

PROVENANCE AND TECTONIC
INFERENCES CONCERNING THE
KEWEENAWAN INTERFLOW SEDIMENTS
OF THE LAKE SUPERIOR REGION

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
GEORGE P. MERK
1972



This is to certify that the

thesis entitled

PROVENANCE AND TECTONIC INFERENCES CONCERNING
THE KEWEENAWAN INTERFLOW SEDIMENTS OF
THE LAKE SUPERIOR REGION

presented by

George P. Merk

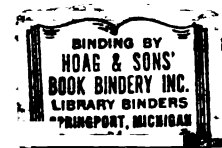
has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Geology

Major professor

Date Aug. 11, 1972

Q-7639



The K
 significant
 extent of
 ally immat
 overlie th
 of a major
 accumulati
 relationsh
 borderland

In o
 background
 and the r
 the surro
 study con
 flows as
 carrying

ABSTRACT

PROVENANCE AND TECTONIC INFERENCES CONCERNING THE KEWEENAWAN INTERFLOW SEDIMENTS OF THE LAKE SUPERIOR REGION

By

George P. Merk

The Keweenawan geology of the Lake Superior basin is significant because of the great thickness and lateral extent of the extrusive rocks it contains, the compositionally immature red beds which are intercalated with and overlie the flows, and the fact that this basin forms a part of a major tectonic feature of North America. The Keweenawan accumulation also invites speculation as to the structural relationship between the volcanic pile and the surrounding borderland.

In order to determine the structural and physiographic background of Keweenawan events in the Lake Superior basin and the relationship between the volcanic accumulation and the surrounding borderland during the Keweenawan time, this study concentrated upon the sediments intercalated with the flows as that portion of the sequence uniquely capable of carrying such information.

Representative
collected
Keweenawan
and the Midcontinent
of this period
indicates
from local
volcanics.
canics was
from present
Keweenawan
tectonic in
local areas
record.

Although
disproven,
region during
not support

Representative interflow sedimentary rock samples were collected from the Keweenawan sections exposed on the Keweenawan Peninsula, Michigan; Mamainse Point, Ontario; and the Minnesota shore region of Lake Superior. The results of this petrographic study coupled with the work of others indicates that much of the Keweenawan sediments were derived from local tectonic highs which were mantled by Keweenawan volcanics. Therefore, the area covered by Keweenawan volcanics was probably much more extensive than that indicated from present outcrops. The general tectonic pattern for the Keweenawan is then one of local positive and negative tectonic instability coupled with volcanism. At least three local areas of uplifts can be discerned from the sedimentary record.

Although a rift valley hypothesis cannot be totally disproven, inferred structural relationships in the outcrop region during at least lower and middle Keweenawan time do not support such a conclusion.

PRO

i-

PROVENANCE AND TECTONIC INFERENCES CONCERNING
THE KEWEENAWAN INTERFLOW SEDIMENTS OF
THE LAKE SUPERIOR REGION

By
George P. Merk

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Geology

1972

Foreword
are the main
of Keweenaw
been drawn
this study

The author
Thomas Vogel
critically
suggestions
siderations
Department
Emanuel Haddad

Support
National Science
Penrose Beck
of America,
The Calumet
Company grant
I thank the

ACKNOWLEDGMENTS

Foremost among those to whom the author is indebted are the many geologists who have preceded him in the study of Keweenawan geology. Their published works, which have been drawn upon freely, make up the references cited in this study.

The author is also indebted to Drs. Robert Ehrlich, Thomas Vogel, Bennett Sandefur and Harold Stonehouse for critically reading this manuscript and offering constructive suggestions. I am also glad to acknowledge the many considerations rendered by my colleagues in the Natural Science Department at Michigan State University, particularly Drs. Emanuel Hackel, Richard Seltin, and Raymond Hollensen.

Support for field and lab expenses was provided by a National Science Foundation Science Faculty Fellowship, a Penrose Bequest Research Grant from the Geological Society of America, and a Michigan State University Research Grant. The Calumet and Hecla Corporation and the White Pine Copper Company graciously made drill cores available for sampling. I thank these agencies for their support.

CHAPTER

LIST

LIST

I. INTER

C

M

II. GENE

L

L

M

U

K

III. THE

R

T

T

T

T

IV. THE

TABLE OF CONTENTS

CHAPTER	Page
LIST OF TABLES	v
LIST OF FIGURES.	vii
I. INTRODUCTION	1
Objectives of This Study.	2
Methods Used in This Study.	3
II. GENERAL GEOLOGY OF KEWEENAWAN SEQUENCE OF LAKE SUPERIOR REGION.	5
Lower Keweenawan Rocks.	5
Middle Keweenawan Rocks	9
Upper Keweenawan Rocks.	10
Keweenawan Intrusive Rocks.	10
III. THE KEWEENAWAN GEOLOGY OF THE EAST SHORE REGION OF LAKE SUPERIOR	12
The Alona Bay Sequence.	16
The Gargantua Cape Sequence	17
The Michipicoten Island Sequence.	18
The Mamainse Point Volcanic Series.	19
Interflow Sediments.	21
Conglomerates.	21
Sandstones and Sandy Phases.	25
Vertical Compositional Variation	29
Sedimentary Synopsis.	37
Provenance	37
Paleogeography and Sedimentation	39
IV. THE SOUTH SHORE REGION	41
The South Range Lava Series	43
The Portage Lake Lava Series.	44

TABLE OF CO

CHAPTER

V. THE

VI. SUMM
REFERENCES

TABLE OF CONTENTS--Continued

CHAPTER	Page
The Portage Lake Interflow Sediments. . .	45
Conglomerate.	47
Sandstone and Sandy Phases.	48
Vertical Compositional variation in the Calumet Area Section	52
Lateral variation in Composition.	54
The Copper Harbor Conglomerate	58
The Conglomerates	59
Sandstone	61
Vertical compositional variation.	63
Lateral compositional variation	66
Sedimentary Synopsis	77
Paleogeography and Sedimentation.	81
V. THE NORTHWEST SHORE REGION OF LAKE SUPERIOR . .	83
The Isle Royale Sequence	85
The Isle Royale Volcanic Series	86
The Isle Royale Conglomerate.	86
The North Shore Volcanic Series.	88
Interflow Sediments	90
Vertical Compositional Variation.	96
Lateral Variation in Composition.	104
Sedimentary Synopsis	106
Provenance.	106
Paleogeography and Sedimentation.	108
VI. SUMMARY AND CONCLUSIONS	111
REFERENCES CITED	119

TABLE

1. Corre
Super
2. Litho
gravel
3. Compar
mafic
measur
4. The co
stitu
sedime
analy
5. Verti
Mamai
6. Kewee
Penin
7. Mean
Porta
8. Verti
Porta
Michi
9. Later
Allou
10. Later
St. I
11. Mean
Copp
12. Vert.
sand
at C

LIST OF TABLES

TABLE	Page
1. Correlation chart for the Keweenaw of Lake Superior.	8
2. Lithology of the Mamainse Point interflow gravels coarser than 19 mm.	23
3. Comparison between the size (long axis) of mafic and plutonic clasts at Mamainse Point as measured in outcrop	24
4. The composition of the detrital sand-size constituents within the Mamainse Point interflow sediments, as represented by the mean and modal analyses of 64 thin sections.	26
5. Vertical variation within the sandy phases of Mamainse Point interflow sediments.	30
6. Keweenaw stratigraphic column on Keweenaw Peninsula	46
7. Mean composition of the sandy phases within the Portage Lake interflow sediments.	49
8. Vertical compositional variation within the Portage Lake interflow sediments at Calumet, Michigan.	53
9. Lateral compositional variation within the Allouez Conglomerate.	55
10. Lateral compositional variation within the St. Louis Conglomerate.	56
11. Mean composition of the sandy phases within the Copper Harbor Conglomerate.	62
12. Vertical compositional variation within the sandy phases of the Copper Harbor Conglomerate at Calumet.	64

LIST OF TABLES

TABLE

13. Vertical
sandy
at Co
14. Vertical
sandy
at Por
15. Lateral
phases
16. Mean of
Series
17. Vertical
southw
interf
18. Vertical
within
Volcan
19. Lateral
Shore

LIST OF TABLES--Continued

TABLE	Page
13. Vertical compositional variation within the sandy phases of the Copper Harbor Conglomerate at Copper Harbor	65
14. Vertical compositional variation within the sandy phases of the Copper Harbor Conglomerate at Porcupine Mountain, Michigan.	71
15. Lateral compositional variation within the sandy phases of the Copper Harbor Conglomerate	72
16. Mean composition of the North Shore Volcanic Series interflow sediments	94
17. Vertical compositional Variation within the southwest limb of the North Shore Volcanic interflow sediments.	98
18. Vertical compositional variation of constituents within the northeast limb of the North Shore Volcanic interflow sediments	101
19. Lateral compositional variation within the North Shore Volcanic Series interflow sediments.	105

FIGURE

1. General
region
2. Geologic
Superior
3. Geologic
Bay of
4. Graphical
with
5. Graphical
with
6. Geologic
Lake
7. Geologic
adjoining
study
8. Graphical
with
California
9. Graphical
with
California
10. Latitude
san
11. Geologic
of
12. Location
Series
13. Graphical
with
Volume

LIST OF FIGURES

FIGURE	Page
1. General geological map of the Lake Superior region.	7
2. Geological map of the east shore region of Lake Superior.	13
3. Geological map of the Mamainse Point and Alona Bay areas	27
4. Graphs of the vertical compositional variation within the Mamainse Point interflow sediments .	34
5. Graphs of the vertical compositional variation within the Mamainse Point interflow sediments .	36
6. Geological map of the south shore region of Lake Superior, Upper Peninsula of Michigan. . .	41
7. Geological map of the Keweenaw Peninsula and adjacent area, showing sites sampled for this study	50
8. Graphs of the vertical compositional variation within the Portage Lake interflow sediments at Calumet, Michigan	68
9. Graphs of the vertical compositional variation within the Portage Lake interflow sediments at Calumet, Michigan	70
10. Lateral compositional variation within the sandy phases of the Copper Harbor Conglomerate.	74
11. Geological map of the northwest shore region of Lake Superior.	84
12. Location map showing the North Shore Volcanic Series and the sites sampled.	92
13. Graphs of the vertical compositional variation within the southwest limb of the North Shore Volcanic Series interflow sediments	100

LIST OF FIGURES

FIGURE

14. Gray
with
Volc

15. Pale
Kewe
posi

LIST OF FIGURES--Continued

FIGURE	Page
14. Graphs of the vertical compositional variation within the northeast limb of the North Shore Volcanic Series interflow sediments	103
15. Paleogeography of Lake Superior Syncline in Keweenawan time showing location of postulated positive and negative tectonic areas.	117

The K
significant
extent of
ally immatu
overlie the
of a major,
shows many
rift zones.
the center
plateau bas
other such
continent.

The K
of the cur
relationsh
of particu
the Keween
borderland
Even
basalt and

CHAPTER I

INTRODUCTION

The Keweenawan geology of the Lake Superior basin is significant because of the great thickness and lateral extent of the extrusive rocks it contains, the compositionally immature red beds which are intercalated with and overlie the flows, and the fact that this basin forms a part of a major, linear, tectonic feature of North America, which shows many characteristics similar to those of continental rift zones. The Keweenawan basalt accumulation is now in the center of the continent and may be the oldest such plateau basalt known in the geologic record. It differs from other such accumulations which tend to be marginal to the continent.

The Keweenawan accumulation is of much interest because of the current attention to continental structure and the relationship between the crust and the underlying mantle. Of particular interest is the structural relationship between the Keweenawan volcanic accumulation and the surrounding borderland.

Even though the structural relationship between the basalt and the borderland is of great interest, most studies

of the Kew

petrology,

These stud

rocks and

of the par

this seque

land is th

Some

been perfo

(1929); Sa

Thiel (194

Eite (1968

no attempt

on a unifi

This

examination

From these

dynamic rel

bordering u

A comp

flow sedime

three major

The areas s

Keweenaw Pe

of the Keweenawan have concentrated on the stratigraphy, petrology, and the geochemistry of the volcanic rocks. These studies serve to shed light on a time scale for these rocks and present evidence on the origin and differentiation of the parent silicate melt. However, the only portion of this sequence which carries evidence of a contemporary borderland is the sediments intercalated with the flows.

Some examination of the interflow sediments has already been performed; i.e., Lane (1911); Butler, Burbank et al. (1929); Sandberg (1938); Grogan (1940) Tyler, Marsden, Grout, Thiel (1940); Thomson (1955); White (1957, 1960, 1967); Hite (1968); and Hubbard (1968). However, to my knowledge, no attempt has been made to examine the interflow sediments on a unified basis all around the Lake Superior basin.

This report describes the result of such a detailed examination and is integrated with studies already performed. From these results, an attempt to deduce the passive and dynamic relationship between the volcanic rocks and the bordering uplands and basins has been made.

Objectives of This Study

A comprehensive study was made of the Keweenawan interflow sediments, especially the sandy phases, in each of the three major Keweenawan outcrop areas around Lake Superior. The areas studied were at Mamainse Point in Ontario, the Keweenaw Peninsula of Michigan, and the North-west Shore

area of M

were to:

1. de

so

2. de

ve

3. de

gr

Ke

4. if

po

be

ou

The p

outcrops w

three Kew

randomly s

ing the r

such samp

pre-Kewee

sitional

interflow

sampled f

area of Minnesota and Ontario. The objectives of this study were to:

1. determine the degree of contribution of local sources to the sediment;
2. determine the degree of compositional variation vertically and laterally within each area;
3. determine the structural and physiographic background of events in each of the three major Keweenawan outcrop areas, and
4. if possible, build models showing the range in potential stratigraphic and tectonic relationships between these three now isolated major Keweenawan outcrop areas.

Methods Used in This Study

The purpose of this study was to compare Keweenawan outcrops within each area and then compare and contrast the three Keweenawan outcrop areas. Outcrops and cores were randomly sampled to obtain representative sand samples showing the range of variability present. Approximately 800 such samples were collected to include (1) possible clasts of pre-Keweenawan source rocks and (2) the textural and compositional range present in the interflow sediments. The interflow sediments present on the Keweenawan Peninsula were sampled from both core and outcrop collections, whereas the

samples c

Point ser

The d

binocular

thin sect

Bailey and

recognizat

stone were

technique.

counted in

genous str

ates was d

zones with

per site w

pebbles we

or thin se

samples collected from the North Shore Volcanic and Mamainse Point series were taken solely from outcrops.

The collected samples were studied in hand specimen by binocular microscope and over 252 were also examined in thin section. The thin sections were stained according to Bailey and Stevens' (1960) technique to facilitate feldspar recognition and discrimination. The modes of the sandstone were determined in thin section by point-counter technique. At least two hundred grains per thin section were counted in traverses parallel to the bedding within homogeneous structural units. The composition of the conglomerates was determined at the outcrop by point counting selected zones within conglomeratic units. At least 100 point counts per site were made. The identities of certain problematical pebbles were determined by subsequent binocular microscope or thin section study.

Struc

now occupi

Exposures

margins of

up to vert

Kewee

divided in

tary rocks

Keweenawan

in age. T

necessaril

its maximu

consists o

thins sout

stone near

Other sedi

Bessemer f

CHAPTER II

GENERAL GEOLOGY OF KEWEENAWAN SEQUENCE OF LAKE SUPERIOR REGION

Structurally, the Keweenawan rocks form a large syncline now occupied by most of Lake Superior itself (Figure 1). Exposures of Keweenawan rocks are primarily confined to the margins of the lake, where dips range from only a few degrees up to vertical.

Lower Keweenawan Rocks

Keweenawan rocks in the Lake Superior area may be subdivided into three lithologic divisions (Table 1). Sedimentary rocks lying between the Animikean and the earliest Keweenawan lava flows are referred to as lower Keweenawan in age. Their time equivalence around Lake Superior has not necessarily been established. The lower Keweenawan attains its maximum development on the Sibley Peninsula where it consists of sandstones, marls, and shales. The sequence thins southwestward to form only a thin conglomeratic sandstone near Duluth, called the Puckwunge formation (Table 1). Other sediments thought to be lower Keweenawan are the Bessemer formation east of Mellen in Wisconsin and Michigan,

Figure 1. General geological map of the Lake Superior region (modified after Hall, 1966) showing the main areas of outcrop of Keweenaw volcanic, sedimentary, and intrusive rock. The areas sampled for this investigation are numbered as follows: (1) The Mamainse Point area of Ontario, (2) The Keweenaw Peninsula of Michigan, and (3) The North Shore Volcanics Series of Minnesota.



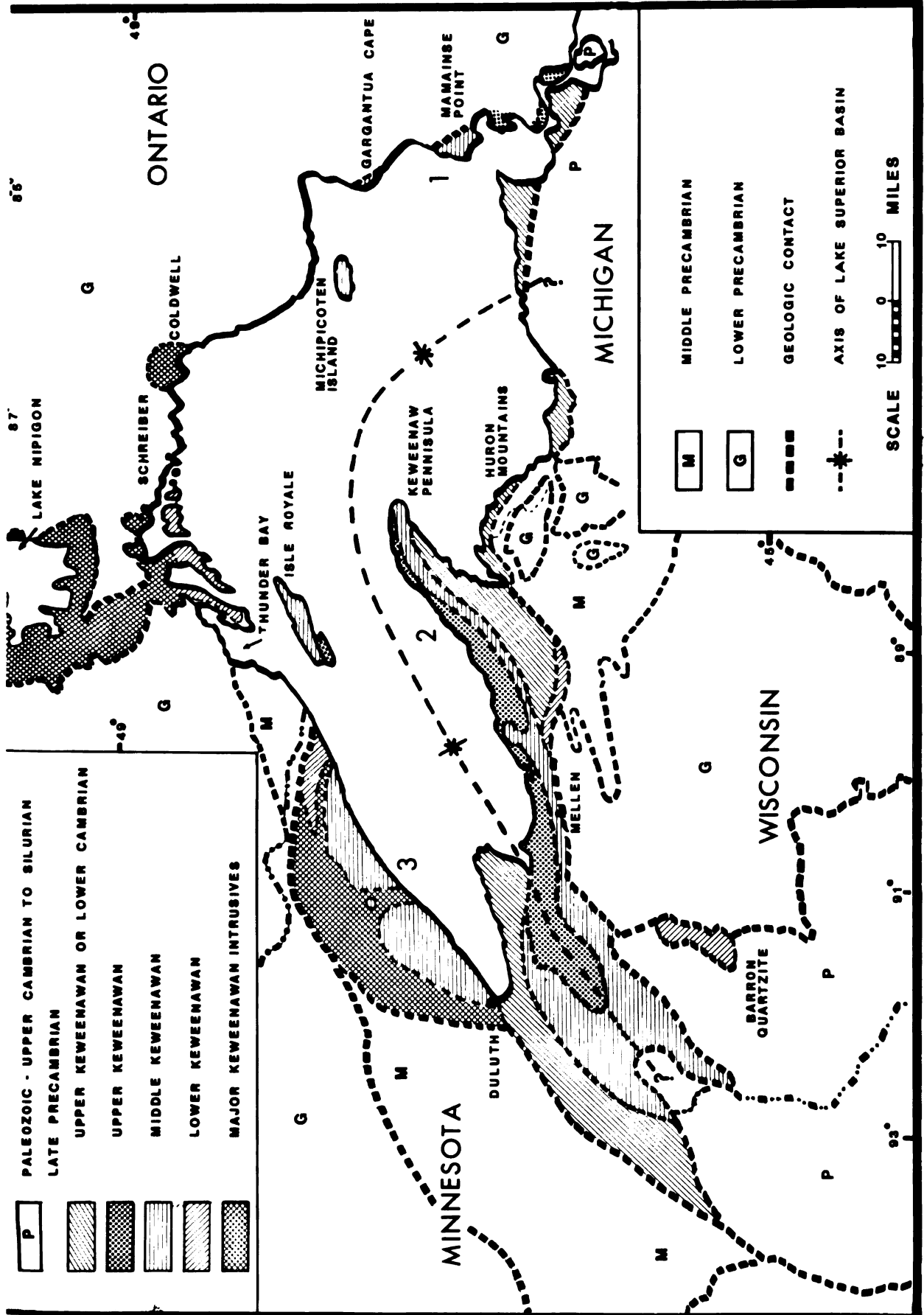


Figure 1

the Barro

formation

Thes

lava flow

netic pol

thought t

sequences

Series on

Puckwunge

Series at

North Sho

limb of t

between t

Michigan

in Wiscon

however,

pre-Kewee

Bay, and

The

of mafic

interflow

intrusive

rocks are

the Barron quartzite in northern Wisconsin and the Sioux formation in southwestern Minnesota.

These sediments are conformably overlain locally by lava flow sequences whose age, based upon a reversed magnetic polarization for both the sediments and volcanics, is thought to be lower Keweenawan. Examples of such lava sequences overlying sedimentary rocks are the Sibley-Osler Series on the north limb of the Lake Superior syncline, the Puckwunge-Grand Portage Series and the Puckwunge-Nopeming Series at the north and south end, respectively, of the North Shore Volcanic Group in Minnesota. And on the south limb of the Lake Superior basin, a similar situation occurs between the Bessemer Sandstone-South Range Lava Series in Michigan and the Bessemer Sandstone-Mellen and Hurley Lavas in Wisconsin (Table 1). On the east limb of the syncline, however, lower Keweenawan lava flows rest unconformably on pre-Keweenawan crystalline rocks at Mamainse Point, Alona Bay, and Cape Gargantua.

The Middle Keweenawan Rocks

The middle Keweenawan is made up of a thick succession of mafic lavas, with lesser amounts of felsic rocks and interflow sediments. Rhyolite occurs as both flows and small intrusive bodies. Prominent exposures of middle Keweenawan rocks are found along the Minnesota shore of Lake Superior,

in east of
Northern
In addition
Island and

The
of sandstone
shales.
the Keweenaw
Isle Royale
Superior.

Keweenaw
the areas
intrusives
exposed Keweenaw
is significant
feeder systems
of borderland
quiescence

The
Duluth gabbro
Keweenaw
irregular

in east central Minnesota, on the Keweenaw Peninsula, in Northern Wisconsin, and at Maminse Point in Ontario. In addition, middle Keweenaw rocks form Michipicoten Island and most of Isle Royale.

The Upper Keweenaw Rocks

The upper Keweenaw sequence consists predominantly of sandstones and conglomerates overlain by sandstones and shales. Upper Keweenaw rocks are extensively exposed on the Keweenaw Peninsula, in Northern Wisconsin, and on Isle Royale, and possibly along the east shore of Lake Superior.

Keweenaw Intrusive Rocks

Keweenaw intrusives are widespread and abundant in the areas marginal to Lake Superior. The location of these intrusives bodies marginal to the Lake Superior syncline, the exposed Keweenaw lava flows, and the interflow sediments is significant. These intrusives represent not only potential feeder systems for the flows, but could also indicate the site of borderlands which shed detritus in times of volcanic quiescence.

The largest intrusive in the Lake Superior area is the Duluth gabbro complex which intrudes the lower and middle Keweenaw rocks in Minnesota. Other mafic sills, dikes, and irregular bodies known collectively as the Logan intrusives

also intr

the north

Another d

the Kewee

Rhyolete

portion o

is Mount

phyre and

on the no

the basis

mostly th

dant in a

especiall

Point, th

the south

near Marg

also intrude middle Precambrian and Keweenawan rocks along the northwest shore of the lake from Duluth to Schreiber. Another complex of gabbro and granophyre rocks intrudes the Keweenawan volcanics in the Mellen area of Wisconsin. Rhyolite intrusive bodies are present throughout northern portion of the Keweenawan Peninsula. The largest of these is Mount Bohemia, an intrusive complex consisting of granophyre and syenodiorite. A large syenite complex at Coldwell on the north shore is also thought to be Keweenawan in age on the basis of radiometric studies. Diabase dike swarms, mostly thought to be lower Keweenawan in age, are also abundant in areas marginal to the lake. These swarms are especially abundant along the northwest shore near Pigeon Point, the east shore from Schreiber to Mamainse Point; along the south shore in the Huron Mountains, near Lake Gogebic, near Marquette; and also along the north shore of Lake Huron.

