THE PETROLOGY AND SEDIMENTATION OF THE BASAL KERENNAWAN SANDSTONES OF
THE NORTH AND SOUTH SHORES OF LAKE SUPERIOR

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ABSTRACT

The Puckwunge Formation of northeasternmost Minnesota is intermittently exposed for a 25-mile stretch beneath the Keweenawan North Shore Volcanic Group. The formation consists of a basal conglomerate and an overlying orthoquartzite, with the maximum estimated total thickness of the formation being 300 feet. Its composition, texture, and structures indicate that the formation was derived from pre-Keweenawan rocks to the north, and was deposited in a high-energy, near-shore environment. The formation disconformably rests on the Middle Precambrian Rove Formation, and is disconformably overlain by Keweenawan lava flows. The Puckwunge Formation is inferred to be correlative with the nearby Sibley Formation of Ontario. The Sibley Formation is disconformably overlain by sedimentary rocks and lava flows of the Osler Formation, also Lower Keweenawan in age. Sedimentary rocks correlating with the Osler Formation are not present in northeasternmost Minnesota.

At Nopeming, just west of Duluth, Minnesota, 28 feet of orthoquartzite and interbedded conglomerate are exposed beneath Keweenawan lava flows. Quartzite is the dominant lithology present, with minor metasiltstone interbedded with the quartzite just below the lava flows. The sediments were principally derived from pre-Keweenawan rocks of the area, and deposited by northward-flowing currents, with minor amounts of volcanic detritus being deposited in the metasiltstone. The sedimentary rocks overlie the Middle Precambrian Thomson Formation with an angular unconformity, and are conformably overlain by Keweenawan lava flows. Deposition of the sediments took place in a high-energy, shallow water environment.

The Bessemer Formation of Michigan and Wisconsin is intermittently exposed beneath Keweenawan lava flows along a 55-mile stretch. The dominant lithology is orthoquartzite; however, minor amounts of interbedded siltstone and a basal conglomerate are also present. The formation was principally derived from pre-Keweenawan rocks to the north, with deposition again having taken place in a shallow water, near-shore environment. The formation disconformably overlies the Middle Precambrian Tyler Formation, and is conformably overlain by Keweenawan lava flows.

South of the Lake Superior Region, several lower Upper Precambrian quartzite formations are exposed, and may be correlative with some of the Lower Keweenawan formations to the north. Three orthoquartzites, the Barron, Baraboo, and Sioux Formations are very similar in composition, lithology, and sedimentation, and appear to have been deposited during the northward transgression of a sea into a stable region.

The Sioux, Baraboo, Barron, Puckwunge, and Sibley Formations were deposited in a shallow water, near-shore, tectonically stable environment, before the outbreak of Keweenawan igneous activity in their depositional areas; while deposition of the Osler, "Nopeming," and Bessemer Formations, which contain minor amounts of volcanic rock fragments, was interrupted by extrusion of the Keweenawan lavas. The Sioux, Baraboo, Barron, Puckwunge, Sibley, and Bessemer Formations are inferred to be correlative with each other, while the Lower Keweenawan sediments at Nopeming and the Osler Formation appear to be younger in age.
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INTRODUCTION

Purpose of Study

Little is known about the geologic events which occurred in the Lake Superior Region between the 1.7 billion-year-old Penokean Event, and the 1.1 billion-year-old Keweenawan lava outpouring. A study of the petrology and sedimentation of Lower Keweenawan sedimentary rocks in the Lake Superior Region was undertaken in order to learn more about the events which immediately preceded the massive extrusion of Keweenawan lava flows in the region. The thin layer of Lower Keweenawan sedimentary rocks present beneath the lava flows is the only rock record of the intervening 600 million-year period.

Location of Lower Keweenawan Sedimentary Rocks

Lower Keweenawan sedimentary rocks are present on both the north and south shores of Lake Superior (Figure 1). The Sibley Formation of Ontario is exposed on the Sibley Peninsula east of Thunder Bay. Just east of the Sibley Peninsula, the basal portion of the Osler Formation is exposed. In northeastern Minnesota, the Puckwunge Formation is intermittently exposed along a 25 mile-long belt extending westward from Lucille Island south of Pigeon Point in Lake Superior. At Nopeming, Minnesota, just west of Duluth, Lower Keweenawan sedimentary rocks are intermittently exposed along a ½-mile stretch. On the South Shore, the Bessemer Formation crops out along a 55 mile-long belt extending east from Mellen, Wisconsin. The Barron Formation of Wisconsin is exposed 65 miles south of Lake Superior in portions of Sawyer, Rusk, and Barron Counties. The Sioux Formation of southwestern Minnesota and the Baraboo
LOWER KEWEENAWAN SEDIMENTS OF THE LAKE SUPERIOR REGION

PALEOZOIC ROCKS

UPPER KEWEENAWAN SANDSTONES

KEWEENAWAN LAVA FLOWS AND INTRUSIVES

LOWER KEWEENAWAN SEDIMENTARY ROCKS

UNDIFFERENTIATED LOWER AND MIDDLE PRECAMBRIAN ROCKS

MIDDLE PRECAMBRIAN ROCKS

LOWER PRECAMBRIAN ROCKS

SCALE

0 50 100 150 MILES

FIGURE 1
Formation of south-central Wisconsin are Lower Keweenawan sedimentary formations present south and southwest of the Lake Superior Region. Detailed studies were undertaken of the Puckwunge Formation of north-eastern Minnesota, the Lower Keweenawan sedimentary rocks at Nopeming, near Duluth (referred to as the Nopeming Formation in this report), and the Bessemer Formation of Michigan and Wisconsin, as well as reconnaissance investigations of the Sioux and Baraboo Formations.

**Regional Geologic Setting**

The Lake Superior Syncline is the regional geologic setting of these Lower Keweenawan sediments (Figure 1). On the North Shore, Lower and Middle Precambrian rocks are exposed to the north of the Puckwunge, Sibley and Osler Formations, and also to the west of the Nopeming Formation, near Duluth. On the South Shore, Lower and Middle Precambrian rocks are exposed to the south of the Bessemer Formation. Rocks of the Keweenawan lava series and the Upper Keweenawan sedimentary rocks are exposed between the Lower Keweenawan sediments of the North and South Shores. All three groups of Lower Keweenawan sedimentary rocks studied are underlain by Middle Precambrian slates, and overlain by Keweenawan lava flows. These similarities suggest that the tectonic events responsible for deposition of these formations were widespread, and apparently affected the entire Lake Superior Region.

**Methods Employed in the Study**

The Puckwunge Formation of northeasternmost Minnesota was examined at eleven evenly spaced locations along the 25 mile-long belt where the formation is exposed beneath the Keweenawan lava flows. Samples were
collected for thin sections and heavy mineral analyses. Several stratigraphic sections were measured. Paleocurrent indicators (cross-beds, troughs, and ripple marks) were measured. Where exposed, the basal conglomerate was examined in detail, and pebble lithologies were noted.

All exposures of the Nopeming Formation, near Duluth, were examined. Samples were collected for thin sections and heavy mineral analyses. Paleocurrent indicators (cross-beds, troughs, and parting lineation) were measured. Stratigraphic sections were measured at several locations along the half-mile-long belt where the sediments are intermittently exposed beneath the Keweenaw lava flows. Conglomeratic layers were carefully examined, and pebble counts were taken. In an effort to shed further light on the nature of the unexposed lower contact of the sediments, two magnetic and two gravity profiles with a station spacing of 100 feet were run across the area.

The Bessemer Formation of Michigan and Wisconsin was examined at five locations along the 55 mile-long belt where it is exposed. A stratigraphic section was measured near Iron Belt, Wisconsin, where both the lower and upper contacts are exposed. Paleocurrent indicators (cross-beds and ripple marks) were measured at each of the five exposures visited. Samples were collected for thin sections and heavy mineral analyses. The basal conglomerate was carefully examined, and pebble lithologies were noted.

Brief comparative studies of other Lower Keweenawan sedimentary rocks in the Lake Superior Region were also conducted. The lower portion of the Sibley Formation was examined at Pass Lake, Ontario. Several samples were collected for thin sections and heavy mineral analyses. Cross-bedding and ripple marks were measured for paleocurrent analysis, and pebble and cobble lithologies in the basal conglomerate were noted. The Barron Formation
was examined at eight different exposures in the southwest portion of Sawyer County, Wisconsin. Samples were collected for thin sections and heavy mineral analyses. When present, cross-bedding was measured for paleocurrent analysis. The Sioux Formation of southeastern Minnesota was examined at several exposures near Pipestone, and one sample was collected for petrographic study. A thin section was also made of a sample of the Baraboo Formation from an exposure near North Freedom, Wisconsin.

All pebble counts were taken by measuring along a grid, with measurement taken perpendicular to bedding. The number of centimeters of matrix and pebbles along parallel lines ten centimeters apart was recorded. Pebbles of different lithologies were tabulated separately. Percentages of matrix, pebbles, and individual pebble lithologies in the conglomerates were determined on the basis of percentage of the total number of measured centimeters.

In the laboratory, samples for heavy mineral analyses were crushed by hand with a mortar and pestle. The mass of the samples was determined, and clay was removed by washing. Accessory heavy minerals were separated in a separatory funnel, using 1,1,2,2 tetrabromoethane. After washing and drying, the heavy mineral residue was weighed. Magnetic heavy mineral grains were removed by use of a small, alternating current electromagnet. The remaining accessory heavy mineral grains were mounted on glass slides using Canada balsam. Only non-magnetic, non-opaque, detrital accessory heavy mineral grains were counted during grain counts. At least 300 grains were counted if possible.

Petrographic analysis of thin sections were done by counting 600 points on each thin section. A random number table was used to determine the traverses to be counted. The traverses counted were oriented per-
Pendicular to bedding.

Paleocurrent data were corrected for the dip of the formations by use of a stereonet in the manner presented by Potter and Pettijohn (1963). The vectoral mean and a chi-square value of preferred orientation for paleocurrent data were determined by using the Tukey Chi-Square Test of Orientation (Tukey, 1954; Rusnak, 1957).

