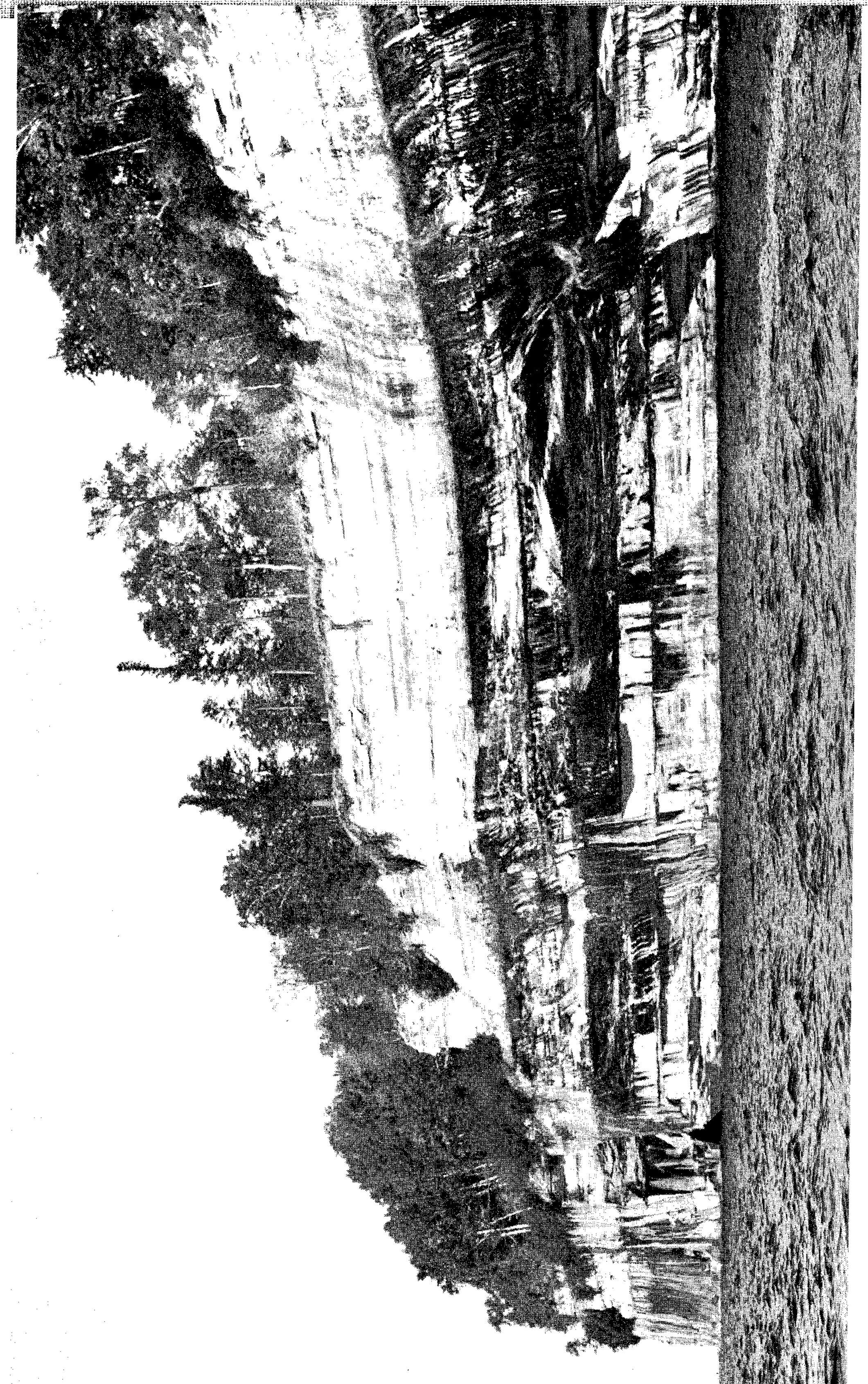
CAMBRIAN SANDSTONES

OF

NORTHERN MICHIGAN

The Cambrian Sandstones
of
Northern Michigan



Frontispiece. The Munising formation exposed in the cliffs of Pictured Rocks

STATE OF MICHIGAN
DEPARTMENT OF CONSERVATION
Gerald E. Eddy, Director

GEOLOGICAL SURVEY DIVISION
William L. Daoust, State Geologist

Publication 51

THE CAMBRIAN SANDSTONES of NORTHERN MICHIGAN

BY
WM. KENNETH HAMBLIN

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the University of Michigan
1958

SPEAKER-HINES AND THOMAS, INC.
PRINTERS - LITHOGRAPHERS - BOOKBINDERS
LANSING - 1958

Foreword

To the Director and the Commissioners
of the Department of Conservation

Gentlemen:

In compliance with Act No. 65, 1869 as amended by Act No. 179, 1871 of the Public Acts of Michigan under which the Geological Survey Division of the Department of Conservation operates, I have the pleasure and honor to present herewith a report on The Cambrian Sandstones of Northern Michigan by Dr. Wm. Kenneth Hamblin and recommend that it be published as Publication 51 of the Geological Survey Division.

Dr. Hamblin's report was prepared as a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the University of Michigan. The work upon which the dissertation is based was carried out as a cooperative agreement between the Department of Geology of the University of Michigan and the Geological Survey Division of the Department of Conservation, to study and describe the surface rocks of the southern shore of Lake Superior from Bete Grise on the Keweenaw Peninsula eastward to the St. Marys River, which include the famous Pictured Rocks of Michigan.

The report not only fills a long felt need of scientists who study the Cambrian rocks, but also adds much data of value to tourist enjoyment of the Lake Superior shore of Michigan.

Respectfully submitted

William L. Daoust

State Geologist
May 1958

CONTENTS

ILLUSTRATIONS

Plate

Table

THE CAMBRIAN SANDSTONES OF NORTHERN MICHIGAN

Introduction

PURPOSE AND SCOPE OF INVESTIGATION

The sandstones which crop out along the southern coast of Lake Superior occupy a rather unique position in the stratigraphy of Michigan. The upper units are generally considered to be Cambrian in age and to represent the first encroachment of the Paleozoic seas onto the Canadian Shield. The origin and age of the lower red sandstones, however, have been a subject of controversy for over a century. Many geologists believe that the lower red sandstones are marine and simply represent the basal part of the Upper Cambrian sequence, and others argue that the lower members are more closely related to the terrestrial deposits of the Keweenawan. Therefore, when considered together, these sandstones contain the best clues to the sequence of events which took place in the Lake Superior region during the transition between two great eras of geologic time: the Precambrian and the Paleozoic.

Many geologists have speculated on the origin and stratigraphic position of these rocks, but very little detailed work has been done on them. Most of the previous workers, because they were concerned primarily with the copper and iron deposits, were able to examine only a part of the readily accessible outcrops. Consequently, detailed mapping of these sandstones has been restricted to only a few small areas.

A comprehensive study of these sediments was undertaken in order to determine as far as possible their geologic history. This entailed areal mapping to determine their extent and distribution and a detailed study of the stratigraphy, sedimentation, and paleontology. Special emphasis was placed on the study of the source area and the nature of the surface upon which these sandstones were deposited.

LOCATION

The formations studied for this report are exposed along most of the southern coast of Lake Superior from the tip of Keweenaw

Peninsula to Encampment d'Ours Island in the St. Mary's River. Throughout most of this distance the outcrop belt extends from 1 to 20 miles inland where it either pinches out or is covered by younger sediments. Exposures are also found in a lowland area, about 20 miles wide east of the Keweenaw fault, extending southward from Keweenaw Bay to Gogebic Lake. Another thin outcrop belt swings southward in the Princeton-Gwinn area and can be traced as a narrow band extending in a north-south direction through eastern Dickinson and western Menominee counties.

FIELD WORK AND METHODS

Exposures of bedrock are extremely scarce and difficult to locate because of the heavy cover of glacial drift and dense vegetation. Erosion has produced three general types of outcrops, each requiring different methods of location and study.

The first type of outcrop which includes the greatest number of rock exposures is shore cliffs along the coast of Lake Superior where the only satisfactory method of study is by boat. The writer used a small fourteen-foot metal boat propelled by a five-horsepower outboard motor which proved very satisfactory because it is light enough to be carried on top of a car and small enough to land even on a rocky ledge. This permitted the writer to examine the cliffs from the water at close range and to land almost anywhere to collect samples and take measurements.

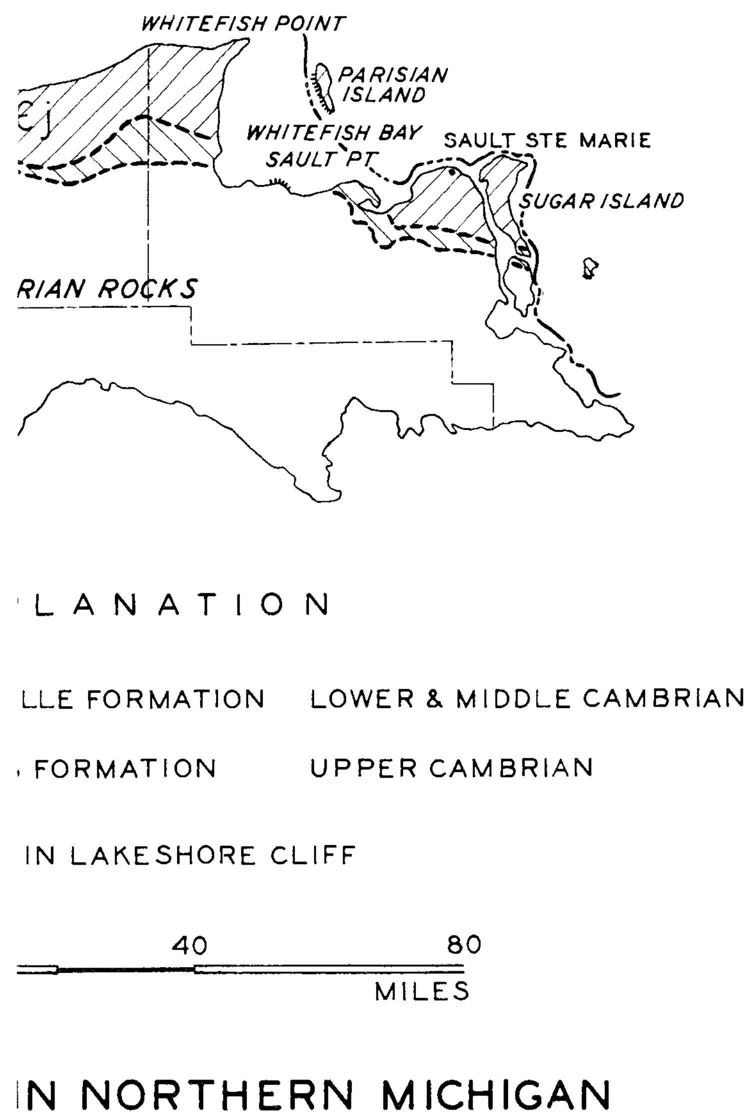
Since the shore cliffs form vertical walls which attain a height of more than 200 feet, only the base of the section could be studied from a boat and it was necessary at times to use a rope and to rappel over the cliffs in order to study contacts and other special features exposed high above the water level. The entire coast of Lake Superior from Bete Grise Bay to Grand Marais was mapped and studied in this manner.

A second type of outcrop is in the channels of the major streams where erosion has produced falls and rapids, many of which are along formational contacts. Thus, in mapping areal distribution inland, the most effective method of locating contacts is to walk up all major streams.

The third general type of outcrop occurs as isolated outliers, most of which are in Dickinson County. It was found that many of these outliers are erosional remnants capping the hills and filling minor valleys. By careful study of the topography of the area a large number of these outcrops were found, many of which showed interesting details of both basal and upper contacts of the formation.

The topography of much of the Northern Peninsula has recently been mapped by the U. S. Geological Survey and some preliminary

PLATE I



topographic maps were available during the latter part of this study. Where topographic maps were not available, mapping was done on areal photographs.

The study of areal photographs both in the field and in the office permitted mapping details on a regional basis which could be accomplished in no other way in the time available. Two different sets of photographs were made available to the writer. One set, taken on panchromatic film, was flown during the month of November, 1939. An astonishing amount of physiographic detail is shown on these photographs since no foliage was on the trees at the time the pictures were taken. The other set, taken on infrared film, was flown during the month of July, 1954. The great advantage of the second set is that many new features are shown, such as roads, logging operations, etc., which greatly facilitates locating oneself on the photograph, a major problem in such a wooded area. By using these two sets of photographs, numerous streams, waterfalls, and topographic features not shown on existing maps were located. A surprisingly large number of outcrops were found in this manner, many of which show contacts of the formations studied.

Cores of the Paleozoic section were made available to the writer by several of the iron companies in the Northern Peninsula. Study of these greatly supplemented information obtainable from outcrops.

The field work for this study was accomplished during the summers of 1955, 1956, and part of 1957. All laboratory work was conducted at the University of Michigan and consisted of thin section studies, grain size analyses, heavy mineral studies, and binocular-microscope examination of cores, samples, and specimens collected in the field.

ACKNOWLEDGMENTS

Deep appreciation and thanks are extended to all those who helped make this work possible. Funds were generously provided by the Michigan Geological Survey and the University of Michigan. Dr. E. C. Stumm supervised the entire study and spent a week in Northern Michigan with the writer checking the field work. He was very helpful in giving advice and identifying the fossils. Dr. R. M. Denning and Dr. L. I. Briggs devoted many hours to consultation and made many suggestions and constructive criticisms. The personnel of the Michigan Geological Survey were extremely helpful in supplying maps, photographs, published and unpublished data from previous investigations, outcrop locations, and field equipment. Miss Helen Martin of the Michigan Survey, who suggested the study, was especially helpful in giving encouragement and suggestions. Special thanks are extended to Mr. Bruce Franklin for his faithful assistance in the field during the entire summer of 1955 and to Mr. Harry Sorensen and Mr. Berndt Baetcke who accompanied the writer in the field for several weeks during the later phases of the study. Mr. Kenneth Wier and Mr. Kenneth Vanlier of the U. S. Geological Survey gave valuable help in locating outcrops. The writer is also indebted to his wife, Sally, for her assistance in the field during the second summer, typing the preliminary manuscript and constant encouragement and help during the entire period of investigation.

PREVIOUS WORK

As early as 1821 notations were made of the various physiographic and geologic features along the southern coast of Lake Superior by the exploratory expeditions of Schoolcraft (1821). Douglass Houghton (1814), however, was the first competent geologist to study systematically the rocks of the area. Since the publication of Houghton's report in 1841, the Lake Superior region has been recognized as a classic region for Precambrian iron and copper. It has therefore received considerable attention from both American and foreign geologists.

Most of the reports on Lake Superior geology mention the "Lake Superior Sandstone" primarily because of the problem of its age and stratigraphic relationships to the Keweenawan series. The question whether the "Lake Superior Sandstones" are more closely related to the copper-bearing rocks of Keweenawan age or to the fossiliferous Paleozoic rocks of the Michigan Basin has been debated for over a century, but a complete review of all the papers discussing this problem will not be presented. The principal contributions to the developments of the nomenclature of the "Lake Superior Sandstone" are shown in figure 1 and will be discussed briefly on the following pages. The reader interested in a more complete treatise on the early historical development of Lake Superior geology is referred to Foster & Whitney's (1850) report Number one and to Wadsworth (1880).

Houghton (1837-1845, ed. Fuller, 1928) first applied the term "Lake Superior Sandstones" to the lowest Paleozoic rocks in Northern Michigan which rest upon the Precambrian complex. He considered the "upper gray" sandstones, extending from Point Iroquois to Grand Island, as resting unconformably upon the "lower red," which are exposed from Munising to Bete Grise Bay. He used the term "Sandy Lime Rock" for the sandy dolomite which immediately overlies the "upper gray" (pp. 498-500). Houghton later changed his views regarding the contact between the "upper gray" and "lower red" sandstones and concluded that no angular unconformity existed.

In 1851 Foster & Whitney published the results of their extensive studies of the geology and physiography of the Lake Superior area and presented the first detailed descriptions of the "Lake Superior Sandstones" (part II, pp. 110-139). They considered the sandstone on both sides of the Keweenaw Peninsula to be the same age and to be equivalent to the Potsdam of New York.

Rominger (1873) studied the Paleozoic section in Northern Michigan and included some detailed descriptions of a number of outcrops of the "Lake Superior Sandstones." He recognized a division between the "lower hard red sandstone" and the upper section which was "friable and white," but concluded the contact was gradational. Since the "Lake Superior Sandstones" are overlain by a sandy dolomite which he considered to be equivalent to the "Calciferous and Chazy," he concluded that the "Lake Superior Sandstones" were equivalent to the Potsdam of New York.

Irving (1883, pp. 351-366) introduced the term "Eastern Sandstones" and "Western Sandstones" to the literature for sandstones similar in appearance, but located on opposite sides of the Keweenaw Peninsula. He considered them to be equivalent in age and to be the "downward continuation of the Mississippi Valley Cambrian Sandstone."

Van Hise & Bayley (1900, p. 11), from their studies of the rocks in the Menominee district, proposed the term "Hermansville" for the strata which overlies the "Lake Superior Sandstone." Apparently the "Hermansville" includes all the strata which Rominger considered as "Calciferous and Chazy."

Lane & Seaman (1907, p. 692) recognized the need for separate names for the divisions in the "Lake Superior Sandstones" and proposed "the term Freda sandstone for that west of the Copper range, . . . Jacobsville sandstone for that east of the Copper Range, and . . . Munising sandstone" for the light sandstone "which crosses the bluffs back of Munising" and constitutes the upper 250 feet of the "Lake Superior Sandstone."

Work by Helen M. Martin (1936) in compiling the "Geologic Map of the Northern Peninsula of Michigan" indicates the opinion of the Michigan Geological Survey at that time concerning the nomenclature of the "Lake Superior Sandstone." Following the correlation proposed by Thwaites (1934, p. 426) the "Lake Superior

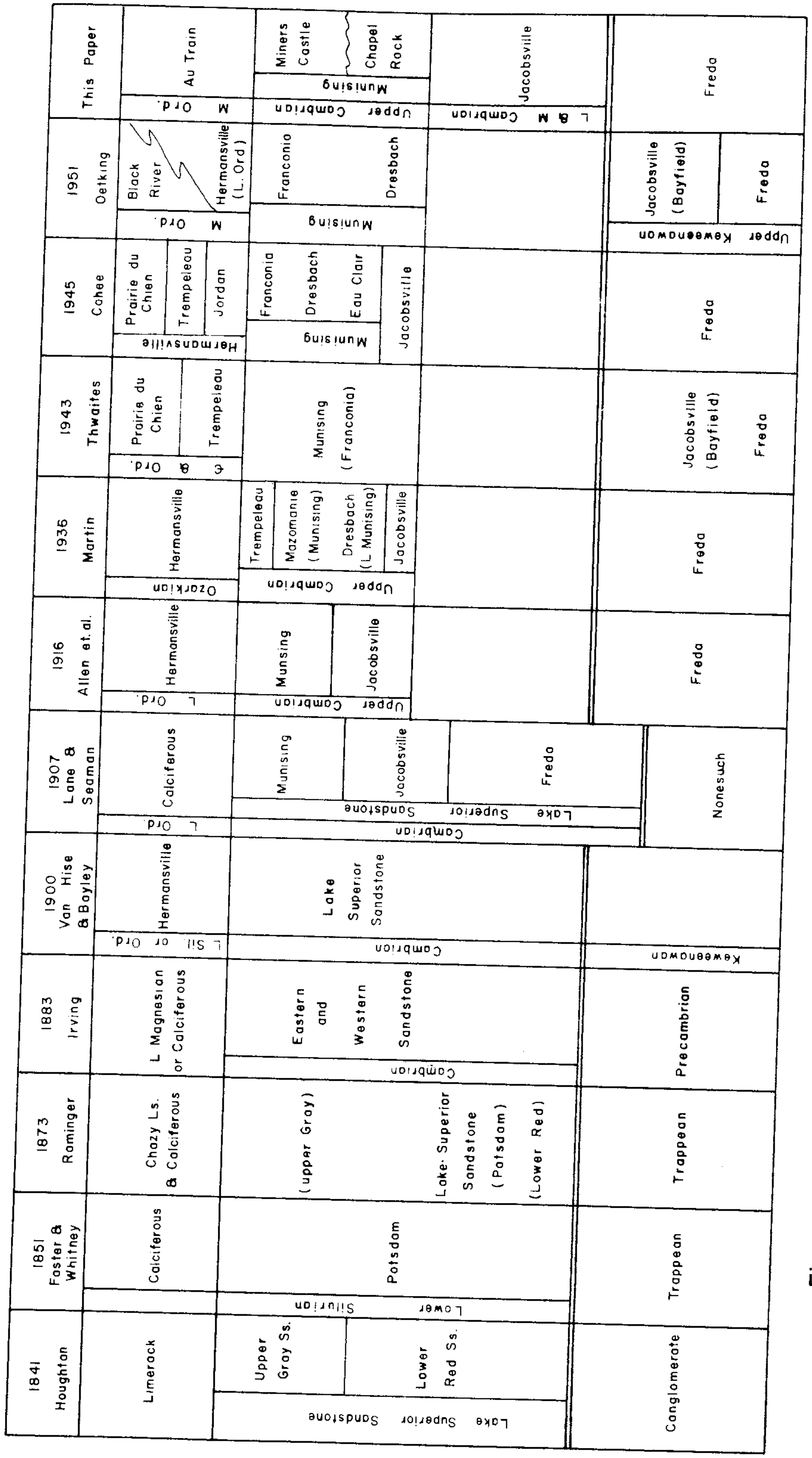


Figure 1. Development of the Cambrian Nomenclature of Northern Michigan

Sandstone" was divided into the Munising formation which was considered equivalent to the Dresbach, Mazomanie, and Trempealeau, and the Jacobsville formation which was indicated as Cambrian. The Michigan Geological Survey used the term Hermansville for the dolomitic sandstone which overlies the "St. Croixan" and considered it to be "Ozarkian" or "Canadian" following the nomenclature proposed by Ulrich.

During the period from 1922 to 1934, the Land Economic Survey Division of the Michigan Department of Conservation studied the soil, use of the land, geology, and mineral resources of the eastern part of the Northern Peninsula. These studies, particularly those of Bergquist and Ver Wiebe, resulted in some significant contributions to the Cambrian geology of the Northern Peninsula. Ver Wiebe (1927) discovered an outcrop of sandstone on the east side of Sault Point which contained numerous poorly preserved gastropods identified by Ulrich as the genus *Ophileta.* Because of their lithologic similarity to part of the section at Pictured Rocks, Ver Wiebe considered these sandstones to be an outcrop of the "Lake Superior Sandstone."

In 1937 Bergquist published the results of his studies of the upper contact of the Cambrian sandstone exposed in several waterfalls in Alger County. On the basis of lithologic and chemical characteristics, he established what he considered to be the Cambrian-Ozarkian contact following the nomenclature suggested by Ulrich.

In 1934 Thwaites published a paper entitled "Well Logs in the Northern Peninsula of Michigan" in which he concluded that the Mazomanie and Dresbach formations of Wisconsin extend into northern Michigan and form the Munising sandstone. He also thought it possible that a disconformity exists between the Jacobsville and Munising.

Thwaites (1943, p. 499) considered the "Calciferous and Chazy" of Rominger to be equivalent to the Trempealeau and lower Magnesian. He suggests that the term "Hermansville" included both the Trempealeau and Prairie du Chien and that it should be dropped because of the incomplete descriptions given by Van Hise & Bayley. Contrary to the conclusions in his 1934 paper, Thwaites found no division in the Munising and therefore concluded that it was equivalent to the Franconia of Wisconsin. He believed, therefore, that the Cambrian-Ozarkian contact studied by Bergquist was the Trempealeau-Franconia contact and that the Paleozoic section progressively overlapped to the north.

In 1945, as the result of subsurface stratigraphic work in the Michigan Basin, Cohee published the U.S.G.S. Oil and Gas Investigation Preliminary Chart Number Nine. He considered the Hermansville to be equivalent to Jordan, Trempealeau and Prairie du Chien and the Munising formation equivalent to Eau Claire, Dresbach and Franconia.

Several unpublished theses have been written on various parts of the Munising or Jacobsville formations. The earliest of these was by Roberts (1940), who studied the geology of the Alstan district in Houghton and Baraga counties. Roberts recognized the unconformity between the Jacobsville and Middle Keweenawan flows and concluded that the Jacobsville was Cambrian in age.

Denning (1949) studied the petrology of the Jacobsville sandstone and made detailed heavy mineral analyses of a number of samples collected in the Keweenaw Bay area. His work shows that the heavy mineral assemblage of the Jacobsville formation remains relatively constant over a large area and throughout the stratigraphic section.

Oetking (1951) studied the Lower Paleozoic rocks in the Munising area in an effort to determine their origin and stratigraphic relationships. He recognized an unconformity between the Jacobsville and Munising and on the basis of similarities in lithology and heavy mineral suites correlated the Jacobsville with the Bayfield of Wisconsin. Although he recognizes no lithologic break in the Munising formation, Oetking reports a break in heavy mineral suites and correlates the Munising with Dresbach and Franconia. On the basis of fossils collected in the "Au Train" formation Oetking establishes its age as Middle Ordovician which is indicated on his map to overlap the Hermansville formation.

Hultman (1953) mapped the geology of the Marquette quadrangle, and considered the Jacobsville sandstone in that area to be terrestrial and to have been derived from the nearby highlands.

Driscoll (1956) studied the heavy minerals from samples collected from the Munising and Jacobsville between Marquette and Grand Marais. His heavy mineral work was much more detailed than Oetking's and it shows that the change in the heavy mineral suite is at the contact between the "Pictured Rocks" and "Miner's Castle" members, as defined by this writer. Driscoll believes that the Upper Munising represents a transgressive-regressive cycle of the upper Cambrian seas. The lower units of the Upper Munising or transgressive phase represent the Franconia and the upper regressive phase represents the Jordan of southern Wisconsin. He bases these conclusions on the "upwardly increasing garnet percentages" in the Munising formation.

Table 1 is a summary of some of the theories proposed during the last 100 years for the stratigraphic position of the Jacobsville

TABLE 1

THEORIES PROPOSED FOR THE STRATIGRAPHIC POSITION OF THE JACOBSVILLE FORMATION

AGE	INVESTIGATOR	DATE	BASIS FOR CONCLUSIONS
Subsequent to Carboniferous	Owen, D. D.	1848	Strat. position
Triassic	Jackson, C. T.	1861	Lithology and strat. position
	Bell, R.	1869	Lithology and strat. position
New Red SS equivalent	Houghton, D.	1843	
	Rogers, H. D.	1848	Unconformity
	Jackson, C. T.	1849	Reported fossils
	Marcou, J.	1850	Strat. position
Permian	Macfarlane, T.	1866	Lithology
Old Red SS equivalent	Schoolcraft, H. R.	1821	Lithology
	Bigsby, J. J.	1824	Lithology
	Bayfield, H. W.	1845	Strat. position
	Locke, J.	1847	Strat. position
Silurian	Bigsby, J. J.	1852	
	Brooks & Pumpelly	1872	
Calciferous	Dana, J. D.	1862	
Potsdam	Hubbard, B.	1850	
	Foster & Whitney	1851	Strat. position
	Owen, D. D.	1851	
	Rivot, L. E.	1856	
	Rominger, C.	1873	Strat. position
	Wadsworth, M. E.	1880	Strat. position
	Irving, R. D.	1883	Strat. position
	Allen, *et. al.*	1916	Strat. position
Older than Potsdam	Logan, W.	1847	
	Whittlesey, C.	1867	
Cambrian	Van Hise & Leith	1911	Strat. position
	Lane & Seaman	1907	Strat. position
Middle Cambrian	Raasch, G. O.	1951	Strat. position
	Winchell, N. H.	1895	Unconformity
	Logan, W.	1851	
Keweenawan	Hotchkiss, W. O.	1933	Unconformity
	Thwaites, F. T.	1934	Similarity to Bayfield
	Leith, *et. al.*	1935	Similarity to Bayfield
	Oetking, P.	1951	Similarity to Bayfield

formation. Many of the early workers based their correlation on the lithologic similarity between the Jacobsville and various red sandstones of Late Paleozoic age. The more recent correlations, however, are based primarily on stratigraphic position with most of the disagreements resulting because the authors were unable to examine enough outcrops to establish a regional picture for the problem.

PHYSIOGRAPHY

The physiography of the outcrop belt of the "Lake Superior Sandstones" may be conveniently divided into four main divisions: (1) highlands of the Keweenaw Peninsula, (2) Keweenaw Bay lowlands, (3) Precambrian highlands, and (4) eastern lowlands. Glacial debris is irregularly scattered throughout the entire area, but in regions where the cover is relatively thin, the structure and type of bedrock is the controlling factor for the type of physiographic features which develop.

HIGHLANDS OF KEWEENAW PENINSULA

A series of monoclinal ridges known as the "Trap Range" or "Copper Range" extends from Keweenaw Point southwestward through the middle of Keweenaw Peninsula and into Wisconsin. The highland formed by these monoclines is approximately 12 miles wide. It is composed of Keweenawan basalts, conglomerates, and sandstones which dip to the northwest at an angle between 35 and 60 degrees. These ridges stand out in bold contrast to the lowlands to the east and constitute the major physiographic feature of the area. The surface of the truncated edges of these resistant rocks is a smooth peneplain, about 700 feet above the level of Lake Superior, dissected in only a few places by transverse streams. To the south between Iron and Presque Isle rivers, a spur branches off north and west of the Porcupine Mountains and in the same area another offshoot from the main chain trends eastward and forms the South Range.

The Keweenaw Highlands are terminated abruptly on the east by the Keweenaw fault, which forms a steep escarpment and marks the junction of the Jacobsville formation with the Keweenaw basalts.

KEWEENAW BAY LOWLANDS

The Keweenaw Bay lowland occupies the eastern half of the Keweenaw Peninsula. It extends approximately 60 miles southwest of Keweenaw Bay and is 20 miles wide. It is bounded on the northwest by the Keweenaw fault, on the east by the Huron Mountains, and on the south by the South Trap Range. The entire area is underlain by the flat-lying Jacobsville sandstone, which, being younger and less resistant than the surrounding crystalline rocks, is preserved only by virtue of down-warping and down-faulting in that region. When compared to the surrounding crystalline rocks, the lowland appears to be featureless except for the cliffs along the coast and few knobs of basalt which protrude through the sandstone cover. During the late Pleistocene a considerable thickness of lake deposits accumulated in parts of the lowland which adds to the flatness of the general area. This soft, unconsolidated material is easily eroded by water action and gorges as much as 200 feet deep have been eroded by some of the major streams.

PRECAMBRIAN HIGHLANDS

The physiography of the Precambrian highlands depends upon the character of the rock exposed. A hilly, and in places mountainous, topography reaches an elevation of 1,200 to more than 1,900 feet above sea level. Instead of the continuous ranges or series of parallel ranges common to the Keweenaw Peninsula, the Precambrian highland is in most places an irregular mountainous area with numerous hills, swamps, and lakes. In the Marquette, Felch, and Menominee regions, a definite series of east-west trending valleys and ridges were eroded from the alternating weak and resistant members of the Huronian[1] series. In the Menominee and Felch districts it is clear that the valleys and ridges were formed prior to the invasion of the Cambrian sea but have been modified by the present cycle of erosion in areas where the Cambrian and younger sediments have been removed. No outliers of the Munising sandstone are in the Marquette region, but several exposures of the Jacobsville as high as 1,000 feet above sea level indicate that many of the present features were once covered by sandstone.

EASTERN LOWLANDS

The eastern lowlands occupy the entire Northern Peninsula east of the meridian of Waucedah and Foster City. Although the greater part of this area is covered by glacial drift, a gentle southward dipping cuesta formed on the resistant Au Train formation is well developed in most of Alger County and in the eastern part

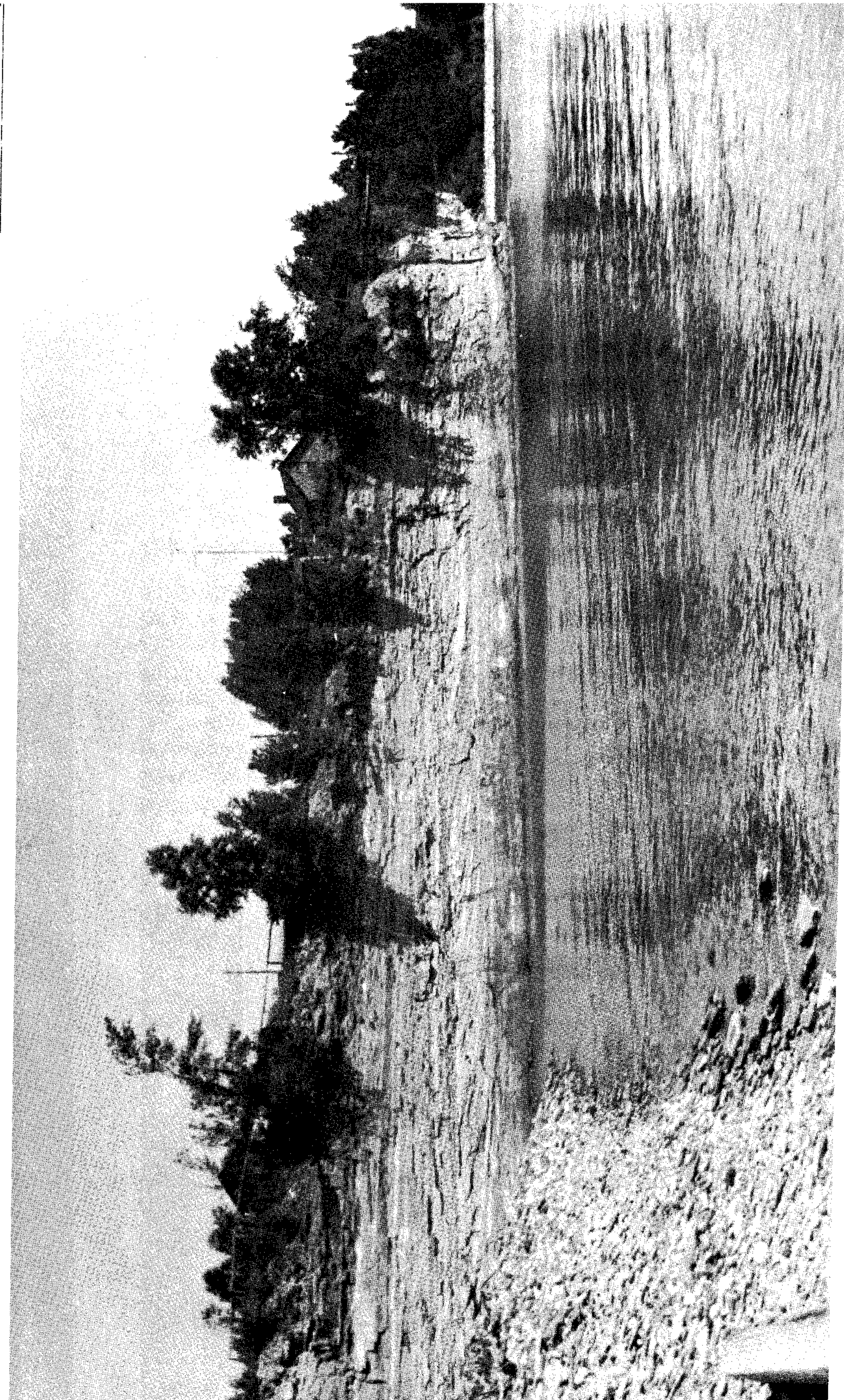
[1]Editor's Note: In January 1958 the U. S. Geological Survey Committee on Geologic Names adopted the name Animikie for official use for Michigan rocks formerly named Huronian.

of Marquette County. The most prominent breaks through the cuesta are the valleys of the Au Train, Laughing Whitefish, and Rock rivers. Headward erosion by these rivers has cut long, deep gorges in the soft Cambrian sandstone which underlies the more resistant Au Train formation. All of the north-flowing streams in Alger County form waterfalls as they cross the cuesta, but drainage is poor and swamps are very common. From Munising eastward to Beaver Lake the face of the cuesta follows the shoreline of Lake Superior and forms the famous Pictured Rocks. Eastward the cuesta retreats inland and disappears beneath a cover of glacial drift. The elevation of the cuesta in Alger County ranges from 200 to 500 feet above the level of Lake Superior.

In Schoolcraft and Luce counties great swamps drained by the Tahquamenon and Manistee rivers occupy most of the area and the only major outcrop is at Tahquamenon Falls. East of Alger County the bedrock is covered by lake clays and recessional and ground moraines as much as 400 feet thick.

Old shorelines are well developed along much of the southern coast of Lake Superior and are especially conspicuous in the area of Whitefish Point. East of Waucedah and Foster City numerous drumlins cover an area of several townships and present striking topographic features. Several drumlins are also in Alger County, south of Chatham.

For a more detailed description of the physiography of the Northern Peninsula of Michigan, the reader is referred to Leverett (1910, 1929), Van Hise & Leith (1911), and Irving (1883).



Type locality of Jacobsville Formation, Jacobsville, Houghton County.

Jacobsville Formation

GENERAL DESCRIPTION

The Jacobsville formation was named by Lane & Seaman (1907, p. 692) after the little town of Jacobsville where the once famous "Portage Redstone" was quarried. The term was applied to the red sandstone east of the Copper Range, which is well exposed along the shore from the tip of the Keweenaw Peninsula to Grand Island. It includes the "lower red member" of Houghton's "Lake Superior Sandstone" and most of the "Eastern Sandstones" of Irving. Although opinions differ, most geologists have considered the Jacobsville to be Cambrian in age and to be the downward continuation of the Upper Cambrian of the Mississippi Valley. Thwaites (1934, p. 426), however, questioned the Cambrian age of the Jacobsville and suggested that it might be Upper Keweenawan. This view was shared by Leith, Lund & Leith (1935, p. 12) and Oetking (1951, p. 88). As a result, on most geologic maps the age of the Jacobsville appears as Cambrian or Precambrian.

AREAL EXTENT

Shore cliffs composed of the Jacobsville formation extend along the entire length of the southern coast of Lake Superior from Bete Grise Bay to Grand Island and are interrupted only by a few sandy beaches (Plates 1, 2). Along most of the coast from Munising to Beaver Lake, the Jacobsville is completely below water level and is overlain by the Munising formation, which constitutes the Pictured Rocks in that area. In several places, however, in the Pictured Rocks area, the Jacobsville can be recognized a few feet above the lake level. Farther east, good exposures are found at Au Sable Point and in the bluffs behind Grand Marais. Although the Jacobsville sandstone is covered with glacial drift throughout most of the area east of Grand Marais, well logs and geophysical data indicate that it constitutes the bedrock of most of Whitefish Point (Vanlier, 1956). Several small exposures were found in the north end of Sugar Island and on the west coast of Parisian Island in Whitefish Bay. Exposures of the Jacobsville were also reported in the rapids of the St. Mary's River during the construction of the locks at Sault Ste. Marie (Landes, 1942).

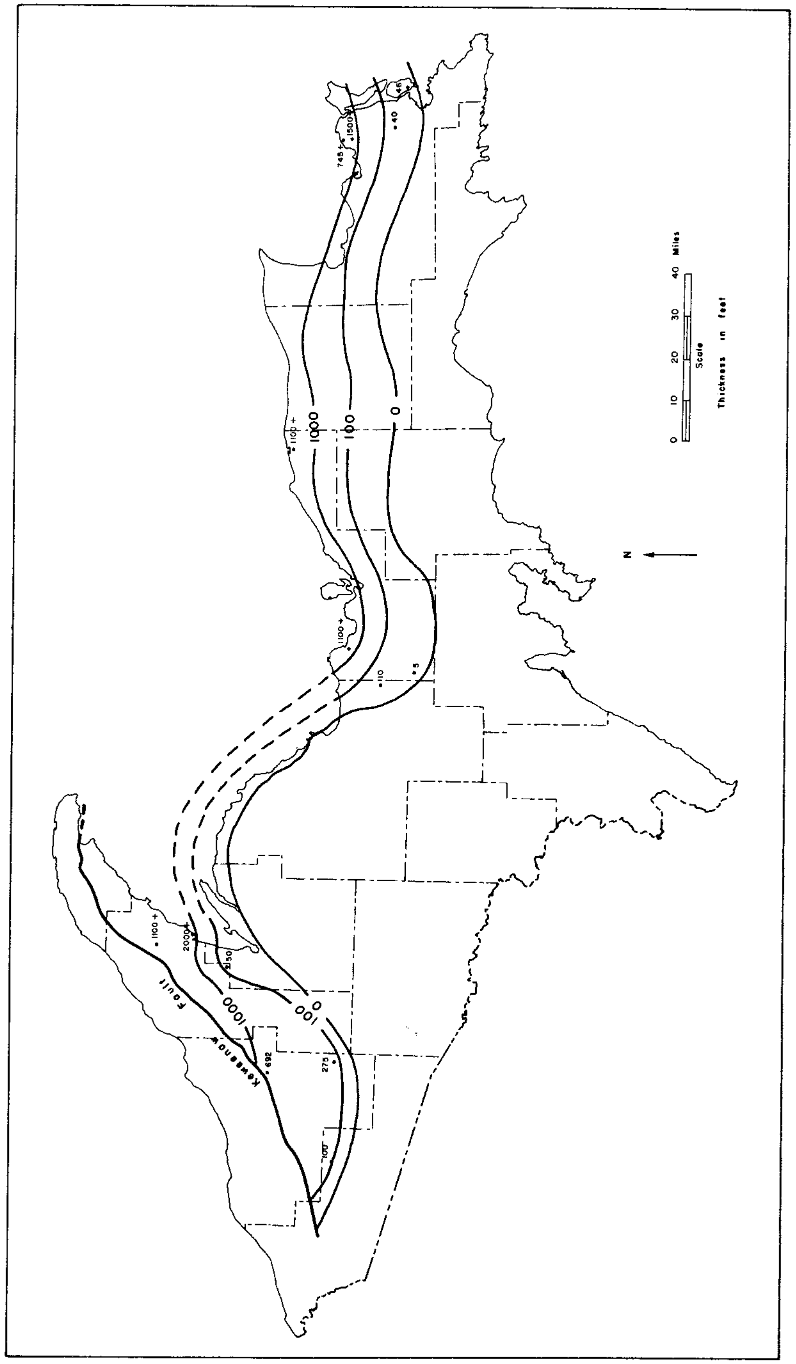


Figure 2. Isopach map of the Jacobsville formation

The Jacobsville sandstone between L'Anse and Munising extends 3 to 4 miles south of the coast. In the eastern part of the Northern Peninsula it is overlain by the Munising formation, but west of Marquette it pinches out upon the Precambrian highlands. To the west in the Keweenaw Peninsula the Jacobsville is truncated abruptly by the Keweenaw fault, but a number of outcrops indicate that it occupies the lowlands between the Copper Range and the South Trap Range (Plate 1). Jacobsville-like sediments have not been reported on the north shore of Lake Superior but evidence on the south shore indicates that the Jacobsville undoubtedly constitutes the bedrock for much of the bottom of Lake Superior, especially west of the meridian passing through Munising.

THICKNESS

The thickness of the Jacobsville formation is extremely diverse because of the relief of the Precambrian surface upon which it was deposited. In many places along the coast just north of Marquette the Jacobsville pinches out completely to the south where it laps upon the old Precambrian highland. Elsewhere along the shore cliffs, more than 300 feet of Jacobsville was measured at one outcrop. Well logs and geophysical data provide the best information of the great range in thickness and present the most accurate estimate of the order of magnitude of the maximum thickness.

In the Keweenaw Bay lowlands just north of the South Range, the log of a well in sec. 11, T. 47 N., R. 38 W. records the total thickness of the Jacobsville in that area as 275 feet. Another well in T. 47 N., R. 42 W. in the same general area, drilled through only 100 feet of Jacobsville before reaching the Keweenaw Basalt. To the north, in the vicinity of Hancock, a well drilled through 1,100 feet of Jacobsville without reaching its base. Likewise at Grand Marais, drilling operations prove that the Jacobsville is over 1,100 feet thick. In T. 47 N., R. 1 E., 1,800 feet of Jacobsville was drilled through in the Radar Station well without reaching the base of the formation, but, only 10 miles to the south, the Neebish well penetrated only 46 feet of Jacobsville before reaching the Precambrian quartzites.

A few miles southeast of Marquette in sec. 36, T. 46 N., R. 23 W., the Jacobsville, resting unconformably upon granite, is only 15 feet thick. This was probably the entire thickness of the Jacobsville in that area at the time of the invasion of the Munising seas since the base of the Munising is exposed only a short distance away. Approximately 7 miles south of this outcrop a drill hole near Kiva drilled through only 5 feet of Jacobsville before entering the Precambrian.

Using an assumed velocity 10,000 feet per second, Bacon (1957) made a seismic shot near the town of Jacobsville in an effort to gain some idea of the formation thickness in the type locality. The first anomaly at a depth of 2,000 feet might be the base of the Jacobsville, but the evidence is not conclusive.

It is obvious from these data that the Jacobsville thickens greatly to the north where it may be over several thousand feet thick and pinches out entirely to the south approximately at 46° 30′ north latitude or along an east-west line passing through the Princeton and Gwinn area, Marquette County (fig. 2).

COMPOSITION

Rounded to subangular quartz grains constitute over 75 percent of the detrital constituents in the Jacobsville formation. Most of the quartz grains show straight extinction and contain tiny gas bubbles and bubble trains which suggest that they were derived from an igneous source. Other grains (approximately 15 percent) show extreme undulatory extinction and in most samples a few grains of polycrystalline quartz were recognized, indicating part of the material was derived from metamorphic rocks. Authigenic quartz is generally present only in small amounts as overgrowths on detrital grains, but locally it is abundant enough to produce an orthoquartzite. Feldspar is the next most abundant mineral and occurs as fresh or slightly altered angular grains. Throughout most of the formation it is present in amounts less than 15 percent, but near the contact with the Precambrian feldspar may locally constitute 35 percent of the mineral composition. Microcline is the most abundant variety followed by orthoclase and plagioclase. Pyroxene, amphibole and fragments of basalt and iron formation occur in minor amounts, generally less than 8 percent.

The matrix consists of fine particles of quartz mixed with sericite and a white clay mineral, probably illite, which acts as a clastic binder. Iron oxide, authigenic quartz and some calcium carbonate are also important cementing materials.

HEAVY MINERALS

During the past few years several workers have studied the heavy mineral suites from various localities in the Jacobsville formation. The most detailed work was done by Denning (1949) on samples collected in the Keweenaw Bay area and by Driscoll (1956) on samples collected in the Munising area. The writer supplemented these data by analyzing the heavy minerals from samples collected in other strategic localities. Each worker used a slightly different method of treating the samples but all analyzed the same size fraction so that it is possible to make a general comparison of their results.

Fifty to 80 percent of the heavy minerals in the Jacobsville formation are opaque, with magnetite, hematite and ilmenite being the most abundant species. Other minerals consistently present are garnet, tourmaline, leucoxene, and zircon. Anatase, apatite, augite, biotite, collophane, epidote, and staurolite were reported by Denning from some samples but in amounts of less than 5 percent of the total heavies. Epidote, collophane, and staurolite were not recorded by Driscoll, but he did find small amounts of rutile in some samples. Figure 4 shows the localities from which the samples were taken for heavy mineral analysis and fig. 5 represents a summary of the results of the various studies made.

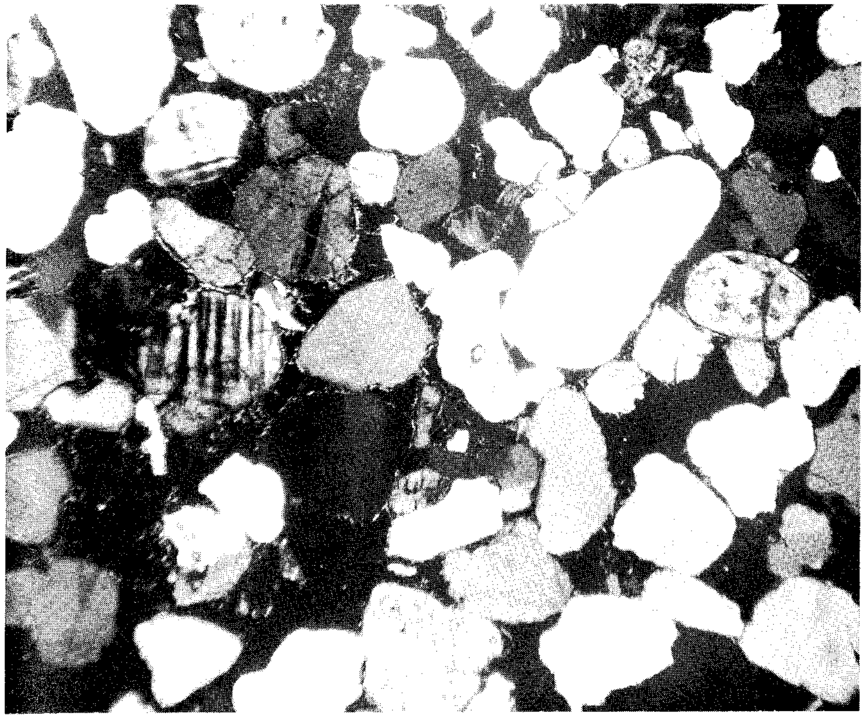


FIGURE 3

Photomicrograph of the Jacobsville formation at Au Sable Falls, Alger County. Crossed nicols. X33.

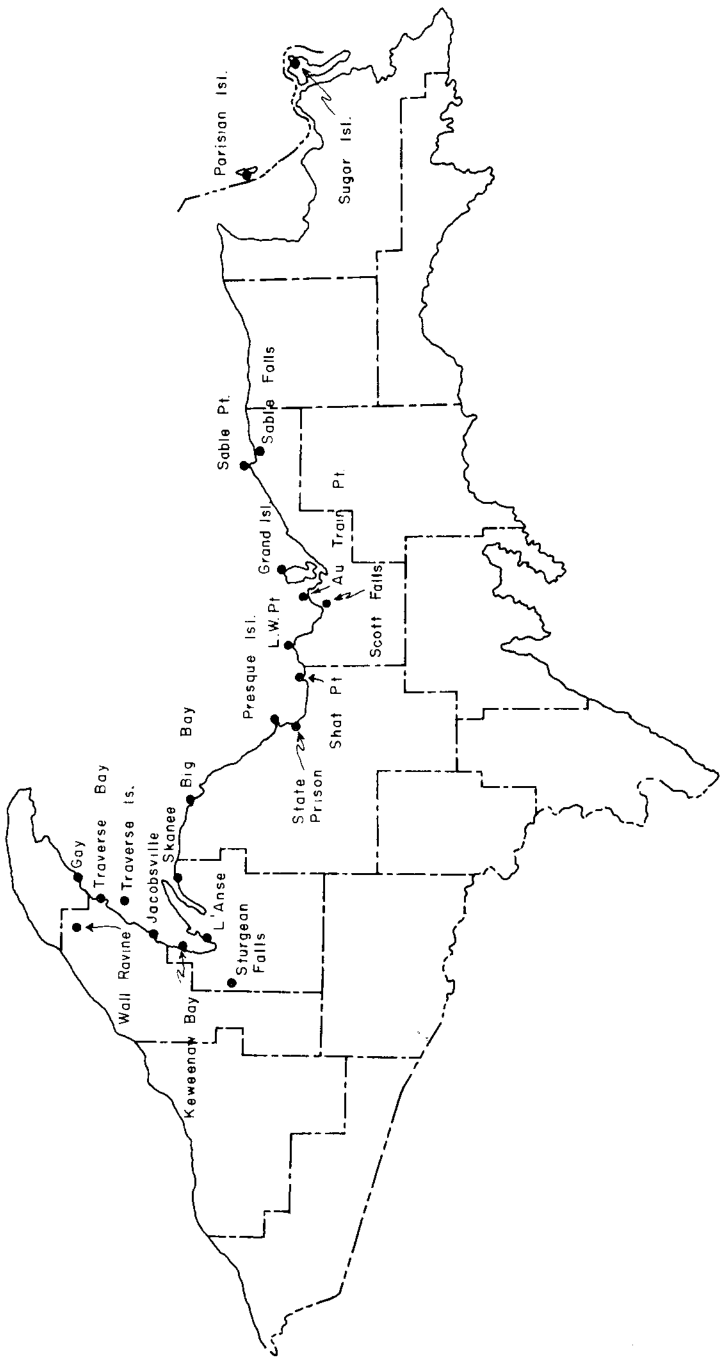


Figure 4. Map showing locations where samples were taken for heavy mineral analysis of the Jacobsville formation.

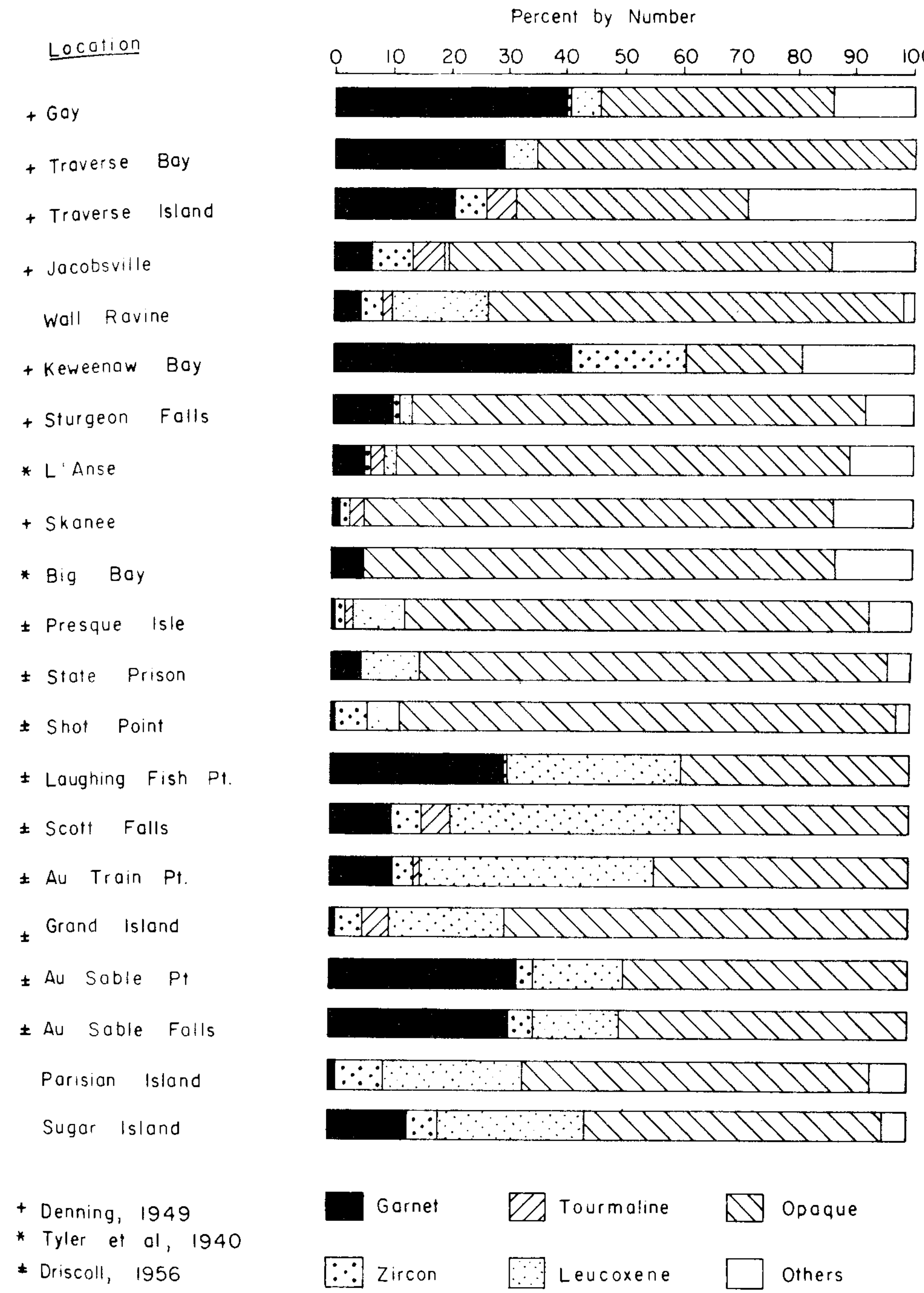


Figure 5. Heavy minerals of the Jacobsville formation

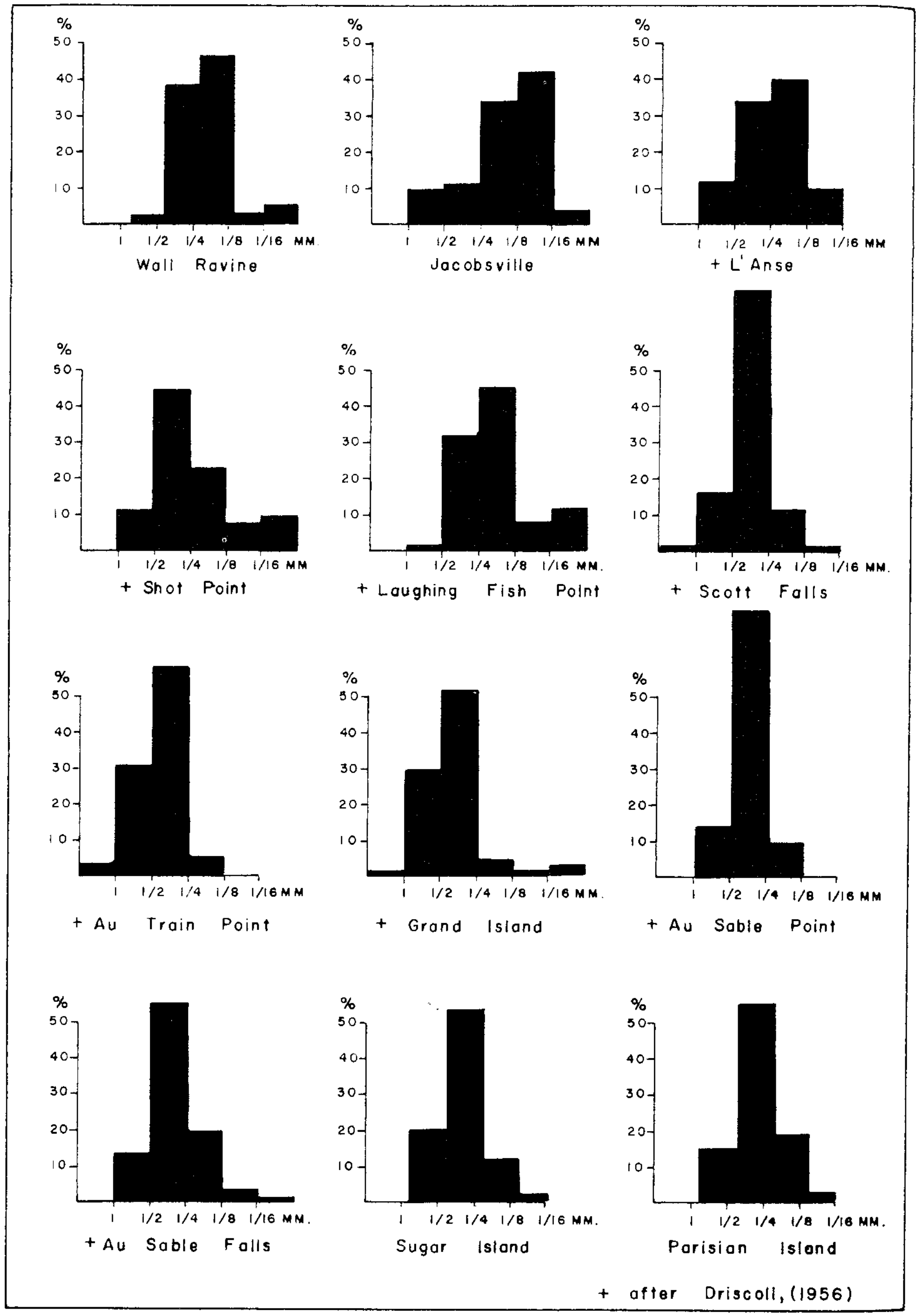


Figure 6. Grain-size distribution in typical samples of the Jacobsville sandstone

Throughout the entire extent of the Jacobsville formation the heavy mineral assemblage remains relatively constant. The opaques, together with garnet, constitute the major part of the species present, but small amounts of zircon and tourmaline are found in practically every sample. In samples taken from sections close together, the percentage of the species present is almost identical. This is well illustrated by the results obtained from Au Sable Falls, Au Sable Point, Scott Falls, Au Train Bay, Gay, Little Traverse Bay, Skanee, and Big Bay. The difference from area to area undoubtedly reflects slight differences in the lithology of the source area.

TEXTURE

Although the grain size of the Jacobsville formation ranges from shale to conglomerate, typical samples taken throughout the entire area show that the average grain size is between ¼ and ½ millimeter in diameter. Driscoll (1956) made a size-grade analysis of 23 samples collected along the coast from Marquette to Sable Falls. Histograms of his results, shown in fig. 6, are compared with samples taken from other localities and analyzed by the writer. Excepting minor conglomerate lenses, most of the samples studied are well sorted and are skewed toward the fine grains. Most of the coarse material is concentrated at the base of the formation near the contacts with the Precambrian. Higher in the section stringers of very coarse sand and conglomerate are concentrated along several horizons or in zones parallel to the cross-bedding.

COLOR

The color of the Jacobsville formation is one of its most striking characteristics. Red and reddish-brown predominate, but in practically every outcrop the basic red color is mottled with white streaks, blotches, and circular spots. The boundary between the red and white colors is sharp and well defined, showing little or no gradation even when observed under magnification. In general the shale beds and fine-grained sandstone units have the greatest intensity of red coloration and the least amount of white mottling, whereas the massive coarse-grained units are white or light pink and are mottled with red streaks. Most of the abrupt color changes are at bedding planes separating units which differ in permeability. Leaching of the red color follows planes of cross-bedding in many places and produces alternating red and white streaks parallel to the stratification. In many sections, sets of cross-strata do not

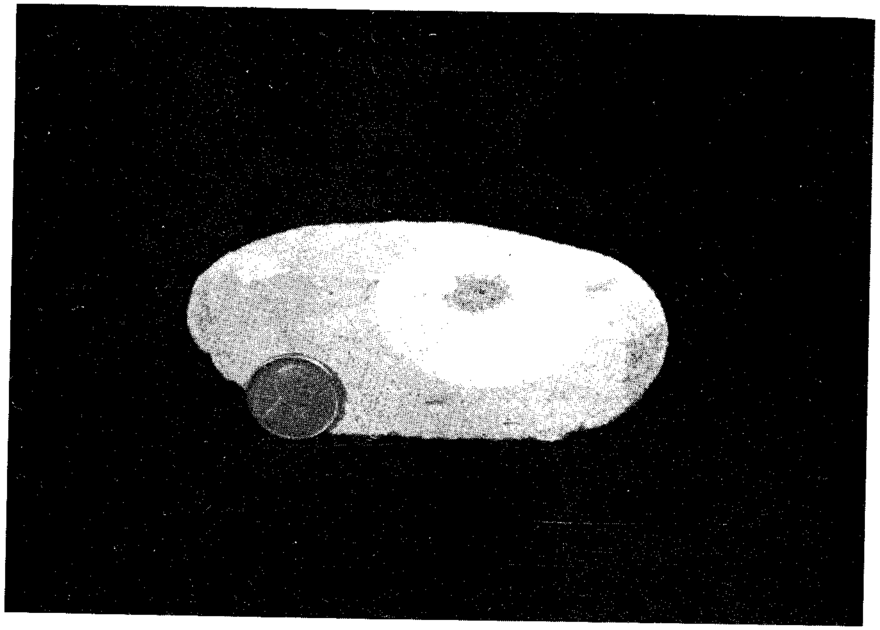


FIGURE 7

Reduction sphere in the Jacobsville formation showing the black center which presumably acted as a control for the localized reducing environment which produced the white color.

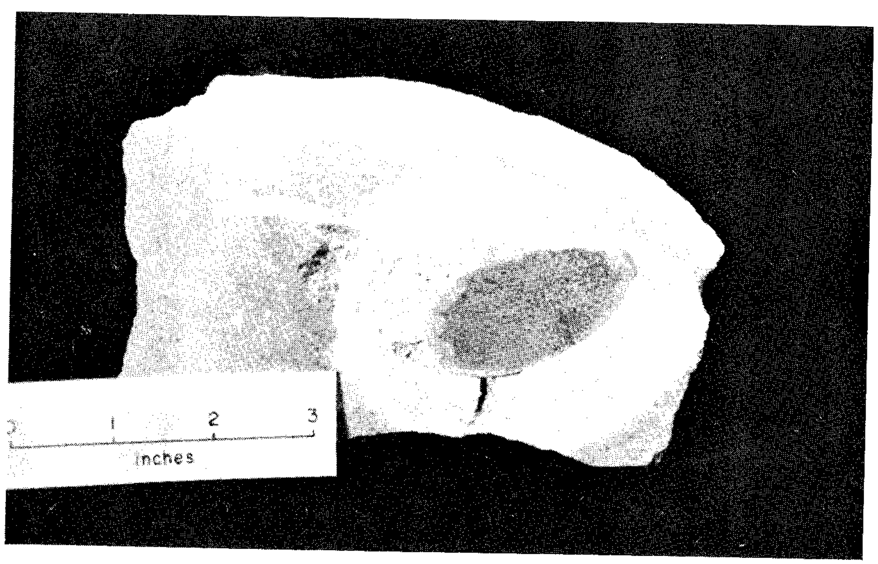


FIGURE 8

Reduction sphere in the Jacobsville formation showing an isolated sandstone pebble in the center. Note the reduction rim around the pebble.

have the same permeability and one set may be entirely red and the other white.

White reduction spheres ranging from an ill-defined speck to large perfect spheres more than 10 inches in diameter are found in nearly every outcrop. Many spheres are scattered randomly throughout the section, but some are concentrated in selected beds and merge with each other to form ellipsoids and blebs. In two dimensions the spheres look like circular spots. Many contain a black speck in the center (fig. 7). It is quite probable that more reduction spheres contain black centers than show in the outcrop, since it is only by chance that the surface of the outcrop intersects the exact center of the sphere. Pebbles are also found in the center of many of the larger spheres and like the black spots appear to have controlled the leaching of the red coloration (fig. 8). Most of the reduction spheres are completely white but a few show one or two alternating zones of red, white and pink with deeper shades of red surrounding the white spot.

The red coloration has also been leached along most of the major joint sets in the Jacobsville formation so that the joints are marked by long straight white bands ranging from a fraction of an inch to more than 2 feet wide. Many of these bands extend along the entire length of the joint and can be traced for several hundred feet. A direct relationship between the width of the leached band and the size of the joint suggests that the increased permeability due to fractures was the controlling factor in leaching.

All evidence indicates that the red color of the Jacobsville formation is a primary feature, and that subsequent leaching in selected areas produced the white mottling. Permeability probably played an important role in the formation of most of the white mottling. The reduction spheres, however, were most likely controlled from the localization of organic matter and scattered pebbles which had a composition sufficient to produce a reducing environment.

DESCRIPTION OF FACIES

Four distinct lithic units are recognized in the Jacobsville formation but outcrops are too discontinuous to reveal all the details of their relationships. Most of the outcrops are so small that only one lithic type is exposed, but in several places along the shore cliffs the lithic units interfinger or grade laterally from one type to another. These units are therefore considered as facies representing environmental conditions which were local as well as temporary. The most abundant facies is a lenticular sandstone which is found in most of the shore cliffs and in many of the outcrops inland. Massive sandstone is common, however, in many exposures in the Keweenaw Bay lowlands and constitutes an appreciable part of the Jacobsville formation in that area. The composition and texture of these facies are very similar but sedimentary structures indicate that they were formed in different environments. Where the basal contact of the Jacobsville formation is exposed, most conglomerate lenses are associated with topographic highs of the old Precambrian surface. The regional slope of the Precambrian surface at the time the Jacobsville was deposited was to the north, so that the Jacobsville forms a progressive onlap to the south (see section on paleogeography). The conglomerate facies therefore transgresses time boundaries. In some localities thin-bedded shale is near the top of the formation and although it is relatively minor, the shale is important because it indicates an upward change from a predominately fluvial to a lacustrine environment.

CONGLOMERATE FACIES

General Features

Lenses of conglomerate are scattered in places throughout the Jacobsville sandstone, but for the most part such lenses are confined to the base of the formation, especially around the margins and flanks of the old buried Precambrian hills. Between Marquette and Big Bay several of these hills are partly exhumed and protrude through the Jacobsville formation forming islands and small peninsulas along the coast (Plate 3). Around the margins of the Precambrian highs the conglomerate facies is as much as 15 feet thick, but when traced laterally away from the hills it generally pinches out within a distance of 30 to 40 feet (fig. 9). The conglomerate facies is also present in this area as channel-fill deposits not directly associated with the Precambrian topography.