Seve

age, occur

Recent ra

isolated

metrical

rocks el

also ind

Keweenaw

correlat

Alt

Ontario

Lower Pr

Montorie

volcanic

promine

is at 1

Island

is thou

of Kewe

Bay; ho

does no

CHAPTER III

THE KEWEENAWAN GEOLOGY OF THE EAST SHORE REGION OF LAKE SUPERIOR

Several isolated volcanic sequences, Keweenawan in age, occur on the east shore of Lake Superior (Figure 2). Recent radiometric data indicates that the ages of these isolated outcrops fall within the same range as other radiometrically derived dates for lower and middle Keweenawan rocks elsewhere around Lake Superior. Paleomagnetic studies also indicate that magnetic divisions within these isolated Keweenawan sequences permit the various sequences to be correlated on the basis of magnetic polarity.

Although the Lake Superior shore between Schreiber, Ontario and Sault Ste Marie, Ontario is formed largely of Lower Precambrian rocks, several prominent, isolated, promontories along the east coast are made up of Keweenawan volcanic flows and sedimentary rocks. The thickest and most prominent exposure is at Mamainse Point where the succession is at least 14,000 feet thick (Figure 2). Michipicoten Island also contains a middle Keweenawan rock series that is thought to be about 11,000 feet thick. Lesser occurrences of Keweenawan rocks are found at Cape Gargantua and Alona Bay; however, the thickness of the series at these locations does not exceed 3,000 feet.

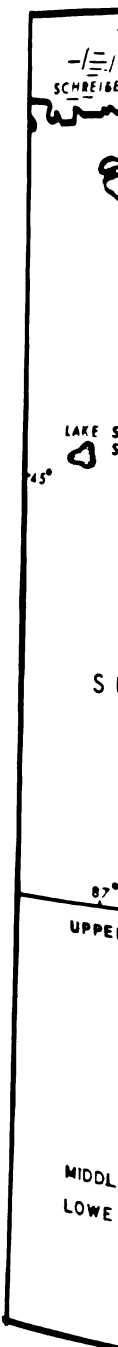


Figure 2.

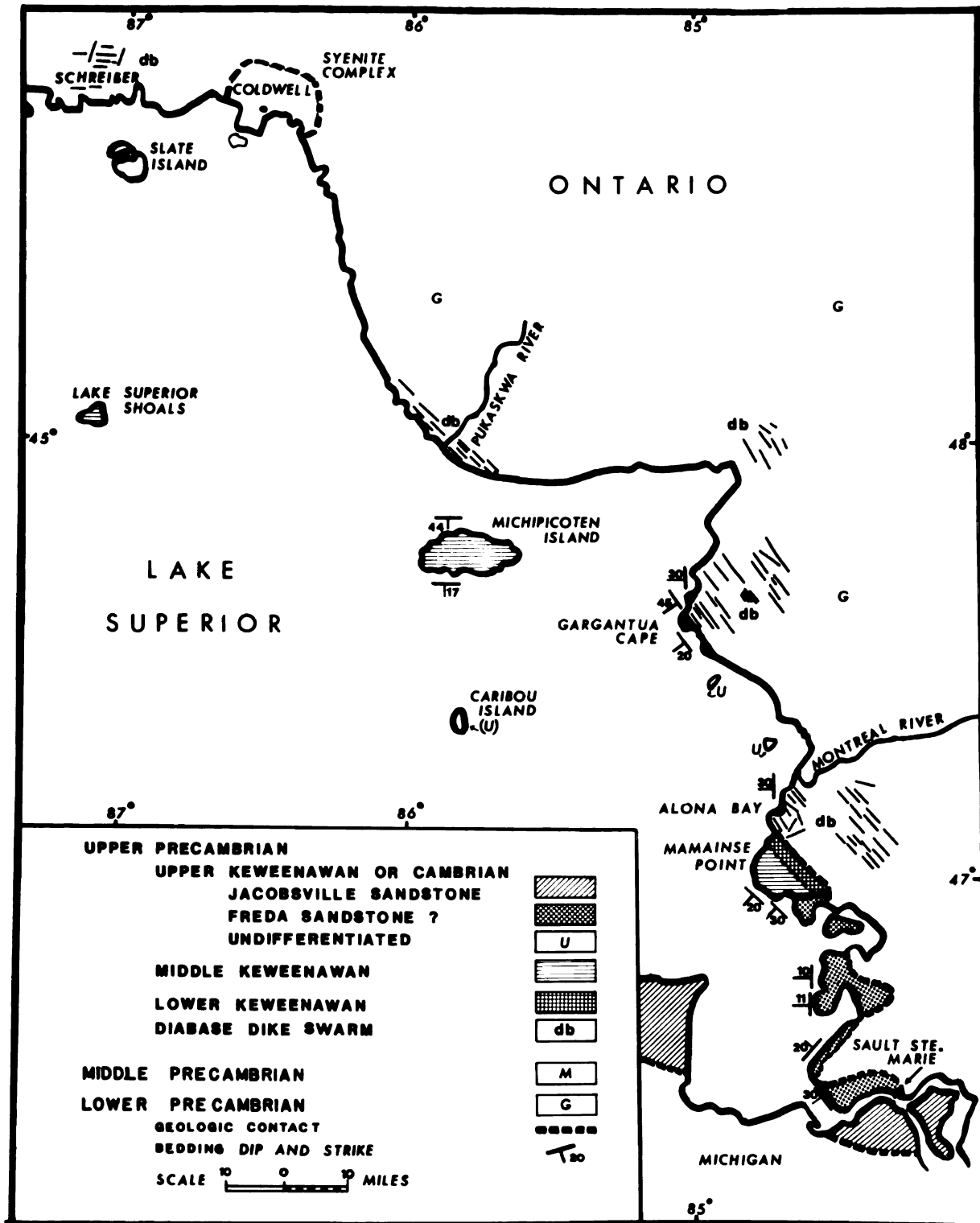


Figure 2. Geological map of the east shore region of Lake Superior (modified after Halls, 1966).

Generally speaking, the strike of the various series is parallel to the broad curve of the shore line and the axis of the Lake Superior Syncline, with dips inclined lakeward at angles from 15° to 50° . Burwash (1905) suggested that these isolated Keweenawan exposures along the lake may be associated with anticlinal arches marginal to the lake but plunging lakeward. Structural data on Michipicoten Island (Burwash, 1905) and Mamainse Point (Thomson, 1953) appear to lend credence to this idea.

The first detailed geologic map of these Keweenawan rocks on the eastern shore area of Lake Superior were made of the Michipicoten Island sequence by Burwash (1905) and revised more recently by Annells (1970). The first detailed map of the Mamainse Point succession was made by Moore (1925), followed by Thomson (1953) and Giblin (1965, 1969). Nuffield (1955) has described the geology at Alona Bay. The Cape Gargantua Keweenawan rocks were described by Ayres (1969). Recently a detailed stratigraphic-petrographic study relating the Keweenawan volcanic rocks at Mamainse Point, Alona Bay, Cape Gargantua, and Michipicoten Island was carried out by Annells (1970, 1971). Palmer (1970) made paleomagnetic studies which are useful in correlating these Keweenawan volcanic exposures.

Van Schmus (1971) states that the best estimate for the age of middle Keweenawan igneous activity along the east shore is $1,070 \pm 50$ m.y. By conducting Rb-Sr analyses on felsites

interlayered with volcanic sequences, he assigned the following over-all ages to these sequences: Mamainse Point ($1,070 \pm 50$ m.y.); Cape Gargantua (1.091 ± 40 m.y.) and Michipicoten Island (953 ± 50 m.y.).

The over-all age range for these igneous rocks around the east shore is within the same range of other radiometric data for middle Keweenawan rocks elsewhere in the Lake Superior region. Paleomagnetic studies by Du Bois (1962) and Palmer (1970) suggest a lower Keweenawan age for the Alona Bay sequence, the lower 1,000 feet of the Cape Gargantua series, and the lower 3,000 feet of the Mamainse Point succession on the basis of their reversed polarity. Palmer (1970) indicates that normal directions of magnetization prevail in the upper parts of the Mamainse Point, Cape Gargantua, and Michipicoten Island sections and magnetically these units should be considered middle Keweenawan in age.

Any reconstruction of Keweenawan volcanic and tectonic events must account for at least two factors. One factor concerns the geology of those areas marginal to Lake Superior and adjacent to the presently exposed Keweenawan outcrops; it is assumed that these adjacent areas were also blanketed by Keweenawan lavas at one time, but the flows have subsequently been removed by erosion. The second factor concerns the observation that large scale intrusive complexes and dike swarms of Keweenawan age occur closer to the margins rather than to the axis of the basin.

A n

occur in

of Lake

Wawa, and

Keweenaw

at all le

Anells,

the Michi

Diab

the Montr

phosed, s

in region

been remo

The

of lava c

Keweenawa

A s

1962; Pa

southeas

flows un

Nuf

observed

A number of Keweenawan alkalic intrusives complexes occur in areas marginal to the northeastern and eastern shore of Lake Superior. The largest such bodies occur at Coldwell, Wawa, and Chapleau, Ontario (Kerr, 1910; Parsons, 1961). Keweenawan rhyolitic plugs, dikes and intrusive sheets occur at all levels in the Mamainse Point section (Thomson, 1953; Annells, 1971). Felsic intrusives have also been reported in the Michipicoten Island sequence (Annells, 1971).

Diabase dike swarms occur from the Schreiber area to the Montreal River regions. The dikes are fresh, unmetamorphosed, strongly magnetic (Hall, 1966), and presently exposed in regions where the arched cover of Keweenawan rocks have been removed by erosion.

The dikes may represent a widespread peripheral system of lava conduits which served as feeders for an extensive Keweenawan volcanic terrain that has been eroded.

The Alona Bay Sequence

A series of lava flows of lower Keweenawan age (Du Bois, 1962; Palmer, 1970) is exposed as a narrow rim around the southeastern shore of Alona Bay (Figure 2). These mafic flows unconformably overlie pre-Keweenawan rocks.

Nuffield (1955) notes that no interflow sediments were observed intercalated with the volcanic succession.

The
approximate
conglomerate
Keweenaw

The
may be con-
separated
section of
studies by
of section
lower Kew-
should be

Ayre
least 5 p
Gargantua
tectonic in
percent b
pebbles o
The clast
boulders
tion is s
horizons

The Gargantua Cape Sequence

The Keweenawan section in the Gargantua Cape area is approximately 2,700 feet thick and consists of basalts, conglomerates and rhyolite unconformably overlying pre-Keweenawan granitic rocks.

The Keweenawan succession in the Gargantua Cape area may be conveniently divided into three basalt members separated by 2 conglomerate members, with the top of the section capped by Rhyolite (Ayres, 1969). Paleomagnetic studies by Palmer (1970), indicate that the lower 1,000 feet of section (within the lower basalt member) is probably lower Keweenawan, whereas the upper half of the section should be considered middle Keweenawan.

Ayres (1969) indicates that the conglomerates form at least 5 percent of the total Keweenawan series at Cape Gargantua. He also notes that the conglomerates are polymictic in nature, with a composition comprised of 80 to 90 percent basaltic clasts and minerals derived from the basalts; pebbles of diabase and plutonic rocks are also observed. The clasts have an average diameter of 3 inches; however, boulders as much as 2 feet in diameter occur. This composition is similar to that of the lower interflow sedimentary horizons at Mamainse Point.

The

as a row

1911).

of mafic

mentary

Island and

localities

up at least

of the M.

parts of

The

occur mainly

These sections

island, but

northeast

gested that

a local area

erosion and

The

derived from

but also

gneisses

in lesser

polymictic

Point and

The Michipicoten Island Sequence

The Keweenawan rocks occupy the entire island as well as a row of smaller islands of its south shore (Van Hise, 1911). The section on the island consists of 11,230 feet of mafic and felsic extrusive, felsic intrusive, and sedimentary rocks (Burwash, 1905). The rocks of Michipicoten Island are unique in comparison with other middle Keweenawan localities around Lake Superior in that felsitic lavas make up at least half of the succession. The more mafic members of the Michipicoten sequence are most abundant in the lower parts of the succession.

The interflow sedimentary rocks on Michipicoten Island occur mainly in the lower horizons of the sequence (Figure 2). These sediments are confined to the northwestern part of the island, being thickest in the west and thinning out to the northeast. Because of their location, Burwash (1905) suggested that the interflow conglomerates are associated with a local anticlinal uplift which resulted in more rapid erosion and deposition of clastic sediments in that area.

The conglomerates are composed primarily of material derived from felsic rocks. Mafic clasts are subordinate but also abundant; granites, greenstones, and biotite gneisses derived from pre-Keweenawan rocks are also present in lesser amounts (Burwash, 1905; Van Hise, 1911). These polymictic conglomerates are similar to those at Mamainse Point and suggest the nearby presence of a tectonically

active borderland which was shedding both volcanic-surficial and nonvolcanic-basement type rocks simultaneously.

The Mamainse Point Volcanic Series

The thickest and most prominent Keweenawan section on the east shore of Lake Superior occurs at Mamainse Point, Ontario (Figure 1). It contains appreciable amounts of pre-Keweenawan plutonic rock fragments in addition to volcanic clasts. This combination of observations suggests the presence of a tectonically active borderland which was able to supply coarse detritus from both volcanic flows and an underlying nonvolcanic basement simultaneously throughout the middle Keweenawan succession preserved at Mamainse Point.

Thomson (1953) noted that the Mamainse Point Volcanic section forms a broadly plunging anticline, which is accentuated by faulting. The dips range from 20° to 48° , with the steepest dips appearing at the top of the section. The fanning of dips characteristic of most Keweenawan sections exposed elsewhere around Lake Superior appears to be reversed at Mamainse Point. This observation, coupled with the presence of abundant dike swarms at nearby Alona Bay, indicates that some kind of tectonic folding and fissuring was in progress during Keweenawan time. The coupling of folding and dike-intrusion tectonism does not appear to be unique to the east shore of Lake Superior. Similar occurrences along with sedimentological and lithologic criteria will be

presente

diastrop

superior

flows in

as on th

shore, i

shore.

The

Point Key

slightly

to 14,300

ness esti

good outc

exposed,

produce s

Mafi

series at

extrusive

1955; Ann

Plug

at all le

are rare

Nuffi

Keweenawan

of Mamains

Keweenawan

presented in the course of this study to suggest that such diastrophism and volcanism may have occurred around Lake Superior whenever Keweenawan sediments are intercalated with flows in areas where diabase dikes are present nearby, such as on the south shore, the northwest shore, and the east shore, if not perhaps completely around the Lake Superior shore.

The estimates of the apparent thickness of the Mamainse Point Keweenawan succession made in the past vary from slightly over 16,000 feet (MacFarland, 1866; Moore, 1925) to 14,300 feet (Annells, 1971). This variation among thickness estimates is understandable in view of the fact that good outcrops are scarce, a continuous succession is nowhere exposed, and the effects of possible strike faulting may produce spurious thickness values.

Mafic lavas make up the greater part of the Keweenan series at Mamainse Point. Some rhyolite sheets, possibly extrusive, are also present throughout the sequence (Thomson, 1955; Annells, 1971).

Plugs, dikes and sheets of fine grained rhyolite occur at all levels in the Mamainse section. However, mafic dikes are rare (Thomson, 1925).

Nuffield (1955) found numerous dikes cutting the pre-Keweenawan terrain at the Point aux Mines, just to the north of Mamainse Point, but only one dike appears to cut the Keweenawan lavas. Therefore, most diabase dikes are either

younger

flows wh.

Interflow

Inte

are at le

make up a

Mamainse

averages

section e

horizons

feet with

more clos

change in

sequence

of the in

sediments

Keweenaw

where are

Mamainse

such as

graphic

coalesci

Conglome

The

than 19

Point we

younger than the exposed Keweenaw flows, or they fed flows which have since been eroded away.

Interflow Sediments

Interbedded with the lava, in the Mamainse Point area, are at least 9 sedimentary horizons which in total thickness make up about 13 percent of the aggregate thickness of the Mamainse section. The thickness of the conglomerate beds averages over 100 feet, with one near the middle of the section exceeding 1,700 feet in thickness. The conglomerate horizons occur on the average at intervals of about 1,900 feet within the Mamainse Point Series. However, they appear more closely spaced in the upper half of the section. This change in spacing is also characteristic of the Portage Lake sequence on the Keweenaw Peninsula. The greater thickness of the interflow sedimentary beds, and the fact that these sediments comprise a greater percentage of the total middle Keweenaw volcanic succession at Mamainse Point than elsewhere around the lake, suggests that the terrain east of the Mamainse depositional site was a major physiographic feature such as a fault scarp or a mountain range. This physiographic feature was flanked on its westward margins by coalescing alluvial fans.

Conglomerates

The lithology and size (long axis) of gravel coarser than 19 mm (-4.25 phi) in the interflow sediments of Mamainse Point were determined in the field to obtain data pertaining

to: (1)

(2) rela

and (3)

upward m

lected z

were cho

availabi

The iden

determine

section s

A gr

conglomer

of pluton

pre-Kewee

conglomer

vein quar

generally

however,

throughou

fanglomer

Because t

been far

absence o

front of

slope, or

miles west

to: (1) the lithology present in the source terrain, (2) relative location of the western margin of the highland, and (3) whether the highland underwent a single or several upward movements. The analyses were made by counting selected zones within the conglomeratic units. The sites were chosen on the bases of stratigraphic distribution and availability. At least 100 point counts per site were made. The identities of certain problematical pebbles were determined in the laboratory by binocular microscope or thin section study.

A great variety of rock types are represented among the conglomerate clasts (Table 2). The largest boulders consist of plutonic rocks and mafic lava fragments (Table 3). Other pre-Keweenawan, but smaller, rock fragments present in the conglomerates are Keewatin-type greenstones, and schists, vein quartz and sedimentary clasts. Mafic lava fragments generally form the majority of the conglomerate clasts; however, plutonic rock fragments are generally abundant throughout the Mamainse Point section (Table 2). No angular fanglomerates were observed in the Mamainse Point succession. Because the source of many of the rock fragments may not have been far east of the present Mamainse outcrop belt, the absence of fanglomerates suggests that either the mountain front of the highland did not involve an abrupt break in slope, or that sections along the outcrop belt are several miles west of the possible break in slope.

Table 2. Lithology of the Mamainse Point interflow gravels coarser than 19 mm. (-4.25 phi) as determined by point counting the outcrop. Point count was based upon 100 counts per site.

	Interflow Horizon	Lithic Constituents				Total Percent	Sites Counted Per Outcrop
		Mafic Clasts	Felsite Clasts	Metasedimentary Clasts	Plutonic Clasts		
Top	M-6	67.9	9.2	01.5	21.4	100.0	1
	M-2	47.2	2.7	05.0	45.2	100.0	3
	M-7	48.0	10.5	09.1	31.7	100.0	2
	M-8	66.9	01.4	01.4	30.5	100.0	1
	M-9	82.1	-	14.6	03.3	100.0	3
	M-3	68.0	06.3	03.7	22.0	100.0	5
Bottom	M-4	100.0	-	-	-	100.0	2
Average Volume Frequency		68.7	04.3	05.0	22.0	100.0	N = 1700

Point count, excluding matrix and cement, was recalculated to 100% in order to portray only those constituents coarser than 19 mm.

Table 3. Comparison between the size (long axis) of mafic and plutonic clasts at Mamainse Point as measured in outcrop

Table 3. Comparison between the size (long axis) of mafic and plutonic clasts at Mamainse Point as measured in outcrop.

Age	Sediment Horizon	Size (long axis) Category	Mafic Clast Size (long axis) (in cm)	Plutonic Clast Size (long axis) (in cm)
Middle Keweenawan	M-6	Mean size Max. size	10.6 27.9	17.8 43.4
	M-2	Mean size Max. size	05.3 45.7	05.1 83.8
	M-7	Mean size Max. size	08.4 15.2	10.7 35.6
	M-8	Mean size Max. size	06.6 30.5	05.1 06.4
	M-9	Mean size Max. size	07.6 20.3	15.2 73.7
	M-3	Mean size Max. size	12.2 30.5	12.7 50.8
	M-4	Mean size Max. size	16.3 48.3	- -
	Summary	Avg. of Means Avg. of Maximums	09.7 31.2	10.1 48.3
	Measurements to nearest 0.1 cm.			

It appears that a nearby source terrain consisting of metasedimentary and plutonic rocks was being eroded during Keweenawan time. The fact that the lower-most flows rest on weathered granites possessing considerable relief (Nuffield, 1955; Ayres, 1969) rather than sedimentary or low ranked metamorphic rocks probably indicates that much unroofing had occurred prior to Keweenawan time.

It is worth noting that the lower Keweenawan interflow sediments at both Cape Gargantua and Mamainse Point are comprised almost solely of coarse mafic volcanic clasts whereas the stratigraphically higher interflow sediments are polymictic. This observation about the lower Keweenawan sediments lends credence to the idea that extensive basalts flows probably blanketed much of the source terrain in lower Keweenawan time. Uplift of the areas marginal to the present Lake Superior syncline during periods of volcanic quiescence allowed these flows to be eroded, thus forming a source of detritus for the interflow sediments. Continued erosion with time laid bare the underlying pre-Keweenawan rocks which then also contributed detritus to the depositional site throughout middle Keweenawan time.

Sandstones and Sandy Phases

Sandstones occur in the Mamainse Point Keweenawan series in thin beds, as sandy lenses within the conglomerates, or as conglomeratic matrix. Sixty-four thin sections were made from samples collected from within these sandy phases.

All samples were collected solely from outcrops (Figure 3).

Table 4. The composition of the detrital sand-size constituents within the sandy phases of the Mamainse Point interflow sediments, as represented by the mean of the modal analyses of 64 thin sections.

Constituents	Volume Frequency (%)	
	$\bar{Y}$	S
Mafic rock fragments	29.9	30.3
Plutonic rock fragments	28.6	25.5
Metasedimentary rock fragments	21.8	23.7
Felsic rock fragments	13.6	15.7
Simple quartz	01.8	1.4
Plagioclase	02.1	2.8
Undulatory Quartz	01.1	1.5
Potassium feldspar	00.8	1.7
Polycrystalline quartz	00.2	0.5
	99.9	

$\bar{Y}$ = mean of 64 thin sections.

