-west direction. This hypothesis however, would not explain the trend in areas other than the Marquette district.

A brief review of the major Keweenawan structural features is given here so as to facilitate and understanding of the relationship the intrusion pattern of the olivine diabase dikes may have with the stress patterns of the Keweenawan epoch. The most conspicuous structural feature of the Keweenawan epoch is the Lake Superior Basin. This

linear, asymmetrical structure has a strike of N. 60° E. west of Keweenaw Point, extending in this direction into southern Minnesota. East of Keweenaw Point the basin probably strikes close to SE, extending to the east end of Lake Superior (Butler and Burbank 1929) (Figure #10). The Keweenawan succession may extend as far southwest as Kansas (Thiel 1956).

The Keweenaw fault parallels the main axis of the Lake Superior Basin. The fault is of a reverse nature, with the north block overthrusting to the south with varying dips (17°- 60°). The length of the fault is in excess of 110 miles (Butler and Burbank 1929). This fault (which may have formed during the intrusion of the Duluth Gabbro (Hotchkiss 1923), at which time basin was uplifted and subsequently collapsed) may have a throw of more than 3 miles.

The Lake Superior Basin was probably subsiding during the deposition of the Keweenawan sequence. This is inferred from the observed progressive flattening of the dip in a stratigraphically up direction, and from the direction of the flow of the lavas (Hotchkiss 1923). This subsiding linear basin, which was probably formed as the result of magmatic extrusion and subsequent subsidence (Hotchkiss 1923), would have certain stress patterns associated with it, and these patterns would control intrusion during this subsiding period.

Experimental data indicate that in macroscopically homogeneous and isotropic rocks, tension fractures develop parallel to the intermediate principal stress axis and are perpendicular to the direction of the greatest stress axis. Using an idealized concept of a subsiding linear basin as a model, it is possible to predict with some reservations, the strike of the fracture pattern likely to have been formed in the Lake Superior region during Keweenawan time. The least stress axis would everywhere be perpendicular to the axis of the basin. The angle of dip of the fracture formed under these conditions would be controlled by the dip of the plane of the intermediate and least stress axes. Linear zones of weakness, if not failure, resulting from tension would be expected to form parallel to the axis of the linear element. Extension fractures or zones of weakness, perpendicular to the basin axis, would also be expected. The system of dikes exhibited in northern Michigan is probably subject to conditions which would cause deviation from the ideal. However, the system is fairly consistent over a large area.

The olivine diabase dikes in Marquette county exhibit the same strike as the theoretical tensional fractures proposed for the area. This is also true in western Baraga county where the change in strike, north of east, of the dikes corresponds to the probable change in strike of the basin axis at that point. The strike of the reversely polarized dikes in Iron county corresponds to that in Baraga county. In the Goulas River area of Ontario, Canada, a pair of olivine diabase dikes, intersecting all other

Precambrian formations, strike N. 45° W. and N. 45° E. (Moore 1946), corresponding to the theoretical fracture pattern of the Lake Superior Basin. They are parallel and perpendicular, respectively, to the probable basin axis. In the Michipicoten area of Ontario, a late Precambrian olivine diabase dike strikes N. 35° W. (Moore 1946). This strike would approximate the probable strike of the basin axis in this area. However, it is not known whether the Goulas River or the Michipicoten dikes are of the same chemical composition or if they exhibit the reversed polarization of the dikes in northern Michigan. They are described petrographically only, as olivine diabase. Van Hise and Leith (1911) state that fresh diabase dikes are parallel and perpendicular to the shore line of Minnesota.