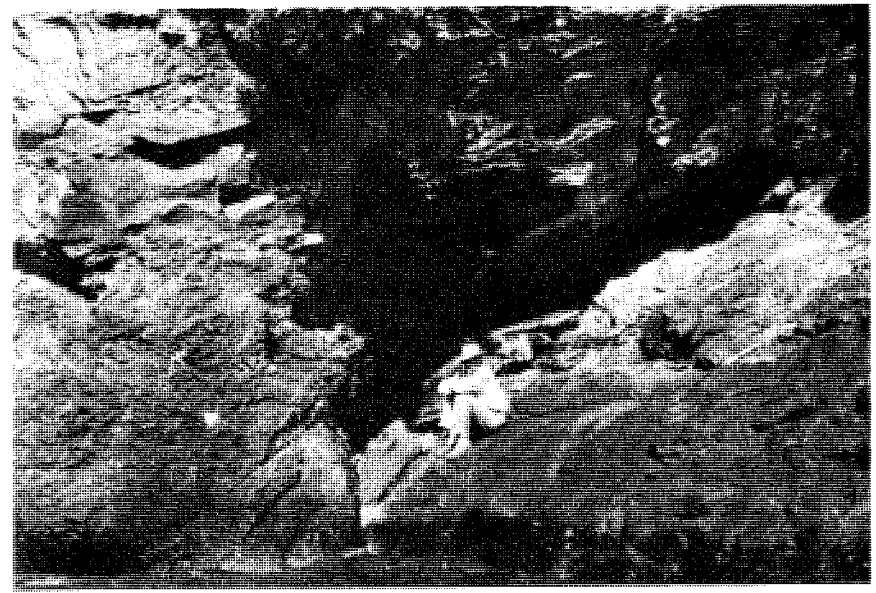


FIGURE 9

Contact between the Jacobsville formation and a knob of Precambrian granite at Thoney Point showing the conglomerate lens restricted to the flank of the Precambrian hill, and caves produced by differential erosion along the weathered zone which separates the two formations.

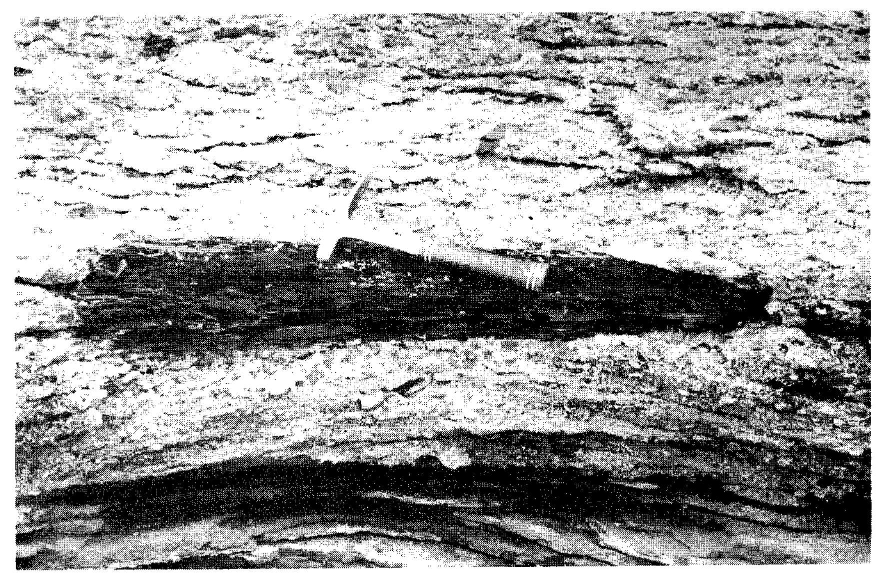


FIGURE 10

Large clay block imbedded in the conglomerate facies at Granot Loma Lodge between Marquette and Big Bay.

Excellent exposures are in the cliffs at Wetmore Landing and along the shore in the vicinity of Granite Point.

Granule and pebble size predominate in most of the exposures but cobbles are common and a few boulders are present, especially near the contact with the Precambrian and where the conglomerate is thickest. Vein quartz is the most common detrital constituent in this area. It constitutes from 50 to 60 percent of the particles larger than 2 millimeters (table 2). Most of the quartz pebbles are subangular to rounded and many have a surficial stain of iron oxide. The next most abundant mineral, potash feldspar, ranges in amounts from 15 to 25 percent. The abundance of feldspar increases rapidly as the pebble size decreases. The particles are fresh and very angular indicating that they were derived from a local source. Pebbles of quartzite, chert, slate, iron formation, and peridotite are in amounts of less than 10 percent.

TABLE 2

PEBBLE COUNTS OF THE CONGLOMERATE FACIES IN THE JACOBSVILLE FORMATION

Type of pebble	Thoney Point*		Garlic Island**		Carp River*** (after Hultman, 1953)	
	No.	percent	No.	percent	No.	percent
Vein quartz	137	51.5	230	62.0	0	0
Potash feldspar	63	23.8	59	15.7	0	0
Quartzite	23	8.5	8	2.2	108	40.0
Peridotite	12	4.5	0	0	0	0
Clay pellet	12	4.5	23	6.2	4	1.8
Chert	8	3.0	2	0.5	0	0
Iron formation	8	3.0	24	6.5	18	8.3
Slate	1	0.4	18	4.9		
Dolomite	0	0	1	0.2	47	21.0
Sandstone pebbles	0	0	5	1.3	3	1.4

*Calcite cement constitutes approximately 20 percent of the rock.
**Calcite cement constitutes approximately 30 percent of the rock.
***Conglomerate facies consists of large boulders occurring in lenses throughout a stratigraphic thickness of approximately 200 feet.

An interesting characteristic of the conglomerate facies in this area is the occurrence of shale pebbles and blocks in amounts as much as 5 percent. Most of the pebbles have the characteristic red color and white reduction spots so distinctive of the Jacobsville formation, but shades of green are also common in the smaller sizes. The sizes range from less than 1/4 inch to more than 2 1/2 feet in diameter (fig. 10). The larger blocks are extremely

angular and show absolutely no abrasion, whereas many of the smaller particles are disc-shaped and well rounded. In many vertical outcrops weathering processes have completely removed the shale blocks, leaving numerous rectangular cavities. Local derivation and short transportation must be inferred for these pellets and blocks because even the most indurated varieties are extremely weak and non-resistant.

Large, rounded pebbles of sandstone were found imbedded in the conglomerate at Granot Loma Lodge. The grains composing these pebbles are angular, well sorted, and tightly cemented together. The color is a dark, dirty brown and is quite unlike the typical Jacobsville. Similar pebbles were found in the area of Grand Island, and Spiroff (1956) reports sandstone pebbles imbedded in channel structures in the Jacobsville formation at L'Anse. Although it is possible that these pebbles were derived from the Jacobsville in the processes of the development of the channel structures, it is more likely that they are erosion debris derived from an older sandstone which may have covered parts of the source area. Unlike the clay pebbles and blocks, the sandstone pebbles are well indurated and show a considerable degree of rounding. In many respects the gross lithologic characteristics of these pebbles resemble those of the Freda sandstone, but evidence that they were derived from the Freda formation is not conclusive.

From Marquette to Big Bay, calcite cement constitutes as much as 35 percent of the rock material in the conglomerate facies. Very large crystals of calcite envelop the pebbles and thus completely fill all the interstices (fig. 11). Although the conglomerate is tightly cemented, it is still fairly friable since fractures readily develop along the cleavage planes of the calcite cement and permit easy breakage.

South of Marquette along the banks of the Carp River in secs. 34 and 35, T. 48 N., R. 25 W. a section of interfingering sandstone and conglomerate over 100 feet thick is exposed. The discontinuous lenticular nature of all the lithic units suggests that the entire section was formed by the process of channel-and-fill. Hultman (1953) made a pebble count of this conglomerate and found that the main constituents are angular to well rounded cobbles and boulders of quartzite, dolomite and iron formation. His results are shown in table 2, and are compared with the writer's analysis of the conglomerate facies exposed between Marquette and Big Bay. Although the base of the section is not exposed, large outcrops of Precambrian rocks are found in the hills on both sides of Carp River and indicate that the conglomerate was deposited in a steep valley over 700 feet deep and less than 1,000 feet wide. The angularity and composition of the cobbles and boulders suggest derivation from adjacent and neighboring Precambrian hills.

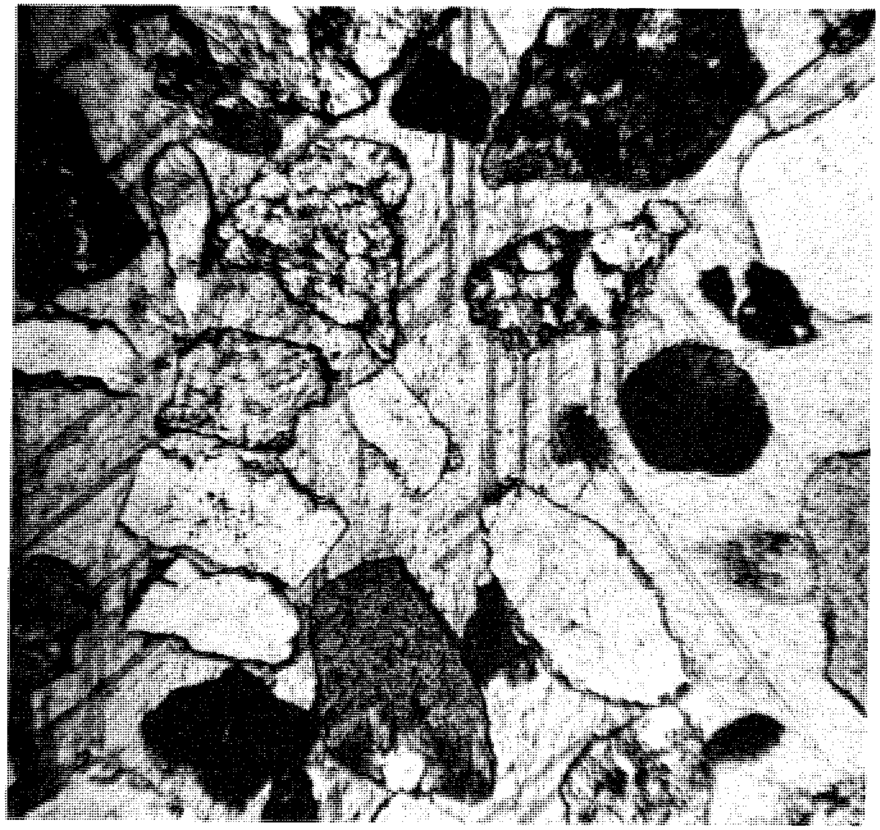


FIGURE 11

Photomicrograph of a thin section of the conglomerate facies showing large crystals of calcite completely filling the interstices between the pebbles. Crossed nicols. X63.

A marked change in the composition of the conglomerate facies occurs in the exposures on the east side of Keweenaw Bay where the Jacobsville formation lies unconformably upon the Michigamme slates. As pointed out by Spiroff (1956) pebbles of vein quartz, quartzite, ferruginous chert, amygdaloidal basalt, graywacke, slate, and microcline fragments are all present in appreciable amounts making the conglomerate in these exposures very heterogeneous.

FIGURE 12

Interbedded sandstone and conglomerate of the Jacobsville formation exposed in the nearly vertical strata at the Wall Ravine, Houghton County, Michigan.

A number of good exposures of the conglomerate facies are in several localities in the vicinity of the Wall Ravine near Laurium, Keweenaw County (fig. 12). Unlike the conglomerate in the localities previously described, these outcrops expose a section more than 500 feet thick, which contains a number of interbedded sandstone and shale units. No relationship is visible between the conglomerate facies in this area and a buried Precambrian topography because the Jacobsville is in fault contact with the older rocks. Exposures of the conglomerate, however, are confined to the limb of a syncline produced by compressional uplift and drag along the Keweenaw fault, and quite likely these are the oldest exposures of the Jacobsville formation. The individual beds are traceable laterally for almost 100 yards and through that distance show no appreciable thinning. Some conglomerate beds exceed 20 feet in thickness but most of the sandstone and shale units are much thinner. The gravels are well rounded and range from granules to boulders over 2 feet in diameter.

As pointed out by Irving & Chamberlin (1885, p. 25) the main constituents of this conglomerate are pebbles of felsite and granite porphyries with minor amounts of diabase and amygdaloids. Vein quartz and quartzites so abundant in the exposures between Marquette and Big Bay are noticeably lacking here. Most of the particles are well rounded and have a high degree of sphericity, but many are so highly decomposed that even the larger boulders can be completely shattered with a small hammer. The matrix consists of poorly cemented sand grains; consequently, the conglomerate is loose and weathers much faster than the associated sandstone beds.

It has been suggested that the conglomerate at the Wall Ravine is equivalent to the Upper Keweenawan sediments and is not part of the Jacobsville formation. Such a correlation is quite unlikely in view of the fact that the lithology of the sandstone interbedded with the conglomerate resembles the typical Jacobsville in every respect and is entirely unlike the sandstones of the Keweenawan series. In addition the heavy mineral suite from the sandstone at the Wall Ravine is identical with the heavy mineral assemblage from other Jacobsville samples.

Interpretation

Well-developed channel-fill structures many of which contain large angular blocks of soft shale clearly indicate that the conglomerate facies accumulated in a fluvial environment. In most areas the source of the gravels was very near the site of deposition. This is proved by the close association of the conglomerate facies to the Precambrian topography and by the abundance of fresh angular feldspar in several areas. Significant changes in the composition of the gravels from one exposure to another further indicate that each deposit was derived from a local source. From Marquette to Big Bay the vein quartz and feldspar which constitute the greater part of the detrital constituents were probably derived from the Precambrian granites in the Huron Mountain area. South of Marquette the cobbles and boulders of quartzite, carbonate rock, and ferruginous slate were undoubtedly derived from the Huronian rocks exposed in the Marquette trough. In the L'Anse area the heterogeneous nature of the conglomerate facies is probably due to the relatively large variety of Precambrian rocks exposed in that area.

It is obvious from the composition of the conglomerate in the Keweenaw Peninsula that the source was the more acidic eruptives of the Keweenawan series. The location of the source area, however, is not quite so evident. Irving & Chamberlin (1885, p. 98-100) believed that a fault scarp was produced prior to Jacobsville time and gave rise to a relief differential which was sufficient to produce an "orogenic" conglomerate. In their opinion the Keweenaw fault scarp "stood as a sea-cliff in the Potsdam Sea." This theory, however, is untenable in view of the fact that cross-bedding dip directions indicate that the direction of sediment transport in that area was N. 45° E. or essentially parallel to the fault line. The source area must have been a section of the Keweenaw flows which lay to the south. Erosion of these rocks and the subsequent deposition of the conglomerate was probably the first event to take place in Jacobsville time. As erosion removed the Keweenaw cover in the source area the older Laurentian and Huronian rocks were exposed and produced younger conglomerates with a different composition. Thus, although the lenticular conglomerates of the Huron Mountain area are basal Jacobsville, they are much younger than the thick conglomerate section at the Wall Ravine, and probably represent the later stages of Jacobsville sedimentation when the source area was being buried in its own debris.

LENTICULAR SANDSTONE FACIES

General Features

The dominant facies in the Jacobsville formation both from the standpoint of lateral distribution and vertical extent is a red to reddish-brown, medium-grained sandstone characterized by lenticular bedding. This facies constitutes the major part of the exposed Jacobsville formation west of Huron Bay, but it is present in only a small percentage of the outcrops in the Keweenaw Bay lowlands.

It is extremely difficult to measure the maximum exposed thickness of the lenticular sandstone facies because of the discontinuous nature of the bedding. Regional dips from 2 to 6 degrees indicate that the rocks from one outcrop to the next are not always equivalent and since there are no marker beds it is impossible to correlate from area to area and compute the composite thickness. Over 300 feet of the lenticular sandstone facies was measured in a single outcrop but this figure is undoubtedly much less than the maximum. Inasmuch as this facies is dominant in the outcrops it is very likely to be abundant in the subsurface, so the maximum thickness could be well over 1,000 feet.

Sedimentary Structures

Bedding.—As the name implies the lenticular nature of the bedding is the most outstanding characteristic of the lenticular sandstone facies. Although the beds range from less than an inch to over 15 feet in thickness, no single unit can be traced laterally for any great distance. On the vertical shore-cliffs where it is possible to view several miles of continuous outcrop more than 50 feet thick, all beds are seen to lens out. In only a very few of the smaller outcrops is it possible to follow a bed from one end of the exposure to the other. Both rapid lensing and gradual thinning are common. In some places thick sandstone units extend laterally only a short distance whereas other beds pinch out gradually over a distance of several hundred feet (fig. 13). The lenticular nature of the bedding appears to be the direct result of the processes which formed the channel structures and cross-stratification.

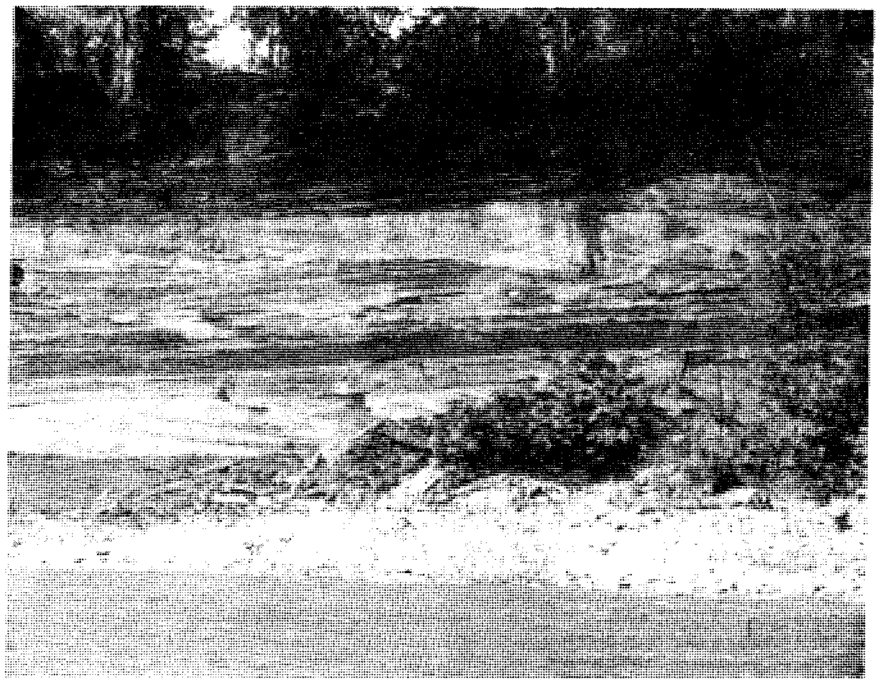


FIGURE 13

Typical shore-cliff exposure of the lenticular sandstone facies of the Jacobsville formation along the coast west of Big Bay. Note the cross-bedding and the selective leaching of the red color along certain horizons.

Channel Structures.—In several areas between Grand Island and Huron Bay, well-defined channel structures are very numerous. The sizes range from small lenses to channels over 10 feet thick and 30 feet wide. The size of the particles filling the channels ranges from sand to cobble conglomerate, but is relatively uniform in each local area. In the cliffs at Wetmore Landing numerous well-defined channels are cut in medium-grained sandstone and are filled with

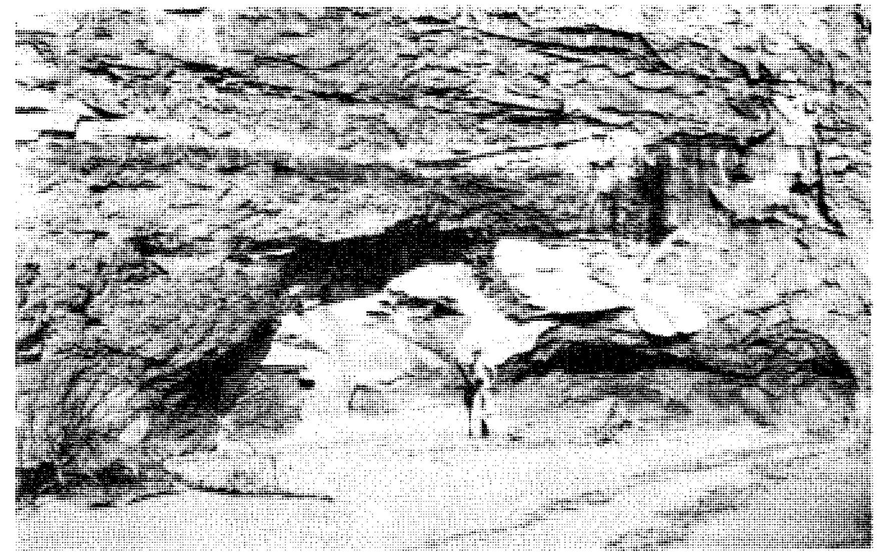


FIGURE 14

Channel structures exposed in the cliff at Wetmore Landing.

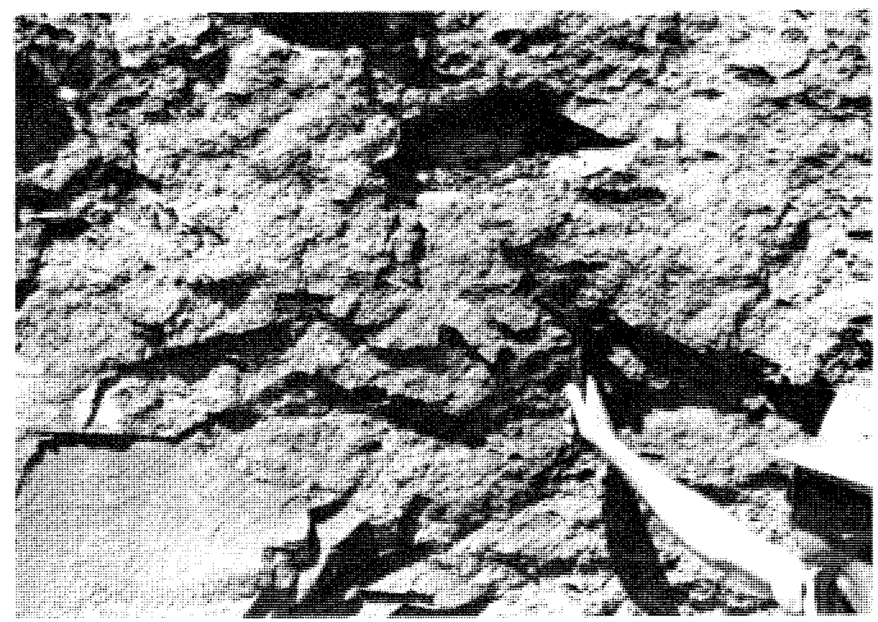


FIGURE 15

Close-up of the channel structures at Wetmore Landing showing textural contrasts between the conglomerate in the channel fill and the country rock. Note the large angular cavities which have resulted from weathering of clay blocks which were embedded in the conglomerate.

coarse conglomerate ranging from ½ inch to 8 inches in diameter (figs. 14, 15). The outlines of the individual channels are well defined by marked textural difference between the host rock and the channel fill.

In the Huron Bay area channel deposits are predominately finer-grained as the average size of the particles ranges from a medium-grained sand to fine pebbles. The pebbles are angular to subrounded and nearly everywhere are well sorted. In contrast to the channel structures at Wetmore Landing, the channeling is so extensive that it is essentially the only mode of sedimentation. No country rock is visible because parts of every channel have been truncated by younger channels.

Elsewhere in the lenticular sandstone facies, channels are abundant, but are not so striking, since most of them are filled with sand and show no marked textural difference from the texture of the host rock. In addition, the cross-bedding of the sandstone which fills the channels tends to obscure the channel outline.

Even where good channel and fill structures are absent, stream action is still considered to have been the most important agent in producing the lenticular bedding in this facies. Throughout the entire period of deposition, contemporaneous erosion kept the depositional interface highly irregular. Stratification of most of the succeeding younger beds conforms to the form of the depositional interface which helped produce the lenticular bedding. Deposition in some places was confined to the individual stream channels, but in several localities adjacent channels were filled simultaneously. The form of the stratification which resulted appears to be a series of broad anticlines and synclines, but actually represents variations in primary dip governed by the size and shape of the erosion channels. Bedding of this nature is properly classified as a form of cross-stratification. In addition to developing an irregular surface favorable for the formation of lenticular bedding, erosion, in many places, truncated older units which may originally have been more extensive. This process is thought to be very common in the formation of certain types of cross-bedding.

Cross-bedding.—Cross-bedding is the most prominent sedimentary structure in the lenticular sandstone facies and is in nearly every outcrop. In most exposures selective leaching of the red coloration along the bedding planes produced alternating red and white bands which greatly accentuated the stratification. In addition, weathering processes and wave-action have, in places, etched the individual cross-strata into prominent relief because of textural differences from one lamination to the next. In most of the vertical

shore cliffs the cross-bedding is exposed only in two dimensions, but in many places wave action has carved a narrow wave-cut terrace which exposes the complete form of the stratification.

Following the classification of cross-stratification suggested by McKee & Wier (1953, p. 387), the cross-bedding in the lenticular sandstone facies may be grouped into two basic types: (1) the planar cross-bedding in which the lower bounding surfaces are planar surfaces of erosion, and, (2) trough cross-bedding in which the lower bounding surfaces are curved surfaces of erosion. The simple cross-bedding in which the lower bounding surfaces are non-erosional surfaces was not found. Variations of the trough type of cross-bedding are by far more abundant than the planar type and have been classified according to mode of origin which may be inferred from the size, shape, and the attitude of the axis of the sets of cross-strata in addition to other environmental indicators of the formation.

Two types of trough cross-stratification are recognized in the lenticular sandstone facies, both of which are considered to be of fluvial origin. The principal physical differences between the two types are the attitudes of the axes, the shape of the sets of cross-strata, and the length of the cross-strata. In addition to the physical differences a very important difference in the mode of origin and relationship to the stream flow is inferred.

Fluvial trough cross-stratification is the most abundant and useful type of trough cross-stratification. The size of the trough ranges from 1 to 10 feet in width and from 6 inches to 5 feet in depth. Stokes (1953, p. 27) recognizes that a relatively constant ratio between width and depth probably represents a constant relationship between current strength, depth, and velocity. The axis of the trough plunges in a down-current direction at a relatively high angle which decreases rapidly and approaches a horizontal position where it is truncated by younger laminae (figs. 16, 17). In a section normal to the directon of current flow the form of the trough is essentially symmetrical and forms a festoon pattern. In the horizontal section this cross-lamination forms a crescent-like pattern aligned in a row and overlapped by younger sets in a down-current direction (fig. 18). The length of the set of cross-strata may reach considerable proportions. In the Grand Island area a set of fluvial trough cross-strata only 3 feet wide was followed for a distance of more than 30 feet. These troughs do not eliminate the form of the ancient stream channel, but are thought to originate on the channel floor by a vortex action cutting a trench parallel with the direction of stream flow. Stokes (1953, p. 28) believes that the trough, eroded by a vortex action, is filled by the sediments derived

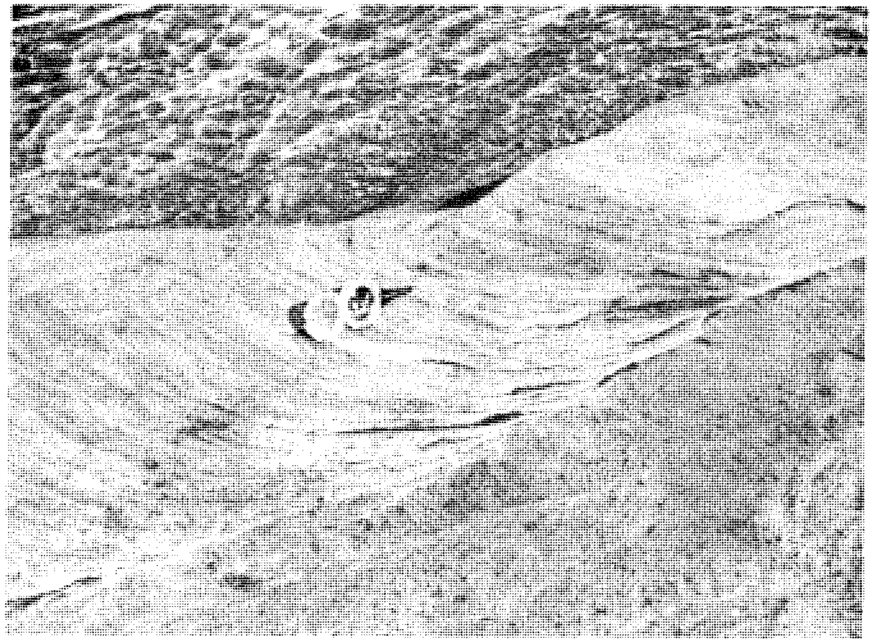


FIGURE 16

A perspective view of the fluvial trough cross-bedding in the Jacobsville formation. Compass is pointing in direction of inferred stream flow. View taken along the coast of Lake Superior at Au Train Point.

from up stream and that deposition is due to the dissipation of the vortex which picked them up. Thus, both erosion and filling of the trough is a single and continuous phase of activity. McKee (1953, p. 58), from experimental work in stream tanks, believes that two cycles are necessary and that deposition may take place long after erosion. Field evidence found in the lenticular sandstone facies indicates that the double cycle is most plausible since numerous exposures show continuous stratification through several adjacent troughs. If the troughs were filled immediately after they were formed, stratification would be restricted to a single trough.

Simple trough or channel-fill cross-bedding differs from the fluvial trough in several significant ways. The size of the simple trough ranges from 10 to 50 feet in width and from 3 to 10 feet in depth. Because of its tremendous size, the simple trough is seldom exposed sufficiently in three dimensions; therefore, all the details of its shape and physical characteristics are not completely observed in a single exposure. All of the exposures examined, however, indicate that the axis is essentially horizontal and that the form of the cross-strata reflects the form of the original erosional

FIGURE 17

A vertical exposure showing the appearance of the fluvial trough cross-lamination in an axial section. Direction of depositing currents was in the direction in which the compass is pointing. Same locality as Figure 16.

channel. McKee (1953) conducted a series of experiments in water tanks at the University of Arizona in which he reproduced cross-stratification under stream current conditions. The channels formed by McKee's experiment were characteristically flat-bottomed and straight-walled at the beginning. However, with rise of water following scour of the channel, the walls slumped and formed a rounded channel. Subsequent deposition conformed to the form of the slumped trough. This experiment supports the conclusions derived from field studies where it was observed that simple trough cross-stratification results from the deposition upon the curved surface of the erosional channel (fig. 19). Deposition apparently took place under relatively quiet water conditions. The simple trough cross-stratification or channel fill is common only where the individual particles are less than 10 millimeters in diameter. No stratification was observed in channels filled by coarser conglomerate.

Planar cross-stratification is not nearly so common as the trough type, but it was observed at various localities. Few sets of planar

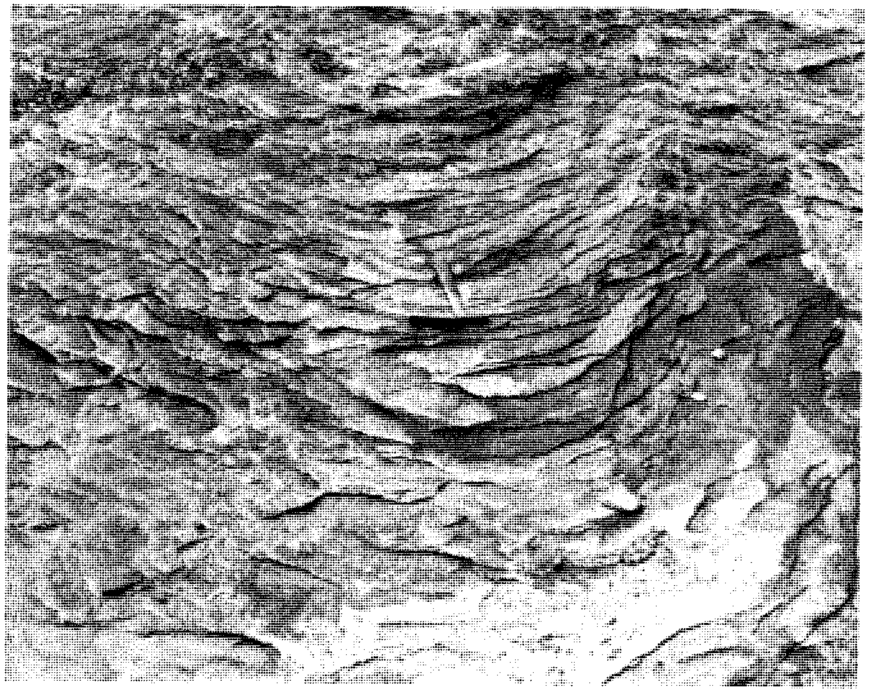


FIGURE 18

Surface of Jacobsville sandstone showing the horizontal section of the fluvial trough type of cross-bedding. Hammer handle lies along inferred direction of stream flow. View taken at Parisian Island in Whitefish Bay, Canada.

cross-strata exceed 3 feet in thickness and the individual stratum ranges in length from 2 to 6 feet. The angle of inclination is constant from top to bottom; the average dip is approximately 22 degrees. Very few exposures present the planar type of cross-stratification completely in three dimensions so that much less is known about their true dimension and form. However, that the horizontal traces of the inclined strata are slightly concave in a down-current direction is strongly indicated. The radius of curvature is large so that it is detected in only a few outcrops.

Other Structures.—Disc-shaped shale pebbles ½ inch to 6 inches in diameter are randomly scattered throughout several strata within the lenticular sandstone facies. These pebbles are identical in every respect to the smaller shale fragments found in the conglomrate facies. They were apparently derived by penecontemporaneous erosion and redeposition of the finer sediments within the Jacobsville formation and might be considered as a type of intraformational conglomerate. Their occurrence throughout the lenticular

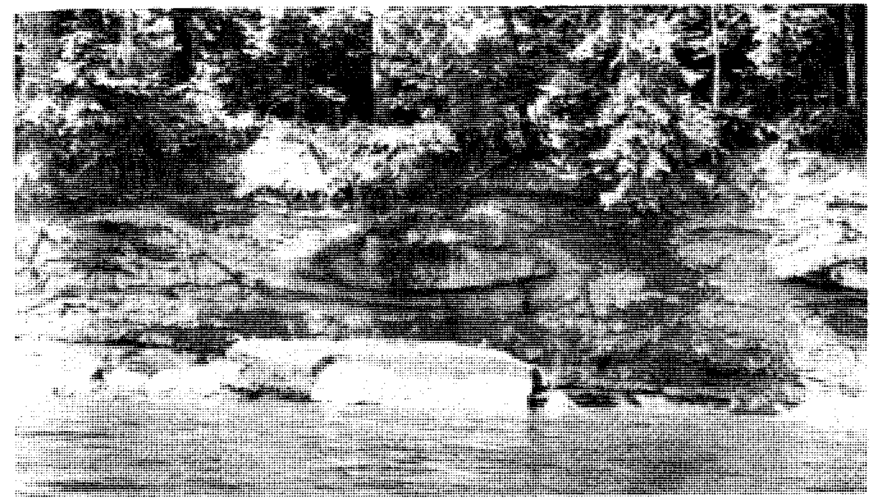


FIGURE 19

Transverse section of simple trough type cross-bedding or channel fill. View taken along the coast between Wetmore Landing and Granite Point.

sandstone facies indicates repeated interruptions in sedimentation accompanied by local erosion.

Current ripple marks and desiccation cracks are well developed in some beds but are not a prominent feature of the lenticular sandstone facies as a whole. They are most abundant in the finer-grained sediments which are relatively free from cross-bedding.

Interpretation

The discontinuous nature of the bedding in the lenticular sandstone facies, which in many places is definitely the result of channeling, clearly indicates that this facies accumulated in a predominantly fluvial environment. This conclusion is strongly supported by the presence of clay pebbles, mud cracks, ripple marks, and cross-bedding.

In many localities the relationship of the lenticular sandstone facies to the conglomerate facies is clearly exposed. The conglomerate facies is concentrated near the flanks and margins of the old Precambrian highs and interfingers with, passes laterally into, and is overlain by the lenticular sandstone facies. The relationship of the lenticuar sandstone facies to the other facies in the Jacobsville formation, however, is less clear. In the Munising area the lenticular sandstone appears to interfinger with the massive sandstone, but in the Keweenaw Bay lowlands the massive sandstone appears to be higher in the section.

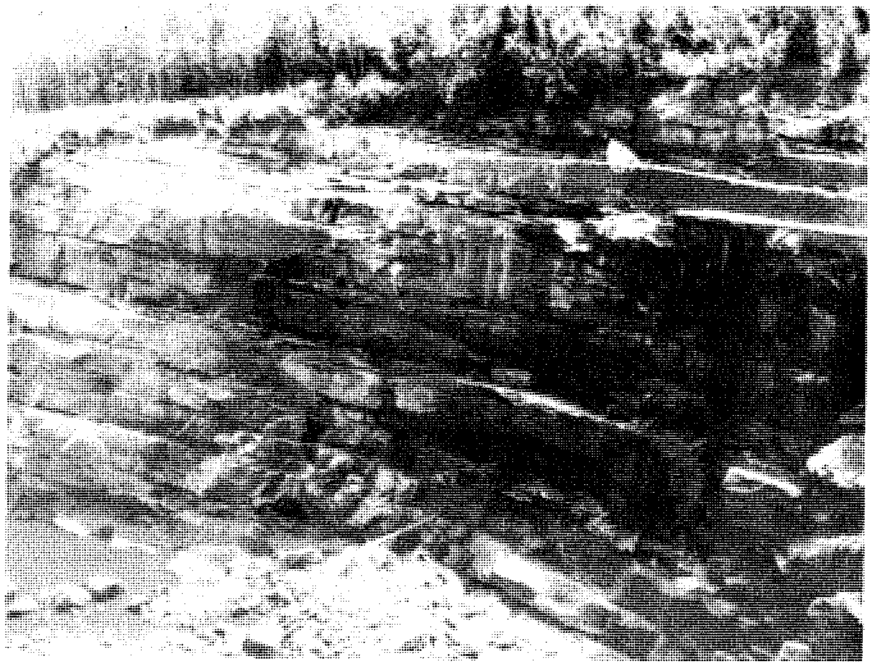


FIGURE 20

Upper part of the section exposed at Victoria Falls showing the typical massive sandstone facies.

MASSIVE SANDSTONE FACIES

General Features

The term "massive sandstone facies" is applied to the part of the Jacobsville formation which is distinguished by massive and relatively persistent bedding. Excellent exposures of this facies are found at Victoria Falls, Hungarian Falls, and in many of the shore cliffs in Keweenaw Bay. It is also recognized in several localities along the coast west of Big Bay and in parts of the section on the west and north sides of Grand Island. Exposures of the base and top of the massive sandstone facies were nowhere found in the same area so its maximum thickness is not known. At Victoria Falls a measured section 692 feet thick consists almost entirely of massive sandstone beds more than 10 feet thick. Elsewhere many shore cliffs are composed entirely of massive sandstone indicating that this facies constitutes an appreciable part of the Jacobsville formation.

The color of the massive sandstone facies in most outcrops is light shades of red, reddish-brown, pink or white. Solid colors pre-

dominate but the conspicuous white mottling so striking in the lenticular sandstone facies is lacking in many exposures. Some beds are a dark purple with minor irregular white mottling. It is very likely that the predominance of light red, pink and white and very little mottling is due to the more permeable nature of the massive beds which allowed relatively free circulation of ground water solutions which reduced much of the iron.

Sedimentary Structures

Bedding.—The average thickness of the beds in the massive sandstone facies is approximately 5 feet, although beds more than 18 feet thick were noted in the Victoria Falls section (fig. 20). Most of the bedding planes which separate these massive units are weak and non-resistant so they have been accentuated by weathering and are very conspicuous. Within most of the massive sandstone beds some indication of either horizontal or cross-stratification is shown, especially near their base. This lamination is most commonly expressed by a change in color associated with a slight textural variation. In other massive units lamination is entirely absent and the bed appears to be completely structureless.

The cross-stratification is predominately small scale as the sets of cross-strata range from 8 to 10 inches in thickness. Much of the cross-bedding is very difficult to detect, however, because the laminations have not been accentuated by differential weathering and may be masked by the darker color to which the fresh rock weathers. Exposures of the cross-stratification are almost everywhere limited to vertical cliffs as the sets of small-scale cross-bedded units are incorporated in the massive beds which characteristically maintain a vertical face. Thus, exposures of cross-stratification in three dimensions are uncommon and it is difficult to determine the true form of the lamination. Both planar and trough cross-stratification have been recognized, but the trough type seems to be most abundant.

Ripple Marks.—Oscillation ripple marks are in the massive sandstone facies in several localities. Where the exposures are continuous, a single zone of perfectly symmetrical ripple marks may be traced laterally for several hundred feet. The average ripple has a wave length of 2.5 inches and an amplitude of 0.5 inch. Most of the crests are sharp and the troughs are smooth with no indication of secondary crests. In some areas along the west shore of Keweenaw Bay oscillation ripple marks having the same amplitude and wave length were found at numerous horizons which indicates a relatively constant relationship between water depth and wave energy throughout the period of deposition.

Current and interference ripple marks are also found in the massive sandstone facies but are not nearly so common as the oscillation type.

Interpretation

The massive sandstone facies is believed to have been developed in a lacustrine environment associated with the fluvial deposition of the lenticular sandstone facies. This environment is indicated by the massive and continuous nature of the bedding plus the lateral persistence of oscillation ripple marks. The complete absence of channel and fill structures and fluvial trough cross-stratification also tends to support this conclusion. It appears from the distribution of the massive sandstone facies that the lacustrine environment was more removed from the source area than the lenticular sandstone facies, and existed only intermittently in the central part of the inter-mountain basin in which the Jacobsville formation accumulated.

In the small exposures a detailed study of the stratigraphic relationship of the massive and lenticular sandstone facies cannot be made. They are, in part, time equivalent and they appear to interfinger to a certain extent in some outcrops. In the most extensive exposures, however, such as Victoria Falls and Keweenaw Bay, the massive sandstone facies appears to be higher in the section than the lenticular sandstone facies. The evidence is far from conclusive, but suggests a change during deposition of the Jacobsville formation from a predominantly fluvial to lacustrine environment.

RED SILTSTONE FACIES

At Agate Falls and in the cliffs west of Laughing Fish Point, the Jacobsville formation is composed predominantly of red siltstone and shale. This facies is also in several exposures along the coast north of the town of Jacobsville, but elsewhere it is completely absent or occurs only in minor amounts. The section at Agate Falls is 80 feet thick and is composed of alternating beds of thin platy shale and silty sandstone. The bedding in the shale is horizontal and can be traced laterally throughout the entire exposure. Large mica flakes are abundant and give the red shale a satiny luster where broken along the bedding. A characteristic of the siltstone and shale is that it shows a greater intensity of red coloration and that it lacks the white mottling so common to the

coarser sediments in the Jacobsville formation. The interbedded sandstone units contain small-scale trough cross-bedding similar to the type of cross-bedding in the lenticular sandstone facies.

The nature of the environment represented by the red siltstone facies is not clearly understood. The horizontal bedding and the fineness of grain suggest that the deposit accumulated in a lacustrine environment free from strong currents. On the other hand, the sedimentary structures of the interbedded sandstone are identical to structures in the lenticular sandstone facies and suggest a fluvial environment. In several exposures the red siltstone facies is associated with the massive sandstone facies and probably represents alternating fluvial and lacustrine deposition during the later phases of Jacobsville sedimentation.

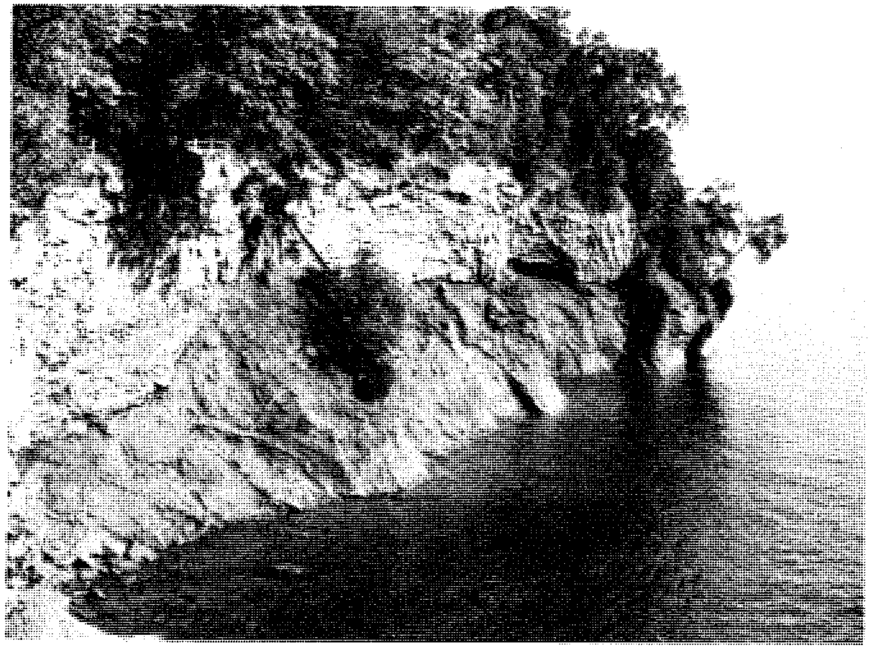


FIGURE 21

Unconformity between the Jacobsville formation and Precambrian peridotites at Presque Isle.

THE PRE-JACOBSVILLE EROSIONAL SURFACE

Exposures of the basal contact of the Jacobsville formation are not widespread but are almost entirely in the area bordering the northern half of the Precambrian highlands. Between Marquette and Big Bay the pre-Jacobsville surface has been developed, for the most part, on massive homogeneous granitic rocks cut by numerous basic dikes. Excellent exposures are at Presque Isle, Partridge Island, Wetmore Landing, Thoney Point, Garlic Island, Granite Point, and on the west side of Big Bay (figs. 9, 21). These outcrops show rounded hills and knobs of granite partly covered with Jacobsville sediments and indicate that the Precambrian surface was highly irregular at the time the Jacobsville was deposited. At Thoney Point the hills are rugged and steep extending almost vertically as high as 120 feet above the lake. Elsewhere only the top 30 to 40 feet of the Precambrian hills are exposed but contours on the lake bottom suggest that the base of many of these hills is over 60 feet below the water level. Erosional remnants of the Jacobsville at an elevation of approximately 1,000 feet indicate that the local relief of the pre-Jacobsville surface was at least 400

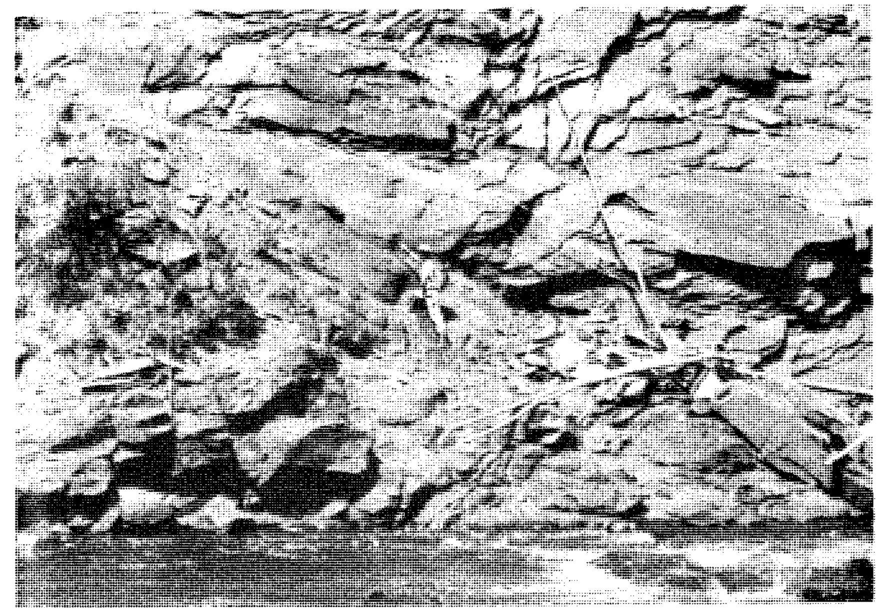


FIGURE 22

Jacobsville-Keweenawan unconformity at Sturgeon Falls showing the top of a basaltic hill covered with the Jacobsville sandstone. Note the primary dip of the Jacobsville away from the old Precambrian high.

feet. The highest exposures were found in the rapids of Chocolay River in the NE 1/4, NW 1/4, sec. 36, T. 46 N., R. 24 W. Other isolated outcrops found in valleys and around the flanks of hills suggest that much of the present surface in the vicinity of Marquette is an exhumed topography and was developed, for the most part, before the Jacobsville was deposited. West of the Huron Mountains several outcrops show hills and knobs of the pre-Jacobsville erosional surface developed on Middle Keweenawan basalts and Michigamme slates (figs. 22, 23). The form of these hills is very similar to the form of hills developed on the granites in the Marquette area.

From these data the pre-Jacobsville erosional surface appears to be similar in many respects to the present topography in the Precambrian highlands. Martin (1911, p. 90) describes the Precambrian highlands as a peneplain with monadnocks seldom higher than 400 feet, but the relief of the pre-Jacobsville surface was probably somewhat greater since the Precambrian highlands have been subjected to several cycles of erosion. Variations in the thickness of the Jacobsville indicate that the maximum relief of the pre-Jacobsville erosional surface is over 2,000 feet.

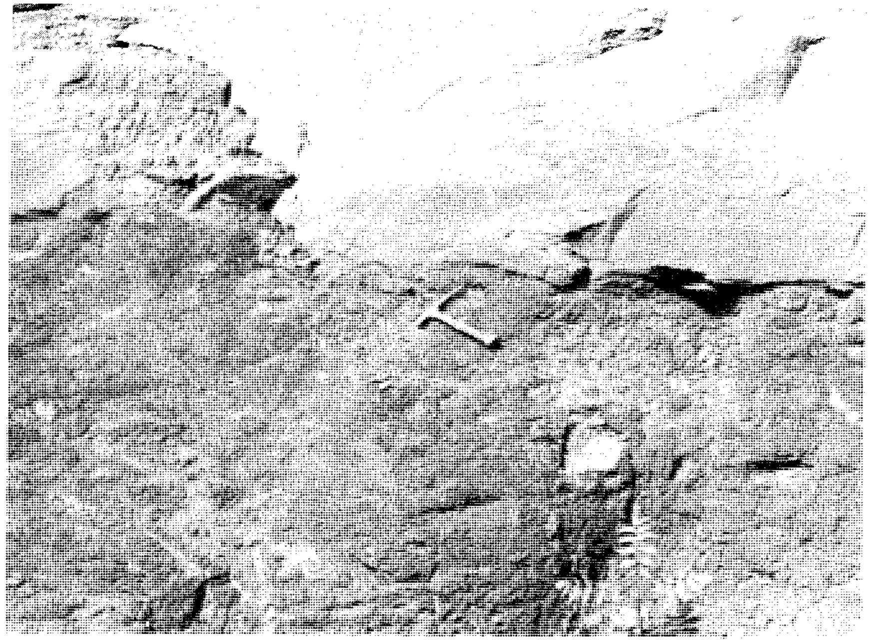


FIGURE 23

Close-up of the contact between the Jacobsville formation and Middle Keweenawan basalts at Sturgeon Falls. Note the weathered nature of the basalt and the small stringers filled with Jacobsville sandstone.

In many places a zone of weathered debris as much as 6 feet thick separates the Jacobsville from the underlying Precambrian. This zone appears to be a paleoregolith formed by subaerial weathering on the pre-Jacobsville erosional surface (figs. 24, 25). Its local absence is probably due to stream erosion accompanying Jacobsville deposition. Residual boulders resulting from deep chemical weathering are found near the basal part of the regolith where it passes gradationally downward into the less weathered rock. These boulders are highly altered to residual clay and quartz but some of the larger fragments retain a solid core. The contact between the regolith and the Jacobsville is nearly everywhere sharp and distinct although much of the material from the regolith has been reworked and incorporated into the basal units of the Jacobsville. By and large the regolith is much softer than either the Precambrian or the Jacobsville and is commonly eroded into small lenticular caves by wind and waves. The significance of the regolith containing residual boulders is that it indicates a considerable period of predominantly chemical weathering prior to Jacobsville sedimentation.

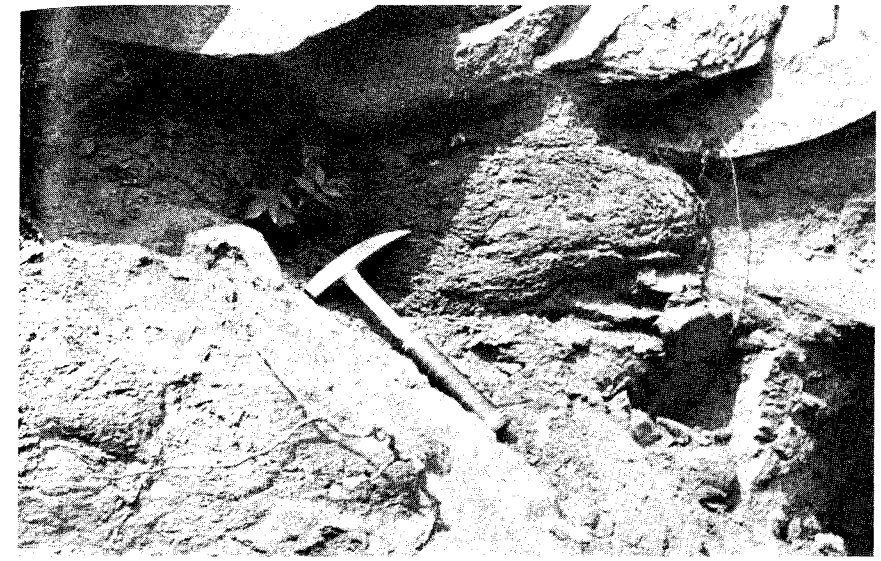


FIGURE 24

Zone of weathered debris between the Jacobsville formation and Middle Keweenawan basalts at Sturgeon Falls, SW ¼, sec. 16, T. 49 N., R. 35 W. Note the large residual boulder included in the weathered zone.

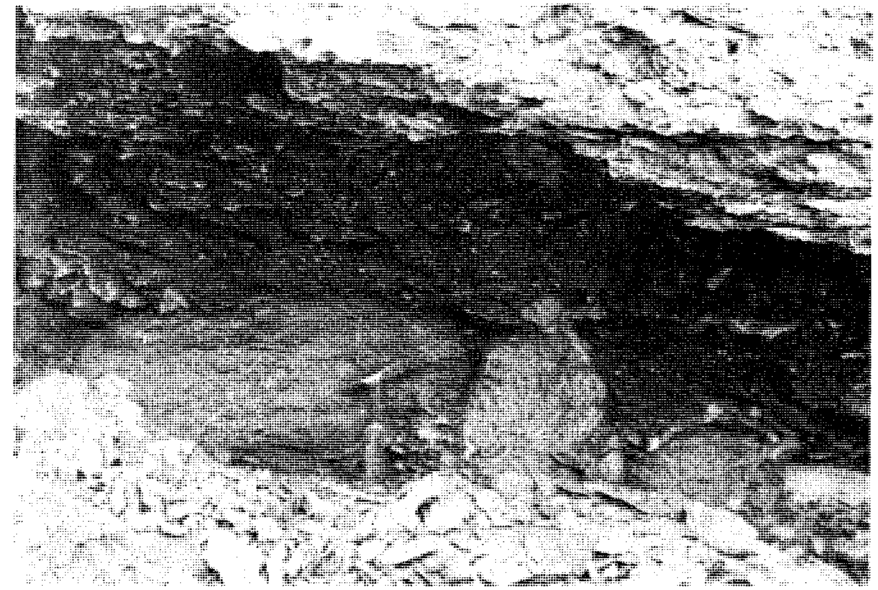


FIGURE 25

Jacobsville-Precambrian contact showing zone of weathered debris containing large residual boulders of granite. Exposure is located along the coast of Lake Superior two miles north of Thoney Point.

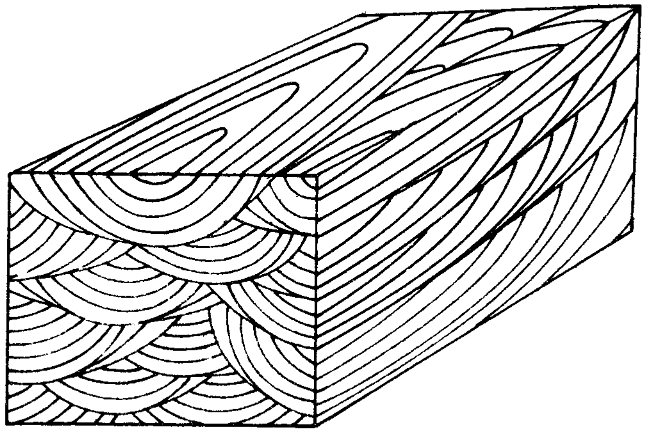


Figure 26. Block diagram showing fluvial trough cross - bedding as it appears on horizontal, transverse and axial sections

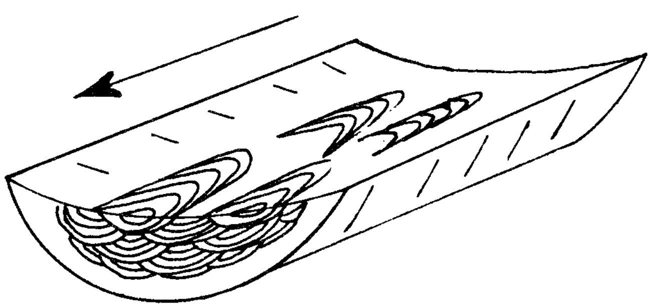


Figure 27. Schematic diagram showing relationship of fluvial trough cross - bedding to stream flow direction and stream channel.

PALEOGEOGRAPHY

The location and nature of the source area of the Jacobsville formation can be established rather accurately by several independent lines of evidence. Cross-bedding dip directions, the shape of the Jacobsville formation, structural trends of the underlying Precambrian rock, composition of the Jacobsville, variations in thickness of the overlying Munising formation and geophysical data all indicate that the source of the Jacobsville was an east-west trending highland which extended through the central part of Northern Michigan and connected the Wisconsin Arch with a positive area in Canada.

LOCATION OF THE SOURCE AREA

In recent years considerable advancement has been made in the study and understanding of the directional properties of sedimentary rocks and their paleogeographic significance. Various workers have shown that by systematically mapping the attitude of cross-bedding it is possible to determine the regional slope at the time the sediment was deposited and thereby establish the trend of ancient shore lines or the location of probable source areas.

The cross-stratification in the Jacobsville formation is predominantly the trough type (McKee & Wier, 1953, p. 387). Figures 26 and 27 show idealized block diagrams illustrating the appearance of the trough cross-strata on the horizontal, transverse and axial sections and its relationship to the direction of current flow. The horizontal section is by far the best for directional measurements as the direction of stream flow is the direction in which the trough plunges. Accurate directional measurements on the vertical section are difficult and often impossible to make because of the difficulty in distinguishing apparent dip from true dip when the structure is not exposed along the axial plane.

Dip direction measurements were made at every outcrop where trough cross-bedding was exposed sufficiently in three dimensions to permit the determination of the direction of plunge. Measurements made on one stratigraphic unit were analyzed separately and then combined with measurements from other units in the same locality. The mean and standard deviation for all measurements made in each township were calculated and plotted on a map.

Any interpretation of cross-bedding measurements beyond the indication of regional slope is dependent upon a correct interpretation of the environment in which the cross-bedding was formed. In the Jacobsville formation the trough cross-bedding is considered

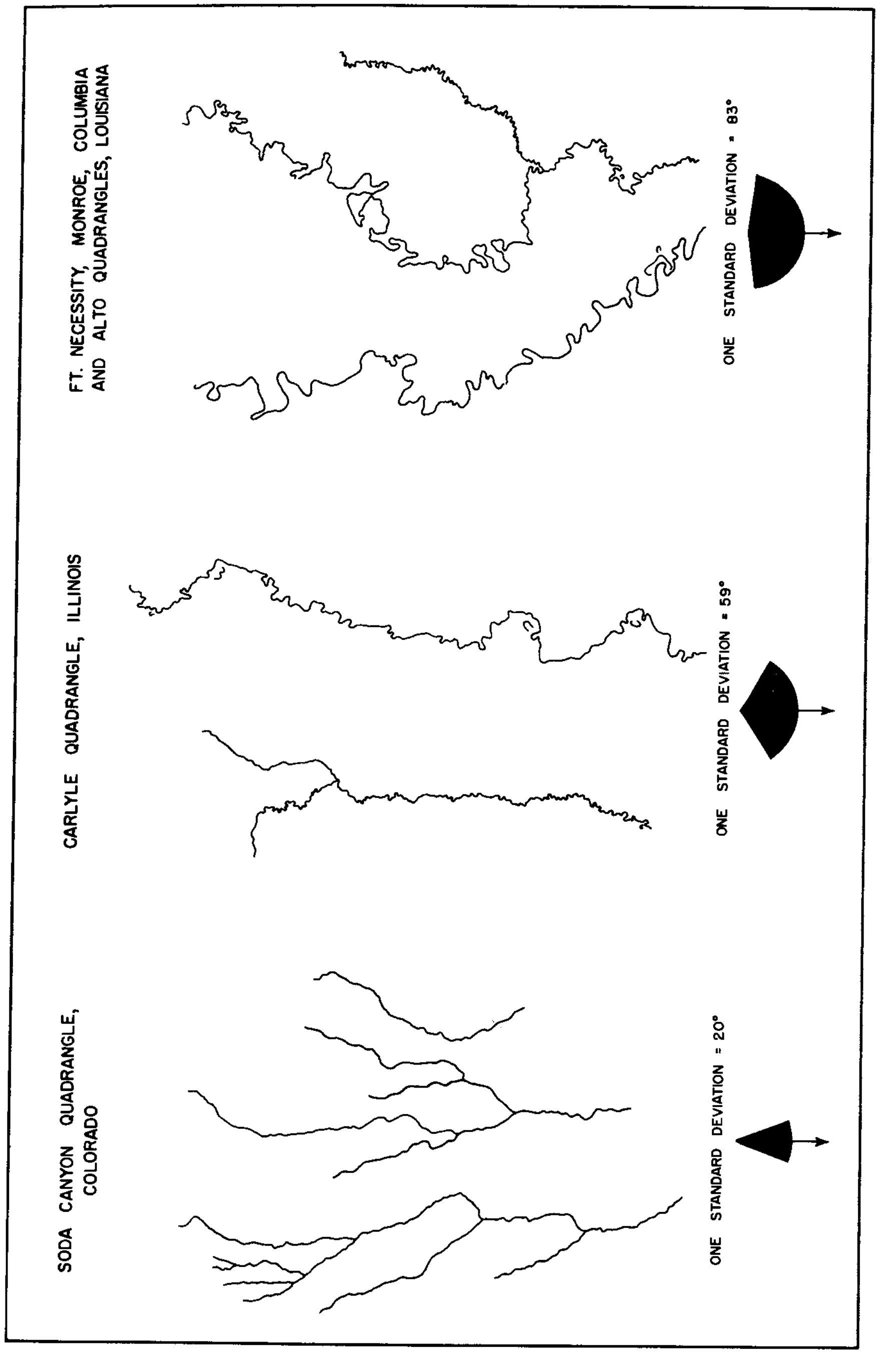


Figure 28. Relationship between stream patterns and the standard deviation of the direction of sediment transport

to have developed in stream channels (see section on cross-bedding of lenticular sandstone facies) ; therefore, a measurement of the direction of plunge is actually a measurement of the direction of stream flow.

Theoretically, therefore, if one could make a large number of measurements on a rock surface of a single age and over a broad area, a skeleton drainage pattern would be developed when the dip directions were plotted on a map. A large number of measurements taken and mapped for each formation of the stratigraphic section would consequently result in a series of drainage patterns superimposed one above another.

In an effort to establish a basis for the interpretation of random measurements of the direction of stream flow, which is in essence what one measures when he measures the dip direction of fluvial trough cross-stratification, random measurements were made on the direction of stream flow on three different types of streams. This was done on selected topographic maps by measuring the stream flow direction at every place a section line crossed the stream. The results are shown in figure 28 and clearly indicate that the size of the standard deviation of the direction of stream flow is directly proportional to the amount of meandering in the stream pattern. One is, therefore, able to interpret certain paleogeologic characteristics from the size of the standard deviation and the nature of any changes in the standard deviation from locality to locality and throughout the stratigraphic section.

If sampling is made in a very restricted stratigraphic zone, it is possible to detect changes in the nature of the stream from place to place. The largest standard deviations would be expected to result from highly meandering streams far removed from the source area and as the sampling approached the source area the standard deviation would be expected to become smaller. Changes in the standard deviation throughout the section at one locality would reflect the development of the physiography of the source area.

The results of cross-stratification studies in the Jacobsville formation are shown in figure 29. It is apparent from the average dip direction that the regional slope in the Lake Superior district during Jacobsville time was northward toward the Canadian Shield and that the source of the Jacobsville sediments was south of the present outcrop belt.

A second and highly significant finding is that very little dispersion in the average direction of sediment transport is in the southern outcrops between Marquette and Parisian Island, whereas appreciable dispersion is noted in the northern outcrops along the

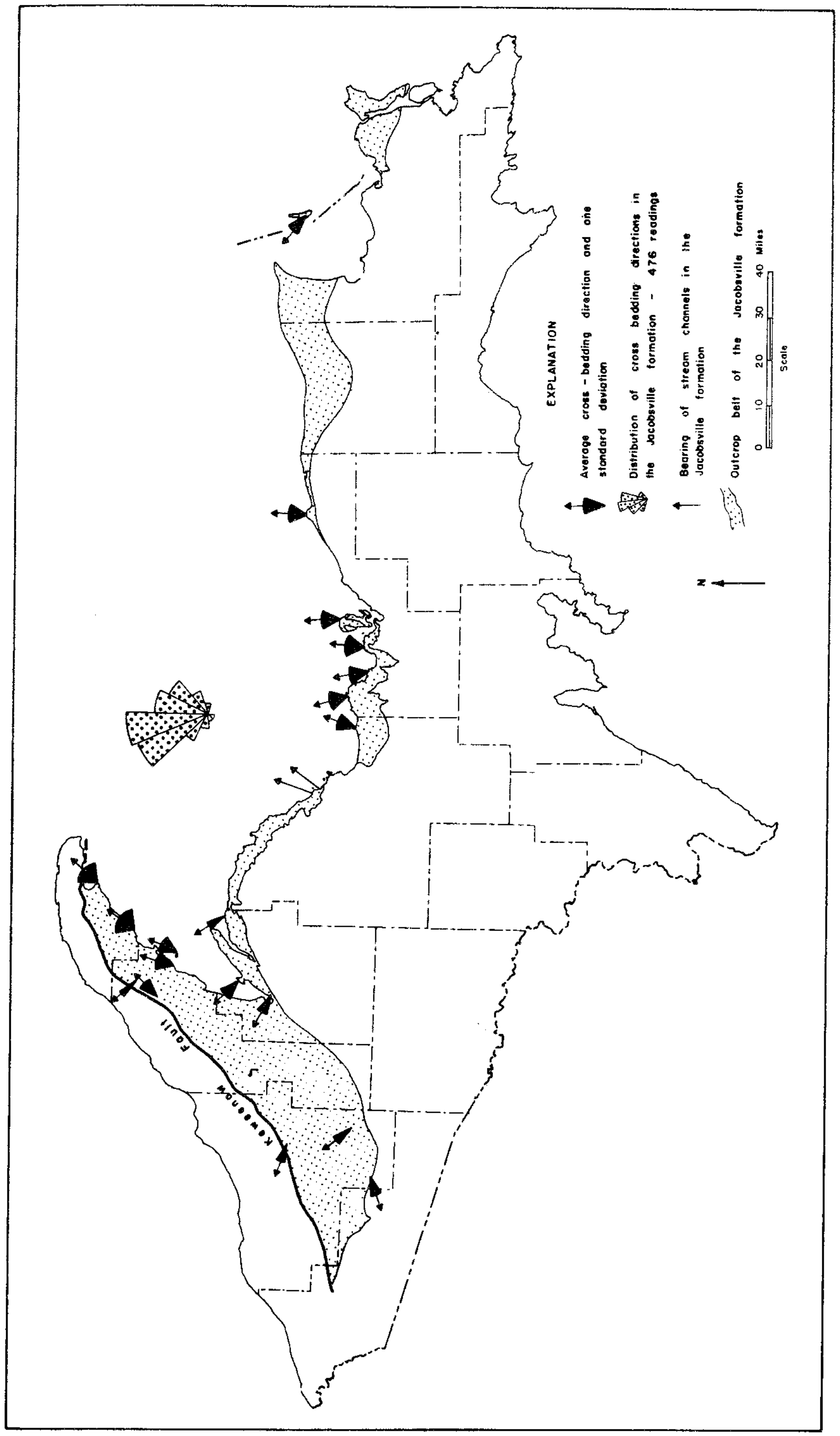


Figure 29. Cross - bedding directions in the Jacobsville formation

Keweenaw Peninsula. At every locality in the southern part of the outcrop belt the direction of stream flow at the time the Jacobsville was deposited was from south to north. This indicates that the source area was an elongated east-west trending highland. The extremely small standard deviation of the cross-bedding direction in the southern exposures suggest steep gradients and straight stream courses indicative of a source area only a few miles south of the present outcrop belt. This conclusion is consistent with the larger standard deviation in the direction of sediment transport and the greater dispersion of the averages for the readings taken at the northern outcrops in the Keweenaw Peninsula. The larger standard deviation indicates greater stream meandering, and a greater dispersion of the average directions for this area suggests a greater diversity in the general direction of the course of each stream. This dispersion likely resulted from a fanning out of the streams into the basin of deposition.

A southern source is also indicated by regional variations in the thickness of the Jacobsville formation. Although data are not sufficient to permit construction of a detailed isopach map, available information indicates that the Jacobsville formation is roughly wedge-shaped and pinches out completely to the south (fig. 2). The thickness of the Jacobsville decreases from over 1,800 feet in the vicinity of Sault Ste. Marie to less than 50 feet at Neebish Island. A similar increase in thickness to the north and pinch out to the south is indicated by well data in Keweenaw Bay area and in the western part of Alger County. Exposures of the basal contact show that the decrease in thickness towards the south is due to progressive overlap. Isopach lines of the Jacobsville formation are therefore parallel to the contour lines of the underlying Precambrian surface and indicate a highland extending through Northern Michigan.