S = standard deviation of 64 thin sections

The mafic rock fragments appearing in the sandy phases of the Mamainse Point interflow sediments comprise approximately 30 percent of the total volume of these sediments. These sand sized mafic fragments display a wider range of textures than other mafic clasts in exposures elsewhere in Lake Superior. The mafic clasts at Mamainse Point range in texture from the fine basaltic to basaltic amygdaloidal to

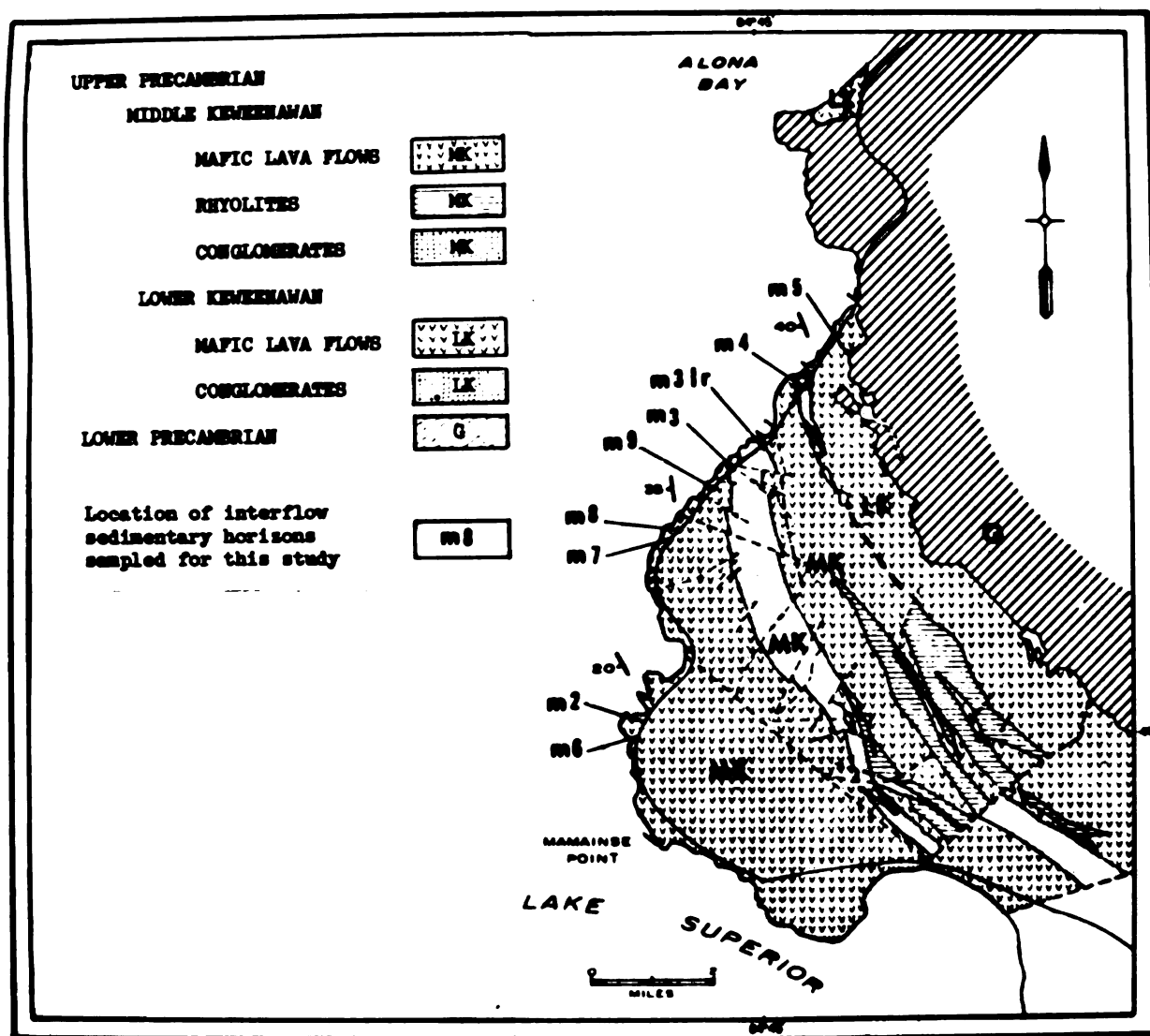


Figure 3. Geological map of the Mamainse Point and Alona Bay areas (after Palmer, 1970).

diabasic to coarse diabasic. This variety is often present in a single thin section.

The plutonic rock fragments comprise approximately 29 percent of the volume of the sandy phases within the interflow sediments. These clasts appear to be either gneiss or granites.

Metasedimentary fragments constitute approximately 22 percent of the volume of the interflow sediments and consist primarily of micaceous schists and immature sandstones in an approximate ratio of 4 to 1.

The felsite rock fragments comprise 13.6 percent of the sandy phases of the interflow sediments at Mamainse. The felsite clasts commonly consist of uniformly fine-grained quartz and feldspar, which commonly show gradations in their relative proportions, although the feldspars are generally dominant. No granophyre fragments were observed in the various sedimentary horizons at Mamainse Point.

The various kinds of detrital quartz grains comprise 3.1 percent of the average volume of the sandy phases. Unstrained quartz is the dominant quartz variety and makes up 58 percent of the total quartz volume within the sediment. Quartz grains showing moderate to strong undulose extinction comprise 35.5 percent, while polycrystalline quartz makes up the remainder (6.5%) of the total quartz volume.

Detrital feldspars constitute 2.9 percent of the total volume of the sandy phases within the interflow sediments.

Plagic

of the

sist m

ally h

0.8 pe

most a

howeve

ingly

Point

Vertic

E

within

sedime

occurr

T

in suc

repres

during

locati

I

rene r

change

sition

size, c

in gra

detrita

Plagioclase is the dominant feldspar comprising 72 percent of the total feldspar volume. The plagioclase grains consist most commonly of labrodorite and andesine and generally have a fresh appearance. Potassium feldspar makes up 0.8 percent of the total volume of the sandy phases. The most abundant potassium feldspar is an untwinned variety, however, grains showing gridiron twinning become increasingly abundant in the upper-most horizons in the Mamainse Point succession.

Vertical Compositional Variation

Evaluation of the vertical compositional variation within the sandy phases of the Mamainse Point Interflow sediments was made to detect any changes in provenance occurring during Keweenaw time.

The sedimentary samples were collected from outcrops in such a way as to portray a composite vertical section representative of the interflow succession at Mamainse Point during lower and middle Keweenaw time. Figure 3 shows the location of the outcrops sampled for this study.

If it is assumed that the location of the source terrane remains constant throughout the vertical section, then changes in the volume frequencies among the various compositional constituents can only arise from variation in grain size, depositional environment, or provenance. As variation in grain size effects the volume frequencies of the various detrital constituents within the sediment even in the absence

Table 5. Vertical compositional variation within the sandy phases of the Mamainse Point interflow sediments.

Horizon	Mafic Clasts		Felsic Clasts		Metasedimentary Clasts		Plutonic Clasts		Simple Quartz		Undulatory Quartz		Polycryst. Quartz		Plagioclase		Potassium Feldspar		
	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	
TOP	M6	13.9	9.4	27.4	13.1	17.0	16.4	20.6	15.6	3.0	3.5	3.1	3.0	0.0	-	9.5	4.5	5.5	2.1
	M2	25.7	27.4	22.4	17.7	25.9	15.3	16.5	14.5	2.6	3.8	2.7	3.6	0.0	-	3.0	3.5	1.2	2.4
	M7	17.4	12.9	4.3	8.7	38.6	23.9	37.2	14.6	0.7	2.1	0.3	3.1	0.0	-	1.5	3.3	0.0	-
	M1	52.7	13.1	46.2	14.6	0.0	-	0.0	-	1.1	1.5	0.0	-	0.0	-	0.0	-	0.0	-
	M8	15.5	18.5	18.3	15.9	52.3	31.1	13.1	21.1	0.8	1.5	0.0	-	0.0	-	0.0	-	0.0	-
	M9	59.0	11.3	0.0	-	4.1	5.2	28.8	10.5	4.2	4.5	2.1	2.8	0.0	-	1.8	-	0.0	-
	M3	31.1	2.9	11.3	7.8	3.8	5.4	52.3	13.8	0.9	1.2	0.0	-	0.0	-	0.6	0.7	0.0	-
	M3LR	69.2	19.8	2.5	4.2	9.2	15.9	14.5	9.7	1.9	1.6	1.0	1.5	0.7	1.2	1.0	1.8	0.0	-
	M4	97.0	5.9	3.0	5.9	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
BOTTOM	M5	0.9	1.6	3.8	4.4	21.7	18.7	68.1	20.5	1.9	2.4	0.5	1.2	0.4	1.1	2.7	3.0	0.0	-

 $\bar{Y}$ = mean volume frequency of each sedimentary horizon

S = standard deviation of each sedimentary horizon

of other effects, any analysis of compositional variation must first take this effect into account. Therefore, the method chosen to evaluate the vertical variation among volume frequencies of the various detrital constituents was that procedure utilizing the least square regression analysis.

Regression analysis was employed to allow the deviation in the volume frequency (dependent variable) to be minimized as the grain size (independent variable) for that compositional component was assumed fixed. Thus the volume frequency was regressed about the grain size. This method allows the variation in the volume frequency to be explained in terms of the variation in grain size. Any portion of the total variation not accounted for by the differences in grain size remains as a residual and must be due to changes in provenance or the depositional environment.

The following method was used to evaluate vertical compositional variation. The existence of a linear relationship between grain size and volume frequency was verified by graphing, thus meeting the assumption of linearity necessary for use of regression analyses. The least square line of best fit and the correlation coefficient were calculated. The (observed-expected) values of the volume frequency versus depth were plotted. All plots were then evaluated by 2 x 2 Chi square contingency analysis to judge if the scatter of points about the zero line showed a trend possibly indicating a significant ($P_{\chi^2} < 0.05$) residual.

Figures 4 and 5 graphically portray the relationships between the (observed-expected) volume frequency and depth for the important sand-size compositional constituents present within the interflow sedimentary horizons at Mamainse Point. When the grain size effect is statistically removed from the compositional elements present in the Mamainse Point section and results are plotted the only compositional elements which show a significant ($P_{\chi^2} < 0.05$) residual trend are the mafic, plutonic, and felsite rock fragments. The mafic and plutonic rock fragments show a decrease in volume frequency upward in the section, while the felsite fragments show an increase. The increase in felsite clasts appears to correlate with the Michipicoten Island sequence which Annels (1971) believes is stratigraphically higher than the Mamainse Point sequence. In the Michipicoten Island succession the felsite clasts dominate the composition of the interflow sediments.

Analysis of the vertical variation in composition and grain size in the Mamainse Point interflow succession with time suggests that the grain-size effect exerts the greatest degree of control on composition vertically. Gradual changes in the source terrain are also suspected to have occurred, based on the significant changes in the volume frequency of the mafic, plutonic, and felsite constituents. The analysis indicates that a definite lessening of importance of the volcanic and plutonic terrains as a source of rock fragments

Figure 4. Graphs of the vertical compositional variation within the Mamainse Point interflow sediments. Graphs show the residuals when the (observed-expected) volume frequencies of the various detrital constituents are plotted versus their depth of occurrence in the Mamainse Point section. Graph A is the plot for mafic clasts, Graph B is for plutonic clasts, and Graph C is for felsite clasts.

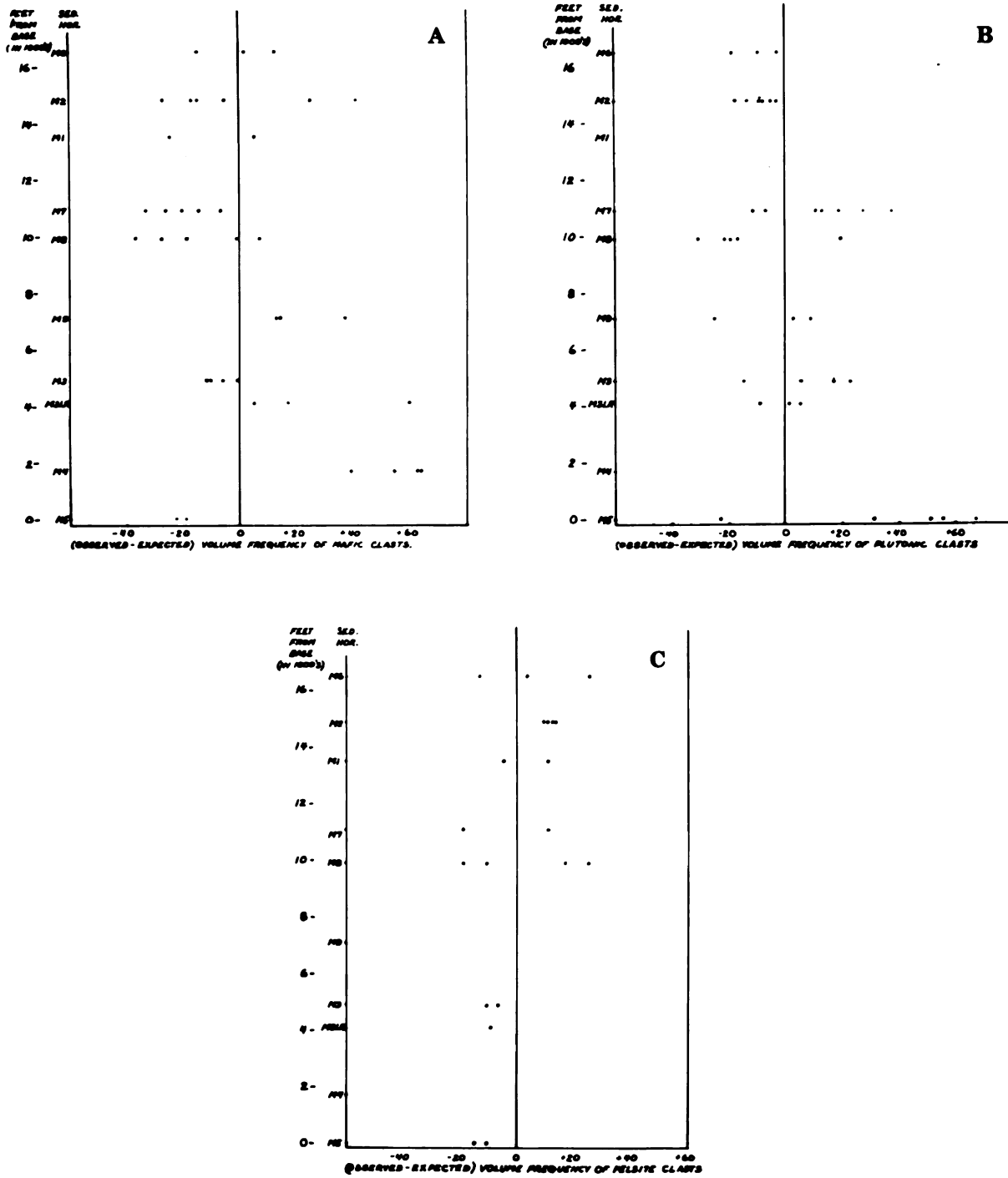


Figure 4

Figure 5. Graphs of the vertical compositional variation within the Mamainse Point interflow sediments. Graphs show the residuals when the (observed-expected) volume frequencies of the various detrital constituents are plotted versus their depth of occurrence in the Mamainse Point section. Graph D is the plot for metasedimentary clasts, Graph E is for unstrained quartz clasts.

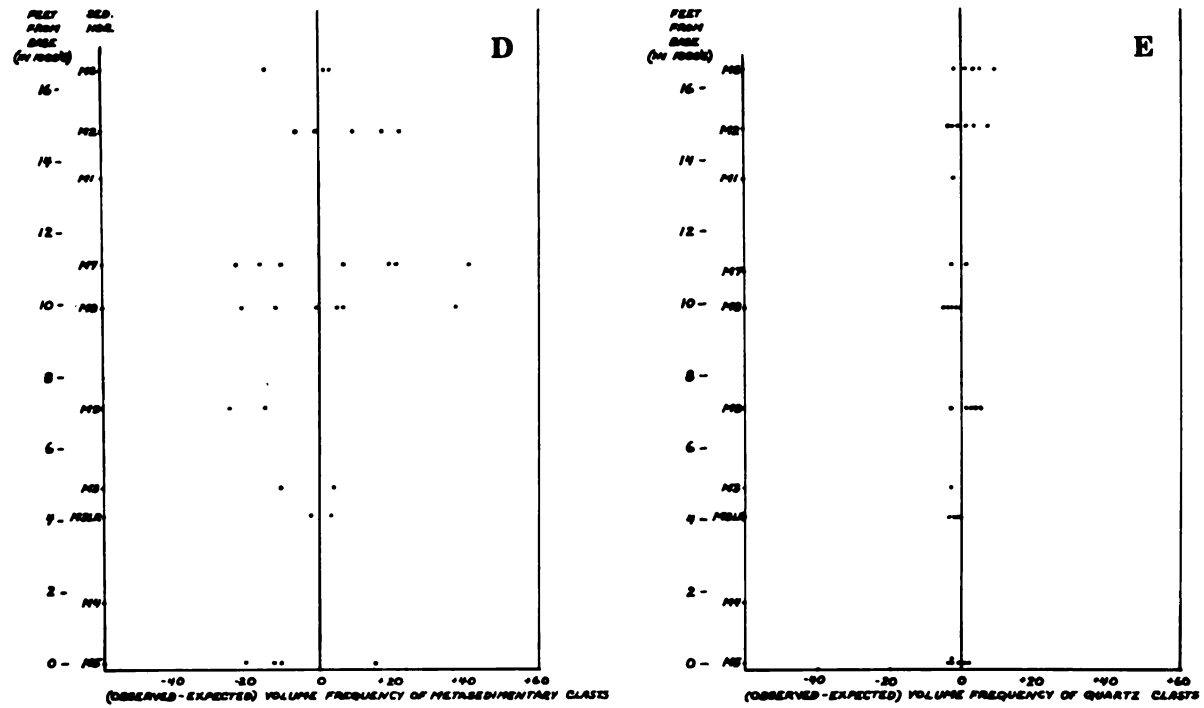


Figure 5

oc

th

in

th

si

le

Ke

re

mi

Pr

vi

ce

te

ne

fe

fl

an

gr

li

il

ay

es

occurred during Keweenawan time. The analysis also suggests that felsitic rocks as a source of detritus are becoming increasingly important upward in the sequence with time. This trend of decreasing mafic and plutonic clasts could signify decreasing tectonism with time. Erosion then would less vigorously be attacking the basalt mantled pre-Keweenawan non volcanic rocks, thereby permitting a relatively greater contribution of the more weathered monomineralic fragments to be present in the sediment.

Sedimentary Synopsis

Provenance

The compositional immaturity of the interflow sediments within the Mamainse Point series allows deductions to be readily made concerning the nature of the Keweenawan source terrain. The composition of the Keweenawan interflow sediments suggests a nearby source terrain consisting of mafic, felsic, metasedimentary and plutonic rocks.

Annels (1971) points out the striking similarity of the flows in the lower levels of the Mamainse Point, Alona Bay, and the Cape Gargantua volcanic sequences, which are petrographically similar to those forming the basal part of the Michipicoten Island sequence. He suggests that these latter flows may represent the upper part of an extensive and largely uniform flood basalt pile whose earliest members rest directly on the Lower Precambrian rocks of the east shore

of Lake Superior. These observations, plus the presence of coarse interflow conglomerates near the base of both the Mamainse Point and Cape Gargantua which consist entirely of detritus from mafic flows, in addition to the presence of widespread diabase dike swarms of lower Keweenawan age located eastward of the presently exposed volcanic series, indicates that the basal flows were once more extensive. It is conceivable that they could have covered much of the source terrain during Keweenawan time.

The source area, dominated by an extensive and thick sequence of volcanic rocks, was tectonically unstable, which encouraged the production of considerable amounts of coarse detritus to be shed from local sources intermittently during periods of little or no volcanic activity.

The coarse texture of the Mamainse Point Keweenawan interflow sediments, in which the volcanic fraction locally may be as coarse as the pre-Keweenawan plutonic fraction, suggests that the Keweenawan lavas and the pre-Keweenawan rocks, acting dually as a source, existed as a continually active borderland from which the sediments were derived. Concomitant with this active borderland, the deposition and preservation of such a thick series of flows and sediments suggests a nearby rapidly subsiding basin in which continued downwarping produced a topographic depression into which not only lavas but streams flowed and deposited detritus shed from the nearby tectonically active borderland during periods of volcanic quiescence.

The fact that the sediment intercalated between the flows appears periodically in the section need not necessarily imply that there were discrete periods of volcanism, uplift, sedimentation, and subsidence, but that continued erosion and sedimentation were taking place elsewhere as their locii were shifting laterally as given drainage areas were locally blocked by flows.

Paleogeography and Sedimentation

The coarseness and compositional immaturity of the conglomerates and sandstones constituting the Mamainse Point series indicates a nearby source of some relief. These characteristics also suggest that the sediment underwent a short transportational history and rapid deposition in a sedimentary basin which was rapidly sinking.

The uplift of the marginal source terrain coupled with subsidence of the central portions of the basin initiated erosion, transportation and deposition of immature, polymictic conglomerates and arenites by a fluvial system on a piedmont fan.

The lack of shale and fine sand, the coarse nature of the sand and conglomerate, the crude bedding, and the typically poor sorting and lack of rounding existing in the sandy phases suggests that the interflow sediments comprising the Mamainse Point series were transported by a fluvial system characterized by relatively high energy conditions and high gradients.

Steep gradients and rugged relief in the source area provided the topographic control necessary to allow lava flows to be dissected by streams. Renewed vertical erosion by incised streams cut completely through the flows, locally exposing the underlying pre-Keweenawan rocks. This enabled fresh volcanic rock fragments showing a complete range of textures, pre-Keweenawan rocks, and weathered detritus from the interfluve areas to be mixed together.

The evidence presented in this study suggests that the most likely location for the source area borderland of both the east shore Keweenawan volcanic rocks and their intercalated sediments was just eastward of the presently exposed Keweenawan outcrops. This area is represented by the occurrence of abundant lower Keweenawan diabase dikes exposed in lower Precambrian metasedimentary and plutonic rocks.

CHAPTER IV

THE SOUTH SHORE REGION

The Keweenawan rocks of the south shore region of Lake Superior are found on the Upper Peninsula of Michigan and in northern Wisconsin (Figure 6).

The rock units exposed on the Keweenaw Peninsula are the Bessimer sandstone and the South Range Lava Series of lower Keweenawan age, the Portage Lake Lava Series of Middle Keweenawan age, the overlying Copper Harbor conglomerate, the Nonesuch Shale, and the Freda sandstone of Lake Keweenawan age, and the Jacobsville sandstone of late Keweenawan or Cambrian age. Modal analyses were made only on the Portage Lake and Copper Harbor interflow sediments for this phase of the investigation.

Hubbard (1967, 1968) has described the South Range Series. He suggests that these rocks, which are located adjacent to both the Huron Mountain dike swarms and the Mellen Complex, may be the source of the interflow sediments present in the overlying Portage Lake Series and the Copper Harbor conglomerate.

The proposed source area for the Keweenawan interflow sediments is thought to have consisted of pre-Keweenawan

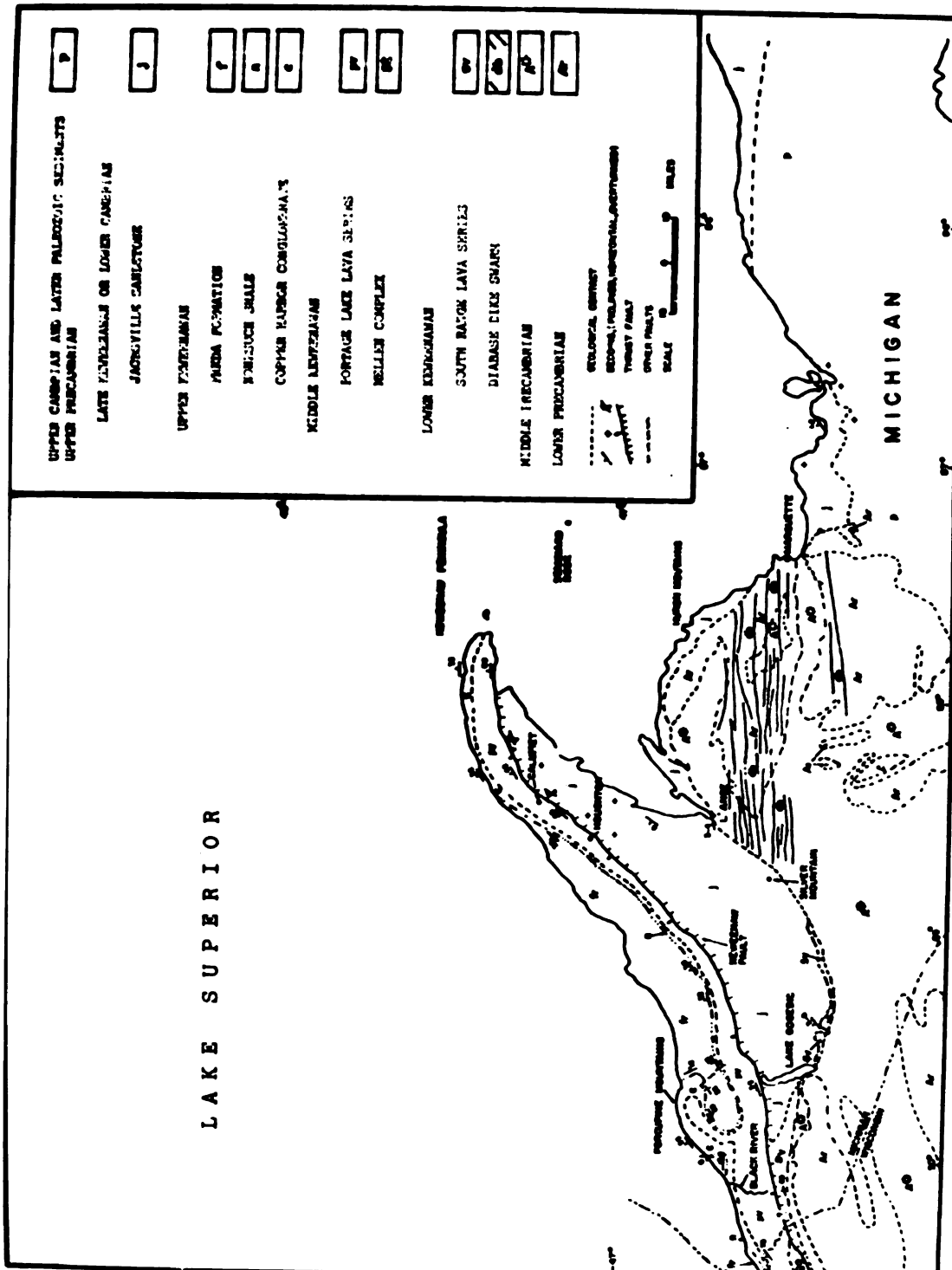


Figure 6. Geological map of the south shore region of Lake Superior: Upper Peninsula of Michigan (modified after Halls, 1966).

metasedimentary and plutonic rocks mantled by a thick cover of Keweenawan volcanic rocks. The source area was uplifted and intruded by a large gabbro-granophyre complex in the Mellen area of Wisconsin (Aldrich, 1929; Tyler, 1940; Leighton, 1954; White, 1966). Goldich et al. (1961) and Silver and Green (1963) have reported that the granitic portion of body intruding the Keweenawan lavas at Mellen, Wisconsin has been dated by the K/A method as being approximately 1.0 b.y. old. This age determination corresponds well with ages for Keweenawan time.