The geophysical data from Nopeming were corrected and evaluated by standard procedures. The gravity data were corrected by use of simple Bouguer gravity corrections. Base stations were used in both the gravity and magnetic surveys to correct for diurnal effects. Standard accepted methods were employed in the interpretation of the final corrected geophysical data.

Previous Work

In general, the Lower Keweenawan sedimentary rocks of the Lake Superior Region have not been studied in detail. In Ontario, the Osler and Sibley Formations were mapped by Tanton (1931). Because the basal conglomerate of the Osler Formation contains pebbles of the underlying Sibley Formation, Tanton recognized the presence of an unconformity between the two formations. Hamblin (1965) determined that the Osler sediments were deposited by westward-flowing currents. Pye (1962) studied the Sibley Formation along the North Shore, and concluded that the lower Sibley Formation was deposited in a shallow, inland sea environment. The upper Sibley, according to Pye, represents deposition on a flood plain under the conditions of seasonal rainfall. Moorhouse (1960), Franklin (1970), and Franklin and Kustra (1970) studied the Sibley Formation, and also noted the significant change in depositional environment. The presence of a southerly direction of sediment
transport during deposition of the lower Sibley Formation was also recognized by Franklin.

In northeastern Minnesota, Winchell (1897, 1899) named the Puckwunge Formation, and designated a type section. The significance of the basal conglomerate on Grand Portage Island was discussed by Grant (1894). Nelson (1942) did a limited petrographic study of the Puckwunge Formation, and recognized that deposition of the Puckwunge Formation preceded the Keweenawan lava outpourings in the area.

Possible correlation of the Nopeming Formation, just west of Duluth, with the Puckwunge Formation of northeastern Minnesota was discussed by Winchell (1889). Nelson (1942) did a petrographic study of several nearby conglomerate outcrops which had been correlated with the Nopeming Formation, and concluded that the conglomerate outcrops closely resembled the Upper Keweenawan Fond du Lac Formation. Morey (1967) later assigned these outcrops to the basal portion of the Fond du Lac Formation. A study of accessory heavy minerals in the Nopeming Formation was done by Tyler and others (1940), but, because the nearby exposures of the basal Fond du Lac Formation were included in the study, the data are of questionable value to this investigation.

The Bessemer Formation in Wisconsin and Michigan was briefly discussed by Van Hise and Leith (1911). Aldrich (1929) mapped portions of the formation in Wisconsin, and concluded that the origin of the formation was related to the surface changes which immediately preceded the Keweenawan lava outpourings. In Michigan, a portion of the Bessemer Formation was mapped by Seaman (1944).

Hotchkiss (1915) and Hotchkiss and Bean (1929) did generalized geologic mapping of the Barron Formation in Wisconsin. Utzig (1972)
did a petrographic study of the formation. Pettijohn (1957a) published the measurement of four cross-beds in the Barron Formation, showing a southwesterly direction of sediment transport. In the same article, Pettijohn also published 39 measurements indicating a southeasterly paleocurrent direction in the Lower Keweenawan Sioux Formation of southwestern Minnesota. A detailed study of the Sioux Formation was done by Miller (1961).

Brett (1955) studied the Baraboo Formation of south-central Wisconsin, and did a detailed paleocurrent analysis (283 measurements) which indicated a south-southeasterly paleocurrent direction. A more recent study of the Baraboo District by Dalziel and Dott (1970) suggested a marine shallow water depositional environment for the Baraboo Formation. From the results of Rubidium-Strontium whole rock analyses of underlying rhyolite, and a Rubidium-Strontium date from muscovite in a younger pegmatite dike which cuts the formation, the above authors estimate that deposition of the Baraboo took place between 1.4 and 1.6 billion years ago.

PETROLOGY AND SEDIMENTATION OF THE BASAL KEWEENAWAN
SANDSTONES NORTH OF LAKE SUPERIOR

Puckwунge Formation of Northeastern Minnesota

Stratigraphy

In extreme northeastern Minnesota, the Lower Keweenawan Puckwunje Formation is intermittently exposed along a 25-mile stretch extending westward from Lucille Island (Figure 2). The formation is composed of
FIGURE 2. GEOLOGY OF THE GRAND PORTAGE AREA, NORTHEASTERN MINNESOTA
sandstone and conglomerate, and is exposed beneath the North Shore Volcanic Group at the base of a steep northward-facing slope. The contact between the Puckwunje Formation and the underlying Rove Formation is not exposed; however, a conglomerate, believed to be a basal conglomerate, is exposed at two locations.

N. H. Winchell visited northeastern Minnesota in 1893 and designated the NE^4, Section 25, T.64N., R.3E. as the type section of the Puckwunje Conglomerate (Winchell, 1897 and 1899). Winchell stated that the type section was located in the valley of Puckwunje Creek (now called Stump River), but the exposure is actually located on a small, intermittent northward-flowing tributary of Portage Brook (Grout, et al., 1959).

Winchell described the stratigraphy of the Puckwunje Conglomerate at the type section by dividing the unit into two members, a basal conglomerate and an overlying sandstone. According to Winchell, eighteen feet of coarse conglomerate containing cobbles up to six inches in diameter are overlain by an additional eighteen feet of finer conglomerate. The pebbles in the conglomerate are well-rounded, and consist of vein quartz, red and white quartzite, gray chert, and banded red jasper. The conglomerate grades upward into the overlying sandstone. Ninety feet of sandstone overlies the basal conglomerate at the type section.

Winchell estimated the maximum thickness of the conglomerate and sandstone in the area to be 200 feet. Because the sandstone is more widely exposed than the conglomerate, the unit is now known as the Puckwunje Formation (Grout, et al., 1959).

The exposure of Puckwunje Formation on Grand Portage Island was one of the first locations where the Lower Keweenawan sandstone and conglomerate were studied by geologists. Irving (1883) first classi-
fied the sandstone and conglomerate exposed beneath the lava flows on Grand Portage Island as part of the Middle Precambrian (Animikian) group of sediments in the region. Grant (1894) first recognized that the sediments exposed beneath the lava flows were of Keweenawan age, and that a conglomerate containing pebbles of quartz, quartzite and slate was present, indicating that an unconformable relationship existed between the Keweenawan rocks and the underlying Middle Precambrian (Animikian) rocks.

The lower contact of the Puckwunge Formation is not exposed, but the two outcrops of conglomerate discussed above are believed to represent a basal conglomerate. The pebbles in the conglomerate at both locations appear to have been derived from the weathering of the pre-Keweenawan rocks in the area. Grout, et al. (1959) state that the contact between the Rove Formation and the Puckwunge Formation lies just south of Susie Island beneath Lake Superior. The presence of a few pebbles attached to the dip-slope surface of the slate (Rove Formation) on the south edge of Susie Island was interpreted by Grout, et al. to mean that the dip-slope surface is very close to the surface of the unconformity. Because the underlying Rove Formation was not deformed during the Penokean Event (Morey, 1969), the relationship between the Rove and Puckwunge Formations is a disconformity, rather than an angular unconformity.

The Puckwunge Formation appears to be disconformably overlain by the Upper Precambrian North Shore Volcanic Group. The basal lava flows and the Lower Keweenawan sediments both dip gently to the south, with the Puckwunge Formation being exposed beneath the lava flows at the base of a steep northward-facing slope. However, the presence of
angular sandstone inclusions in the basal lava flow on Grand Portage Island indicates that lithification of the Puckwunje Formation preceded extrusion of the lavas, and therefore, a disconformity is indicated. Furthermore, a small angular discordance in bedding is locally present at the contact between the sandstone and overlying lava flow. In general, this contact appears to be a relatively flat surface. The lack of three-dimensional exposures of the contact prohibits a detailed study of the relief on the surface of the Puckwunje Formation prior to extrusion of the lavas. However, probable erosional features of several feet relief were observed at two localities.

Several igneous units intrude the Lower Keweenawan sedimentary rocks. Logan diabase sills cut the bottom of the formation at several locations, apparently following the contact with the underlying Rove Formation. Large diabase dikes cut the Puckwunje in several areas, notably near Mt. Sophie in T.63N., R.5E. The Duluth Complex also intrudes the Puckwunje Formation. With the exception of a small outcrop near Stump Lake in T.64N., R.2E., the Duluth Complex forms the western boundary of the Puckwunje where it truncates the formation near Devilfish Lake in T.64N., R.3E.. A small sill of rhyolitic composition also intrudes the sediments in Section 33, T.64N., R.5E.

Stratigraphically, the formation may be divided into two members, a basal conglomerate and an overlying sandstone. Because the lower contact is not exposed, the total thickness of the formation is not known. Approximately 30 feet of sandstone are exposed at the easternmost exposure of the Puckwunje Formation on Lucille Island, where it is overlain by the basal Keweenawan lavas. The formation appears to thicken to the west, with a maximum exposed thickness of nearly 150 feet.
being reached near the type locality in T.64N., R.3E.

The Puckwunge Formation was examined at eleven different locations (Figure 2). Stratigraphic sections at each of these locations are shown in Figures 3, 10, and 13.

The easternmost exposure examined in the study is Locality 1, located on the north shore of Lucille Island in the Susie Islands south of Pigeon Point in Lake Superior. More than 30 feet of sandstone are exposed beneath the North Shore Volcanic Group. The thick-bedded sandstone is occasionally cross-bedded, and ranges from white to pink in color. Possible exposures of the Puckwunge Formation are present on several nearby islands, including Brick Island, Little Brick Island, and a small un-named island just south of Little Brick Island. Because these sandstones are only found in contact with Keeweenawan intrusive rocks, and have been altered and recrystallized, it cannot be determined whether they belong to the Puckwunge Formation or are part of the underlying Rove Formation.

Eighteen feet of sandstone underlain by fifteen feet of conglomerate compose the exposure of Puckwunge Formation at Locality 2, on Grand Portage Island. The basal flow of the overlying North Shore Volcanic Group contains angular inclusions of sandstone, indicating the presence of an unconformity (Figure 4). The sandstone of the Puckwunge Formation on Grand Portage Island is thick-bedded, ranges from white to pink in color, and is occasionally cross-bedded. The conglomerate contains rounded pebbles of quartzite and quartz, and angular chips and fragments of slate and argillite, probably derived from the underlying Rove Formation (Figure 5). Both the sandstone and conglomerate contain carbonate cement. The sandstone matrix in the
FIGURE 13: STRATIGRAPHIC SECTIONS, FUNCHANCE FORMATION, NORTHEASTERN MINNESOTA

Mineral Center
Sec. 2, T.63N., R.5E.