Variations in the thickness of the Munising formation which directly overlies the Jacobsville reflect the position of part of the highland at the time of the first advance of the Paleozoic seas (fig. 30). Although in much of the Northern Peninsula no information concerning the thickness of the Munising formation is available, data from a number of drill-hole cores obtained from several mining companies supplement the data available from well logs and measured sections, so that regional differences in thickness may be estimated. Thinning of the Munising formation from over 200 feet at the northern and southern shore of the Northern Peninsula to less than 50 feet in the center of the Peninsula establishes the approximate position of the east-west trending

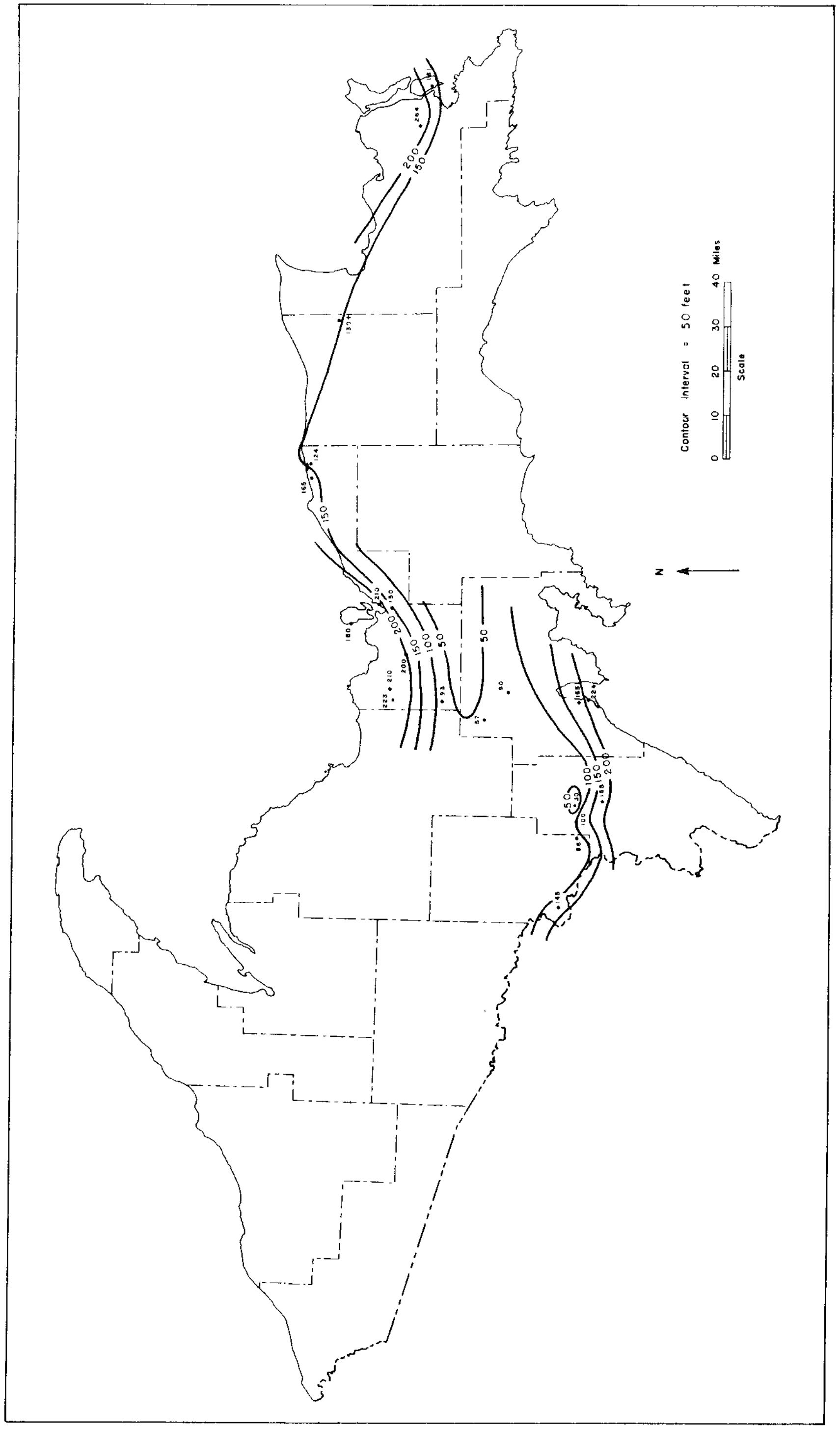


Figure 30. Isopach map of the Munising formation

highland and indicates that parts of it were high during the deposition of the basal part of the Upper Cambrian sequence.

One of the most conclusive evidences that the source area of the Jacobsville formation was very close to the present outcrop belt is the composition of the conglomerate facies. Pebble counts indicate that the differences in composition may be correlated directly with local differences in the lithology of the Precambrian rocks immediately to the south (see section on conglomerate facies). In addition the angularity of pebbles and the inclusion of clay pebbles and blocks, and in places, sandstone pebbles, indicates a local derivation and short transport for the Jacobsville sediments.

Structural trends in the exposed Precambrian rocks and geophysical data are consistent with the pebble data in indicating the position and extent of the source area of the Jacobsville formation. Throughout the Precambrian highlands in Northern Michigan an east-west structural trend in the Huronian rocks is indicated by the Marquette syncline, the Felch trough, and the Menominee trough. The eastward extension of these structural features is concealed by the cover of Paleozoic rocks of the Michigan basin, but similar trends reappear in the Precambrian rock of Canada exposed across the St. Mary's River. This strongly indicates a predominant east-west trend for the structure of the Precambrian rocks beneath the Paleozoic cover and suggests the possibility of a buried east-west mountain range.

Gravity work done by Bacon (1956) and his students indicates an east-west trending gravity high extending from the Precambrian highlands to Canada (fig. 31). The gravity highs could be explained, in part, by a buried Precambrian ridge extending from the Wisconsin Arch to Canada. The gravity low to the north would then result from burial of the dense Precambrian rocks beneath several thousand feet of Jacobsville sediments.

In summary, the position and extent of the source area of the Jacobsville appears to be well established from a large variety of independent evidence. This highland was a major structural feature apparently developed during the Killarney revolution. Inasmuch as the positive area extended through the major part of the Northern Peninsula of Michigan and connected the Wisconsin Arch with Canada, it seems appropriate that it be called the Northern Michigan Highland.

NATURE OF THE SOURCE AREA

The lithology of the Northern Michigan Highland differed considerably from place to place. In some areas granitic rocks pre-

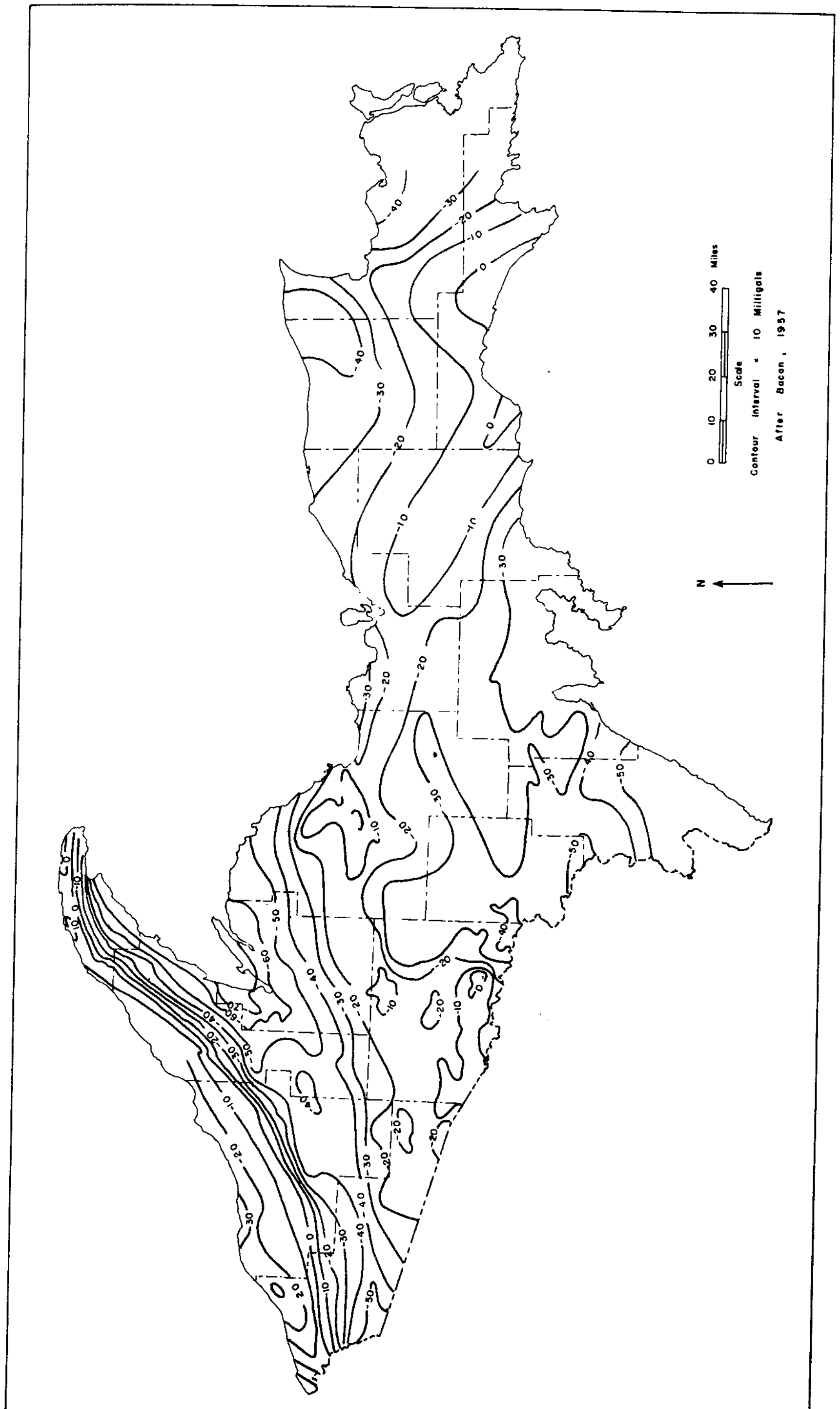


Figure 31. Bouguer gravity anomaly map of Northern Michigan

dominated as indicated by the abundance of feldspar and vein quartz in the lower part of the Jacobsville formation. Elsewhere the acidic and basic flows were important rock types in the source area, which accounts for the composition of the conglomerate facies in the area of the Wall Ravine and in several areas near the South Trap Range. The quartzite pebbles in parts of the conglomerate facies and sand grains composed of quartzite fragments in the sandstone facies indicate that meta-sediments were also abundant. Sandstone pebbles having a gross lithology similar to the Freda were found in a number of localities and strongly suggest that parts of the source area were once covered by the Freda sediments. The high quartz content of the Jacobsville supports this theory as one would expect a greater diversity in mineralogy if the source area consisted of granitic and metamorphic rocks exclusively.

From this information it appears that the present Precambrian highlands in Michigan and Canada closely represent the rock types which were eroded to produce the Jacobsville formation.

The source area was apparently tectonically active during most of Jacobsville time as the direction of sediment transport during the entire period of deposition is remarkably constant. When the cross-bedding dip directions taken on a restricted horizon are combined with other horizons in the same section, the overall standard deviation is only slightly larger than the standard deviation obtained from the individual restricted horizon. If the source area were uplifted and had remained stable during erosion, one would expect a larger standard deviation to result from the increased meandering in the streams during the later phases of deposition. This should be reflected in a larger standard deviation in the cross-bedding directions in the younger strata of the Jacobsville. Since no increase in the standard deviation was detected in the upper part of the section, it is quite probable that the source area was continually being uplifted so that the high regional gradient and the relatively straight courses of the depositing streams were maintained.

AGE AND CORRELATION

The age of the Jacobsville has been a matter of conjecture for many years because of the complete absence of fossils and the limited number of exposures showing its stratigraphic relationship with older and younger rocks. Many of the early geologists considered the Jacobsville to be Upper Cambrian in age because of the apparent gradation between it and the overlying St. Croixan series. Houghton (1841) and Hotchkiss (1933), however, recognized the unconformity at Grand Island between the Upper Cambrian and the Jacobsville. Unfortunately Houghton later reversed his opinion regarding this relationship and Hotchkiss failed to publish his findings so that the tradition of the Upper Cambrian age for the Jacobsville continued. Thwaites (1912, p. 62) questioned the Cambrian age of the Jacobsville and suggested the possibility of its being uppermost Keweenawan. He based his conclusions upon an apparent gradational contact between the Bayfield (considered equivalent to the Jacobsville) and the arkosic sediments of accepted Upper Keweenawan age.

The present study confirms the early reports of an unconformity between the Jacobsville and Upper Cambrian rocks. In the cliffs surrounding Grand Island the Jacobsville dips to the north at an angle between 4 and 6 degrees, whereas the overlying Munising formation dips southward. In addition, a widespread basal conglomerate in the Munising formation truncates numerous clastic dikes in the Jacobsville. This unconformity indicates a major break in sedimentation between the Jacobsville sandstone and the Upper Cambrian sequence. The fundamental problem, therefore, is whether the Jacobsville is genetically, stratigraphically, and structurally associated with the Keweenawan series or is independent of it.

FACTORS FAVORING KEWEENAWAN AGE

In Northern Michigan no evidence was found to indicate that the Jacobsville is Upper Keweenawan in age. The great Keweenaw fault separates the Jacobsville from the Upper Keweenawan sediments so that their stratigraphic relationships cannot be studied in Michigan. The only area where the stratigraphic relationship of the Upper Keweenawan sequence can be studied in outcrops is in Wisconsin; therefore, those favoring a Keweenawan age for the Jacobsville must first accept its equivalence to part of the Bayfield group. This correlation, which seems plausible, is based entirely on lithologic similarities and cannot be proved because of lack of areal continuity and lack of fossils. Even if the correlation of the Bayfield and the Jacobsville is accepted, the evidence presented by Thwaites (1912, p. 62) that the Bayfield is Upper Keweenawan is very scanty. Thwaites (1912, p. 62) states as follows:

> "Outcrops are so scarce that we can at no place trace the two sandstone groups to a point of contact where their relations may be absolutely determined. But it is possible to find exposures where we should expect to find the contact of the Bayfield and the Oronto (Upper Keweenawan) groups. At all these localities there is a conformable gradation from quartz sandstone of the general type of the Bayfield group downward into red shales and arkose sandstone or conglomerate of the same general type as the main body of the Oronto group."

When it is realized that the Jacobsville (and probably the Bayfield group) is not part of the St. Croixan series, much of the case for favoring their Keweenawan age disappears because the bulk of the argument favoring Keweenawan age indicates only that the Bayfield, Jacobsville, or Red clastics are not Upper Cambrian. Thus, the evidence suggested by Thwaites remains the best reason for assigning the Jacobsville to the Keweenawan series.

EVIDENCE OPPOSING KEWEENAWAN AGE

The Jacobsville and Upper Keweenawan rocks were apparently derived from widely separated source areas and are, therefore, not genetically related. The southern source for the Jacobsville formation is well established by cross-bedding dip directions, regional thinning, composition, and other criteria (see section on paleogeography). The Keweenawan rocks, however, appear to have been derived from a northern source. Hotchkiss (1923, p. 671), from a study of the primary structures in the Keweenawan rocks, concludes that the regional slope during Keweenawan time was from north to south and that the lavas and sediments were derived from a source area north of the present outcrops. This marked change in the regional slope indicates that a period of considerable regional tilting or diastrophism occurred between Upper Keweenawan and Jacobsville time.

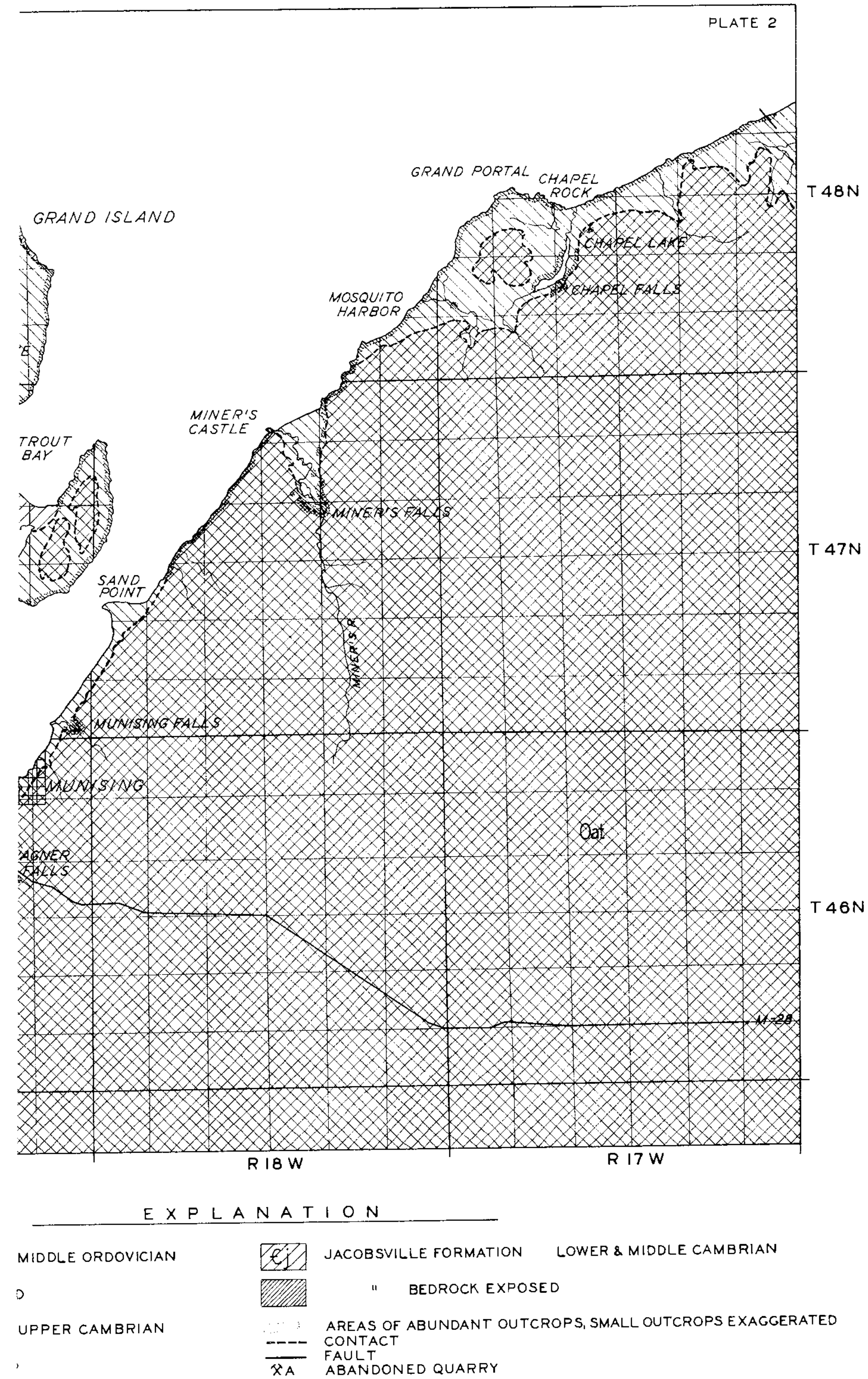
Differences in composition between the Jacobsville and Upper Keweenawan sandstones also indicate that they were derived from different sources and are not part of the same sequence. Thwaites (1912, p. 51) describes the Upper Keweenawan sediments as being "mainly composed of angular to subangular fragments derived from igneous rocks without much chemical decomposition." These sandstones are repeatedly referred to as "arkosic" and differ greatly in composition from the Jacobsville sandstones. The only place where the Jacobsville formation has a high feldspar content is near the basal contact with granitic rocks. Throughout the rest of the section the Jacobsville consists primarily of rounded quartz grains. This indicates that the Jacobsville is more mature than the Keweenawan sediments and may be in part a second-cycle sand. With the presence of sandstone pebbles very similar to the Freda imbedded in the Jacobsville, a very likely source for much of the quartz in the Jacobsville formation is the sediments of the Upper Keweenawan series.

In the Sturgeon Falls area horizontal Jacobsville sandstones lie unconformably upon Middle Keweenawan basalts which dip approximately 10 degrees to the northwest. This contact indicates that the Middle Keweenawan rocks were tilted, weathered, and eroded prior to the deposition of the Jacobsville formation. Since the contact between the Upper and Middle Keweenawan rocks shows no angular discordance, it is highly probable that the tilting of the basalts at Sturgeon Falls took place after the deposition of the Upper Keweenawan sediments. The strike and dip of the basalts in the Sturgeon Falls area suggests that tilting was produced by the same forces which folded the Keweenawan series into a syncline. If the Jacobsville is considered part of the Keweenawan series, the relationships at Sturgeon Falls become very difficult to explain.

Suggestions of an angular unconformity between the Freda and Jacobsville formation are also found in several outcrops in Whitefish Bay. Along the Canadian coast between Goulais Point and Batchawana Bay, sediments which are identical to the Freda in gross lithology, sedimentary structures, and heavy minerals consistently dip 10 to 12 degrees to the north, whereas exposures of the Jacobsville formation found inland and on the west side of Parisian Island are essentially horizontal. The distance between outcrops renders this evidence far from being conclusive but since the Jacobsville is characteristically undisturbed, except near the Keweenaw fault, the unconformable relationship appears quite probable.

CONCLUSION

The unconformity between the Jacobsville and Munising formations exposed at Grand Island proves that the Jacobsville is older than Upper Cambrian. It is impossible, however, to estimate the magnitude of this unconformity and to state whether the Jacobsville is Lower and Middle Cambrian or Upper Keweenawan. The evidence opposing the Keweenawan age for the Jacobsville, however, appears to be quite substantial. The writer, therefore, concludes that the Jacobsville formation represents continental deposition in an enclosed basin during the time marine sediments of Lower and Middle Cambrian age were being deposited in other parts of the continent.



R COUNTIES, MICHIGAN

THE PRE-MUNISING EROSIONAL SURFACE

The basal contact of the Munising formation is well exposed in numerous widely separated outcrops in Alger and Dickinson counties. In Alger County the Munising rests upon the Jacobsville formation, but in Dickinson County the Jacobsville is absent and the Munising formation lies directly upon the highly deformed Precambrian rocks.

Evidence that a major unconformity separates the Upper Cambrian from the Huronian (now Animikie) rocks in Dickinson County is so striking that it was one of the first features to be noted by the early geologists. The unconformable relationship of the Upper Cambrian and the Jacobsville formation is not nearly so evident and for many years geologists have considered the contact to be gradational. In the Grand Island area however, ample evidence, indicates that the Jacobsville in Northern Michigan was tilted and eroded prior to the advancement of the Munising seas. A low dip angular unconformity between the Jacobsville and Munising can be seen on the east side of Grand Island where the Jacobsville dips slightly to the north and the Munising dips a few degrees to the south. The unconformable relationship between the two formations is further indicated on the west side of Grand Island where clastic dikes in the Jacobsville sandstone are truncated by the basal conglomerate of the Munising formation (figs. 32, 33).

Inasmuch as the rock type and topographic expression of the pre-Munising erosional surface is distinctly different in the north and southwest, it seems desirable to consider these areas separately in describing the surface upon which the initial Upper Cambrian sediments were deposited.

SURFACE IN ALGER COUNTY

The Jacobsville-Munising contact is exposed in a number of small outcrops from Grand Marais to Skandia, but the most extensive and informative exposures are the shore cliffs which surround Grand Island. On the east and west sides of the island the contact can be traced for several miles without interruption. Although in many places the Jacobsville seems to be practically horizontal, a distinct northerly dip can be seen in the cliffs on the west side of Trout Bay (fig. 34). The erosional surface developed upon the slightly tilted Jacobsville is almost a straight line when seen on the vertical shore cliffs. The only irregularities are a few shallow undulations probably produced by channeling of the Munising sea. The contact of the Jacobsville with the overlying basal conglomerate is sharp and distinct with no evidence of a fossil

FIGURE 32

View of the west side of Grand Island showing clastic dikes in the Jacobsville formation (appearing as straight vertical lines in the photograph) truncated by the overlying Munising formation.

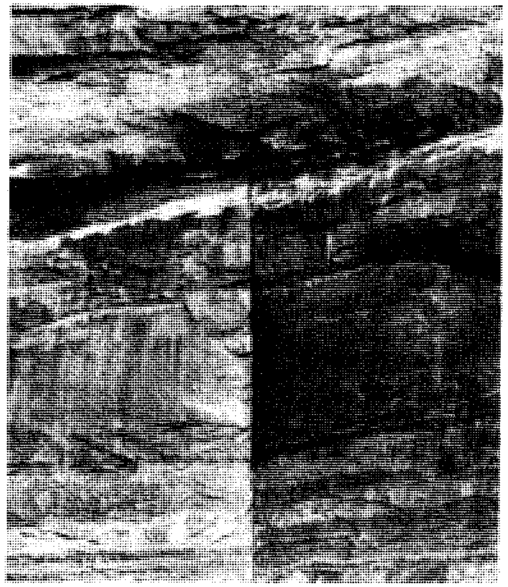
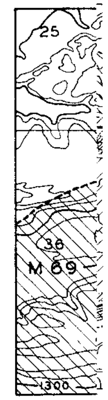


FIGURE 33

Telescopic picture of clastic dike in the Jacobsville formation which is truncated by the younger Munising formation.



BASE MAP F
OF U. S. GEO
TOPOGRAPH

GEOLOGY

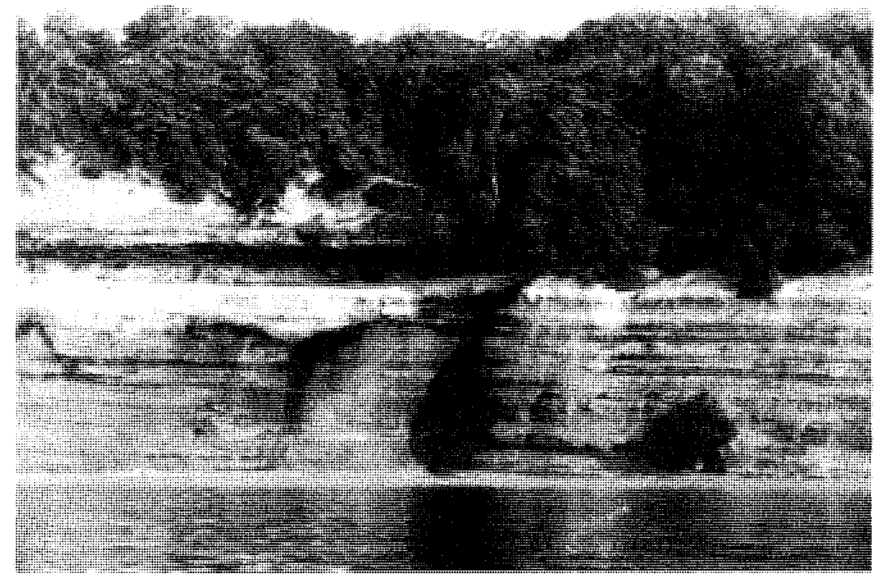


FIGURE 34

View of a part of the east coast of Grand Island showing the low dip angular unconformity between the Jacobsville and Munising formations. The alternating red and white beds of the Jacobsville show a slight northern dip component (to the right of photograph). The basal conglomerate of the Munising formation appears as the thick dark unit near the top of the picture. The section exposed in the cliffs is parallel to the strike of the Munising formation so the conglomerate appears to be horizontal. Actually the Munising formation dips toward the viewer so that it is at lake level a mile east of this exposure.

soil or weathered zone. It is very probable that if a regolith was developed on the Jacobsville it was completely destroyed by wave action of the advancing sea.

A topographic map made from elevations established on the Jacobsville-Munising contact shows that, except for a southerly regional slope which was produced by subsidence of the Michigan Basin, the erosional surface developed on the Jacobsville formation is almost a featureless plane (fig. 35).

SURFACE IN DICKINSON COUNTY

Numerous outliers of the Munising formation have been found throughout most of Dickinson County and are known to extend westward as far as Iron River, Iron County. Many outliers expose the Munising-Precambrian contact and reveal that the pre-Munising erosional surface in this area is in striking contrast to the surface exposed in Alger County (fig. 36). The Precambrian rocks are highly deformed and erosion has developed a topography

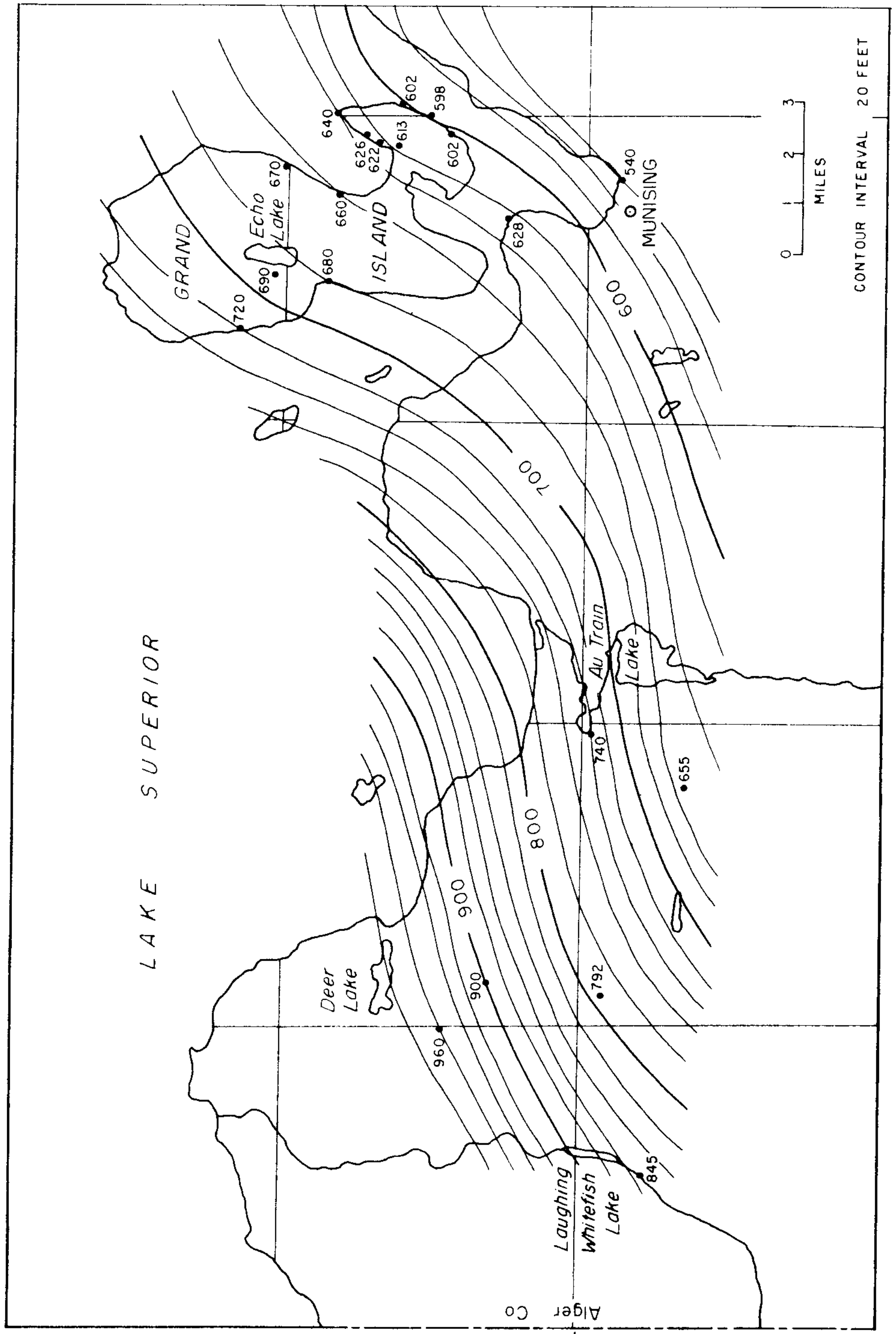


Figure 35. Contours on the pre-Munising surface in western Alger County

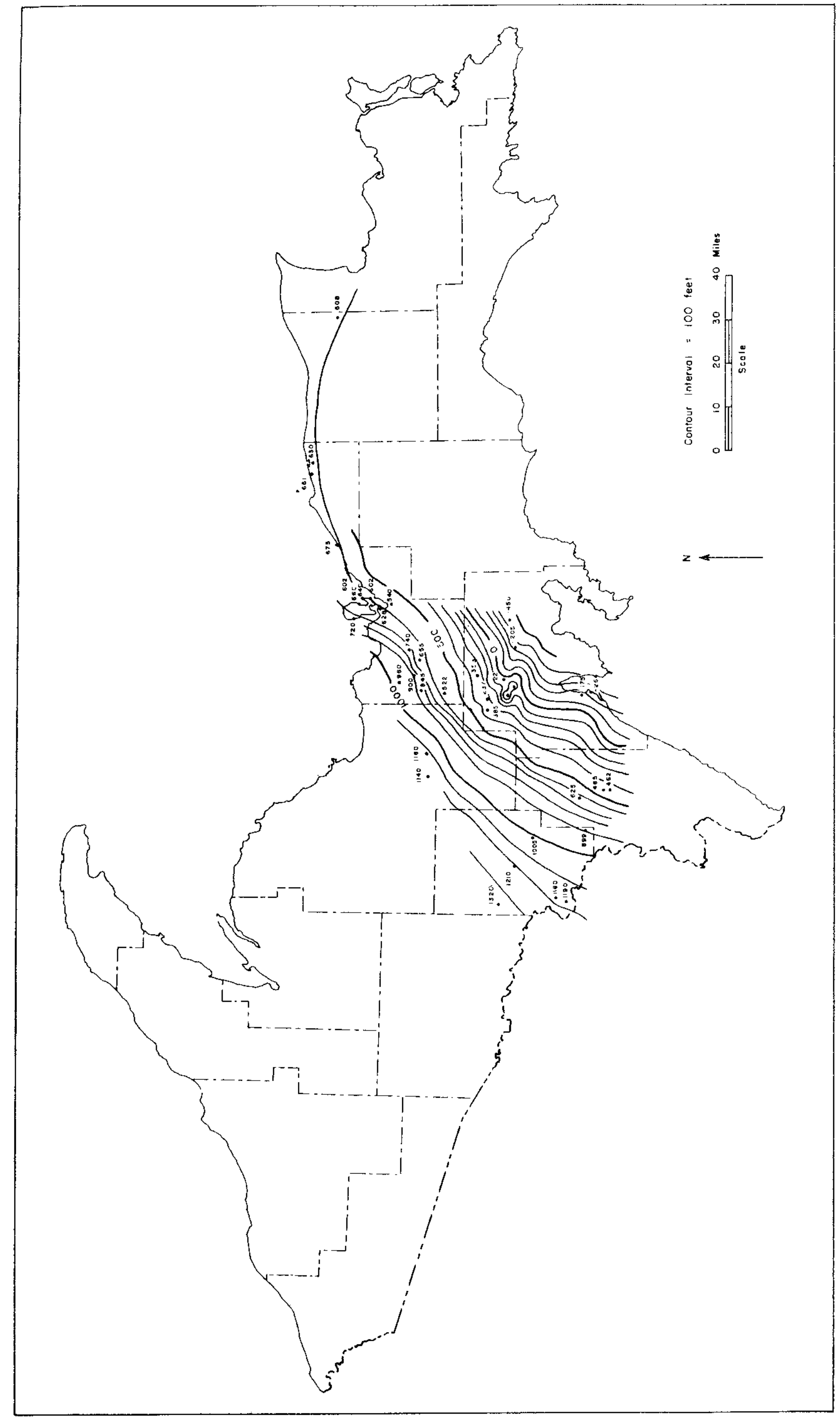


Figure 36. Contours on the pre - Munising surface

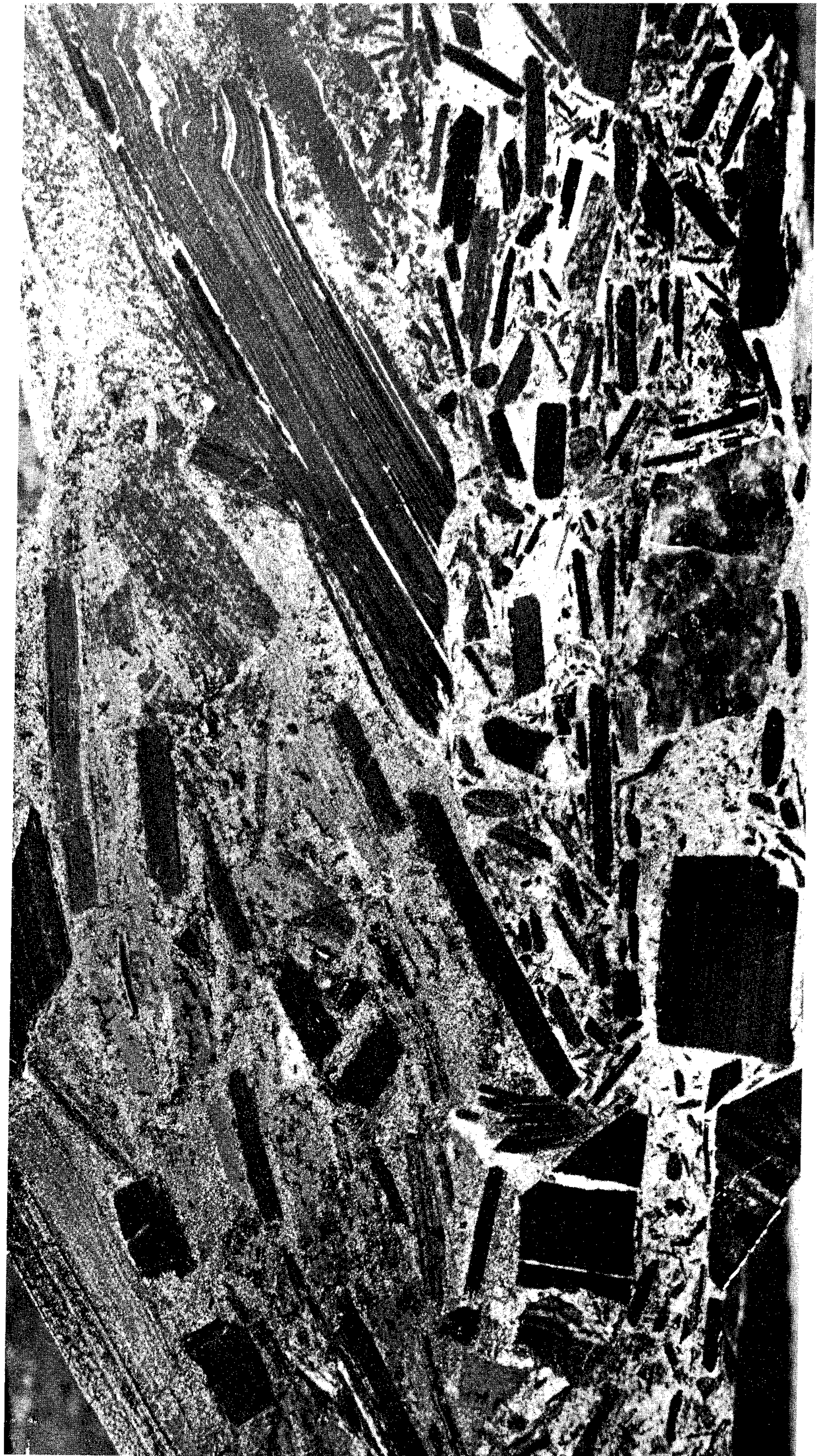


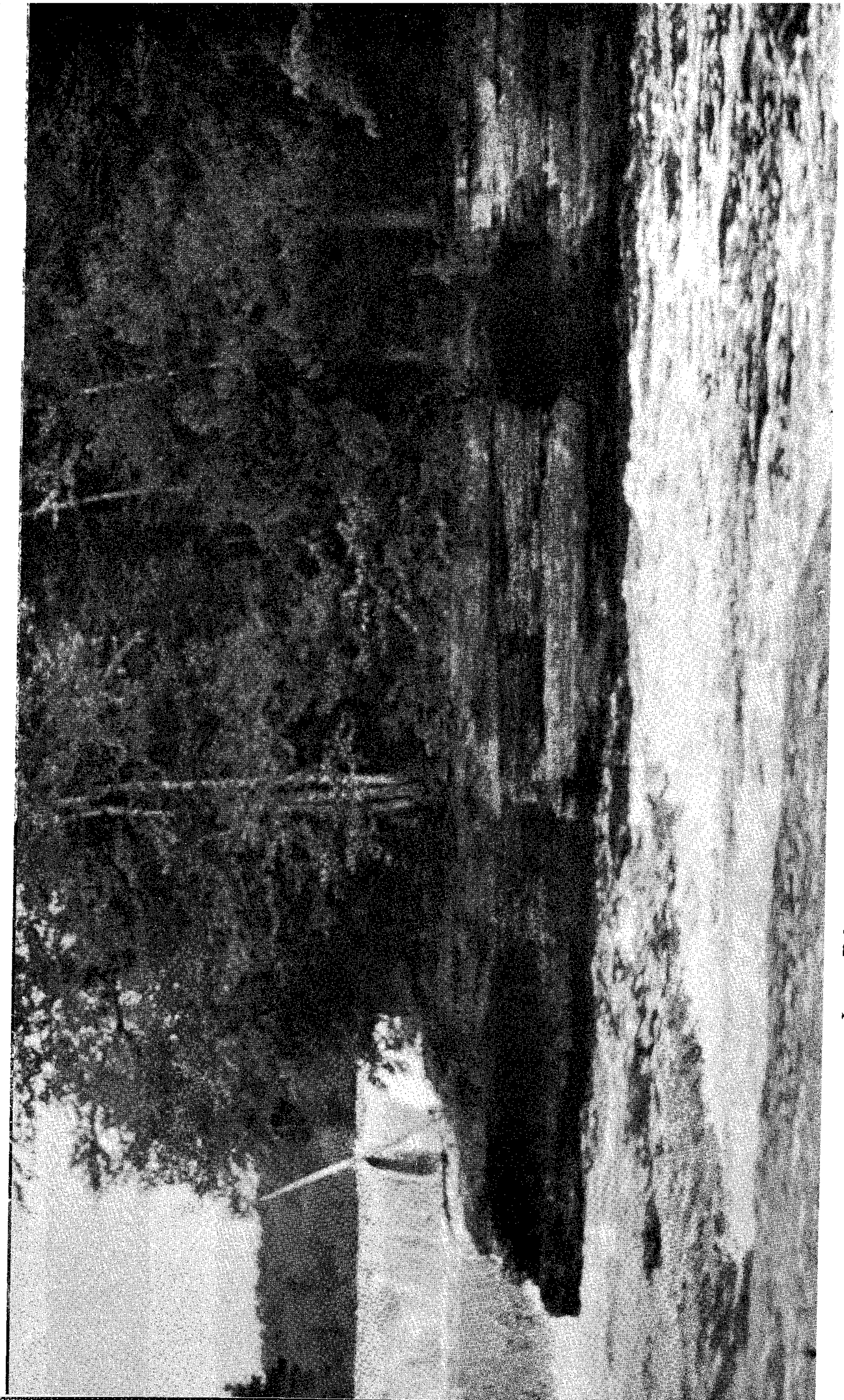
FIGURE 37

Polished section of conglomerate near the base of the Munising formation in the exposures throughout Dickinson County showing the angular nature of the iron formation pebbles and their imbricate arrangement. Sample taken from the Quinnesec Mine. Photograph is X1.

of considerable relief upon the older and more resistant rocks. In many respects the general features of this topography is very similar to the pre-Jacobsville erosional surface and it is probable that parts of it were formed during pre-Jacobsville time.

The isolated outcrops of the Munising sandstone are most commonly found capping the higher mountains but small patches of the sandstone are also in protected pockets in the valleys. An interesting example of this is at the Breen mine near Waucedah where a patch of sandstone is almost completely surrounded by hills of the iron formation. This suggests that the present topography of the Precambrian rocks is exhumed and only slightly modified by post-Paleozoic erosion.

In all but a few exposures of the Munising-Precambrian contact, lenses of highly angular fragments of slate and iron formation flank the Precambrian highs. These conglomerate lenses are as much as 6 feet thick near the margins of the highs, but pinch out within a very short distance. The discrete fragments average 4 to 6 inches in their longest dimension, but few are more than 1 inch thick (fig. 37). In some places large blocks of the iron formation more than 2 feet in diameter are imbedded in the sandstone close to the contact. It is obvious that the angularity of the fragments is due primarily to the slaty nature of the iron formation and to the short distance that these fragments were transported. The maximum local relief of the pre-Munising surface is at least 400 feet, with knobs and hills that average 50 to 75 feet high. The eastern extension of the irregular pre-Munising topography is proved by the records of a number of holes drilled recently by several iron companies.



Lower Tahquamenon Falls. Chapel Rock Member, Munising Formation.

Munising Formation

The upper 250 feet of the "Lake Superior Sandstone," which is characteristically light gray to white in color, was named the Munising formation by Lane & Seaman (1907, p. 692). The early geologists recognized this natural division in the "Lake Superior Sandstones" because of the marked color change from red to white, and various attempts have been made to subdivide the "Upper Gray" or Munising formation into members and correlate it with the Cambrian section of the Upper Mississippi Valley.

Thwaites (1934, p. 426) considered the Munising to be equivalent to the Mazomanie and Dresbach of northeastern Wisconsin, but did not indicate where such a division occurs in the Pictured Rocks section. Later, Thwaites (1943, p. 510) considered the Munising to be only of Franconia age.

Ulrich (1936) believed that the entire Upper Cambrian section, including Dresbach, Franconia, Mazomanie, Upper and Lower Trempealeau and Jordan of the Wisconsin section, was exposed in the vicinity of Munising.

Oetking (1951) probably did more detailed work on the Munising than any of his predecessors and used the terminology "Dresbach" and "Franconia" for lower and upper Munising, but he based his correlation entirely upon heavy minerals and reported no lithologic change throughout the section.

Much of the confusion concerning the division and correlation of the Munising results from the inaccessibility of the vertical Pictured Rocks cliffs which constitute the principal exposure of the formation. These outcrops can be studied in detail only from a small boat or by rappelling over the cliffs with a rope. Most of the isolated outcrops inland are too small to be of value in correlation. Since the section exposed in the Pictured Rocks is unfossiliferous and the lithic units of Wisconsin cannot be traced into the area, the terminology of the Cambrian of Wisconsin should not be used in Northern Michigan.

The present study reveals that the Munising formation consists of three distinct lithic units. They are in ascending order: The basal conglomerate, the Chapel Rock member, and the Miner's Castle member. These units persist with only slight lateral changes throughout the entire outcrop belt and can be distinguished on the basis of grain size, sorting, composition, and sedimentary structures.

FIGURE 38

Basal conglomerate of the Munising formation exposed near the level of Lake Superior on the east side of Grand Island. Note the sharp contact with both the underlying Jacobsville formation and the overlying Chapel Rock member.

FIGURE 39

Close-up view of the basal conglomerate of the Munising formation.

BASAL CONGLOMERATE

The basal member of the Munising formation is an orthoquartzitic conglomerate which attains a maximum thickness of 15 feet. Although this member is relatively thin, it is widespread and is present in almost every locality where the contact with the underlying Jacobsville is exposed. The most continuous exposures are in the shore cliffs of Grand Island and in several places along the base of the Pictured Rocks. Smaller isolated outcrops are found at Sable Falls and in several localities in western Alger County. No outcrops of the basal conglomerate were found in the outliers in Dickinson County nor in any of the drill cores taken south of Rock. This suggests that the conglomerate pinches out southward against the flanks of the Northern Michigan Highland and is thus restricted to the northern part of the Northern Peninsula. The basal conglomerate varies from 2 to 15 feet in thickness but is remarkably uniform at each exposure. In several localities of the east side of Grand Island and along the Pictured Rocks the conglomerate is in very sharp contact with both the overlying Chapel Rock member and the underlying Jacobsville formation (fig. 38). In places, however, the upper contact of the conglomerate member is gradational and large pebbles form stringers which follow the cross laminations in the basal part of the overlying Chapel Rock member. Isolated pebbles imbedded in the sandstone of the lower Chapel Rock member are also very common. It thus appears, from the wide distribution of outcrops and relative constant thickness, that the basal conglomerate is a thin blanket deposit somewhat elongated in an east-west direction.

COMPOSITION

Throughout the entire outcrop area the pebbles which make up the basal conglomerate are almost exclusively rock types which are chemically and mechanically stable. Vein quartz, quartzites, and chert invariably constitute over 90 percent of the conglomerate. Only very small amounts of slate, iron formation, basalt, granite and sandstone pebbles are present in any of the samples.

Quartzite pebbles constitute from 25 to 80 percent of the basal conglomerate. In most samples the abundance of quartzite pebbles is independent of pebble size. White, red, purple, black, and brown are the predominant colors, but the percentage of each variety is not constant from one locality to the next. The surface of the quartzite pebbles is characteristically pitted with small holes, some of which are more than 2 millimeters in diameter and 5 millimeters deep. Most of the pebbles show a slight weathered rim which is more granular and less vitreous than the unweathered interior. All pebbles are rounded to well rounded and have a high degree of sphericity.

From 15 to 60 percent of the pebbles in the basal conglomerate are composed of vein quartz. The percentage of vein quartz is greater in the smaller fractions of nearly every sample. The varieties of vein quartz include rose, clear, smoky, and milky. The clear and milky varieties are most abundant. As in the quartzite pebbles, the surface texture of much of the vein quartz is pitted although most of the vein quartz in the smaller size fractions is polished. Rounded to well-rounded pebbles predominate although many pebbles have one or more flat faces with more angular edges.

Small amounts of several types of chert are generally restricted to the finer size fractions. Most of the chert pebbles are flat and disc-shaped, probably the result of original bedding. Otherwise they possess the general characteristics of the quartz and vein quartz pebbles.

In the eastern exposures of the conglomerate member a brown oölitic chert is an important constituent since it comprises as much as 20 percent of the rock types of the conglomerate. East of Chapel Rock, however, oölitic chert is completely absent. The percentage of oölitic chert decreases rapidly in the finer size fractions probably because of its less resistant nature. All degrees of alteration from a solid, hard, polished chert pebble to a soft, white, friable mass having only a few resistant oölites in the center were noted. Most of the brown oölitic chert pebbles are less round than pebbles of other rock types. The surface texture is characterized by numerous large deep pits and holes. These holes appear to result from more rapid decomposition at points where pressure is greater because they are invariably at points of contact with other smaller pebbles.

A few sandstone pebbles of the Jacobsville formation are in every sample of the basal conglomerate examined, but in amounts of less than 1 percent. Most of the Jacobsville pebbles are restricted to the size fractions between 2 and 5 millimeters. In the few larger pebbles, the typical red color of the Jacobsville is preserved with the characteristic white reduction spots.

Since the basal conglomerate member lies directly upon the Jacobsville, one might expect to find more Jacobsville pebbles included in the conglomerate. It is apparent, however, from the compositional maturity of the basal conglomerate that pebbles as mechanically unstable as the Jacobsville would not be a common constituent.

Minor amounts of slate, iron formation, basalt, clay pellets, and decomposed felsite and granite pebbles were found in the several samples studied showing a complex lithology of the source area.

Pebble counts made at several localities throughout the outcrop belt of the basal conglomerate indicate some significant variations in composition from one locality to the next. The most striking variation in composition is in the percent of brown oölitic chert which is abundant in the eastern end of the outcrop area but is completely absent in all other localities studied. Significant changes in the percentage of black quartzites, vein quartz, and pebbles of the iron formation also are found in an east-west direction. West of Chapel Rock, black quartzite constitutes over 24 percent of the rock types, whereas east of Chapel Rock black quartzite does not exceed 9 percent. Vein quartz, on the other hand, is much more abundant east of Chapel Rock where it is in amounts exceeding 43 percent. In the western end of the outcrop belt the total amount of vein quartz does not exceed 26 percent. Pebbles of cherty iron formation and granite are also restricted almost exclusively to the western end (table 3).

These variations undoubtedly indicate east to west differences in the rock types of the source area.

TABLE 3

Pebble Counts of Basal Conglomerate of Munising Formation.

Type of Pebble	L. W. F. Spur. percent	AuTrain Spur. percent	Grand Island percent	Pictured Rocks percent	Chapel Falls percent	Sable Falls percent
Vein Quartz						
clear	10.3	11.3	9.3	6.8	28.5	54.2
milky	10.3	9.4	3.2	6.2	14.7	4.5
smoky	4.6	0.9	1.2	3.1	0.0	1.0
Total Vein Quartz	25.2	21.6	13.7	16.1	43.2	59.7
Quartzites						
red	20.6	4.2	14.7	26.0	4.6	0.3
brown	4.6	1.4	3.2	13.6	1.5	12.1
white	8.6	7.0	30.0	13.0	20.0	3.4
purple	0.0	2.8	4.2	1.8	0.0	0.0
black	28.0	24.4	28.5	27.8	7.6	8.7
banded	2.3	0.0	1.5	0.0	0.0	0.6
Total Quartzites	64.1	39.8	82.1	82.2	33.7	25.1
Chert	5.5	10.8	0.0	0.6	2.3	2.0
Cherty Iron Fm.	2.3	5.6	0.0	0.6	0.4	0.0
Brown Oölite Chert	0.0	0.0	0.0	0.0	20.0	12.6
Jacobsville	1.5	8.5	4.2	0.5	0.4	0.6
Granite	1.4	4.8	0.0	0.0	0.0	0.0
Slate	0.0	7.0	0.0	0.0	0.0	0.0
Basalt	0.0	1.9	0.0	0.0	0.0	0.0

TEXTURE

Based on estimations made at the outcrops, the average diameter of the pebbles in the basal conglomerate is from 2 to 3 inches. In each exposure the sorting of the particles greater than 2 millimeters in diameter is very good. The largest pebble observed was less than 12 inches in its longest dimension but such large cobbles are rather uncommon. Most of the pebbles are well rounded and exhibit a wide variety of shapes. The present shape of the individual pebbles does not appear to have much significance in indicating the environment of deposition. The shape of the quartzites and vein quartz pebbles is a modification, to a great extent, of the shape of the larger pebbles (from which they were derived) by fracturing prior to deposition. The conchoidal fracture of quartz produces a concave surface which is soon modified by abrasion to a smooth plane. The result is that spherical, elliptical, and disc-shaped pebbles break into smaller pebbles having one flat face. If the pebble is broken several times, the resulting shape approaches a tetrahedron which may later be modified by abrasion to a sphere. All gradations from an angular to well-rounded tetrahedron were observed. The abundance of pebbles broken only a short time prior to deposition indicates exceptionally high current velocities in the encroaching seas.

ORIGIN

A number of features in the basal conglomerate clearly indicate its mode of origin. The composition is very simple as more than 95 percent of the pebbles are either vein quartz, quartzite, or chert. Most of the gravels are well worn and rounded and nearly everywhere well sorted. The conglomerate is a thin blanket deposit having a maximum thickness of only 15 feet and extends laterally a distance of over 60 miles. Exposures of the basal conglomerate at Limestone Mountain indicate that prior to the present cycle of erosion, the conglomerate may have extended an additional 100 miles to the west. The conglomerate is closely associated with the large-scale cross-bedded sandstone of the Chapel Rock member and in places it forms several layers interbedded with sandstone units. In many places the gravels are deposited as lenses and stringers following the cross-laminations of the overlying Chapel Rock member, and "floating pebbles" are very common. All of these features indicate that the basal conglomerate of the Munising formation is a classic example of an orthoquartzitic conglomerate deposited by a transgressive sea over a surface of low relief.

The contact between the basal conglomerate and the Chapel Rock member, in many places, is very sharp indicating rapid transgression of the sea. Elsewhere the contact is gradational, but evidence of a hiatus between the two members was not found. Deposition appears to have been continuous from the basal conglomerate to the Chapel Rock member.

The thinning of the conglomerate to the south and east suggests that the Huronian quartzites of the Northern Michigan Highland were the source for the major part of the basal conglomerate. This supposition is strongly supported by the presence of angular pebbles of the iron formation in the western part of the outcrop belt.

CHAPEL ROCK MEMBER

The Chapel Rock member overlies the basal conglomerate and consists of well-sorted medium-grained sandstone characterized by large-scale cross-bedding. The name, here proposed, is derived from the excellent exposures at Chapel Rock near the eastern end of the Pictured Rocks cliffs (fig. 40).

Excellent exposures of the Chapel Rock member are along the entire extent of the Pictured Rocks. East of Mosquito Harbor this member constitutes virtually the entire section exposed in the cliffs, but because of a southwest component of dip only the upper 10 to 15 feet of the Chapel Rock member is exposed above the lake level from Munising to Miner's Castle. West of Munising the Chapel Rock member is exposed in a number of localities in the drainage basin of the Rock River, but it is structurally too low to be exposed in the numerous waterfalls of Alger County. The southern extent of the Chapel Rock member is poorly defined because of the limited number of good outcrops south of the coast of Lake Superior. The Chapel Rock member is recognized in the drill cores taken at Kiva and Rock, but it has never been recognized in outcrops or wells south of Rock. Westward the Chapel Rock member is exposed on the east and the west flanks of Little Limestone Mountain and at the base of a limestone quarry on the east flank of Limestone Mountain in the NW $1/4$, sec. 24, T. 51 N., R. 35 W. Eastward, exposures are found in the lower falls of the Tahquamenon River and on Encampement d'Ours Island in the St. Mary's River.

The exact thickness of the Chapel Rock member could be determined in only a few places. Along the Pictured Rocks and apparently throughout most of Alger County it is from 40 to 60 feet thick. Complete sections measured at Grand Marais indicate that the Chapel Rock member, like the basal conglomerate, thins gradually to the east. The southern extent and thickness of the member is uncertain because of insufficient data.

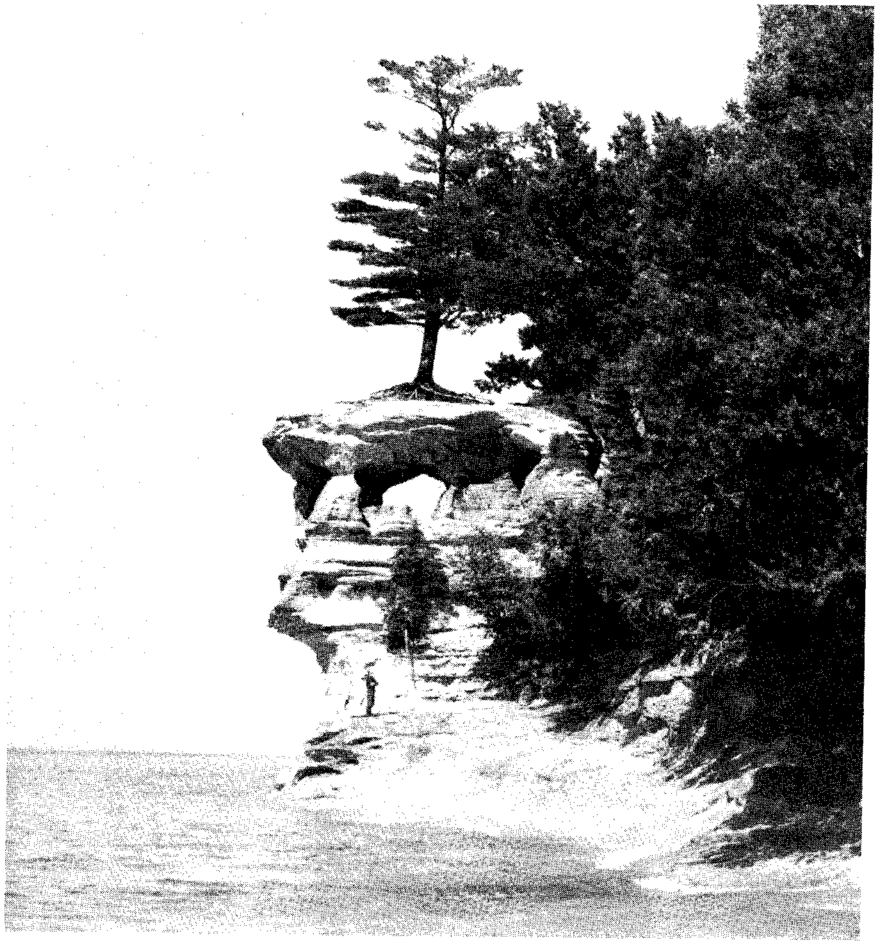


FIGURE 40

Chapel Rock, the type locality of the Chapel Rock member of the Munising formation. The stratification is a result of large-scale cross-bedding. Note the arches carved by wave action when lake level was higher.

COMPOSITION

The sandstone of the Chapel Rock member is composed almost entirely of quartz, chert and quartzite grains. Most of the quartz grains contain numerous bubble trains and gas bubbles and are therefore considered to have originated from igneous rock. Only minor amounts of feldspar are present. Calcium carbonate is locally abundant but is restricted to zones near fractures and cannot be considered as the predominant cementing material. Many small angular quartz fragments constitute a matrix for larger grains and

thus act as a clastic binder. Silica, however, is in most places the predominant cementing material and occurs as secondary overgrowths in crystallographic continuity with the detrital grains. The degree of secondary quartz overgrowths varies considerably throughout the outcrop belt. Generally the Chapel Rock member is friable but at Tahquamenon Falls the degree of secondary quartz overgrowths is so extreme that an orthoquartzite with very little porosity has been produced (fig. 41).

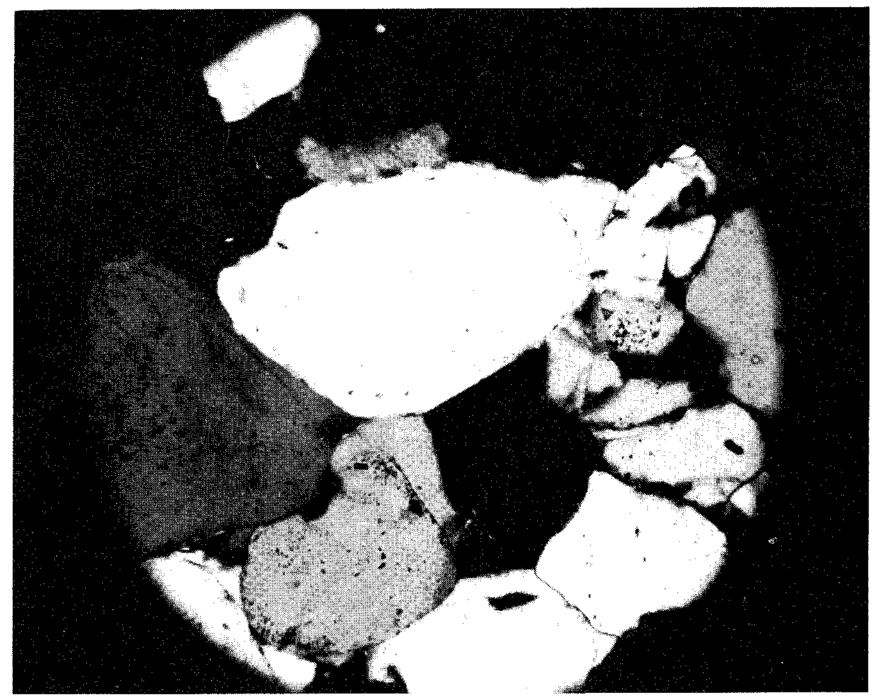


FIGURE 41

Secondary overgrowths of quartz on well-rounded sand grains of the Chapel Rock member. Crossed nicols. X63.

HEAVY MINERALS

The heavy mineral suite of the Chapel Rock member constitutes between ½ and 2 percent by weight and is not markedly different from the heavy mineral content of the Jacobsville formation. The main differences are a decrease in opaques and an increase in the percentage of zircon and tourmaline. A summary of the heavy minerals from this member and lateral variations are shown in figure 43.

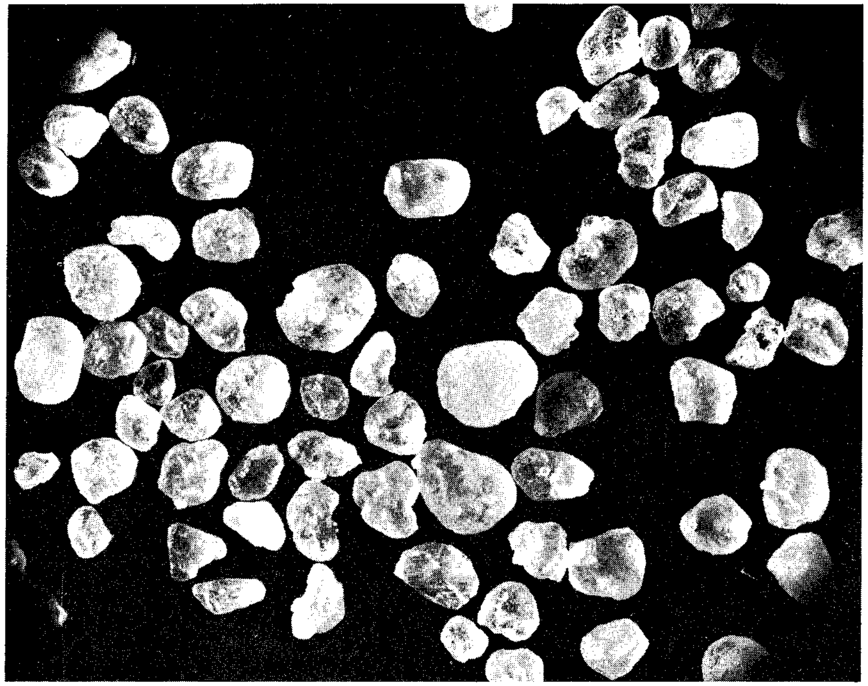


FIGURE 42

Typical sand grains of the Chapel Rock member illustrating the degree of roundness and sorting and surface texture of the grains. X10.

Zircon is the most abundant mineral because it consistently constitutes from 20 to 50 percent of the heavies. Two types are recognized: a fresh, light-gray to pink variety which is most abundant, and an altered variety in which a dark yellowish-brown coating obscures the true color. The shapes of the grains range from nearly spherical to elongated, slightly rounded prisms many of which show crystal faces. Inclusions are common and zoning is distinguished in most of the altered varieties of grains (fig. 44).

Tourmaline occurs as well-rounded grains, some of which contain inclusions. Brown, black, blue, and green varieties were found, but the brown variety is the most common.

Minor amounts of apatite occur as well-rounded, almost perfectly spherical grains generally free from inclusions and alterations. The mineral is readily distinguished by its spherical shape and low birefringence.

Well-rounded elliptical grains of rutile are nearly opaque, but may be distinguished by their dark reddish-brown color and faint pleochroism.

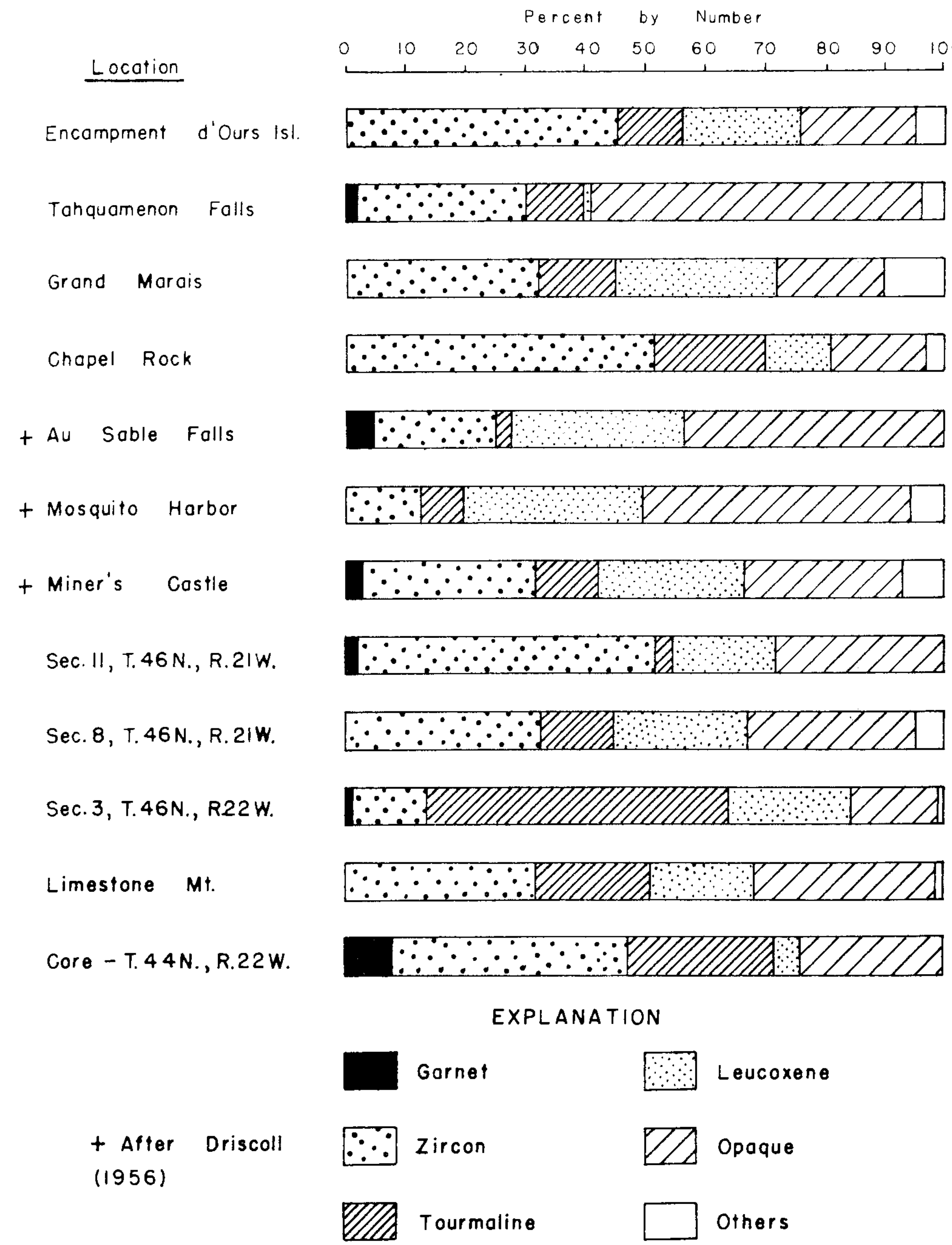


Figure 43. Heavy minerals of the Chapel Rock member

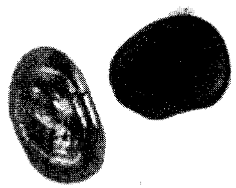


FIGURE 44, *A*

Tourmaline and altered zircon from the Chapel Rock member. Sample from Chapel Rock. X65.