Furthermore, paleomagnetic studies by Du Bois (1962), and Books (1968) indicate that the South Range Lava flows are of reverse polarity and are thus magnetically defined as lower Keweenawan in age. The overlying Portage Lake Lava Series and the Copper Harbor Conglomerate are considered to be of middle Keweenawan age on the basis of having normal polarity and a remanent magnetization significantly different from that of the South Range Series.

The South Range Lava Series

The oldest Keweenawan rocks on the Keweenaw Peninsula are the quartzose sandstones of the Bessemer formation. These are overlain by the South Range Lavas which locally also overlie Middle Precambrian rocks. The South Range Lava Series crops out in an east-west trending band near Ironwood, Michigan which extends approximately to the southern end of Lake Gogebic (Figure 6). Hubbard (1967, 1968) indicates that the

lava series is at least 10,000 feet thick. The rocks of the South Range Series are separated from the overlying Portage Lake Lava Series by a covered interval approximately 2 miles wide near Ironwood. The rocks underlying the covered interval have smaller magnetic anomalies than either of the two mafic sequences above or below it. Hubbard (1968) indicates that the magnetic data are compatible with the covered interval being underlain by sedimentary rocks or by siliceous volcanic rocks. Outcrops of felsite are reported on strike with the covered interval in adjacent Wisconsin (Aldrich, 1929; Hubbard, 1968).

The dips of the South Range Series increase toward Lake Superior. This observation is diametrically opposed to the normal fanning of dips characteristic of the Portage Lake and Copper Harbor successions over most of the Keweenaw Peninsula. Hubbard ascribes this variation in dips between the South Range Series and other Keweenawan rocks to anticlinal flexure on the limb of the syncline.

The middle member of the South Range Series contains a few interflow sandstones, while the upper member contains some intercalated conglomerates, but exposures are rare (Hubbard, 1968).

The Portage Lake Lava Series

The Portage Lake Lava Series extends as a belt one to three miles wide from the tip of Keweenaw Point southward

into Wisconsin. The southern margin of the lava series over most of the peninsula is marked by the Keweenaw fault (Figure 6). The rocks of the South Range Series, the Portage Lake Series, and Copper Harbor Conglomerate all thin westward west of Lake Gogebic, with the higher Portage Lake flows extending the furthest west of Lake Gogebic (Hubbard, 1968). White (in Hubbard, 1968) attributed this thinning to progressive lapping against a topographic high near Mellen, Wisconsin.

The Portage Lake flows are coarser in texture than the South Range series (Hubbard, 1967) and consist primarily of basalt and andesite flows. Rhyolite flows are rare and on the average constitute no more than 0.5 percent of the sequence on the Keweenaw Peninsula (Cornwall, 1951); however, the upper portion of the section at Porcupine Mountain consists of over 2000 feet of rhyolite extrusives (Rohrbacker, 1960).

The Portage Lake Interflow Sediments

The Portage Lake Lava Series are interbedded with conglomerate and sandstone beds; these rocks constitute 1 to 3 percent, and locally as much as 11 percent of the aggregate rock volume of the lava series on the Keweenaw Peninsula (Johnson and White, 1969). Marvin (1873) recognized and enumerated 22 such sedimentary horizons within the lava series (Table 6). The conglomerate and sandstone beds range in thickness from a fraction of an inch to as much as 370 feet locally, and occur at stratigraphic intervals of approximately

Table 6. Keweenaw stratigraphic column on Keweenaw Peninsula (after Spriooff and Slaughter, 1961).

Upper Precambrian	Upper Keweenaw	Freda	
		Nonesuch	
		Copper Harbor	Outer Conglomerate Lake Shore Traps Great (Eagle River) Conglomerate
	Middle Keweenaw	Portage	Hancock Conglomerate (No. 17) Ashbed Lode Pewabic West Conglomerate (No. 16) Pewabic Lode The Greenstone Flow Allouez Conglomerate (No. 15) Houghton Conglomerate (No. 14) Iroquois Amygdaloid
			Calumet & Hecla Conglomerate (No. 13)
			Calumet Amygdaloid Osceola Amygdaloid
			Kingston Conglomerate (No. 12) Kearsarge Flow
		Lava	National Sandstone Wolverine Sandstone (No. 9) Old Colony Sandstone
			Scales Creek Flow Gratiot Flow
		Series	Isle Royal Lode Behemia Conglomerate (No. 8) Copper City Flow St. Louis Conglomerate (No. 6) Lac La Belle Conglomerate Baltic Lode Baltic Conglomerate (No. 3)

- - - - - Keweenaw Fault - - - - -

1

1,000 feet, however they are more closely spaced in the upper part of the column above the Greenstone flow and in the lower portion of the series beneath the Bohemia conglomerate (Table 6). The sedimentary beds within the Portage Lake series are excellent marker horizons because of their persistence. Two of the beds, the Allouez and the Bohemia conglomerates have been recognized from the east end of the Keweenaw Peninsula to Victoria, Michigan, a distance of approximately 100 miles along the strike (Cornwall, 1955).

The conglomerate horizons are sub-parallel to one another and the aggregate thickness of the lava flows separating them remains relatively uniform along the strike. The conglomerate beds probably represent relative planar surfaces suggesting that the depositionary site was probably a piedmont alluvial fan.

Conglomerate

The conglomerate beds within the Portage Lake Lava Series are lenticular, poorly sorted, crudely stratified, and commonly a dark red to reddish brown in color. The bulk of the clastic particles range from a fraction of an inch to 6 inches in diameter. The coarsest clasts occur in the thicker beds, but rarely exceed a foot in diameter (Butler, and Burbank, 1929; White, Cornwall, Swanson, 1953). The pebbles and cobbles are generally well rounded. The beds are compact and tightly cemented. Lenses of sandstone are commonly present even in the thicker conglomerates and often

contain cross-bedding, ripple marks, and mud crack features. Shales are rare indicating that the associated finer size grains must have bypassed this region and were deposited elsewhere.

Based upon examination of underground workings and numerous drill cores in the mining districts throughout the Keweenaw Peninsula, Lane (1911), and Butler, Burbank, et al. (1929) noted the existence of two lithologically distinct conglomeratic types within the Portage Lake lava series: (1) "a felsite conglomerate" consisting largely of felsitic rock fragments with minor mafic fragments, and (2) an "amygdaloidal conglomerate" composed of mafic amygdaloidal rock fragments in a mafic sand. According to these observers, where both types are present in the same exposure, a bed of the amygdaloid type almost invariably underlies the felsite conglomerate.

Sandstone and Sandy Phases

Sandstones occur in the Portage Lake Lava Series as thin beds, as sandy lenses within conglomerates, as sandy phases marginal to thicker conglomerate lenses, and as matrix within conglomerates.

Sixty thin sections were made from samples taken within the sandy horizons and from the sandy matrix of the conglomerate horizons within the Portage Lake interflow sedimentary zones. Forty-seven of these thin sections were taken from a composite vertical section composed of several cores

drilled through the Portage Lake Lava series in the vicinity of Calumet, Michigan. Thirteen thin sections were made from samples collected from cores and outcrops elsewhere on the peninsula to indicate any lateral variation in composition when compared with the Calumet section as a standard. Figure 7 shows the sites sampled.

Table 7. Mean composition of the sandy phases within the Portage Lake interflow sediments. The composition of the detrital sand size constituents within the sandy phases of the Portage Lake Interflow sediments as represented by the mean of the modal analyses of 60 thin sections.

Constituents	Volume Frequency (%)	
	$\bar{Y}$	S
Felsite rock fragments	35.4	23.8
Rhyolite rock fragments	28.6	23.6
Mafic rock fragments	23.5	25.6
Unstrained quartz	4.6	8.5
Plagioclase	4.1	5.8
Granophyre rock fragments	2.9	4.6
Potassium feldspar	1.0	3.1
Total	100.1	

$\bar{Y}$ = mean of 60 thin sections

S = standard deviation for 60 thin sections

The felsite fragments most commonly possess a xenomorphic granular texture and consist primarily of plagioclase or potassium feldspar with only minor amounts of mafic

Figure 7. Geologic map of Keweenaw Peninsula and adjacent area, showing sites sampled for this study.

minerals. The mafic minerals commonly occur as thin needles or as small disseminated clots.

The mafic rock fragments in thin section most commonly possess either a basaltic or ophitic texture; however, those possessing an amygdaloidal texture, although rare, may be locally abundant. The mafic fragments are commonly hematized to some degree. Often, both fresh and altered mafic fragments will occur in the same thin section, but for the most part fresher mafic fragments predominate.

The rhyolite fragments most commonly consist of uniformly fine grained potassium feldspar and quartz. In some horizons large phenocrysts of quartz or feldspar were observed in the rhyolite rock fragments.

The granophyre fragments consist of radially fibrous or vermicular quartz grains inclosed within potassium feldspar host grains. Rock fragments showing textural characteristics transitional between rhyolite and granophyre were observed in certain horizons.

Feldspars constitute approximately 5 percent of the volume of the interflow sediment. Plagioclase is dominant, comprising over 80 percent of the total feldspar volume. The plagioclase consists most commonly of labradorite and andesine, of which the majority present a fresh appearance. Potassium feldspar is usually present in subordinate amounts. The most abundant potassium feldspar is an untwinned variety. Grains with gridiron twinning also occur but are rare. Perthitic feldspar was not observed.

Unstrained quartz constitutes 3 percent of the total volume of the interflow sediments. The quartz grains show simple extinction or only slightly undulose extinction. The larger grains are often embayed.

Vertical Compositional Variation in the Calumet Area Section

An analysis of the vertical compositional variation in the sedimentary succession at Calumet was made to detect any changes in provenance during middle Keweenawan time.

Table 8 shows the vertical variation in the volume frequency of the constituents in the sand phases of the Portage Lake interflow sediments in the composite section at Calumet, Michigan.

Because of the similarity in composition between the Portage Lake and Copper Harbor sediments, and because of their similar remanent magnetism, magnetic polarity, and local interfingering; the model analyses of both units within the Calumet section were combined to make a composite Keweenawan sequence. Therefore, the data, detailed analyses, and conclusions concerning the Portage Lake interflow sediments will be deferred and discussed along with the discussion of the vertical variation within the Copper Harbor Conglomerate. cursory examination of Table 8, however, suggests that the detrital constituents of the Portage Lake interflow sediments were derived from a volcanic source terrain consisting of felsic, mafic, rhyolitic and locally granophyric

Table 8. Vertical variation in Portage Lake interflow sands in the section at Calumet, Michigan.

Sediment Horizon	Mafic		Rhyolite		Grano- phyre		Felsite		Unstrained Quartz		Potassium Feldspar		Plagioclase		
	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	
TOP	18	16.9	8.6	49.0	19.7	2.1	0.1	22.3	22.2	1.6	0.8	7.6	10.7	0.5	0.7
	PHC	73.2	24.7	9.0	8.8	4.6	8.0	13.2	22.8	-	-	-	-	-	-
	PP	16.4	8.1	30.0	17.4	-	-	50.9	18.3	1.2	2.5	-	-	1.5	2.9
	PA	5.9	6.2	43.7	9.4	2.9	3.5	38.4	11.3	4.8	1.8	0.4	5.7	3.9	3.7
	PH	19.5	10.4	25.1	27.8	3.3	3.3	41.3	20.7	5.0	4.9	3.5	4.5	2.3	1.6
	PKC	3.0	4.6	62.8	28.8	-	-	8.2	13.5	21.4	16.4	0.8	2.0	3.8	6.9
	PW	14.0	11.9	15.0	18.5	-	-	63.0	16.1	2.4	2.1	-	-	5.6	7.2
	POC	18.7	5.2	17.7	14.8	2.0	3.5	41.6	16.0	2.5	2.3	4.1	7.0	13.4	13.2
	PS	85.9	4.6	2.4	2.8	-	-	1.7	2.5	0.3	0.7	-	-	9.7	4.9
BOTTOM	PB	27.4	7.8	19.2	10.5	9.6	2.7	33.0	7.7	-	-	-	-	10.8	3.5
Average volume		28.1	28.1	27.4	19.1	2.4	3.0	31.4	19.6	3.9	6.4	1.6	2.6	5.2	4.6
Average Phi Size		0.42		0.09		0.52		-0.04		1.76		1.70		1.82	

$\bar{Y}$ = mean of 47 thin sections

S = Standard deviation of 47 thin sections

rocks. No contribution from a non volcanic borderland could be detected. The local provenance did not change significantly during Portage Lake time.

Lateral Variation in Composition

In order to determine the character of lateral variation in different outcrops of the same horizon in the Portage Lake sediments, samples were taken from various locations on the Keweenaw Peninsula. The horizons chosen for sampling and comparison were those known for their lateral persistence. The Allouez Conglomerate and the St. Louis Conglomerate were selected for analysis and comparison on this basis (Table 6, Figure 7). Table 9 shows the average volume frequency of constituents within the sandy phases of the Allouez Conglomerate in the Calumet, Allouez, and Delaware area, Keweenaw Peninsula.

Comparison of the modal analyses of the Allouez Conglomerate shown in Table 9, indicates that the same lithic clasts are present in each area, but that the average volume frequency of each varies considerably from one locality to another in most cases. Of the rock fragments, the mafic grains show the least variation, whereas the felsite grains possess the most variation between outcrops. There also appears to be a proportional relationship between high rhyolite and high quartz volume frequency between outcrops of the Allouez Conglomerate.

Table 9. Lateral compositional variation within the Allouez Conglomerate. Y represents the mean volume frequency within the sandy phases of the Allouez Conglomerate in the Calumet, Allouez, and Delaware, Michigan areas, respectively.

Constituent	% Calumet		% Allouez		% Delaware	
	Area		Area		Area	
	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S
Mafic rock fragment	5.9	6.2	5.1	2.5	1.7	1.6
Rhyolite rock fragment	43.7	9.4	32.1	4.4	50.1	14.1
Granophyre rock fragment	2.9	3.5	3.8	2.5	13.6	8.6
Felsite rock fragment	38.4	11.3	55.6	1.0	17.3	6.2
Quartz, simple	4.8	1.8	3.4	3.1	17.9	2.2
Potassium feldspar	0.4	5.7	-	-	-	-
Plagioclase	3.9	3.7	-	-	-	-
Total Number (N) Counts	N = 1200		N = 400		N = 400	

The second persistent sedimentary horizon chosen for sampling and comparison of lateral variation within the Portage Lake Lava Series was the St. Louis Conglomerate. Samples of the St. Louis Conglomerate at Mass, and Donken were collected and compared with those collected in the Calumet area. Analysis of Table 10 shows that considerable variation exists laterally between the volume frequency of the various lithic constituents contained within the St. Louis Conglomerate. The table suggests that mafic grains decreased southwestward toward Mass. In addition, Table 10 indicates that the local felsic bodies were probably not rich in porphyritic

Table 10. Lateral compositional variation within the St. Louis Conglomerate. Y represents the mean volume frequency within the sandy phases of the St. Louis Conglomerate in the Mass, Donken, and Calumet, Michigan areas respectively.

Constituent	Mass Area		Donken Area		Calumet Area	
	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S
Mafic rock fragment	3.8	2.3	33.3	27.3	85.9	4.6
Rhyolite rock fragment	30.0	18.0	8.7	3.3	2.4	2.8
Granophyre fragments	-	-	2.5	5.0	-	-
Felsite rock fragments	64.3	15.0	55.2	29.4	1.7	2.5
Quartz - simple	1.1	1.6	-	-	0.3	0.7
Potassium Feldspar	-	-	-	-	-	-
Plagioclase	0.8	1.0	0.3	0.6	9.7	4.9
Total number (N) of counts	N = 400		N = 800		N = 800	

quartz at this time as there does not appear to be any correlation between high rhyolite and high quartz volume frequencies.

Analysis of the lateral variation between outcrops of the same sedimentary horizon within the Portage Lake Lava Series shows that the same compositional constituents may be present in each outcrop throughout the extent of a given sedimentary horizon. However, the analysis also indicates that the volume frequency of any constituent may be expected to vary appreciably relative to the volume frequencies of the other constituents for any given exposure within the sedimentary horizon.

The lateral variation in the volume frequencies of the various compositional constituents within the sediment may be due to the interaction between composition and topographic relief within the source area. For instance, whenever the source terrain composition is heterogenous in its extent, and the topographic relief does not vary in general character from one sector of the source area to another, then any lateral variation in the volume frequencies of the various constituents within the sediment reflect a real difference in provenance.

However, if the composition of the source terrain is essentially homogenous in its heterogeneity throughout its extent, but the topographic relief shows real changes in character from one sector to another, then any apparent lateral variation in volume frequency of the various constituents is probably weighted in favor of the specific composition of the higher elevations. The higher elevations would be expected to shed a disproportionately greater volume of sediment than the lower elevations. Thus lateral variation in the volume frequencies reflects only an apparent difference in provenance.

Regardless of the reason for variation in volume frequencies laterally, it may be said that the source for the Portage Lake interflow sediments was a volcanic source terrain consisting of mafic, felsic, rhyolitic and locally granophyric rocks.

The Copper Harbor Conglomerate

The Copper Harbor Conglomerate lies with apparent conformity upon the lavas of the Portage Lake Series and locally interfingers with them (Cornwall, 1955). The direction of magnetization of Middle Keweenaw Portage Lake Lavas is not significantly different from that of the supposedly Upper Keweenaw Copper Harbor Conglomerate (Du Bois, 1962, Book, 1968), indicating that a uniform magnetic field direction existed during the emplacement of the Portage Lake Lava Series and extended through deposition of the Copper Harbor Conglomerate.

The Copper Harbor may be divided into an upper unit, the Outer Conglomerate, and a lower unit, the Great Conglomerate, by an intervening lava sequence known as the Lake Shore Traps. These three units are present as such in the Copper Harbor conglomerate exposures from Houghton eastward to the tip of the peninsula. However, south of Houghton, the Great Conglomerate thins appreciably over a high in the Portage Lake Lava series.

The mafic Lake Shore Traps within the Copper Harbor Conglomerate succession attain their greatest development at the northeastern end of the Keweenaw Peninsula. Their thickness decreases to the southwest from a maximum of 2000 feet near the tip of the peninsula (Cornwall, 1955) to zero at Houghton (Cornwall and Wright, 1956) but reappear farther to the southwest. Only the Outer Conglomerate member and

the top of the underlying Lake Shore Trap are present farther south in the Porcupine Mountain area. In northern Wisconsin, the Outer Conglomerate is the only member of the Copper Harbor Conglomerate present.

The Copper Harbor Conglomerate varies considerably in thickness. Its thickness ranges from 6,000 feet at the tip of the Keweenaw Peninsula to about 2,000 feet in the vicinity of Houghton, to about 5000 feet in Wisconsin (White and Wright, 1960). However, in the Porcupine Mountain area the unit thins to about 300 feet over a thick pile of rhyolite flows at the top of the underlying Portage Lake series. White and Wright (1960) suggest that these rhyolitic flows formed a topographic high around a volcanic center on the surface. This rhyolitic high in the Porcupine Mountain area apparently persisted as a center of dispersal for siliceous sediments until it was buried in Outer Conglomerate time.

The Conglomerates

The sedimentary portion of the Copper Harbor consists primarily of thick conglomerates interbedded with sandstone lenses or locally of sandstone beds with scattered pebbles and conglomerate lenses. Individual sandstone units as thick as 400 to 700 feet have been reported (Cornwall, 1954,C; White and Wright, 1960).

The composition of the conglomeratic phase of the Copper Harbor varies significantly, both vertically and laterally in the Keweenawan Peninsular region. On Manibou Island, the

conglomerate phase of the Copper Harbor consists primarily of coarse basalt, andesite and rhyolite rock fragments, but notable amounts of pre-Keweenawan quartzite, granite, syenite and schist clasts appear near the top of the Great Conglomerate (Cornwall and White, 1955). Throughout much of the Keweenaw Peninsula, however, the conglomerate composition consists primarily of felsitic and mafic detritus derived from the Keweenawan terrain. Lateral comparison of clast composition suggests that the percentage of mafic fragments decrease to the southwest as the felsitic debris increases in that direction. At the southwestern end of the Keweenaw Peninsula in Wisconsin, these volcanic fragments appear to decrease upward, while pre-Keweenawan metasedimentary, granitic, and vein quartz clasts increase in abundance upward in the section (Hite, 1968).

The appearance of the pre-Keweenawan metasedimentary and plutonic clasts in the upper Copper Harbor Conglomerate on both Manitou Island and the southwestern portion of the Keweenaw Peninsula suggest that the source terrain volcanic cover was denuded in these areas exposing the underlying pre-Keweenawan rocks to the effects of erosion at this time.

Studies by Hamilton (1965) indicate that the non volcanic detritus in the southern areas of the Peninsula were derived from a source terrain located south and southwest of the present outcrop area. According to Hamblin and Horner (1961)

lithologic studies and cross stratification measurements show that the Huron Mountain area was an important center of sediment dispersal during Upper Keweenawan time.

Sandstone

The sandstone within the Copper Harbor occurs as small discontinuous lenses a few inches thick to more continuous layers 400 or more feet in thickness.

Seventy-three thin sections were made from samples collected within the sandy horizons and from the sandy matrix of the conglomerates, which locally is abundant. Forty-two of these thin sections were taken from core and outcrop samplings along the section of the Copper Harbor Conglomerate in the Calumet area, four from the section at Horseshoe Harbor, eight from the section at Copper Harbor, five from exposures in the Glazon Lake area, four from the section exposes near Eagle Harbor, and ten from a core in the Porcupine Mountain area near White Pine, Michigan (Figure 7).

The mafic rock fragments comprise approximately 24 percent of the total volume of the sandy phases within the Copper Harbor. They are predominantly basaltic in texture, hematized, and have a more weathered and opaque appearance than similar types in the underlying Portage Lake Lava Series.

The felsite, rhyolite and granophyre fragments constitute approximately 24 percent, 30 percent, and 4 percent,

Table 11. Mean composition of the sandy phases within the Copper Harbor Conglomerate. The mean composition of the sandy phases of the Copper Harbor Conglomerate as determined by the modal analyses of 73 thin sections.

