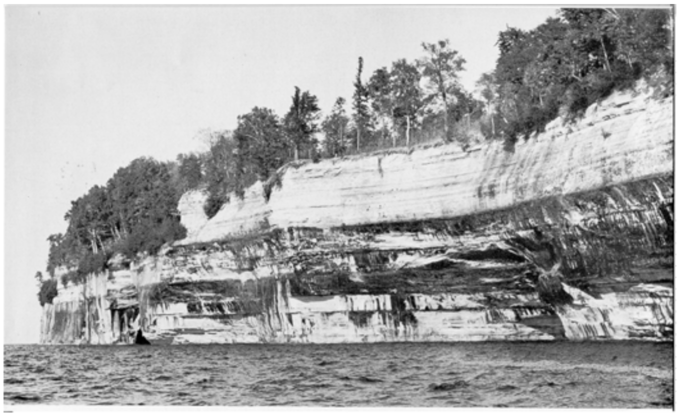

Frontispiece. The Munising formation exposed in the cliffs of Pictured Rocks.

STATE OF MICHIGAN
DEPARTMENT OF CONSERVATION
GEOLOGICAL SURVEY DIVISION

Publication 51
THE CAMBRIAN SANDSTONES of NORTHERN MICHIGAN

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

Contents

Illustrations

Figures

Plates

Tables

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 31 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

State Geologist
May 1958

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 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.

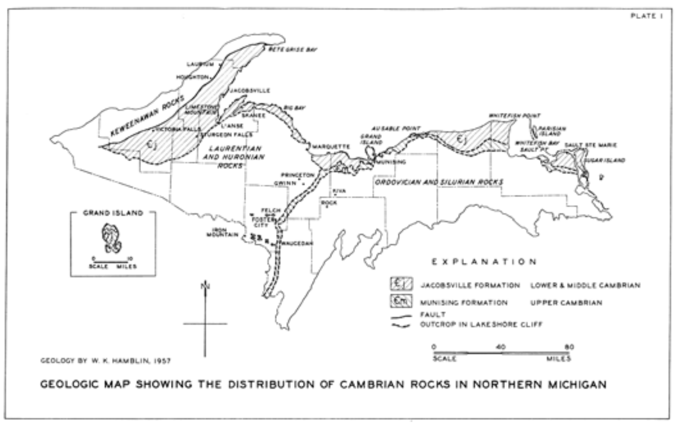

Plate 1. Geologic map showing the distribution of Cambrian rocks in northern Michigan.

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 his views regarding the contact between the "upper gray" "lower red" sandstones and concluded that no angular unconformity existed.

In 1851 Foster & Whitney published the results of their extensive 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 sec-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 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."

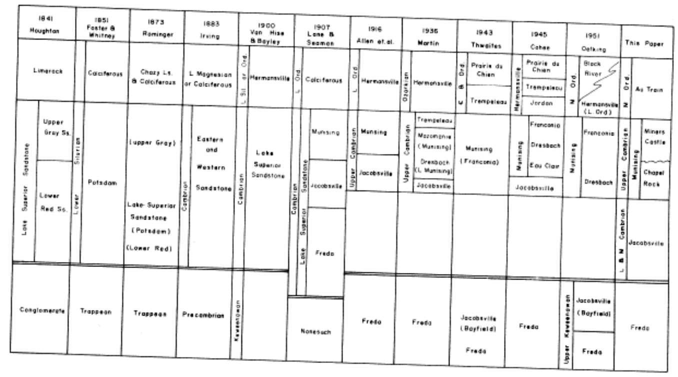

Figure 1. Development of the Cambrian Nomenclature of Northern Michigan.

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.

Thwaits (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 shoud 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 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.