FIGURE 44, *B*

Altered and unaltered zircon grains from the Chapel Rock member. Sample from bluff south of Grand Marais. X65.

The small amount of garnet in the Chapel Rock member is similar in most respects to the garnet which characterizes the heavy mineral suite of the Miner's Castle member. However, a few well-rounded grains free from the characteristic surface features were found.

Magnetite, hematite, ilmenite, and minor pyrite comprise the opaque heavy minerals. Magnetite was separated from the remaining heavies and was not studied microscopically. Hematite is generally recognized by its metallic luster but like ilmenite could not always be rapidly distinguished from other opaques. Most of the ilmenite in the samples show some degree of alteration to leucoxene.

TEXTURE

The Chapel Rock member is primarily a well-sorted, medium-grained sandstone with varying amounts of scattered pebbles near the base of the section. From 60 to 70 percent of the grains are between ¼ to ½ millimeter in diameter (fig. 45), and most sections are free from shale lenses or partings, which makes the Chapel Rock member a relatively clean sandstone.

COLOR

Excepting surficial stains along the Pictured Rocks, the color of the Chapel Rock member is white, buff, or salmon red. The color differs from place to place but changes are not abrupt. Along the

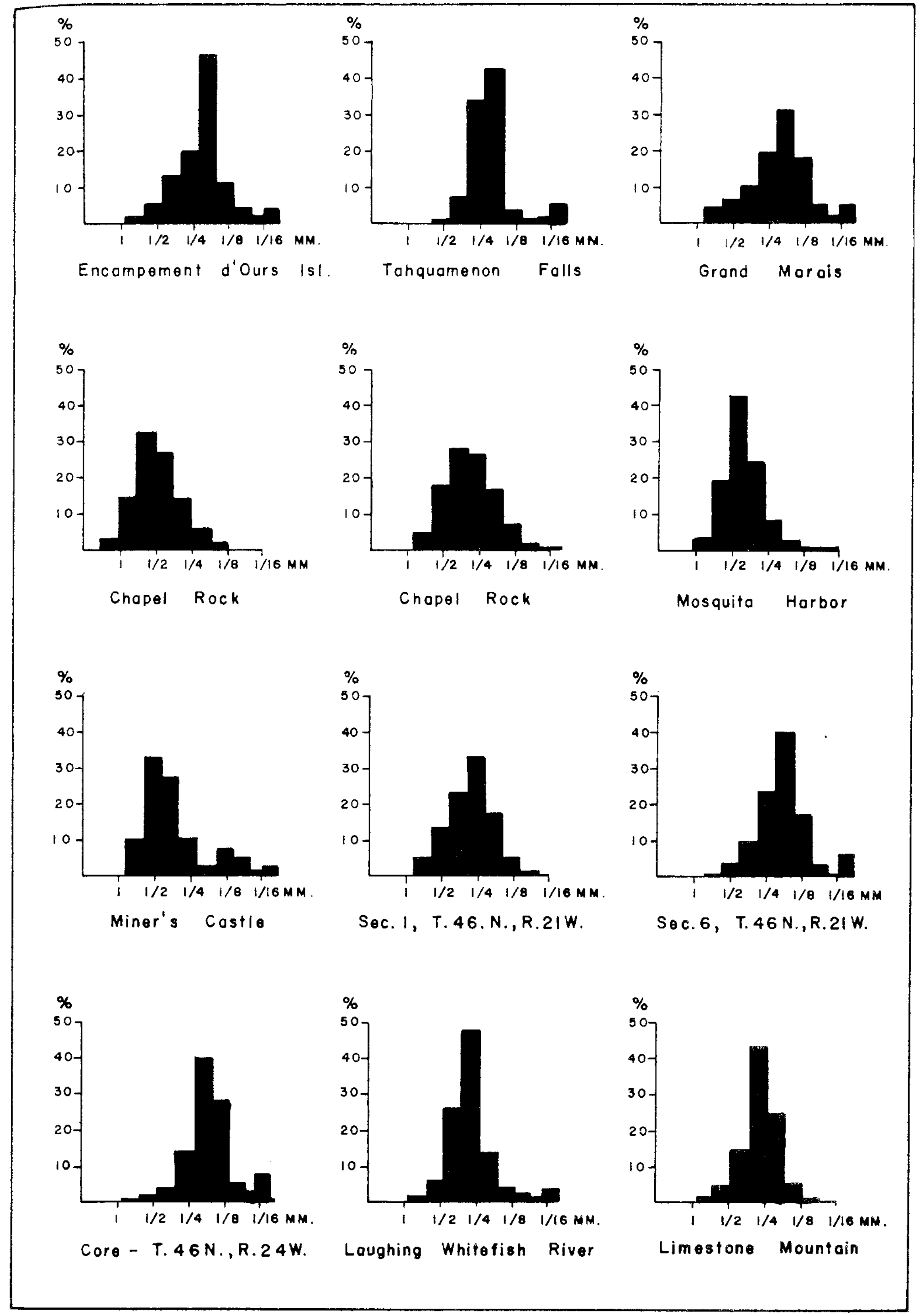


Figure 45. Grain - size distribution in typical samples of the Chapel Rock member

Pictured Rocks, the Chapel Rock member is colored in brilliant shades of red, yellow, green, black, brown, and white. The various colors are in vertical bands where mineral and organic matter is deposited from the effluent seepage of ground water down the face of the cliffs.

SEDIMENTARY STRUCTURES

Cross-bedding

Large-scale trough cross-bedding is the most striking and abundant sedimentary structure in the Chapel Rock member. The size of the troughs ranges from 3 feet to more than 600 feet in width, but the average width is in the magnitude of 30 feet. The larger troughs are most abundant south of Chapel Rock and at Mosquito Harbor. Excepting the section at Lower Tahquamenon Falls, nearly every outcrop of the Chapel Rock member exhibits this typical large-scale cross-bedding and thus it is one of the most useful megascopic features which can be used to distinguish the Chapel Rock member from the Jacobsville formation and from the Miner's Castle member. Good exposures of the complete trough in three dimensions are rather rare, however, because of their tremendous size. Most of the outcrops inland are only large enough to expose a small part of a limb of the troughs and most of the cliffs along the Pictured Rocks expose only a vertical section. At Miner's Castle, Mosquito Harbor, and Chapel Beach, however, good exposures of these structures in three dimensions are numerous (figs. 46, 47). In these localities wave action has produced wide wave-cut terraces which extend out into the lake for a considerable distance. Since the water covering these terraces is only a few feet deep, the horizontal section cutting the troughs can be studied in detail over a large area. Symmetrical and asymmetrical troughs are both common in the Chapel Rock member but it was noted that the number of symmetrical troughs decreased as the size of the troughs increased. The individual lamina which fill the troughs range from 1/8 to 1/2 inch in thickness and in many outcrops have been etched into relief by weathering. In many places along the Pictured Rocks, however, the cross-bedding is obscured by deposits precipitated by the seepage of ground water down the vertical cliffs. Where the cross-bedding is exposed, each lamina maintains a uniform thickness throughout its entire length and in the larger exposures the individual laminae can be traced without interruption from one limb of the trough to the other. In a horizontal section of the larger troughs, this distance is more than 1,000 feet.

The lower surface of each set of cross-strata show that considerable erosion cut deep channels in the older units prior to the

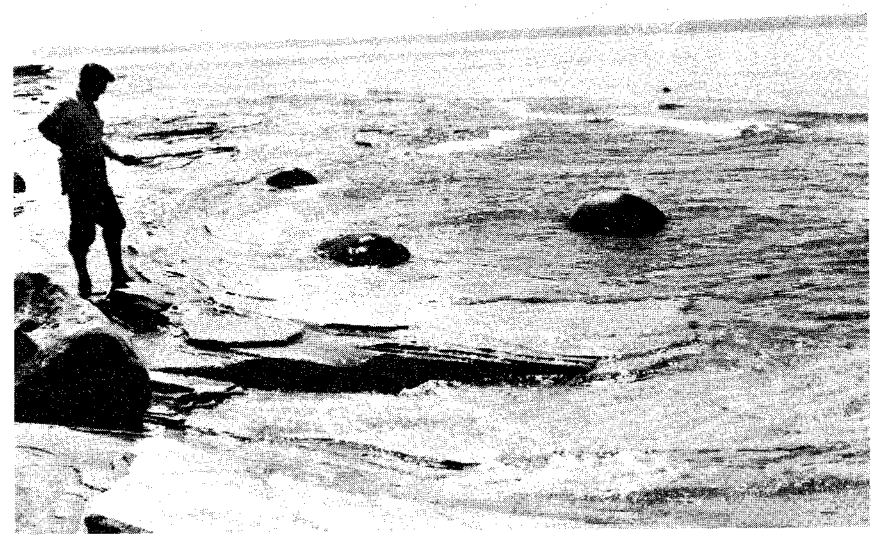


FIGURE 46

Horizontal surface of the Chapel Rock member showing the well-developed large-scale trough cross-stratification. Hand is pointing in the direction in which the axes of the trough plunge, which is considered to be the direction of current flow. View taken at Mosquito Harbor.

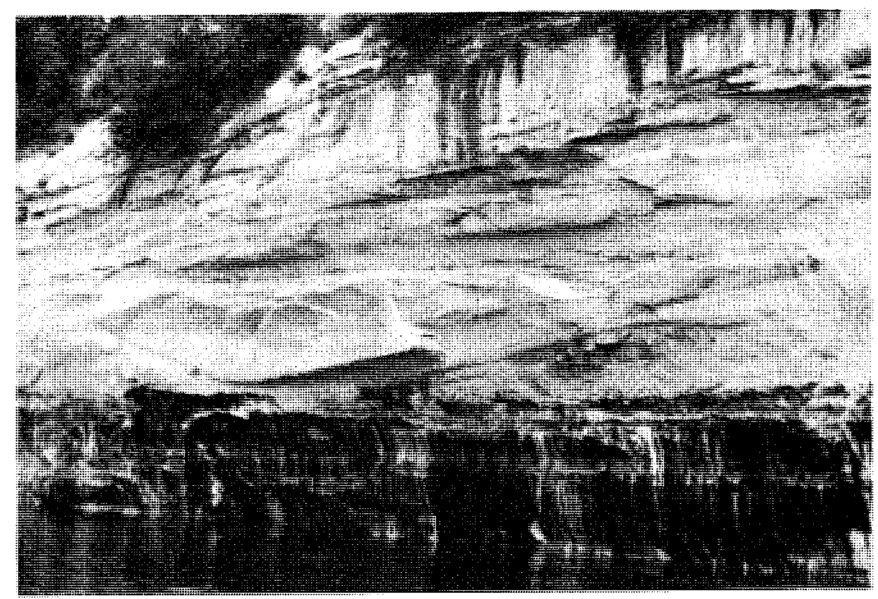


FIGURE 47

Cliff along the Pictured Rocks showing the appearance of the large-scale trough cross-stratification in a profile perpendicular to the plunge of the trough.

deposition of each succeeding set of cross-strata. The form of the erosional channels generally controls the shape of the set of cross-strata which fills it, but the erosional surface is remarkably smooth and regular; therefore, the shape of the laminae approaches a smooth gentle curve. Most of the lower bounding surfaces are concave upward but in several localities two or more erosional channels were filled simultaneously so that the arches separating the troughs produce cross-bedding that is convex upward (fig. 48). The average angle of plunge of the axis of the trough is very steep near the top of the trough but decreases rapidly in a down-current direction and becomes almost horizontal. Near the base of the Chapel Rock member stringers of pebbles follow the cross-lamination and near the contact with the basal conglomerate pebble-size particles constitute an appreciable part of the cross-bedded material. The close association of the Chapel Rock member with the underlying orthoquartzitic conglomerate leaves little doubt that the large-scale cross-bedding was produced in a marine environment. It appears from the large size and trough-like shape of these structures that they formed in embayments along a cuspate shore.

Mud Cracks

The upper part of the Chapel Rock member is characterized by a 5-foot section of interbedded black shale and buff sandstone (fig. 49). Most of the sandstone and shale beds are only 5 to 10 inches thick but traced laterally many shale lenses are found to coalesce and form a shale bed 3 to 4 feet thick. Locally this unit is absent but in several localities along the Pictured Rocks it marks the uppermost unit of the Chapel Rock member and is directly overlain by the Miner's Castle member. Large mud cracks as much as 3 inches wide form polygonal patterns in essentially every shale lens in this zone. Most of the cracks have been filled with sand which is more resistant to weathering and they stand out in relief, forming a structure which resembles a honeycomb. The polygonal pattern formed by these mud cracks ranges from 4 to 18 inches in diameter. The depth of the crack, however, is restricted by the thickness of the shale bed and in few places exceeds 6 inches. Most of the larger mud cracks have somewhat rounded corners and edges. Many smaller secondary cracks 1 to 1½ inches wide are clearly developed across the areas outlined by the larger crevices and in turn enclose an area which contains short minor incomplete cracks of a third generation. The form of most of the larger cracks is tabular and does not exhibit the characteristic "V"-shaped profile.

It is significant to note that the zone containing the mud cracks is the uppermost unit of the Chapel Rock member and in many places it is in direct contact with basal units of the Miner's Castle member. This indicates that the upper Chapel Rock member was deposited in a shallow-water environment which was repeatedly exposed to subaerial conditions. This might be interpreted as a regressive phase of the Chapel Rock sea.

Ripple Marks

Several strata of the Chapel Rock member exhibit well-developed ripple marks. These structures are especially numerous at Mosquito Harbor and Lower Tahquamenon Falls. Both oscillation and current ripples appear to be present, but many of the crests have been flattened by erosion; therefore, it is impossible to determine in all exposures if currents were responsible for their formation. Only very slight differences were noted in the wave length and amplitude of the current ripple marks exposed, indicating that they were produced by constant current velocities.

Tracks

Two different original structures formed on the ripple marks at Mosquito Harbor may possibly have been formed by organisms. One type trends almost perpendicular to the direction of current flow and consists of a series of parallel grooves. The width of the cluster of grooves is approximately 6 inches and the observable length is more than 10 feet. The grooves are remarkably straight and parallel, deviating from a straight line in broad gentle curves. In all the clusters of grooves observed, the medial groove is the widest and deepest. The straight course and the orientation normal to the strike of the ripple marks indicate that these markings may possibly have been formed by debris pushed along by moving water. The only other explanation is that they represent tracks made by some organism.

The other type of marking found on the ripple marks exposed at Mosquito Harbor is sets of lenticular impressions which show no definite orientation to the ripple marks. The average size of these markings is approximately 4 inches long and 1 to 1½ inches wide, but the size varies to a considerable extent. Where these markings are very numerous they appear at first to be interference ripple marks, but where markings are few, they appear to have a definite systematic orientation (fig. 50).

Concretions

Sand concretions averaging 1 to 2 inches in diameter are common in the Chapel Rock member in some localities where calcite-filled fractures and stringers are abundant. The largest concretions are more than 10 inches in their longest dimension and the smallest are

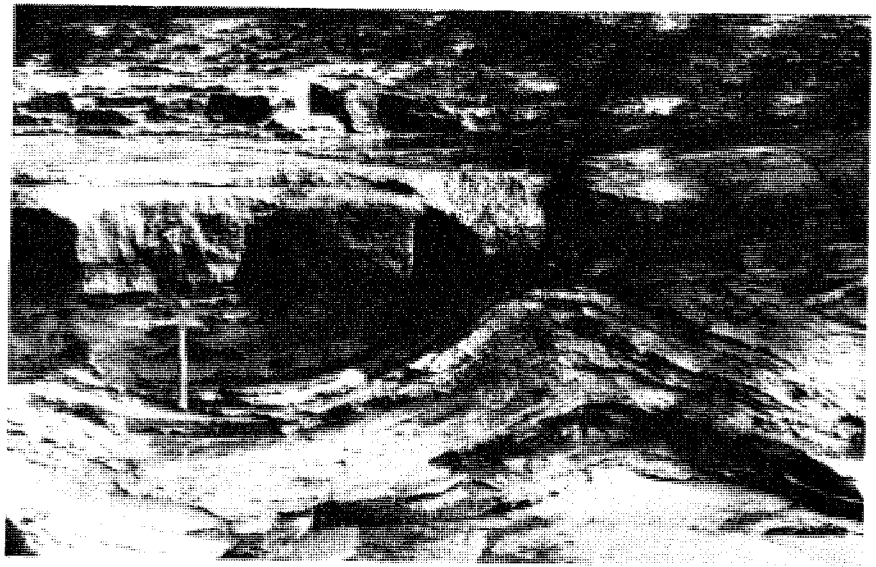


FIGURE 48

Adjacent troughs in the Chapel Rock member filled simultaneously so that the stratification produced is continuous through a trough, over an arch and into another trough.

FIGURE 49

Zone of interbedded sandstone and shale showing the extensive development of mud cracks in the upper units of the Chapel Rock member.

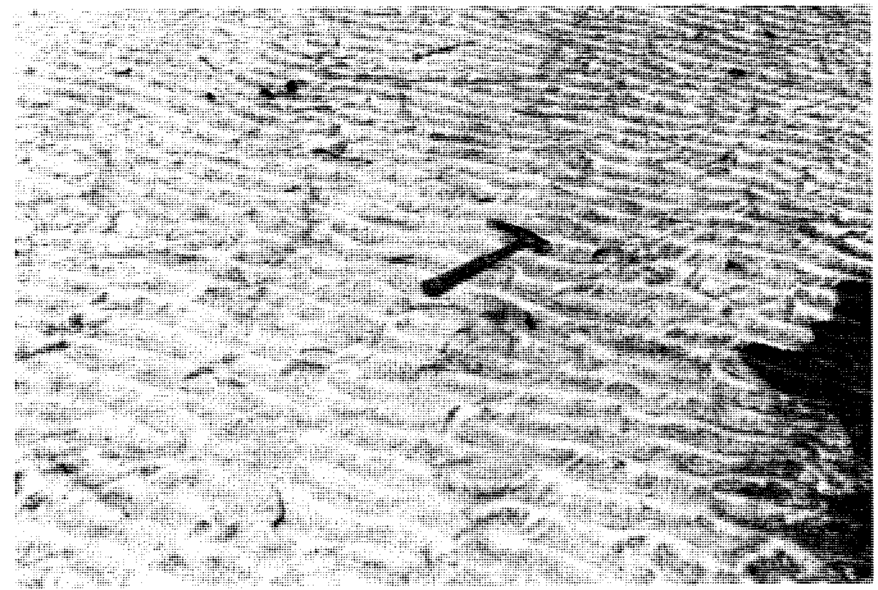


FIGURE 50

Current ripple marks in the Chapel Rock member at Mosquito Harbor. Hammer handle points in the direction of current flow. Note the markings on the surface which are possibly due to organisms.

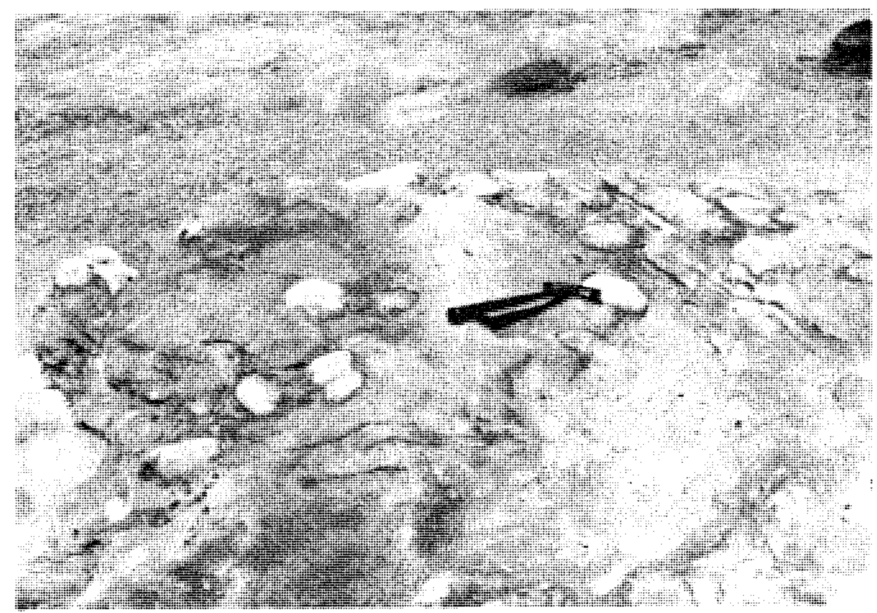


FIGURE 51

Large concretions in the Chapel Rock member.

only a fraction of an inch in diameter. The concretions consist of concentric zones of abundant carbonate cement and small amounts of iron oxide. The increase in cementing materials makes them more resistant to weathering and they stand in relief as hard nodules resembling well-rounded pebbles. Bedding planes pass through the concentric structure indicating that they are definitely secondary. Their localized occurrence in the vicinity of fractures, many of which are filled with calcite, suggests that they originated from the diffusion and localization of calcite made available by the increased permeability of fractured zones (fig. 51).

Clastic Dikes

In several localities small irregular sandstone dikes penetrate the Chapel Rock member to a depth of from 3 to 6 feet below its upper contact. Unlike the clastic dikes in the Jacobsville formation, these dikes are only a few inches wide and contain numerous branches or sills which in places connect neighboring dikes. They are entirely restricted to the upper units of the Chapel Rock member and pinch out downward within a few feet. Most of the major dikes are at right angles to the bedding, and they expand upward in such a way that some dikes may be as much as a foot wide at the contact.

The dikes are composed of poorly-sorted sand and blue shale from the overlying Miner's Castle member. These materials are distinctly banded parallel to the walls of the dike. In some localities bedding planes and shale lenses of the Miner's Castle member do not extend across the top of the dike as they would have if the dikes had been truncated at the contact. Instead, they bend down into the dike and thus indicate that the dikes were filled by forceful injection from above.

Clay Pellets

Clay galls or pellets are very common in the upper part of the Chapel Rock member, especially near the zones that contain mud cracks. These pellets range in size from $\frac{1}{8}$ of an inch to 4 inches in diameter and are rounded to angular in outline. Most are flattened and discoid but some have upcurled ends. They were undoubtedly derived from the desiccation and breaking of the shale which contains some of the mud cracks.

CONTACT BETWEEN THE CHAPEL ROCK AND MINER'S CASTLE MEMBERS

Along most of the coast of the Pictured Rocks cliffs the contact between the Chapel Rock and Miner's Castle members can be easily recognized. In many places a definite change in color and in the size

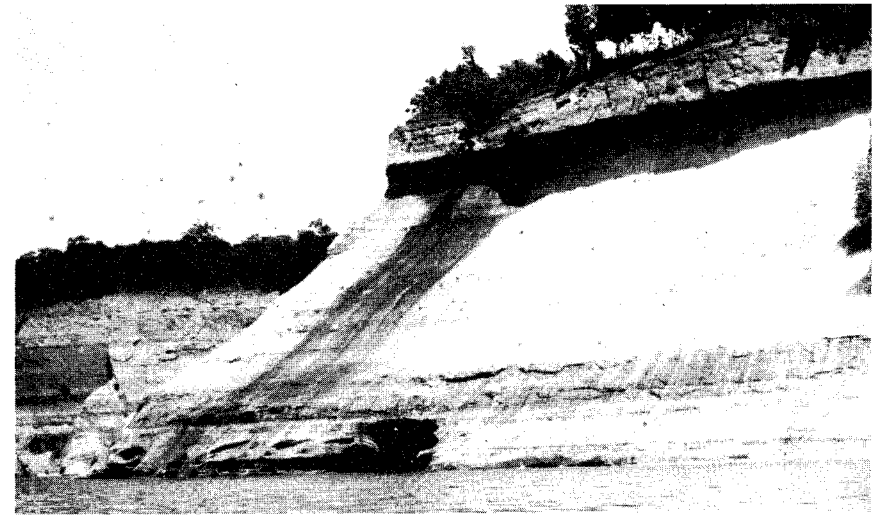


FIGURE 52

View of the Pictured Rocks showing the contact between the Chapel Rock member (lower, resistant unit protruding 15 to 20 feet above the water level) and the Miner's Castle member (non-resistant, light-colored, slope-forming unit). Note the resistant cap rock of the Au Train formation.

FIGURE 53

View looking west along the Pictured Rocks cliffs between Miner's Castle and Munising, showing the terrace developed at the contact between the Chapel Rock and Miner's Castle members. Note the difference in outcrop texture above and below the contact.

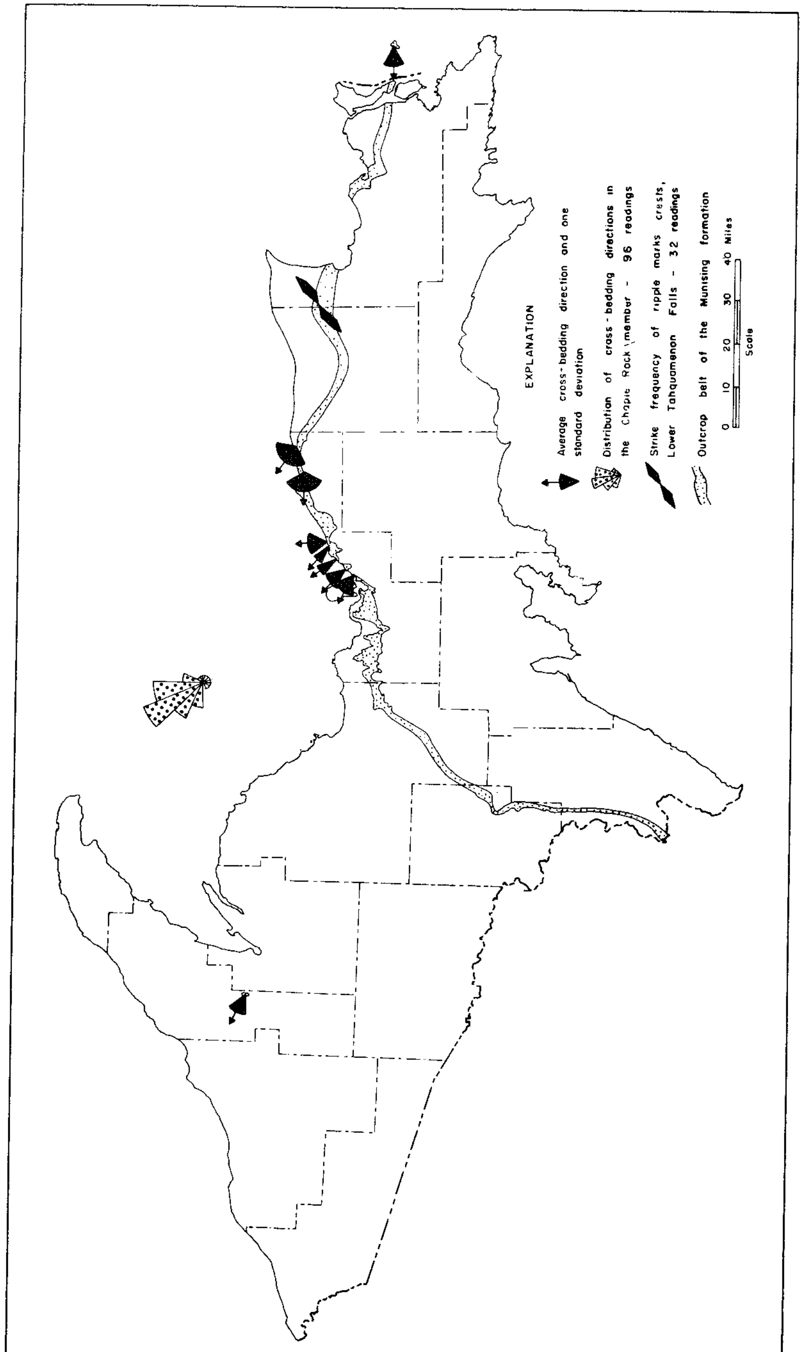


Figure 54. Cross - bedding directions in the Chapel Rock member

of cross-bedding marks the contact which also has been accentuated by differential erosion. The Miner's Castle member is a weak, non-resistant, slope-forming unit whereas the Chapel Rock member is more resistant and tends to form a steep cliff (fig. 52). Since the contact between these members is sharp, a narrow terrace has developed in many places on the top of the Chapel Rock member. In many places this terrace is more than 20 feet wide but it is commonly much less (fig. 53). From Sand Point to Miner's Castle the terrace is practically continuous so that it is possible to walk for several miles right on the contact which appears in the vertical section to be a horizontal plane.

An unconformity separating the Chapel Rock and Miner's Castle members is indicated by significant changes in sorting, sedimentary structures, and heavy mineral assemblages. The Chapel Rock member is a clean, well-sorted sandstone characterized by large-scale cross-bedding. In the Miner's Castle member, however, the sorting is poor and the cross-bedding is distinctively small scale (compare figs. 45 and 65, 46 and 66). The changes in sorting and sedimentary structures are abrupt and occur right at the contact between the two members indicating abrupt changes in environmental conditions. A striking change in the heavy mineral assemblage at the contact between the Chapel Rock and Miner's Castle members further indicates that the two members were derived from different source areas. The Chapel Rock member is characteristically high in zircon and low in garnet, whereas the Miner's Castle member is low in zircon and remarkably high in garnet (compare figs. 43 and 61). Different source areas are also indicated by cross-bedding dip directions which show the source of the Chapel Rock member to be southeast of the present outcrops and the source of the Miner's Castle member to be to the northeast (compare figs. 54 and 68).

When these evidences are considered together the conclusion that an unconformity separates the two members seems inescapable. The size and extent of this unconformity, however, is not known.

PALEOGEOGRAPHY

Analysis of Cross-bedding

The trough cross-bedding in the Chapel Rock member apparently was developed in embayments on a cuspate beach (see section on cross-bedding). Thompson (1937, p. 735) described this type of sedimentary structure of modern beaches and found that the axes of the "scooplike embayments" plunge toward the sea. A statistical analysis of the plunge direction of this type of trough cross-bedding would, therefore, indicate the average seaward direction in the wave zone during the time the sediment was being deposited. The plunge direction of the large-scale trough cross-bedding can be measured accurately only in a horizontal section which exposes the complete trough or in a vertical section containing the axial plane. All other sections expose only an apparent plunge direction or the dip direction of a limb, neither of which is considered to accurately represent the direction of regional slope. Measurements were therefore restricted to exposures showing complete horizontal sections. Such exposures are primarily along the Pictured Rocks, since the outcrops inland in western Alger County are too small to completely expose these large-scale structures. An average of only 12 measurements was obtainable from each locality, but the small variation between measurements indicates that this number is sufficient to present a reliable average.

Figure 54 shows the mean and standard deviation for all the cross-bedding measurements taken at each locality. The average plunge direction of the large-scale trough cross-bedding in the Chapel Rock member is N. 45° W. which indicates that the regional slope and seaward direction in Northern Michigan during the first advancement of the Paleozoic seas was to the northwest. This is undoubtedly due to the fact that the Northern Michigan Highland which provided the sediments for the Jacobsville formation remained a positive area during the beginning of Upper Cambrian time. It formed an obstacle to the advancement of the seas onto the Canadian Shield from the south and southeast permitting an encroachment only from the west and north. In all probability the Jacobsville covered much of the highland and supplied a large part of the sand which was redeposited to form the Chapel Rock member. This theory is strongly supported by the striking similarities between the two units in sorting and in heavy mineral suites. The differences between the two units may be ascribed primarily to the different environments in which they were deposited.

Ripple Marks

The strike of asymmetrical ripple marks is a highly significant feature because it may be closely correlated with the direction of current flow and is thus a good indicator of the direction of sediment transport. The strike of oscillation ripple marks, however, is not necessarily related to current directions, but is still significant in paleogeographic studies because it is generally related to the prevailing wave direction and trend of the shoreline.

At Lower Tahquamenon Falls ripple marks are exposed in a sufficient number of strata to indicate the general trend of the ancient shoreline. Figure 54 shows that the average strike of the ripple

marks is practically perpendicular to the average direction of the plunge of the large-scale trough cross-bedding. The trend of the shoreline, as indicated by the average ripple-mark strike, is northeast-southwest and is in very close agreement with the position of the shoreline which might be inferred from cross-bedding measurements.

Shape of the Chapel Rock Member

Details of the thickness, shape and distribution of the Chapel Rock member are not known, but sufficient data indicate regional trends which are significant. Outcrops indicate that the Chapel Rock member is quite extensive in an east-west direction. The outlier at Limestone Mountain further indicates that at one time the Chapel Rock member extended at least an additional 100 miles to the west of the present outcrop belt. The southern extent, however, is probably quite limited inasmuch as it is not recognized anywhere in the southern half of the peninsula.

This restricted southern limit could be best explained by a thinning towards the source area and a pinch-out at the shoreline which extended through the center of the Northern Peninsula. This would imply a southeastern source and the advancement of the seas from the northwest, as previously adduced.

MINER'S CASTLE MEMBER

The Miner's Castle member constitutes the upper 140 feet of the Munising formation and consists of poorly sorted sandstone which is characteristically cross-bedded. The size of the sets of cross-strata is remarkably small as they average between 4 and 6 inches thick. This small-scale cross-bedding stands out in bold contrast to the large-scale cross-bedding of the Chapel Rock member and in most outcrops it is sufficient to distinguish the two members. Thin lenses of blue shale nearly everywhere separate the sets of cross-strata in the lower part of the section but most of the upper units are pure sandstone and the sorting is much better. Excellent exposures of the complete section are found at Miner's Castle which is selected as the type locality (figs. 55, 57).

The characteristic lithology of the Miner's Castle member, which can be traced throughout the entire outcrop belt of the Munising formation, shows only minor lateral variations. The entire section is exposed in the vertical walls of the Pictured Rocks between Sand Point and Miner's Castle, a distance of more than 6 miles. East of Miner's Castle is a well-defined western component dip so that the lower Chapel Rock member constitutes most of the section exposed in the Pictured Rocks cliffs and only the lower part of the Miner's

FIGURE 55

Miner's Castle—type locality for the Miner's Castle member of the Munising formation. Note the contact with the underlying Chapel Rock member just above the water level.

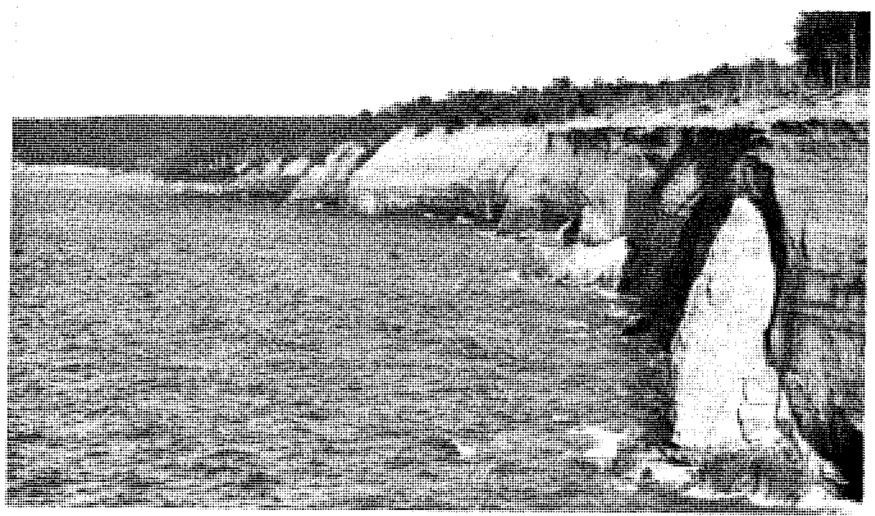


FIGURE 56

View of the eastern part of the Pictured Rocks cliffs which are composed almost entirely of the Miner's Castle member.

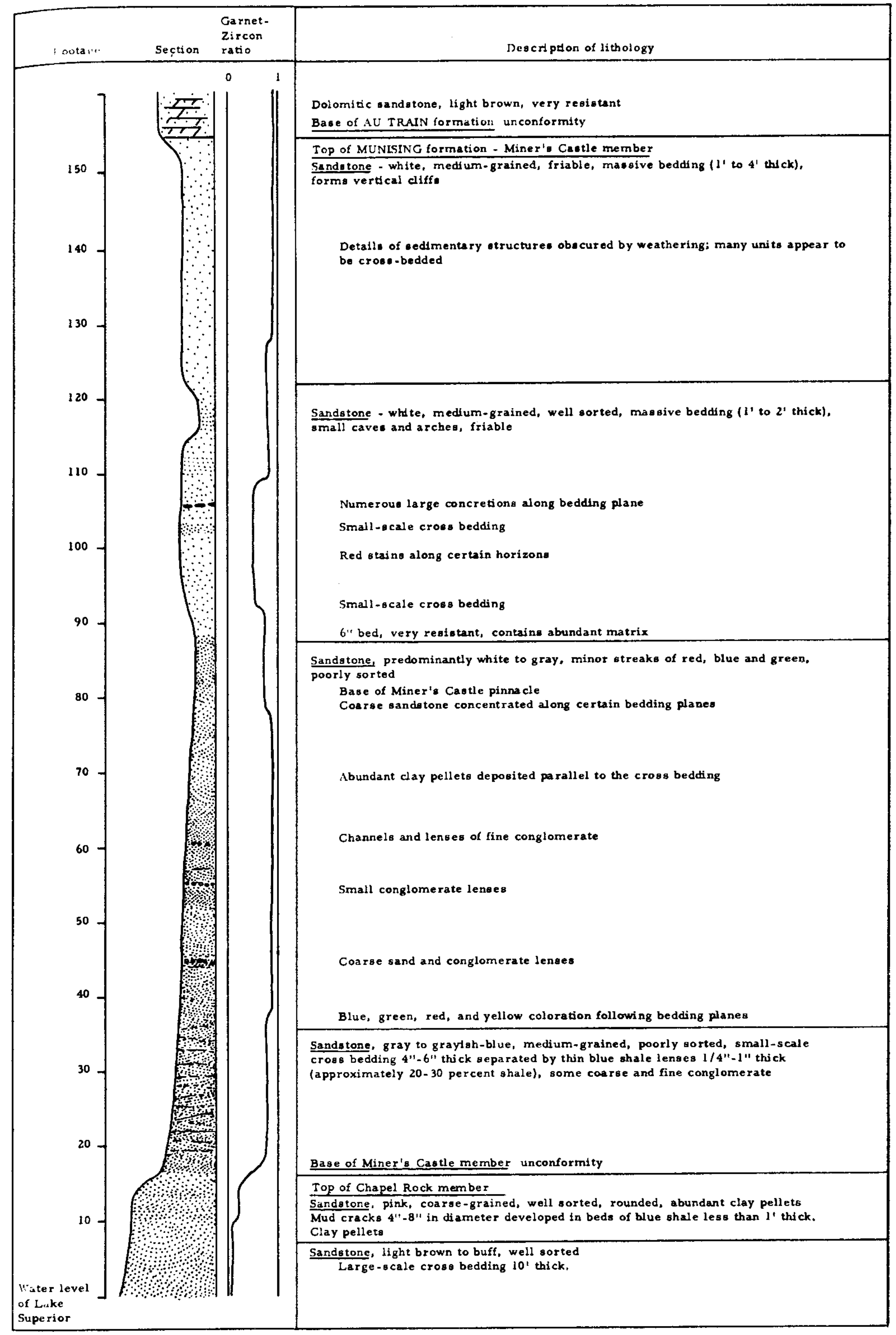


Figure 57. Columnar section of the Munising formation, Miner's Castle, NW 1/4, SW 1/4 sec. 3, T. 47 N., R. 18 W., Alger County, Michigan.

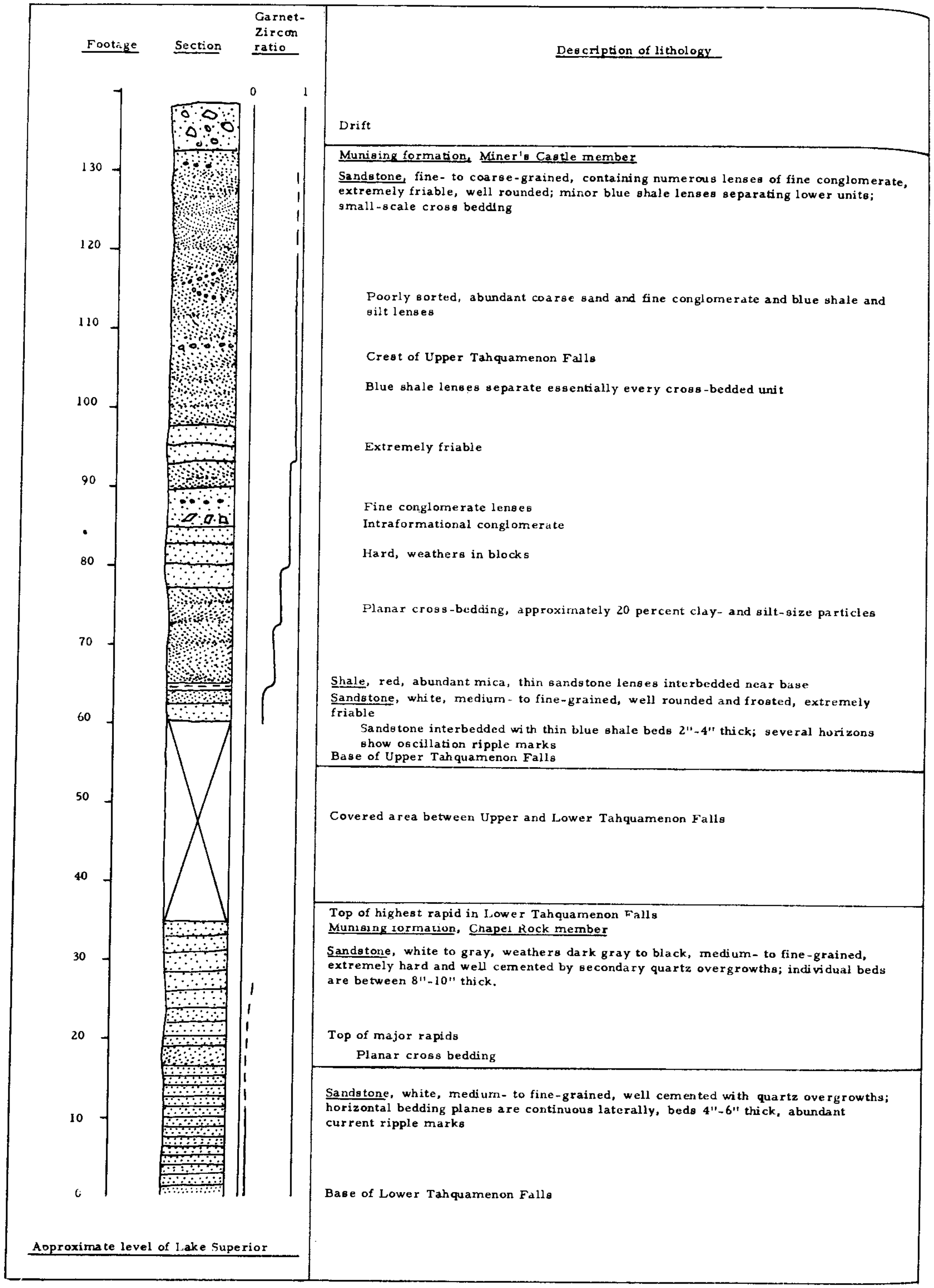


Figure 58 Columnar section of the Munising formation, Upper and Lower Tahquamenon Falls, Chippewa and Luce Counties, Michigan

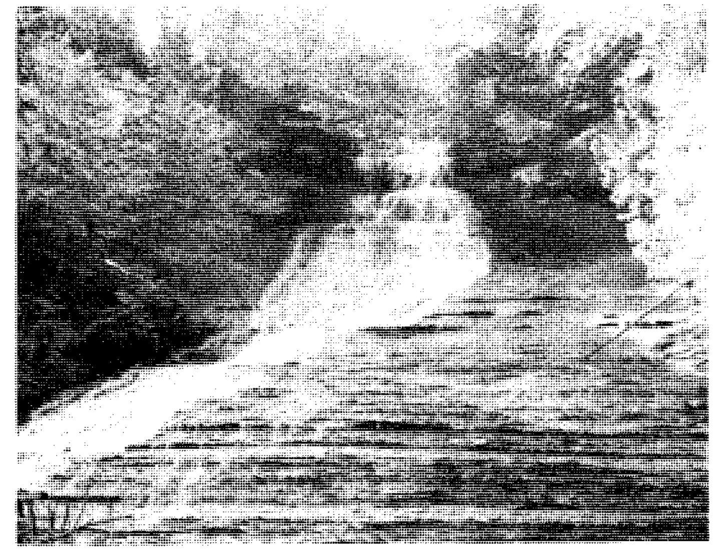


FIGURE 59

Laughing Whitefish Falls, Alger County, Michigan. An excellent example of the numerous waterfalls developed throughout Alger County, where the north-flowing streams across the cuesta developed on the resistant Au Train formation. Except for a thin cap rock of Au Train the entire exposed section is the Miner's Castle member. Note the thin irregular bedding developed by interbedded small-scale cross-laminated units and thin shale lenses.

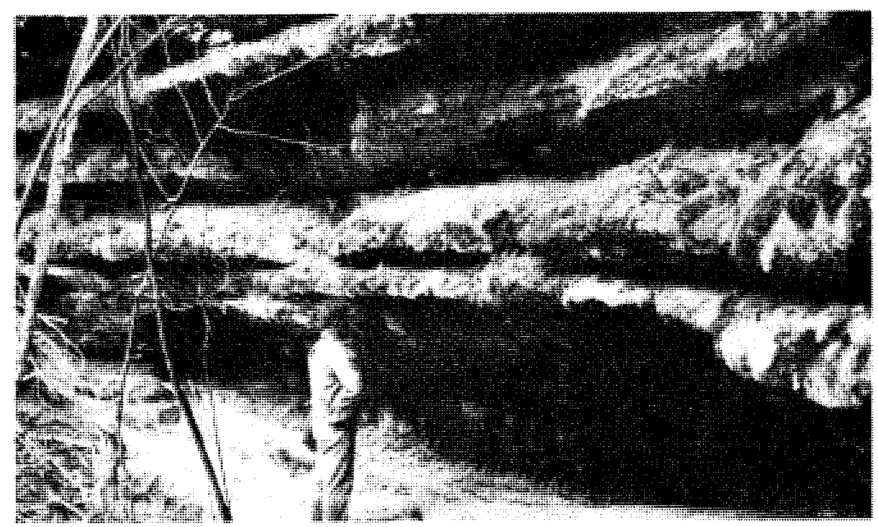


FIGURE 60

Outcrop of the upper Miner's Castle member in the Silver Creek valley. This outcrop is typical of the type of exposure developed high in the stream valleys just below the protective Au Train formation. Note the small caves developed along the bedding planes by weathering.

Castle member is exposed. Practically all of the Miner's Castle section is exposed at Tahquamenon Falls (fig. 58) and in the bluffs behind Grand Marais. Westward, at least the upper part of this member is exposed in all the major falls in Alger County and in numerous minor falls not shown on the map (figs. 59, 60). The distinctive lithology can also be recognized in all the rock cores drilled in Alger, Dickinson, Delta, and Menominee counties and in most of the outcrops in Dickinson County (Plate 4). Thus the Miner's Castle member is the most widespread unit of the Munising formation.

At the type locality and throughout most of the exposures in the Pictured Rocks, the Miner's Castle member is 140 feet thick. Some slight thinning is indicated to the east and west of Pictured Rocks. Thinning southward over the Northern Michigan Highland (fig. 30) is definite.

COMPOSITION

Quartz grains constitute over 95 percent of the Miner's Castle member, but minor amounts of feldspar were found in most samples studied. Chemical analysis by Bergquist (1937) indicates that thoughout Alger County silica occurs in the Miner's Castle member in amounts exceeding 98 percent. Most of the sand grains are considered to be igneous quartz, but chert fragments and quartzite grains are also common. Differential thermal analysis of the silt and shale lenses indicates that only minor amounts of clay minerals are in those units.

Authigenic quartz surrounding detrital grains is a common feature in the Miner's Castle member but the degree of secondary overgrowths differs considerably from place to place. In most samples only slight secondary enlargement of the detrital grains can be detected. Without much secondary quartz, which is the major cementing agent, the rock remains porous and friable. In a few areas in Dickinson County, however, authigenic quartz constitutes an appreciable amount of the quartz as it fills all the interstices and produces a very hard orthoquartzite. This extreme degree of secondary overgrowths is a local phenomenon, however, since many beds in the same section as the orthoquartzites are as friable and weak as the sandstone in Alger County. Calcite is also abundant in some beds, but is not widespread and is not considered an important cementing material. Authigenic pyrite is common in the middle of the Miner's Castle member and in some strata it is in sufficient amount to be easily recognized in a hand specimen.

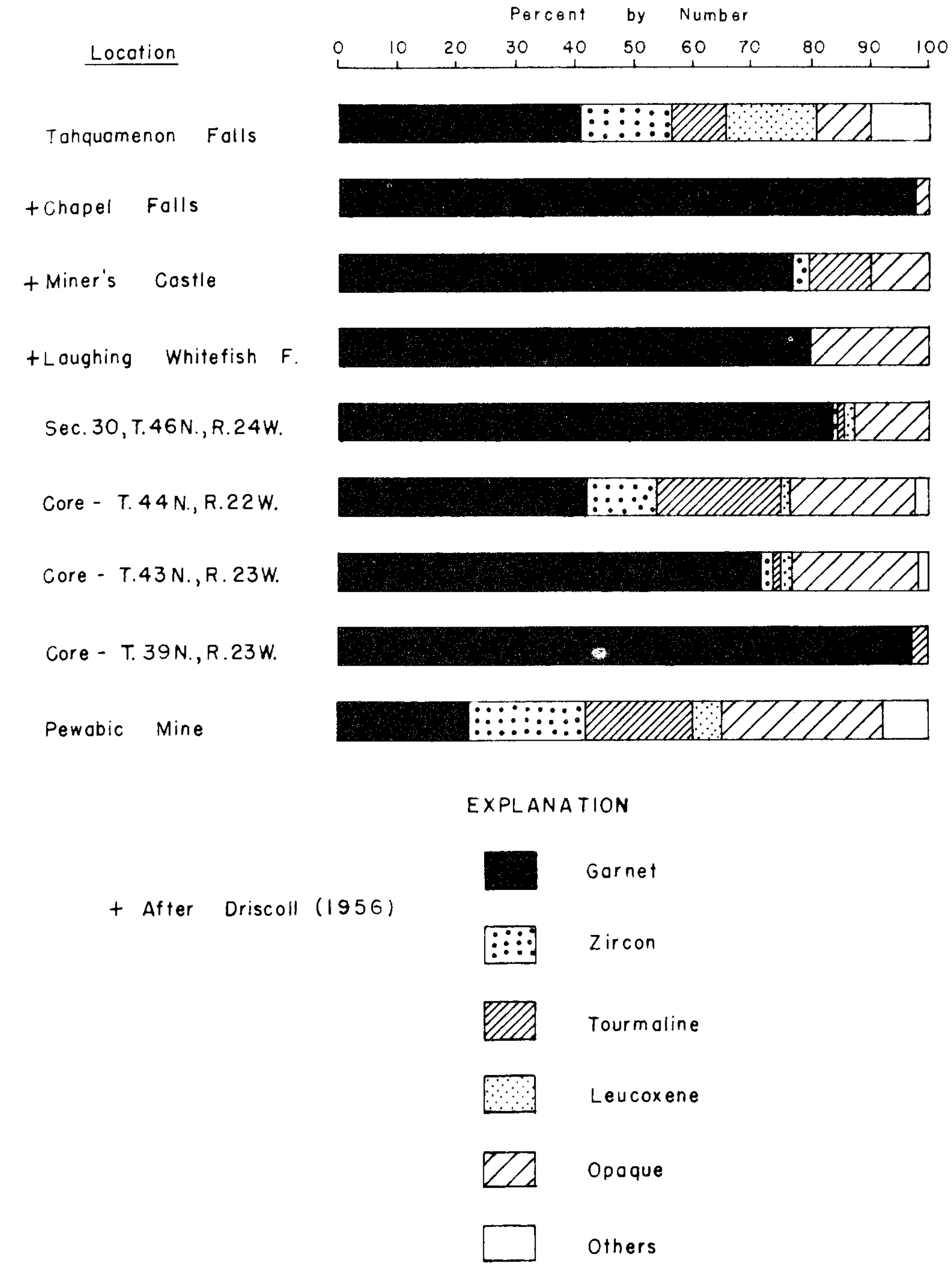


Figure 61. Heavy minerals of the Miner's Castle member

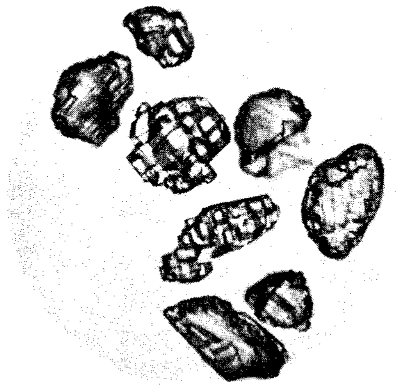


FIGURE 62, *A*
Garnet grains from the Miner's Castle member. Sample from drill-hole core from Dickinson County. X65.

FIGURE 62, *B*
Garnet grains from the Miner's Castle member. Sample from drill-hole core from Alger County. X63.

HEAVY MINERALS

Heavy minerals constitute between 1 and 2 percent by weight of the Miner's Castle member. The assemblage is very simple but highly characteristic and therefore it can be readily distinguished from the Chapel Rock member or the Jacobsville formation (compare figs. 5, 43, 61). The distinction is due to the abundance of garnet which constitutes 45 percent of the heavies near the base of the section and increases upward to nearly 100 percent near the top. The garnet is colorless to dark pink grains with surface features which resemble crystal faces. Few, if any, of the grains show any rounding or effects of abrasion. Instead numerous rectangular patterns aligned steplike completely cover many grains and give an extremely angular aspect (fig. 62). Many of the smaller grains have only a few large faces which approach a dodechedral pattern. Such angular grains in the samples in which all other minerals are extremely well-rounded indicate that the faces are authigenic.

Bramlette (1929, p. 336-337) describes a similar feature on garnets from Venezuela and attributes it to an etching by alkaline solutions since he found no tendency for development of crystal faces on the samples he studied. From the appearance of several dodechedral faces on many of the garnet grains in the Miner's Castle member, it is quite possible that these faces result from secondary overgrowths, although most of the surface features are probably the result of etching.

In addition to opaque minerals which constitute between 5 and 35 percent of the heavy minerals, zircon, tourmaline, and rutile are generally present in small amounts. The characteristics of these minerals are similar to the same heavy minerals of the Chapel Rock member.

The percentage of garnet in the Miner's Castle member differs but slightly throughout the entire Northern Peninsula of Michigan. The greatest variation is an increase in garnet vertically in the section; consequently, it is possible to estimate with fair certainty the position in the section by the percentage of garnet.

TEXTURE

The grain size of the Miner's Castle member ranges from that of fine conglomerate to silt and shale (figs. 63, 64). This extreme range in size is primarily between sedimentary units. It is very

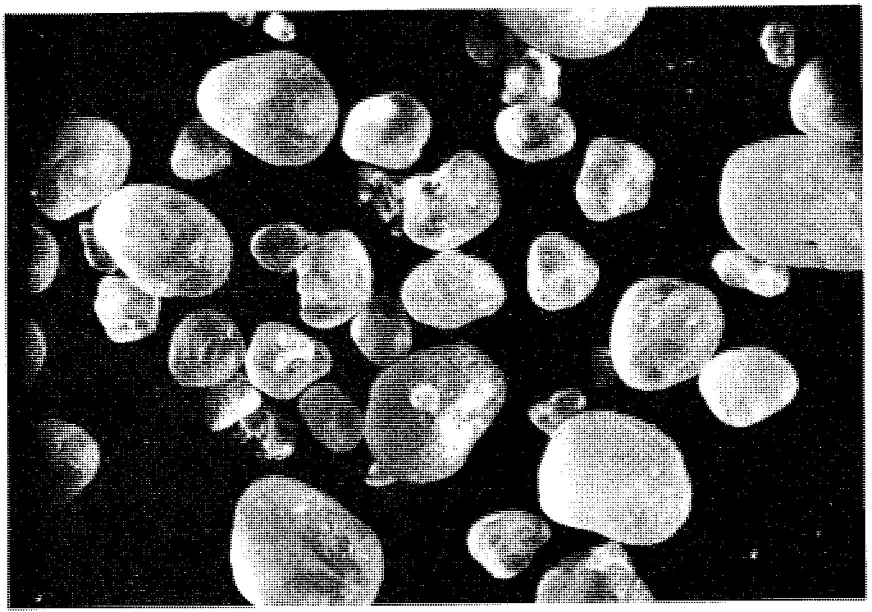


FIGURE 63
Photomicrograph showing the surface features, size, and sorting of a sample of the Miner's Castle member. Sample taken at Chapel Falls. X10.

common to find a medium- to fine-grained cross-bedded unit 4 to 6 inches thick overlain by a shale lens 1 inch thick, which in turn is overlain by a cross-bedded unit 4 inches thick in which coarse sand to fine conglomerate sizes predominate. Many of the individual sedimentary units, however, have a range in grain size from silt

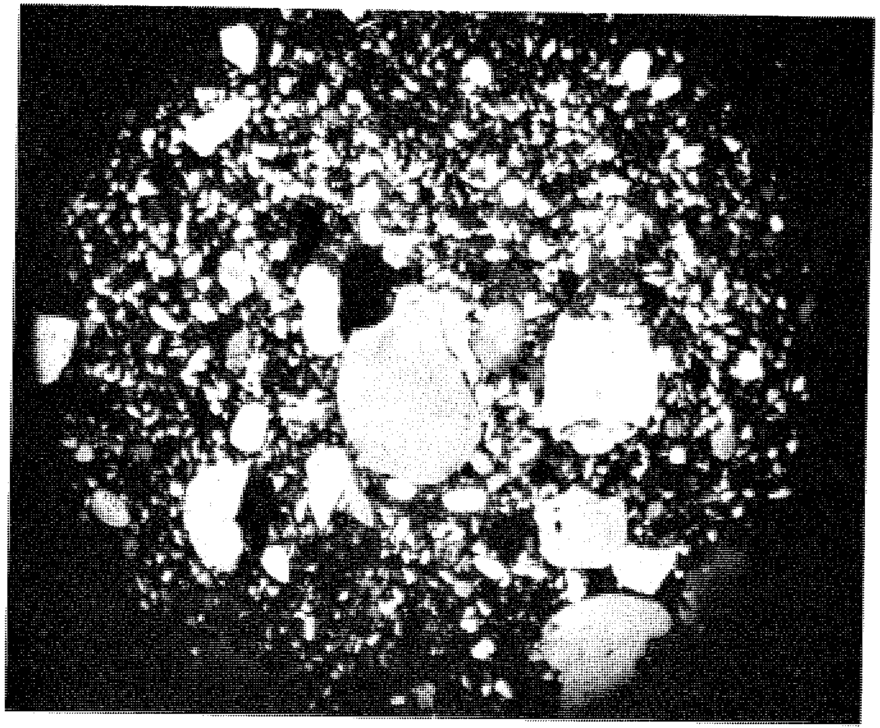


FIGURE 64

Photomicrograph showing the poor sorting and abundance of fine angular grains in the Miner's Castle member. Sample taken from Miner's Castle. Crossed nicols. X33.

to fine conglomerate. Coarse sand and fine conglomerate are concentrated near the base of most cross-laminations and in places even constitute the predominant grain size in several laminae of an otherwise medium- to fine-grained unit. The average grain size of most of the samples analyzed by the writer is from 1/4 to 1/2 millimeter in diameter, which agrees with the measurements obtained by Driscoll (1956) (fig. 65). Some samples, however, have an average grain size of less than 1/8 millimeter and others are greater than 1 millimeter. Thus, considered as a unit, the Miner's Castle member is very poorly sorted. The sorting of the individual sets of cross-strata is somewhat better, but poor sorting is characteristic even within the smaller units.

Sorting is much better in the upper part of the Miner's Castle member which is relatively free from shale and conglomerate. Most of the sand grains are well rounded, but the degree of rounding decreases rapidly with size decrease; therefore the fine sands and silts are characteristically subangular to angular.

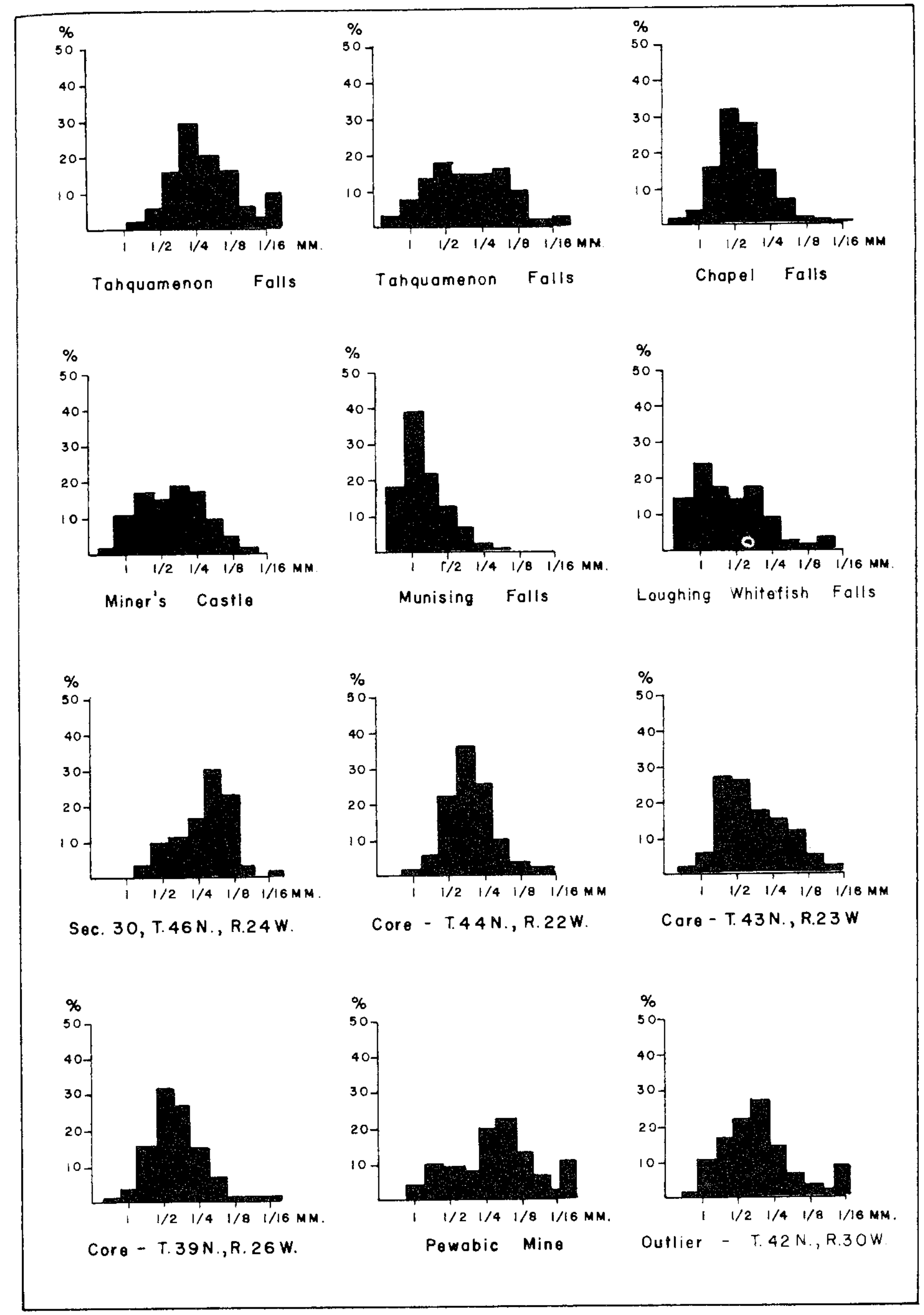


Figure 65. Grain - size distribution in typical samples of the Miner's Castle member

COLOR

In most outcrops the color of the fresh sandstone of the Miner's Castle member is primarily light-gray to white, but in Dickinson County the sandstone is buff to reddish-brown. A striking deviation from the gray to white color is produced by the abundant greenish-blue shale in the lower units. This gives a greenish-blue hue to that part of the section, whereas the upper units, devoid of shale, are characteristically light gray to white. Like the Chapel Rock member, surficial stains produce various shades of red, brown, yellow, and black in the major outcrops, especially in the Pictured Rocks cliffs.

SEDIMENTARY STRUCTURES

Cross-bedding

Small-scale cross-stratification constitutes the only type of bedding in the lower 90 feet of the Miner's Castle member and is present, but less abundant, in the upper units. This characteristic sedimentary structure is not a local phenomenon but is well exposed in every outcrop extending from Tahquamenon Falls to the outlier in Dickinson County and can even be recognized in drill-core samples. The dominant type of cross-bedding is the trough type of McKee & Wier (1953, p. 387), although planar cross-stratification is present in minor amounts in various localities. The smallest cross-bedded unit observed is only 2 inches deep, but the average size of the troughs is from 15 to 20 inches in width and 4 to 6 inches in depth (fig. 66, 67). The size of these structures is remarkably constant throughout the entire outcrop belt and only slight differences in size are found throughout the section.

In the basal part of the Miner's Castle member, thin shale lenses from ⅛ to 1 inch thick were deposited upon the undulatory erosional surface which separates each set of cross-strata. The section is thus characterized by alternating sets of small-scale cross-bedding and thin lenses of bluish-green shale. In many places small pellets of this shale are included in the cross-bedded units as clay galls in the inclined strata. Coarse sand and even fine conglomerate are commonly concentrated near the base of each set of cross-strata and grade upward into the finer sands. The amount of shale and coarse material decreases upward becoming practically absent in the uppermost units.

Bedding

Extensive horizontal bedding characterizes the upper part of the Miner's Castle member and can be traced laterally for several miles along the Pictured Rocks cliffs. The beds are from 2 to 8 inches

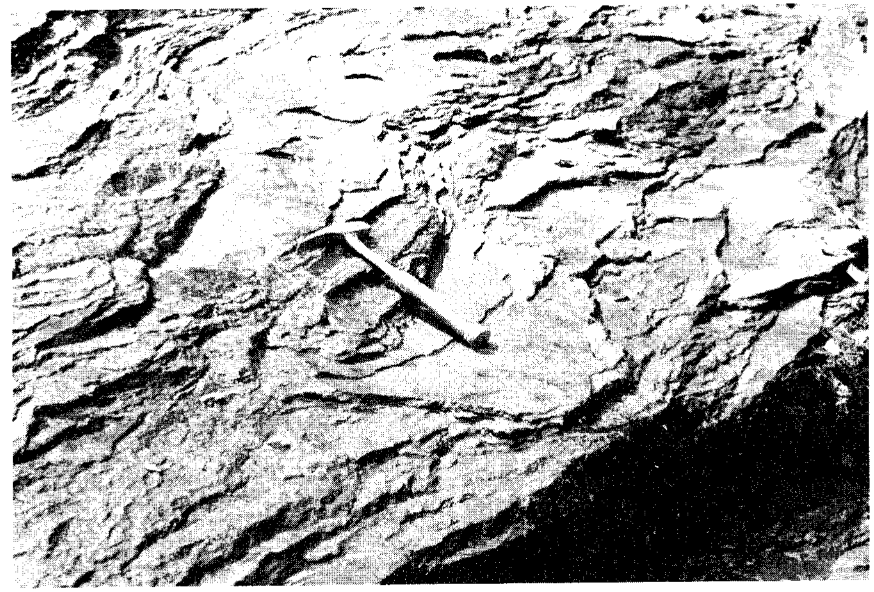


FIGURE 66

Small-scale trough cross-stratification in the Miner's Castle member, Laughing Whitefish Falls. Hammer handle points in the direction of inferred current flow.

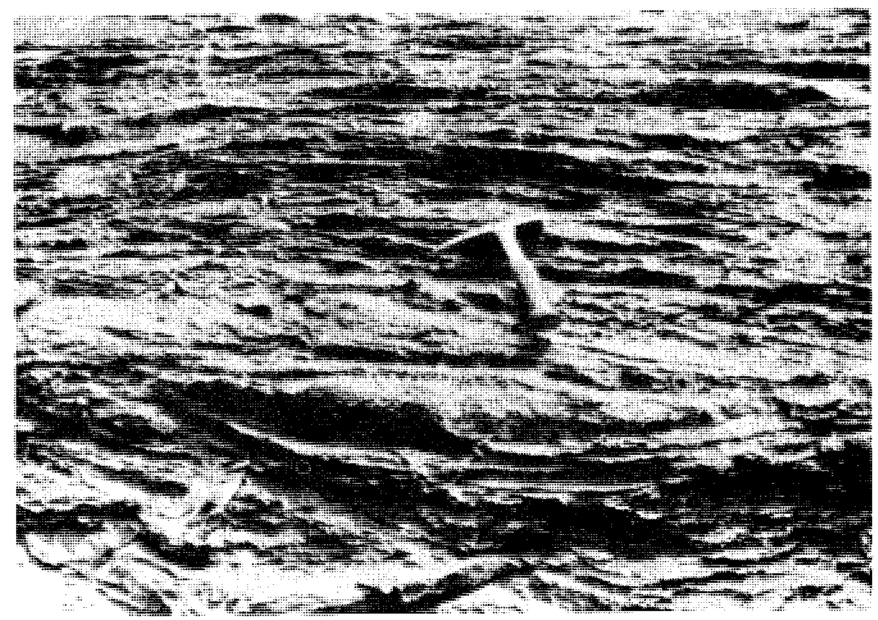


FIGURE 67

Channel filled with fine conglomerate in the Miner's Castle member, Laughing Whitefish Falls.

thick and although some appear to be massive, close examination reveals that they contain numerous sets of small-scale cross-bedding. Many of the horizontal beds are more resistant than the cross-bedded units and they stand out in relief in the outcrop. Others weather in a vertical face primarily because they are directly overlain by the resistant Au Train formation and not because they are resistant.