Constituents	Volume Frequency (%)	
	$\bar{Y}$	S
Rhyolite rock fragments	30.5	21.3
Mafic rock fragments	24.2	22.0
Felsite rock fragments	24.2	18.5
Plagioclase	5.9	6.5
Unstrained quartz	5.5	8.0
Potassium feldspar	3.8	5.2
Granophyre rock fragments	3.7	7.1
Undulatory quartz	1.8	4.4
Polycrystalline quartz	0.3	0.7
Total %	99.9	

$\bar{Y}$ = mean volume frequency of 73 thin sections

S = standard deviation of 73 thin sections

respectively, of the total volume of the sandy phases within the Copper Harbor Conglomerate, and have the same attributes as those fragments found in the underlying interflow sediments of the Portage Lake Lava Series.

Detrital, quartz grains comprise approximately 5.5 percent of the total volume of the sandy phases within the Copper Harbor succession. In most sections the quartz grains show only slight or no undulose extinction, however, there

are two exceptions: strongly undulose quartz grains occur near the top of Great Conglomerate in the Calumet section and throughout the Outer Conglomerate in the Porcupine Mountain section, constituting 0.8 and 10.3, respectively, of the total volume frequency of detrital constituents within those sections.

Feldspars constitute approximately 10 percent of the total volume of the sandy phases within the Copper Harbor Conglomerate. Plagioclase is the dominant feldspar comprising approximately 61 percent of the total feldspar volume. The plagioclase grains consist most commonly of labradorete and andesine; they commonly show a more altered aspect than those in the underlying Portage Lake Series.

Potassium feldspars make up 3.8 percent of the total volume of the sandy phases. The most abundant potassium feldspar is an untwinned variety. Perthitic feldspars occur in the Porcupine Mountain section and in the Calumet section near the top of the Great Conglomerate just beneath the Lake Shore Trap.

Vertical Compositional Variation

Evaluation of the vertical compositional variation within the sandy phases of the composite section containing the Portage Lake interflow sediments and the Copper Harbor Conglomerate at Calumet (Tables 7 and 11), and within the Copper Harbor Conglomerate sections at Copper Harbor (Table 12), and at Porcupine Mountain (Table 13) was made to detect

Table 12. Vertical compositional variation within sandy phases of the Copper Harbor Conglomerate in the section at Calumet.

Sedimentary Horizon	Mafic		Rhyolite		Grano- phyre		Felsite		Unstrained Quartz		Undulose Quartz		Polycrystal Quartz		Potassium Feldspar		Plagio- clase	
	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S
TOP																		
GCF	20.7	10.8	34.6	4.7	-	-	1.5	2.4	12.8	2.1	4.0	1.4	1.2	1.4	17.0	7.9	8.2	6.1
GCE	14.0	7.3	39.5	21.6	1.6	2.6	-	-	14.0	5.9	3.7	4.8	-	-	9.1	4.0	18.1	12.3
122	15.0	5.7	52.1	12.5	6.1	7.5	13.7	13.5	3.0	2.4	0.1	1.4	-	-	6.4	4.8	3.6	4.8
US1	17.7	4.5	66.3	8.4	-	-	-	-	5.2	7.4	-	-	-	-	8.1	0.3	2.7	3.7
US2	12.4	8.2	29.7	24.0	2.9	4.9	44.0	19.7	2.3	1.9	-	-	-	-	2.1	4.2	6.6	4.9
221	9.4	0.4	51.7	13.1	1.4	2.0	16.6	21.5	1.4	2.0	-	-	-	-	7.8	6.7	11.7	2.8
US3	19.5	8.0	34.4	19.0	-	-	34.6	17.1	1.3	21.2	-	-	-	-	1.0	1.7	9.2	4.8
220	8.8	4.1	41.4	10.4	5.1	7.4	30.7	13.9	1.5	1.9	0.6	0.8	-	-	2.3	2.3	9.6	4.0
US4	11.4	5.2	34.2	11.2	20.5	8.6	22.4	8.3	5.4	5.4	-	-	-	-	2.1	1.7	4.0	1.4
BOTTOM	219	7.6	3.5	54.0	17.5	0.6	1.1	29.3	16.0	2.1	2.0	-	-	-	1.3	1.5	5.1	3.4
Volume Average Frequency	13.7	4.6	43.8	11.7	3.8	6.2	19.3	15.6	4.9	6.5	0.8	1.6	0.1	0.4	5.6	5.1	7.9	4.6
Average Phi Size	1.43		0.80		0.81		0.80		1.73		1.70		1.39		2.08		2.04	

 $\bar{Y}$ = mean volume frequency within each sedimentary horizon

S = volume frequency standard deviation present in each sedimentary horizon

Table 13. Vertical compositional variation within the sandy phases of the Copper Harbor Conglomerate in the section at Copper Harbor.

Sedimentary Horizon		Mafic (%)	Rhyolite (%)	Felsite (%)	Plagioclase (%)
TOP	CH-1A	67.1	1.1	31.8	-
	CH-1B	62.8	2.6	34.6	-
	CH-61	68.5	12.3	19.2	-
	CH-62	76.6	1.3	22.1	-
	CH-71	79.2	3.9	11.7	5.2
	CH-72	72.8	2.5	19.8	4.9
	CH- 8	72.1	27.9	-	-
BOTTOM	CH-10	69.4	8.1	17.7	4.8
Avg. Vol. Freq. (%)		73.1	9.3	15.1	2.5
Standard Deviation		4.1	10.0	8.2	2.7
Average Phi Size		0.36	0.60	0.57	1.14

any changes in provenance occurring during Keweenawan time as represented by these units.

Least square regression analysis and the 2 x 2 chi square contingency method were used to evaluate the vertical variation among the volume frequencies of the various detrital constituents. The analysis procedure is identical to that employed in evaluating the vertical variation within the Mamainse Point section.

Analyses of the plots of the (observed-expected) volume frequency with depth reveal no significant residual effects

for the mafic, felsite, and granophyre rock fragments or the quartz or plagioclase clasts upward within the combined section at Calumet. However, significant residuals ($P_{\chi^2} > 0.05$) were found for both the rhyolite fragments and the potassium feldspar clasts (Figures 8 and 9).

Thus it may be concluded that only the rhyolite and potassium feldspar show significant changes in their volume frequencies upward in the section; both increasing in abundance upward. Since there is no real change in the volume frequencies of the other compositional constituents, then any apparent changes in the volume frequencies of these constituents vertically in the section must be due largely to the grain-size effect and the capricious nature of the depositional environment.

Lateral Compositional Variation

The six vertical sections through the Copper Harbor Conglomerate which were studied in this report, from south to north, respectively, are in the vicinity of the Porcupine Mountain, Calumet, Eagle Harbor, Glazon Lake, Copper Harbor and Horseshoe Harbor (Figure 7).

The lateral variability of the Copper Harbor Conglomerate is shown in Table 15 and suggests the existence of local compositional variations.

In the Horseshoe Harbor, Copper Harbor, and Glazon Lake areas, mafic clasts are the most abundant detrital sand constituent ranging from 44 to 73 percent. In the Calumet

Figure 8. Graphs of the vertical compositional variation within the Portage Lake interflow sediments. Graphs show the residuals resulting when the (observed-expected) volume frequencies of the various detrital constituents are plotted versus their depth in the composite Keweenawan interflow section at Calumet. Graph A is the plot for mafic clasts, Graph B is rhyolite clasts, Graph C is for felsite clasts, and Graph D is for granophyre clasts.

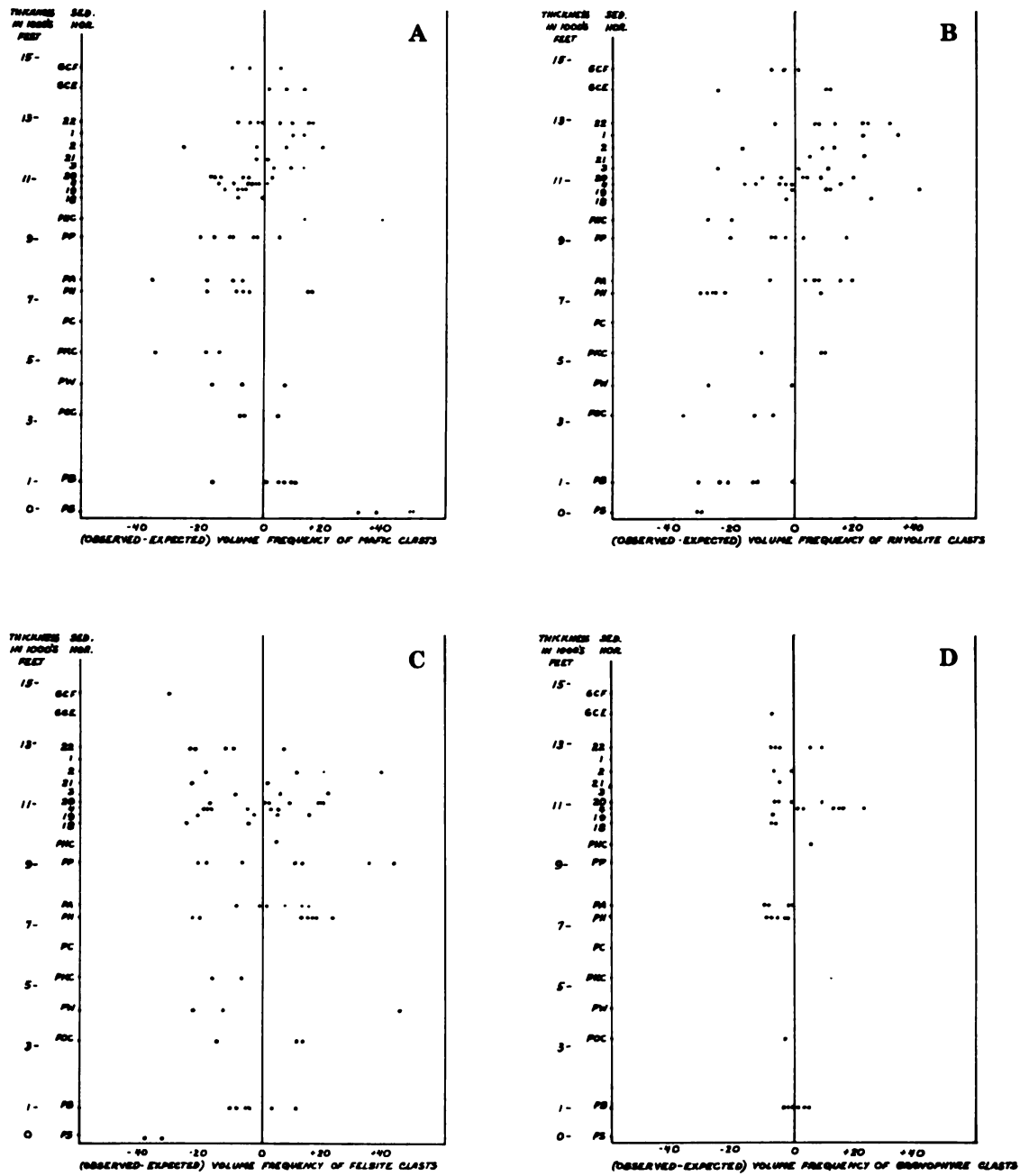


Figure 8

Figure 9. Graphs of the vertical compositional variation within the Portage Lake interflow sediments. Graphs show the residuals resulting when the (observed-expected) volume frequencies of the various detrital constituents are plotted versus their depth in the composite Keweenawan interflow section at Calumet. Graph E is the plot for unstrained quartz clasts, Graph F is for potassium feldspar clasts and Graph G is for plagioclase clasts.

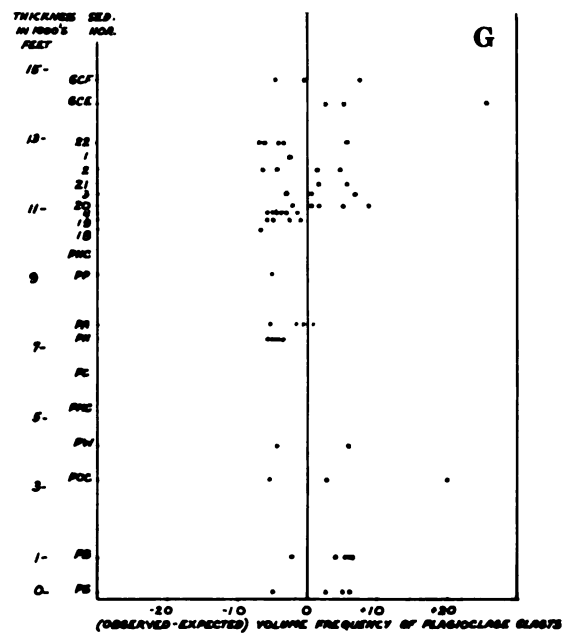
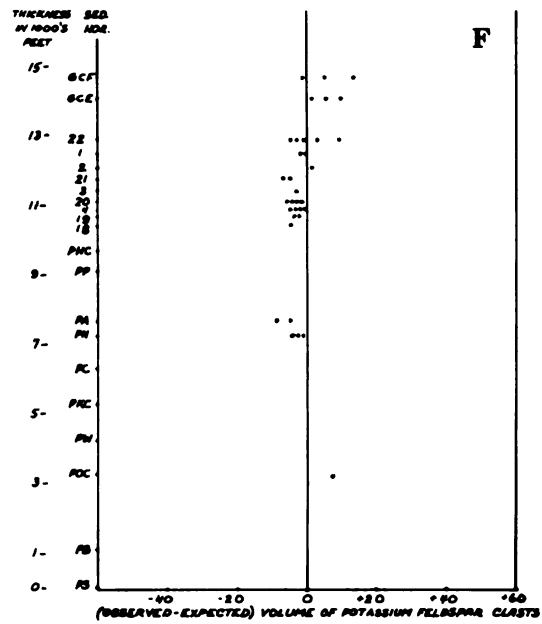
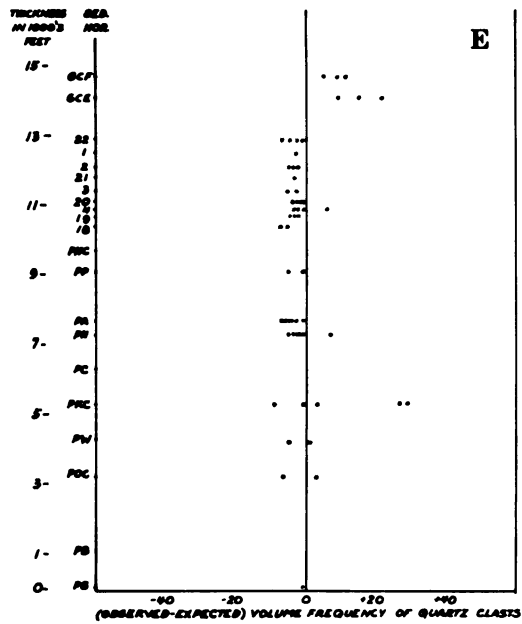


Figure 9

Table 14. Vertical compositional variation within the sandy phases of the Copper Harbor Conglomerate in the section at Porcupine Mountain.

Sedimentary Horizon	Mafic (%)	Rhyolite (%)	Granophyre (%)	Felsite (%)	Unstrained Quartz (%)	Undulose Quartz (%)	Polycryst. Quartz (%)	Potassium Feldspar (%)	Plagioclase (%)
TOP									
WP-2	4.9	11.1	14.8	21.0	19.8	4.9	-	16.1	7.4
WP-3	5.6	10.0	-	20.0	37.8	23.3	-	2.2	1.1
WP4-A	13.3	19.4	2.4	26.8	18.2	10.9	2.4	3.0	3.6
WP-4	37.5	20.5	2.3	29.5	3.4	-	-	2.3	4.5
WP-5	14.1	25.9	-	21.2	16.5	9.4	3.5	4.7	4.7
WP-6	9.7	14.9	-	17.7	26.8	21.7	2.3	2.9	4.0
WP-7	19.6	10.6	-	30.7	22.3	8.9	2.2	3.9	1.7
WP-8	15.2	22.4	4.2	22.4	20.6	8.5	-	6.7	-
WP-9	20.4	8.6	-	14.5	25.0	9.2	2.6	5.9	13.8
BOTTOM WP-10	17.1	9.2	-	21.1	17.1	5.9	1.3	11.2	17.1
Avg. Vol. Frequency	15.7	15.3	2.4	22.5	20.8	10.3	1.4	5.9	5.8
Standard Deviation	9.3	6.3	4.6	5.1	8.7	7.1	1.3	4.5	5.6
Average Phi Size	0.88	0.75	0.51	0.84	1.48	1.54	1.31	1.78	1.37

$\bar{Y}$ = mean volume frequency within each horizon

S = volume frequency standard deviation within each horizon

Table 15. Lateral composition variation within the sandy phases of the Copper Harbor Conglomerate.

Constituent	Porcupine Mountain		Calumet Section		Eagle Harbor Section		Glazon Lake Section		Copper Harbor Section		Horseshoe Harbor Section	
	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S	$\bar{Y}$	S
Mafic	15.7	9.3	13.7	4.6	15.2	10.7	50.8	11.3	73.1	4.1	44.4	27.5
Rhyolite	15.3	6.3	43.8	11.7	39.4	23.9	10.2	9.3	9.3	10.0	3.6	0.6
Granophyre	2.4	4.6	3.8	6.2	3.5	4.7	0.5	1.2	-	-	-	-
Felsite	22.5	5.1	19.3	15.6	29.0	35.9	36.5	19.1	15.1	8.2	54.6	25.8
Unstrained Quartz	20.8	8.7	4.9	4.7	1.3	1.0	0.5	1.2	-	-	-	-
Undalose Quartz	10.3	7.1	0.8	1.6	-	-	-	-	-	-	-	-
Polycrystalline Quartz	1.4	1.3	0.1	0.4	-	-	-	-	-	-	-	-
Potassium Feldspar	5.9	4.5	5.6	5.1	0.9	1.8	0.3	0.6	-	-	-	-
Plagioclase	5.8	5.6	7.9	4.6	10.7	13.7	1.2	0.9	2.5	2.7	0.7	1.3
Total "N"	2000		8200		800		1000		1600		600	

Average Diameter (phi size)				
Average Phi Size	Porcupine Mountain		Eagle Harbor Section	
	$\bar{Y}$	S	$\bar{Y}$	S
Rock Fragments	0.86		0.96	
Detrital Mineral Grains	1.54		1.88	
			0.30	
			0.64	
			0.51	
			1.14	
			0.68	
			1.55	

and Eagle Harbor areas rhyolite clasts rank first in abundance, averaging between 44 to 40 percent. Figure 10 indicates that an inverse relationship exists between the mafic and rhyolite volume frequencies.

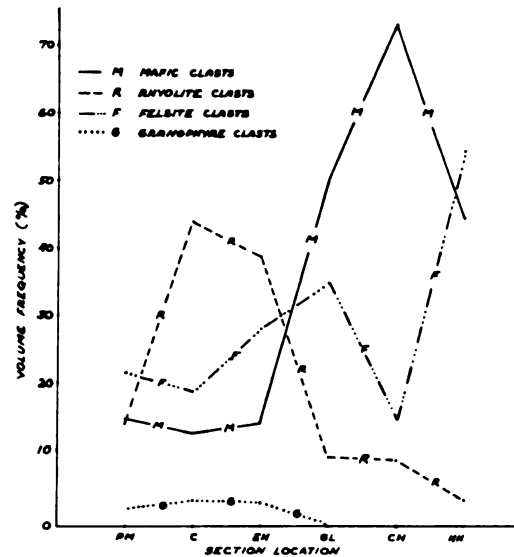
Felsite rock fragments are present in all sections and range in average volume frequency from a low of 19 percent in the Calumet area to a high of almost 55 percent in the vicinity of Horseshoe Harbor.

Granophyre grains are most abundant in the Calumet and Eagle Harbor sections where the average volume is approximately 3.7 percent, but elsewhere range in abundance from 0 (Copper Harbor) to 2.4 percent in the Porcupine Mountains. This distribution suggests there were several nearby centers of dispersal: the mafic constituents appear to increase to a maximum in volume frequency northeastward, while the rhyolite and granophyre clasts reach a maximum frequency in the Calumet-Eagle Harbor area (Figure 10).

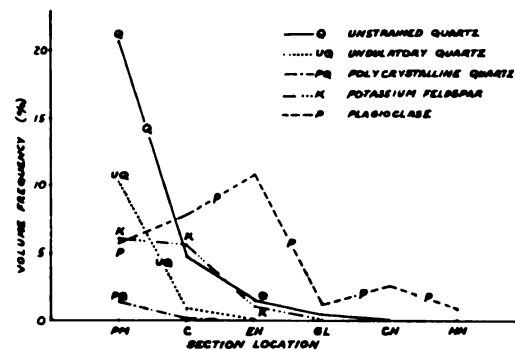
Unstrained quartz grains are most abundant in the Porcupine Mountain and Calumet sections with an average volume frequency of 20 and 4.9 percent, respectively. Elsewhere unstrained quartz grains occur in amounts of 1 percent or less. Undulose quartz grains were observed only in the Porcupine Mountain (10.3 percent) and Calumet sections (0.8 percent).

The unstrained quartz, undulose quartz, polycrystalline quartz, and potassium feldspar are most abundant in the

A. LATERAL VARIATION IN LITHIC SAND-SIZE CLAST COMPOSITION WITHIN THE COPPER HARBOR CONGLOMERATE



B. LATERAL VARIATION IN DETRITAL MINERAL COMPOSITION WITHIN THE COPPER HARBOR CONGLOMERATE



LOCATION		LEGEND	
PM	PODCUPINE MOUNTAIN	SL	SLAZON LAKE
C	CALUMET	CH	COPPER HARBOR
EH	EAGLE HARBOR	NH	NORSEMAN HARBOR

Figure 10. Lateral compositional variation within the sandy phases of the Copper Harbor Conglomerate.

Porcupine Mountain area where the volume of monomineralic grains within the sediment collectively makes up 44 percent of the detrital composition. The Porcupine Mountain section is stratigraphically higher than the more northern sections on the Keweenaw peninsula. The greater percentage of detrital monomineralic grains within the Porcupine Mountain section, therefore, may indicate a more advanced stage of weathering and breakdown of the rocks in the source area, resulting in a greater percentage of monomineralic grains within the sedimentary detritus in late Copper Harbor time.

Throughout the sections studied on the Keweenaw peninsula the amount of feldspar and quartz appears to be inversely related to the amount of mafic debris. Where the volume of mafic detrital grains are high, low values of feldspar occur due to the failure of the lava flows to decompose and release the individual grains. Low quartz volumes occur in any case because of the deficiency of quartz in a mafic source rock. Grain size undoubtedly exerts an affect on lateral compositional variation, but it is thought that the major factor causing the lateral variation is a difference in provenance laterally.

Thus the majority of the Upper Keweenawan interflow sediments were derived from a Keweenawan age volcanic source terrain consisting of mafic, felsitic, rhyolitic, and granophyric rocks. However, the relative scarcity of unstrained, strained, and polycrystalline quartz in the northernmost

sections and their increasing abundance southwestward in the Porcupine Mountain and CaIumet sections (especially just below the Lake Shore Trap horizon) suggests incursion of detritus locally from a pre-Keweenawan plutonic and/or metamorphic source terrain.

The source area borderland therefore probably consisted of plutonic and/or metamorphic rocks mantled by volcanic rocks. The volcanic rock cover may have been breached near the Mellen to Porcupine Mountain area and again near the Manitou Island area, thus exposing the underlying plutonic and/or metamorphic rocks to erosion.

The source area borderland was probably located just southward of the presently exposed Keweenawan outcrops and is represented by the occurrence of abundant lower Keweenawan diabase dikes exposed in Animikean metasedimentary and plutonic rocks and a gabbro-granophyre complex which intrudes Keweenawan and possibly pre-Keweenawan rocks (Aldrich, 1929; Tyler, 1940; Leighton, 1954; White, 1966). The bordering source area front would at least follow a line connecting the Mellen-Huron Mountain area. According to Hamblin and Horner (1961) lithologic studies and cross stratification measurements show that the Huron Mountain area was an important center of sediment dispersal during upper Keweenawan time.