Grand Portage
Sec. 6, T.63N., R.6E.

Grand Portage Island

Lucille Island
Figure 4. Sketches of sandstone inclusions in basal lava flow, Locality 2, Grand Portage Island.
Figure 5. Conglomerate slab from Puckwunge Formation, Locality 2, Grand Portage Island. Angular chips and fragments of slate and argillite are present in the conglomerate.
lowermost exposed conglomerate beds has been partially replaced by carbonate.

Locality 3 is located 1 ½ miles southwest of the village of Grand Portage. A small discordance in attitude between the sandstone and overlying lava flow is present at this locality (Figure 6). Truncation of the Puckwunge bedding (Figure 7) has also been observed by J. C. Green along the contact between the Puckwunge Formation and the overlying lava flow at this locality, suggesting that lithification of the Puckwunge Formation preceded extrusion of the lavas (Personal communication, 1971). Six feet of medium-bedded, well cross-bedded, white sandstone is exposed immediately beneath the Keweenawan lava flows (Figure 8). This cross-bedded unit grades downward into four feet of thick-bedded, white sandstone, containing a few oscillatory ripple marks. Six feet of thin-bedded, red "shaly" sandstone is exposed beneath the white sandstone (Figure 9). The red "shaly" sandstone grades into a red sandstone, which extends down into the talus slope beneath.

Approximately 35 feet of sandstone are exposed at Locality 4, 1 ½ miles northeast of Mineral Center. Twenty-five feet of thick-bedded, massive, white sandstone is exposed beneath the lava flows. The ten feet of massive red sandstone which underlies this unit continues down under the slope at the base of the cliff.

Several important features were noted 2 ½ miles west of Mineral Center at Locality 5, where over 135 feet of sandstone appear to be present. Approximately fifteen feet beneath the Keweenawan lava flows, a two foot-thick intrusive sill of rhyolitic composition has intruded a 30 foot-thick white sandstone unit. The sill can be traced for a
Figure 6. Discordance in attitude between Puckwange Formation and overlying lava flow, Locality 3, SE1, Sec. 8, T.63N., R.6E.
Figure 7. Field sketch of lava - Puckwunge contact, after J. C. Green, 1969, Locality 3, SE¹, Sec. 8, T.63N., R.6E.
Figure 8. Cross-bedding in Puckwunge Formation at Locality 3, cross-bedded sandstone (light-colored) overlain by lava (dark-colored).

Figure 9. Thin-bedded "shaly" sandstone of Puckwunge Formation, Locality 3, SE1, Sec. 8, T.63N., R.6E.
horizontal distance of about twenty feet before it pinches out at one end, and is buried under a covered interval at the other end. No other intrusive bodies of a similar composition were noted during the study. A talus slope extends down the cliff for 95 feet below the 30 foot-thick sandstone unit; all of the talus blocks are sandstone. Ten feet of medium-bedded red-brown sandstone, a short covered interval, and six feet of gray sandstone are exposed below the talus slope.

Locality 6, 1½ miles north of Swamp Lake, also contains several important features. An irregularity along the contact between the lava flows and the Puckwunge Formation occurs at this location. The bedding of the sandstone is truncated by the lowermost lava flow (Figure 11), suggesting that lithification of the sandstone occurred prior to extrusion of the lava. Ten feet of gray, medium-bedded sandstone is exposed immediately below the lowest lava flow. Beneath this unit, ten feet of pink, thick-bedded sandstone are exposed. A 30 foot high talus slope occurs below the sandstone, with all of the talus blocks being composed of sandstone. Thirty feet of thick-bedded, massive, white sandstone is exposed below the talus slope. A diabase sill has been intruded beneath, cutting off the lower portion of the Puckwunge Formation.

Another impressive talus slope is present along the west boundary of the Grand Portage Indian Reservation at Locality 7. Almost thirty feet of light brown, cross-bedded sandstone is exposed beneath the Keweenawan lava flows. A calcite vein ranging up to three feet in thickness is present within this unit. The vein runs parallel to the bedding in the sandstone, and minor bending and folding of the sandstone beds are associated with it. Below the upper sandstone unit, an
FIGURE 10: STRATIGRAPHIC SECTIONS, PUCKINGER FORMATION, NORTHEASTERN MINNESOTA
Figure 11. Sketch of Puckwunje - Lava contact at Locality 6, near Swamp Lake, SW, Sec. 31, T.64N., R.5E.
80 foot talus slope is present. As at the other exposures, the talus blocks are composed of sandstone. Ten feet of gray sandstone are exposed below the talus slope, with the remaining eight feet of the slope covered by talus.

A small northward-flowing stream has cut a small canyon through the Keweenawan lavas and the Puckwunge Formation ½ mile northeast of Prout Lake at Locality 8. Bent pipe vesicles in the lower lava flow were measured, and indicate a S.20E. direction of movement for the lava flow. Eighteen feet of thick- to medium-bedded, brown sandstone underlies the lava flows. A six inch-thick calcite vein similar to the one described at the west boundary of the Grand Portage Indian Reservation (Locality 7) is present within this unit. The brown sandstone is underlain by sixteen feet of thick-bedded, white cross-bedded sandstone. Eight feet of medium-bedded, gray sandstone continues downward to the valley floor.

The type section of the Puckwunge Formation is Locality 9, located ½ mile northeast of Otter Lake. Eighty feet of massive, thick-bedded, gray to buff colored sandstone is exposed beneath the lava flows. A twenty-foot covered interval lies below the sandstone. Below this covered interval, twenty feet of conglomerate and conglomeratic sandstone are exposed (Figure 12). Sixteen feet of coarser conglomerate beneath completes the exposure at the type section; its lower contact is covered. The pebbles and cobbles in the conglomerate are well-rounded, and average 1½ inches in diameter, with the maximum observed cobble diameter being eight inches. The pebbles consist of quartz, quartzite, jasper - iron formation, and white chert.

Locality 10, a more scenic exposure of the Puckwunge Formation, is located along Portage Brook just below Portage Falls. The small canyon
Figure 12. Basal conglomerate of Puckwange Formation, type section,
Locality 9, NE1/4, Sec. 25, T.64N., R.3E..
FIGURE 13: STRATIGRAPHIC SECTIONS, FULGAROV FORMATION, NORTHEASTERN MINNESOTA
cut by Portage Brook exposes twenty feet of massive white sandstone. The area has been intruded by a large diabase dike, and is also apparently faulted. The upper contact of the Puckwunge Formation is not exposed. Farther downstream, eight feet of cross-bedded, yellow-brown sandstone are exposed beneath the massive white sandstone. The lower contact of the Puckwunge Formation is not exposed, but slate and argillite pebbles in the bed of the brook suggest it is close.

The westernmost exposure visited during the study is Locality 11, 1½ miles northeast of Loft Lake. Six feet of gray sandstone is exposed beneath the Keweenawan lava flows. A twelve-foot covered interval lies below the sandstone, and then a diabase sill containing sandstone inclusions is exposed. It is not known whether this diabase belongs to the group of Logan diabase sills, or whether it is part of the Duluth Complex. The Duluth Complex truncates the Puckwunge Formation a short distance to the west near Devilfish Lake.

Petrology

Conglomerate

At the type section ½ mile northeast of Otter Lake (Locality 9), the basal conglomerate of the Puckwunge Formation is composed of pebbles and cobbles in a coarse sandstone matrix. The sand grains in the matrix are rounded to well-rounded and are fairly well sorted. In hand specimen, the grains appear to be dominantly quartz, with a minor amount of pink feldspar also present. A modal analysis of a thin section (Table 1a, sample OL-2) indicates that the conglomerate matrix is composed of 65 percent quartz (42 percent unit quartz, 23 percent polycrystalline quartz), 7 percent feldspar (potassium feldspar dominant),
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**Table 3a:** Mineralogical composition of the Buckhorn Formation, southwestern Minnesota

*Figures in percent. All rock fragment, trace (less than one percent) = x.*
TABLE 1b. DESCRIPTION OF MINERAL TYPES, FUCKWUNGE FORMATION, NORTHEASTERN MINNESOTA

1) Quartz
   a) Unit quartz - Grains usually rounded, very few bubbles or inclusions, sharp extinction.
   b) Polycrystalline quartz - Grains usually rounded, subject to greater degree of alteration and replacement than unit quartz, sutured contacts between different crystals in same grain, undulosity common.
   c) Recrystallized quartz - Grains usually rounded, non-sutured contacts between different crystals in same grain, undulosity common.
   d) Schistose quartz - Grains usually rounded, contacts between crystals in same grain may be either straight or sutured, crystals elongated in one direction, undulosity common.

2) Feldspar
   a) Plagioclase - Grains usually subangular to subrounded, fresh unaltered grains rare, grains with kaolinitic alteration more common.
   b) Orthoclase - Dominant feldspar present, grains subangular to subrounded, fresh unaltered grains rare, grains with kaolinitic alteration more common.
   c) Microcline - Grains subangular to subrounded, fresh unaltered grains very rare, grains with kaolinitic alteration more common, generally more highly altered than other feldspars.

3) Rock Fragments
   a) Chert Fragments - Grains usually rounded, commonly altered or replaced along edges.
   b) Orthoclase-Quartz Rock Fragments - Coarse-grained, grains subrounded to rounded, highly altered, particularly around orthoclase, most common felsic rock fragment present.
   c) Plagioclase-Quartz Rock Fragments - Coarse-grained, grains subrounded to rounded, highly altered, particularly around plagioclase portions of grains.
   d) Microcline-Quartz Rock Fragments - Coarse-grained, grains subrounded to rounded, highly altered, particularly around microcline portions of grains.
   e) Quartzite Rock Fragments - Grains well rounded, grains in rock fragments consist of unit quartz and are cemented by silica.
   f) Fine-grained Mafic Volcanic Rock Fragments - Only one grain observed, sample GP-16, subrounded, plagioclase laths present, grain moderately altered.
   g) Slate Fragments - More common in lower portions of formation, fragments are angular to subangular, usually highly altered or replaced.
TABLE 1b continued

4) Miscellaneous Mineral Grains
   a) Muscovite - Very rare, appears to be present as detrital flakes.
   b) Zircon - Both malacon and normal zircon present in thin sections, described in Table 2b.