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
	Houghton, D.	1843	
New Red	Rogers, H. D.	1848	Unconformity
SS equivalent	Jackson, C. T.	1849	Reported fossils
	Marcou, J.	1850	Strat. position
Permian	Macfarlane, T.	1866	Lithology
	Schoolcraft, H. R.	1821	Lithology
	Bigsby, J. J.	1824	Lithology
Old Red	Bayfield, H. W.	1845	Strat. position
SS equivalent	Locke, J.	1847	Strat. position
Silurian	Bigsby, J. J.	1852	
	Brooks & Pumpelly	1872	
Calciferous	Dana, J. D.	1862	
	Hubbard, B.	1850	
	Foster & Whitney	1851	Strat. position
	Owen, D. D.	1851	
Potsdam	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	Logan, W.	1847	
	Whittlesey, C.	1867	
Cambrian	Van Hise & Leith	1911	Strat. position
	Lane & Seaman	1907	Strat. position
	Raasch, G. O.	1951	Strat position
Middle Cambrian	Winchell, N. H.	1895	Unconformity
	Logan, W.	1851	
	Hotchkiss, W. O.	1933	Unconformity
Keweenawan	Thwaites, F. T.	1934	Similarity to Bayfield
	Leith, *et. al.*	1935	Similarity to Bayfield
	Oetking, P.	1951	Similarity to Bayfield

Table 1. Theories proposed for the stratigraphic position of the Jacobsville Formation.

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.

[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.

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 of Marquette County. The most prominent breaks through the 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).

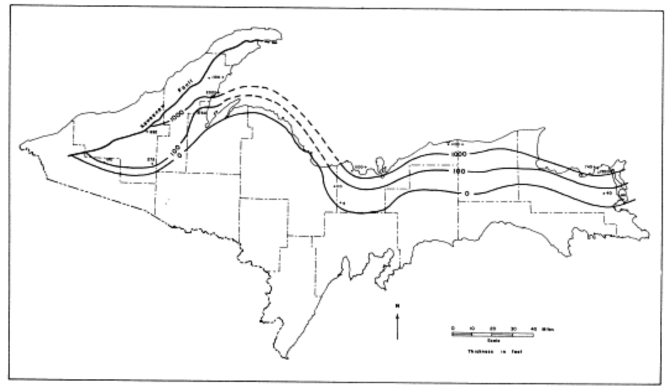

Figure 2. Isopach map of the Jacobsville formation.

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 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.

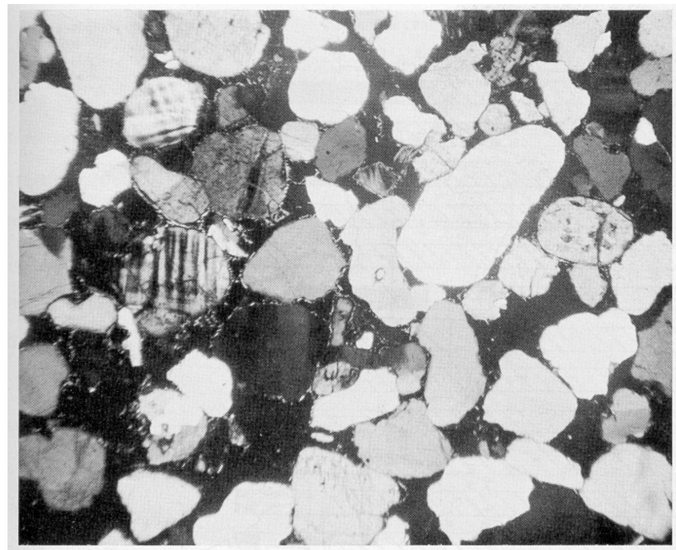

Figure 3. Photomicrograph of the Jacobsville formation at Au Sable Falls, Alger County. Crossed nicols. X33.

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.

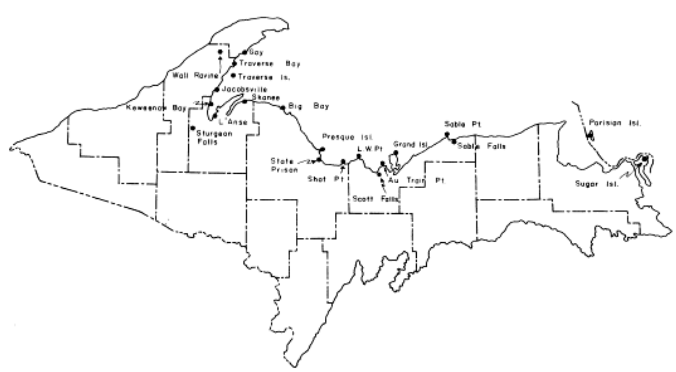

Figure 4. Map showing locations where samples were taken for heavy mineral analysis of the Jacobsville formation.