Mud Cracks

Numerous small, thin mud cracks not more than 3 inches in diameter have developed in the shale lenses which separate the small-scale cross-bedding. It is difficult to detect these structures on the vertical cliffs, but they are well exposed in the slopes developed at various waterfalls in Alger County.

Ripple Marks

Forty-four strata containing ripple marks were observed in the lower 50 feet of the outcrop at Laughing Whitefish Falls, but at other outcrops these structures are noticeably lacking. This may be due to the fact that Laughing Whitefish Falls is the only outcrop exposing the horizontal view of numerous bedding planes. The wave length and amplitude of the ripple marks differs considerably from stratum to stratum, indicating fluctuating conditions. Most ripple crests have been flattened by erosion; therefore, it is impossible to determine if the ripple marks are due to currents or to oscillation.

Concretions

Large elliptical concretions are concentrated along several horizons in the upper Miner's Castle member. The size of the concretions ranges from 3 inches in diameter to more than 1½ feet in their largest dimension. No indication of interruption in the bedding planes was observed near the concretions, although the sandstone is better cemented in their immediate vicinity.

PALEOGEOGRAPHY

Analysis of Cross-Bedding

A statistical analysis of the plunge direction of the small-scale trough cross-bedding in the Miner's Castle member was made following the general methods employed in studying the cross-bedding of the Jacobsville formation and the Chapel Rock member. The small size of the cross-bedding in the Miner's Castle member, however, makes sampling possible in much greater detail, and a complete understanding of the paleocurrents of that member.

Figure 68 shows the average direction and standard deviation of the readings taken at each exposure. The average plunge direction is between west-southwest in nearly all localities, indicating that throughout the entire Northern Peninsula the regional slope was remarkably consistent. The direction of this slope remained stable throughout the time required to deposit the Miner's Castle member, as the plunge direction is substantially the same throughout the section at Laughing Whitefish Falls (fig. 69). This marked change in the direction of regional slope during the deposition of the Chapel Rock and Miner's Castle members further indicates that the two members are separated by an unconformity. The Wisconsin arch and the Northern Michigan Highland, which were prominent source areas during Jacobsville and Chapel Rock time, were eroded down and almost completely covered with the Chapel Rock sediments. It is probable that regional tilting caused a regression of the Chapel Rock sea so that by the beginning of Miner's Castle time the regional slope was to the southwest. The transgression of the Miner's Castle sea was from the southwest, across the eroded Wisconsin arch and Northern Michigan Highland, but the major source area lay farther to the northeast in Canada. This change in principal source area clearly explains the change in heavy mineral suite from a high zircon-low garnet in the Jacobsville formation and Chapel Rock member to a high garnet-low zircon in the Miner's Castle member. The irregular Precambrian surface undoubtedly produced many islands in the Cambrian sea, but cross-bedding readings indicate that these islands had little effect upon the regional pattern of sedimentation. The influence of such islands was limited to the formation of conglomerate lenses around their flanks. Such a limited effect of an irregular surface upon local sedimentation suggests a rapid encroachment of the sea.

Ripple Marks

The numerous zones containing ripple marks at Laughing Whitefish Falls clearly indicate that the Miner's Castle member accumulated in a shallow-water environment. The average strike of the ripple marks is north-south, practically perpendicular to the direction of sediment transport (fig. 68) and indicates that the trend of the ancient shoreline was in a general north-south direction.

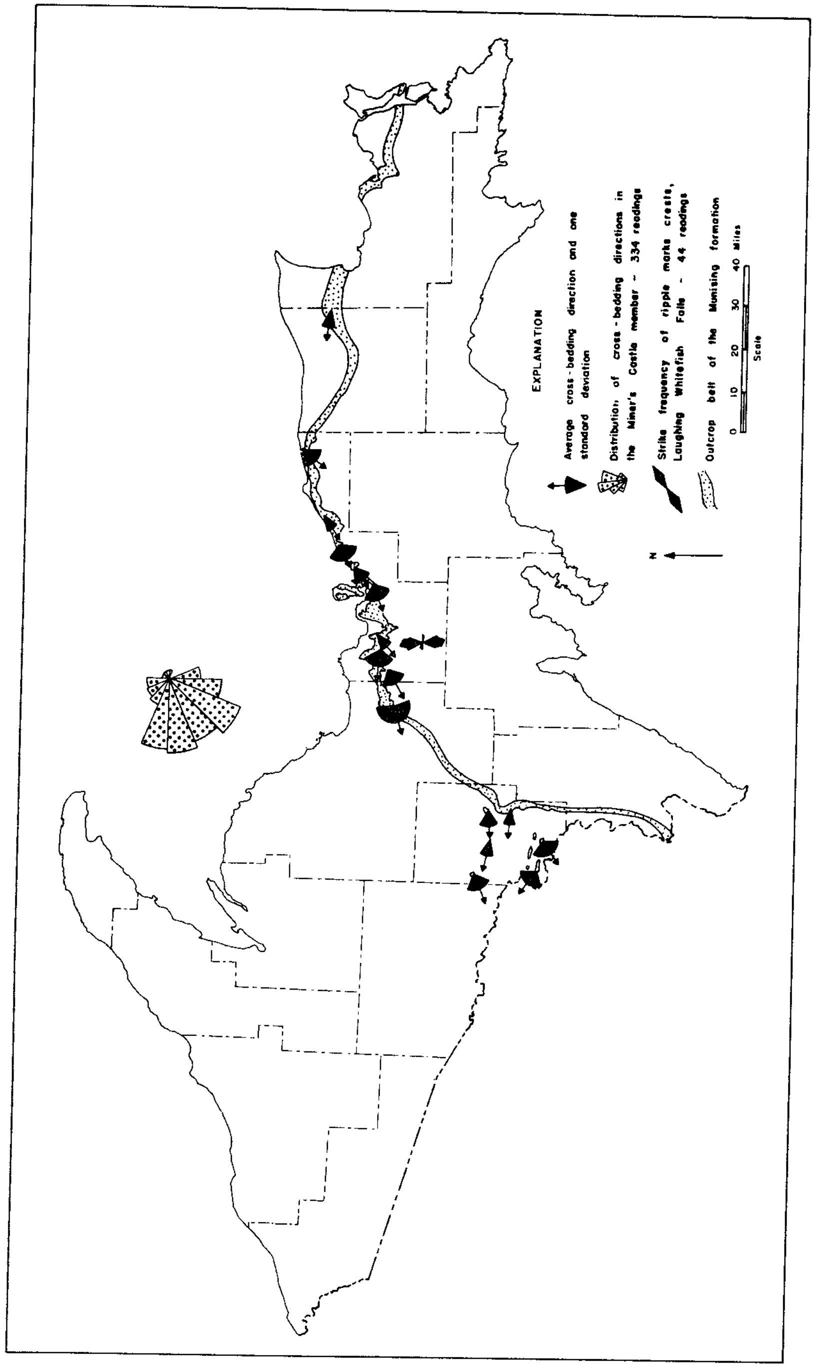


Figure 68 Cross - bedding directions in the Miner's Castle member

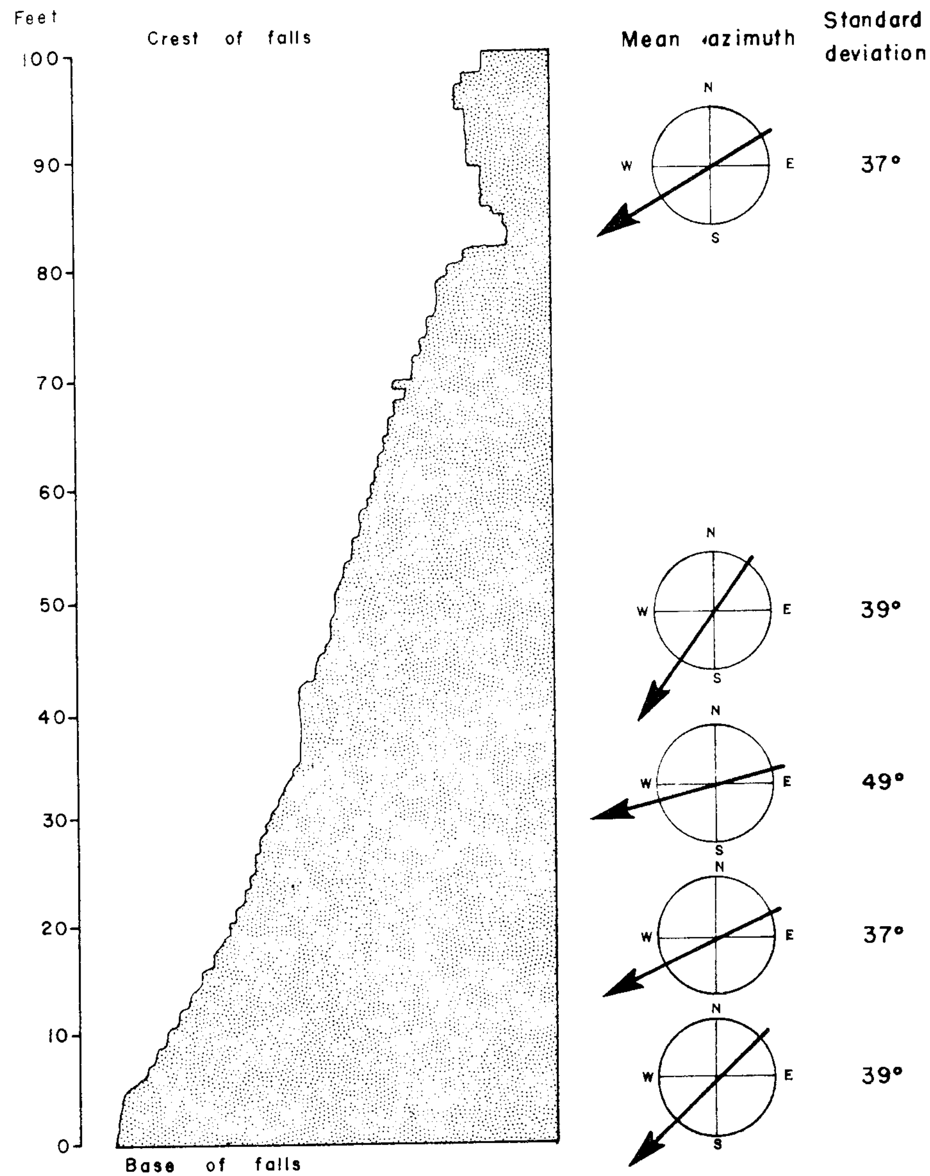


Figure 69. Cross - bedding directions through the section of the Miner's Castle member exposed at Laughing Whitefish Falls, Alger County, Michigan.

PLATE 5

Fossils from the Munising sandstone and the Au Train formation, all X1 except where noted. All specimens in Museum of Paleontology, University of Michigan.

Prosaukia curvicostata Ulrich and Resser

1. Cast of pygidium with complete posterior margin. Hypotype no. 33343. Munising sandstone. Ledges along north side of U. S. Highway 2, 0.1 mile east of junction with Foster City road, 0.5 mile north of Waucedah, Dickinson County, Michigan.
2. Cast of cranidium with well preserved glabella. Hypotype no. 33338. Munising sandstone. Ledges at top of abandoned Breen Mine, sec. 22, T. 39 N., R. 28 W., Dickinson County, Michigan.
3. Cast of free cheek. Hypotype no. 33337. Munising sandstone. Same locality as original of fig. 1.
4. Part of thoracic segment. Hypotype no. 33342. Munising sandstone. Same locality as original of fig. 1.
5. Unusually large pygidium. Hypotype no. 34811. Munising sandstone. Base of north side of abandoned Pewabic Mine, Iron Mountain, Dickinson County, Michigan.
6. Free cheek with incomplete genal spine. Hypotype no. 34812. Munising sandstone. Same locality as original of fig. 1.
7. Small glabella with well developed brim and fixed cheeks. Hypotype no. 34813. Munising sandstone. Same locality as fig. 1.

Lungulepis ? sp.

8. Broken dorsal valve. Figured specimen no. 34814. Munising sandstone. Same locality as original of fig. 1.
9. Small complete dorsal valve. Figured specimen no. 34815. Munising sandstone. Same locality as original of fig. 1. X2.
10. Incomplete ventral valve. Figured specimen no. 34816. Munising sandstone. Same locality as original of fig. 1.

Lungulepis pinnaformis (Owen)

11. Well preserved ventral valve. Hypotype no. 34817. Munising sandstone. Same locality as original of fig. 5.

Briscoia sp.

12. Right pleural lobe of pygidium showing ribs and smooth peripheral area. Figured specimen no. 29959. Munising sandstone. Same locality as original of fig. 2.

Undescribed trilobite genus and species

13. Part of cranidium showing smooth glabella. Figured specimen no. 33348. Munising sandstone. Same locality as original of fig. 1.

Idioniesus sp.

14. Pygidium showing smooth peripheral lobes. Figured specimen no. 34818. Munising sandstone. Same locality as original of fig. 5.

Prosaukia ? sp.

15. Glabella with occipital and two glabellar furrows. Figured specimen no. 34823. Munising sandstone. Same locality as original of fig. 1.
16. Free cheek with short genal spine. Figured specimen no. 34824. Munising sandstone. Same locality as original of fig. 1.

Idahoia sp.

17. Part of cranidium showing glabella and occipital ring with axial node. Figured specimen no. 33347. Munising sandstone. Same locality as original of fig. 1.

Michelinoceras ? sp.

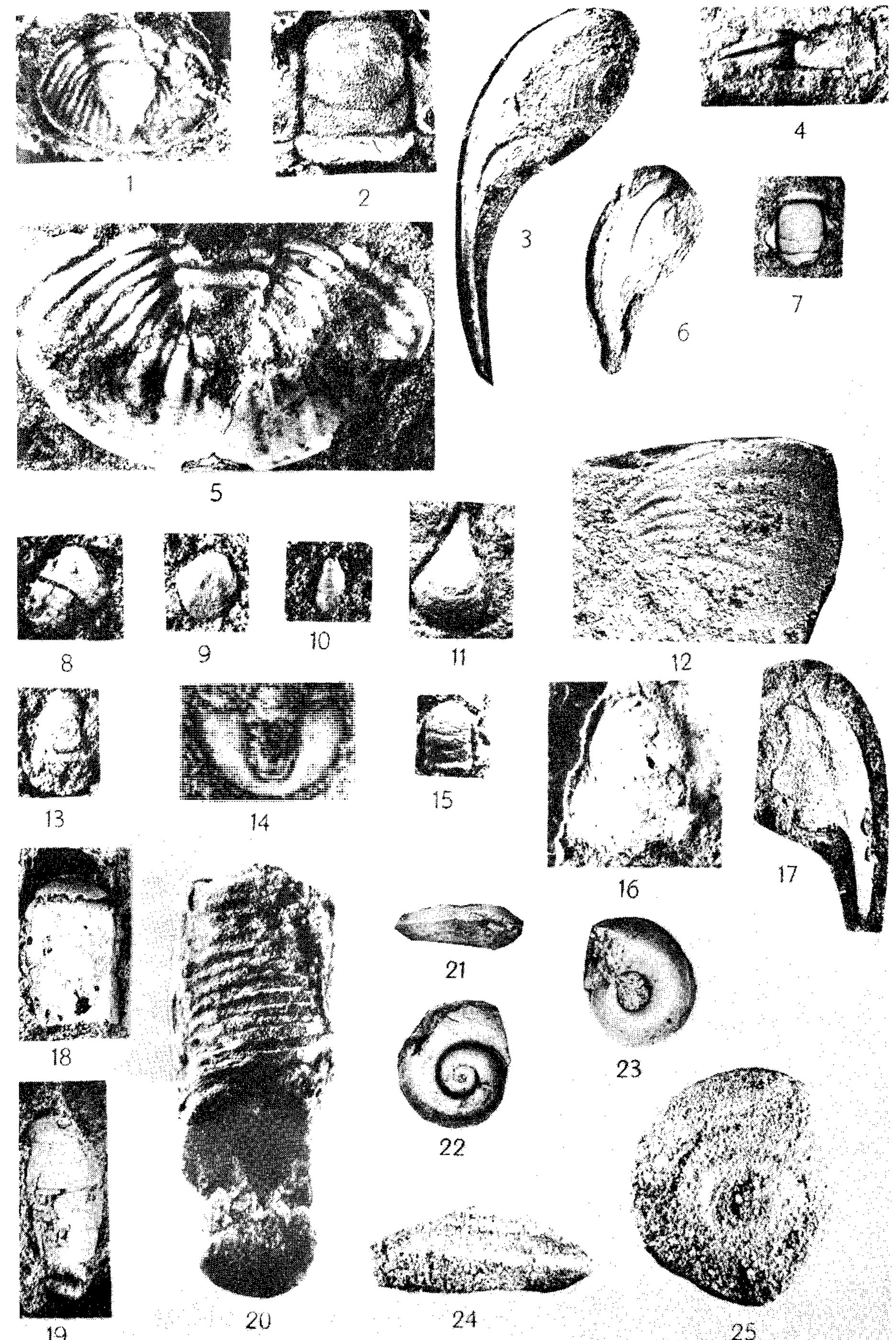
18. Part of living chamber. Figured specimen no. 34818. Au Train formation. Miner's Castle, Alger County, Michigan.
19. Part of cone showing closely set septa. Figured specimen no. 34819. Au Train formation. Same locality as original of fig. 18.
20. Fragment of cone of larger specimen. Figured specimen no. 34820. Au Train formation. Ledges at top of abandoned Austin Mine No. 2, NE¼, NE¼ SW¼, sec. 20, T. 48 N., R. 25 W. Marquette County, Michigan.

Liospira ? sp.

21-23. Lateral, dorsal, and ventral views of a specimen. Figured specimen no. 34821. Au Train formation. Same locality as original of fig. 18.

Ophileta ? sp.

24-25. Lateral and dorsal views of a specimen. Figured specimen no. 34822. Au Train formation. Sault Point on south shore of Whitefish Bay, Lake Superior, Chippewa County, Michigan.

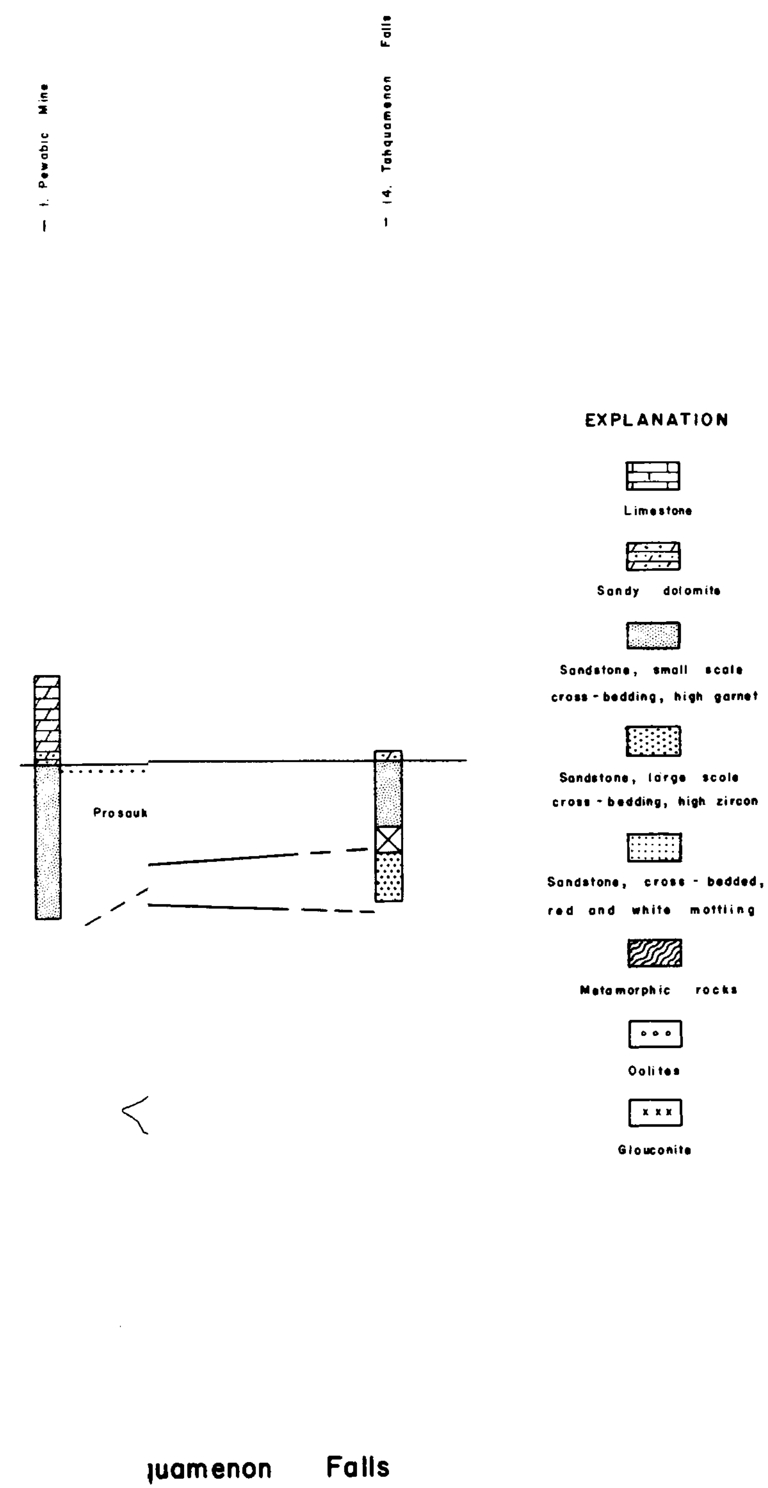


AGE AND CORRELATION

Fossils are extremely rare in the Munising formation, but a few trilobites and brachiopods have been found in the isolated outliers in Dickinson County. Stumm (1956) collected many trilobite fragments from a small roadcut a few hundred feet east of the junction of Highway 2 and the road to Foster City. From this material he was able to identify 4 trilobite genera and 1 species. The species is *Prosaukia curvicostata* and indicates that the zone may be correlated with the *Prosaukia-Ptychaspis* zone of the standard Cambrian section, equivalent to the upper part of the Middle Franconia formation of the type area of the Upper Cambrian St. Croixan series.

The *Prosaukia* zone was recognized by the writer in the north side of the Pewabic mine at Iron Mountain and again in a drill-hole core from sec. 7, T. 39 N., R. 26 W. In both sections the *Prosaukia* zone is 5 feet below the contact with the overlying Au Train formation. The section exposed in the Pewabic mine can be correlated with the Miner's Castle member exposed along the Pictured Rocks. The small-scale cross-bedding and high-garnet heavy mineral suite so distinctive of the Miner's Castle member is readily recognized in all the measured sections and drill-cores between the two areas (fig. 70). The control for such a correlation has been greatly increased by the cores drilled through the Paleozoic section by several iron companies. From Munising to Iron Mountain the distance between an outcrop or core-drill site in which the complete Cambrian section and at least 25 feet of the Au Train formation is available averages 9 miles and does not exceed 25 miles. Inasmuch as the uppermost section of the Cambrian in Dickinson County can be correlated with the upper part of the Middle Franconia, the Miner's Castle member must be equivalent to at least the middle and probably the lower Franconia. The upper Franconia, Trempealeau and lower Ordovician are thus missing in Northern Michigan and are overlapped by the middle Ordovician Au Train formation.

The unconformity which separates the Miner's Castle and Chapel Rock members suggests the equivalence of the Chapel Rock member to the Dresbach formation. This correlation is strongly supported by the remarkable similarities in heavy minerals between the Dresbach and Chapel Rock member. Both are high in zircon and low in garnet. This is strikingly different from the definite high-garnet sands of the Franconia formation and Miner's Castle member.



Au Train Formation

INTRODUCTION

Throughout the Northern Peninsula the Munising formation is overlain by a sequence of thin- to medium-bedded sandy dolomites and dolomitic sands which contain many thin lenses of pure quartzose sandstone. Confusion has existed concerning the age and nomenclature of these rocks because the outcrops which expose them are very small and isolated and only a few poorly preserved fossils have been reported. Even locally these rocks have not been studied in detail. No single outcrop exposes the complete section and very little is known about the upper and lower contacts.

Rominger (1873) considered this sequence of rocks to be equivalent to the "Chazy" and "Calciferous" groups of the New York system on the basis of stratigraphic position and lithologic similarities. In 1900, Van Hise and Bayley (1900, p. 11) proposed the term "Hermansville" for the "limestones" which overlie the "Lake Superior Sandstones" in the Menominee district and subsequent workers have used this term for the "Ozarkian" of Northern Michigan. The only description given by Van Hise & Bayley (1900, p. 11) is that "the Hermansville limestone is a coarse grained sandstone with abundant calcareous cement, in alternation with pure dolomite or sometimes oölitic beds." The only descriptions of a type locality is that "the limestone may be seen near the top of the hill east of Iron Mountain, on the bluff north-east of Norway, and at several places on the hills north of Waucedah."

Grabau (1906, p. 583) suggested that the term "Aux Trains" would be a much better name since a considerable section is exposed at Au Train Falls and no type section was given by Van Hise and Bayley. Bergquist (1937), however, used the term "Hermansville" in his studies on the Cambrian-"Ozarkian" contact in Alger County and again in his publication in 1930, but Thwaites (1943, p. 510) and Driscoll (1956, p. 20) favored dropping the term. Inasmuch as no type locality nor type section was presented by Van Hise and Bayley or by any subsequent workers for the term Hermansville, and since the type of lithology and age of the rocks referred to by that term has been so vague and confused, the writer feels that the term is so poorly defined that it should be abandoned.

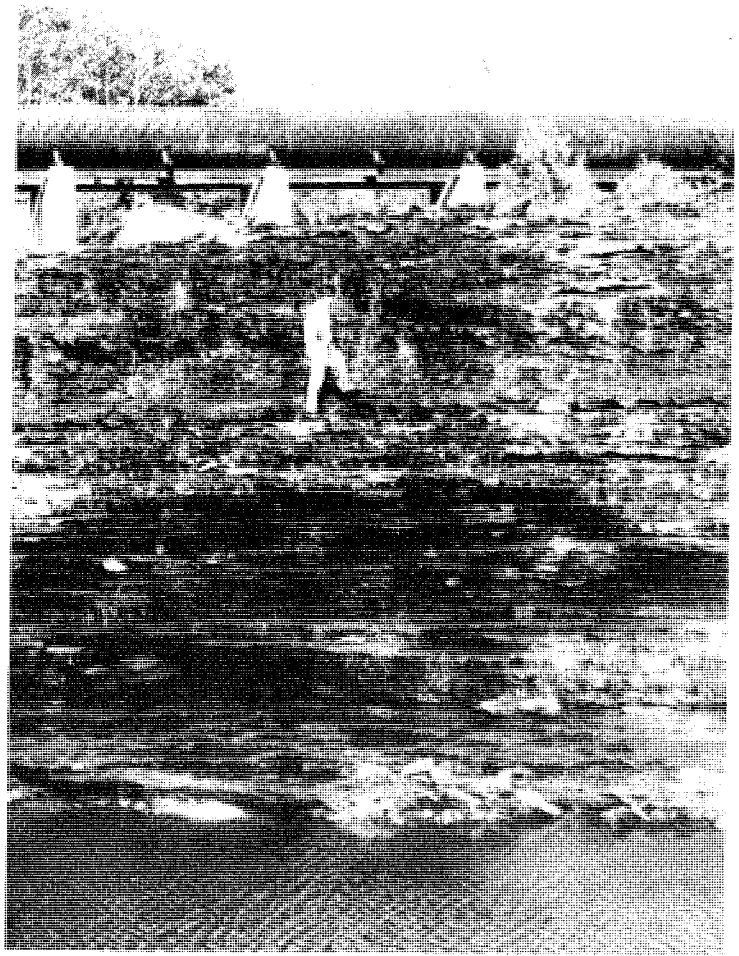


FIGURE 71

Upper Au Train Falls—upper part of type locality for the Au Train formation.

In recent exploratory drilling by several iron companies, complete cores of the Paleozoic section were obtained from several localities in Alger, Delta, and Menominee counties. The cores and sections measured in the field indicate that a section of rock approximately 300 feet thick separates the Ordovician Black River and Cambrian Munising formations. The writer, following Grabau, proposes that "Au Train" formation be used for these rocks, because the best exposures and thickest sections are at Au Train Falls in Alger County (figs. 71, 72, & 73).

FIGURE 72

Lower Au Train Falls—lower part of type locality for the Au Train formation.

GENERAL DESCRIPTION

The Au Train formation is a relatively resistant formation that forms the cap rock of the outermost northern cuesta of the Michigan Basin. The escarpment is prominent in Alger County, but is obscured to the south and west by a thick drift cover. Isolated outcrops are at Sault Point, Tahquamenon River about a quarter of a mile above the upper Falls, and in the bluffs approximately 1 mile south of Grand Marais. The Au Train formation is exposed at the top of Chapel Falls and forms the uppermost units of the Pictured Rocks between Miner's Castle and Sand Point. Isolated patches are also at the highest elevation on Grand Island (Plate 2). West of Munising the escarpment has receded several miles south of the shore, but it maintains its bold character and provides a drop of approximately 100 feet for many of the water falls of Alger County. In Marquette County, the escarpment swings southward and is lost under the greater drift cover in that area. In many places the Au Train formation overlaps the Munising and rests directly upon Precambrian rocks. Numerous isolated outcrops in Marquette and Dickinson counties are either erosional

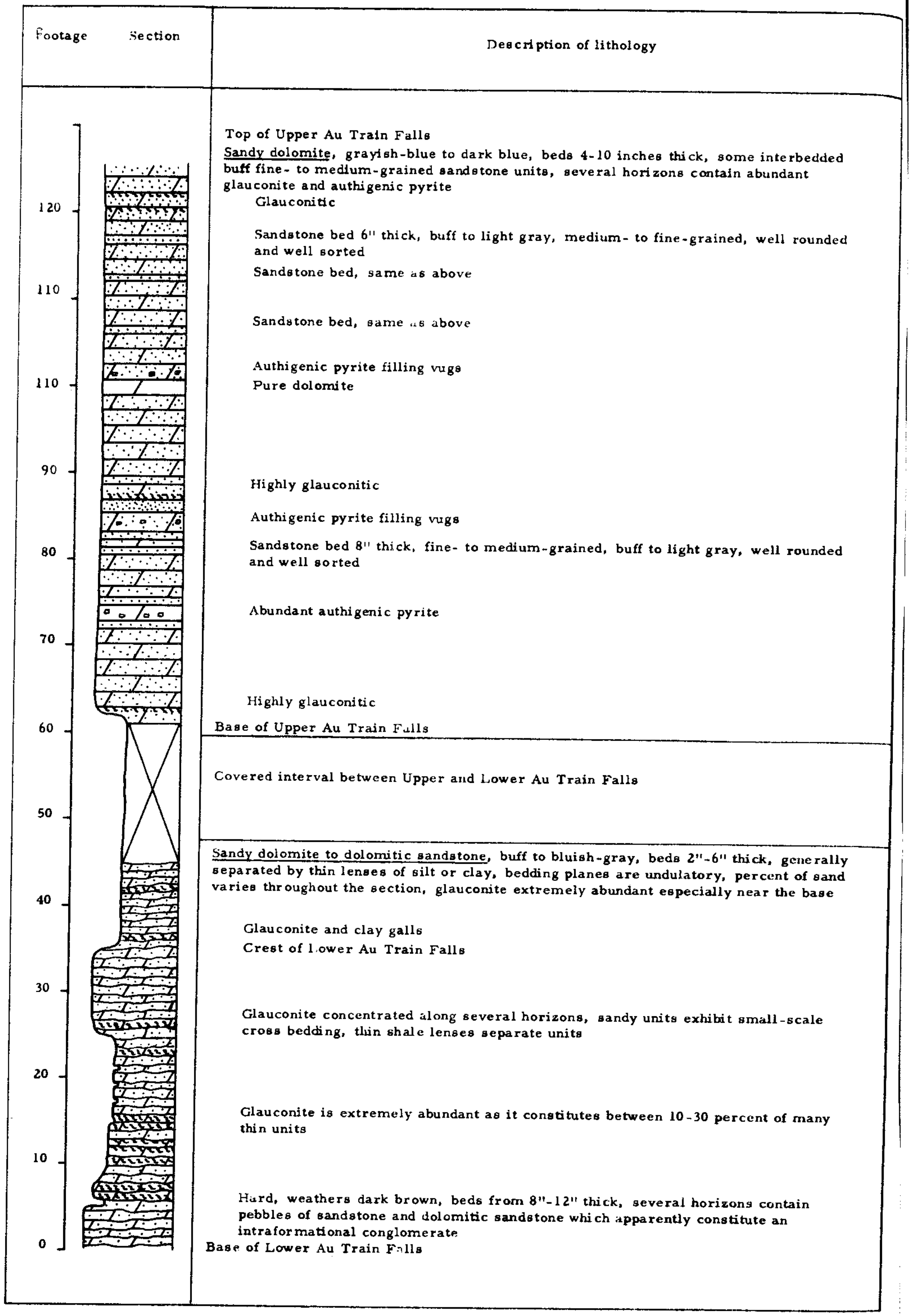


Figure 73 Columnar section of the Au Train formation, Au Train Falls, Alger County, Michigan

remnants resting on Munising or Precambrian or isolated patches poking through the drift. Subsurface data indicate that the Au Train formation extends throughout most of the Northern Peninsula. However, a definite facies change is noted southwestward with an increase in dolomite.

The basal contact of the Au Train formation is easily recognized by the lithologic break from a hard dolomitic sand to the soft, friable quartzose sand of the Munising formation. The upper contact, however, is much more difficult to recognize. Core samples indicate that the transition from dominant Au Train to typical Black River lithology takes place in an interval of less than 20 feet. The maximum thickness of the Au Train as indicated in core samples is slightly more than 300 feet, but only the lower 125 feet is exposed at Au Train falls. Good thick exposures of the upper part of the section have not been found.

The dominant lithology of the Au Train formation is a medium-to fine-grained dolomitic sandstone. The ratio of sand grains to dolomite throughout the section differs considerably, as some beds are pure dolomite with only an occasional floating sand grain, and other beds are pure sandstone.

Lithologic variation in the Au Train makes it convenient to divide the formation into two members. The lower member is approximately 100 feet thick and is characterized by abundant glauconite. The glauconite occurs as disseminated grains in the dolomitic sand, and in thin dark-green beds in which glauconite constitutes over 35 percent of the mineral composition. The thin beds of concentrated glauconite are more abundant near the base of the section at 3 to 12 foot intervals. Higher in the glauconitic member the beds of concentrated glauconite are less numerous. Locally individual glauconite zones may be used as key beds for correlation (fig. 70). The bedding in the glauconite member is thin and undulatory and accentuated by numerous shale lenses and blebs. The color of the glauconitic member is buff to brownish-gray; but where glauconite is extremely abundant a speckled green or solid dark-green color predominates. Some of the more dolomitic beds are characteristically blue to bluish-gray. Much of the weathered surface of the lowermost beds is a definite brown color which stands out in contrast to the white Munising formation along the Pictured Rock cliffs.

In the upper member of the Au Train formation glaucionite is completely absent and thin sandstone lenses are numerous. The thickness of the sandstone lenses measured in drill-cores ranges from ½ to 2 feet. Sandstone beds more than 10 feet thick are present, however, but cannot be traced with any confidence from one core to the next.

The lenticular sandstone is remarkably similar to the sandstone of the upper part of the Miner's Castle member. It is characteristically medium- to fine-grained and contains a few thin lenses of blue to greenish shale along the bounding surfaces of small-scale cross-bedded units. Indeed, exposures of these sandstone beds are easily mistaken for the Miner's Castle member. Numerous thin beds of oölites are also in the upper section. Some oölite beds can be correlated from core to core, but they do not appear to be of value for regional correlation (fig. 70). Authigenic pyrite is very common throughout the section, some large vugs are completely filled by it. Driscoll (1956, p. 39) reports that, like the Miner's Castle member of the Munising formation, the dominant heavy mineral in the Au Train formation is garnet, so it is very possible that the Munising was a part of the source area for the sand.

AGE AND CORRELATION

Oetking (1951, p. 27) reported an impressive suite of Black River fossils from the Au Train formation collected from a road cut exposure less than ½ mile south of Miner's Castle. The writer was unable to find specimens of all the species reported by Oetking, but some well-preserved gastropods and cephalopods of Middle Ordovician age were found (Plate 5) indicating the age of the Au Train formation to be lowermost Black River. Thus lower Ordovician and parts of the upper Cambrian are missing in the area covered by this study.

Structure

GENERAL ATTITUDE OF THE BEDDING

The Jacobsville formation is relatively undisturbed except near the Keweenaw fault where it has been dragged toward a vertical position. In most of the outcrops along the shore the Jacobsville dips from 1 to 6 degrees to the north or northwest. Dips to the south and east were observed in some localities but they are not common.

In addition to the drag folding near the Keweenaw fault, the Jacobsville has undergone considerable deformation in the vicinity of Limestone Mountain. Unfortunately exposures are not sufficient to determine the details of the structure over a broad area. Approximately 1½ miles east of Limestone Mountain, along the road between sections 17 and 20, T. 51 N., R. 35 W., the Jacobsville strikes N. 40° E. and dips 62 degrees to the northwest, but along the same section line ½ mile west of Limestone Mountain the Jacobsville dips 20 degrees to the east. Several other outcrops a mile farther west were reported by Roberts (1940) in which the Jacobsville strikes northeast and dips 20 to 50 degrees west. It therefore seems quite possible that the syncline at Limestone Mountain is a major structural feature and is flanked on the west by an anticline of equal or greater magnitude. An anticline, monocline, or fault may be east of the syncline at Limestone Mountain since the Jacobsville is horizontal in the shore cliff exposures just north of Baraga.

Although both the Jacobsville and Munising formations are relatively undisturbed their regional attitude differs. The Munising formation constitutes the outermost cuesta of the northern Michigan basin and the dip is predominantly to the south and southeast (fig. 74). The southern dip is difficult to detect in the field as it exceeds 2 degrees in a very few places. Numerous elevations established on the top of the Munising formation, however, indicate that the low dip toward the center of the Michigan basin is remarkably constant and averages between 20 and 40 feet per mile (fig. 75). The only area in which the Munising has been subjected to appreciable deformation is at Limestone Mountain where, together with the Jacobsville and sediments as young as Devonian, it has been folded into a tight syncline.

FIGURE 74

View along the Pictured Rocks showing the Munising formation dipping to the south at a low angle.

KEWEENAW FAULT

The Keweenaw fault can be traced for a distance of more than 100 miles and is considered one of the major structural features in Northern Michigan. It strikes in a general northeast direction and dips 20 to 70 degrees northwest (Butler, Burbank, *et al.*, 1929, p. 48-49). Numerous branches deviate from the general strike, however, and in many places the fault is offset by later cross-faulting. Extensive deformation of the Jacobsville strata, resulting from drag along the Keweenaw fault, can be observed in many of the stream valleys which cut the scarp. At the Wall Ravine the Jacobsville is almost vertical but the dips decrease eastward; within a few hundred yards the formation is almost horizontal and undisturbed (fig. 76). Considerable drag along the Keweenaw fault was observed downstream from Victoria Falls but the Jacobsville is practically undisturbed farther north along the fault contact at Houghton and Hungarian Falls.

The age and amount of displacement of the Keweenaw fault has been a matter of conjecture for many years. The amount of dis-

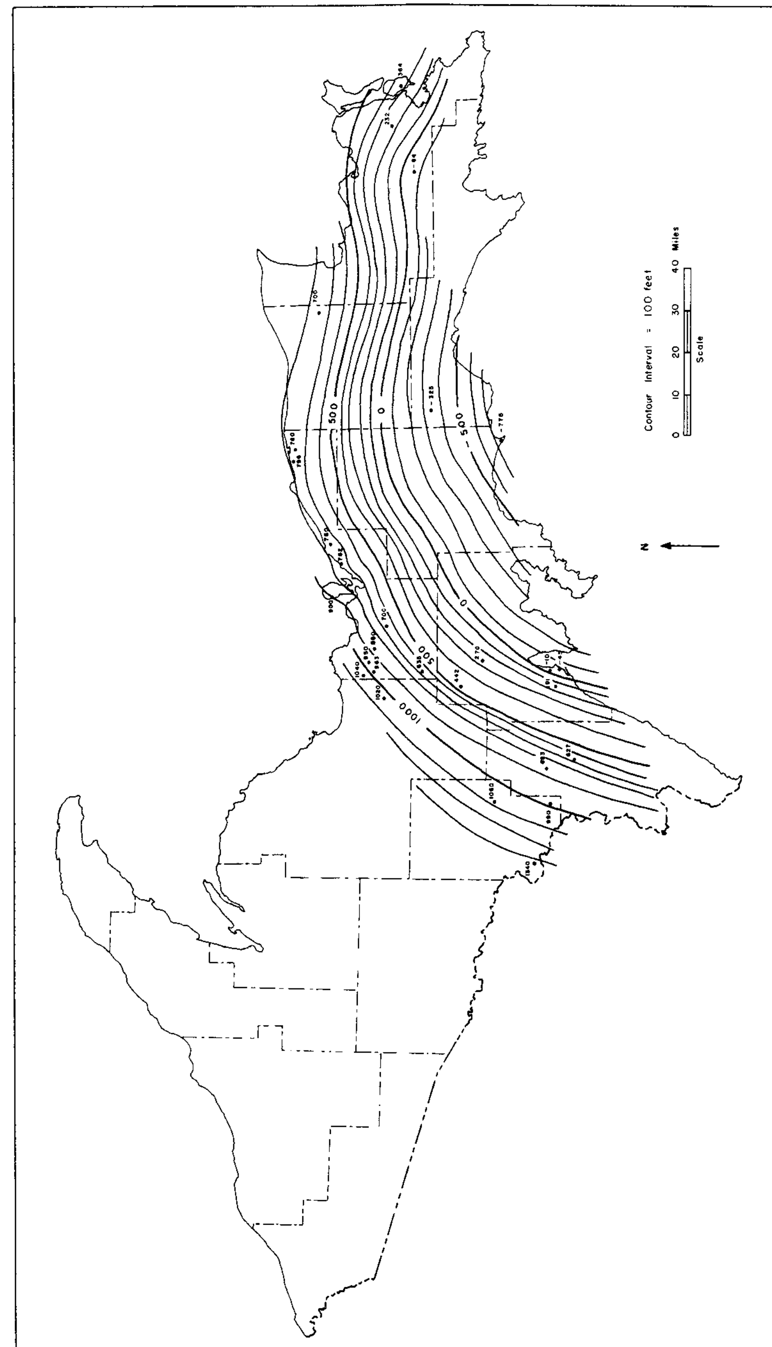


Figure 75. Structure contours on the top of the Munising formation

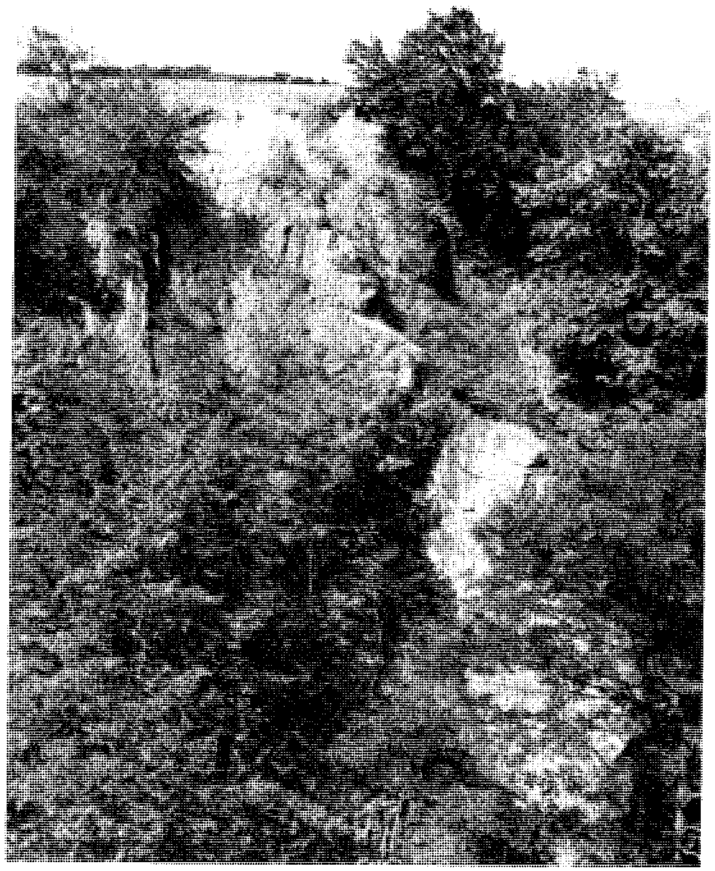


FIGURE 76

View of the Wall Ravine near Laurium, Houghton County, showing the Jacobsville sandstone in a nearly vertical attitude resulting from drag along the Keweenaw fault. The fault is to the right of the photograph and the younger Jacobsville units are to the left.

placement necessary to bring the middle Keweenawan basalts in contact with the Jacobsville is in the order of 3 miles (Butler, Burbank, *et al.*, 1929, p. 50) and has led some geologists to believe that a large amount of displacement took place prior to the deposition of the Jacobsville. It has also been proposed (Irving & Chamberlain, 1885, p. 98-100) that the present fault scarp existed as a shore cliff during Jacobsville sedimentation and that the post-Jacobsville movement was only minor.

In considering the age and movement of the Keweenaw fault three important facts should be kept in mind: (1) the direction of sediment transport during Jacobsville time, as determined by cross-

bedding measurements, was to the north and the source of the Jacobsville sediments was to the south. This indicates that the Keweenaw fault scarp did not constitute the shore line and we have no real evidence for pre-Jacobsville movement; (2) the Jacobsville lies unconformably upon tilted Keweenawan basalts as shown in the exposures at Sturgeon River. This suggests that the Keweenawan series was tilted and eroded before the Jacobsville was deposited and that the minimum displacement on the fault is, therefore, not the thickness of the upper Keweenawan rocks but only the thickness of the Jacobsville. This thickness is in the order of magnitude of 2,000 feet; (3) the predominant structural trends of the Jacobsville at Limestone Mountain parallel the Keweenaw fault, suggesting that the folding in the Limestone Mountain area is related to the compressional forces which caused the faulting.

These facts indicate that the age of the Keweenaw fault is post-Jacobsville and probably post-Devonian since Devonian rocks are involved in the folding at Limestone Mountain. The angular unconformity at Sturgeon Falls further indicates that the displacement necessary to bring the Jacobsville in contact with Middle Keweenawan lavas was only a few thousand feet.

NORMAL FAULTING

Thirteen minor normal faults striking between N. 15° E. and N. 20° E. were mapped in the Keweenaw Bay area. These faults have an average displacement of 10 feet and form small horsts and grabens. Their strike, movement, and location near the Keweenaw fault indicate that they probably resulted from the release of the stress which caused the Keweenaw thrust. Minor copper mineralization was found along the fault plane at Pequaming Point and along several points east of Skanee. Normal faults with small displacement were also observed at Au Train Island and at the east end of Pictured Rocks (figs. 77, 78).

MINOR THRUST FAULTS

Small thrust faults are exposed on the east and west sides of Grand Island where clastic dikes are displaced from 1 to 3 feet (fig. 79). The faults strike east-west and dip 4 degrees to the north with the direction of displacement S. 15° W. The fault plane follows a shale bed and is not far below the contact of the Jacobsville and the glacial drift. It is therefore quite probable that these faults are not the result of tectonism, but are drag effects produced by the Pleistocene glacier. Other minor thrust faults were re-

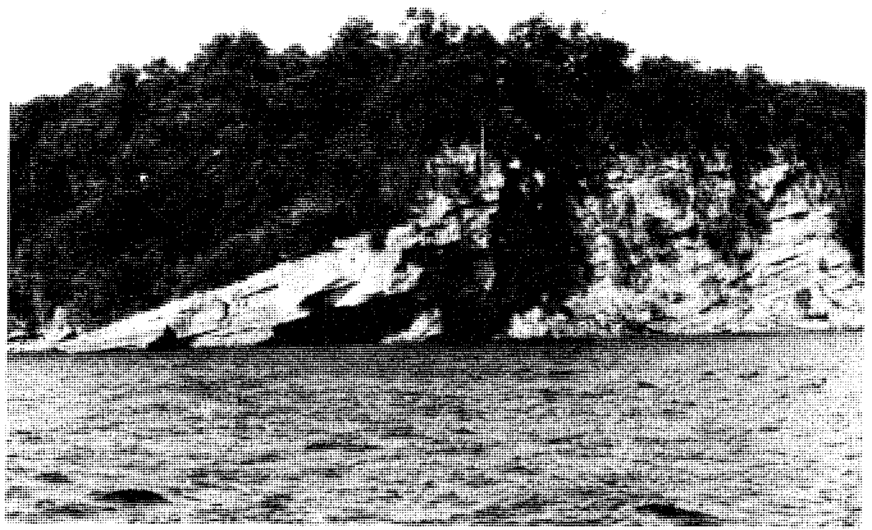


FIGURE 77

View of the east side of Au Train Island showing the south side of a fault block in which the Jacobsville has been tilted to the south.

ported by Oetking in the Au Train Bay area and on Laughing Fish Point. Such movement in the Jacobsville could well explain the striations on the Michigamme slate at L'Anse which were considered by Murry (1955) to be evidence for pre-Jacobsville glaciation.

JOINTS

Long straight joints are in most outcrops of the Jacobsville formation, they are very numerous in the shore cliffs just east of Skanee and on the northwest side of Grand Island. In most outcrops the typical red color of the Jacobsville has been leached from the joint walls so that the joint is marked by a straight white band from 2 to 30 inches wide extending along its entire length (figs. 80, 81). This color contrast makes the joints so conspicuous that some can be seen extending out into the lake several hundred feet before being obscured by deep water.

The joint planes are remarkably smooth and flat with no warping or irregularities at places where the joints cut contrasting rock types. This is well demonstrated at Wetmore Landing where many moderately well-cemented conglomerate lenses are in a medium- to massive-bedded sandstone. Several joint planes which cut the conglomerate are exposed, but show no deviation of the

FIGURE 78

High angle normal fault with small displacement. Pequaming Point, Keweenaw Bay.

strike as they pass from the sandstone to the conglomerate. Even the individual pebbles of hard quartzite and soft clay pellets within the conglomerate are cut by an equally smooth joint plane. The writer therefore concludes that these are shear joints since tension fractures would be short, irregular and would not cut contrasting rock types.

Two sets of shear joints intersecting at nearly right angles are recognized in the Jacobsville. In the Keweenaw Bay area one set strikes N. 70° W. and the other N. 10-30° E. Eastward this pattern rotates clockwise so that at Grand Island one set strikes N. 50° W. and the other N. 40° E. (fig. 82). Continued rotation to the east is implied by the joints at Parisian Island in Whitefish Bay, but only one set is present. In the field, the intersection of two joints forms a 70- to 80-degree angle which points in an east-west direction; however, when the measurements are grouped in a frequency diagram, this acute angle is not discernible and the two sets form a rigorously perpendicular system. In all localities the east-west joints have a constant strike but the north-south set varies 10 to 15 degrees. These joints were probably produced by the forces that tilted the Jacobsville to the north and northwest.

FIGURE 79

Small low-angle thrust fault on the east side of Grand Island showing clastic dike displaced approximately 2 feet.

Two sets of long straight shear joints are also recognized in the Munising formation but they are not nearly so numerous as in the Jacobsville. In the Pictured Rocks area one set of joints strikes N. 40° E. and the other N. 80° E. Rotation of this pattern occurs along the rim of the Michigan Basin; therefore, the strike of one set remains nearly parallel to the strike of the beds. The jointing in the Munising is one of the main reasons for the preservation of the Pictured Rocks cliffs. One joint set strikes parallel to the shore and causes the cliffs to be eroded back in big blocks instead of a slope. Many of the faces on the vertical cliffs thus expose the joint plane.

Many shear joints are in the Au Train formation at Au Train Falls and form a conjugate system parallel to the system in the Munising formation (fig. 82). In places one set of joints truncated the other and a zig-zag pattern resulted. The abundance of joints

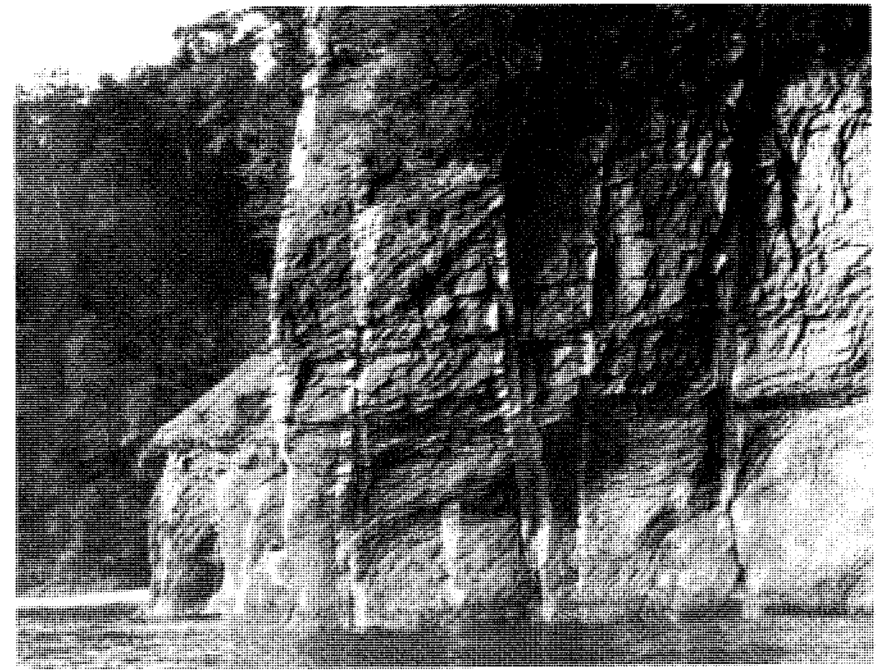


FIGURE 80

Vertical jointing in the Jacobsville formation showing the white band produced where the red color is leached away from the joint wall. View taken just north of Wetmore Landing.

in the Au Train formation indicates that the number of joints, but not their orientation, is probably dependent on the brittleness of the rock.

The orientation of the joint system in the Jacobsville formation differs from the orientation of joints developed in younger rocks indicating that the joints in each formation resulted from different stresses. Apparently however no relationship exists between jointing in either the Jacobsville or younger formations and the forces which caused the Keweenaw fault. Jointing in the Jacobsville probably developed during the tilting which took place prior to the advancement of the Upper Cambrian seas, whereas jointing in the Munising and younger formations appears to be related to the subsidence of the Michigan Basin.

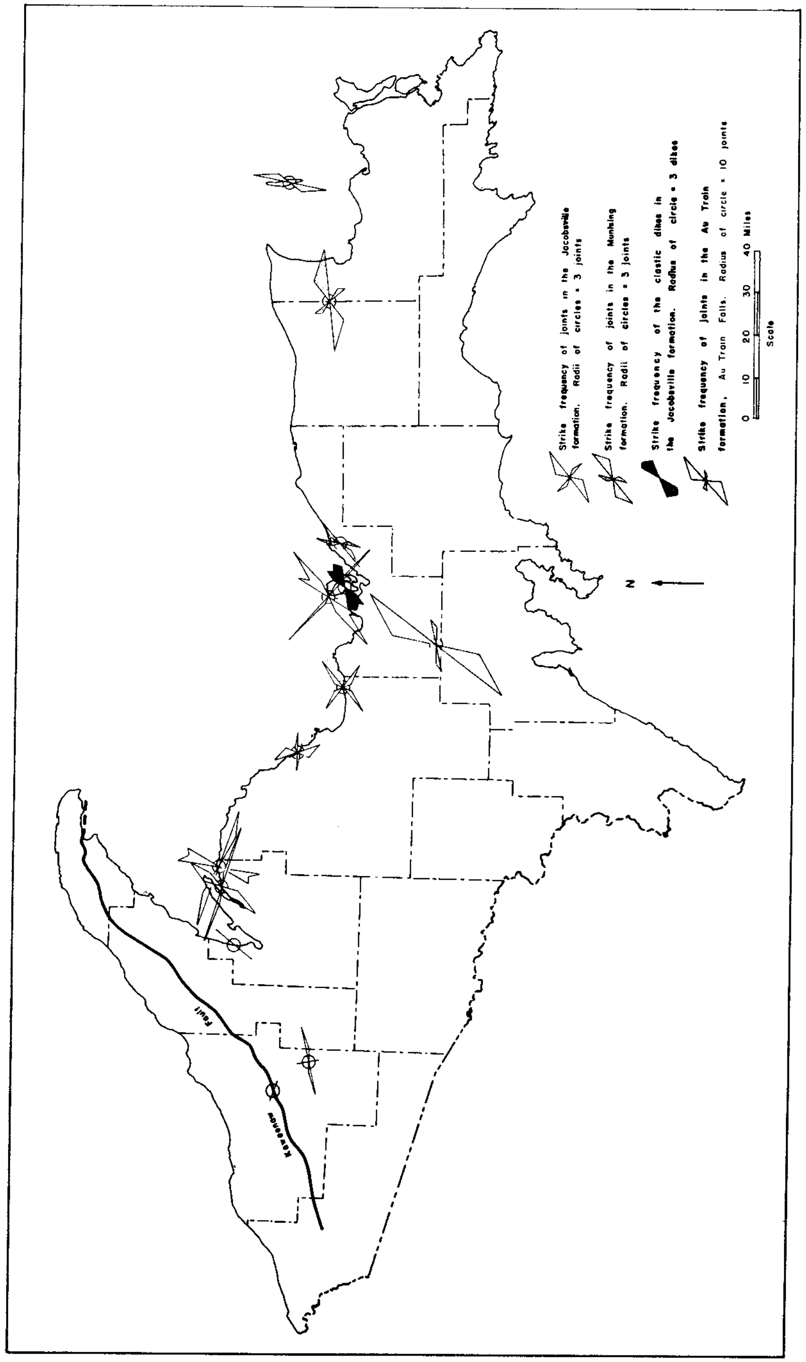


Figure 82. Joint patterns in the Jacobsville, Munising and Au Train formations

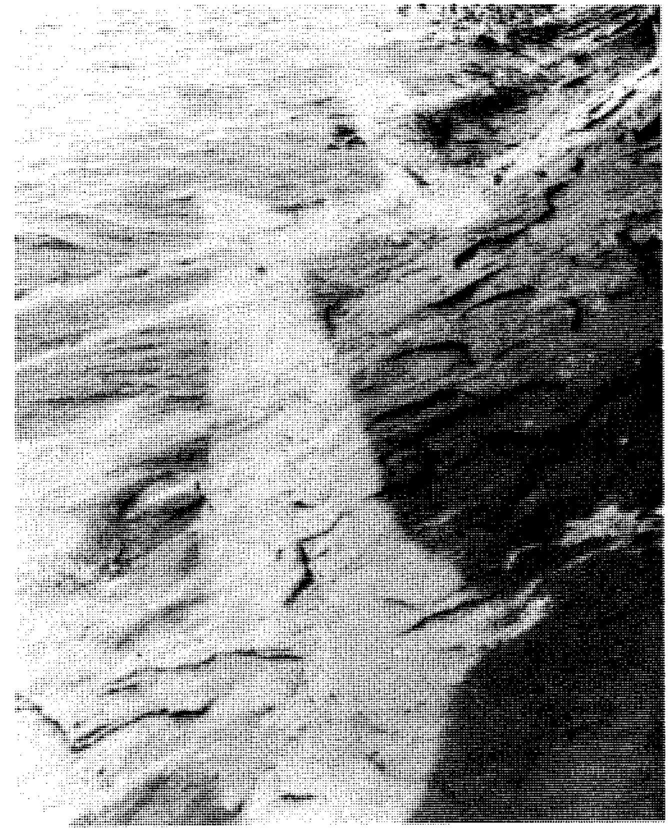


FIGURE 81

Conjugate shear system of joints in the Jacobsville formation east of Skanee showing white band resulting from leaching of red color from joint walls. Note the sharp contact between the red and white colors.

CLASTIC DIKES

Numerous tabular sandstone dikes in the Jacobsville formation have been briefly described by Oetking (1951, p. 61). They seem to be restricted to the Grand Island area where 30 dikes were mapped on the island itself and 4 on the mainland between Munising and Au Train Bay. Elsewhere along the coast dikes are absent. The outstanding characteristics of the dikes is their constant thickness. They exist as vertical tabular masses 6 to 30 inches wide and can be traced throughout the entire vertical extent of the outcrop, which, in places, is more than 100 feet (fig. 83). Throughout this distance the walls of the dike remain remarkably parallel. The distance in which the dike persists along strike can only be postulated since the only exposures are in vertical cliffs.

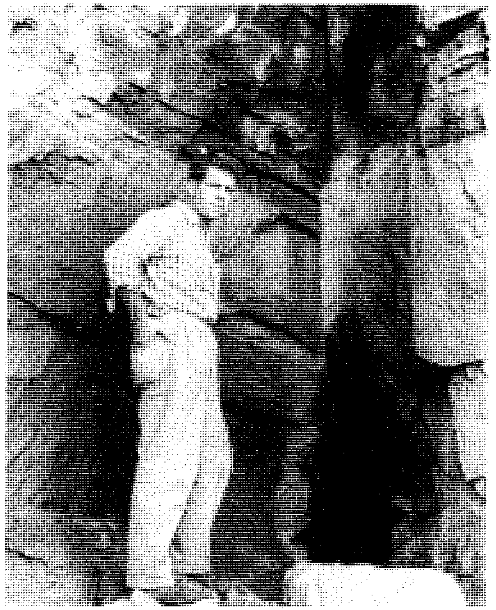


FIGURE 83

Large clastic dike cutting the Jacobsville formation on the west side of Grand Island. Note the sharp straight contacts with the wall rock and the cave produced by differential erosion by the waves.

FIGURE 84

Conglomerate dike on the southward side of the "thumb" of Grand Island. Note the white band produced by leaching of the red coloring near the contacts between the dike and the wall rock.

The position of a number of dikes mapped on the opposite sides of the "thumb" of Grand Island, however, suggests that the dikes may be connected and extend along the strike for over a mile. Fragments of the wall rock are, in places, included in the dikes but the contact between the dike and wall rock is characteristically very straight and sharp.

COMPOSITION

Excepting in a conglomerate dike on the southwest side of the thumb of Grand Island the material filling the dikes is a poorly-sorted sandstone which contains an abundance of silt- to clay-sized particles. The color is typically dark-red to purple, but along the contact with the wall rock the coloring material has been leached white in a manner similar to the leached zones along the joints. Nearly all the narrow dikes are therefore completely white. Quartz grains constitute more than 90 percent of the dike material but feldspar and chert are everywhere present in minor amounts. The grains are typically angular to subrounded and poorly sorted. Overgrowths of quartz, calcite and other cementing materials are noticeably lacking. The dikes are therefore less resistant than the country rock and wave action erodes much dike material away leaving straight narrow caves at the water level. The conglomerate dike is composed predominantly of quartzite and vein quartz pebbles 6 inches in diameter. Rounded pebbles of the Jacobsville, particularly in the smaller size fraction, are also in every sample. The only other rock types are small amounts of granitic pebbles and brown oölitic chert.

The strike of the dikes closely parallels the strike of one joint set in the conjugate system so well exposed on the northwest side of Grand Island (fig. 82). This parallelism and the fact that the dike walls are straight and persist along strike for a considerable distance suggest that the dikes resulted from a widening of one of the joint sets by tension forces younger than the forces which produced the conjugate shear systems. It is quite probable that such tension forces developed during the subsidence of the Lake Superior syncline.

The mechanics by which the fractures became filled is not completely clear. The presence of rounded pebbles of Jacobsville and oölitic chert suggests that the fractures were filled from above and were derived from the basal part of the Munising formation. No stratification within the dikes is indicated, but in several dikes a faint lineation of coarser sand is parallel to the dike walls (fig. 85). This lineation and small apophysis implies forceful injection (fig. 86).

With these facts in mind, the most plausible explanation of the origin of the dikes seems to be the opening of a set of shear joints in the Jacobsville and injection of unconsolidated clastic material from the basal Munising as a slurry under hydrostatic pressure.

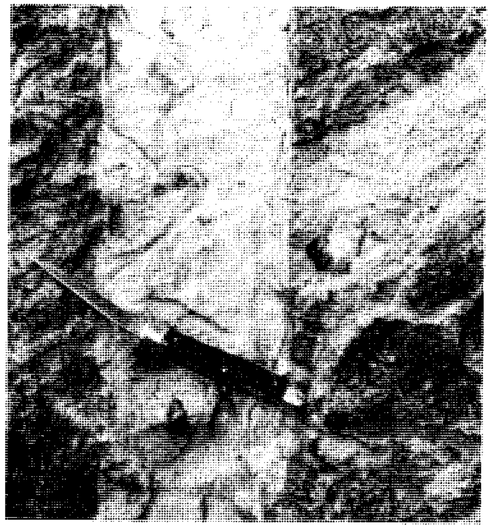


FIGURE 85

Clastic dike located on the east side of the thumb of Grand Island showing faint lineations parallel with the dike walls. These lineations are produced by difference in grain size and suggest that the dike was filled by forceful injection.

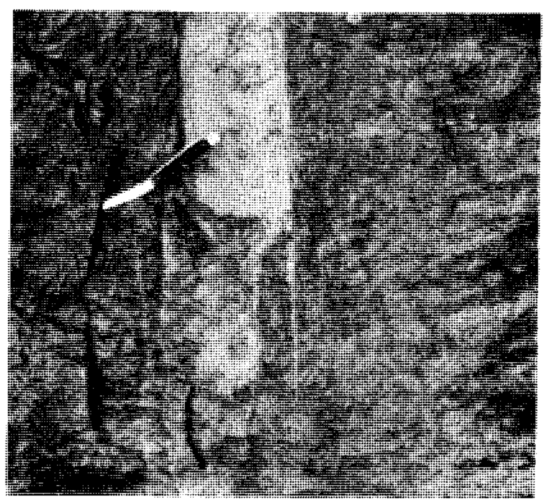


FIGURE 86

Clastic dike showing apophysis which suggest that the dike was filled by forceful injection. Location same as Fig. 85.

Summary of Geologic History

The angular unconformity between the Jacobsville and middle Keweenawan basalts exposed at Sturgeon Falls and the angular relationship between the Freda and Jacobsville that is implied from the exposures in Whitefish Bay indicate that the Keweenawan series was deformed prior to the deposition of the Jacobsville formation. Following this deformation a period of erosion produced an irregular surface of low relief probably very similar to the present topography of the Huron Mountains area. Deep chemical weathering of this surface is indicated by a regolith containing highly decomposed residual boulders. This erosional interval is considered to include the transition from Precambrian to Paleozoic time.

Jacobsville sedimentation was initiated with the uplift of the Northern Michigan Highland and the deposition of its erosional debris in a basin which developed in approximately the present site of Lake Superior and extended somewhat west of the Keweenaw Peninsula (fig. 87). The regional slope during Jacobsville time was to the north and the principal source area was the Northern Michigan Highland, which connected the Wisconsin Arch with the Precambrian highlands in Ontario. During early Jacobsville time, sedimentation was predominantly fluvial, especially near the upland front. Small lakes undoubtedly were in the center of the basin and as time progressed the lacustrine environment became more widespread. This is indicated by the massive sandstone facies exposed in many of the outcrops in Keweenaw Bay which are considered to be some of the younger units of the Jacobsville formation. With this type of sedimentation the Northern Michigan Highland became buried in its own debris. It is not known if the Northern Michigan Highland was completely covered by the Jacobsville but ample evidence indicates that Jacobsville sediments once covered a greater part of the Huron Mountains than do the formation at the present time.