5) Cement and Matrix
   a) Silica Cement - Original cement present in formation, occasionally 120 degree angles between crystal faces present on overgrowths.
   b) Carbonate Cement - Sparry variety, has replaced portions of silica cement and filled in pore spaces between silica overgrowths.
   c) Sericite Matrix - More common in finer-grained portions of formation, appears to replace carbonate cement.
   d) Epidote Matrix - Usually present near or mixed with sericite matrix.
   e) Chlorite Matrix - Only locally common in formation, usually present in trace amounts.
   f) Hematite Cement - Present in trace amounts in portions of formation where silica cement is dominant, gives red-brown color to formation.
   g) Authigenic Orthoclase Cement - Occasionally present around orthoclase grains in lower portion of formation.
9 percent granitic rock fragments, and 16 percent authigenic orthoclase cement, carbonate cement, and sericite - epidote matrix. The pebbles and cobbles in the conglomerate are well-rounded, and average 1\(\frac{1}{2}\) inches in diameter. In order of decreasing abundance, they consist of white quartzite, jasper - iron formation, and white chert.

The basal conglomerate exposed on Grand Portage Island differs considerably from the conglomerate near Otter Lake. In unaltered portions of the conglomerate on Grand Portage Island (Locality 2), the matrix is composed of sand-sized grains. However, in much of the conglomerate, the matrix is largely replaced by carbonate (Figure 14), with modal analysis of a thin section indicating a carbonate content of 56 percent (Table 1a, sample GP-14). A weight analysis of carbonate content by Nelson (1942) indicated a 42 percent carbonate content for the conglomerate. The grains composing the unreplaced portion of the conglomerate matrix consist of quartz, with traces of feldspar also present. Silica cement and sericite are also present in the unaltered portions of the matrix. The principal non-opaque accessory heavy minerals are zircon (63 percent) and apatite (34 percent), with tourmaline and rutile present in minor amounts (Table 2a). The pebbles in the conglomerate consist of rounded quartzite and quartz pebbles, and angular chips and fragments of slate and argillite. In some beds, the argillite and slate chips form an imbricate structure, with the chips dipping to the northwest, indicating deposition in a south-easterly-flowing current (Figure 15). A similar flat pebble imbricate structure has been studied in a Middle Keweenawan conglomerate in Michigan (White, 1952).
Figure 14. Photomicrograph of basal conglomerate, Puckwunje Formation, Locality 2, Grand Portage Island. Crossed nicols. Slate fragments present in a sandstone matrix that has been partially replaced by sparry carbonate. Sample GP-14.
<table>
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<th>Sample Locality</th>
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<th>Apatite</th>
<th>Amphibole</th>
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Table 2a. HEAVY MINERAL DATA, PUCKWUNGE FORMATION, MINNESOTA
Figures in percent, trace (less than one percent) = x.
TABLE 2b. HEAVY MINERAL DESCRIPTIONS, FUCKJUNGE FORMATION, NORTHEASTERN MINNESOTA.

1) Zircon
   a) Normal or Keweenawan type of Tyler, et al. (1940) - clear, colorless, high birefringence, usually present as well developed crystals with sharp crystal angles, occasionally zoned, may contain inclusions.
   b) Malacite - Generally slightly lower birefringence than normal zircon, cloudy altered appearance to grains, zoning very rarely present, grains usually well rounded.
   c) Hyacinth - Pink to light purple color, darker colored grains slightly pleochroic, zoning and inclusions common, grains usually subrounded.

2) Tourmaline
   a) Brown - Usually rounded, angular grains may be fragments of rounded grains broken by crushing of sample.
   b) Blue-green - Usually rounded, secondary tourmaline overgrowths present around several grains, angular grains may be fragments of rounded grains broken by crushing of sample.
   c) Black - Grains very well rounded, pleochroism usually masked by dark color.

3) Apatite
   a) Angular - Clear, short prismatic crystals usually terminated by basal planes, but occasionally terminated by first order pyramids.
   b) Rounded - Clear, subrounded crystals of shape described above.
   c) Subspherical - Nearly spherical grains, cloudy appearance due to pitted surface on grains.

4) Amphibole - Angular, brown grains, extinction angle of about ten degrees.

5) Rutile - Well rounded, red-brown grains.

6) Sphene - Angular dirty white to light yellow colored fragments, original grains broken by crushing of sample.

7) Garnet - Clear angular fragments, occasionally containing bubbles and inclusions.
Figure 15. Imbricate slate fragments and chips in basal conglomerate at Locality 2, Grand Portage Island. White disk in right center of photo is a 25 cent piece. Pebble imbrications indicate current flowed from right to left.
Sandstone

In hand specimen, the sandstone of the Puckwunje Formation generally appears to be composed of fair to well-sorted, subrounded to well-rounded grains of quartz, with traces of feldspar occasionally visible. Silica appears to have been the original cement, and has since been partially replaced by carbonate. The average mineralogical composition of the sandstone consists of 75 percent quartz (61 percent unit quartz, 14 percent polycrystalline quartz), 4 percent feldspar (orthoclase dominant), and 18 percent carbonate cement, silica cement, and sericite matrix (Table 1a). The sandstone of the Puckwunje Formation is an orthoquartzite (after Pettijohn, 1957b). Zircon (76 percent) and apatite (13 percent) are the abundant non-opaque accessory heavy minerals, with tourmaline, amphibole, rutile, sphene, and garnet present in minor amounts (Table 2a). Figure 16 is a photomicrograph of a typical sandstone from the Puckwunje Formation.

Provenance

Mineralogic Evidence

The basal conglomerate of the Puckwunje Formation appears to have been derived from the weathering of the nearby pre-Keweenawan rocks. The pebbles in the conglomerate at the type section are composed of white, red, and dark gray quartz, red and white quartzite, jasper iron formation, and white chert. All of these lithologies are present in the nearby Middle Precambrian (Anidicidan) and Lower Precambrian (Archean) rocks.

Examination of thin sections indicates that the matrix of the
Figure 16. Photomicrograph of typical sandstone, Puckwunga Formation, Sample GP-19, Locality 10. Crossed nicols. Traces of K feldspar and polycrystalline quartz are present along with dominant unit quartz. Many grain edges are altered to a mixture of carbonate and sericite.
conglomerate at the type section was also derived from the nearby pre-Keweenawan rocks. The polycrystalline quartz (23 percent) present in the conglomerate matrix is typical of metamorphic rocks. The granitic rock fragments (9 percent) in the conglomerate matrix indicate the presence of granite in the source area. Rocks of these types are exposed in the Lower Precambrian (Archean) formations of northeastern Minnesota and southwestern Ontario.

The pebbles in the conglomerate on Grand Portage Island appear to have been principally derived from the underlying Rove Formation. Pebbles of slate, argillite, white quartz, and white quartzite are present. The angular to subrounded chips and fragments of slate and argillite in the conglomerate were almost certainly derived from the Rove Formation. The rounded quartz pebbles in the conglomerate could have been derived from the numerous quartz veins present in the pre-Keweenawan rocks of the area.

Tyler, et al. (1940) did a detailed study of the detrital heavy minerals present in the Precambrian rocks of the Lake Superior Region. Three types of zircon were found to be present. Lower Precambrian rocks in the Lake Superior Region contain hyacinth (described by Foldervaart, 1955; Morgan and Auer, 1941), and Middle Precambrian rocks contain malacon (described by Morgan and Auer, 1941), a second type of zircon. The Upper Precambrian rocks were found to contain a third zircon type termed normal or Keweenawan zircon (see Table 2b). Thus the zircon types present in a rock from the Lake Superior Region may be used in a limited capacity to determine the general age of a rock. The white quartzite pebbles in the conglomerate on Grand Portage Island were analyzed for non-opaque accessory heavy mineral content, and found to
contain hyacinth and malacon, but not normal or Keweenawan zircon described by Tyler, et al. (1940) as being present in the Keweenawan rocks of the Lake Superior Region. Thus the pebbles were apparently derived from a pre-Keweenawan quartzite. The pebbles are very similar to the white quartzites present in the upper portion of the Rove Formation (Grout and Schwartz, 1933; Morey, 1969), and were probably derived from that source.

The matrix of the conglomerate on Grand Portage Island also appears to have been derived from rock types common in the nearby pre-Keweenawan formations. Granite and quartzite fragments are present in the conglomerate matrix (Table 1a, sample GP-16). The presence of hyacinth zircon (Table 2a, sample GP-16) suggests that the granites in the source area may have been Lower Precambrian (Archean) in age.

The sandstone of the Puckwunge Formation also appears to have been derived from the nearby pre-Keweenawan rocks. Modal analyses of thin sections of the sandstone (Table 1a) indicate the presence of poly-crystalline quartz (14 percent), probably derived from metamorphic rocks. Traces of schistose quartz in the sandstone also attest to the presence of metamorphic rocks in the source area. Potassium feldspar (4 percent) and traces of granitic rock fragments indicate that granitic rocks were also exposed in the region. In addition, traces of chert and slate fragments indicate the presence of these rock types in the source area. One grain of basalt was observed in a thin section of sandstone (Table 1a, sample GP-16) from Grand Portage Island. No other basalt grains were noted in the Puckwunge Formation during this study; however, Nelson (1942) also observed one grain of basalt in a petrographic analysis of sandstone from Grand Portage Island. Basalt, whether exposed as
a flow or dike, was of only very minor importance in the source area. The presence of a second-cycle quartz grain with an abraded overgrowth (Figure 17) suggests that sandstone or quartzite was also a source of sediment during Puckwunje deposition.