Sedimentary Synopsis

The compositional immaturity of the interflow sediments within the Portage Lake Lava Series and the Copper Harbor Conglomerate easily facilitates the determination of the parent material. It appears evident that the middle Keweenawan and the majority of the upper Keweenawan interflow sediments were derived from a Keweenawan age volcanic source terrain consisting of mafic, felsitic, rhyolitic and granophyric rocks. However, the presence of appreciable undulose quartz in the Porcupine Mountain and Calumet sections of the upper Copper Harbor Conglomerate just below the Lake Shore Trap horizon suggests incursion of detritus locally from a pre-Keweenawan plutonic and/or metamorphic source terrain.

The source area, dominated by an extensive and thick sequence of volcanic rocks was tectonically unstable which encouraged the production of large amounts of detritus from local sources during periods of little or no volcanic activity. The coarse texture of the Keweenawan interflow sediments and their predominantly volcanic composition bear witness that the Keweenawan lavas, acting as a source, existed as local uplands.

The deposition and preservation of such a thick succession of flows and sediments indicates a rapidly subsiding basin in which continued downwarping produced a topographic depression into which not only lava flows moved but streams

flowed and deposited detritus shed from borderlands during periods of volcanic quiescence.

An apparent difference in volume frequency exists between the composition of the middle and upper Keweenaw lava flows and the composition of the interflow sediments contained within them. According to Butler, Burbank et al. (1929), Cornwall (1951) the middle Keweenaw lavas consist of approximately 92 percent or more basalt and andesite rocks and locally no more than 8 percent rhyolitic (0.5% p and felsitic rocks (7.5%). Yet the average composition of the interflow sediments consists of 30 percent felsite, 29 percent rhyolite and only 24 percent mafic fragments. All fragments show little effects of extensive weathering. This disparity suggests two possible alternative explanations: either (1) the more silicic middle Keweenaw rock bodies locally formed the higher elevations, consequently they were subjected to more severe erosion than the mafic flows and thus furnished a disproportionate amount of sediment, or (2) the interflow sediments are not of immediate derivation from middle Keweenaw rocks but came from long-lived uplands composed of a higher percentage of felsitic-rhyolitic rocks.

Hubbard (1967, 1968) suggests that the rocks of the South Range Series; existing locally as upland highs, furnished the sediment intercalated with the middle Keweenaw lava flows during Portage Lake and Copper Harbor time. His deductions are based upon his observation that (1) the

mafic pebbles within the Portage Lake sediments are typically fine grained--no ophitic pebbles having been found, whereas the Portage Lake flows tend to be much coarser with ophitic flows being common throughout its succession. The presence of abundant pebbles typical of the South Range Series suggests to him that the South Range was therefore the source for the middle Keweenawan interflow sediments.

2. The interpretation of the magnetic anomaly present in the covered interval separating the South Range Series from the overlying Portage Lake Series suggests that this interval is underlain by felsites and sedimentary rock (Hubbard, 1968). This is corroborated by the observation that outcrops of felsite are reported in Wisconsin along the strike of the covered interval (Hubbard, 1968). Here also, Aldrich (1929) describes rhyolite flows with rhyolite conglomerate resting upon them, in which the conglomerate appears to be derived from the flows. Thus, the thick succession of rhyolite postulated to occur in the covered interval would be conveniently located to supply the abundant felsic detritus present in the middle Keweenawan sediments.

(3) The unconformable relationship between the South Range Series (of lower Keweenawan age) and the Portage Lake Series (of middle Keweenawan age) agrees with paleomagnetic data which indicate reversed polarity for the former and normal polarity for the latter, and

(4) The dips of the South Range Series indicate that they were part of an anticlinal flexure (Hubbard, 1968)

whose formation may be related to the intrusion of a large gabbroic-granophyre complex in the Mellen area of Wisconsin.

But regardless of the identity of the source rock, the existence of a nearby source terrain of some height and relief located to the south of the present Keweenawan exposures is suggested by the coarseness, thickness, and directions of cross bedding and imbrication contained within the Portage Lake and Copper Harbor sedimentary sequences (White and Wright, 1960; Hamilton, 1965; Hite, 1968).

The source terrain was probably related to the intrusions of the gabbro-granophyric complex at Mellen, Wisconsin. The scale of these intrusions suggests they were associated with tectonic uplift in areas which were mantled with Keweenawan volcanic rocks. Furthermore unroofing and much erosion has occurred in this area as indicated by the exposure of an extensive and widespread diabase dike swarm of lower Keweenawan age within pre-Keweenawan metasedimentary and plutonic rocks in the Huron Mountain area to the south of present Keweenawan exposures.

In summary, it is suggested that a volcanic sequence south of the present Keweenawan outcrops was uplifted and was being eroded during Portage Lake and Copper Harbor time. The thick succession of rhyolite postulated to occur in the covered interval between the Portage Lake Series and South Range Series would be conveniently located to supply the abundant felsic detritus present in Portage Lake and Copper

Harbor sedimentary zones. The thick sequence of rhyolitic flows in the Porcupine Mountain area, which existed as a topographic high throughout much of Copper Harbor time (White in Hubbard, 1968) and possibly earlier, may have also furnished felsic debris to be incorporated in the interflow sediments.

Paleogeography and Sedimentation

The coarseness and compositional immaturity of the conglomerates and sands comprising the Portage Lake and Copper Harbor sequences indicate a nearby source of some relief. These attributes also suggest that the sediment underwent a short transportational history and rapid deposition in a sedimentary basin which was rapidly sinking.

The marginal uplift of the volcanic terrain coupled with subsidence of the central portions initiated erosion, transportation, and deposition of volcanic conglomerates and arenites by a fluvial system on a piedmont fan. Shales are rare, indicating that the associated finer sized grains must have bypassed this region and were deposited elsewhere, probably as a flood plain sequence in the more central portion of the basin.

The coarse nature of the sands and conglomerates, the presence locally of channels with disconformable bases, high angle cross strata, and the typically poor sorting and rounding generally present in the sandy phases suggests that the interflow sediments comprising both the Portage Lake and

1

Copper Harbor series were transported by a fluvial system characterized by relatively high energy conditions and high gradients. Uplift of the highlands plus subsidence of the basin maintained a well-drained, dissected surface consisting of channels and flood plains. The presence of standing bodies of water is affirmed by the presence of algal-ball-like bodies in the Porcupine Mountain area (Hite, 1968) and stromatolites (Cornwall, 1951) in the section exposed at Horseshoe Harbor. The upland was probably rugged but possessed only moderately high relief.

The evidence presented in this study suggests that the most likely location for the source area borderland of both the south shore Keweenaw volcanic rocks and their intercalated sediments was just southward of the presently exposed Keweenaw outcrops. This area is represented by the occurrence of abundant lower Keweenaw diabase dikes exposed in Animikean metasedimentary and plutonic rocks and a gabbro-granophyre complex which intrudes Keweenaw and possibly also pre-Keweenaw rocks (Tyler, 1940; White, 1966).

CHAPTER V

THE NORTHWEST SHORE REGION OF LAKE SUPERIOR

The northwest shore region of Lake Superior, extending from Duluth to Schreiber forms a crescent shaped area occupied by the Sibley-Osler Series and the North Shore Volcanics which comprises the northwest flank of the Lake Superior Syncline (Figure 9). It contains Keweenawan sequences which when taken together represent all three divisions of Keweenawan rocks. Sedimentary sequences of lower Keweenawan age are exposed in the Thunder Bay area, where they are known as the Sibley Series, and in northeastern Minnesota, where they are represented by the Puckwunge formation. The Osler Lava Series of lower and possibly middle Keweenawan age overlaps the Sibley Series. The North Shore Volcanic Group exposed along the Lake Superior shore of Minnesota is of lower and middle Keweenawan age. The section on Isle Royale consists of middle Keweenawan lavas overlain by an upper Keweenawan sedimentary sequence.

The Keweenawan rocks of the northwest shore are intruded by the Duluth Gabbro complex of lower to upper Keweenawan age, the Logan diabase dikes largely of middle Keweenawan age (Figure 11).

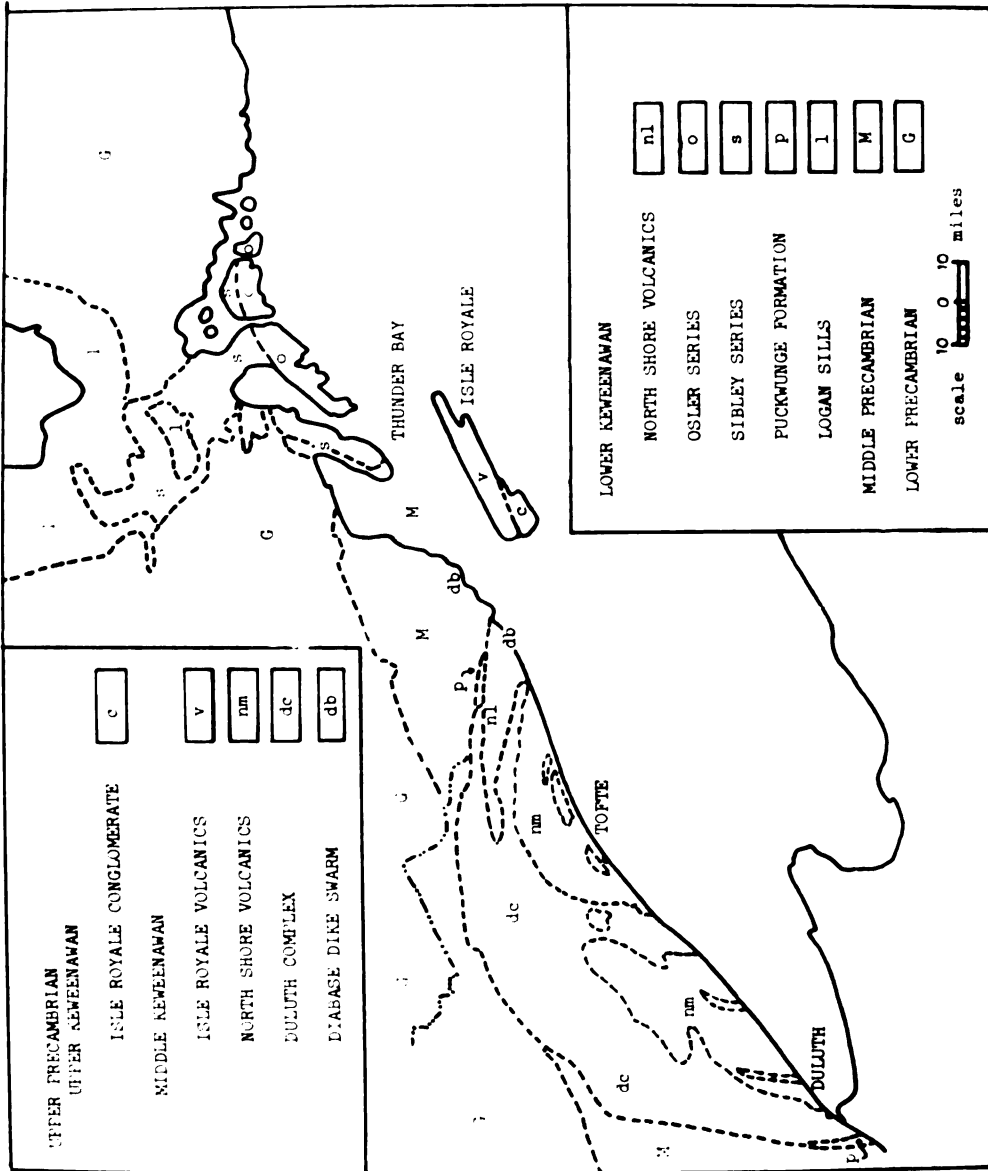


Figure 11. Geological map of the northwest shore region of Lake Superior (after Halls, 1966; Palmer, 1970; Green, 1971).

Detailed mapping of the North Shore Volcanic Group began with Sandberg's (1938) description of the succession between Duluth and Two Harbors. Additional stratigraphic studies elsewhere in the sequence have been made by Schwartz (1959, 1949), Grogan (1940), Gehman (1957), Grout et al. (1949), and Green (1966, 1968, a. b., 1970). The section on Isle Royale has been mapped and described by Lane (1898, 1911), Huber (1971), and Wolff (1968). The Sibley and Osler Series were mapped and described by Tanton (1931).

The Isle Royale Sequence

Isle Royale possesses the only Keweenawan section on the northwest limit of the Lake Superior syncline which exhibits the top of the volcanic sequence and also an overlying Keweenawan sedimentary succession. The shape of the island closely follows the strike of the Keweenawan rocks of which it is composed. The bulk of Isle Royale is occupied by the volcanic sequence (which is similar to the Portage Lake Lava Series) and the remainder by the overlying sedimentary unit (much like the Copper Harbor Conglomerate) which is limited to the southwest part of the island (Lane 1898, 1911; Huber, 1971).

According to Huber (1971), the only major structural distortion on the island involves the upper portion of the Portage Lake Lava Series, which is warped around a node of apparent uplift and fracturing. Evidence of the presence of

nearby uplift seems to be a typical attribute to most Keweenaw sections exposed around Lake Superior.

The Isle Royale Volcanic Series

The volcanic sequence on Isle Royale consists of a series of basaltic, andesitic, and rare rhyolitic flows, with interbedded sandstones, conglomerates and tuffaceous rocks. The fragmental rocks make up less than 10 percent of the lava series on the island (Huber, 1971). Huber (1971) also recognized seven interflow conglomerates and sandstone units in the uppermost part of the volcanic sequence. He notes that these units are generally less than 25 feet thick and normally persist over the length of the island.

According to Lane (1898) the interbedded conglomerates are composed of volcanic rock fragments consisting primarily of abundant felsite and quartz porphyry pebbles in addition to mafic clasts. As with the Portage Lake interflow sediments, the presence of felsite and quartz porphyry pebbles is somewhat anomalous in view of the rarity of felsite volcanic rocks within the lava succession.

The Isle Royale Conglomerate

The Isle Royale Conglomerate overlies the Isle Royale Volcanic series and forms a clastic wedge which thickens in an easterly direction in a distance of 20 miles from a minimum of 1,500 feet to over 6,000 feet between stratigraphic marker horizons (Huber, 1971). Lane (1898, 1911), and Huber

(1971) report that with the exception of a few quartzite pebbles, essentially all rock fragments in the Copper Harbor Conglomerate are of volcanic origin, with felsic fragments predominating slightly over mafic ones.

Wolff (1969) reports that the coarse-grained sandstones within the Isle Royale Conglomerate normally contain greater than 50 percent mafic and felsic volcanic rock fragments. However, the fine to very grained sandstones generally contain less than 2 percent volcanic rock fragments, only traces of sedimentary and metamorphic rock fragments, but about 60 percent quartz, and between 10 to 25 percent feldspars, which suggests that a not-too-distant, non-volcanic source terrain was also contributing important quantities of fine-sized detritus to the basin of deposition of this time.

Huber (1971) noted that the felsic and mafic volcanic pebble types found in the Isle Royale sedimentary sequence are unlike the exposed underlying volcanic sequence on the Island, but are similar to the flows exposed in the North Shore Volcanic Group in Minnesota. These observations led him to suggest the possibility of an unconformity between the North Shore Volcanic Group and the Isle Royale volcanic sequence, similar to that proposed by Hubbard (1968) in western Michigan between the South Range Series and the Portage Lake Lava Series. Such an unconformity would permit the erosion of the lower volcanic sequences at the uplifted margins of the basin during periods of volcanic quiescence,

1

while the sedimentary rocks were being deposited within the basin.

The source terrain for the Isle Royale sediments, based upon studies by Wolff (1969) and Huber (1971) utilizing data derived from their studies of sedimentary directional structures, from textural changes within the sediment; and from the composition of the boulders and cobbles within the conglomerate beds, is deduced to be just west of Isle Royale. The direction of sedimentary transport as inferred from current indicators was from the southwest, west, and northwest and suggests that the source terrain may have been part of the North Shore Volcanic Group.

The North Shore Volcanic Series

The base of the Keweenawan sequence in northeastern Minnesota is made up of the Puckwunge formation, an ortho-quartzite and quartz conglomerate no more than 200 feet thick. It is immediately overlain, wherever found, by the North Shore Volcanic Group of lower and middle Keweenawan age. The North Shore Volcanic Series consists of a thick sequence of Keweenawan lavas intercalated with small amounts of sandstone. The rocks of this series occupy a broad arcuate belt running along almost the entire coast of Lake Superior from Duluth to Grand Portage (Figure 12).

Shoreline exposures of the North Shore Volcanic outline a broad synclinal structure of which the youngest horizons

occur in the vicinity of Tofte. The strike of the volcanics remain parallel to the coast for much of their outcrop length, but intercept the coast at acute angles toward either end at Duluth and Grand Portage. The rocks generally dip lakeward at angles ranging from about 25° to 10° .

The thickness of the North Shore volcanic succession on the south limb of the synclinal structure in Minnesota, has been estimated by Green (1971) to have a minimum total thickness of 28,000 feet. The sequence of flows making up the northeast limb of the North Shore Volcanic Group between Tofte and Grand Portage totals about 21,500 feet (Green, 1971).

Olivine basalt is the most common lava flow-type present in the North Shore Volcanic Group, but andesites and latities are also present (Green, 1971). Rhyolite is thought to comprise about 10 to 15 percent of the total thickness of the southwest limb of the sequence (Sandberg, 1938), Schwartz (1959), while making up approximately 10 percent of the volcanic series on the northeast limb (Schwartz, 1959).

The intrusive rocks, associated with the North Shore Volcanics consist of the Duluth Gabbro Complex and the Logan diabase dikes.

The paleo-magnetic pole positions of the gabbro and the lavas it intrudes are very similar, which suggests that only a short time interval separated the extrusive and intrusive episodes (Du Bois, 1962). A portion of the Complex may even

predate the North Shore Volcanic Series (Nathan, 1969; Davidson, 1971). Thus the intrusion of gabbro must have occurred at intervals throughout lower and beginning upper Keweenawan time. Therefore, partial unroofing of gabbroic bodies may have taken place well before the end of middle Keweenawan time, which would explain the abundant plagioclase and pyroxene within the interflow sediments.

Interflow Sediments

The interflow sediments make up approximately 500 feet or 3 percent of total thickness on the northeast limb of the North Shore Volcanic group in the Grand Portage of Tofte Sequence, but comprise only slightly more than 300 feet or 1 percent of the total succession thickness exposed on the southwest limb.

The interflow sandstones contained within the North Shore Volcanic Series may overlie either amygdaloidal conglomerates or rest directly on the amygdaloidal top of the underlying flow units. Interflow sandstones containing conglomeratic units are very rare within the North Shore Volcanic sequence.

The interflow sandstones within the North Shore Volcanic Series are buff to reddish brown, and consist predominately of fine grained, well-sorted, sub-rounded to rounded grains. A fine lamination is characteristic, but beds from 1/2 inch to several inches in thickness occur in the thicker deposits. The thinly bedded units are often structureless, but in thin

section frequently show graded bedding alternating with laminae consisting of heavy mineral concentrations. Cross bedding occurs commonly in the thicker units with the tabular variety being most frequent, followed by the planar, and trough types, respectively. Asymmetrical ripple marks and shale chips are not uncommon. In one instance ripple marks with the coarsest grains on the crest, suggesting an eolian origin, were observed.

The lower surface of the interflow sands is conformable with the surface structure of the underlying flow, while the upper surface of the sandstone is flat or sometimes slightly undulating. Grogan (1940) and others note that no soil zone was found above any of the sandstone layers.

Interflow sandstones occur within the North Shore Volcanic Group as thin beds, as lenses and as crevice fillings. Fifty-five thin sections were made from samples collected from within these sandstone units. All samples were collected solely from outcrops (Figure 12).

Detrital feldspars constitute almost 48 percent of the total average volume of interflow sandstones within the North Shore Volcanic Group. Plagioclase is the dominant feldspar comprising 97 percent of the total average feldspar volume. The most common varieties of Plagioclase appearing in the interflow sands are labradorite and andesine. The majority of the grains are fresh, especially those appearing within the sediments on the northeast limb of the North Shore Volcanics.

Figure 12. Location map (after Green, 1971) showing the sites at which the North Shore Volcanic Series interflow sediments were sampled for this study. The number code on the map corresponds to the following sedimentary horizons: 1=DUL, 2=LE, 3=LR, 4=PSN, 5=PSD, 6=PSC, 7=PSB, 8=PS3, 9=PS2, 10=PS1, 11=TR, 12=FR, 13=OR, 14=BP, 15=CR, 16=GH, 17=PB.

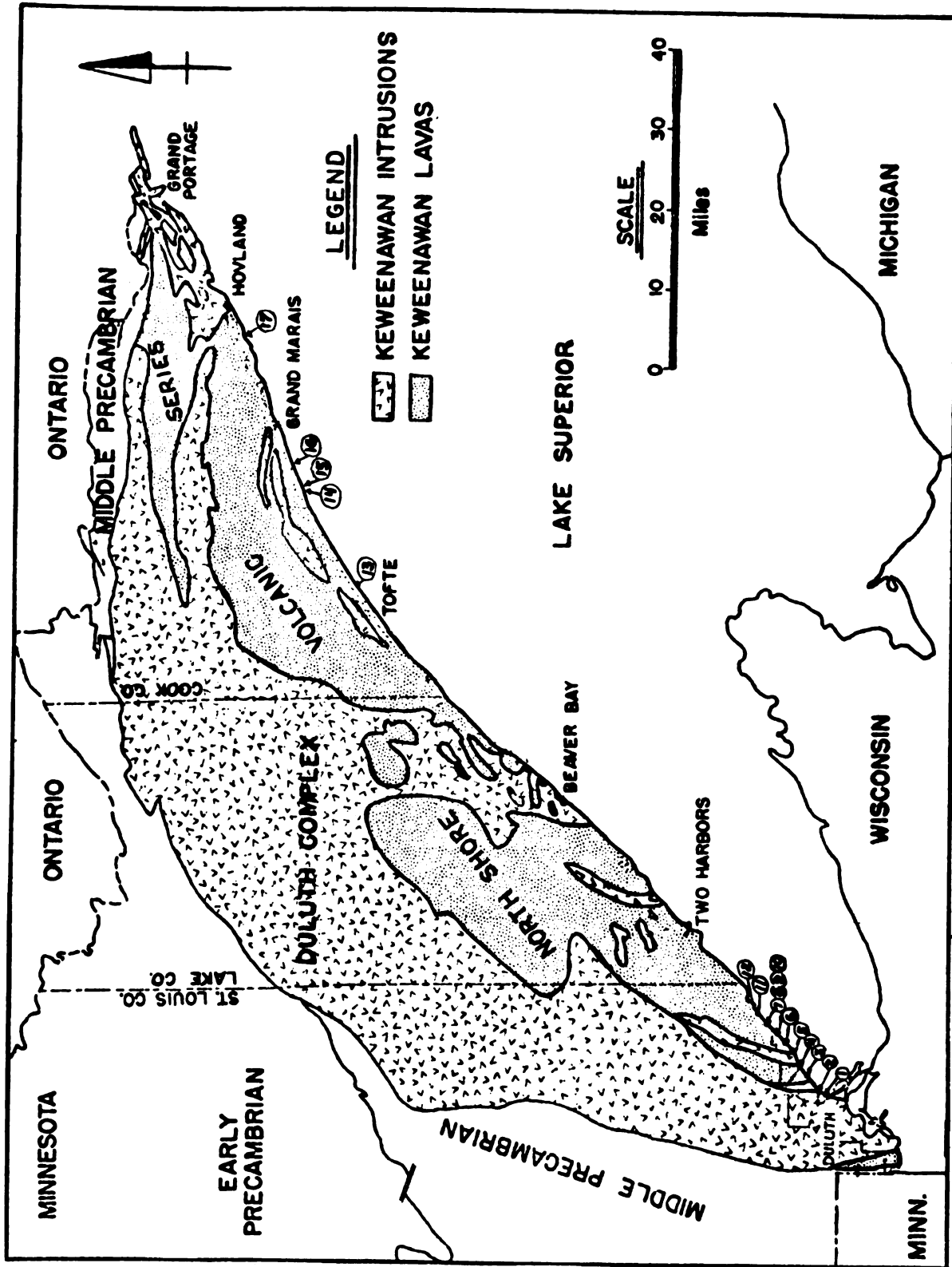


Figure 12

Table 16. Mean composition of the North Shore Volcanic Series interflow sediments. The composition of the detrital sand size constituents within the interflow sediments of the North Shore Volcanic Series as represented by the mean of the modal analyses of 55 thin sections.