Uplift tilted the Jacobsville slightly to the north and northwest and probably produced the system of shear joints which is so conspicuous throughout the formation. Prior to, or during, the first advance of the Paleozoic seas the topography developed on the tilted

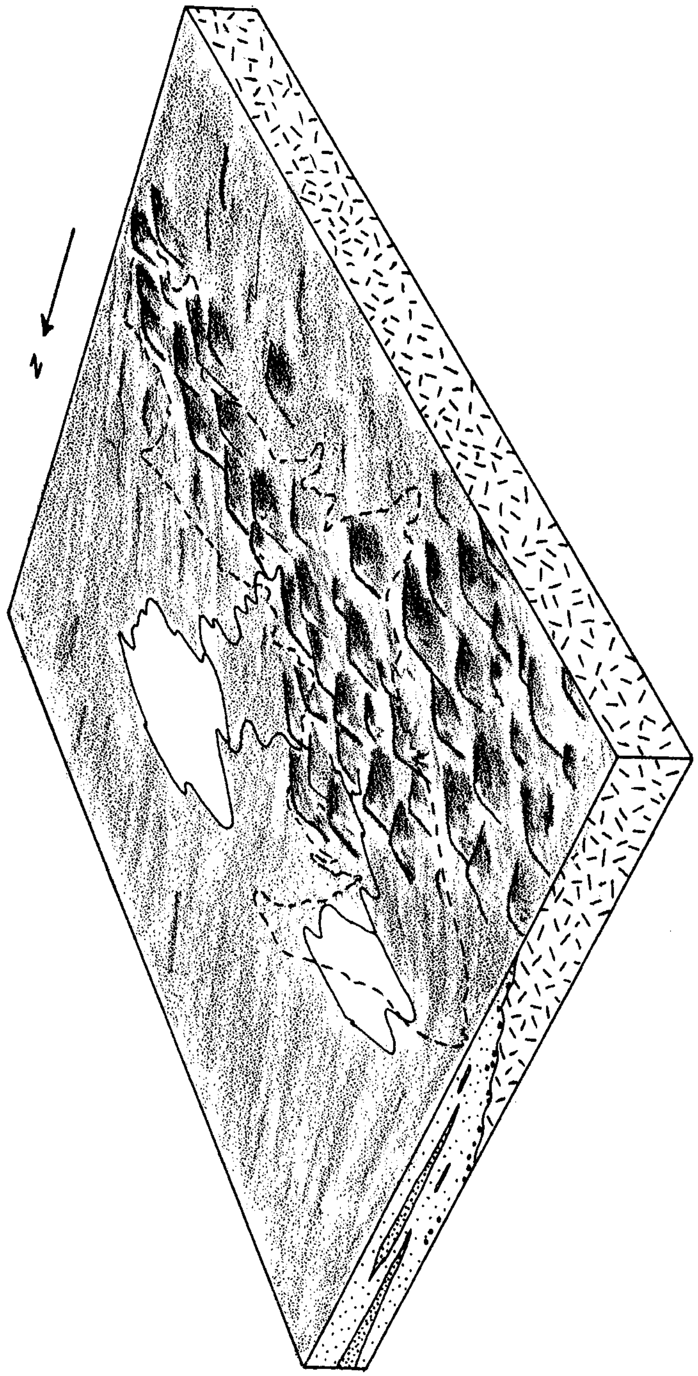


Fig. 87. Paleogeography of Northern Michigan during Jacobsville time. The Northern Michigan Highland extended from the Wisconsin Arch through the central part of Northern Michigan and into Canada. Erosional debris from this highland was shed off to the north and accumulated in a fluvial and lacustrine environment.

Jacobsville was reduced to a featureless plain, but the hard Precambrian rocks to the south retained their irregular surface which was not unlike the present topography of the Precambrian highlands.

If the Northern Michigan Highland was completely covered by Jacobsville, it was partly re-exposed by erosion prior to the transgression of the Upper Cambrian seas. During the early part of St. Croixan time this landmass blocked sea invasion onto the Canadian Shield from the south or southeast (fig. 88). The regional slope during lower Munising time as determined by cross-bedding directions, indicates that the first transgression of the Paleozoic seas in Northern Michigan came from the northwest, probably from the Cordilleran geosyncline. The basal conglomerate and Chapel Rock member represent a single transgressive-regressive cycle during which the principal source area was the Northern Michigan Highland. The clean well-sorted characteristic of the Chapel Rock member and its mineralogical similarities to the Jacobsville indicate that the highlands were probably covered in part by the Jacobsville formation, and that the Chapel Rock member represents a second-cycle sand.

Evidence of a regression of the Upper Cambrian seas prior to the deposition of the Miner's Castle member is found in the abundance of large mud cracks which are in a section of interbedded sand and shale layers at the top of the Chapel Rock member. The unconformity is further indicated by (1) changes in heavy mineral suites, (2) significant changes in the regional slope during the deposition of the two members, and (3) changes in composition, sorting, and sedimentary structures.

The Miner's Castle member represents a rapid transgression of the middle Upper Cambrian seas from the southwest over the Precambrian highlands. In many areas the irregular topography of the Precambrian highlands produced islands in the Miner's Castle sea, but they had little effect on regional sedimentation. The major source area was to the northeast in Canada (fig. 89).

Ripple marks, small-scale cross-bedding, and mud cracks indicate that the Miner's Castle member was deposited predominantly in shallow water but was at times exposed to desiccation on tidal flats. Throughout most of Miner's Castle time sea level remained relatively stable and a near balance was maintained between sedimentation and deposition in the area.

A considerable unconformity separates the Miner's Castle member of Middle Cambrian age and the overlying Au Train formation which is Middle Ordovician. The contact is practically a featureless

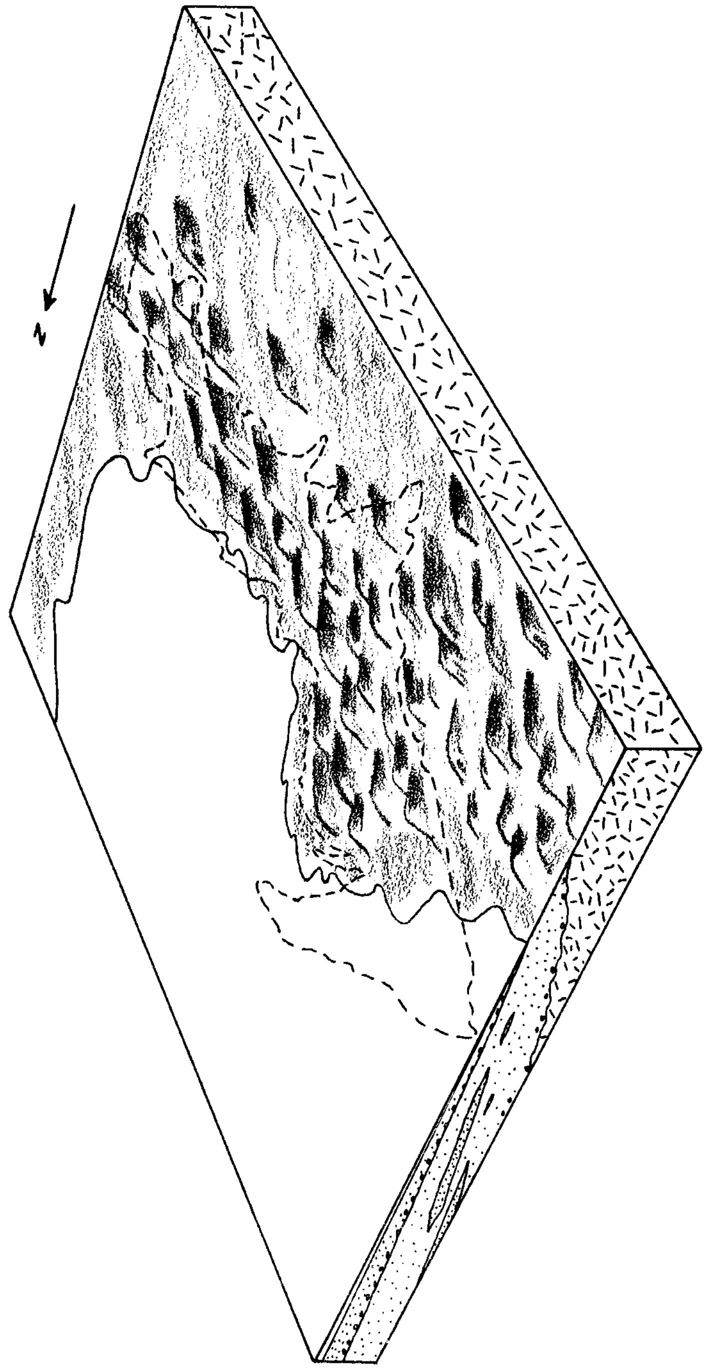


Fig. 88. Paleogeography of Northern Michigan during Lower Munising time. The Northern Michigan Highland remained as a positive area although much of it was covered with Jacobsville sediments. The first advancement of the Paleozoic seas came from the northwest, probably from the Cordilleran geosyncline.

plane with no angular discordance between the Upper Cambrian and Middle Ordovician rocks. However, some evidence of a basal conglomerate is in the lower units of the Au Train formation.

Thrusting from the northwest produced the Keweenaw fault sometime after the Jacobsville formation, but the exact age of movement cannot be definitely determined. In the writer's opinion the evidence indicates that the movement was at least post-Devonian. The relax of the stress which produced this great thrust probably produced the small normal faults in the Jacobsville observed along Keweenaw Bay.

The only deformation of the Munising formation is the slight tilting and related joints and minor normal faults, which resulted from subsidence of the Michigan Basin.

Conclusions

The Jacobsville formation extends from the tip of the Keweenaw Peninsula eastward to Sault Ste. Marie and in that area probably constitutes the bedrock over much of the bottom of Lake Superior. It contains four distinct facies, which represent environmental conditions that were local and temporary. The conglomerate facies and the lenticular sandstone facies represent fluvial deposition, but during the later phases of sedimentation a lacustrine environment became more prominent and in it the massive sandstone facies and the red siltstone facies were formed. The source area for the Jacobsville formation was a highland extending eastward through Northern Michigan connecting the Wisconsin arch with a positive area in Canada. The surface upon which the Jacobsville was deposited was highly irregular and had a local relief of at least 400 feet. Prior to the deposition of Jacobsville sediments this surface was subjected to a period of chemical weathering, which produced a regolith at least 6 feet thick.

The angular unconformity between the Munising and Jacobsville formations exposed at Grand Island indicates that the Jacobsville is not part of the St. Croixan series. At Sturgeon Falls the Jacobsville rests unconformably upon tilted and highly weathered Middle Keweenawan basalts; this relationship suggests that the Upper Keweenawan rocks were eroded away before the Jacobsville was deposited. There are also suggestions of an unconformity between the Jacobsville and Freda in the Whitefish Bay area. Cross-bedding directions indicate that the Upper Keweenawan sediments and the Jacobsville formation were derived from different source areas and are not genetically related. The writer therefore concludes that the

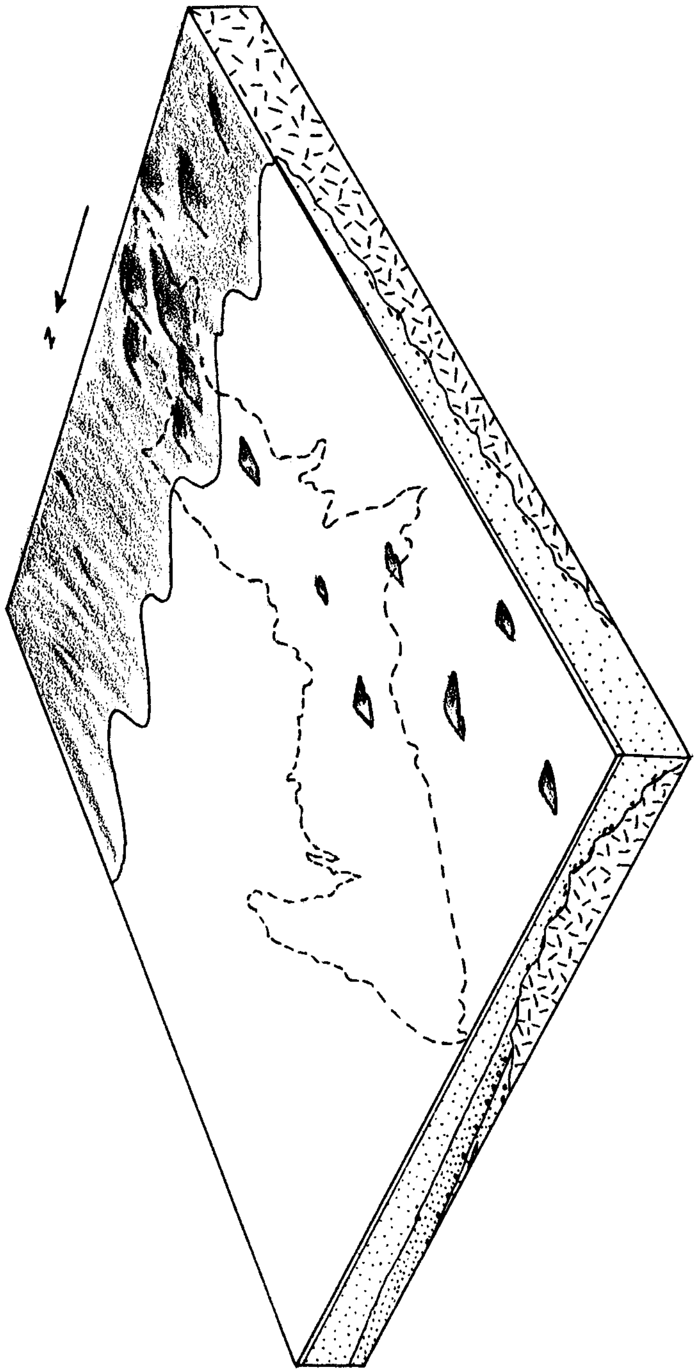


Fig. 89. By the beginning of Miner's Castle time the Northern Michigan Highland was eroded down and almost completely buried in its own debris. The Miner's Castle sea advanced from the southwest and received most of its sediments from the Canadian Shield.

Jacobsville is not related to the St. Croixan nor to the Keweenawan but represents terrestrial sedimentation in a closed basin during the time when marine sediments of Early and Middle Cambrian age were being deposited in other parts of the continent.

The Munising formation represents the first advance of the Paleozoic seas into Northern Michigan. Outcrops are in a narrow band that extends westward from Encampment d'Ours Island to western Marquette County. The outcrop belt then turns southward and can be traced into Wisconsin. Numerous outliers are scattered in Dickinson County, and isolated exposures are as far west as Limestone Mountain.

On the basis of lithology the Munising is divided into three members. The oldest member is an orthoquartzitic conglomerate 3 to 15 feet thick composed of pebbles that are chemically and mechanically very stable. The Chapel Rock member lies conformably upon the basal conglomerate and is characterized by large-scale cross-bedding, good sorting, and a heavy mineral assemblage high in zircon. An unconformity separates the Chapel Rock from the overlying Miner's Castle member and represents a temporary regression of the Munising seas. The basal conglomerate and Chapel Rock members seem to pinch out to the south, but the Miner's Castle member can be recognized throughout the entire outcrop belt by its small-scale cross-bedding, poor sorting, and high garnet content.

The basal conglomerate and Chapel Rock member represent a single transgressive-regressive cycle during which the seas advanced from the northwest and the source area was the Northern Michigan Highland. During Miner's Castle time the seas advanced rapidly from the southwest across the Wisconsin arch and Northern Michigan Highland and the principal source area was located to the northeast in Canada.

The distinctive heavy mineral suites in the Miner's Castle and Chapel Rock members permit a reasonably accurate correlation between the exposures at Pictured Rocks and the outliers in Dickinson County. Fossils found at several localities in the Miner's Castle member indicate that it may be correlated with the Franconia of Wisconsin. On the basis of stratigraphic position and heavy minerals the basal conglomerate and Chapel Rock members are considered to be equivalent to the Dresbach. A major unconformity separates the Munising formation from the overlying Middle Ordovician Au Train formation.

Bibliography

Atwater, G. I. (1935) The Keweenawan-Upper Cambrian unconformity in the upper Mississippi Valley: Kansas Geol. Soc. Guidebook, 9th Ann. Field Conf., pp. 316-319, fig. 214.

—— & Clement, G. M. (1935) Pre-Cambrian and Cambrian relations in the upper Mississippi Valley: Geol. Soc. Am. Bull., v. 46, no. 11, pp. 1659-1686.

Bacon, L. O. (1957) Personal communication.

Bergquist, S. G. (1930) The occurrence of glauconite in the Hermansville formation of Alger County, Michigan: Mich. Acad. Sci., Arts, & Letters, Papers, v. 12, pp. 231-237.

—— (1931) Surface geology of Luce County, Michigan: Mich. Acad. Sci., Arts, & Letters, Papers, v. 14, pp. 437-452.

—— (1937) The Cambrian-Ozarkian contact in Alger County, Michigan: Mich. Acad. Sci., Arts, & Letters, Papers, v. 22, pp. 421-435.

Bramlette, M. N. (1929) Natural etching of detrital garnet: Am. Mineralogist, v. 14, no. 9, pp. 336-337.

Butler, B. S. & Burbank, W. S. (1929) Notes from the Copper Deposits of Michigan: U.S.G.S. Prof. Paper 144, 238 pp.

Case, E. C. & Robinson, W. I. (1915) The geology of Limestone Mountain and Sherman Hill in Houghton County, Michigan: Mich. Geol. & Biol. Survey, Pub. 18, pp. 168-181.

Cohee, G. V. (1945) Stratigraphy of Lower Ordovician and Cambrian rocks in the Michigan Basin: U.S.G.S. Oil & Gas Inves. Prelim. Chart no. 9.

Denning, R. M. (1949) The petrology of the Jacobsville sandstone, Lake Superior: Unpub. Master's thesis, Mich. College Min. & Tech., Houghton, Michigan.

Driscoll, E. G., Jr. (1956) An environmental and heavy mineral study of the "Eastern Sandstones" between Marquette and Grand Marais, Michigan: Unpub. Master's thesis, Univ. Nebraska, Lincoln, Nebraska.

Foster, J. W. & Whitney, J. D. (1850) Report on the geology and topography of a portion of the Lake Superior land district in the State of Michigan; Pt. 1, Copper lands: U.S. 31st Congr., 1st Sess. H. Exec. Doc. 69.

Foster, J. W. & Whitney, J. D. (1851) Report on the geology of the Lake Superior land district; Pt. 2, the iron region, together with the general geology: U.S. 32nd Congr., Spec. Sess. S. Exec. Doc. 4.

Fuller, G. N. (1928) Geological Reports of Douglass Houghton: Mich. Hist. Comm.

Grabau, A. W. (1906) Types of sedimentary overlap: Geol. Soc. Am. Bull., v. 17, pp. 567-636 [see p. 583].

Hotchkiss, W. O. (1923) The Lake Superior geosyncline: Geol. Soc. Am. Bull., v. 34, no. 4, pp. 669-678.

—— (1933a) Lake Superior Region: 16th Internat. Geol. Congr., Guidebook 27, Excursion C-4.

—— (1933b) Personal communication to F. T. Thwaites, cited in Thwaites (1934).

——, Rooney, W. J. & Fish, James (1923) Earth resistivity measurements in the Lake Superior copper country: Am. Inst. Min. Met. Eng., Tech Pub. no. 32.

Houghton, Douglass (1841) Fourth annual report of the State geologist: Mich. House of Representatives, Doc. no. 27, pp. 3-89.

Hultman, J. R. (1953) The Cambrian Sandstones, Marquette Quadrangle, Michigan: Unpub. Master's thesis, Univ. Mich., Ann Arbor, Mich.

Irving, R. D. (1874) On the age of the copper-bearing rocks of Lake Superior: Am. Jour. Sci., ser. 3, v. 8, pp. 45-56.

—— (1883) The copper-bearing rocks of Lake Superior: U.S.G.S. Mon. 5, pp. 161-166, 351-352.

—— (1888) On the classification of the early Cambrian and Pre-Cambrian formations: U.S.G.S. 7th Ann. Rept., pp. 365-454.

—— & Chamberlin, T. C. (1885) Observations on the junction between the eastern sandstone and the Keweenawan series on Keweenaw Point, Lake Superior: U.S.G.S. Bull. 23, pp. 385-498.

Knight, S. H. (1929) The Fountain and Casper formations of the Laramie Basin: Univ. Wyo. Pub. Sci. Geol., v. 1, no. 1, pp. 1-82.

Landes, K. K. (1942) Unpublished report to the Michigan Geological Survey on the geology exposed by new construction at Sault Ste. Marie.

Lane, A. C. & Seaman, A. E. (1907) Notes on the geological section of Michigan, Pt. 1; The pre-Ordovician: Jour. Geol., v. 15, pp. 680-695.

Leith, C. K., Lund, R. J. & Leith, A. (1935) Pre-Cambrian rocks of the Lake Superior region: U.S.G.S. Prof. Paper 184, pp. 1-31.

Leverett, Frank (1910) Surface geology of the Northern Peninsula of Michigan: Mich. Geol. Biol. Survey, pub. 7, geol. ser. 5, pp. 1-86.

—— (1917) Surface geology and agricultural conditions of Michigan; Pt. 1, The surface geology of Michigan: Mich. Geol. Biol. Survey, pub. 25, pp. 47-100.

—— (1929) Moraines and shore lines of the Lake Superior region: U.S.G.S. Prof. Paper 154A, pp. 1-72.

Martin, L. (1911) The geology of the Lake Superior Region: U.S.G.S. Mon. 52, pp. 85-116.

McKee, E. D. (1940) Three types of cross-lamination in Paleozoic rocks of northern Arizona: Am. Jour. Sci., v. 238, no. 11, pp. 811-824.

—— (1953) Report on studies of stratification in modern sediments and in laboratory experiments: U.S. Office of Naval Research Project Nonr. 164(00), NR 081 123, pp. 1-59.

—— & Weir, G. W. (1953) Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. Am. Bull., v. 64, no. 4, pp. 381-389.

Murry, R. C. (1955) Late Keweenawan or Early Cambrian glaciation in upper Michigan: Geol. Soc. Am. Bull., v. 66, pp. 341-344.

Oetking, P. F. (1951) The relation of the Lower Paleozoic to the older rocks in the Northern Peninsula of Michigan: Unpub. Ph.D. thesis, Univ. Wisc., Madison, Wisconsin.

Olson, J. S. & Potter, P. E. (1954) Variance components of cross-bedding direction in some basal Pennsylvania sandstones of the eastern interior basin: statistical methods and geologic application: Jour. Geol., v. 62, no. 1, pp. 26-73.

Pumpelly, Raphael & Brooks, T. B. (1872) On the age of the copper-bearing rocks of Lake Superior: Am. Jour. Sci., ser. 3, v. 3, pp. 428-432.

Raasch, G. O. (1950) Current evaluation of the Cambrian-Keweenawan boundary: Illinois State Acad. Sci., Trans., v. 43, pp. 137-150.

Reiche, Parry (1938) An analysis of cross-lamination; The Coconino sandstone: Jour. Geol., v. 46, no. 7, pp. 905-932.

Roberts, Ellis (1940) Geology of the Alston district, Houghton and Baraga Counties, Michigan: Unpub. Master's thesis, Calif. Inst. Tech., Pasadena, California.

Rominger, C. L. (1873) Paleozoic Rocks: Mich. Geol. Survey, v. 1, pt. 3, 1869-1873, pp. 7-102.

Schoolcraft, H. R. (1821) Narrative journal of travels through the northwestern regions of the United States (Albany, N.Y.), 419 pp.

Smith, R. A. (1916) Mineral resources of Michigan; Pt. 3, Deep well borings: Mich. Geol. Biol. Survey, pub. 24, pp. 210-256.

Spiroff, K. (1956) Personal communication.

Stauffer, C. R. (1927) Age of the Red Clastic series of Minnesota: Geol. Soc. Am. Bull., v. 38, no. 3, pp. 469-477.

Stokes, W. L. (1953) Primary sedimentary trend indicators as applied to ore finding in the Carrizo Mountains, Arizona and New Mexico; Pt. 1, Technical reports for April 1, 1952 to March 31, 1953: U.S. Atomic Energy Comm., RME-3043 (Pt. 1), pp. 1-46.

Stumm, E. C. (1956) Upper Cambrian trilobites from Michigan: Contrib. Mus. Paleont., Univ. Mich., v. 13, no. 4, pp. 95-102.

Thompson, W. O. (1937) Original structures of beaches, bars, and dunes: Geol. Soc. Am. Bull., v. 48, no. 6, pp. 723-752.

Thwaites, F. T. (1912) Sandstones of the Wisconsin coast of Lake Superior: Wisc. Geol. Nat. Hist. Survey, Bull. 25, pp. 1-109.

—— (1931) Buried pre-Cambrian of Wisconsin: Geol. Soc. Am. Bull., v. 42, no. 3, pp. 719-750.

—— (1934) Well logs in the Northern Peninsula of Michigan, showing the Cambrian section: Mich. Acad. Sci., Arts, & Letters, Papers, v. 19, pp. 413-426.

—— (1935) Road log for Monday, September 2. Post-Conference Alternate Trip No. 2: Kansas Geol. Soc. Guidebook, 9th Ann. Field Conf., pp. 221-228.

—— (1943) Stratigraphic work in northern Michigan, 1933-1941: Mich. Acad. Sci., Arts, & Letters, Papers, v. 28, pp. 487-502.

Tyler, S. A., Marsden, R. W., *et al.* (1940) Studies of the Lake Superior pre-Cambrian by accessory-mineral methods: Geol. Soc. Am. Bull., v. 51, no. 10, pp. 1429-1537.

Ulrich, E. O. (1936) Personal communication to Prof. George M. Ehlers, dated March 9, 1936.

Van Hise, C. R. (1893) An historical sketch of the Lake Superior region to Cambrian time: Jour. Geol., v. 1, no. 2, pp. 113-129.

—— & Bayley, W. S. (1895) Preliminary report on the Marquette iron-bearing district of Michigan: U.S.G.S. 15th Ann. Rept., pp. 477-650.

—— & —— (1900) Description of the Menominee quadrangle: U.S.G.S. Geol. Atlas, Menominee folio (no. 62).

—— & Leith, C. K. (1911) The geology of the Lake Superior region: U.S.G.S. Mon. 52, 641 pp.

Vanlier, K. (1956) Personal communication.

Ver Wiebe, W. A. (1927) Stratigraphy of Chippewa County, Michigan: Mich. Acad. Sci., Arts, & Letters, v. 9, pp. 309-331.

Wadsworth, M. E. (1880) Notes on the geology of the iron and copper districts of Lake Superior: Harvard Coll., Mus. Comp. Zool., Bull. 7, pp. 1-157.

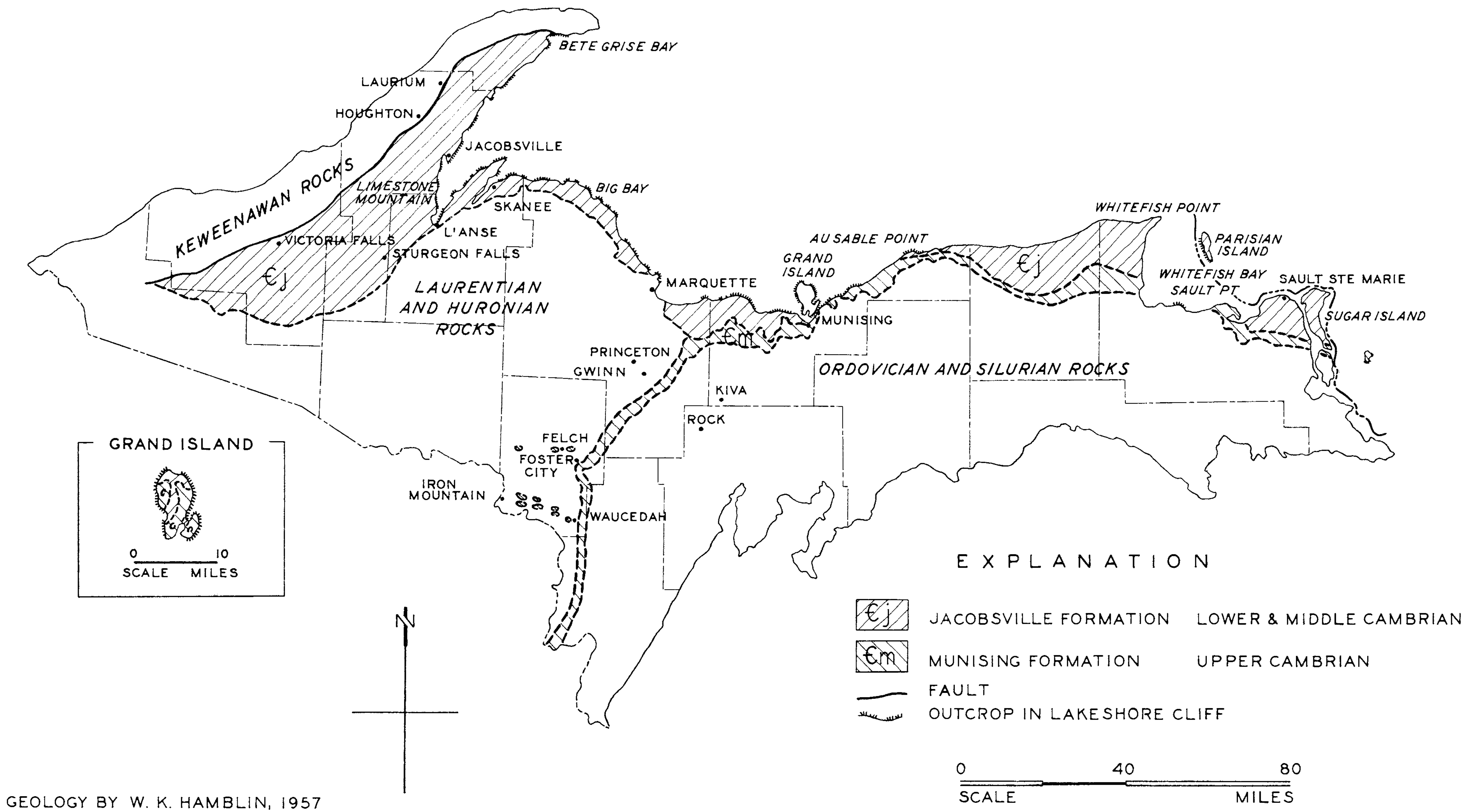
—— (1892) Report of the State Board of Geological Survey for the years 1891 and 1892: Michigan Geol. Survey, Annual Reports of the State Geologist, Chapter 7, pp. 156-167.

Winchell, Alexander (1861) First Biennial report of the progress of the Geological Survey of Michigan (Lansing), 339 pp.

Winchell, N. H. (1895) A rational view of the Keweenawan: Am. Geologist, v. 16, pp. 150-162.

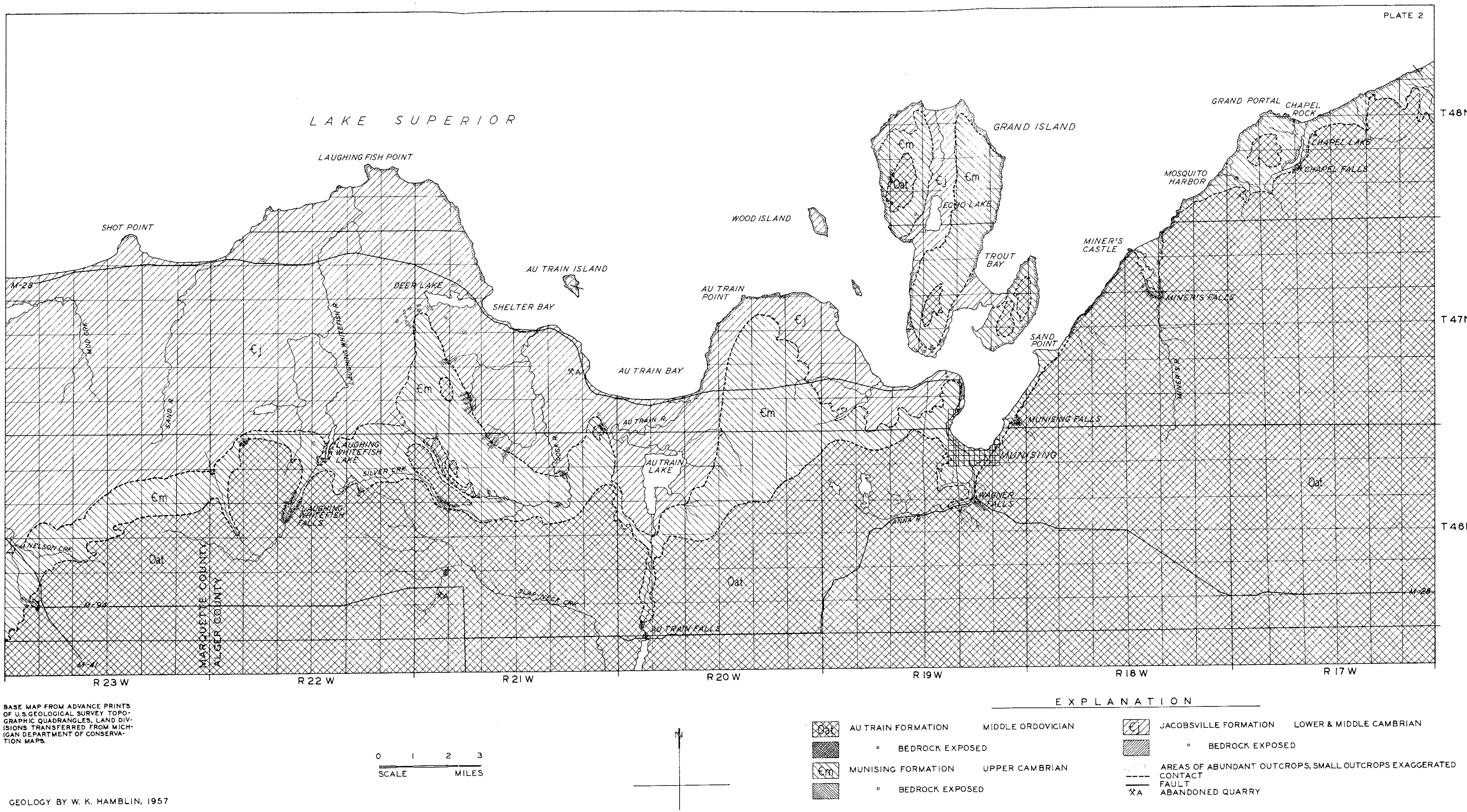
INDEX

PLATE I

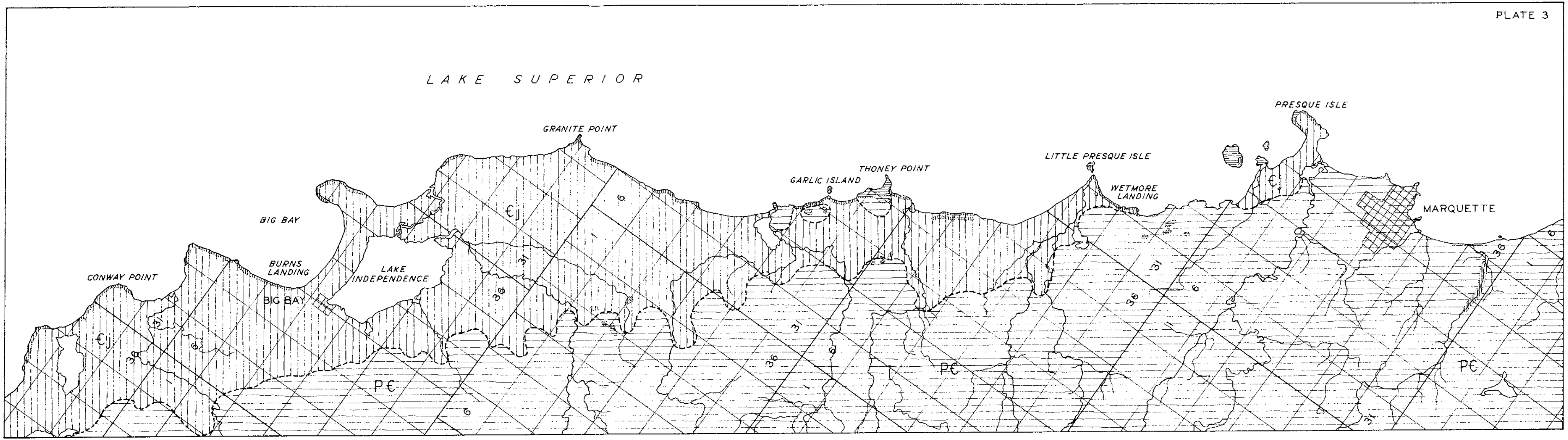


GEOLOGIC MAP SHOWING THE DISTRIBUTION OF CAMBRIAN ROCKS IN NORTHERN MICHIGAN

PLATE 2



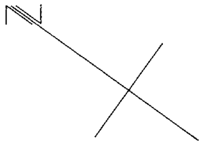
GEOLOGIC MAP OF PORTIONS OF MARQUETTE AND ALGER COUNTIES, MICHIGAN



BASE MAP FROM ADVANCE PRINTS OF U. S. GEOLOGICAL SURVEY TOPOGRAPHIC QUADRANGLES.

GEOLOGY BY W. K. HAMBLIN, 1957

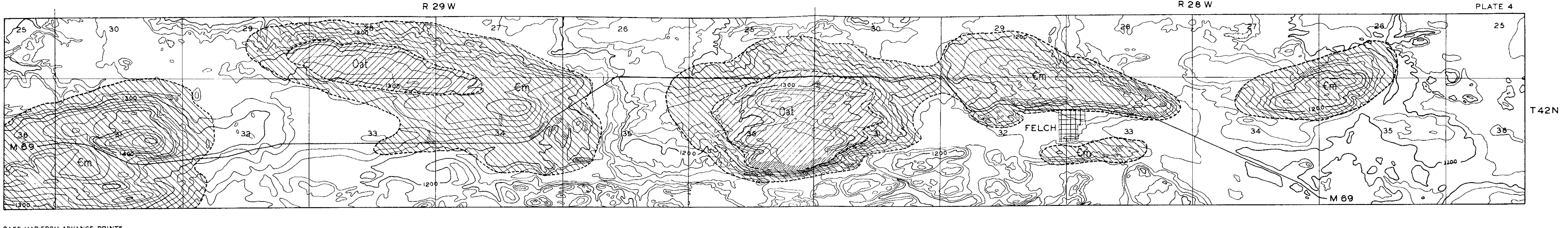
0 1 2 3
SCALE MILES



EXPLANATION

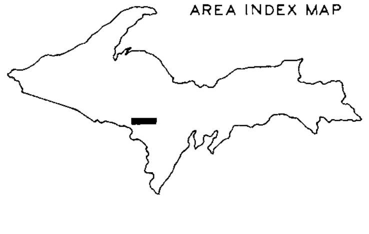
€j	JACOBSVILLE FORMATION	LOWER & MIDDLE CAMBRIAN
	" BEDROCK EXPOSED	
P€	UNDIFFERENTIATED PRECAMBRIAN ROCKS	
	" BEDROCK EXPOSED	
	AREAS OF ABUNDANT OUTCROPS, SMALL OUTCROPS EXAGGERATED	
----	CONTACT	

GEOLOGIC MAP OF THE COAST OF LAKE SUPERIOR BETWEEN BIG BAY AND MARQUETTE



BASE MAP FROM ADVANCE PRINTS
OF U. S. GEOLOGICAL SURVEY
TOPOGRAPHICAL QUADRANGLES.

AREA INDEX MAP



SCALE 0 1 2 MILES

CONTOUR INTERVAL 20 FEET

N

EXPLANATION

Oat AU TRAIN FORMATION ORDOVICIAN

" BEDROCK EXPOSED

€m MUNISING FORMATION CAMBRIAN

" BEDROCK EXPOSED

UNCOLORED-UNDIFFERENTIATED PRECAMBRIAN ROCKS

AREAS OF ABUNDANT OUTCROPS, SMALL OUTCROPS EXAGGERATED

CONTACT

GEOLOGY BY W. K. HAMBLIN, 1957

GEOLOGIC MAP SHOWING THE DISTRIBUTION OF THE CAMBRIAN SANDSTONES IN THE FELCH AREA, DICKINSON COUNTY

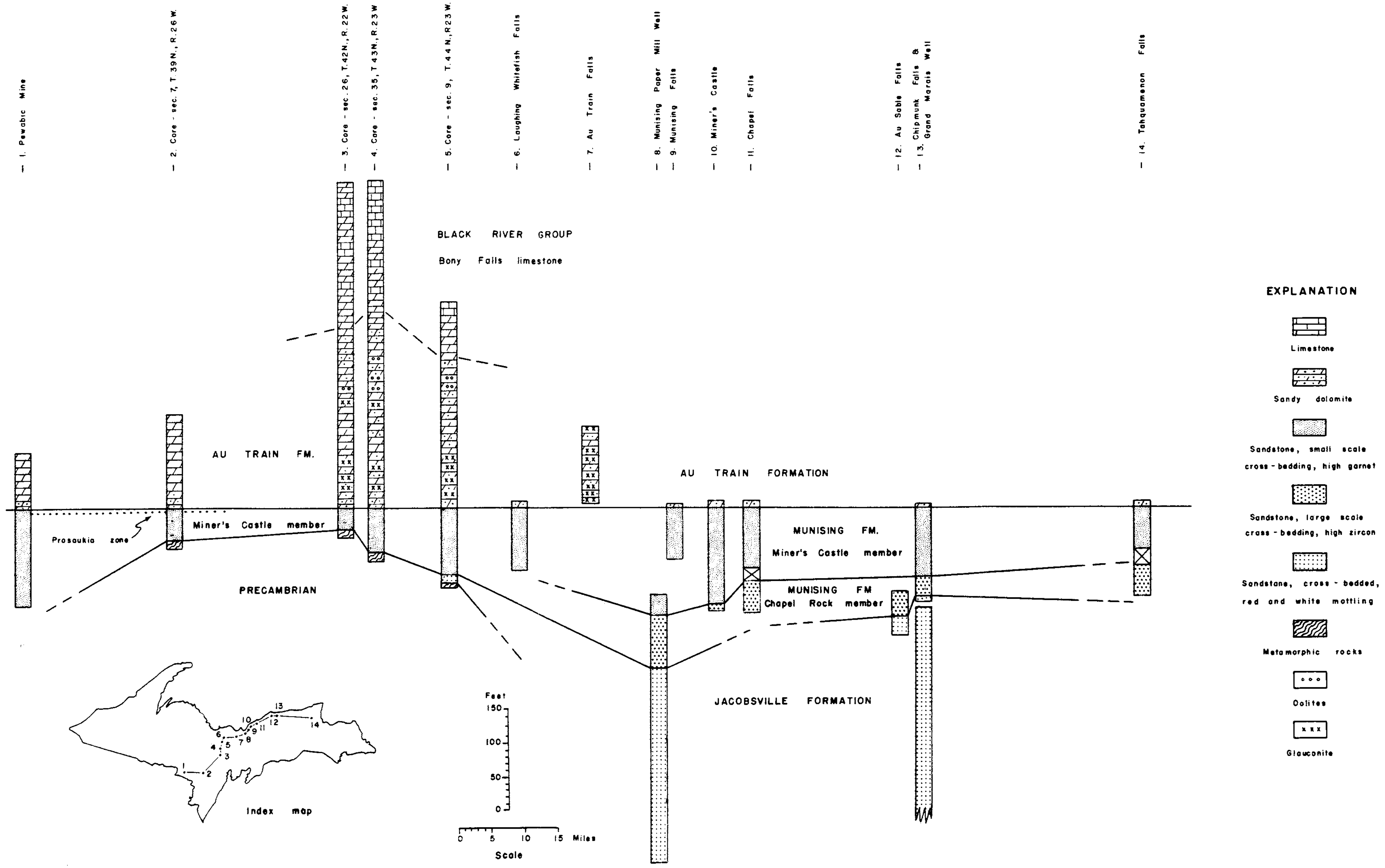
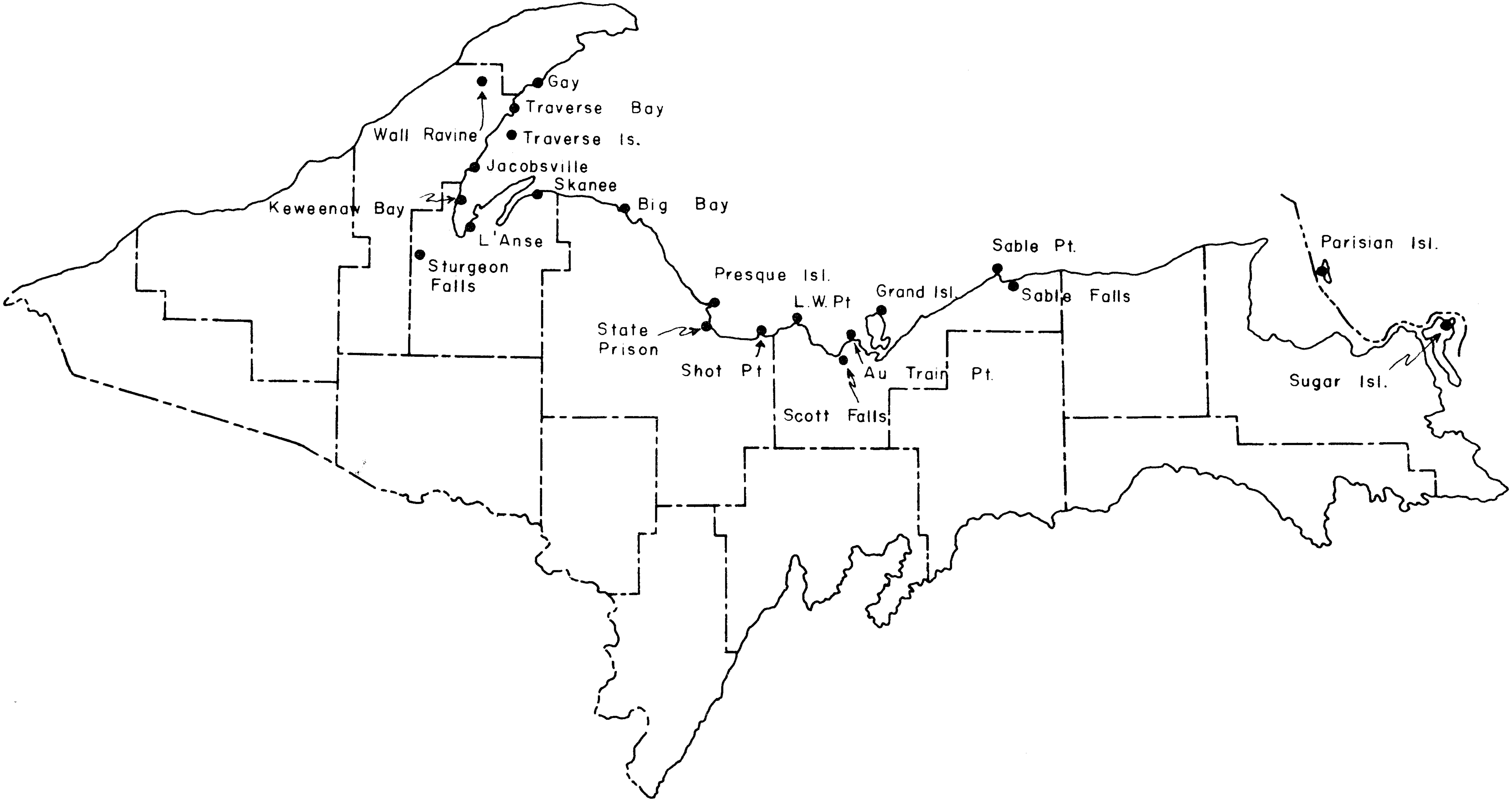
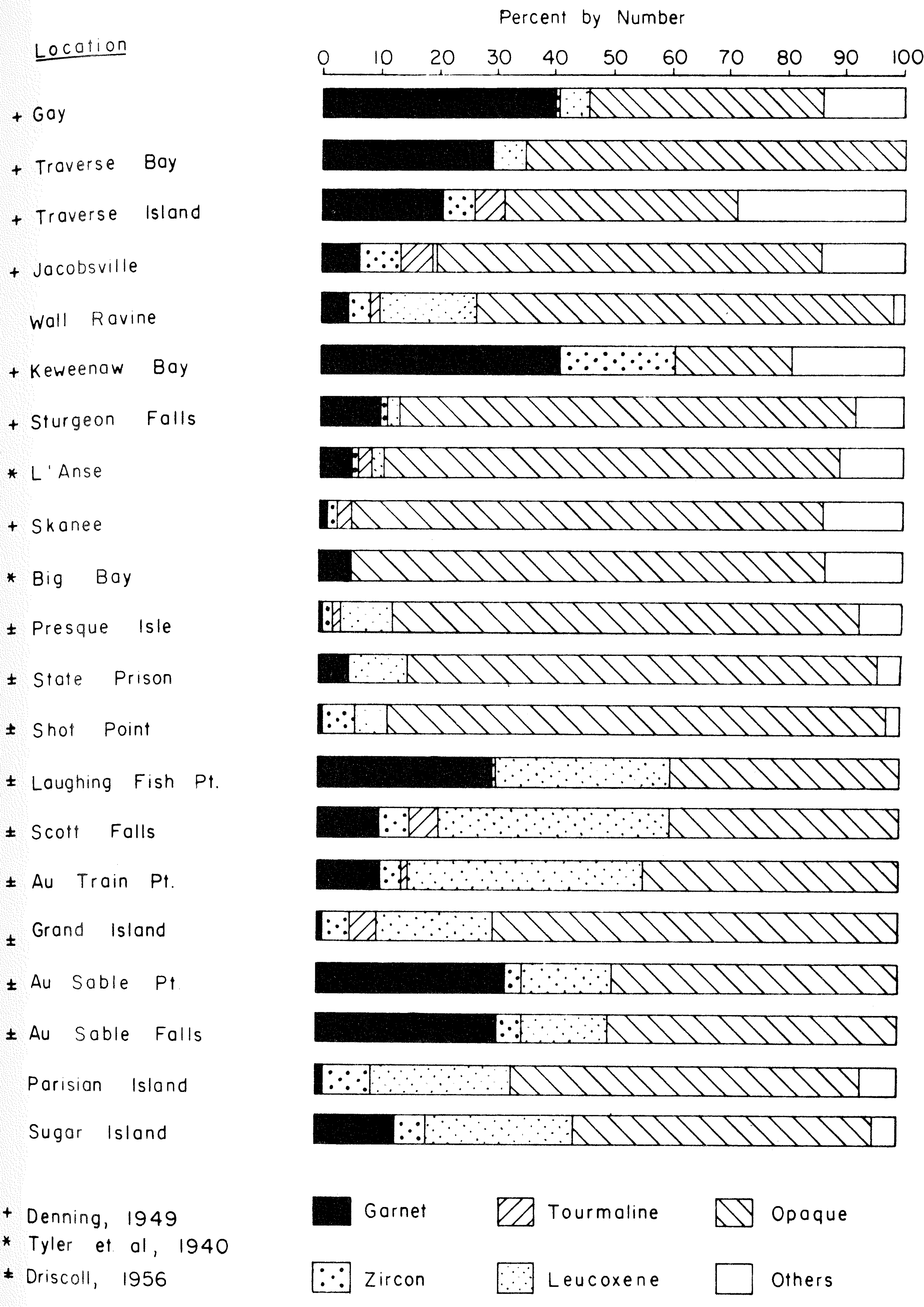
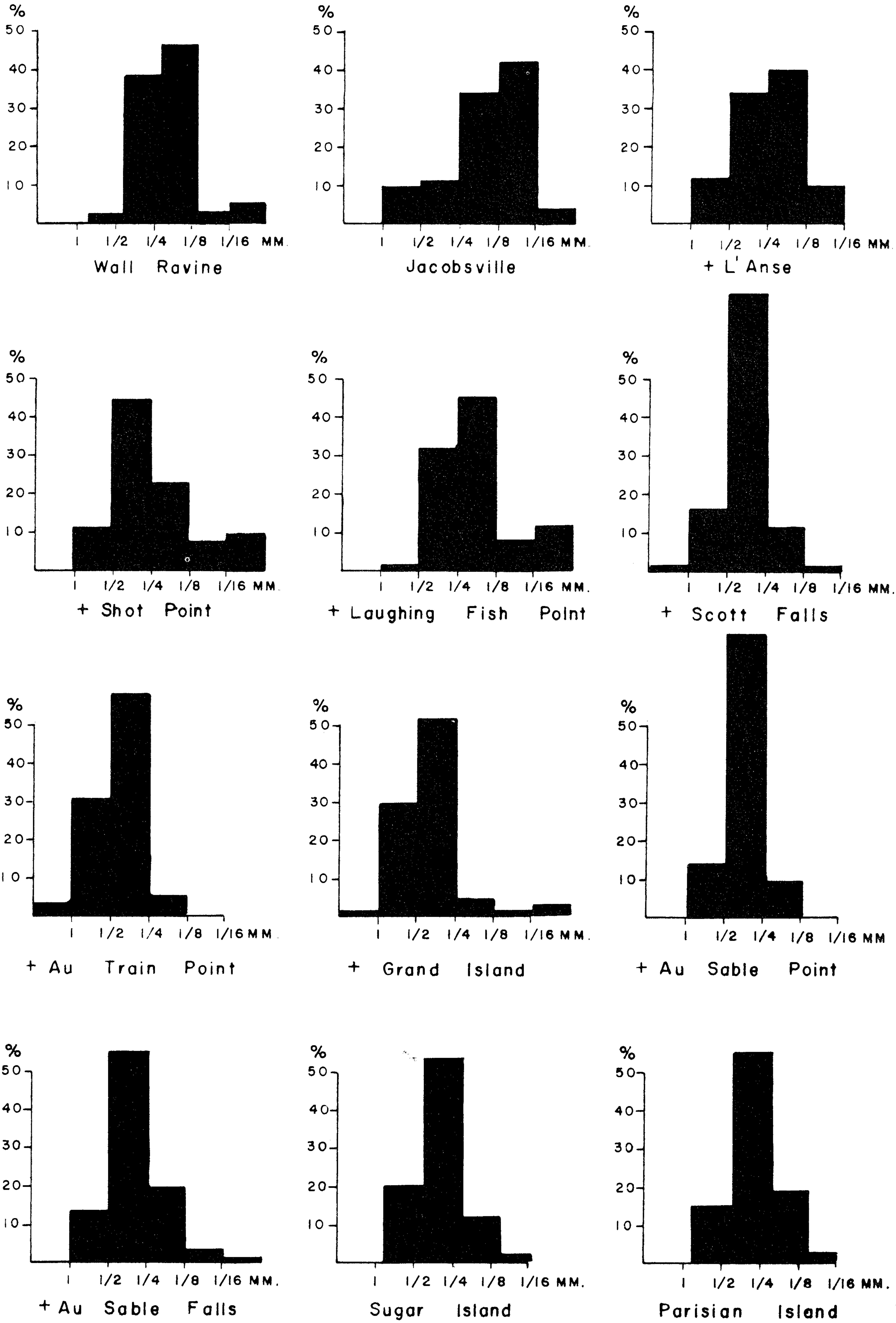


Figure 70. Stratigraphic cross section from Pewabic Mine to Tahquamenon Falls

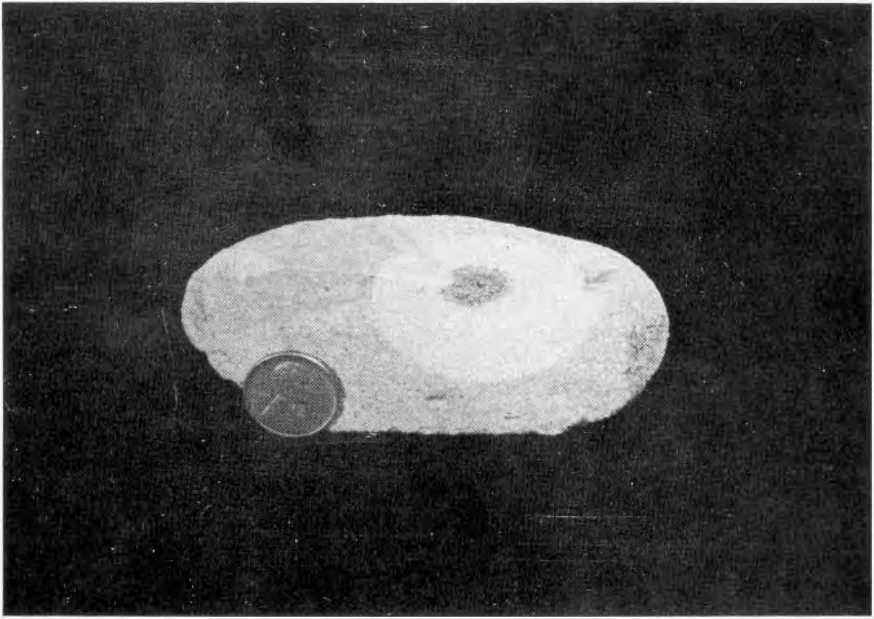

Gay
Traverse Bay
Wall Ravine
Traverse Is.
Jacobsville
Skanee
Keweenaw Bay
Big Bay
L'Anse
Sturgeon Falls
Presque Isl.
State Prison
Shot Pt
L.W. Pt
Grand Isl.
Au Train Pt.
Scott Falls
Sable Pt.
Sable Falls
Parisian Isl.
Sugar Isl.



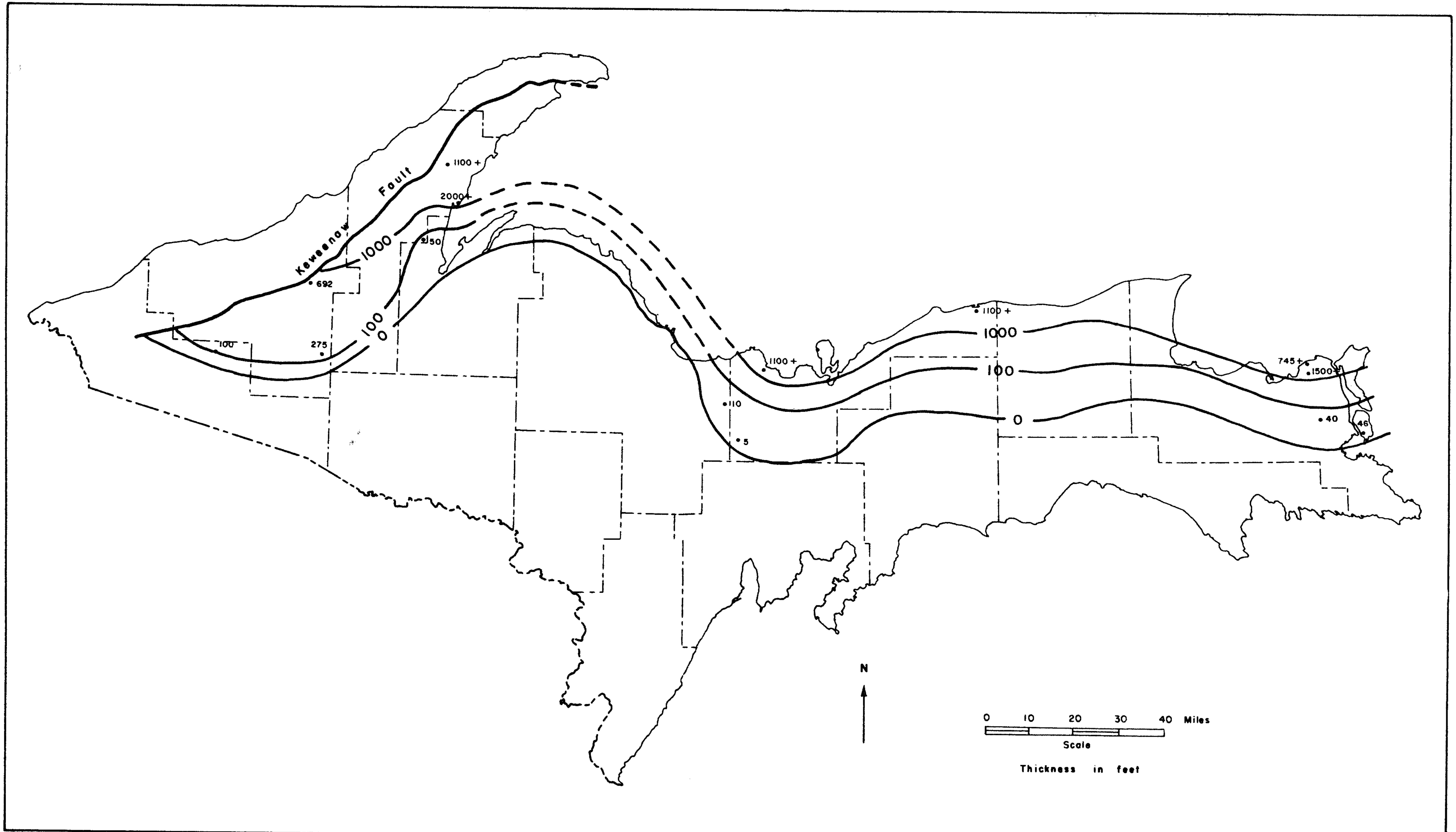
Percent by Number
0 10 20 30 40 50 60 70 80 90 100
Location
+ Gay
+ Traverse Bay
+ Traverse Island
+ Jacobsville
Wall Ravine
+ Keweenaw Bay
+ Sturgeon Falls
* L'Anse
+ Skanee
* Big Bay
± Presque Isle
± State Prison
± Shot Point
± Laughing Fish Pt.
± Scott Falls
± Au Train Pt.
± Grand Island
± Au Sable Pt.
± Au Sable Falls
Parisian Island
Sugar Island
Garnet
Tourmaline
Opaque
Zircon
Leucoxene
Others
+ Denning, 1949
* Tyler et al, 1940
± Driscoll, 1956

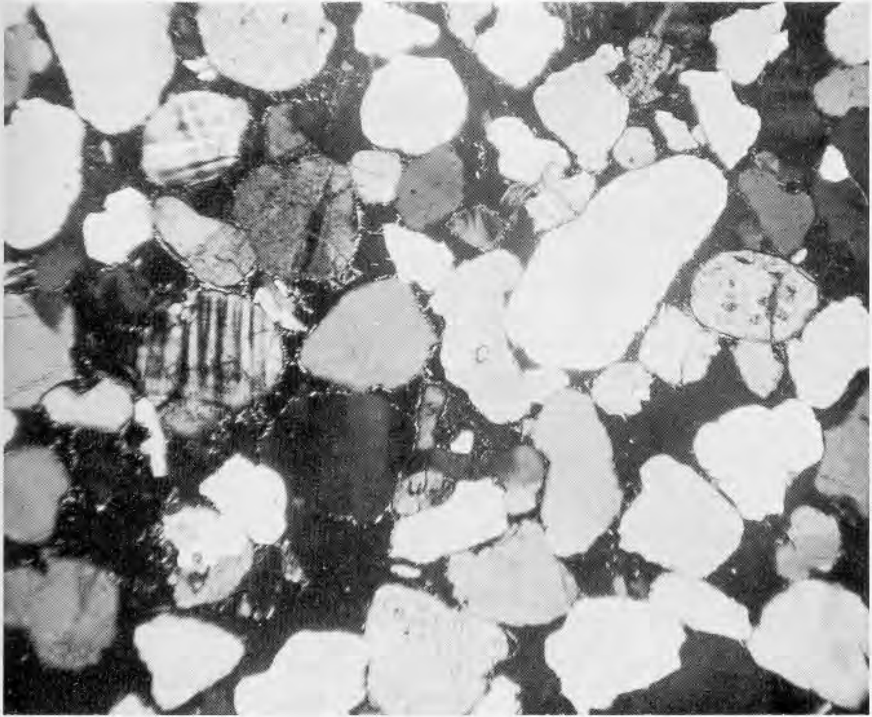


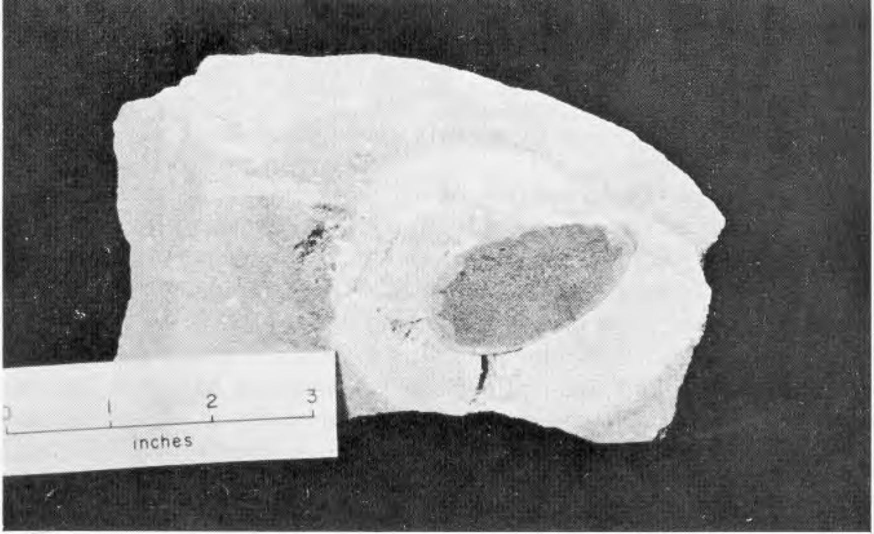
+ after Driscoll, (1956)

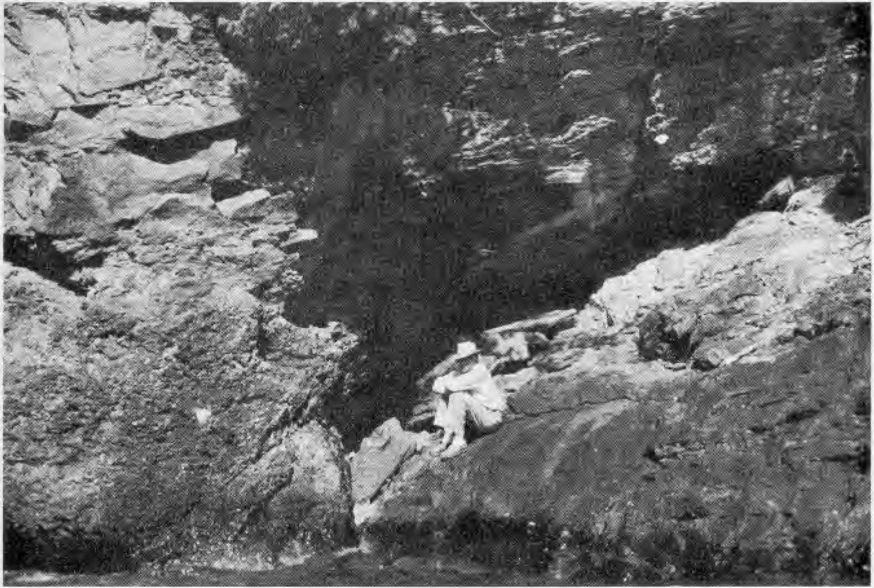


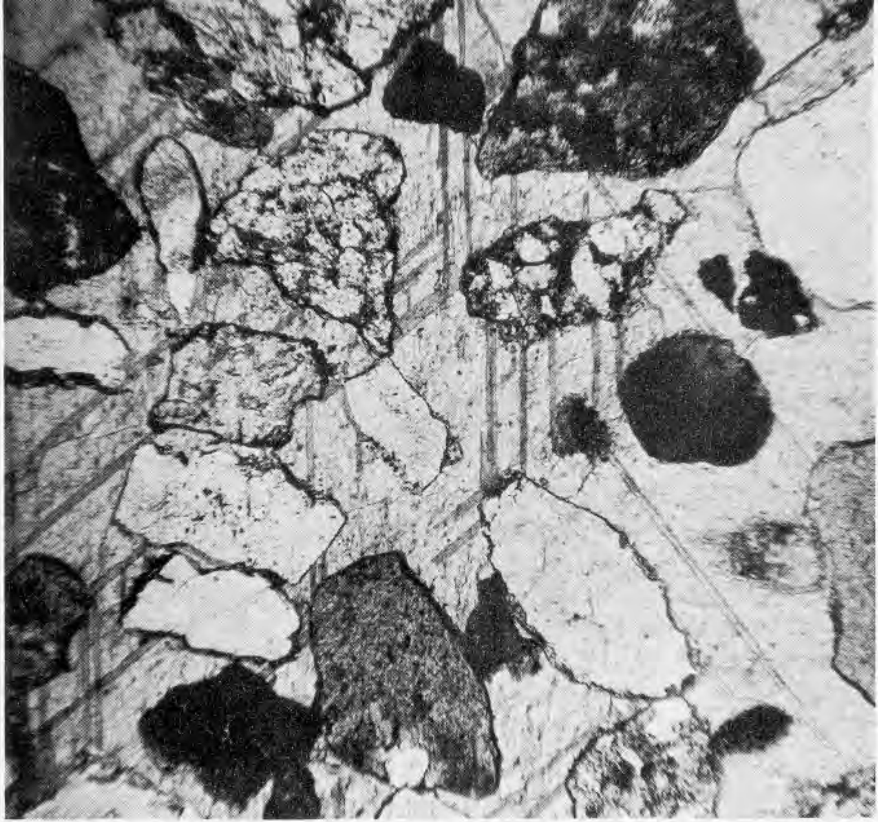
1841 Houghton	1851 Foster & Whitney	1873 Rominger	1883 Irving	1900 Van Hise & Bayley	1907 Lane & Seaman	1916 Allen et. al.	1936 Martin	1943 Thwaites	1945 Cohee	1951 Oetking	This Paper
Limerock	Calciferous	Chazy Ls. & Calciferous	L Magnesian or Calciferous	L Sil. or Ord.: Hermansville	L Ord.: Calciferous	L Ord.: Hermansville	Ozarkian: Hermansville	€ & Ord.: Prairie du Chien; Trempeleau	Hermansville: Prairie du Chien; Trempeleau; Jordan	M Ord.: Black River / Hermansville (L. Ord)	M Ord.: Au Train
Lake Superior Sandstone: Upper Gray Ss.; Lower Red Ss.	Lower Silurian: Potsdam	(upper Gray); Lake Superior Sandstone (Potsdam); (Lower Red)	Cambrian: Eastern and Western Sandstone	Cambrian: Lake Superior Sandstone	Cambrian: Lake Superior Sandstone: Munising; Jacobsville; Freda	Upper Cambrian: Munsing; Jacobsville	Upper Cambrian: Trempeleau; Mazomanie (Munising); Dresbach (L Munising); Jacobsville	Munising (Franconia)	Munising: Franconia; Dresbach; Eau Clair; Jacobsville	Munising: Franconia; Dresbach	Upper Cambrian: Munising: Miners Castle; Chapel Rock. L & M Cambrian: Jacobsville
Conglomerate	Trappean	Trappean	Precambrian	Keweenawan	Nonesuch	Freda	Freda	Jacobsville (Bayfield); Freda	Freda	Upper Keweenawan: Jacobsville (Bayfield); Freda	Freda