All three types of zircon described by Tyler, et al. (1940) (hyacinth, malacol, and normal or Keweenawan) were found in the sandstone. If the presence of these zircon types can be relied on as definite source indicators, Lower, Middle and Upper Precambrian rocks were present in the source area. The principal rocks of the source area would appear to have been Middle and Lower Precambrian in age. Upper Precambrian (Keweenawan) rocks, as evidenced by the relatively small amount of normal zircon present in the sandstone, and the lack of basalt fragments, were a very minor rock type in the source area. Keweenawan lava flows are believed to have been present south of Lake Superior during deposition of the Puckwunje Formation (Books, 1970; DuBois, 1962). Minor amounts of detritus from these lava flows may have been transported northward, or lava flows of the same age may have also been present north of Lake Superior.

Paleocurrent Evidence

A total of 56 paleocurrent measurements were taken at eight of the eleven outcrop areas visited in the study. Analysis of cross-beds, troughs, and ripple marks in the Puckwunje Formation indicates a southeasterly direction of sediment transport during deposition, with the source area possibly lying to the northwest (Figure 18). A chi-square value determined by the Tukey Chi-Square Test of Orientation (Tukey, 1954; Rusnak, 1957) strongly indicates a preferred orientation
Figure 17. Second-cycle quartz grain with abraded overgrowth, Locality 3, Fuczwunge Formation. Sample GP-2A, crossed nicols. Both silica cement and quartz grains are being replaced by younger carbonate cement.
1. Strike of Ripple Marks
2. Plunge of Trough Axes
3. Dip Direction of Cross-beds

Vector Mean

Figure 16. Paleocurrent Data, Puckwunge Formation, Minnesota, 56 Measurements.
for the paleocurrent indicators. The Middle Precambrian Rove Formation and Gunflint Iron Formation, and Lower Precambrian granite and metavolcanic rocks are now the major rock units in the source area as determined by these paleocurrent indicators, and could have supplied all the observed clasts except for the normal zircon.

Sedimentation

The presence of cross-bedding and ripple marks in a well-sorted quartz-rich sediment composed of well-rounded grains suggests a high energy, shallow water depositional environment for the Puckwunge Formation. Both planar and trough types of cross-bedding (Allen, 1963) and oscillatory ripple marks are present in the sandstone. The presence of these features suggests that deposition occurred in a shallow water environment.

The mineralogical maturity of the sandstone suggests that the sediments were well-worked during transportation and deposition. Assuming equal frequency at source, the dominance of unit quartz over polycrystalline quartz in the sediments suggests a great deal of working, with the less stable polycrystalline quartz being eliminated (Blatt and Christie, 1963; Greensmith, 1964). As is usual in sandstones (Conolly, 1965), the percentage of polycrystalline quartz decreases in the fine-grained portions of the Puckwunge Formation. The Z-T-R Index of Hubert (1962) uses the total percentage of zircon, tourmaline, and rutile present in the detrital non-opaque, non-micaceous heavy mineral suite of a sandstone as an index of maturity. Orthoquartzites as defined by Pettijohn (1957b) generally have a Z-T-R Index of 90 or higher. The
Fuckwunge Formation has an average Z-T-R Index of 79, indicating a fair degree of maturity. The degree of mineralogical maturity found in the sandstones suggests moderate abrasion of the sediments, as would occur in a shallow water, near-shore environment.

The basal conglomerate exposed at the type section (Locality 9) near Otter Lake appears to have been deposited in a beach environment. The pebbles have been very well rounded, and cross-bedding is occasionally present. There is no evidence of channel cutting or filling, suggesting that a fluvial origin is unlikely.

The conglomerate on Grand Portage Island appears to be somewhat different in origin. Rounded pebbles of quartz and quartzite are present, along with rounded and angular chips and fragments of slate and argillite. The quartz and quartzite pebbles are well-rounded, and appear to have been worked in a high-energy environment. The slate and argillite chips, however, are very thin, and could not have withstood transport over a long distance, or reworking in a high-energy environment.

Imbricate orientations of the slate and argillite chips are present in certain beds of the conglomerate (Figure 15). Such structures may be used as paleocurrent indicators (Potter and Pettijohn, 1963). The paleocurrent direction indicated by the imbricate conglomerate pebbles shows a current direction to the southeast, the same direction indicated by cross-bedding and ripple marks in the sandstone (Figure 18). Imbricate pebble orientations have been observed in both fluvial and beach environments. An imbricate pebble conglomerate studied by White (1952) was deposited in a fluvial environment. The imbricate structure described by White was not well developed in the conglomerate, and channels and cross-bedding were present. In the Fuckwunge conglomerate on
Grand Portage Island, the imbricate structure is well developed, and no evidence of channel cutting or filling was observed. Imbricate pebble orientations on beaches have also been studied (Krumbein and Griffith, 1938; Krumbein, 1938). On beaches, pebbles of a tabular or disk shape take on a preferred orientation, with the plane of the pebble dipping toward the direction of major wave action, which is ordinarily toward the sea (Fraser, 1935). After studying a beach in detail, Krumbein (1939) observed that the average pebble inclination was 46 degrees toward the water. Because rounded quartz and quartzite pebbles are scattered throughout the conglomerate, and the average corrected dip of the pebbles is much less than 46 degrees, deposition in a beach environment does not appear likely. Because only a small part of the conglomerate contains imbricated pebbles, the imbrication may have been caused by deposition in shallow water under the influence of tidal currents.

It appears that the conglomerate on Grand Portage Island was deposited in shallow water, probably near shore. Because of their degree of rounding, the quartz and quartzite pebbles were probably transported a fair distance before deposition. Because of their angularity and fragile nature, the slate and argillite chips, however, probably had a local source.

Both beach and shallow water environments are represented in the rocks of the Puckwunge Formation. Petrographic examination and paleocurrent analyses have been shown above to indicate that the formation was derived from the pre-Keweenawan rocks to the north. The Puckwunge Formation was probably deposited during the northward transgression of a sea into the region. Because of the disconformable relationship with the overlying Keweenawan lava flows, the transgression of the sea into the region and the subsequent deposition of the Puckwunge Formation probably took place well before the be-
ginning of Keweenawan igneous activity in the immediate area, although volcanism may have started in more distant portions of the source area.

The Sibley Formation of Ontario

Stratigraphy

The Lower Keweenawan Sibley Formation of Ontario is exposed on the Sibley Peninsula east of Thunder Bay, on Edward Island and several other islands in Black Bay east of the Sibley Peninsula, and in an extensive area around Nipigon and Nipigon Bay north and northeast of the Sibley Peninsula (Figure 19). The formation consists of conglomerate, sandstone, and a mudstone unit, with total thickness of the formation varying from one-hundred to six-hundred feet (Tanton, 1931).

On the Sibley Peninsula, the Sibley Formation is underlain by the Middle Precambrian Rove Formation, with a basal conglomerate usually present. The contact between the Rove and Sibley Formations is a general disconformity, with the bedding of the two formations being parallel. The basal conglomerate of the Sibley Formation contains pebbles, cobbles, and small boulders of the pre-Keweenawan rocks of the area (Moorhouse, 1960). Where the basal conglomerate pinches out, the overlying white quartz sandstone rests directly on the Rove Formation.

The Sibley Formation is disconformably overlain by the Osler Series of sandstone and lava flows. On St. Ignace Island south of Nipigon Bay, the Osler consists of 200 feet of conglomerate and sandstone. The basal conglomerate of the Osler Series contains pebbles of sandstone believed to have been derived from the underlying Sibley Formation (Tanton, 1931).

The Sibley Formation may be divided into three general stratigraphic units. Tanton (1931) divided the Sibley Formation into six stratigraphic
Figure 19. Geologic and Location Map of the Sibley and Oslar Formations, Ontario
units; however, a breakdown into three units, a basal conglomerate, a quartz sandstone, and an overlying mudstone is sufficient for this study.

The basal conglomerate has a maximum observed thickness of 36 feet (Moorhouse, 1960). Pebbles, cobbles, and small boulders of granite, iron formation, greenstone, chert, jasper, quartz, and quartzite are present in a coarse sandstone matrix. All of these lithologies are present to the north in the pre-Keweenawan rocks of the immediate area.

The thick-bedded, massive white sandstone unit has a maximum exposed thickness of 200 feet, and is the best-exposed member of the Sibley Formation (Franklin, 1970). The grains of the cross-bedded, ripple-marked sandstone are well-sorted and well-rounded.

The overlying mudstone unit has a maximum thickness of 450 feet, and is the thickest unit (Franklin, 1970). Stromatolites are present in carbonate and chert layers. According to Franklin (1970) occasional "flow wrinkles" are present in the mudstone.

The lower portion of the Sibley Formation was examined at Pass Lake, Ontario, where eight feet of basal conglomerate are overlain by 100 feet of sandstone. The upper unit of mudstone is not present at Pass Lake, and was not studied.

Petrology

The conglomerate at Pass Lake (Figure 20) contains rounded pebbles and cobbles of granite and greenstone, and angular pebbles, cobbles, and boulders of banded iron formation, jasper, and quartzite. The granite and greenstone pebbles and cobbles were more easily rounded than were the fragments of iron formation, jasper, and quartzite. The
Figure 20. Cobble and small boulders of pre-keweenawan rocks in the basal conglomerate, Sibley Formation, Pass Lake, Ontario.

Figure 21. Sandstone (light-colored) overlying basal conglomerate (dark-colored), Sibley Formation, Pass Lake, Ontario.
matrix of the conglomerate consists of coarse-grained, poorly-cemented red sandstone.

The conglomerate at Pass Lake is overlain by 100 feet of white, thick-beded, massive quartz sandstone (Figure 21). The well-cemented sandstone contains well-rounded and well-sorted grains. Modal analyses of thin sections (Table 3a) shows that the composition of the sandstone averages 84 percent quartz (74 percent unit quartz, 10 percent polycrystalline quartz), 3 percent chert rock fragments, traces of feldspar and granitic rock fragments, and 12 percent carbonate cement, silica cement and sericite matrix. The principal non-opaque accessory heavy minerals are zircon (72 percent), tourmaline (15 percent), and apatite (13 percent) (Table 4a).