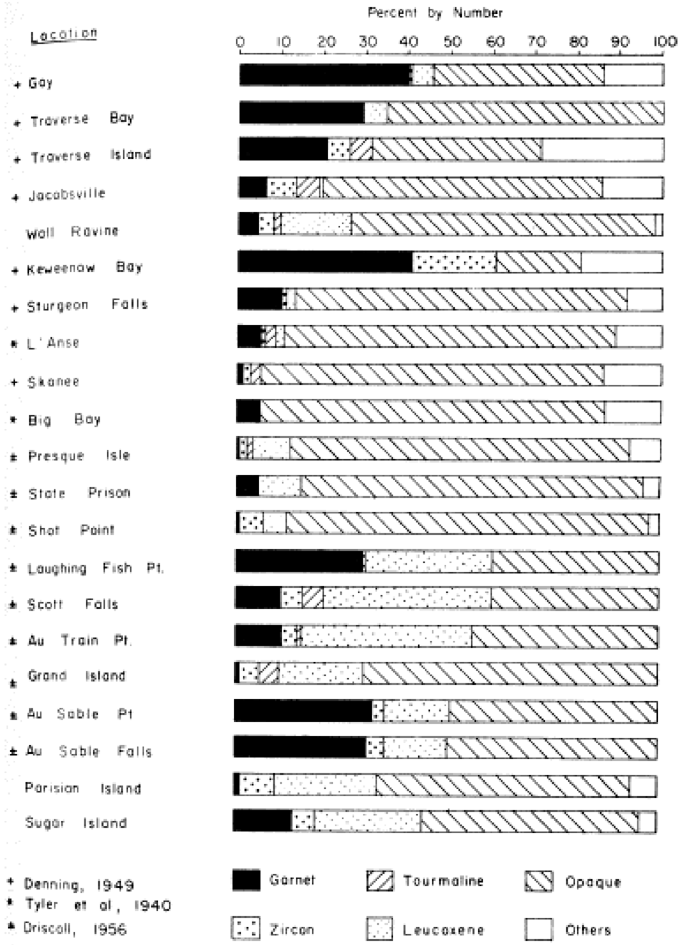

Figure 5. Heavy minerals of the Jacobsville formation.

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 together, the percentage of the species present is almost identical. This is well illustrated by the results obtained from Au 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 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 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.

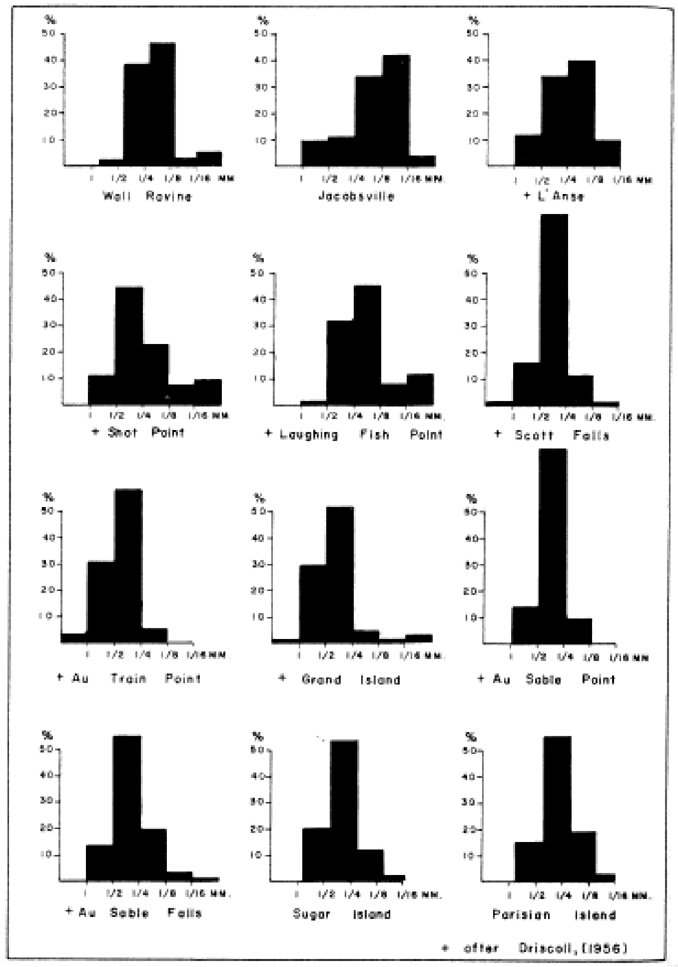

Figure 6. Grain-size distribution in typical samples of the Jacobsville sandstone.