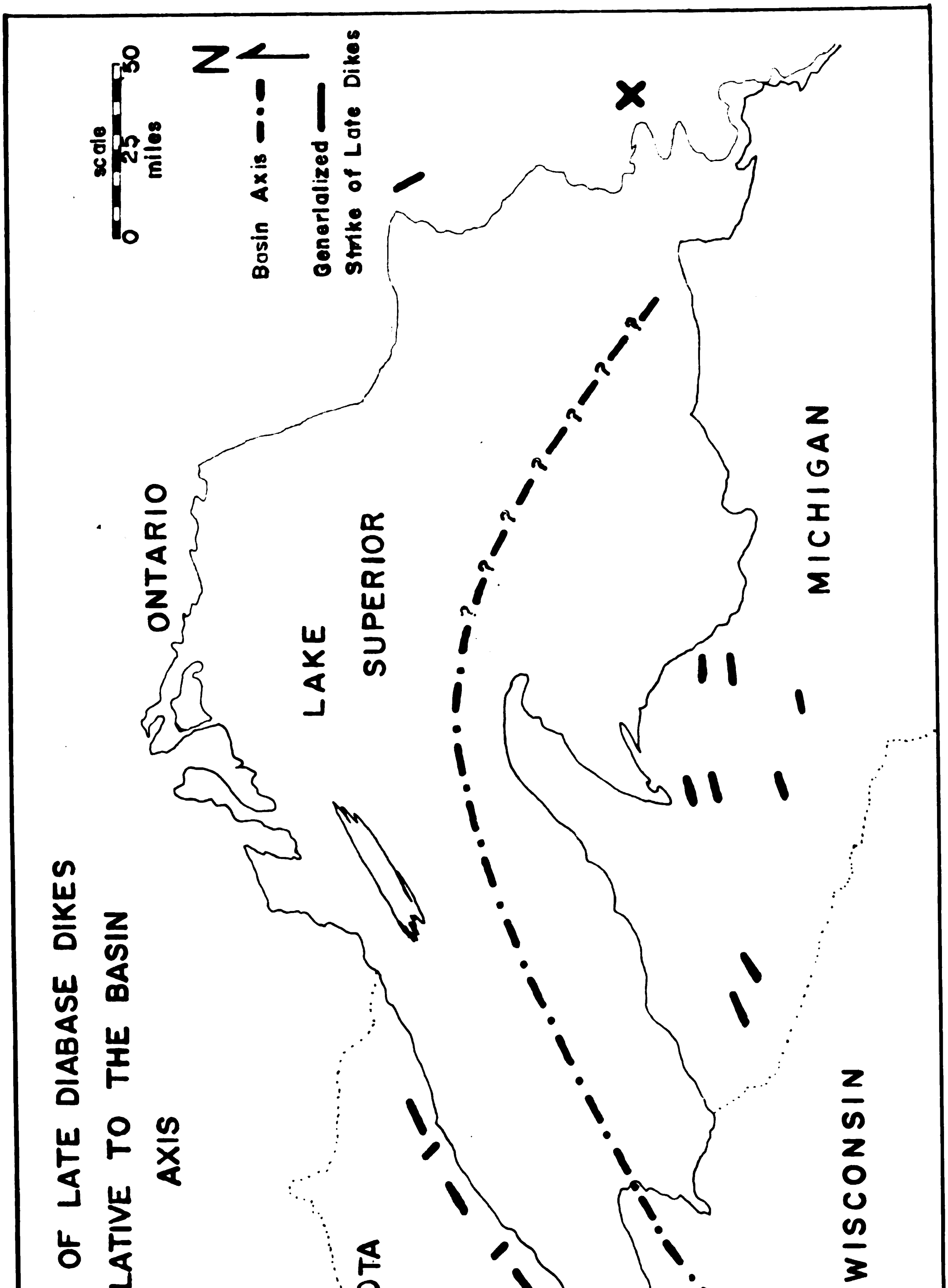
Late Precambrian olivine diabase dikes are mentioned in the literature of the Gogebic Iron district of Michigan. The Gogebic range has been tilted so that the Huronian sediments are dipping 60° to 70° north. The dikes which intersect the Huronian and some of the lower Keweenawan flows dip south at angles of 20° to 30°. If the Huronian sediments were rotated back to a horizontal position, the dikes would be vertical. The corresponding strike upon rotation would be northeast - southwest (Irving and Van Hise 1892); this dip and strike would fit into the proposed fracture pattern of a subsiding linear basin by paralleling the basin axis (Figure #10).

Hotchkiss (1923) believes that the Gogebic area was tilted southward 20° to 30° when the first Keweenawan sediments and flows were deposited. This area then gradually tipped back toward the north as more sediments and flows were deposited; about Middle Keweenawan, the area was horizontal again. It may have been at this point that the Gogebic dikes were intruded. That Middle Keweenawan was a time of great outflow of lava supports a Middle Keweenawan age for these dikes. Dikes which may have fed some of these flows intersect the Lower Keweenawan sequence in the Gogebic area (Irving and Van Hise 1892). Comparison of the Central Mine group flows with the Gogebic dikes (Table #3) confirms their close chemical relationship with one another. The dikes could have intruded at any dip. If they did intrude at the present dip they were probably emplaced at the end of Keweenawan time. However, late Keweenawan intrusives in Michigan were more feldspathic than the olivine diabase dikes of the Gogebic range.

The olivine diabase dikes of northern Michigan appear to fit the hypothetical stress pattern of a subsiding linear basin rather than the hypothesis of compressional release and intrusion. The hypothesis of a subsiding linear basin accounts for all of the known facts without having to call upon special conditions. This conclusion would place the olivine diabse dikes in the Keweenawan series, thus eliminating a post-Animikie - pre-Keweenawan age. An upper limit in time would be placed at pre-Jacobsville. If correlation of the dikes of the Gogebic area with those in the

Marquette district is accepted, a lower time limit of Middle Keweenawan is placed on them, but as was mentioned in the section on petrography, these dikes may not have been intruded at the same absolute time.