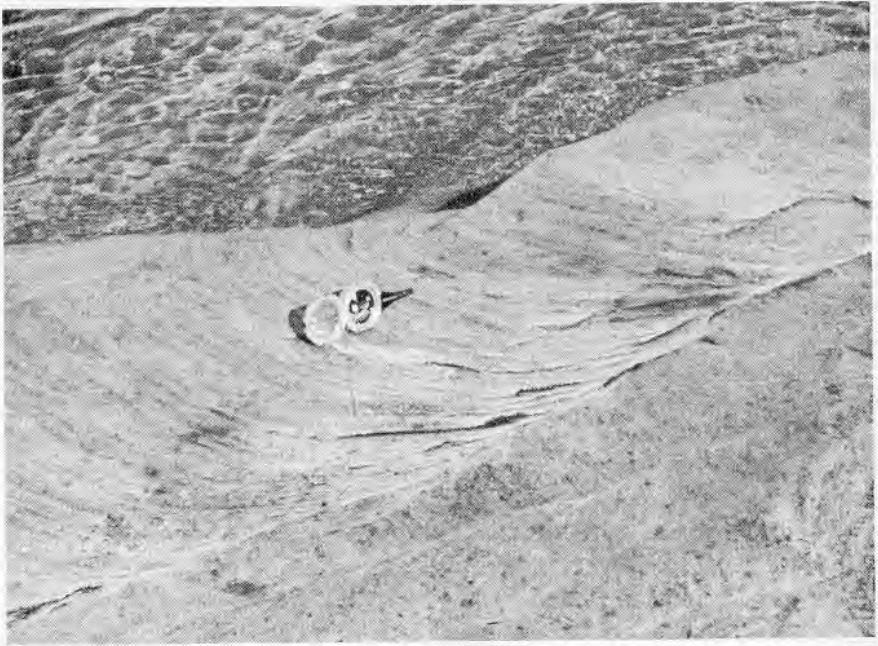

Keweenaw Fault
1100 +
2000+
1000
150
692
100
0
100
275
1100 +
1000
1100 +
100
110
5
0
745+
1500+
40
46
N
0 10 20 30 40 Miles
Scale
Thickness in feet

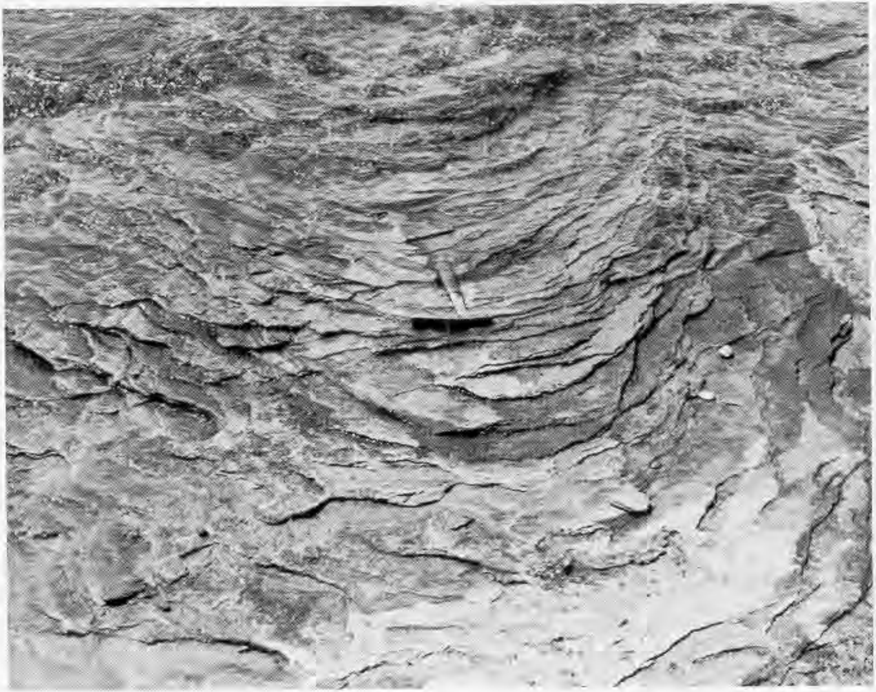


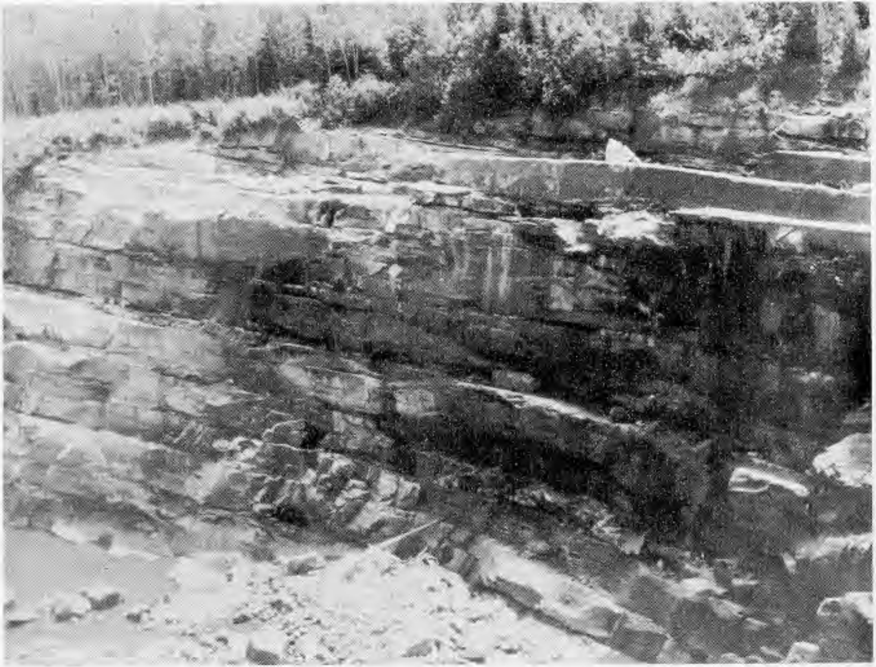

0
1
2
3
inches

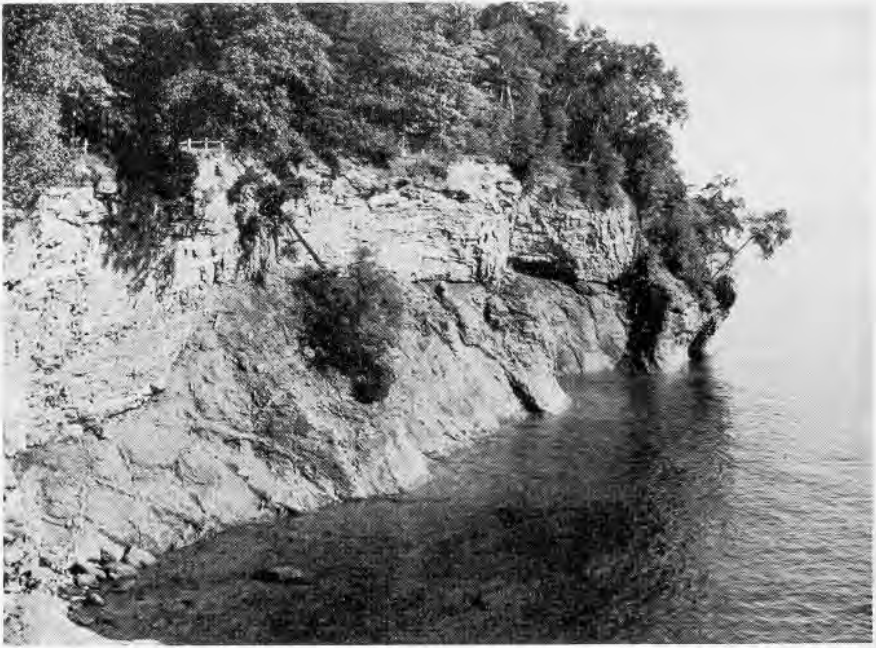


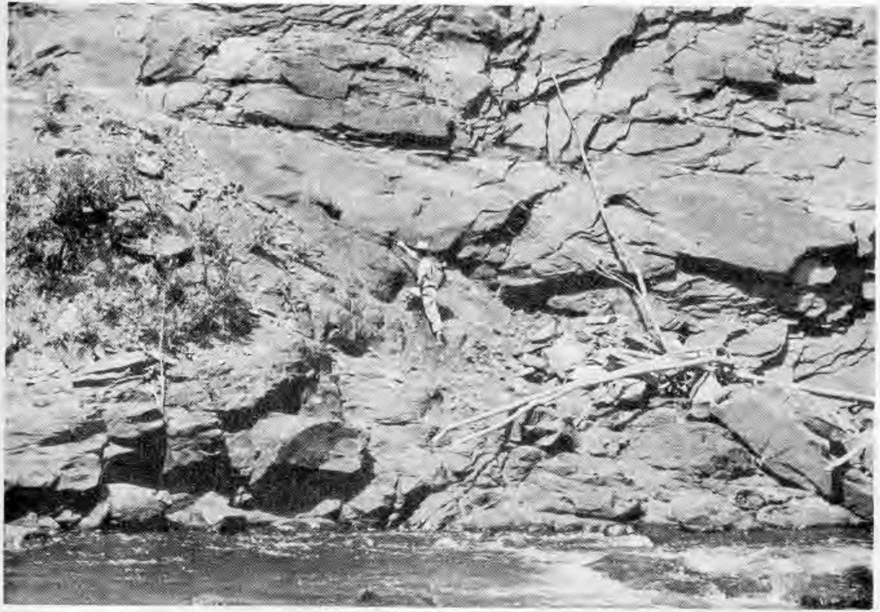


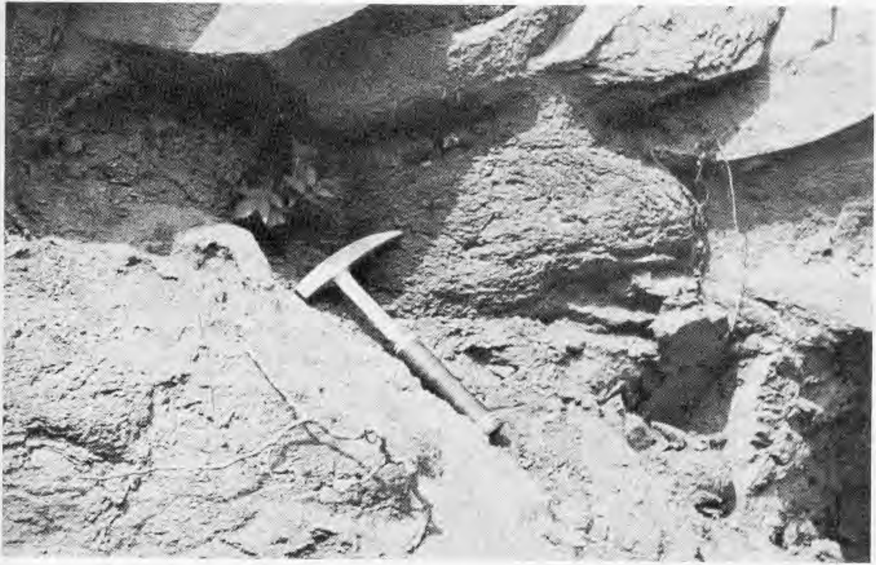


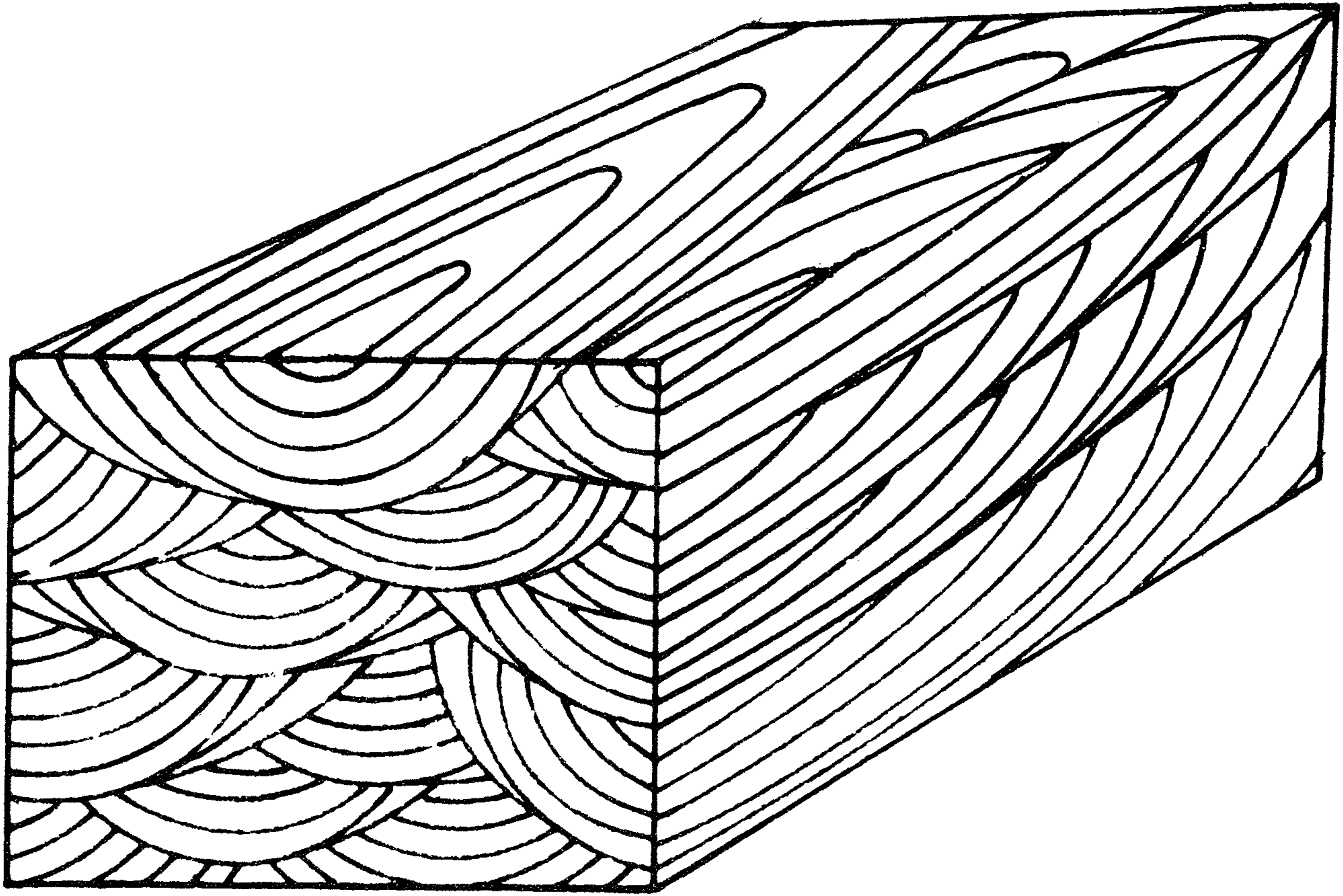


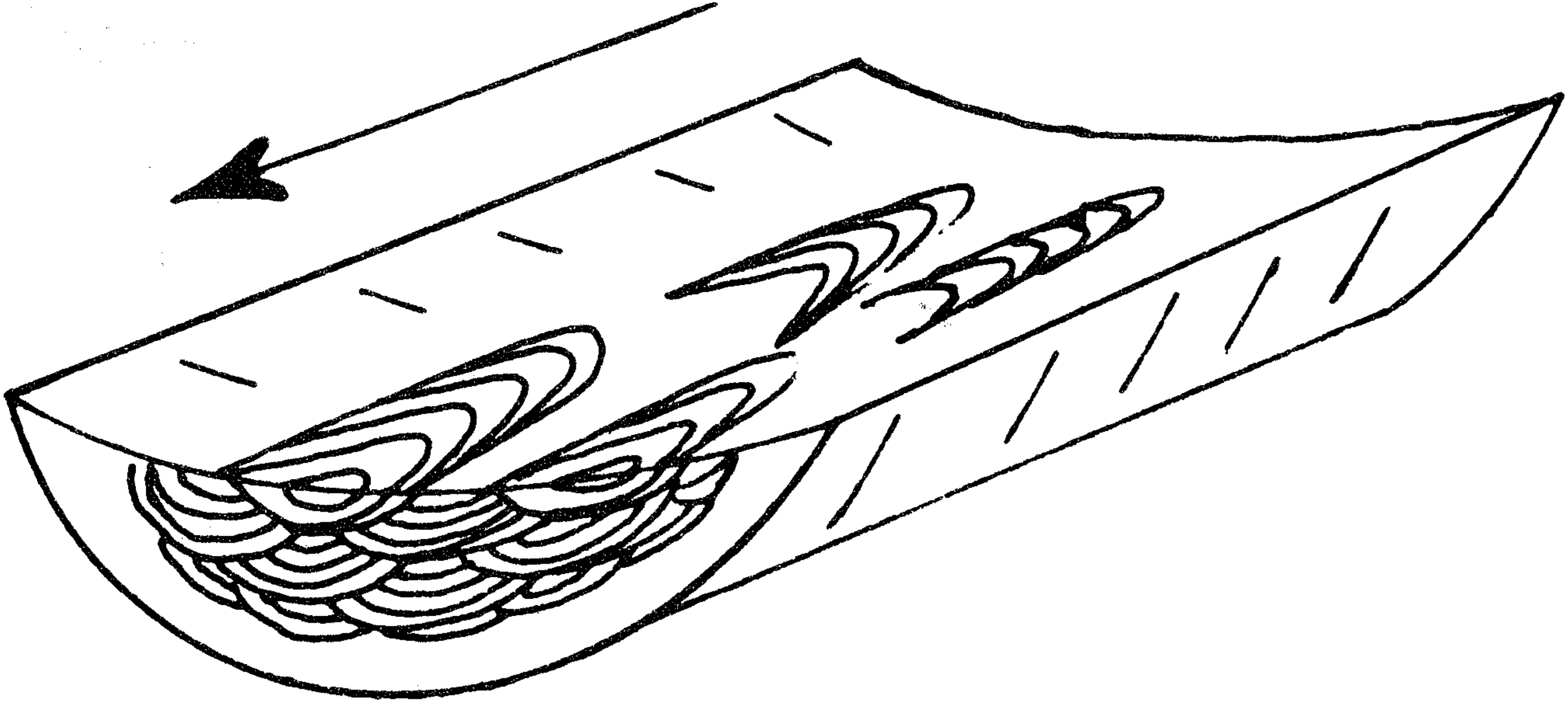


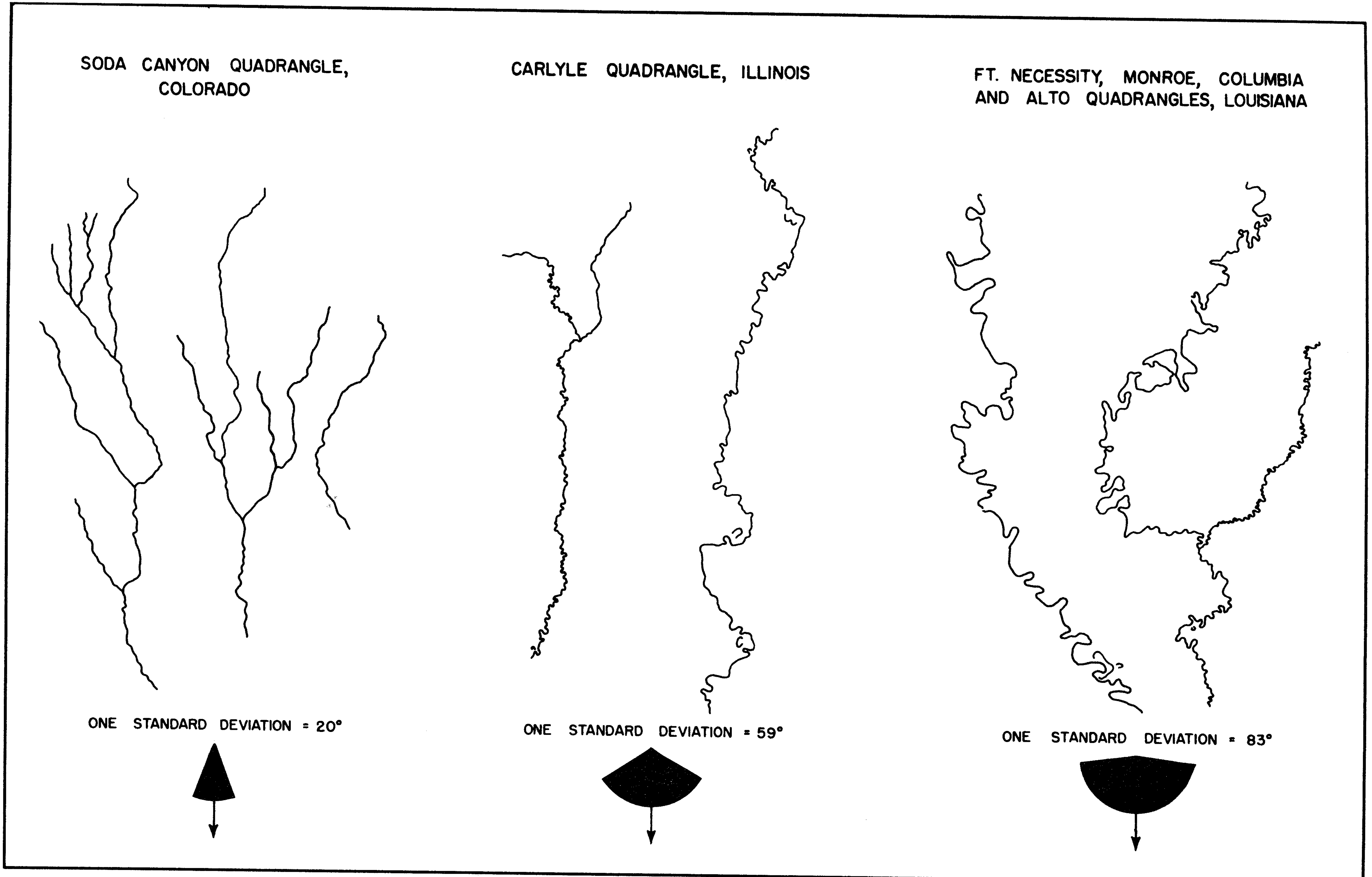




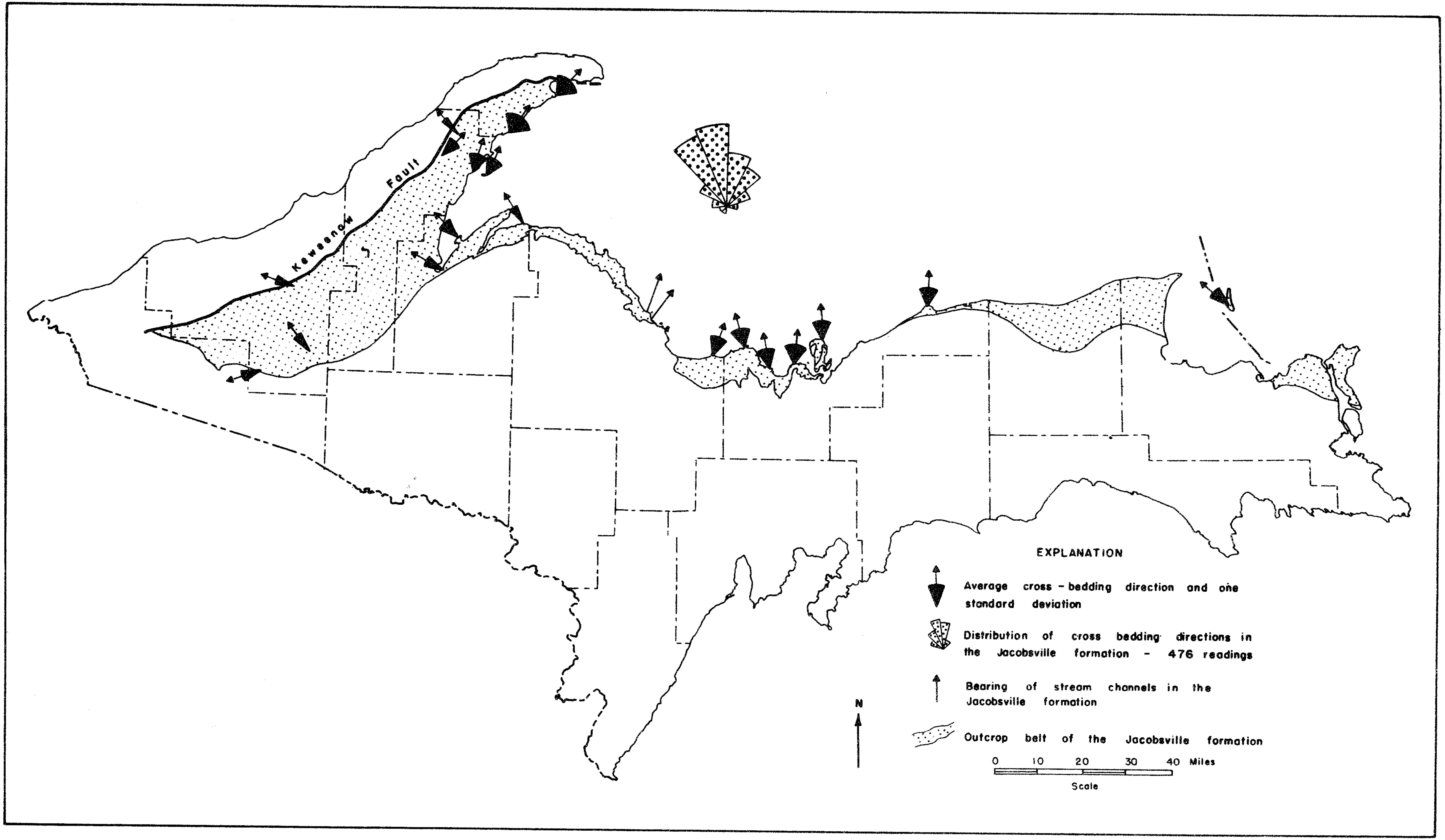


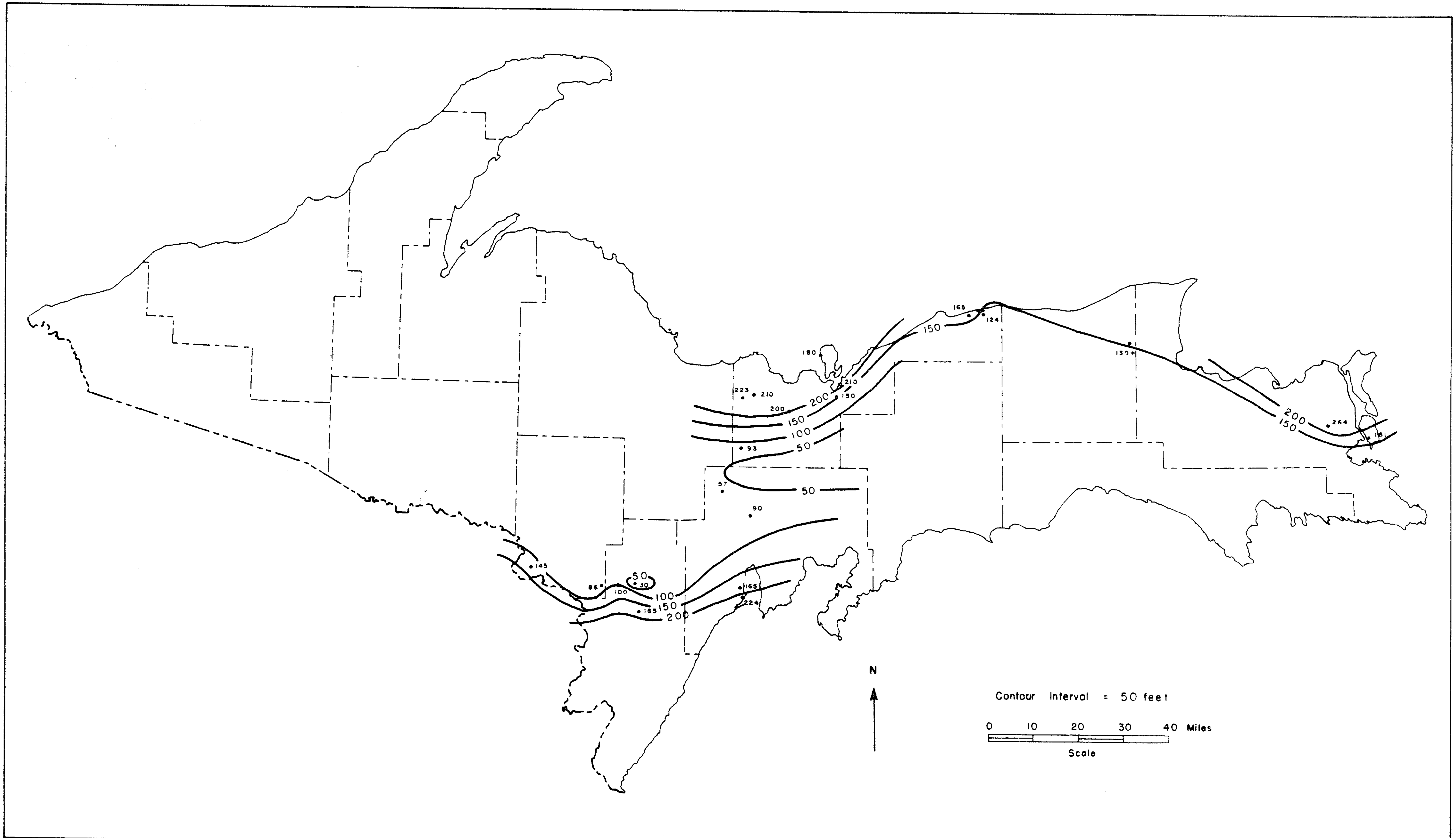




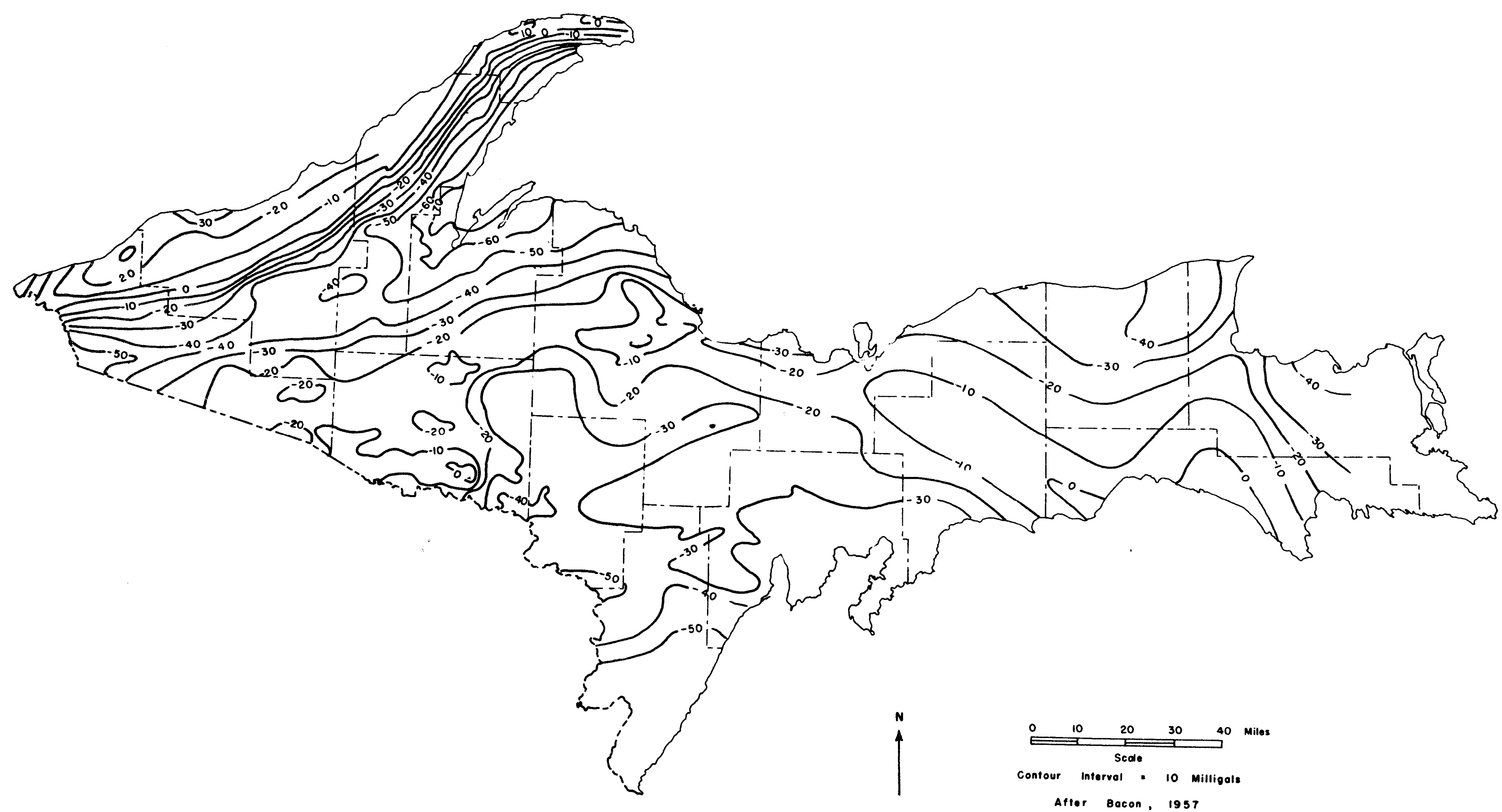


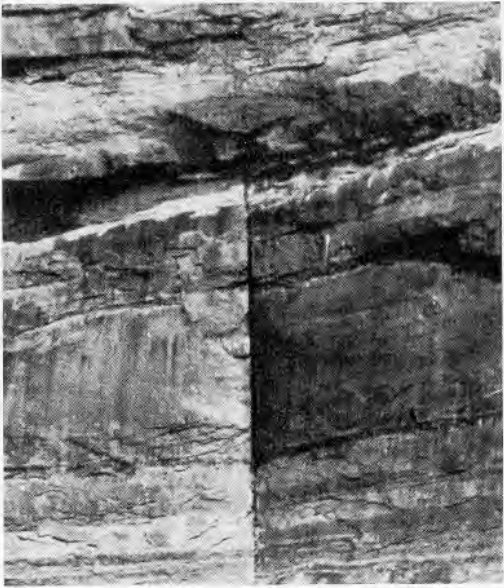
SODA CANYON QUADRANGLE, COLORADO
CARLYLE QUADRANGLE, ILLINOIS
FT. NECESSITY, MONROE, COLUMBIA AND ALTO QUADRANGLES, LOUISIANA
ONE STANDARD DEVIATION = 20°
ONE STANDARD DEVIATION = 59°
ONE STANDARD DEVIATION = 83°

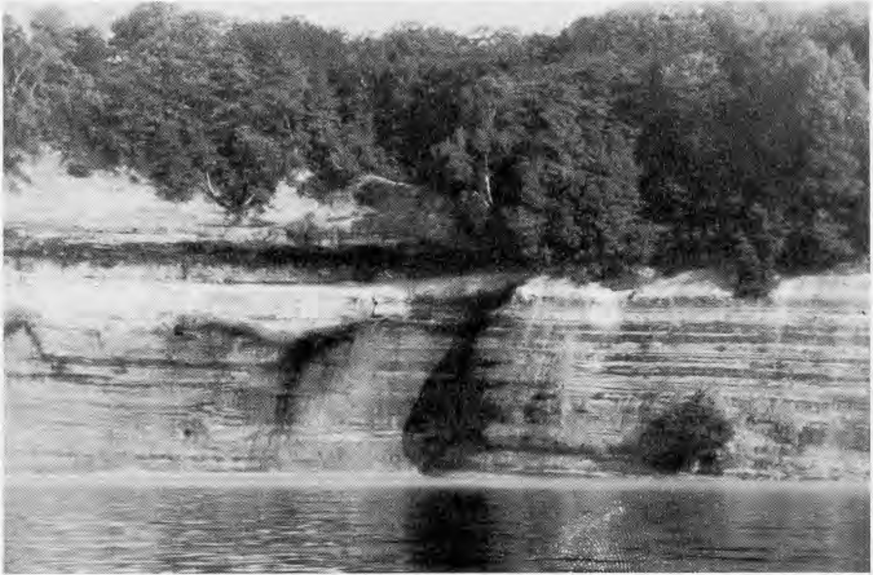

Keweenaw Fault
EXPLANATION
Average cross - bedding direction and one standard deviation
Distribution of cross bedding directions in the Jacobsville formation - 476 readings
Bearing of stream channels in the Jacobsville formation
Outcrop belt of the Jacobsville formation
N
0 10 20 30 40 Miles
Scale

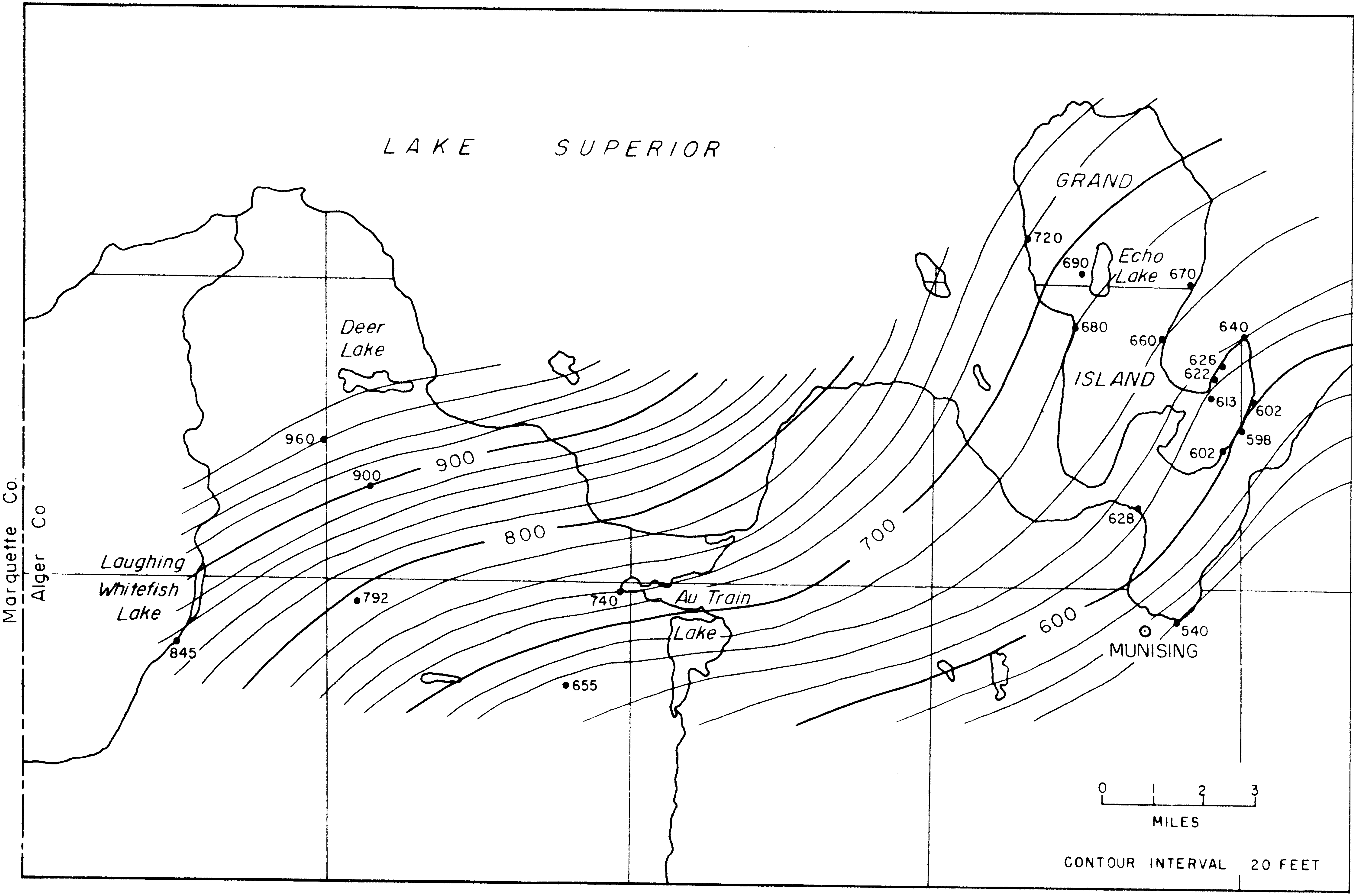


165
124
150
180
210
223
210
200
200
150
150
100
93
50
57
50
90
132+
200
150
264
161
145
86
50
30
100
100
150
165
200
165
224
N
Contour Interval = 50 feet
0 10 20 30 40 Miles
Scale

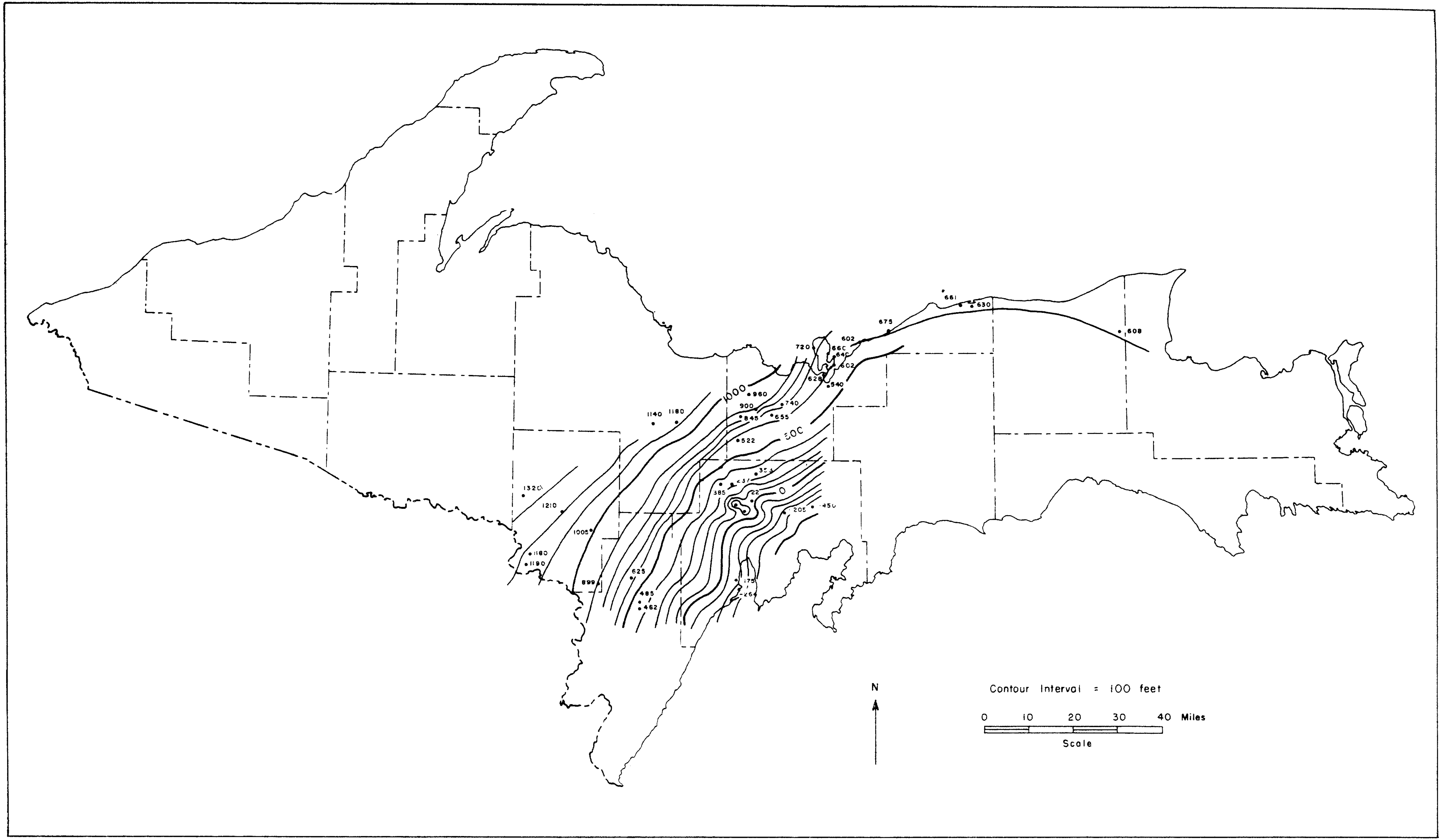

N
0 10 20 30 40 Miles
Scale
Contour Interval = 10 Milligals
After Bacon, 1957

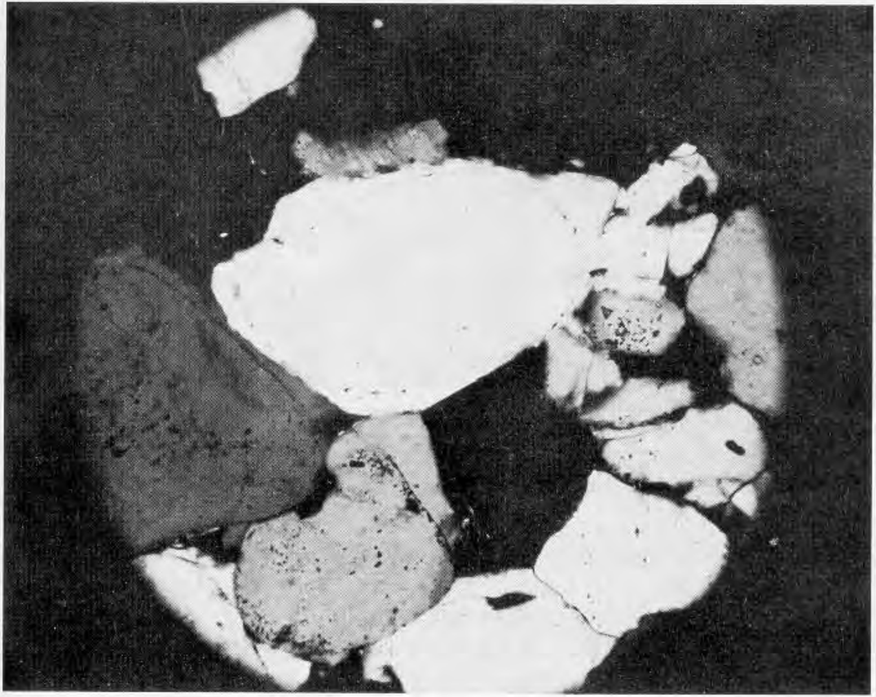


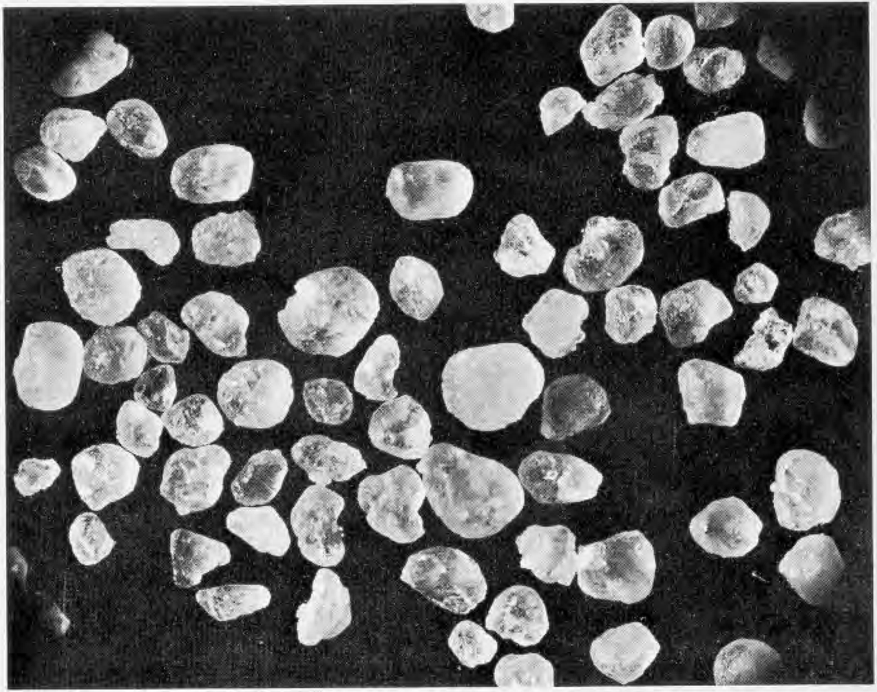


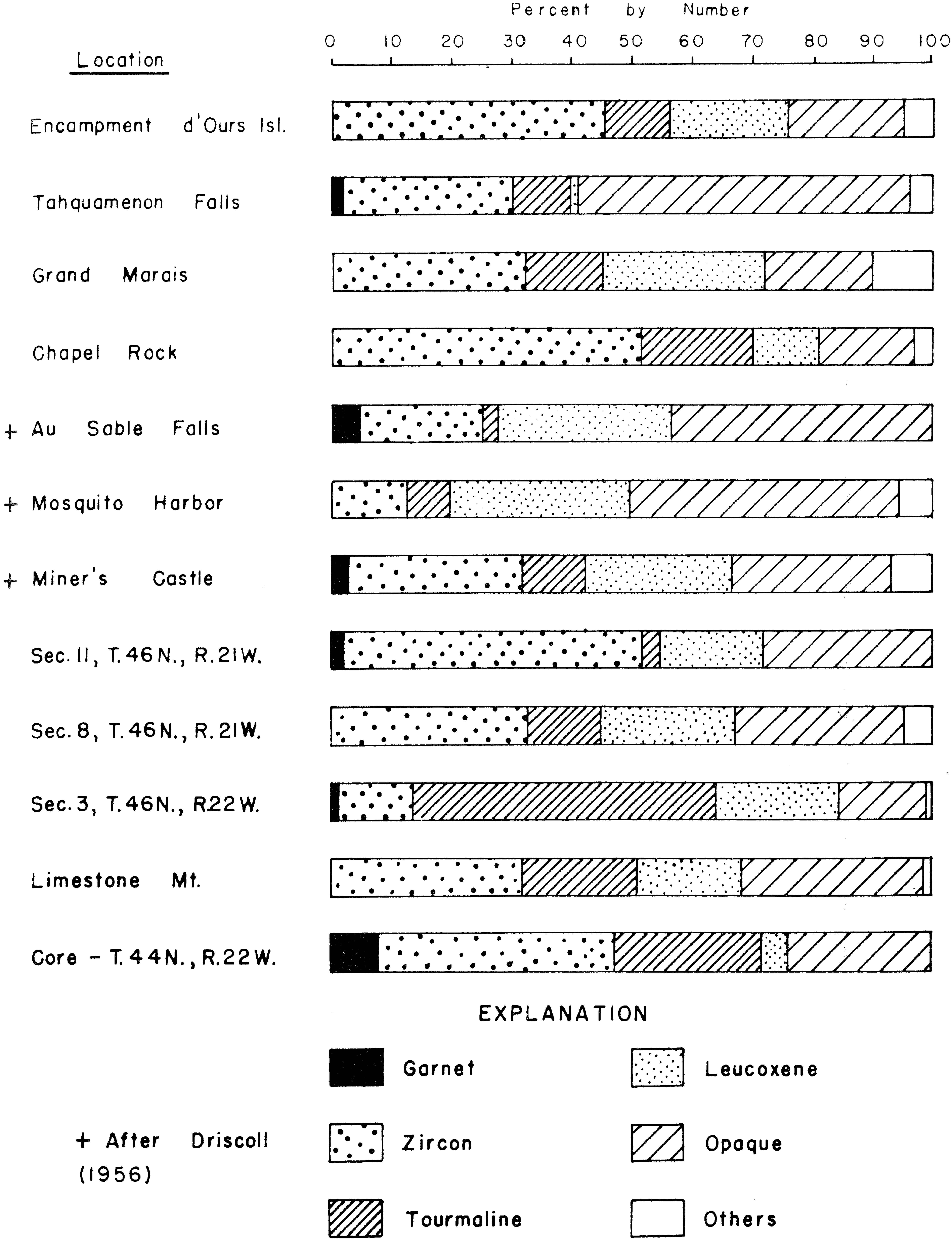


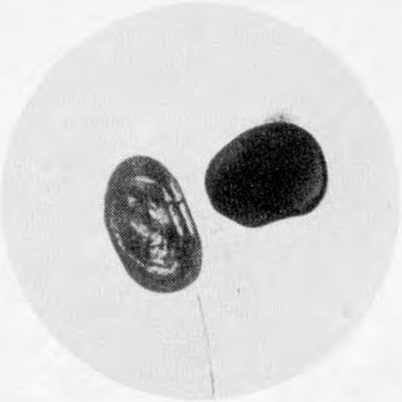
LAKE SUPERIOR
GRAND ISLAND
Echo Lake
Deer Lake
Laughing Whitefish Lake
Au Train Lake
MUNISING
Marquette Co
Alger Co
900
800
700
600
960
900
792
845
740
655
720
690
670
680
660
640
626
622
613
602
598
602
628
540
0 1 2 3
MILES
CONTOUR INTERVAL 20 FEET

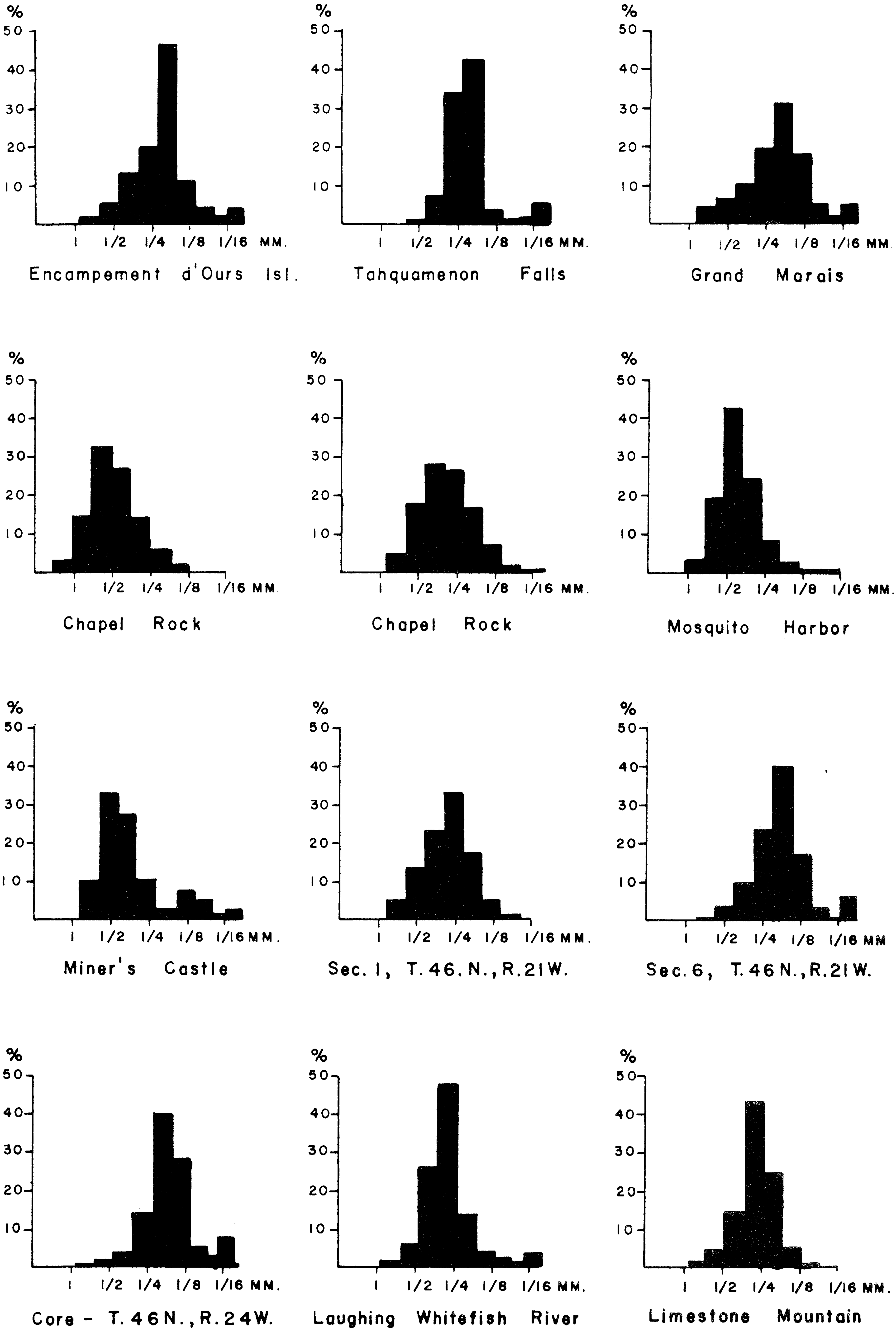

1000
500
0
1320
1210
1005
1180
1190
899
1140
1180
625
485
462
960
900
848
740
655
522
354
237
385
22
205
450
175
-264
720
660
640
602
628
540
602
675
681
630
608
N
Contour Interval = 100 feet
0 10 20 30 40 Miles
Scale



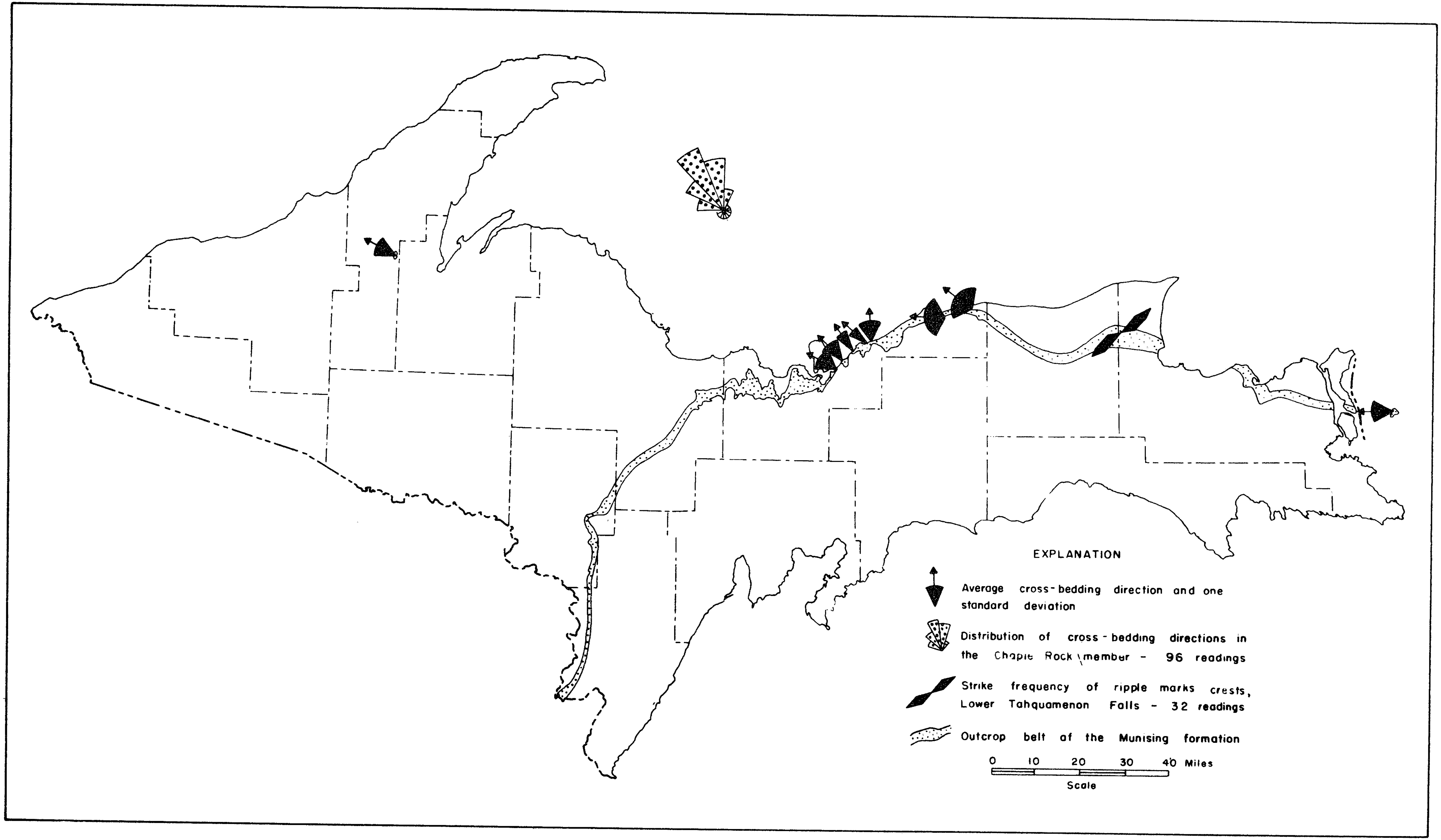


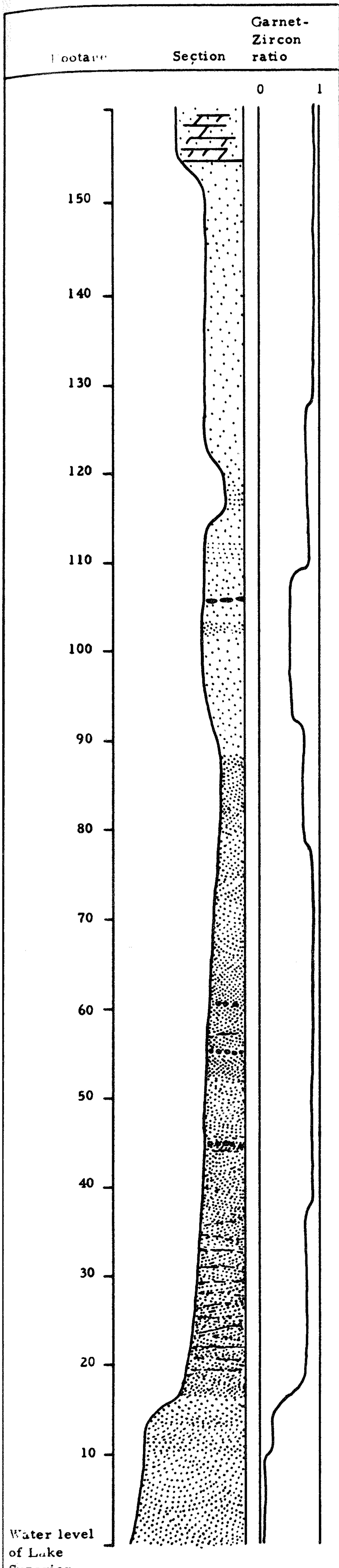

Percent by Number
0
10
20
30
40
50
60
70
80
90
100
Location
Encampment d'Ours Isl.
Tahquamenon Falls
Grand Marais
Chapel Rock
+ Au Sable Falls
+ Mosquito Harbor
+ Miner's Castle
Sec. 11, T. 46 N., R. 21 W.
Sec. 8, T. 46 N., R. 21 W.
Sec. 3, T. 46 N., R22 W.
Limestone Mt.
Core – T. 44 N., R. 22 W.
EXPLANATION
Garnet
Zircon
Tourmaline
Leucoxene
Opaque
Others
+ After Driscoll (1956)





%
50
40
30
20
10
1
1/2
1/4
1/8
1/16 MM.
Encampement d'Ours Isl.
Tahquamenon Falls
Grand Marais
Chapel Rock
Chapel Rock
Mosquito Harbor
Miner's Castle
Sec. 1, T. 46. N., R. 21 W.
Sec. 6, T. 46 N., R. 21 W.
Core - T. 46 N., R. 24 W.
Laughing Whitefish River
Limestone Mountain


EXPLANATION
Average cross-bedding direction and one standard deviation
Distribution of cross-bedding directions in the Chapie Rock member - 96 readings
Strike frequency of ripple marks crests, Lower Tahquamenon Falls - 32 readings
Outcrop belt of the Munising formation
0 10 20 30 40 Miles
Scale



Description of lithology

Dolomitic sandstone, light brown, very resistant

Base of AU TRAIN formation unconformity

Top of MUNISING formation - Miner's Castle member

Sandstone - white, medium-grained, friable, massive bedding (1' to 4' thick), forms vertical cliffs

Details of sedimentary structures obscured by weathering; many units appear to be cross-bedded

---

Sandstone - white, medium-grained, well sorted, massive bedding (1' to 2' thick), small caves and arches, friable

Numerous large concretions along bedding plane

Small-scale cross bedding

Red stains along certain horizons

Small-scale cross bedding

6" bed, very resistant, contains abundant matrix

Sandstone, predominantly white to gray, minor streaks of red, blue and green, poorly sorted

Base of Miner's Castle pinnacle

Coarse sandstone concentrated along certain bedding planes

Abundant clay pellets deposited parallel to the cross bedding

Channels and lenses of fine conglomerate

Small conglomerate lenses

Coarse sand and conglomerate lenses

Blue, green, red, and yellow coloration following bedding planes

---

Sandstone, gray to grayish-blue, medium-grained, poorly sorted, small-scale cross bedding 4"-6" thick separated by thin blue shale lenses 1/4"-1" thick (approximately 20-30 percent shale), some coarse and fine conglomerate

Base of Miner's Castle member unconformity

Top of Chapel Rock member

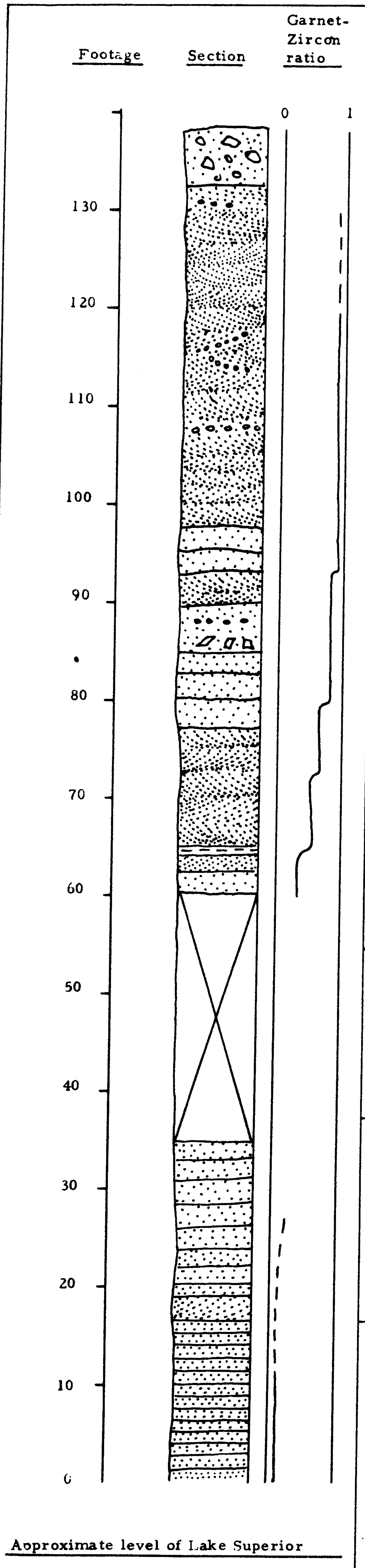
Sandstone, pink, coarse-grained, well sorted, rounded, abundant clay pellets

Mud cracks 4"-8" in diameter developed in beds of blue shale less than 1' thick.

Clay pellets

Sandstone, light brown to buff, well sorted

Large-scale cross bedding 10' thick.



Description of lithology

Drift

Munising formation, Miner's Castle member

Sandstone, fine- to coarse-grained, containing numerous lenses of fine conglomerate, extremely friable, well rounded; minor blue shale lenses separating lower units; small-scale cross bedding

Poorly sorted, abundant coarse sand and fine conglomerate and blue shale and silt lenses

Crest of Upper Tahquamenon Falls

Blue shale lenses separate essentially every cross-bedded unit

Extremely friable

Fine conglomerate lenses

Intraformational conglomerate

Hard, weathers in blocks

Planar cross-bedding, approximately 20 percent clay- and silt-size particles

Shale, red, abundant mica, thin sandstone lenses interbedded near base

Sandstone, white, medium- to fine-grained, well rounded and frosted, extremely friable

Sandstone interbedded with thin blue shale beds 2"-4" thick; several horizons show oscillation ripple marks

Base of Upper Tahquamenon Falls

Covered area between Upper and Lower Tahquamenon Falls

Top of highest rapid in Lower Tahquamenon Falls

Munising formation, Chapel Rock member

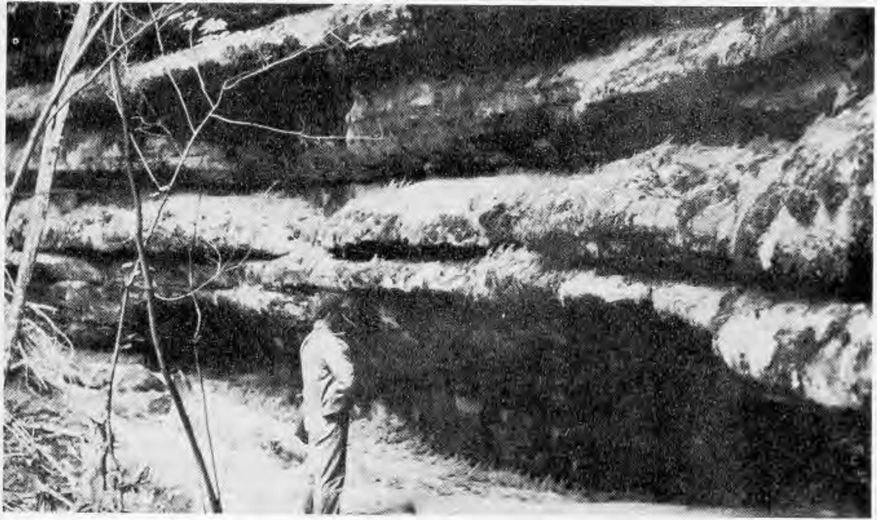
Sandstone, white to gray, weathers dark gray to black, medium- to fine-grained, extremely hard and well cemented by secondary quartz overgrowths; individual beds are between 8"-10" thick.