Constituents	Volume Frequency (%)	
	$\bar{Y}$	S
Plagioclase	46.4	24.5
Mafic rock fragments	25.6	23.5
Rhyolite rock fragments	5.6	20.8
Felsite rock fragments	5.1	10.7
Pyroxene	4.8	8.2
Unstrained quartz	4.2	6.6
Opaque minerals	4.0	4.9
Potassium feldspar	1.5	4.1
Undulatory quartz	1.1	2.4
Epidote	1.0	4.9
Polycrystalline quartz	0.7	2.6
Total percent	100.0	

$\bar{Y}$ = mean of 55 thin sections

S = standard deviation of 55 thin sections

Potassium feldspar comprises only 1.5 percent of the total average volume of the interflow sandstones. The most common variety is untwinned. Grains showing gridiron twinning were observed within the 4 uppermost sedimentary zones of the southwest limb, but were lacking elsewhere within the North Shore Volcanic sequences.

The mafic rock fragments appearing within the interflow sandstones of the North Shore Volcanic Group comprise 25.6 percent of the total average volume of these sediments. The mafic clasts range in texture from basaltic to basaltic-amygdaloidal to diabasic, but the coarser textures predominate. These mafic clasts show less variation within a sedimentary horizon than those in the Mamainse Point section and appear to have a coarser texture than those in the Portage Lake and Copper Harbor Conglomerate.

Rhyolite rock fragments make up 5.6 percent of the total average volume of the interflow sandstones within the North Shore Volcanic Series. The rhyolite clasts commonly consist of uniformly fine-grained quartz and feldspar. No granophyric fragments were observed in the various sedimentary horizons within either limb of the North Shore Volcanic Series.

The felsite rock fragments comprise 5.1 percent of the total average volume of the interflow sandstones. The felsite clasts commonly consist of feldspar with minor or no mafic or quartz grains.

The total detrital quartz grains constitute 6.0 percent of the average volume of the interflow sandstones within the North Shore Volcanic Group. Unstrained quartz is the dominant quartz variety and makes up 70 percent of the total quartz volume within the sediment. Approximately 18 percent of the total detrital quartz grains observed within the interflow sediments possess moderate to strong undulose extinction, whereas only 12 percent consist of polycrystalline quartz.

The opaque minerals comprise 4.0 percent of the total average volume of the interflow sediments and consist of hematite, ilmenite, leucoxene and magnetite.

Detrital pyroxene makes up 4.8 percent of the total average volume of the interflow sandstones within the North Shore Volcanic Series. The grains are commonly pale brownish gray and consist most commonly of augite and possibly some diopside. Detrital pyroxene was observed in eight of the twelve sedimentary horizons sampled on the southwest limb of the North Shore Volcanic sequence, but was noted in only one of five sampled on the northeast limb (Tables 17 and 18) which may indicate that the source rock of the pyroxene was located somewhat to the south and west of the current exposures of the North Shore Volcanic Series. It is also worth noting that detrital pyroxene grains were not observed in either the Keweenaw Peninsula or Mamainse Point samples. Its presence in the North Shore Volcanic Series, coupled with the abundance of detrital plagioclase grains, may indicate that mafic intrusive rocks were being unroofed in the bordering source area during Keweenawan time.

Vertical Compositional Variation

Evaluation of the vertical compositional variation within interflow sandstones of the North Shore Volcanics was made to detect any changes in provenance occurring during the Keweenawan time represented by these sediments.

The samples used to study the North Shore Interflow sediments were collected over an interval spanning 130 miles (Figure 13). This interval represents a line of section across both limbs of the syncline, although not necessarily at right angles to the axis of the structure. Thus, even though each sample has a certain vertical position in the sequence any vertical component may also have a different lateral connotation.

The samples from both limbs of the North Shore Volcanic Series were tested for vertical differences in composition (Table 17, Figure 13; Table 18, Figure 14). The testing procedure was identical to that used on the Keweenaw Peninsula and Mamainse Point samples and consisted of regression analysis and chi square evaluation of the residuals. Chi square analysis of the plots of the (observed-expected) volume frequency with depth reveals no significant residual trends ($P_{\chi^2} < 0.05$) for any of the compositional constituents within the interflow sediments of either limb of the North Shore Volcanic sequence. For brevity Figures 13 and 14 include only the plots for those constituents whose volume frequencies (Tables 17 and 18) appear to show a trend upward within the succession.

The lack of any significant residual trends for any of the detrital constituents after the grain size effect has been statistically removed from the composition suggests that there was no appreciable change in provenance for the interflow sediments within the North Shore Volcanic Series.

Table 17. Vertical compositional variation within the southwest limb of the North Shore Volcanic interflow sediments.

Sedimentary Horizon	% Mafic Y S	% Pelsite Y S	% Rhyolite Y S	% K-Spar Y S	% Plagio- cline Y S	% Unstrained Quartz Y S	% Undulose Quartz Y S	% Polycryst. Quartz Y S	% Pyroxene Y S	% Opaque Minerals Y S	% Epidote Y S											
FR	11.8	5.7	-	-	63.5	2.5	-	-	7.9	0.1	16.8	3.4	-									
TR	71.2	10.4	-	-	-	0.5	1.2	-	28.3	9.2	-	-	-									
PS1	12.0	1.6	-	3.5	0.9	69.4	5.2	3.0	0.6	0.9	0.8	-	-									
PS2	2.3	1.3	-	56.4	44.9	6.7	11.8	13.7	21.2	16.4	13.5	3.1	3.5	1.0	2.5	-						
PS3	11.2	2.9	-	2.4	0.6	71.3	2.8	4.1	1.8	1.1	1.5	-	6.6	4.9	3.3	4.0	-					
PSB	43.6	12.7	-	3.4	4.8	46.1	15.4	0.7	1.0	-	-	-	6.2	3.0	-	-	-					
PSC	19.1	6.7	22.7	12.1	-	0.7	1.3	52.2	8.1	1.5	1.4	0.5	0.7	-	0.3	0.8	3.0	3.1	-			
PSD	12.4	2.2	13.4	12.4	-	4.4	0.3	57.0	4.1	3.1	4.4	2.3	3.3	-	-	-	7.4	2.6	-			
PSW	30.6	15.9	9.2	8.8	-	-	-	51.2	19.3	2.9	2.1	1.4	1.2	-	4.7	5.2	-	-	-			
LR	7.9	3.7	32.0	17.1	-	6.4	2.3	47.0	12.4	1.2	1.6	1.7	0.8	-	1.7	0.8	2.1	3.1	-			
LE	5.4	4.5	-	-	-	-	-	46.1	8.6	-	-	-	-	-	-	-	2.7	3.8	45.8	7.9		
DUL-2	100	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Avg. Vol. Frequency	25.8	26.9	7.3	12.2	7.5	24.6	2.1	4.7	42.1	26.8	3.8	7.0	1.0	1.8	0.1	0.9	5.7	9.4	2.5	4.2	2.0	9.6
Average Phi Size	2.28	1.90	-0.27	2.97	2.61	2.70	2.76	-0.34	3.03	-	-	-	-	-	-	-	-	-	-	-	-	

Y = mean volume frequency within each horizon

S = volume frequency standard deviation within each horizon

Figure 13. Graphs of the vertical compositional variation within the southwest limb of the North Shore Volcanic Series interflow sediments. Graphs show the residuals resulting when the (observed-expected) volume frequencies for some of the various detrital constituents are plotted versus their depth of occurrence in the southern limb of the North Shore Volcanic Series. Graph A is the plot for plagioclase clasts, Graph B is for mafic clasts, and Graph C is for pyroxene clasts.

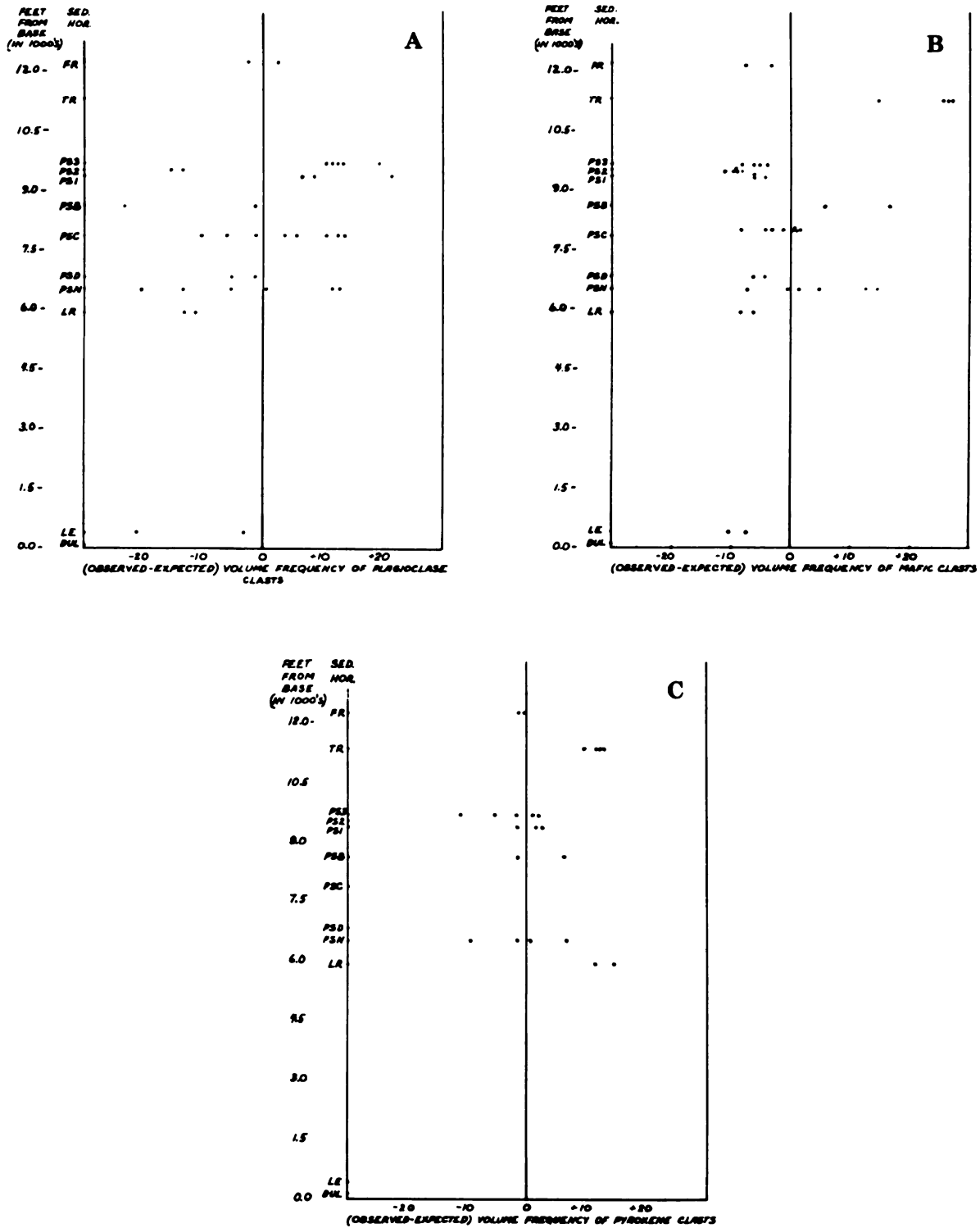


Figure 13

Table 18. Vertical compositional variation of constituents within the northeast limb of the North Shore Volcanic interflow sediments.

Sedimentary Horizon	% Mafic		% Felsite		% Rhyolite		% K-Spar		% Plagio- cline		% Unstrained Quartz		% Undulose Quartz		% Polycryst. Quartz		% Pyroxene		% Opaque Minerals	
	Y	S	Y	S	Y	S	Y	S	Y	S	Y	S	Y	S	Y	S	Y	S	Y	S
OR	3.0	2.5	-	-	-	-	-	-	64.3	7.2	16.7	10.3	9.2	8.7	-	-	-	-	6.8	3.0
BP	38.5	5.2	-	-	0.8	1.4	-	-	49.7	2.9	6.8	4.3	1.5	1.7	-	-	-	-	2.7	1.3
CR	29.2	8.9	-	-	1.4	1.6	-	-	47.4	18.5	3.7	1.9	-	-	6.4	9.0	-	-	11.9	6.8
CE	20.4	6.7	-	-	0.9	2.1	-	-	64.6	10.9	2.8	3.6	-	-	-	-	5.8	3.2	5.5	3.7
PB	37.8	14.6	-	-	2.0	2.8	-	-	47.7	10.2	1.9	2.7	-	-	-	-	-	-	10.6	4.2
Avg. Vol. Frequency (%)	25.1	-	-	-	1.0	-	-	-	56.7	-	5.0	-	1.2	-	1.3	-	2.4	-	7.4	-
Average Phi Size	2.26	-	-	-	2.07	-	-	-	2.41	-	2.41	-	2.84	-	1.24	-	2.67	-	-	-

 $\bar{Y}$ = sample mean

S = sample standard deviation

]

Figure 14. Graphs of the vertical compositional variation within the northeast limb of the North Shore Volcanic Series interflow sediments. Graphs show the residuals resulting when the (observed-expected) volume frequencies of the various detrital constituents are plotted versus their depth of occurrence in the northern limb of the North Shore Volcanic succession. Graph A is the plot for plagioclase clasts, Graph B is the plot for mafic clasts, and Graph C is for unstrained quartz grains.

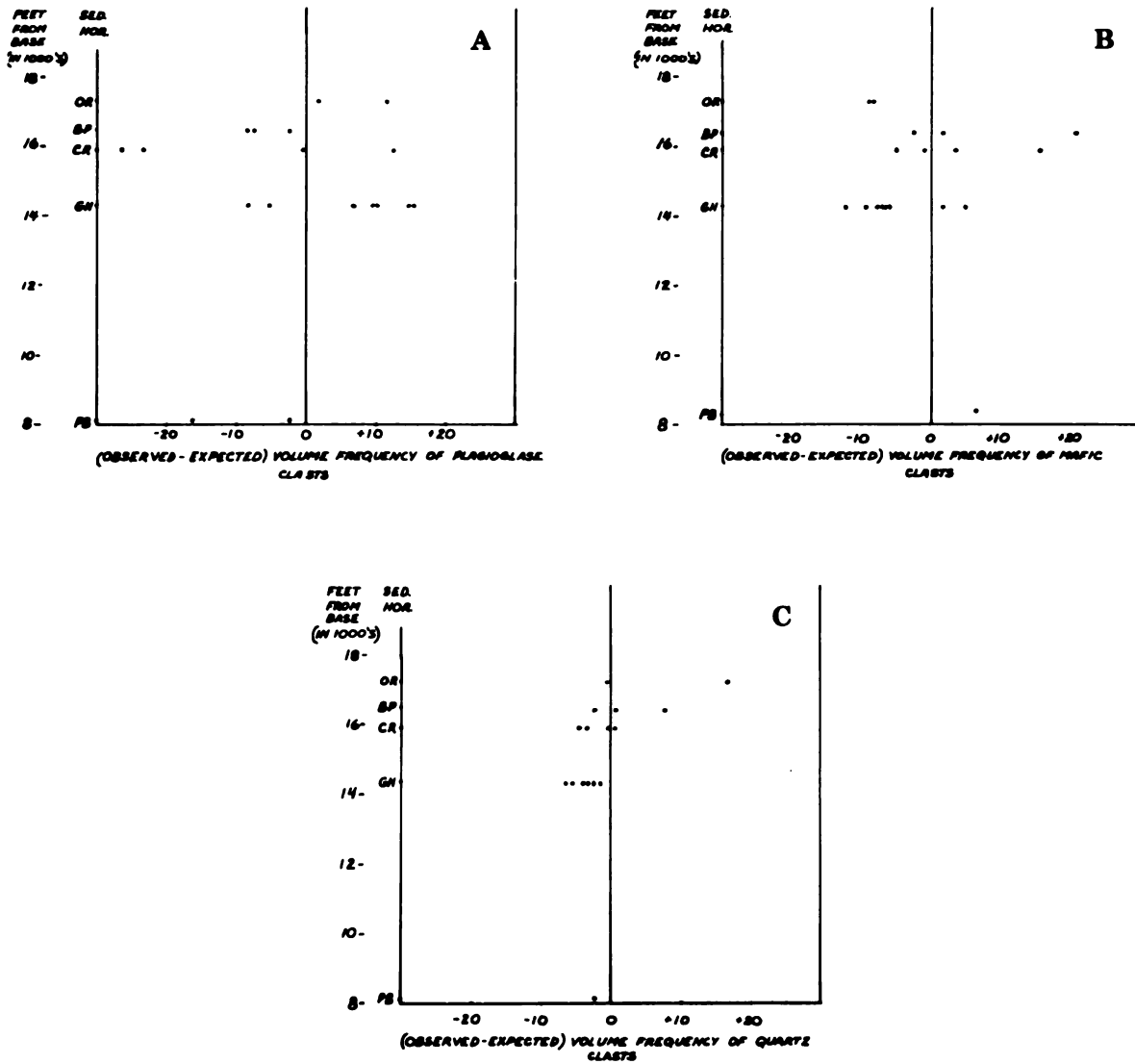


Figure 14

Therefore any apparent changes in the values of the volume frequencies of the various constituents upward in the section, as derived by modal analysis, must be due to the grain-size effect and the capricious nature of the depositional environment.

Lateral Variation in Composition

A comparison of the average grain size shown in Table 19, reveals that the sediments on the southwest limb tend to be slightly coarser (1.96 ϕ) on the average than those on the northeast side (2.27 ϕ) of the North Shore Volcanic Series. The grain-size effect suggests that the coarser sediments should have the higher rock fragment volume frequency. This observation may explain why the southern limb of the volcanic series contains a greater volume of rock fragments (40%) on the average than those on the northeast limb (26%). Even though the mafic rock fragments have the same volume frequency on both limbs, Table 19 indicates that the more siliceous rock fragments are more abundant on the southern limb, while detrital monomineralic grains are more important volume-wise in the sediments on the northeast side. The relative concentration of the felsite and rhyolite clasts within the southern limb may suggest that the more siliceous-rock centers of sediment dispersal were localized closer to the southern limb than elsewhere, whereas those areas shedding mafic detritus were centrally located or evenly distributed through the area.

Table 19. Lateral compositional variation within the North Shore Volcanic Series interflow sediments.

Composition	Southwest Limb Volume Frequency (%)		Northeast Limb Volume Frequency (%)	
	$\bar{Y}$	S	$\bar{Y}$	S
Plagioclase	42.1	26.8	56.7	13.5
Mafic rock fragments	25.8	26.9	25.1	12.7
Rhyolite rock fragments	7.5	24.6	1.0	1.7
Felsitic rock fragments	7.3	12.2	Trace	-
Pyroxene	5.7	9.4	2.4	3.5
Unstrained quartz	3.8	7.0	5.0	5.8
Opaque minerals	2.5	4.2	7.4	4.9
Potassium feldspar	2.1	4.7	Trace	-
Epidote	2.0	9.6	Trace	-
Undulatory quartz	1.0	1.8	1.2	3.5
Polycrystalline quartz	0.1	0.9	1.3	4.5
Total percent	99.9		100.1	
Average Grain Diameter (Long axis - Phi Size)	1.96		2.27	

Analysis of Table 19 indicates that the sediment intercalated within both limbs of the North Shore Volcanic Series represents detritus shed from a source terrain consisting of mafic, felsitic, and rhyolitic volcanic rocks, and mafic intrusive rock.

Sedimentary Synopsis

Provenance

The Keweenawan interflow sediments within the North Shore and Isle Royale Volcanic Series, in addition to the Isle Royale Conglomerate sequence were derived from a Keweenawan volcanic source terrain consisting of mafic, felsitic, and rhyolitic rocks. However, the presence of abundant detrital plagioclase and appreciable pyroxene within the sediments of the North Shore Volcanic Series suggests that mafic intrusive bodies in the source terrain were also being unroofed and broken down by erosion to yield monomineralic detritus.

Although Wolff's analysis (1969) of the coarse sands on Isle Royale indicates they contain abundant felsite and mafic rock fragments, the finer sands are dominated by both simple and undulatory quartz and potassium feldspar detrital grains, which suggests that a not too distant, non-volcanic source terrain was also contributing important quantities of fine-sized detritus to the basin of deposition at the

same time. This inference, based upon data from Isle Royale sediments, does not appear to correlate with the predominantly volcanic detritus encountered in the sedimentary horizons within the North Shore Volcanic series.

It is possible that the differences in composition existing between the Isle Royale and North Shore interflow sands could be due to the difference in age of the two deposits. It has been noted that whenever the upper parts of the middle Keweenaw are observed, as on Isle Royale and the Keweenaw Peninsula, the volcanic sequence contain a much higher proportion of interflow sediments than do the North Shore Volcanic Series, and also that they grade into an almost entirely clastic sequence of the upper Keweenaw. The small percentage of interflow sedimentary rock contained within the North Shore Volcanic sequence suggested to Grout (1959), that the North Shore Volcanics represented only the lower part of the middle Keweenaw, the upper portion lies submerged beneath Lake Superior off the coast of Minnesota. Thus, the Isle Royale sequence, raised by later faulting could represent the upper portion of a more northerly portion of Keweenaw deposits located along the northwest limb of the Lake Superior syncline.

The Keweenaw source area, dominated by an extensive and thick sequence of volcanic rocks, was tectonically unstable as evidenced by the intrusion of the Duluth Gabbro Complex and the Logan intrusives. However, during the lower

Keweenawan and lower-middle Keweenawan time the source terrain was primarily producing magmatic products, as shown by the small amounts of interflow sediments and their fine grained nature within both the North Shore Volcanics and the Osler Series. These characteristics also suggest that the source area was not very high or rugged. However, waning of volcanic activity, and increasing uplift during Keweenawan time apparently occurred as evidenced by the coarser nature of the Isle Royale Interflow sediments and the thick overlying clastic sequence.

Paleogeography and Sedimentation

The fine, subangular to subrounded, well-sorted aspect of the grains, plus the compositional immaturity and relative scarcity of the interflow sediments within the North Shore Volcanic and Osler Series probably indicates a somewhat distant source terrain possessing low relief. These characteristics also suggest that the sediment did not necessarily undergo a short transportational history, but, in conjunction with the thick volcanic sequence, were deposited in a sedimentary basin which was rapidly sinking. However, in the case of the Isle Royale Conglomerate, the coarse nature, generally poor sorting, and compositional immaturity of the sediment implies the existence, at that time, of a nearby source of higher relief, a shorter transportational history, and more rapid deposition in a rapidly sinking basin.

In early Keweenawan time, the uplift of the marginally located source terrain coupled with the subsidence of the central portion of the basin initiated erosion, transportation, and deposition of immature, fine sands by temporary streams meandering across the volcanic terrain surface. More active uplift with time probably moved the northwest located source-terrain-front eastward and subsequently increased the rate of erosion and transportation of immature conglomerates and coarse sands by a fluvial system on a piedmont fan.

The most likely source area borderland for the sediments intercalated in the North Shore Volcanic Series, the Isle Royale succession, and the Sibley-Osler Series is an arcuate area running from the west to the north of the presently crescent-shaped Keweenawan belt of exposures. This deduction is based upon the following observations. Crossbedding within the North Shore Volcanic interflow sediments suggest that the transporting currents flowed toward Lake Superior (Sandberg, 1938; Halls, 1965). Sedimentological studies conducted on the Isle Royale Conglomerate sequence by Wolff (1969) and Huber (1971) utilizing transport direction indicators, and direction of decreasing thickness and decreasing textural maturity suggest that these sediments came from a source area located west or northwest of the island. Tanton (1931) notes that sandstones between the Sibley-Osler Series show crossbedding indicating derivation

of material from a northerly source. This proposed source area is represented variously by the occurrence of extensive exposures of large gabbroic bodies and abundant unmetamorphosed diabase sills and dikes exposed in Archaen meta-sedimentary and plutonic rocks in Minnesota and Ontario.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Sedimentary rock samples were collected from Keweenawan sections exposed at Mamainse Point, Ontario; the Keweenawan Peninsula, Michigan; and the Minnesota shore region of Lake Superior. The results of this petrographic study coupled with work of others indicates that much of the Keweenawan sediments were derived from tectonic highs which were mantled by Keweenawan volcanics.