FIGURE 10


STRIKE OF LATE DIABASE DIKES
RELATIVE TO THE BASIN
AXIS
scale
0
25
50
miles
N
Basin Axis
Generalized
Strike of Late Dikes
ONTARIO
LAKE
SUPERIOR
MICHIGAN
WISCONSIN
MINNESOTA
X

REVERSED POLARITY

In the northern hemisphere, magnetic formations generally attract the north seeking pole of the dip needle. However, most of the late Precambrian diabase dikes of northern Michigan exhibit a reverse polarization which attracts the south seeking pole. This polarization is inclined approximately -85° to the present geomagnetic field, and may have significance as a correlative tool.

Igneous rocks acquire most of their magnetism as they cool through, and slightly below the Curie point of their ferromagnetic minerals. Magnetic intensities for fields as small as that of the earth (approximately 0.5 oersteds) are normally proportional to the field (Nagata 1953). Thermo-remnent magnetism acquired in this manner is generally assumed to lie accurately in the direction of the ambient field. However, recent work by Strangway (1960) has indicated that there is a tendency for some stable magnetism to align parallel to the strike of the dike. This preferential alignment is apparently due to internal demagnetization that is dependent upon the geometric shape of the body and its relationship to the geomagnetic field. The quantity of magnetism so aligned is small but not negligible. This may necessitate the reevaluation of paleomagnetic data previously obtained from dikes.

Isothermal magnetization can generally be neglected in paleomagnetic studies, as the earth's magnetic field is small compared to the coercive forces of rock minerals (more than 100 oersteds, Nagata 1953). However, lightning with large magnetic fields may affect limited areas of the rock. Magneto-crystalline anisotropy is generally neglected in paleomagnetic study of undeformed hypabyssal igneous rocks because of random orientation of the crystals prior to the Curie temperature. Magnetostriction may be important in its ability to alter the magnetic components of minerals (Graham et al., 1957) but as yet, insufficient data is available to evaluate it effectively. This property may also be time dependent (Graham 1959) which would further complicate its evaluation.

From the preceding it follows that igneous rocks generally portray the ambient magnetic field at the time of solidification, providing no physical (rotation, inversion, folding), chemical (alteration, replacement) or a combination of these processes has taken place. The reverse polarization observed in the olivine diabase dikes in northern Michigan can then be stated to probably be due to one of two causes: either the rock cooled in a geomagnetic field similar to the present magnetic field and was reversed due to subtle physical-chemical changes as discussed by Neel (1951, in Blackett 1956), Neel (1955), Graham (1953), Nagata (1953) and others, or the rock cooled in the direction of the geomagnetic field which at that time was essentially the reverse of the present sense (Runcorn 1954, 1955, and others).

Graham (1953) studied several reversely polarized late

Precambrian olivine diabase dikes in Baraga county, Michigan. To account for the reversal, he revised a hypothesis of Neel (1951, in Blackett 1956). Neel called for two components of different Curie points: component A with a higher Curie point imposing a field, which would be opposite on component B with the lower Curie point during the cooling process. Selective chemical action then removes component A and leaves component B with the reversed magnetic moment. Graham hypothesises that similar results could be obtained if only one component was present. His proposal was that one constituent A (magnetite), dispersed by essentially non-magnetic ilmenite lamellae, could be oxidized to a second constituent B (maghemite) at the expense of smaller particles of A. These small particles of constituent B would be magnetized in the inverse sense by the external field of the first magnetized constituent A in the manner suggested by Neel. The external moment of the sample then would later become reversed as a result of demagnetization in time of the larger particles of constituent A (magnetite) which would be too large to remain as domains for long periods of time and could be expected to be demagnetized by forming domain field closure loops with themselves. The smaller size volume of constituent B (maghemite) with the inverse moment, will remain as stable domains with a high coercive force. The chief function of the ilmenite is to break up the large magnetic grains so they can behave like an aggregate of small particles whose fields interact

(Graham 1953). Graham also found that a significant portion of the ferromagnetic material present in the dikes was not contributing to the external natural remanent moment.

A polished section and a qualitative chemical analysis by the writer confirmed the presence of ilmenite lamellae in the magnetic fraction of the rock. This tends to support Graham's hypothesis, however, the hypothesis should be dependent upon the identification of the maghemite in the rock.