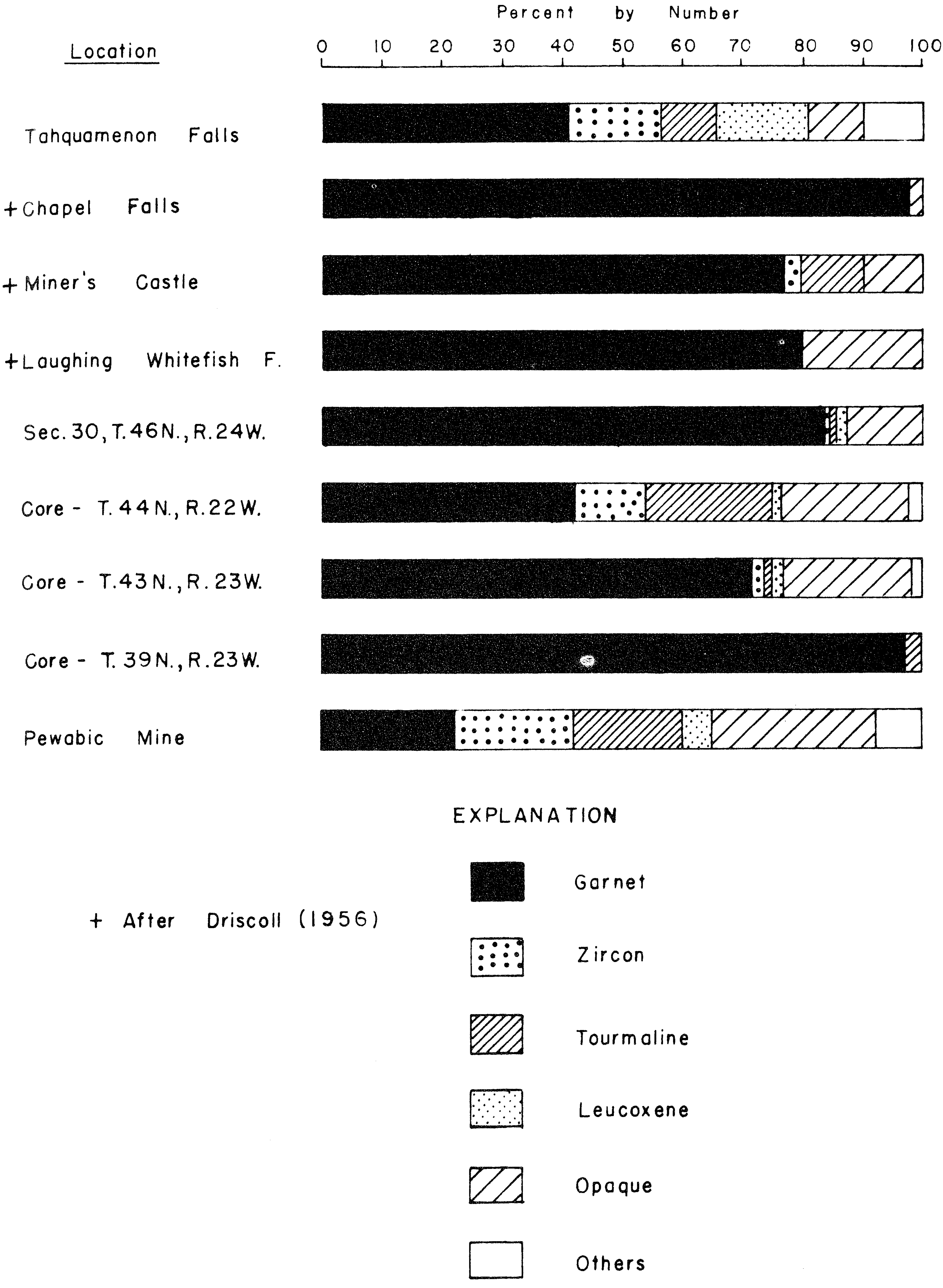
Top of major rapids

Planar cross bedding

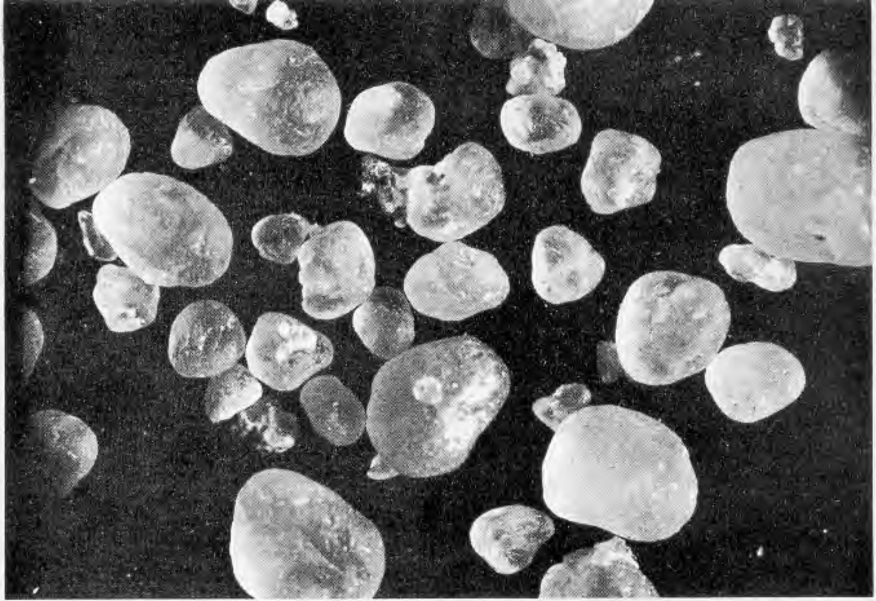
Sandstone, white, medium- to fine-grained, well cemented with quartz overgrowths; horizontal bedding planes are continuous laterally, beds 4"-6" thick, abundant current ripple marks

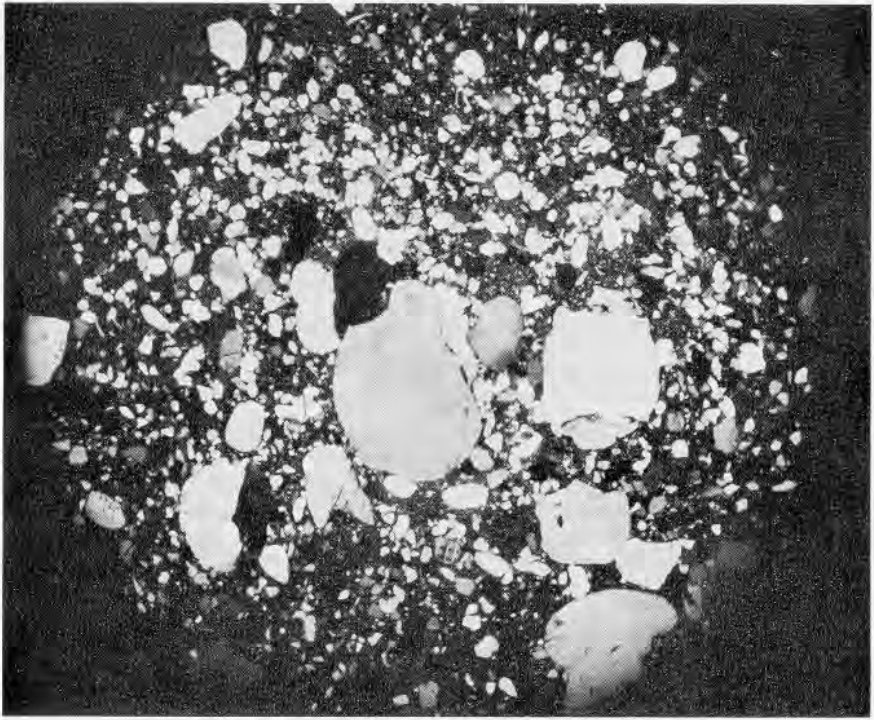
Base of Lower Tahquamenon Falls

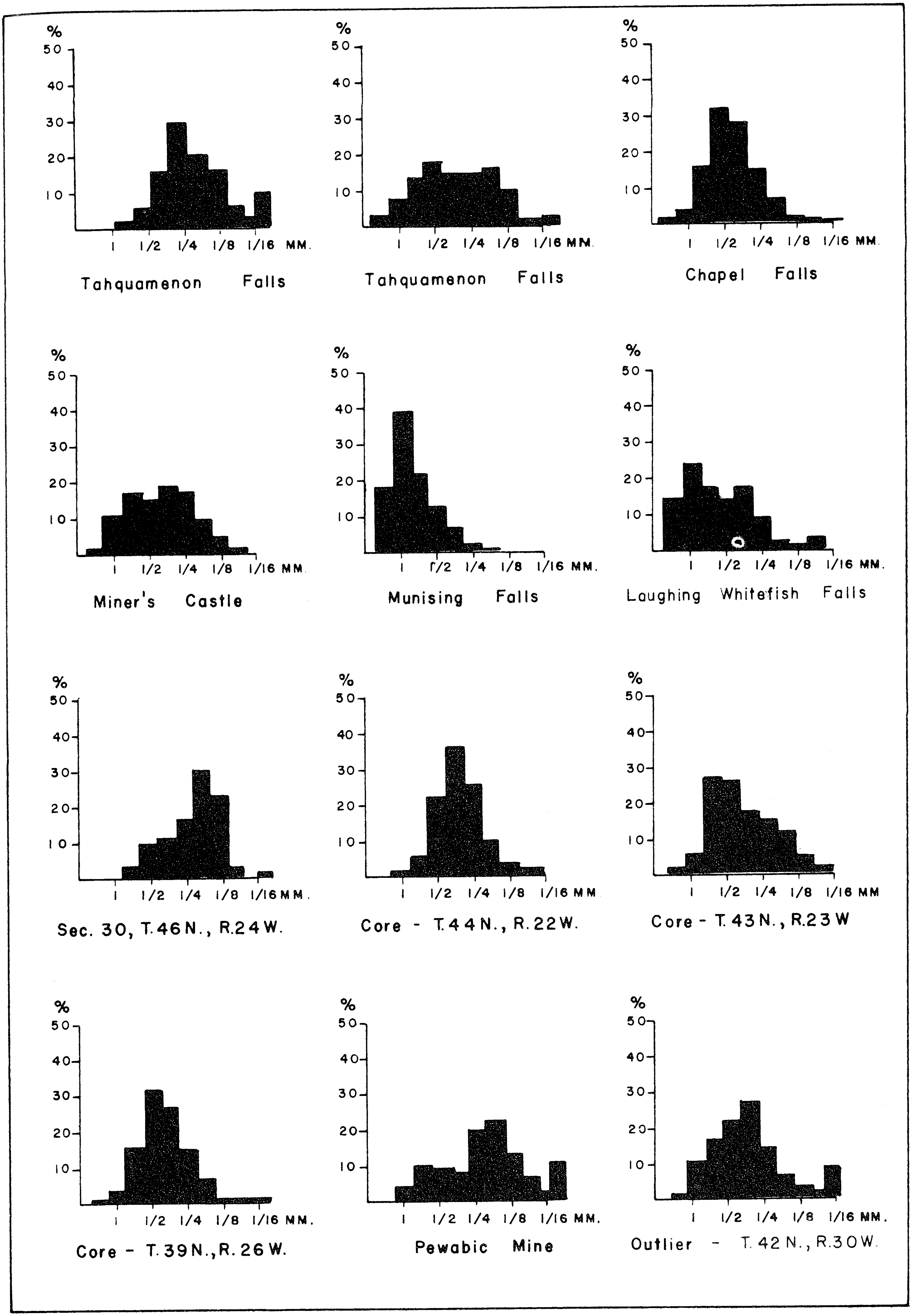


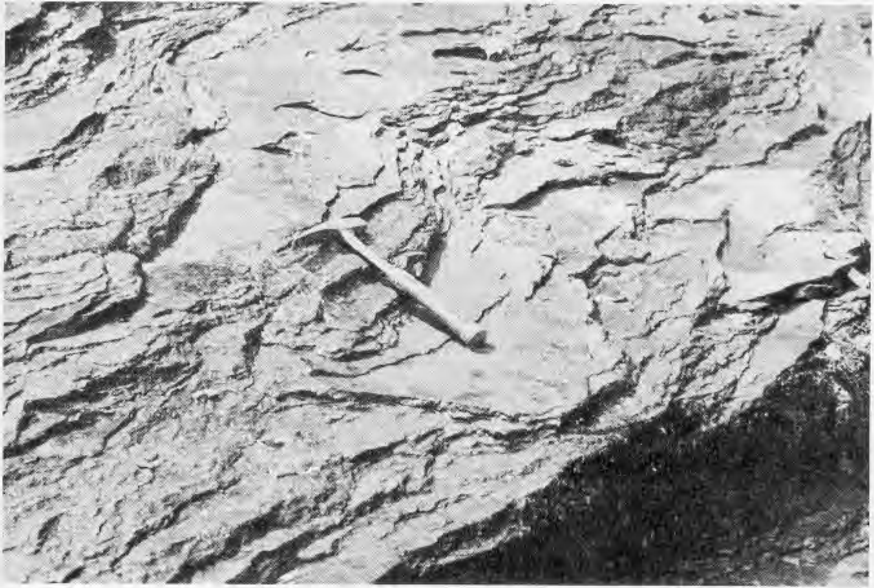


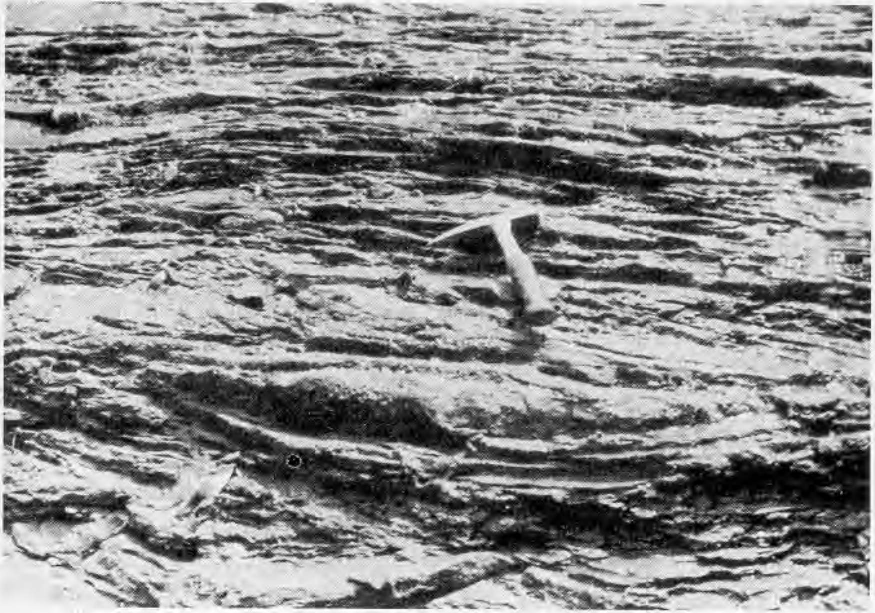
Percent by Number
Location
0 10 20 30 40 50 60 70 80 90 100
Tahquamenon Falls
+Chapel Falls
+Miner's Castle
+Laughing Whitefish F.
Sec. 30, T. 46 N., R. 24 W.
Core - T. 44 N., R. 22 W.
Core - T. 43 N., R. 23 W.
Core - T. 39 N., R. 23 W.
Pewabic Mine
EXPLANATION
Garnet
Zircon
Tourmaline
Leucoxene
Opaque
Others
+ After Driscoll (1956)

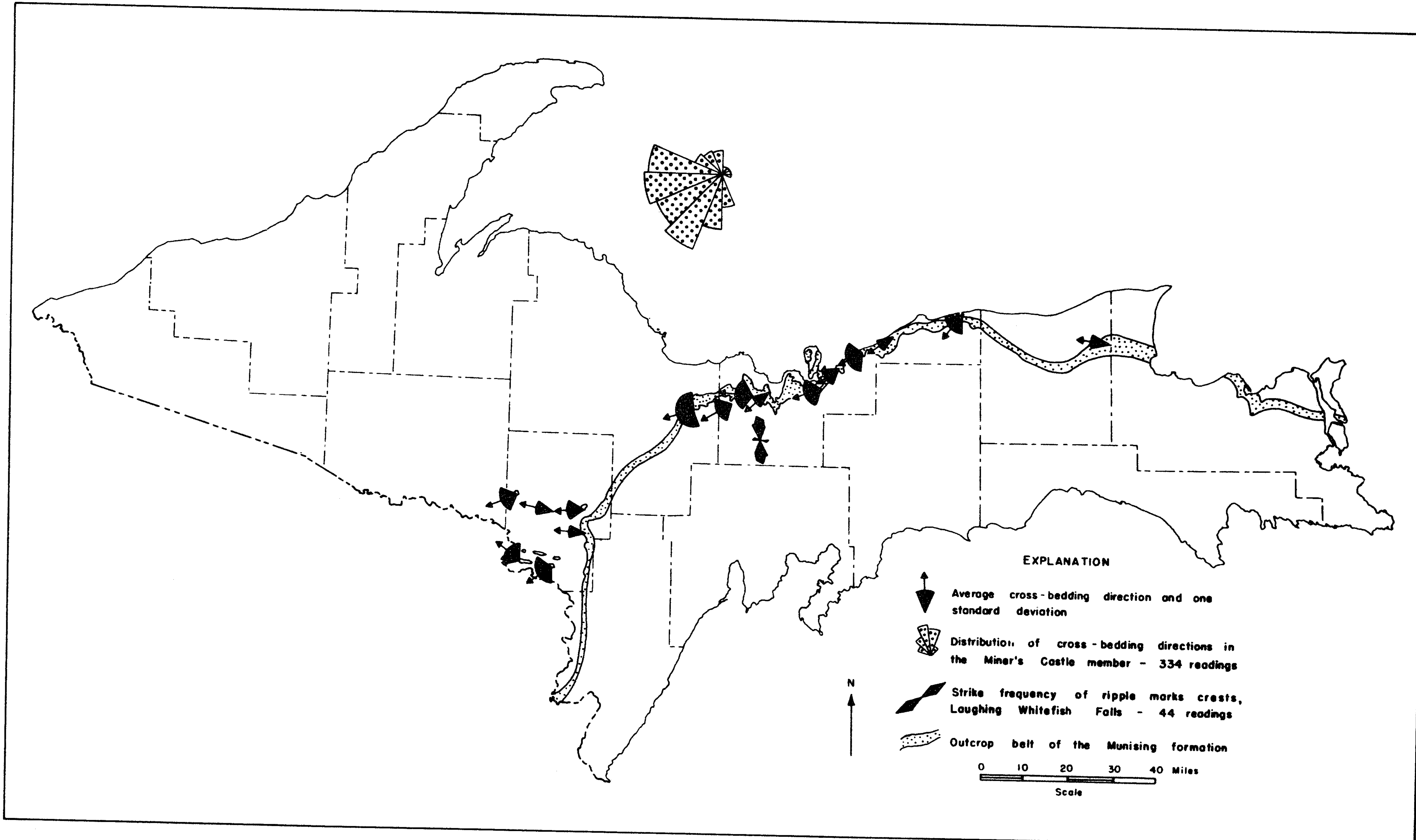


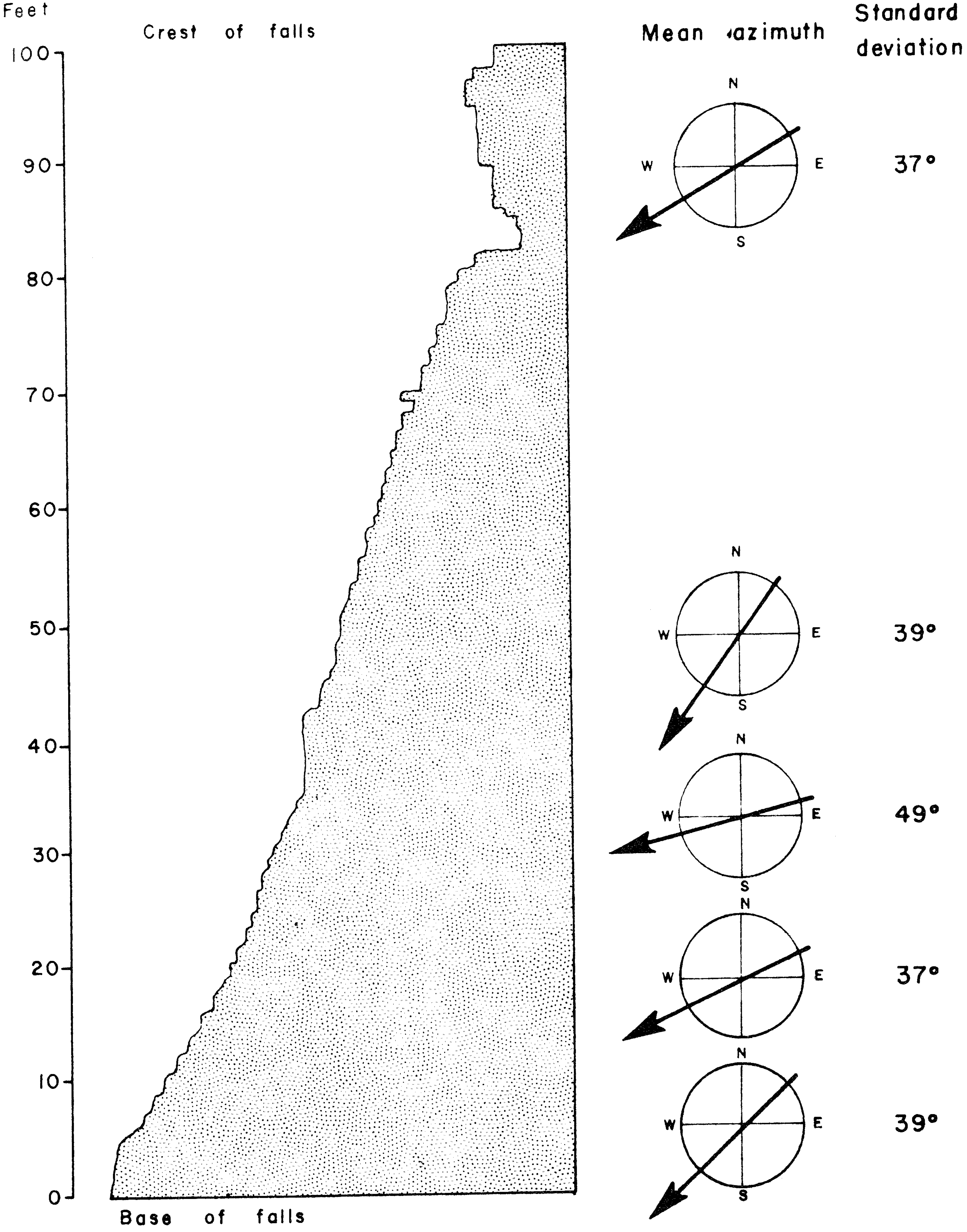



%
50
40
30
20
10
1
1/2
1/4
1/8
1/16 MM.
Tahquamenon Falls
Tahquamenon Falls
Chapel Falls
Miner's Castle
Munising Falls
Laughing Whitefish Falls
Sec. 30, T.46N., R.24W.
Core - T.44N., R.22W.
Core - T.43N., R.23W
Core - T.39N., R.26W.
Pewabic Mine
Outlier - T.42N., R.30W.

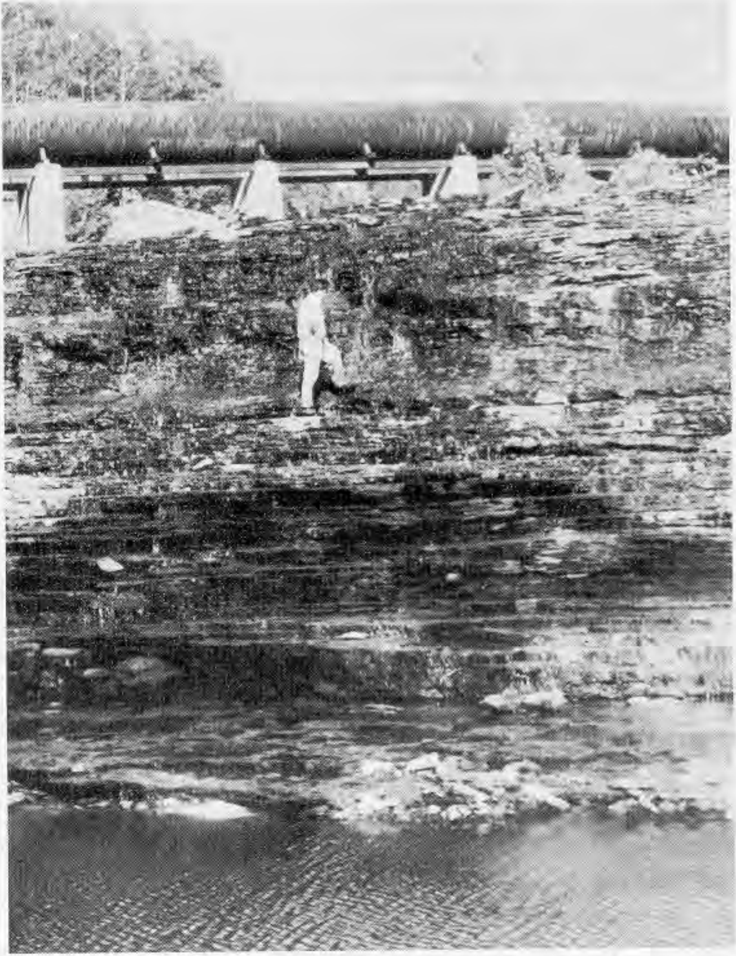




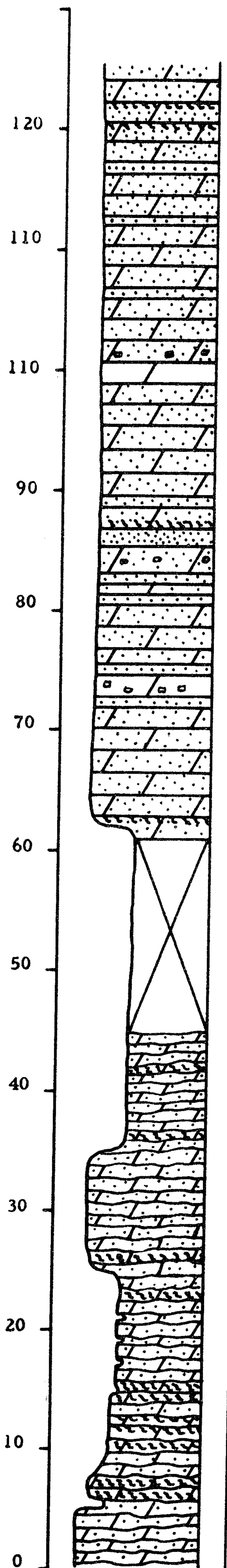

EXPLANATION
Average cross-bedding direction and one standard deviation
Distribution of cross-bedding directions in the Miner's Castle member - 334 readings
N
Strike frequency of ripple marks crests, Laughing Whitefish Falls - 44 readings
Outcrop belt of the Munising formation
0 10 20 30 40 Miles
Scale


Feet
Crest of falls
Base of falls
100
90
80
70
60
50
40
30
20
10
0
Mean azimuth
Standard deviation
N
W
E
S
37°
39°
49°
37°
39°

1. Pewabic Mine
2. Core - sec. 7, T. 39 N., R. 26 W.
3. Core - sec. 26, T. 42 N., R. 22 W.
4. Core - sec. 35, T. 43 N., R. 23 W
5. Core - sec. 9, T. 44 N., R23 W.
6. Laughing Whitefish Falls
7. Au Train Falls
8. Munising Paper Mill Well
9. Munising Falls
10. Miner's Castle
11. Chapel Falls
12. Au Sable Falls
13. Chipmunk Falls & Grand Marais Well
14. Tahquamenon Falls
BLACK RIVER GROUP
Bony Falls limestone
AU TRAIN FM.
AU TRAIN FORMATION
Miner's Castle member
Prosaukia zone
PRECAMBRIAN
MUNISING FM.
Miner's Castle member
MUNISING FM
Chapel Rock member
JACOBSVILLE FORMATION
Index map
Feet
150
100
50
0
0 5 10 15 Miles
Scale
EXPLANATION
Limestone
Sandy dolomite
Sandstone, small scale cross-bedding, high garnet
Sandstone, large scale cross-bedding, high zircon
Sandstone, cross-bedded, red and white mottling
Metamorphic rocks
Oolites
Glauconite



Footage	Section	Description of lithology



Top of Upper Au Train Falls

Sandy dolomite, grayish-blue to dark blue, beds 4-10 inches thick, some interbedded buff fine- to medium-grained sandstone units, several horizons contain abundant glauconite and authigenic pyrite

Glauconitic

Sandstone bed 6" thick, buff to light gray, medium- to fine-grained, well rounded and well sorted

Sandstone bed, same as above

Sandstone bed, same as above

Authigenic pyrite filling vugs

Pure dolomite

Highly glauconitic

Authigenic pyrite filling vugs

Sandstone bed 8" thick, fine- to medium-grained, buff to light gray, well rounded and well sorted

Abundant authigenic pyrite

Highly glauconitic

Base of Upper Au Train Falls

Covered interval between Upper and Lower Au Train Falls

Sandy dolomite to dolomitic sandstone, buff to bluish-gray, beds 2"-6" thick, generally separated by thin lenses of silt or clay, bedding planes are undulatory, percent of sand varies throughout the section, glauconite extremely abundant especially near the base

Glauconite and clay galls

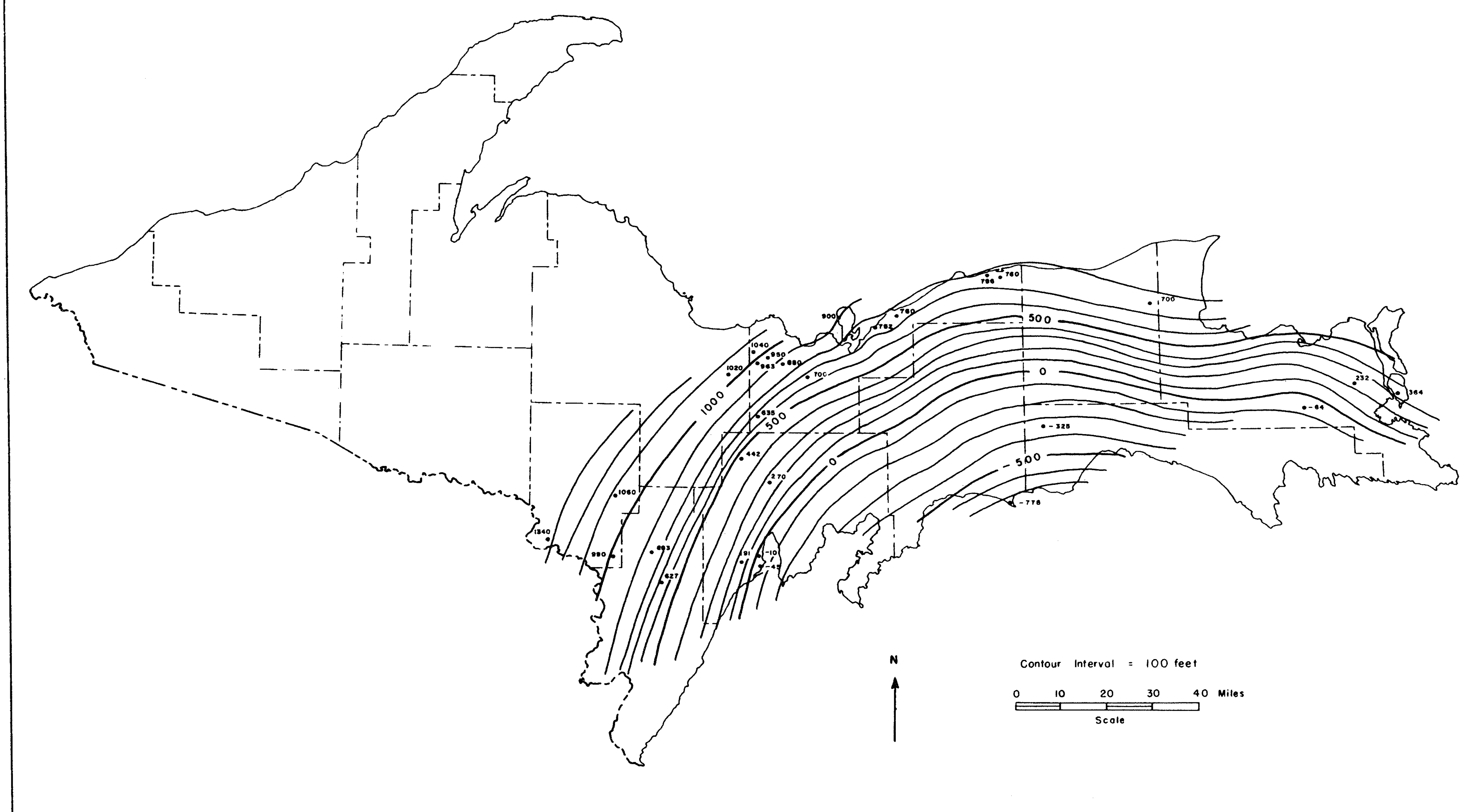
Crest of Lower Au Train Falls

Glauconite concentrated along several horizons, sandy units exhibit small-scale cross bedding, thin shale lenses separate units

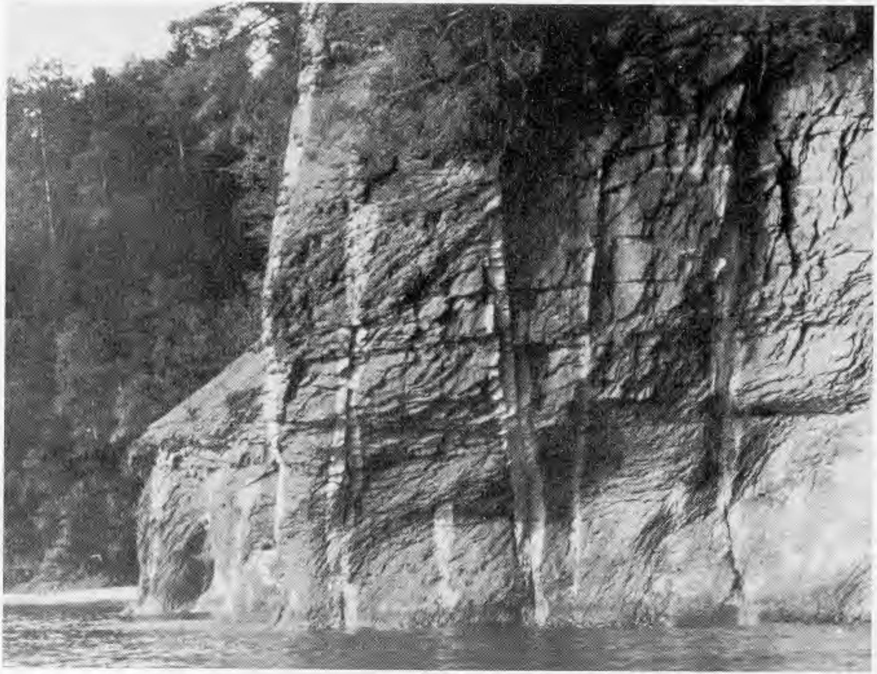
Glauconite is extremely abundant as it constitutes between 10-30 percent of many thin units

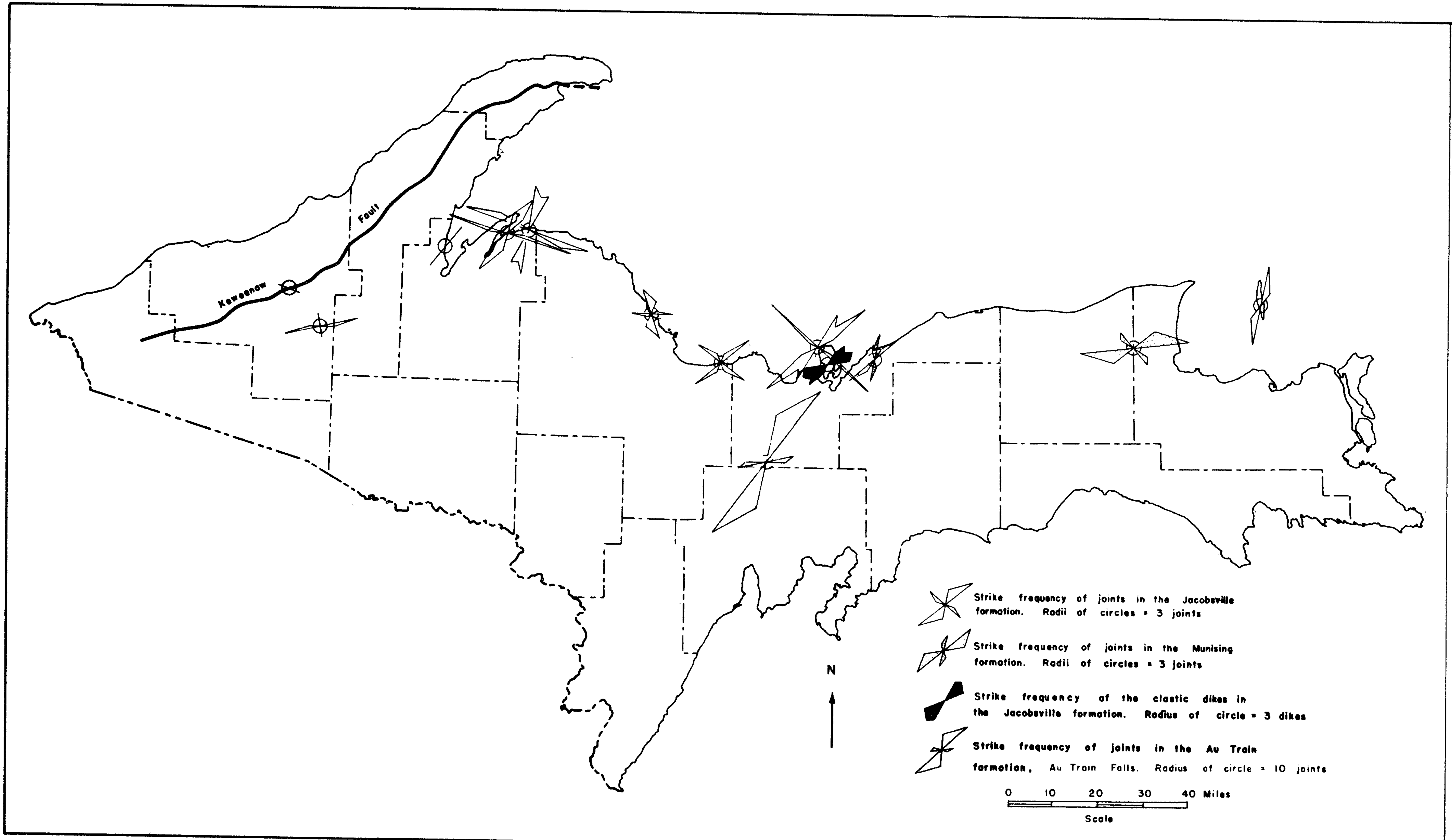
Hard, weathers dark brown, beds from 8"-12" thick, several horizons contain pebbles of sandstone and dolomitic sandstone which apparently constitute an intraformational conglomerate

Base of Lower Au Train Falls

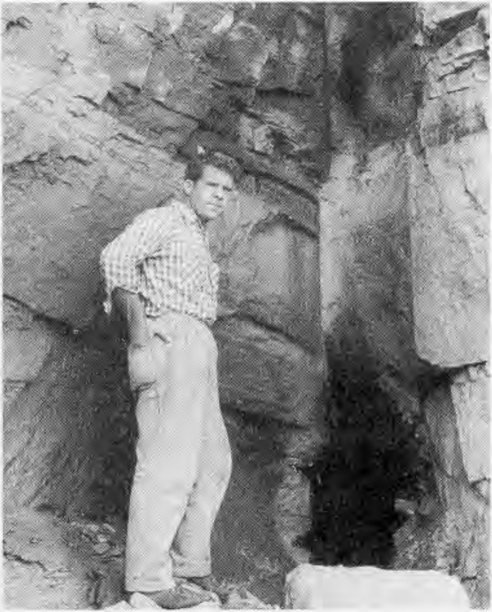


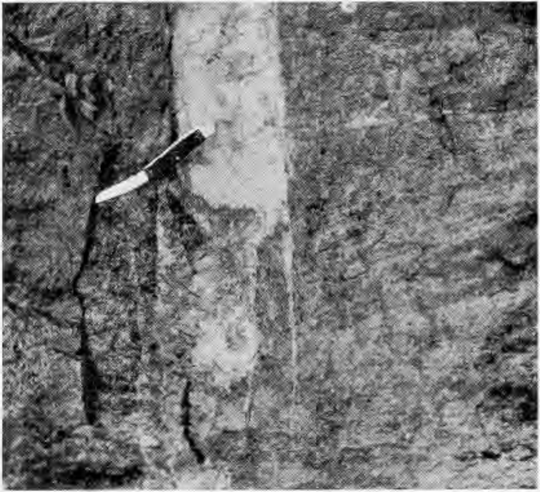
1000
500
0
500
0
-500
1340
1060
990
1020
1040
950
963
880
700
900
762
760
766
760
700
635
442
270
191
-10
-45
627
-325
-776
232
364
-64
N
Contour Interval = 100 feet
0 10 20 30 40 Miles
Scale

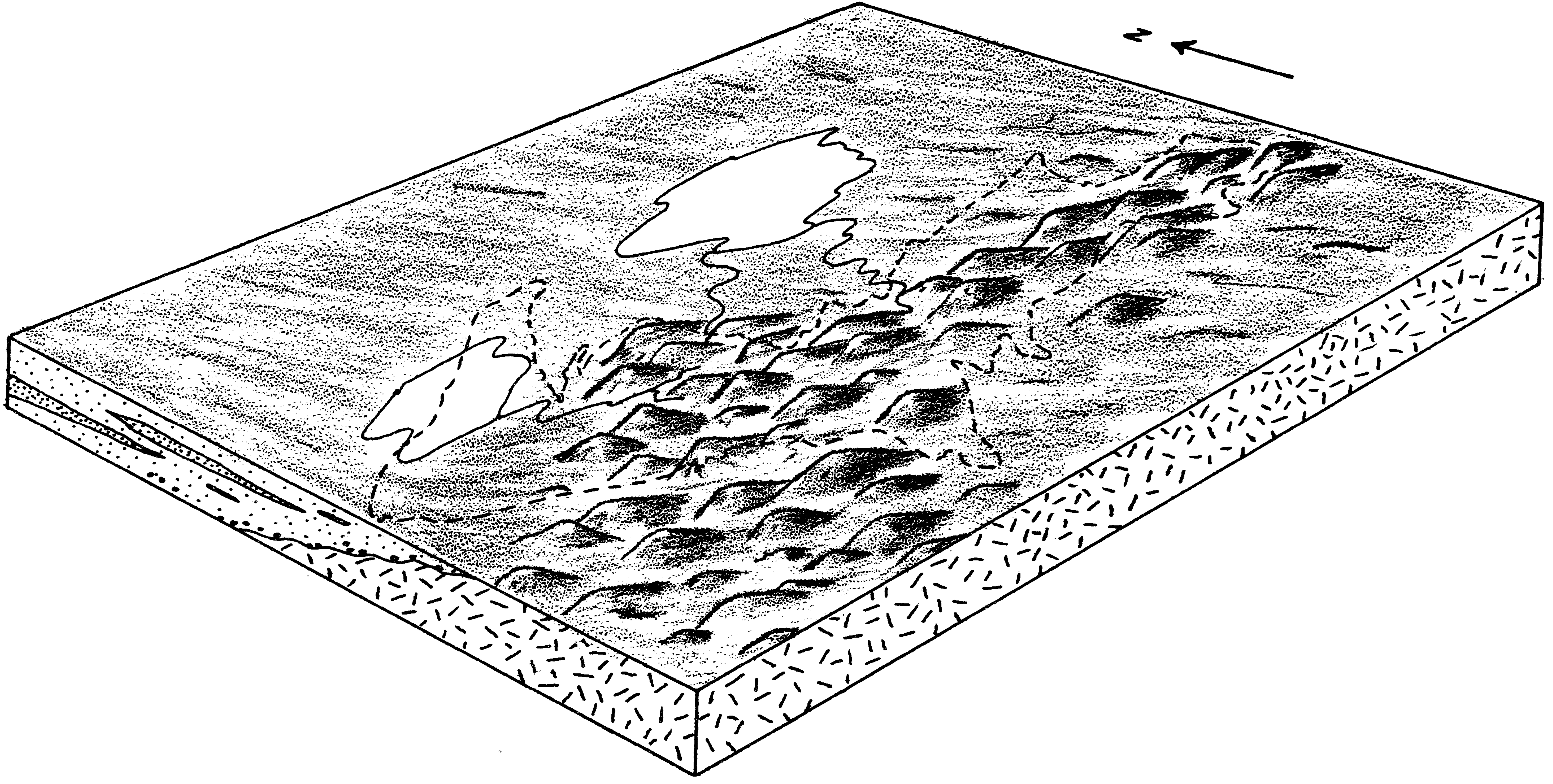


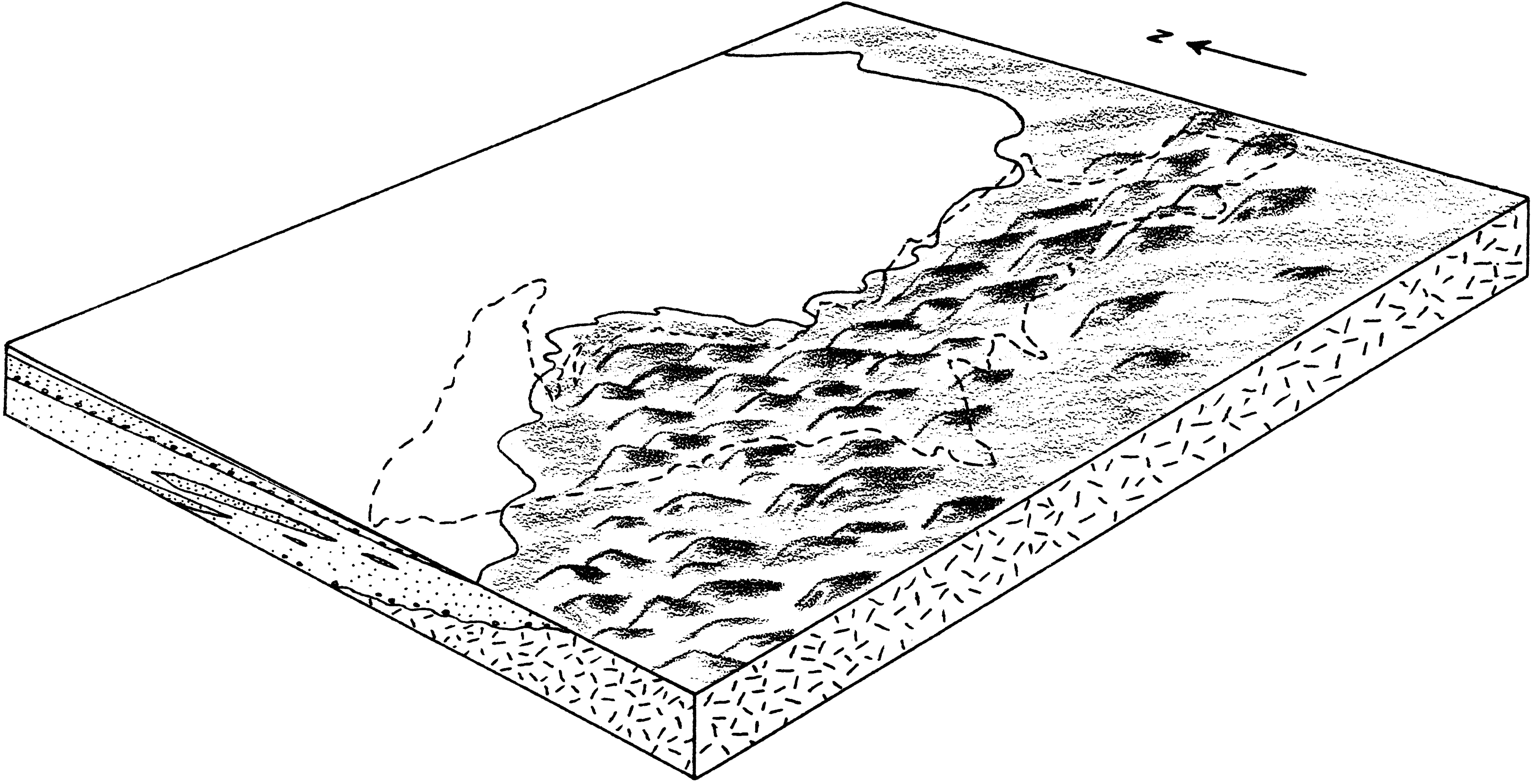


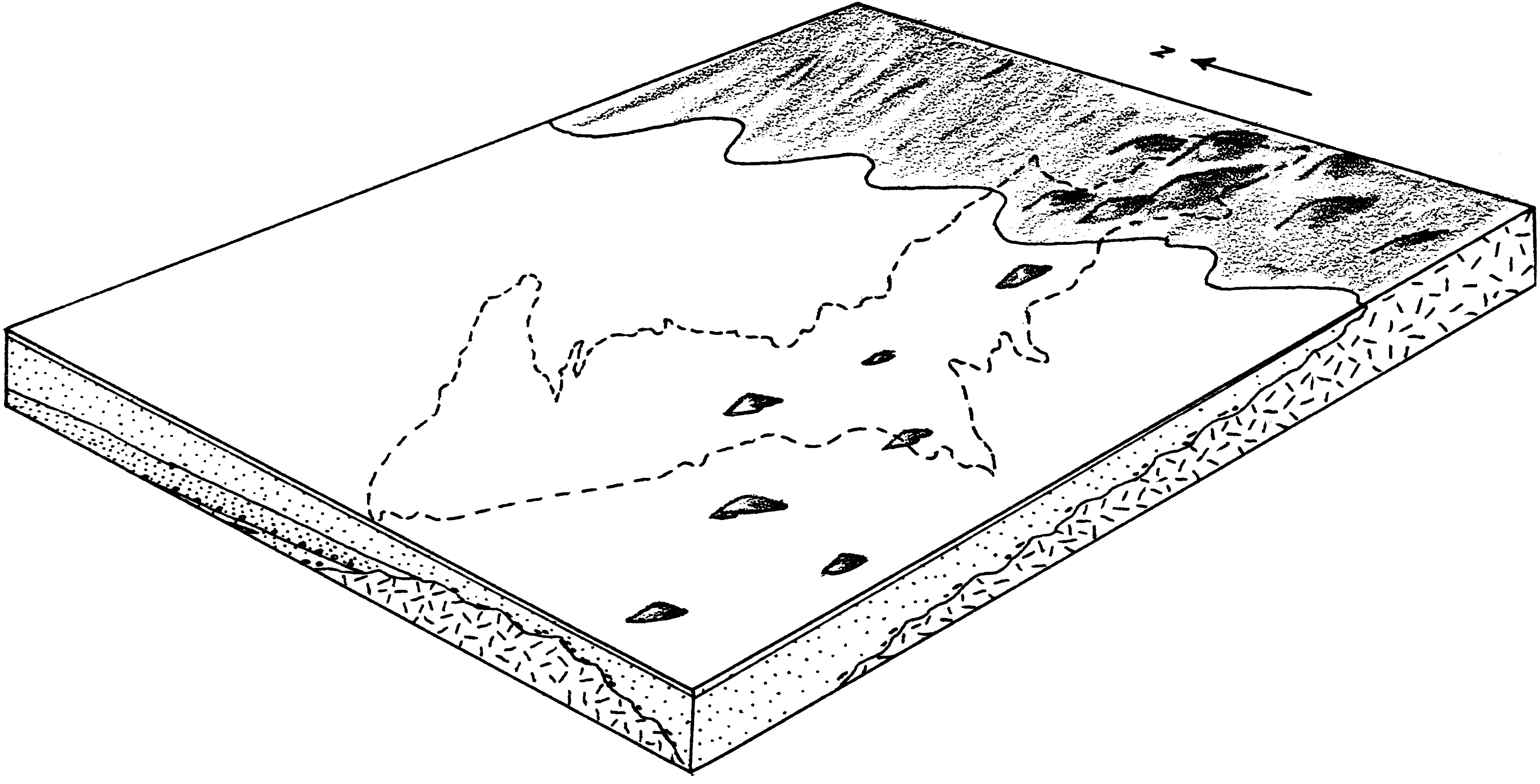
Keweenaw
Fault
Strike frequency of joints in the Jacobsville formation. Radii of circles = 3 joints
Strike frequency of joints in the Munising formation. Radii of circles = 3 joints
Strike frequency of the clastic dikes in the Jacobsville formation. Radius of circle = 3 dikes
Strike frequency of joints in the Au Train formation, Au Train Falls. Radius of circle = 10 joints
N
0 10 20 30 40 Miles
Scale






N


N


N

INDEX

INDEX

GEOLOGIC MAP SHOWING THE DISTRIBUTION OF CAMBRIAN ROCKS IN NORTHERN MICHIGAN

PLATE 2

BASE MAP FROM ADVANCE PRINTS OF U.S. GEOLOGICAL SURVEY TOPOGRAPHIC QUADRANGLES, LAND DIVISIONS TRANSFERRED FROM MICHIGAN DEPARTMENT OF CONSERVATION MAPS.

0 1 2 3
SCALE MILES

N

EXPLANATION

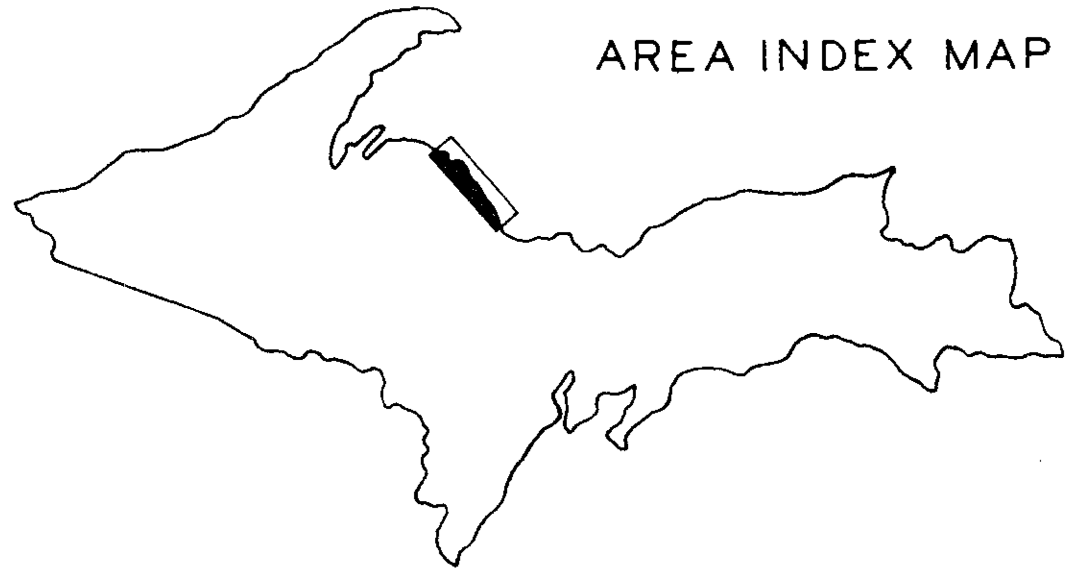
Oat	AU TRAIN FORMATION	MIDDLE ORDOVICIAN
	" BEDROCK EXPOSED	
€m	MUNISING FORMATION	UPPER CAMBRIAN
	" BEDROCK EXPOSED	
€j	JACOBSVILLE FORMATION	LOWER & MIDDLE CAMBRIAN
	" BEDROCK EXPOSED	

AREAS OF ABUNDANT OUTCROPS, SMALL OUTCROPS EXAGGERATED
CONTACT
FAULT
⚒A ABANDONED QUARRY

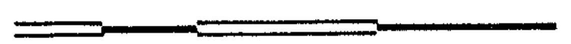
GEOLOGY BY W. K. HAMBLIN, 1957

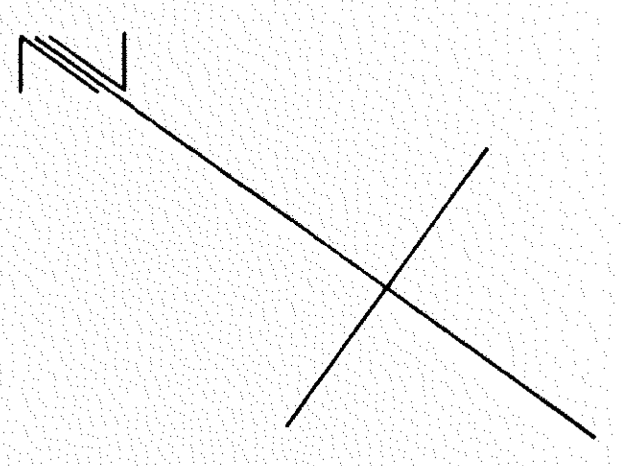
GEOLOGIC MAP OF PORTIONS OF MARQUETTE AND ALGER COUNTIES, MICHIGAN

BASE MAP FROM ADVANCE PRINTS OF U. S. GEOLOGICAL SURVEY TOPOGRAPHIC QUADRANGLES.



GEOLOGY BY W. K. HAMBLIN, 1957





EXPLANATION

€j	JACOBSVILLE FORMATION LOWER & MIDDLE CAMBRIAN
	" BEDROCK EXPOSED
P€	UNDIFFERENTIATED PRECAMBRIAN ROCKS
	" BEDROCK EXPOSED
	AREAS OF ABUNDANT OUTCROPS, SMALL OUTCROPS EXAGGERATED
----	CONTACT

GEOLOGIC MAP OF THE COAST OF LAKE SUPERIOR BETWEEN BIG BAY AND MARQUETTE

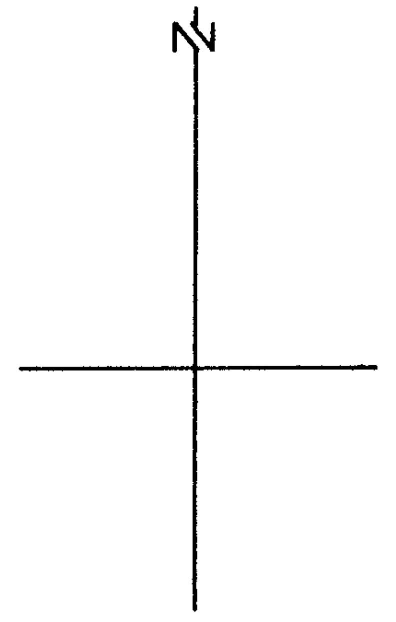
BASE MAP FROM ADVANCE PRINTS
OF U. S. GEOLOGICAL SURVEY
TOPOGRAPHICAL QUADRANGLES.

AREA INDEX MAP

GEOLOGY BY W. K. HAMBLIN, 1957

0 1 2
SCALE MILES

CONTOUR INTERVAL 20 FEET



EXPLANATION

Oat	AU TRAIN FORMATION	ORDOVICIAN
	" BEDROCK EXPOSED	
€m	MUNISING FORMATION	CAMBRIAN
	" BEDROCK EXPOSED	

UNCOLORED - UNDIFFERENTIATED PRECAMBRIAN ROCKS
AREAS OF ABUNDANT OUTCROPS, SMALL OUTCROPS EXAGGERATED
CONTACT

GEOLOGIC MAP SHOWING THE DISTRIBUTION OF THE CAMBRIAN SANDSTONES IN THE FELCH AREA, DICKINSON COUNTY

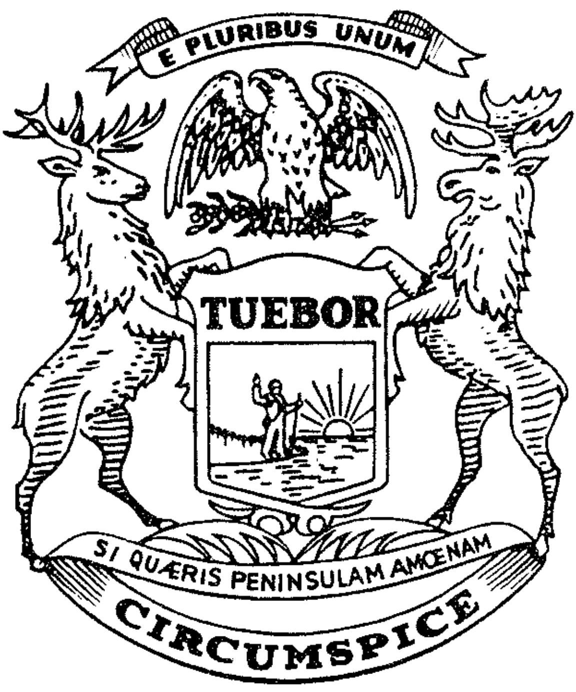

E PLURIBUS UNUM
TUEBOR
SI QUÆRIS PENINSULAM AMŒNAM
CIRCUMSPICE

TABLE 1

THEORIES PROPOSED FOR THE STRATIGRAPHIC POSITION OF THE JACOBSVILLE FORMATION

AGE	INVESTIGATOR	DATE	BASIS FOR CONCLUSIONS
Subsequent to Carboniferous	Owen, D. D.	1848	Strat. position
Triassic	Jackson, C. T.	1861	Lithology and strat. position
	Bell, R.	1869	Lithology and strat. position
New Red SS equivalent	Houghton, D.	1843	
	Rogers, H. D.	1848	Unconformity
	Jackson, C. T.	1849	Reported fossils
	Marcou, J.	1850	Strat. position
Permian	Macfarlane, T.	1866	Lithology
Old Red SS equivalent	Schoolcraft, H. R.	1821	Lithology
	Bigsby, J. J.	1824	Lithology
	Bayfield, H. W.	1845	Strat. position
	Locke, J.	1847	Strat. position
Silurian	Bigsby, J. J.	1852	
	Brooks & Pumpelly	1872	
Calciferous	Dana, J. D.	1862	
Potsdam	Hubbard, B.	1850	
	Foster & Whitney	1851	Strat. position
	Owen, D. D.	1851	
	Rivot, L. E.	1856	
	Rominger, C.	1873	Strat. position
	Wadsworth, M. E.	1880	Strat. position
	Irving, R. D.	1883	Strat. position
	Allen, *et. al.*	1916	Strat. position
Older than Potsdam	Logan, W.	1847	
	Whittlesey, C.	1867	
Cambrian	Van Hise & Leith	1911	Strat. position
	Lane & Seaman	1907	Strat. position
Middle Cambrian	Raasch, G. O.	1951	Strat. position
	Winchell, N. H.	1895	Unconformity
	Logan, W.	1851	
Keweenawan	Hotchkiss, W. O.	1933	Unconformity
	Thwaites, F. T.	1934	Similarity to Bayfield
	Leith, *et. al.*	1935	Similarity to Bayfield
	Oetking, P.	1951	Similarity to Bayfield

TABLE 2

PEBBLE COUNTS OF THE CONGLOMERATE FACIES IN THE JACOBSVILLE FORMATION

Type of pebble	Thoney Point*		Garlic Island**		Carp River*** (after Hultman, 1953)	
	No.	percent	No.	percent	No.	percent
Vein quartz	137	51.5	230	62.0	0	0
Potash feldspar	63	23.8	59	15.7	0	0
Quartzite	23	8.5	8	2.2	108	40.0
Peridotite	12	4.5	0	0	0	0
Clay pellet	12	4.5	23	6.2	4	1.8
Chert	8	3.0	2	0.5	0	0
Iron formation	8	3.0	24	6.5	18	8.3
Slate	1	0.4	18	4.9		
Dolomite	0	0	1	0.2	47	21.0
Sandstone pebbles	0	0	5	1.3	3	1.4

*Calcite cement constitutes approximately 20 percent of the rock.
**Calcite cement constitutes approximately 30 percent of the rock.
***Conglomerate facies consists of large boulders occurring in lenses throughout a stratigraphic thickness of approximately 200 feet.

TABLE 3

Pebble Counts of Basal Conglomerate of Munising Formation.

Type of Pebble	L. W. F. Spur. percent	AuTrain Spur. percent	Grand Island percent	Pictured Rocks percent	Chapel Falls percent	Sable Falls percent
Vein Quartz						
clear	10.3	11.3	9.3	6.8	28.5	54.2
milky	10.3	9.4	3.2	6.2	14.7	4.5
smoky	4.6	0.9	1.2	3.1	0.0	1.0
Total Vein Quartz	25.2	21.6	13.7	16.1	43.2	59.7
Quartzites						
red	20.6	4.2	14.7	26.0	4.6	0.3
brown	4.6	1.4	3.2	13.6	1.5	12.1
white	8.6	7.0	30.0	13.0	20.0	3.4
purple	0.0	2.8	4.2	1.8	0.0	0.0
black	28.0	24.4	28.5	27.8	7.6	8.7
banded	2.3	0.0	1.5	0.0	0.0	0.6
Total Quartzites	64.1	39.8	82.1	82.2	33.7	25.1
Chert	5.5	10.8	0.0	0.6	2.3	2.0
Cherty Iron Fm.	2.3	5.6	0.0	0.6	0.4	0.0
Brown Oölite Chert	0.0	0.0	0.0	0.0	20.0	12.6
Jacobsville	1.5	8.5	4.2	0.5	0.4	0.6
Granite	1.4	4.8	0.0	0.0	0.0	0.0
Slate	0.0	7.0	0.0	0.0	0.0	0.0
Basalt	0.0	1.9	0.0	0.0	0.0	0.0

PLATE 5

Fossils from the Munising sandstone and the Au Train formation, all X1 except where noted. All specimens in Museum of Paleontology, University of Michigan.

Prosaukia curvicostata Ulrich and Resser

1. Cast of pygidium with complete posterior margin. Hypotype no. 33343. Munising sandstone. Ledges along north side of U. S. Highway 2, 0.1 mile east of junction with Foster City road, 0.5 mile north of Waucedah, Dickinson County, Michigan.
2. Cast of cranidium with well preserved glabella. Hypotype no. 33338. Munising sandstone. Ledges at top of abandoned Breen Mine, sec. 22, T. 39 N., R. 28 W., Dickinson County, Michigan.
3. Cast of free cheek. Hypotype no. 33337. Munising sandstone. Same locality as original of fig. 1.
4. Part of thoracic segment. Hypotype no. 33342. Munising sandstone. Same locality as original of fig. 1.
5. Unusually large pygidium. Hypotype no. 34811. Munising sandstone. Base of north side of abandoned Pewabic Mine, Iron Mountain, Dickinson County, Michigan.
6. Free cheek with incomplete genal spine. Hypotype no. 34812. Munising sandstone. Same locality as original of fig. 1.
7. Small glabella with well developed brim and fixed cheeks. Hypotype no. 34813. Munising sandstone. Same locality as fig. 1.

Lungulepis ? sp.

8. Broken dorsal valve. Figured specimen no. 34814. Munising sandstone. Same locality as original of fig. 1.
9. Small complete dorsal valve. Figured specimen no. 34815. Munising sandstone. Same locality as original of fig. 1. X2.
10. Incomplete ventral valve. Figured specimen no. 34816. Munising sandstone. Same locality as original of fig. 1.

Lungulepis pinnaformis (Owen)

11. Well preserved ventral valve. Hypotype no. 34817. Munising sandstone. Same locality as original of fig. 5.

Briscoia sp.

12. Right pleural lobe of pygidium showing ribs and smooth peripheral area. Figured specimen no. 29959. Munising sandstone. Same locality as original of fig. 2.

Undescribed trilobite genus and species

13. Part of cranidium showing smooth glabella. Figured specimen no. 33348. Munising sandstone. Same locality as original of fig. 1.

Idioniesus sp.

14. Pygidium showing smooth peripheral lobes. Figured specimen no. 34818. Munising sandstone. Same locality as original of fig. 5.

Prosaukia ? sp.

15. Glabella with occipital and two glabellar furrows. Figured specimen no. 34823. Munising sandstone. Same locality as original of fig. 1.
16. Free cheek with short genal spine. Figured specimen no. 34824. Munising sandstone. Same locality as original of fig. 1.

Idahoia sp.

17. Part of cranidium showing glabella and occipital ring with axial node. Figured specimen no. 33347. Munising sandstone. Same locality as original of fig. 1.

Michelinoceras ? sp.

18. Part of living chamber. Figured specimen no. 34818. Au Train formation. Miner's Castle, Alger County, Michigan.
19. Part of cone showing closely set septa. Figured specimen no. 34819. Au Train formation. Same locality as original of fig. 18.
20. Fragment of cone of larger specimen. Figured specimen no. 34820. Au Train formation. Ledges at top of abandoned Austin Mine No. 2, NE¼, NE¼ SW¼, sec. 20, T. 48 N., R. 25 W. Marquette County, Michigan.

Liospira ? sp.

21-23. Lateral, dorsal, and ventral views of a specimen. Figured specimen no. 34821. Au Train formation. Same locality as original of fig. 18.

Ophileta ? sp.

24-25. Lateral and dorsal views of a specimen. Figured specimen no. 34822. Au Train formation. Sault Point on south shore of Whitefish Bay, Lake Superior, Chippewa County, Michigan.