Provenance and Sedimentation

The Sibley Formation was derived from the pre-Keweenawan rocks of the area. The conglomerate contains fragments of granite, greenstone, banded iron formation, jasper, and quartzite, all of which are present in the pre-Keweenawan rocks of the area. The sandstone also appears to have been derived from the pre-Keweenawan rocks of the area. The presence of polycrystalline, recrystallized, and schistose quartz in the sandstone indicates that metamorphic rocks (probably Lower Precambrian) were present in the source area. Unit quartz and the small amount of feldspar and feldspar-quartz rock fragments present were probably derived from granite. Chert rock fragments indicate that chert was also present in the source area; this could have been either Lower Precambrian (Archean) or Middle Precambrian (Anisian) (Gunflint Iron Formation) chert.
Table 3a. MINERALOGICAL COMPOSITION OF THE SIBLEY FORMATION, PASS LAKE, ONTARIO

Figures in percent, RF = rock fragment, trace (less than one percent) = x.
Table 3b. DESCRIPTION OF MINERAL TYPES,
SIBLEY FORMATION, PASS LAKE, ONTARIO

1) Quartz - Same as described in Table 1b.

2) Feldspar - Same as described in Table 1b, less total feldspar content.

3) Rock Fragments
   a) Chert fragments - Mostly as described in Table 1b.
      Some oolitic chert fragments as shown in Figure 22.
   b) Plagioclase - Quartz rock fragments (coarse-grained) -
      Same as described in Table 1b.
   c) Microcline - Quartz rock fragments (coarse-grained) -
      Same as described in Table 1b.

4) Cement and Matrix
   a) Sericite matrix - Same as described in Table 1b.
   b) Silica cement - Completely fills in spaces between grains.
   c) Hematite cement - Same as described in Table 1b.
   d) Carbonate cement - Sparry variety, has partially replaced
      silica cement in portions of sandstone.
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<th>Apatite</th>
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</table>

**TABLE 4a.** HEAVY MINERAL DATA, SIBLEY FORMATION, PASS LAKE, ONTARIO

Figures in percent. Trace (less than one percent) = x.
Table 4b. HEAVY MINERAL DESCRIPTIONS, SIBLEY FORMATION, PASS LAKE, ONTARIO

1) Zircon - Same as described in Table 2b.
2) Tourmaline - Same as described in Table 2b.
3) Apatite - Same as described in Table 2b, except no subspherical apatite is present.
Figure 22. Photomicrograph of sandstone sample collected immediately above basal conglomerate, Sibley Formation, Paisley, Ontario. Crossed nicols. Note oolitic chert fragment in left portion of photo. Sample S-11-1.
If the presence of malacon, hyacinth, and normal or Keweenawan zircon described by Tyler, et al. (1940) can be used as an indicator of source rocks, Lower, Middle, and Upper Precambrian rocks were present in the source area. Because of the high percentage of malacon present in the Sibley Formation, the work of Tyler, et al. suggests that Middle Precambrian rocks were a major rock type in the source area.

The lower portion of the Sibley Formation appears to have been deposited in a shallow water environment. Fye (1962) and Franklin (1970) both interpret the sedimentary structures in the sandstone and conglomerate of the Sibley Formation as indicative of a shallow water, near-shore depositional environment. Paleocurrent analysis of cross-beds and ripple marks at Pass Lake (Figure 23), and of paleocurrent indicators in the sandstone at other locations (Franklin, 1970) indicate a southerly direction of sediment transport. The Gunflint Iron Formation, Rove Formation, Kakabeka (Fokegama) Formation, and Lower Precambrian granites, schists, and greenstones probably comprised the major portion of the source area to the north.

The mudstone unit of the upper Sibley Formation has been interpreted as having been deposited in a flood plain environment under the conditions of seasonal rainfall (Fye, 1962). A paleocurrent analysis of the mudstone and upper sandstone (Hamblin, 1965) indicates a southwesterly direction of sediment transport. The mudstone unit was deposited following a significant environmental change during Sibley time. Rubidium - Strontium whole-rock analyses of the mudstone gave an age of 1.376 ± 33 million years before present for deposition of the mudstone (Franklin, 1970).

The deposition of the Sibley Formation probably began with the northward transgression of a sea into the region, with sediment being supplied
1. Strike of Ripple Marks
2. Dip Direction of Cross-beds

Vector Mean

Figure 23a. Paleocurrent Data, Sibley Formation, Pass Lake, Ontario, 14 measurements.
from the north. After deposition of the conglomerate and sandstone, the environment was altered to a fluvial flood plain with seasonal rainfall, and the mudstone unit was deposited.

The Osler Formation of Ontario

Stratigraphy and Petrology

The Osler Formation of Ontario consists of a lower, sedimentary unit and an upper, dominantly volcanic unit. The sedimentary rocks of the lower Osler Formation are exposed on Edward Island in Black Bay and on St. Ignace Island in Osler Bay (Figure 19). The Osler Series disconformably overlies the Sibley Formation. The sedimentary rocks of the lower Osler Formation are conformably overlain by Keweenawan lava flows of the upper Osler Formation. Tanton (1931, p. 57) states:

"The phenomena exhibited at the contact of the lowest lava and the underlying sediments are interpreted as indicating that the sediments were plastic when the lava flowed over them, and that, therefore, no considerable time elapsed between the deposition of the sediments and the overlying lava."

Twelve feet of basal conglomerate of the Osler overlies the Sibley Formation. Tanton (1931) states that the conglomerate contains rounded pebbles, cobbles, and boulders, all closely packed, and lying in a matrix of impure red and gray sandstone. The fragments in the conglomerate are composed of sandstone, jasper - taconite, vein quartz, granite, greenstone, and red quartz porphyry. The red quartz porphyry pebbles have been reported as being similar in lithology and texture to Keweenawan intrusives present in the area, and may have been derived from an early Keweenawan intrusive (Tanton, 1931). The sandstone fragments appear to
have been derived from the Sibley Formation, while the other fragments were probably derived from the pre-Keweenawan rocks of the area.

Two hundred feet of sandstone and red mudstone overlie the basal conglomerate. The mudstones and sandstones are interbedded, and occasionally intermixed. The well cross-bedded, impure white quartz sandstone is best exposed in a thick-bedded, 25 foot-thick layer on Edward Island. Red mudstone overlies the sandstone, and forms the upper portion of the sedimentary rocks of the lower Osler Formation. Thin mudstone units similar in lithology to the lower Osler sedimentary rocks are occasionally interbedded with the overlying lava flows, suggesting that lava extrusion only temporarily interrupted sedimentary deposition.

Provenance and Sedimentation

The depositional environment of the sedimentary rocks of the lower Osler Formation appears to be similar to that of the upper Sibley Formation. The sandstone of the lower Osler Formation is more heavily cross-bedded than the sandstones of the Sibley Formation. Paleocurrent analysis of Osler cross-bedding by Hamblin (1965) indicates that deposition took place in a westward-flowing current. The Osler mudstones appear to be identical in composition and character to the mudstones of the Sibley Formation. Derivation from the same source area, as well as the fact that the Osler sediments are at least in part derived from the Sibley Formation accounts for this similarity.
Lower Keweenawan Sedimentary Rocks at Nopeming, Minnesota

Stratigraphy

At Nopeming, just west of Duluth, 28 feet of Lower Keweenawan quartzite and conglomerate are intermittently exposed beneath basal Keweenawan lava flows over a distance of half a mile in Sections 17 and 20, T.49N., R.15W. (Figure 23). Lithologically, these rocks resemble the Puckwunge Formation of northeastern Minnesota, and in the past have been correlated with the Puckwunge (Goldich, et al., 1961; Nelson, 1942; Schwartz, 1949). Two nearby conglomerate outcrops in Sections 1 and 15, T.48N., R.16W. were previously correlated with the sedimentary rocks at Nopeming; however, Morey (1967) re-assigned these last two exposures to the Upper Keweenawan Fond du Lac Formation. The sedimentary rocks at Nopeming are informally referred to as the "Nopeming Formation" in this report.

The "Nopeming Formation" appears to be underlain by the Middle Precambrian (Annikian) Thomson Formation. The contact between the sediments and the Thomson Formation is not exposed, but appears to be an angular unconformity. The nearest outcrop of the underlying Thomson Formation, 350 feet west of the quartzite, has an attitude of N.85E., 84S., which is typical for the Thomson in this area; the attitude of the quartzite is N.10W., 20E., nearly perpendicular to the steeply-folded Thomson.

Both the basal flows of the Keweenawan lavas and the underlying "Nopeming Formation" dip gently (15-25 degrees) to the east. Small-scale loading structures in the upper six inches of the quartzite
suggest that the sediments were probably un lithified at the time of lava extrusion. Furthermore, the basal surface of the lava shows undulations and re-entrants suggestive of loading on a soft surface rather than on an eroded, lithified surface, and sand grains can be seen to have been squeezed up for a few inches between the lobes or pillows of the lavas. These load structures (Figure 24) are similar to the features present in the Osler sediments immediately below the overlying lava flows as described by Tanton (1931). Pillow structures in the lowest exposed flow at Nopeming (Figure 25) indicate that the lava may have been extruded into the same body of water in which the underlying sediments were deposited.

The stratigraphic relationship between the North Shore Volcanic Group and the "Nopeming Formation" is subject to controversy. At Nopeming, the sedimentary rocks are overlain by what appears to be the basal lava flow; however, in a well drilled in Short Line Park, 2½ miles south, a similar-appearing quartzite and conglomerate are interbedded with the lower 115 feet of lava flows, and the lowermost lava flow rests directly on the underlying Thomson Formation (Winchell, 1889). J. A. Kilburg (Personal communication, 1971) reports the presence of a thin sedimentary unit resembling the upper portion of the "Nopeming Formation" interbedded with the lava flows at Nopeming. Thus deposition of the "Nopeming Formation" appears to have been contemporaneous with extrusion of the lower portion of the North Shore Volcanic Group in the area, and the quartz-rich sediment was supplied from outside the area of volcanic activity.