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

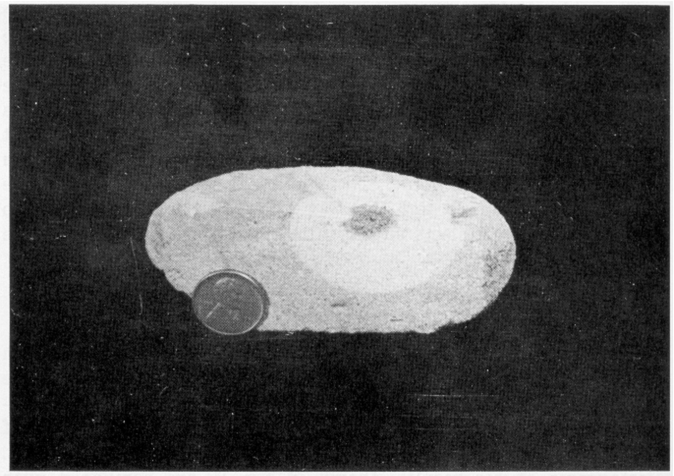

Figure 7. Reduction sphere in the Jacobsville formation showing the black center which presumably acted as a control for the localized reducing environment which produced the white color.

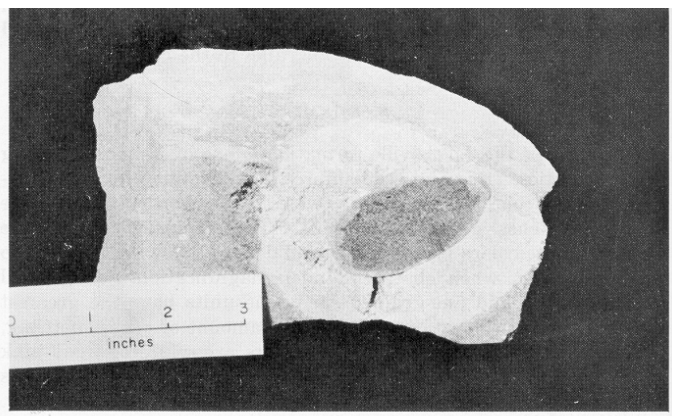

Figure 8. Reduction sphere in the Jacobsville formation showing an isolated sandstone pebble in the center Note the reduction rim around the pebble.

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 fades 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

<u>General Features</u>

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

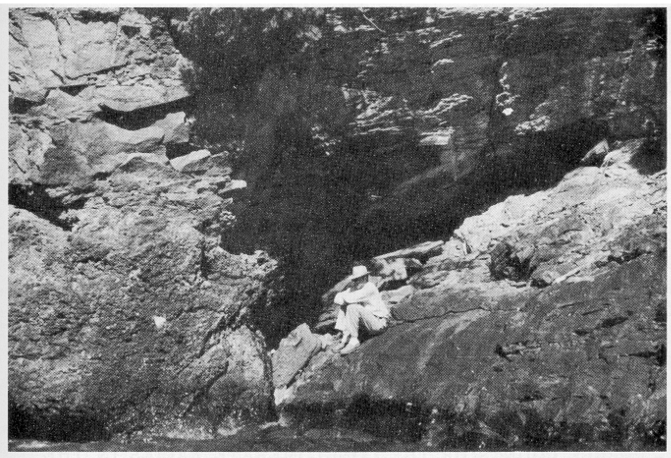

Figure 9. Contact between the Jacobsville formation and a knob of Precambrian granite at Thoney Point showing the conglomerate lens restricted to the flank of the Precambrian hill, and caves produced by differential erosion along the weathered zone which separates the two formations.