The coarse, immature, polymictic-conglomerates and arenites incorporated in the Mamainse Point Volcanic Series were deposited by a fluvial system on a piedmont fan. The fluvial system was characterized by high energy conditions and high gradients marginal to a source area of rugged relief. The source area was tectonically active and shed coarse detritus of both volcanic-surficial and non volcanic-basement aspects simultaneously throughout middle Keweenawan time. Analysis of the vertical compositional variation within the Mamainse Point succession suggests that while there was a definite lessening of importance of the mafic volcanic and plutonic terrain as a source of rock fragments during

middle Keweenawan time, the felsitic rocks as a source of detritus become of increasing importance upward in the sequence with time. The most likely location of the source area borderland for the interflow sediments intercalated within the Mamainse Point Volcanic Series was the area just eastward of the presently exposed Keweenawan outcrops. This area is represented by the occurrence of abundant lower diabase dike swarms exposed in lower and middle Precambrian metasedimentary and plutonic rocks.

The immature, polymictic conglomerates and arenites incorporated within the Portage Lake Lava Series and the Copper Harbor Conglomerate are thought to have been deposited on a piedmont fan by a fluvial system. The fluvial system was characterized by relatively high energy conditions marginal to an upland. The upland was probably rugged, but possessed only moderately high relief. The sediments within the Portage Lake and Copper Harbor series were derived primarily from a nearby Keweenawan volcanic source terrain consisting of mafic, felsitic, rhyolitic, and granophyric rocks. However, the presence of appreciable undulose quartz clasts and non-volcanic lithic clasts locally in the upper portions of the Copper Harbor Conglomerate suggests incursion of sediments from a nearby pre-Keweenawan plutonic and/or metamorphic source terrain. The Keweenawan volcanics mantling the pre-Keweenawan crystalline rocks in the source area were probably breached, at this time, by streams allowing the underlying rocks to be exposed to erosion.

The most likely location for the source area borderland which supplied the various Keweenawan sediments intercalated with the volcanics series on the southern shore of Lake Superior was just southward of the presently exposed Keweenawan outcrops. This area is represented by the occurrence of abundant lower Keweenawan diabase dikes in Animikean metasedimentary and plutonic rocks, and a gabbro-granophyric complex intruding Keweenawan volcanic rocks.

The Keweenawan sediments within the North Shore Volcanic and Isle Royale Series were derived primarily from a Keweenawan volcanic source terrain consisting of mafic, felsitic, and rhyolitic volcanics in addition to mafic intrusive rocks. However, abundant undulatory quartz within the sandy phases of the Isle Royale Conglomerate suggests that a non-volcanic source terrain was also contributing fine-sized detritus to the basin of deposition.

It is possible that the North Shore Volcanic Series represents only the lower part of middle Keweenawan time, the upper portion lying submerged beneath Lake Superior off the coast of Minnesota. The Isle Royale sequence, raised by later faulting, could represent the upper portion of a more northerly portion of the Keweenawan deposits along the northwest limb of the Lake Superior basin.

The fine, well-sorted, but immature nature of the North Shore Volcanic sediments indicate deposition by streams meandering across a rapidly subsiding volcanic terrain.

3

However, the coarser nature of the Isle Royale Conglomerate, plus its immaturity, implies derivation from a nearby source area of higher relief, a shorter transportation history, and more rapid deposition in a subsiding basin.

The most likely source area for the sediments intercalated in the North Shore Volcanic and Isle Royale Series is an arcuate area running from the west to the north of the presently crescent-shaped Keweenawan belt of exposures. This proposed source area is represented variously by the occurrence of extensive exposures of large gabbroic bodies and abundant, unmetamorphosed diabase dikes and sills in lower Precambrian metasedimentary and plutonic rocks in Minnesota and Ontario.

The data assembled herein indicates that much of the Keweenawan sediments of the Lake Superior region were derived from local tectonic highs. These source terrains were probably in all instances initially mantled by Keweenawan volcanics. Therefore, the area covered by the Keweenawan volcanics was probably much more extensive than the accumulation deduced from present outcrops would indicate. The ultimate extension of Keweenawan volcanism cannot be determined at this time, but if the basaltic dikes of Keweenawan age are considered to be conduits for the subsequently eroded flows, then the regional extent would be considerably increased.

The general tectonic pattern for the Keweenawan is then one of considerable positive local tectonic instability as well as a time of volcanism. From the evidence discussed above at least three such local uplifts can be discerned from the volcanic sedimentary record. These positive tectonic areas occur on all sides of the Lake Superior basin and were responsible for contributing perhaps thousands of feet of Keweenawan sediment observed on Isle Royale, the North Shore of Minnesota, the Keweenaw Peninsula, Mamainse Point, Michipicoten Island, and Cape Gargantua.

It is possible that many more such uplifts occurred at this time, whose presence cannot be determined because of a deficiency in the sedimentary record.

The concept that the location of the present exposure of Keweenawan rocks was as much influenced by the surrounding basement tectonics as the areal extent of volcanism is not a new one. Burwash (1905) concluded that the triangular shape of Lake Superior was much controlled by bordering uplifts and the possibility that Keweenawan dikes fed subsequently eroded basaltic terrain. The results cited herein should be viewed as corroboration of the insight of a master geologist.

In recent years, many inferences concerning the tectonic style of the mid continent have been based upon the occurrence and outcrop pattern of Keweenawan basalts. The present outcrop trend coupled with geophysical evidence of sub-surface

Figure 15. Paleogeography of Lake Superior syncline in Keweenawan time showing location of postulated positive and negative tectonic areas. The arrows indicate the inferred direction of sedimentary transport.

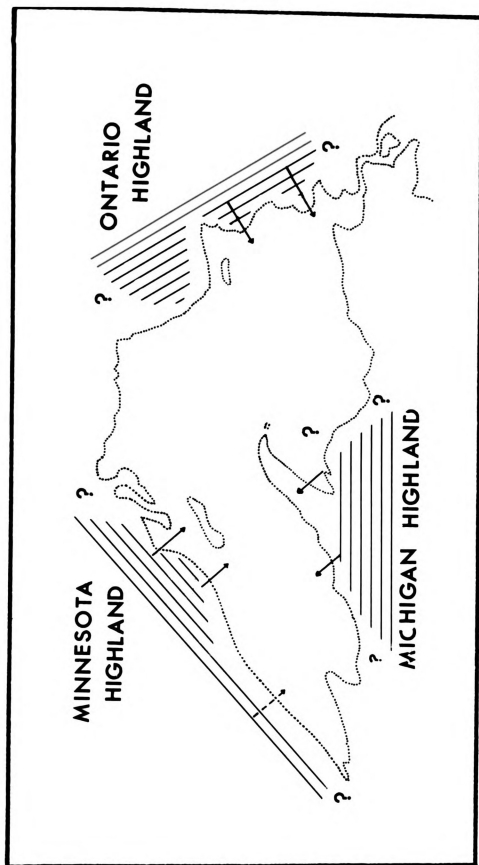


Figure 15

trends has lead to the supposition that the Lake Superior basin is the result of Keweenawan volcanism within a major rift valley. However, the outcropping portion of the Keweenawan rocks, in light of the results presented herein, is thought to be a remnant of a broader deposit. Although a rift valley hypothesis cannot be totally disproven, it can be stated that inferred structural relationships in Keweenawan time in the region of outcrops do not support such a conclusion. White (1966) also disfavors the rift hypothesis, based upon patterns of detailed faulting and stratigraphy within the Keweenawan pile, and suggest that major fault features effecting the flows post date Keweenawan volcanism.

1

REFERENCES CITED

- Aldrich, H. R., 1929, The Geology of the Gogebic Iron Range of Wisconsin, Wisconsin Geol. Nat. Hist. Surv. Bull. 71.
- Annells, R. N., 1971, Middle Keweenawan volcanism of eastern Lake Superior, 17th Ann. Institute on Lake Superior Geol., Duluth, Minn.
- Annells, R. N., 1970. Keweenawan volcanic geology of Michipicoten Island, Lake Superior, 16th Ann. Institute on Lake Superior Geol., Thunder Bay, Ont.
- Atwater, G. I., and G. M. Clement, 1935, Precambrian and Cambrian relations in the upper Mississippi valley, Bull. Geol. Soc. Am., 46, 1659-1686.
- Ayres, L. D., 1969, Geology of Townships 31 and 30, Ranges 20 and 10; Ontario Dept. Mines Geol. Rept., 69, 38.
- Bacon, L. O., 1957, Relation of gravity to geological structure in Michigan's Upper Peninsula, in Geological Exploration, edited by A. K. Snelgrove, pp. 54-58, Michigan College of Mining and Technology, Houghton.
- Bacon, L. O., 1964. Investigation of the thickness of the Jacobsville sandstone by seismic reflection methods--a progress report (abstract), 10th Ann. Inst. Lake Superior Geol., Ishpeming, Mich., p. 57.
- Bailey, E. H. and Steven, R. E., 1960, "Selective Staining of K-feldspar and plagioclase on Rock Slabs and Thin Sections," Amer. Min., Vol. 45, pp. 1020-1025.
- Balsley, J. R., H. L. James, and K. L. Wier, 1949, Aero-magnetic survey of parts of Baraga, Iron, and Houghton Counties, Michigan, with preliminary geologic interpretation, U. S. Geol. Surv. Geophys. Invest.
- Bean, E. F., 1959, Geologic Map of Wisconsin, Wisconsin Geol. Nat. Hist. Surv.
- Books, K. G., 1968, "Magnetisation of the lowermost Keweenawan lava flows in the Lake Superior Area, U. S. Prof. Paper 600-D, 248-252.

- Broderick, T. M., 1935, Differentiation in lavas of the Michigan Keweenawan, *Bull. Geol. Soc. Am.*, 46, 503-558.
- Burwash, E. M., 1905, *Geology of Michipicoten Island*, University of Toronto Studies, Geology Series, no. 3.
- Butler, B. S., and W. S. Burbank, 1929, The copper deposits of Michigan. *U. S. Geol. Surv. Profess. Paper* 144.
- Case, J. E., and J. E. Gair, 1965, Aeromagnetic map of parts of Marquette, Dickinson, Baraga, Alger, and Schoolcraft Counties, Michigan, and its geologic interpretation, *U. S. Geol. Surv. Geophys. Invest. Map* GP-467.
- Coleman, A. P., 1899, Copper regions of the Upper Lakes, *Ontario Bur. Mines 8th Ann. Rept.*, part 2, pp. 121-174.
- Coleman, A. P., 1902, Iron ranges of northwestern Ontario, *Ontario Bur. Mines 11th Ann. Rept.*, pp. 128-151.
- Cornwall, H. R., 1951, Differentiation in lavas of the Keweenawan series and the origin of the copper deposits of Michigan, *Bull. Geol. Soc. Am.*, 62, 159-202.
- Cornwall, H. R., 1954a, Bedrock geology of the Phoenix quadrangle, Michigan, *U. S. Geol. Surv. Quadrangle Map* GQ 34.
- Cornwall, H. R., 1954b, Bedrock geology of the Delaware quadrangle, Michigan, *U. S. Geol. Surv. Quadrangle Map* GQ 51.
- Cornwall, H. R., 1954c, Bedrock geology of the Lake Medora quadrangle, Michigan, *U. S. Geol. Surv. Quadrangle Map* GQ 52.
- Cornwall, H. R., 1955, Bedrock geology of the Fort Wilkins quadrangle, Michigan, *U. S. Geol. Surv. Quadrangle Map* GQ 74.
- Cornwall, H. R., and W. S. White, 1955, Bedrock geology of the Manitou Island quadrangle, Michigan, *U. S. Geol. Surv. Quadrangle Map* GQ 73.
- Cornwall, H. R., and J. C. Wright, 1954, Bedrock geology of the Eagle Harbor quadrangle, Michigan, *U. S. Geol. Surv. Quadrangle Map* GQ 36.
- Cornwall, H. R., and J. C. Wright, 1956a, Geologic map of the Hancock quadrangle, Michigan, *U. S. Geol. Surv. Mineral Invest. Field Studies Map* MF 46.

- Cornwall, H. R., and J. C. Wright, 1956b, Geologic map of the Laurium quadrangle, Michigan, U. S. Geol. Surv. Mineral Invest. Field Studies Map MF 47.
- Craddock, D., E. C. Thiel, and B. Gross, 1963, a Gravity investigation of the Precambrian of southeastern Minnesota and western Wisconsin, J. Geophys. Res., 68(21), 6015-6032.
- Daly, R. A., 1917, The geology of Pigeon Point, Minnesota: American Jour. Science, ser. 4, v 43, p. 423-448.
- Davidson, D. M., 1971, A new view of the Duluth Complex, Minnesota, 17th Ann. Institute on Lake Superior Geol., Duluth, Minn.
- Davidson, E. S., G. H. Espenshade, W. S. White, and J. C. Wright, 1955, Bedrock geology of the Mohawk quadrangle, Michigan, U. S. Geol. Surv. Quadrangle Map GQ 54.
- Du Bois, P. M., 1952, Palaeomagnetism and correlation of Keweenawan rocks, Geol. Surv. Can. Bull. 71.
- Fairbairn, H. W., H. J. Bullwinkel, W. H. Pinson, and P. M. Hurley, 1959, Age investigation of syenites from Coldwell, Ontario, Proc. Geol. Assoc. Can., 11, 141-144.
- Fritts, C. E., 1965, Stratigraphy, structure, and granitic rocks in the Marenisco-Watersmeet area, Michigan (abstract), 11th Ann. Inst. Lake Superior Geol., Univ. Minn., St. Paul, p. 15.
- Giblen, P. E., 1969, Ontario Dept. Mines, Prelim. Geol. Maps 553 and 555.
- Goldich, S. S., A. O. Nier, H. Baadsgaard, J. H. Hoffman and H. W. Krueger, 1961, The Precambrian geology and geochronology of Minnesota, Minn. Geol. Surv. Bull. 41.
- Gordon, W. C., and A. C. Lane, 1906, A geological section from Bessemer down-Black River, Mich. Geol. Surv. Rept.
- Graham, J. W., 1953, Changes of ferromagnetic minerals and their bearing on magnetic properties of rocks. J. Geophys. Res., 58(2), 243-260.
- Grant, U. S., 1900, Preliminary report on the copper-bearing rocks of Douglas County, Wisconsin, Wisconsin Geol. Nat. Hist. Surv. Bull. 6.

- Green, J. C., 1971, The North Shore Volcanic Group, 17th Ann. Institute on Lake Superior Geol., Duluth, Minn.
- Grout, F. F., J. W. Gruner, G. M. Schwartz, and G. A. Thiel, 1951, Pre-cambrian stratigraphy of Minnesota, Bull. Geol. Soc. Am., 62, 1017-1078.
- Grout, F. F., R. P. Sharp, and G. M. Schwartz, 1959, The geology of Cook County, Minnesota, Minn. Geol. Surv. Bull. 39.
- Halls, H. C., 1966, "A Review of the Keweenawan Geology of the Lake Superior Region," Geophys. Union, Monograph 10, pp. 3-27.
- Hamblin, W. K., 1958, The Cambrian sandstones of northern Michigan, Mich. Geol. Surv. Publ. 51.
- Hamblin, W. K., 1961, Palaeogeographic evolution of the Lake Superior region from late Keweenawan to late Cambrian time, Bull. Geol. Soc. Am., 72, 1-18.
- Hamblin, W. K., and W. J. Horner, 1961, Sources of the Keweenawan conglomerates of northern Michigan, J. Geol., 69, 204-211.
- Hinze, W. J., J. W. Trow, N. W. O'Hara, G. B. Secor, and R. J. Wold, 1965, Aeromagnetic survey of Lakes Superior, Huron, and Michigan (abstract), U. S. Progr. Rept. Intern. Upper Mantle Project.
- Hite, D. N., 1968, Sedimentology of the Upper Keweenawan sequence of northern Wisconsin and adjacent Michigan, unpub. Ph. D. thesis, The Univ. of Wisconsin, 217 p.
- Hopkins, P. E., 1921, Schreiber-Duck Lake area, Ontario Dept. Mines 30th Ann. Rept., part 4, pp. 1-26.
- Hotchkiss, W. O., 1923, The Lake Superior geosyncline, Bull. Geol. Soc. Am., 34, 669-678.
- Hotchkiss, W. O., E. F. Bean, and O. W. Wheelwright, 1915, Mineral land classifications, showing indications of iron formation, in parts of northern Wisconsin, Wisconsin Geol. Nat. Hist. Surv. Bull. 44, 35-45.
- Huber, N. K., 1971, The Keweenawan geology of Isle Royale, Michigan, 17th Ann. Institute on Lake Superior Geol., Duluth, Minn.

- Johnson, C. H., and R. L. Foster, 1965, Contaminated Precambrian ash flow tuff, Cascade River, Minnesota (abstract), Geol. Soc. Am. Special Paper 82, 102.**
- Joubin, F. R., and associates, 1964, Mining Geologists Ltd., Geological maps of the Algoma District, prepared for the Algoma Central and Hudson Bay Railway Company.**
- Lane, A. C., 1898, Geological report on Isle Royale, Michigan, Mich. Geol. Surv., 6.**
- Lane, A. C., 1911, The Keweenaw series of Michigan, Mich. Geol. Biol. Surv. Publ. 6, Geological Series, no. 4.**
- Leighton, M. M., 1954, Petrogenesis of a gabbro-granophyre complex in northern Wisconsin, Bull. Geol. Soc. Am., 65, 401-442.**
- Leith, C. K., R. J. Lund, and A. Leith, 1935, Precambrian rocks of the Lake Superior region, U. S. Geol. Surv. Profess. Paper 181.**
- Lowdon, J. A., C. H. Stockwell, H. W. Tipper, and R. K. Wanless, 1963, Age determinations and geological studies (including Isotopic Ages, Rept. 3), Geol. Surv. Can. Paper 62-17.**
- Lyons, P. L., 1959, The Greenleaf anomaly, a significant gravity feature, in Symposium on Geophysics in Kansas, Kansas Geol. Surv. Bull. 137, 105-120.**
- Mattis, A. F., 1971, Lower Keweenaw sediments of the Lake Superior region, 17th Ann. Institute on Lake Superior Geol., Duluth, Minn.**
- McConnell, R. G., 1926, Sault Ste. Marie, District of Algoma, Ontario Dept. Mines 35th Ann. Rept., part 2, pp. 1-52.**
- Moore, E. S., 1926, Batchewana area, District of Algoma, Ontario Dept. Mines 35th Ann. Rept., part 2, pp. 53-85.**
- Moorhouse, W. W., 1957, The Proterozoic of the Port Arthur and Lake Nipigon region, Ontario, in The Proterozoic in Canada, Royal Soc. Can. Special Publ. 2, 67-76.**
- Nathan, H. D., 1969, The Geology of a portion of the Duluth Complex, Cook County, unpub. Ph. D. thesis, Univl of Minn., 198 p.**

- Nuffield, E. W., 1955, Geology of the Montreal River, Ontario Dept. Mines 64th Ann. Rept., part 3.
- Palmer, H. C., 1970, Palaeomagnetism and correlation of some middle Keweenawan rocks, Lake Superior, Can. Jour. Earth Sci., 7, 1410-1436.
- Parker, J., 1961, Sublacustrine topography of eastern Lake Superior, unpublished M. S. thesis, Michigan College of Mining and Technology, Houghton.
- Parsons, A. L., 1918, Slate Islands, Lake Superior, Ontario Bur. Mines 27th Ann. Rept., part 1, pp. 155-167.
- Sandberg, A. E., 1938, Section across Keweenawan lavas at Duluth, Minnesota, Bull. Geol. Soc. Am., 49, 795-830.
- Silver, L. T., and J. C. Green, 1963, Zircon ages for middle Keweenawan rocks of the Lake Superior region (abstract), Trans. Am. Geophys. Union, 44(1), 107.
- Tanton, T. L., 1931, Fort William and Port Arthur and Thunder Cape map areas, Geol. Surv. Can. Mem. 167.
- Tanton, T. L., 1936, Pigeon River area, Thunder Bay District, Canada Dept. Mines Maps 354A to 356A, inclusive.
- Taylor, R. B., 1964, Geology of the Duluth gabbro complex, Minn. Geol. Surv. Bull. 44.
- Thiel, E. C., 1956, Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota, Bull. Geol. Soc. Am., 67, 1079-1100.
- Thomson, J. E., 1953, Geology of the Mamainse Point copper area, Ontario Dept. Mines 62nd Ann. Rept. part 4, pp. 1-25.
- Thwaites, F. T., 1912, Sandstones of the Wisconsin coast of Lake Superior, Wisconsin Geol. Nat. Hist. Surv. Bull. 25.
- Tyler, S. A., R. W. Marsden, F. F. Grout, and G. A. Thiel, 1940, Studies of the Lake Superior pre-Cambrian by accessory mineral methods, Bull. Geol. Soc. Am., 51, 1429-1538.
- Van Hise, C. R., and C. K. Leith, 1911, The geology of the Lake Superior region, U. S. Geol. Surv. Monograph 52, p. 385.

- Van Schmus, W. R., 1971, Rb-Sr age of Middle Keweenawan rocks, Mamainse Point and vicinity, Ontario, Canada, Bull. Geol. Soc. Am., V82, pp. 3221-3226.
- White, W. S., 1956, Geologic map of the Chassel quadrangle, Michigan, U. S. Geol. Surv. Mineral Invest. Field Studies Map MF 45.
- White, W. S., 1957, Regional structural setting of the Michigan native copper district, in Geological Exploration, edited by A. K. Snelgrove, pp. 3-16, Michigan College of Mining and Technology, Houghton.
- White, W. S., 1960, The Keweenawan lavas of Lake Superior, an example of flood basalts, Am. J. Sci., Bradley Volume, 258-A, 367-374.
- White, W. S., 1966, Tectonics of the Keweenawan basin, western Lake Superior region, U. S. Geol. Surv. Profes. Paper 524-E.
- White, W. S., H. R. Cornwall, and R. W. Swanson, 1953, Bedrock geology of the Ahmeek quadrangle, Michigan, U. S. Geol. Surv. Quadrangle Map GQ 27.
- White, W. S., and J. C. Wright, 1954, The White Pine Copper deposit, Ontonagon County, Michigan, Econ. Geol. 49, 675-716.
- White, W. S., and J. C. Wright, 1956, Bedrock geology of South Range quadrangle, Michigan, U. S. Geol. Surv. Mineral Invest. Field Studies Map MF 48.
- White, W. S., and J. C. Wright, 1960, Lithofacies of the Copper Harbor conglomerate, northern Michigan, U. S. Geol. Surv. Profess. Paper 400-B.
- Wilson, A. W. G., 1910, Geology of the Nipigon Basin, Ontario, Geol. Surv. Can. Mem. 1.
- Wold, R. J., 1965, An aeromagnetic survey of western Lake Superior (abstract), 11th Ann. Inst. Lake Superior Geol., Univ. Minn., St. Paul, p. 36.
- Wolff, R. G., 1969, Upper Keweenawan sedimentary rocks on Isle Royale, Lake Superior, Unpub. M. S. thesis, Univ. of Wisconsin.
- Wright, J. C., and H. R. Cornwall, 1954, Bedrock geology of the Bruneau Creek quadrangle, Michigan, U. S. Geol. Surv. Quadrangle Map GQ 35.

Young, G. M., 1966, Huronian stratigraphy of the McGregor Bay area, Ontario: Relevance to the palaeogeography of the Lake Superior region, Can. J. Earth Sci., 3(2), 203-210.

Zietz, I., 1965, Aeromagnetic study of the midcontinent gravity anomaly (abstract), U. S. Progr. Rept. Intern. Upper Mantle Project.

Zumberge, J. H., and P. Gast, 1961, Geological investigations in Lake Superior, Geotimes, 6(4), 10-13.

MICHIGAN STATE UNIV. LIBRARIES



31293101223513