Petrographic study shows that the lowermost exposed sedimentary rocks at Nopeming exhibit a greater degree of recrystallization than the middle and uppermost sedimentary rocks. This recrystallization, as well as gravity and magnetic profiles across the area (Figure 26), suggests the
Figure 24. Sketch of load structure in upper 6 inches of metasiltstone, Sec. 17, T.49N., R.15W., "Nopeming Formation," Minnesota.
Figure 25. Pillow structures in basal lava flow, Sec. 20, T. 49N., R. 15W., "Nopeming Formation," Minnesota.
FIGURE 26. GEOPHYSICAL PROFILES, NOPEMING, MINNESOTA.

- Magnetic Profile
- Gravity Profile

VERTICAL EXAGGERATION 2X
presence of a near-vertical intrusive dike beneath the sediments. This geophysically inferred body may be related to a mafic sill which is intruded into the overlying lava flows (J. A. Kilburg, Personal communication, 1971).

Twenty-eight feet of sedimentary rocks are exposed beneath the Keweenawan lava flows in Section 20, T.49N., R.15W. (Figure 27). Thirteen feet of quartzite are overlain by eight feet of conglomerate. The conglomerate is overlain by four feet of quartzite, which is in turn overlain by a one-foot-thick bed of metasiltstone. The metasiltstone is overlain by one foot of additional quartzite, which is in turn overlain by one foot of metasiltstone. Pillowed basalt rests upon this metasiltstone.

A similar, but more poorly exposed stratigraphic section was measured in Section 17, T.49N., R.15W. (Figure 27). Two feet of conglomerate are exposed 24 feet beneath the base of the lowermost lava flow. This conglomerate is overlain by a 16-foot covered interval. Four feet of quartzite overlain by one foot of metasiltstone are exposed above this covered interval. The metasiltstone is overlain by two feet of additional quartzite, which is in turn overlain by two feet of metasiltstone. A pillowed basalt flow rests upon this metasiltstone.

The conglomerate (Figure 28) contains well-rounded pebbles and occasional broken, angular fragments of rounded pebbles of quartz and quartzite, with the average pebble diameter being 1\(\frac{1}{2}\) inches. The matrix of the conglomerate is white quartzite, and appears to be identical to the overlying and underlying quartzite. Cross-bedding is occasionally present in the conglomerate.

The quartzite (Figure 29) is thick-bedded, and contains well-sorted,
FIGURE 27. STRATIGRAPHIC SECTIONS, NOPEMING FORMATION, MINNESOTA
Figure 28. Quartz-pebble conglomerate, Sec. 17, T.49N., R.15W., "Nopeming Formation," Minnesota.

Figure 29. Quartzite and interbedded metasiltstone (light-colored) overlain by lava flow (dark-colored), Sec. 27, T.49N., R.15W., "Nopeming Formation," Minnesota.
well-rounded grains cemented together by silica. In hand specimen, the quartzite appears to be a mature, quartz-rich sediment.

Two beds of metasiltstone are interbedded with the quartzite just below the overlying lava flow (Figure 29). The light and dark banded metasiltstone is very fine-grained, and contains parting lineation due to the alignment of grains during deposition by current.

Petrology

The conglomerate at Nopeming is composed of ten percent pebbles and ninety percent quartzite matrix. The vast majority of the pebbles are composed of white quartz, with a small number of white quartzite pebbles also present. In a count of 180 pebbles, 162 white quartz pebbles, 17 white quartzite pebbles, and 1 gray chert pebble were noted.

Modal analyses of thin sections (Table 5a) indicate that the conglomerate matrix is composed of 88 percent quartz (73 percent unit quartz, 15 percent polycrystalline quartz), 1 percent chert rock fragments, and 10 percent silica cement and sericite-epidote matrix. Traces of carbonate cement, hematite cement, and metamorphic actinolite are also present. The non-opaque accessory heavy minerals present in the conglomerate matrix (Table 6a) are zircon (50 percent), apatite (44 percent), rutile (5 percent), and tourmaline (1 percent).

The buff-colored, cross-bedded, medium- to coarse-grained quartzite is a very mature sediment. Modal analyses of thin sections indicate that the composition of the quartzite averages 83 percent quartz (64 percent unit quartz, 23 percent polycrystalline quartz, 1 percent recrystallized quartz), and 11 percent silica cement, chlorite matrix, and sericite-epidote matrix. Traces of feldspar and chert fragments are also present.
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Table 5a. MINERALOGIC COMPOSITION OF THE "HOPING FORMATION," MINNESOTA
Figures in percent, RF = rock fragment, trace (less than one percent) = x.
Table 5b. Description of Mineral Types, "Nopeming Formation," Minnesota

1) Quartz - As previously described in Table 1b.

2) Feldspar - As previously described in Table 1b.

3) Rock Fragments - All types not described below are as previously described in Table 1b.
   a) Fine-grained Felsic Fragments - Highly altered, consist of untwinned feldspar and quartz with sutured contacts.
   b) Fine-grained Mafic Fragments - Very highly altered, plagioclase laths still visible, shown in Figures 31 and 32.
   c) Slate Fragments - Usually very highly altered, partially replaced by sericite.
   d) Altered Rock Fragments - Shapes and outlines of replaced rock fragments visible in sericite-epidote matrix, probably slate and fine-grained mafic fragments.

4) Cement and Matrix - Types not described below are as previously described in Table 1b, chronologic order of cementation by various cements is not known.
   a) Sericite-Epidote Matrix - Dominant matrix in metasiltstone, has replaced most silt-sized grains and rock fragments.
   b) Actinolite - Metamorphic product present as light green blades.
   c) Limonite - Present as stain on walls of voids in quartzite, may represent weathered pyrite.
<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Heavy Mineral Percentage of Sample</th>
<th>Zircon</th>
<th>Tourmaline</th>
<th>Apatite</th>
<th>Aegirine</th>
<th>Z-R-R Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metasiltstone, Sec. 17</td>
<td>N-25</td>
<td>36.93</td>
<td>67</td>
<td>17</td>
<td>84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Quartzite, Sec. 20</td>
<td>N-14</td>
<td>.05</td>
<td>9</td>
<td>65</td>
<td>5</td>
<td>79</td>
<td>x 2 x 1</td>
</tr>
<tr>
<td>Quartzite, Sec. 20</td>
<td>N-19</td>
<td>.06</td>
<td>16</td>
<td>60</td>
<td>8</td>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td>Conglomerate Matrix, Sec. 20</td>
<td>N-22</td>
<td>.04</td>
<td>8</td>
<td>51</td>
<td>31</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Conglomerate Matrix, Sec. 17</td>
<td>N-28</td>
<td>.07</td>
<td>x</td>
<td>17</td>
<td>18</td>
<td>-</td>
<td>- x 9</td>
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<tr>
<td>Average</td>
<td></td>
<td>.05</td>
<td>20</td>
<td>42</td>
<td>11</td>
<td>73</td>
<td>x x x x 1</td>
</tr>
</tbody>
</table>

Table 6a. HEAVY MINERAL DATA, "NOPEMING FORMATION," MINNESOTA
figures in percent, trace (less than one percent) = x.

* Flood of metamorphic epidote
Table 6b. Description of Heavy Minerals, "Nopeming Formation," Minnesota

1) Zircon - All three types same as previously described in Table 2b.

2) Tourmaline - All three types same as previously described in Table 2b.

3) Apatite - Same as previously described in Table 2b, no subspherical grains present.

4) Amphibole
   a) Brown - Angular fragments, maximum extinction angle of ten degrees.
   b) Green - Angular fragments, maximum extinction angle of 30 degrees.

5) Rutile - Present as angular, red-brown fragments.

6) Garnet - Present as angular fragments, inclusions are present in larger fragments.
The principal non-opaque accessory heavy minerals present are zircon (82 percent), apatite (10 percent), amphibole (6 percent), and tourmaline (2 percent) (Table 6a). The quartzite at Nopeming is an orthoquartzite. Figure 30 is a photomicrograph of a typical sample.

The light and dark banded, fine-grained metasiltstone is very different from the quartzite in composition. In hand specimen, it has a cherty appearance. Modal analyses of thin sections (Table 5a) indicate that the metasiltstone has a composition of 38 percent quartz (31 percent unit quartz, 7 percent polycrystalline quartz, traces of recrystallized quartz), 1 percent weathered plagioclase, 4 percent weathered orthoclase, 53 percent sericite-epidote matrix, and 1 percent altered rock fragments. About 0.5 percent of the metasiltstone consists of altered basaltic rocks fragments (Figures 31 and 32). Traces of granite, slate, and fine-grained felsic rock fragments are also present. The principal non-opaque accessory heavy minerals present in the metasiltstone are zircon (84 percent), apatite (8 percent), and amphibole (8 percent).

The metasiltstone may have been altered by contact metamorphism caused by the overlying lava flow. Many of the rock fragments in the metasiltstone are highly altered, and completely replaced by a sericite-epidote matrix. Even quartz grains are partially replaced by this matrix. The epidote and actinolite present in the sedimentary rocks at Nopeming are of metamorphic origin, and were formed by this alteration, as well as by low-grade burial metamorphism (J. A. Kilburg, Personal communication, 1971). Figure 33 is a photomicrograph of a typically altered sample of sandy metasiltstone collected just below the lava flows in Section 20.

The lower portion of the sedimentary rocks at Nopeming have been recrystallized, possibly due to the presence of an intrusive body beneath
Figure 30. Photomicrograph of quartzite from Sec. 20, T.49N., R.15W., Sample N-22, crossed nicols. Well-rounded quartz grains are cemented by silica cement.

Figure 31. Photomicrograph of volcanic fragment in metasiltstone. Sec. 20, T.49N., R.15W., Sample KO-7. Sand-sized volcanic rock fragment is present in sandy metasiltstone.
Figure 32. Photomicrograph of volcanic fragment in metasiltstone, Sec. 20, T. 49N., R. 15W., Sample KO-7. Sand-sized volcanic rock is present in highly altered metasiltstone.