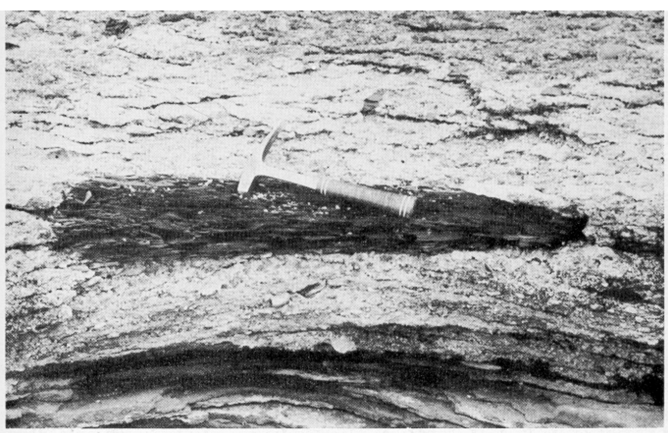

Figure 10. Large clay block imbedded in the conglomerate facies at Granot Loma Lodge between Marquette and Big Bay.

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.

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 2. Pebble counts of the conglomerate facies in the Jacobsville formation.

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 ¼ inch to more than 2½ 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 sees. 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.

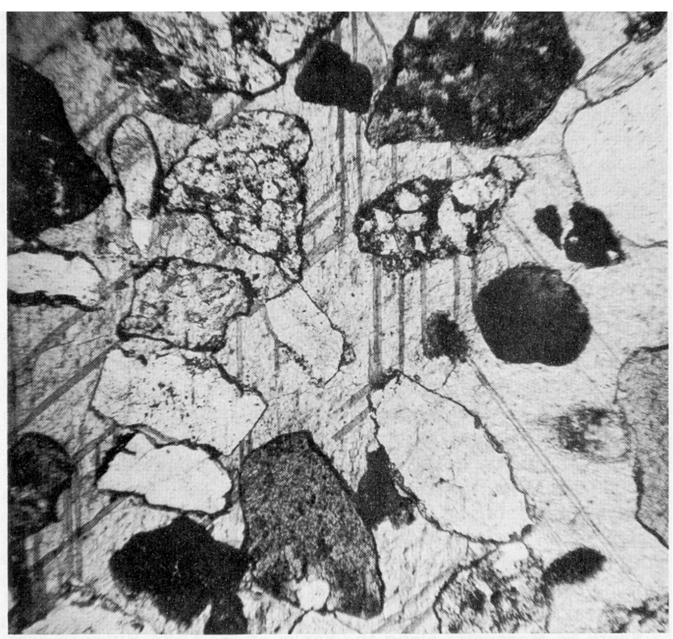

Figure 11. Photomicrograph of a thin section of the conglomerate facies showing- large crystals of calcite completely filling the interstices between the pebbles. Crossed nicols. X63.

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.

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 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.

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.

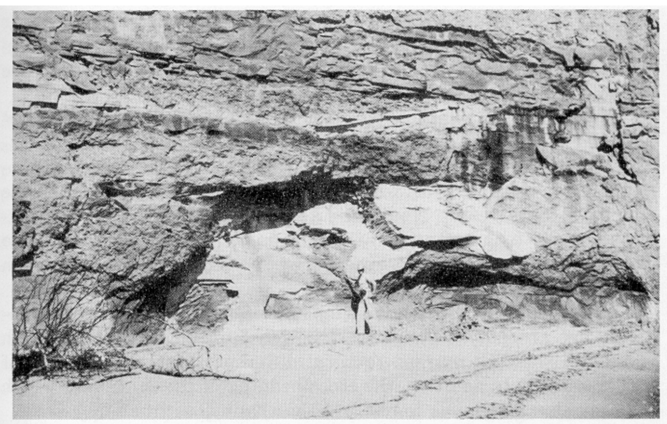

Figure 14. Channel structures exposed in the cliff at Wetmore Landing.

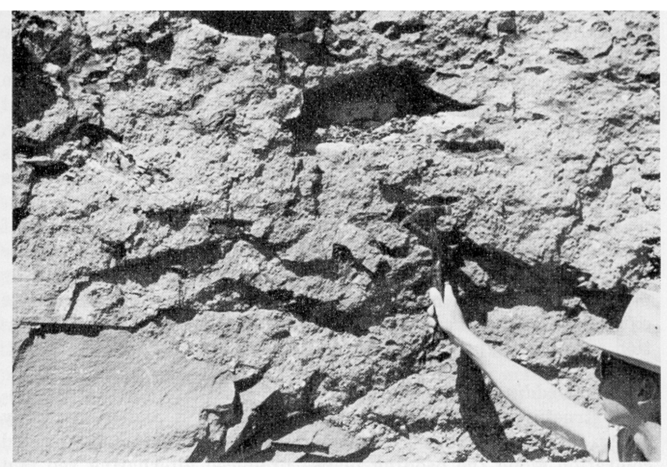

Figure 15. Close-up of the channel structures at Wetmore Landing showing textural contrasts between the conglomerate in the channel fill and the country rock. Note the large angular cavities which have resulted from weathering of clay blocks which were embedded in the conglomerate.