A modification of Graham's (1953) hypothesis, which does not require the formation of maghemite, is suggested in the light of work by Strangway (1960). Strangway believes that some of the magnetic moment of the dikes is the result of magnetite located in slightly altered olivine and pyroxene crystals(Figure #11). This powder magnetite is presumed to have been formed by deuteric alteration. Powder magnetite might be affected in a manner suggested by Neel (1951, in Blackett 1956) by assuming a polarization opposite the field of the previously formed magnetite. The first formed, larger magnetite, would demagnetize in time as suggested by Graham, thus giving a residual magnetic inversion. Strangway found the stable magnetism, which he attributed to the powder magnetite, to lie generally in the plane of the dike. However, this is dependent upon the geometric shape of the body and its orientation in the magnetic field.

The minute size of this later formed powder magnetite suggests great stability, and because of its size the Curie point would be lowered (Neel 1955). Lowering of the Curie point would remove a strong objection to Graham's and similar hypotheses, put forth by Nichols (1955) in which he felt that because maghemite must form from magnetite at temperatures below 600° C and consequently, below its Curie point (675° C) it would be magnetically unstable, whereas Graham and others have found the magnetism of the dikes to be quite stable.

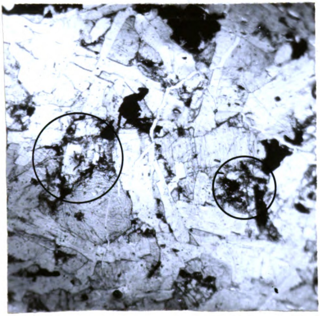
In addition to the above methods of reversal, several other chemical models have been suggested (Neel 1951, in Blackett 1956) some of which have been confirmed as contributing to reversal of polarization. There is however, no singularly clear method which explains all of the reversals. Additionally, an observation which would question chemical reversal might be the chemical similarity between the Keweenawan flows and the fresh dikes, since there are no known reversals of polarization in the Keweenawan lavas.

The alternative hypothesis of dipole reversal explains quite simply all reversed polarizations without calling upon special physical-chemical conditions. However, several observations suggest that the dikes were reversed by some method other than dipole reversal. The varied directions of magnetic orientation found by Graham (1953), the finding of a dike that was normally polarized on one side and reversely polarized on the other by Strangway (1960), Spiroff's (1962, personal communication) finding of dikes that change in direction of polarity along strike, suggest chemical-physical changes rather than geomagnetic inversion.

Figure 11

Sample #5, 40 power plane light. Olivine - Pyroxene altering to magnetite. Possible source of powder magnetite?

Figure 11



ECONOMIC IMPORTANCE OF THE DIKES

There have been many questions raised as to the age and methods of enrichment of the soft ores of northern Michigan. Royce (in Newhouse 1942) believes that the dike in the Isabella mine, in conjunction with ground water, was instrumental in concentrating the soft ore at this location.

> "This ore body is formed by three horizons in the iron formation, which are bent in a fold trough pitching flatly to the northwest and cut across by the Isabella dike. The combined trough influence of the fold and of the dike has resulted in the concentration of ore in three favorable horizons." "The concentration of this ore body was by water circulation down the trough and along the dike."

If Royce is correct, then enrichment of the ore was post dike intrusion. If the dikes of this study, of which the Isabella is one, are Keweenawan in age, a lower time limit can be placed on the enrichment, at least in the Gogebic district and in the Isabella mine.

If most of the enrichment took place in post-Keweenawan time, a rapid economical method of locating soft ore bodies that are controlled by the late dikes could be envisioned. As these dikes are reversely polarized they are readily observed on both ground and aeromagnetic surveys. Inspection of dike locations for trough influence that could concentrate the ore would deliniate areas for further exploration work. This method assumes that enrichment was by ground water, which seems likely when the position of the ore bodies relative to the dikes is considered.

CONCLUSION

The fresh dikes of northern Michigan outcrop in at least a 50 mile wide belt, which apparently extends from the Gogebic district through Marquette into Lake Superior. They are all similar to one another microscopically and in field characteristics, and are believed to be of the same system. These dikes intersect the folded Animikie sediments in Marquette, Baraga, Gogebic and Iron counties; and they probably intersect the post-Animikie - pre-Keweenawan granite in Dickinson county. The late dikes in the Gogebic district, thought to be equivalent of late dikes in the other areas, intersect some of the Lower Keweenawan lava flows. In Baraga county the dikes are overlain by the Jacobsville sandstone of probable Lower Cambrian age. The intrusion pattern indicates that the fresh dikes were controlled mainly by Keweenawan stresses. The chemical similarity between the fresh dikes and the Keweenawan lava flows suggests a similar magma source. The writer therefore concludes that the late fresh dikes of northern Michigan are Keweenawan in age.

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