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 sub-rounded 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 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 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.

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.

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

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.

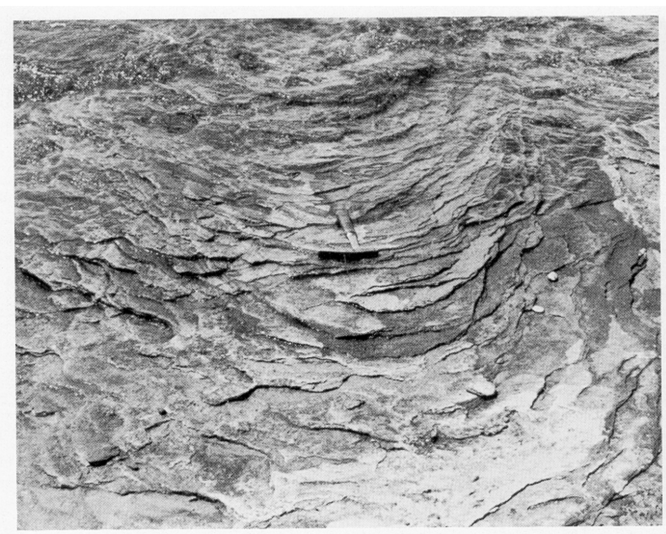

Figure 18. Surface of Jacobsville sandstone showing the horizontal section of the fluvial trough type of cross-bedding. Hammer handle lies along inferred direction of stream flow. View taken at Parisian Island in Whitefish Bay, Canada.

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 conglomerate 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 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.

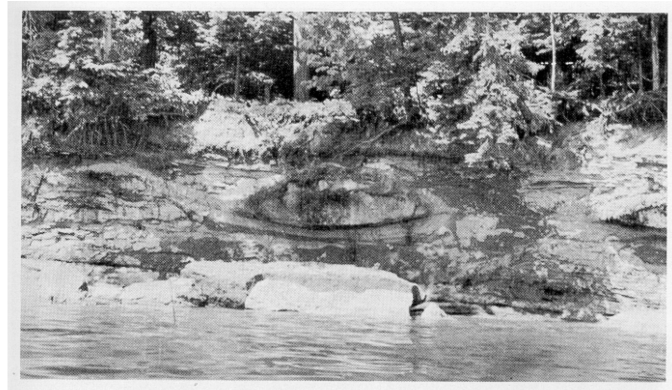

Figure 19. Transverse section of simple trough type cross-bedding or channel fill. View taken along the coast between Wetmore Landing and Granite Point.

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 lenticular 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 missive sandstone appears to be higher in the section.

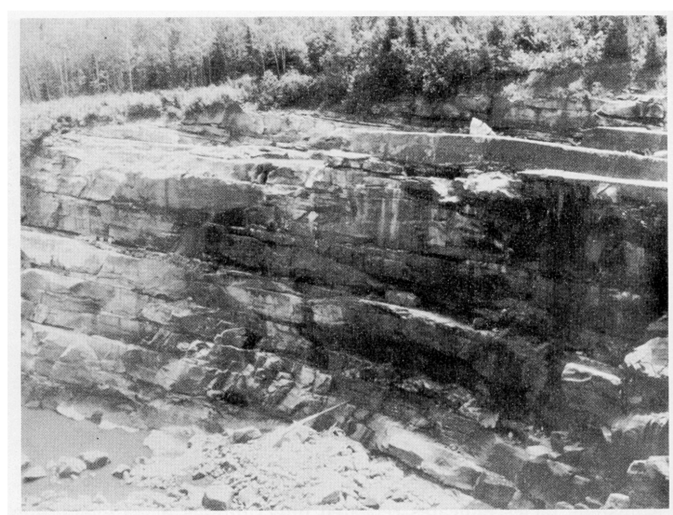

Figure 20. Upper part of the section exposed at Victoria Falls showing the typical massive sandstone facies.