Figure 33. Photomicrograph of sandy metasiltstone, Sec. 20, T. 49N., R. 15W., Sample KO-7, crossed nicols. Edges of sand-sized grains and silt-sized matrix have been altered.
the exposed rocks. The recrystallized quartzite (Figure 34) contains small amounts of sericite matrix. Many of the quartz grains have been fused together by the recrystallization.

Provenance and Sedimentation

Because of the very mature character of the conglomerate and quartzite at Nopeming, petrography offers few clues to their provenance. The quartz pebbles in the conglomerate could have been derived from the quartz veins present in any of the pre-Keweenawan rocks of the area. The quartzite pebbles were possibly derived from the Middle Precambrian (Animikian) Pokegama Formation now exposed on the Mesabi Range. The presence of a gray chert pebble in the conglomerate suggests that banded iron formation was also present in the source area.

Petrographic study (Table 5a) indicates the presence of weathered orthoclase in the quartzite. This orthoclase, as well as the unit quartz, was probably derived from granite. The polycrystalline and recrystallized quartz were probably derived from Middle Precambrian (Penokean) and Lower Precambrian (Archean) metamorphic rocks.

Paleocurrent analysis of cross-bedding and channels in the quartzite and conglomerate indicate a northwesterly direction of sediment transport, with the source area possibly lying to the southeast (Figure 35). It appears that the Middle Precambrian (Penokean) granites and metamorphic rocks to the south may have been source rocks for the conglomerate matrix and quartzite. It is also possible that the Lower and Middle Precambrian rocks to the north also supplied sediment during deposition of the "Nopeming Formation."

The metasiltstone appears to have a somewhat different provenance
Figure 34. Photomicrograph of recrystallized quartzite, Sec. 17, T.15N., R.15W., Sample N-28, crossed nicols. Grains and silica have been recrystallized. Original grain boundaries are not visible, and have been replaced by sutured contacts.
Figure 35. Paleocurrent Data, "Nopeming Formation," Minnesota
22 Measurements

1. Parting Lineation
2. Plunge of Trough Axes
3. Dip Direction of Cross-beds

Vector Mean
than the quartzite. As in the quartzite, unit, polycrystalline, and recrystallized quartz are present. However, a greater amount of weathered feldspar, including both plagioclase and orthoclase, are present in the metasiltstone. Chert fragments are absent from the metasiltstone, possibly indicating a change in the source from quartzite deposition. The metasiltstone contains sand-sized grains of granite, rhyolite, basalt, and slate, as well as highly altered, no longer identifiable rock fragments. Parting lineation in the metasiltstone indicate a current direction towards either the northwest or southeast. Because the metasiltstone contains volcanic fragments, and the quartzite does not, the metasiltstone was probably deposited during or immediately following the initiation of Keweenawan volcanic activity as the lava flows advanced toward the area.

Hyacinth, malacon, and normal (Keweenawan) zircon are present in all the sedimentary rocks at Nopeming. Malacon is the abundant zircon type present in the conglomerate and quartzite, which from the study of Tyler, et al. (1940) suggests that Middle Precambrian rocks were the principal source of the sediment. In the metasiltstone, however, normal zircon is dominant, which from the work of Tyler, et al. (1940) suggests that Keweenawan Igneous rocks were more abundant during deposition of the metasiltstone.

The conglomerate and quartzite are very mature, and appear to have been well-worked during transportation and deposition. Most of the pebbles in the conglomerate are well-rounded, but some of the pebbles are angular fragments of well-rounded pebbles. The pebbles were probably rounded in a high-energy beach environment, with some of the rounded
pebbles being broken by wave action. The high degree of sorting and rounding that is present in the conglomerate matrix and quartzite also suggests that deposition took place in a high-energy near-shore environment. The high percentage of unit quartz as opposed to polycrystalline and recrystallized quartz also suggests that the sediments were well worked. With the exception of one sample of conglomerate matrix which contains an anomalously high amount of apatite, the quartzite and conglomerate have a high Z-T-R Index, also indicative of a high degree of maturity.

The conglomerate and quartzite appear to have been deposited in a near-shore beach or shallow water environment. According to the current indicators, the principal source area may have been located to the southeast, and probably consisted of Middle Precambrian (Penokean) and Lower Precambrian (Archean) granites and metamorphic rocks.

The metasiltstone appears to have been deposited in a slightly different environment than the quartzite. A drop in current velocity, and the addition of small amounts of volcanic sediment during deposition of the metasiltstone appear to be the chief differences between the two depositional regimes. The interbedded metasiltstone indicates that the change in environment was only temporary, and deposition of quartzite again occurred after deposition of the lower metasiltstone bed. The upper metasiltstone bed was possibly deposited during the outburst of volcanic activity which was responsible for extrusion of the overlying lava flow. At no time, however, was the volcanic area the main source of sediment.
The Lower Keweenawan Bessemer Formation is intermittently exposed over a distance of 55 miles beneath Keweenawan lava flows in Michigan and Wisconsin (Figure 36). Conglomerate and quartzite are the main lithologies in the formation, which has a maximum thickness of 300 feet (Van Hise and Leith, 1911). The underlying Tyler Formation, the Bessemer Formation, and the overlying Keweenawan lava flows all dip to the northwest at about 65 degrees. Seaman (1944) has described both felsite and diabase dikes which cut the formation in Michigan, but no dikes were observed during this investigation.

The Bessemer Formation was examined at five different locations as shown in Figure 36. A stratigraphic section totaling 182 feet was measured near the village of Iron Belt, Wisconsin (Locality 2), where both the upper and lower contacts of the formation are exposed (Figure 37). An outcrop near Ironwood, Michigan, (Figure 38) was also studied in some detail (Locality 1). The bedding in the upper four inches of the Bessemer Formation at this location is disturbed, suggesting that the sediments were unconsolidated at the time the overlying lava flow was extruded (Figure 39). The presence of pillow structures in the overlying lava flow (Figure 40) suggests that the flow may have been extruded into the same body of water in which the sediments were deposited.

The contact with the underlying Middle Precambrian Tyler Formation appears to be a disconformity. The bedding of the two formations is
Figure 36. Regional Geologic Map, Bessener and Barron Formations, Northern Wisconsin.

Cambrian Sedimentary Rocks

Upper Keweenawan Sedimentary Rocks

Keweenawan Lavas

Lower Keweenawan Bessener and Barron Formations

Lower and Middle Precambrian Rocks

Localities Visited

1. Ironwood, Michigan, NW\(_1\), SE\(_2\), Sec. 12, T.46N., R.47W.
2. Iron Belt, Wisconsin, NE\(_1\), NW\(_2\), Sec. 4, T.45N., R.1E.
3. Weber Lake, Wisconsin, SW\(_2\), Sec. 5, T.45N., R.1E.
4. Whitecap Mountain, Wisconsin, SE\(_2\), Sec. 6, T.45N., R.1E.
5. Upson Lake, Wisconsin, SE\(_2\), Sec. 11, T.45N., R.1W.
6. T.37 and 38N., R.8 and 9W., Sawyer County, Wisconsin
Figure 37. Stratigraphic Section, Bessemer Formation, NE\textsuperscript{3}, NW\textsuperscript{14}, Sec. 4, T.45N., R.1E., Iron County, Wisconsin, Locality 2.
Figure 38. Lower Keweenawan Bessemer Formation, Locality 1, NW:\, Sec. 12, T.46N., R.47W., Ironwood, Michigan.

Figure 39. Disturbed bedding and semi-load structures, Bessemer Formation, Locality 1, NW:\, Sec. 12, T.46N., R.47W., Ironwood, Michigan.
Figure 40. Pillow structures in basal lava flow, Locality 1, A - F.
Sec. 12, T.46N., R.47W., Ironwood, Michigan.
parallel; however, a basal conglomerate containing pebbles derived from the pre-Keweenawan rocks of the area is present at each location where the lower contact of the formation was observed. The pebbles and cobbles in the conglomerate are well rounded, and range up to eight inches in diameter. The matrix of the conglomerate consists of coarse-grained sandstone which appears to be identical to the overlying sandstone. Occasional cross-bedding is present in the conglomerate, which has a maximum observed thickness of eighteen feet.

The dominant lithology in the Bessemer Formation is quartzite or sandstone. This thin- to thick-bedded, fine- to coarse-grained sediment ranges from white to red-brown in color, and contains fair to well sorted, subrounded to well-rounded grains. Cross-bedding and ripple marks (Figure 41) are common.

Some siltstone is interbedded with the sandstone. Near Upson Lake, Wisconsin (Locality 5), desiccation cracks are present in a dark gray siltstone unit which has a maximum exposed thickness of twelve feet.

**Petrology**

The conglomerate was examined near Iron Belt, Whitecap Mountain, and Upson Lake, all in Wisconsin (Localities 2, 4, & 5). It contains well-rounded pebbles and cobbles derived from the pre-Keweenawan rocks of the area (Figure 42). In order of decreasing abundance, they consist of quartz, quartzite, flint and jasper, iron formation, and gneiss. The matrix of the conglomerate (Figure 43) consists of coarse-grained sandstone composed of 77 percent quartz (50 percent unit quartz, 27 percent polycrystalline quartz), 2 percent feldspar (plagioclase dominant), 4 percent chert, coarse-grained quartz-feldspar rock frag-
Figure 41. Ripple marks in sandstone, Bessemer Formation, Locality 5, SE1/4, Sec. 11, T.45N., R.1W., Upson Lake, Wisconsin.

Figure 42. Basal conglomerate of Bessemer Formation, Locality 5, SE1/4, Sec. 11, T.45N., R.1W., Upson Lake, Wisconsin.
Figure 43. Photomicrograph of conglomerate matrix, Bessemer Formation, Locality 2, Iron Belt, Wisconsin. Sample P-6a, crossed nicols. Quartzite pebble is visible in left portion of field of view. Chlorite, carbonate, and granulated quartz are present between the quartz grains.
ments, fine-grained felsic rock fragments, and fine-grained mafic rock fragments, and 18 percent sericite matrix, chlorite matrix, epidote matrix, and silica cement (Table 7). Traces of granulated quartz believed to have been derived from crushing of silica overgrowths and cement during the folding of the formation are also present. Zircon, apatite, garnet, and tourmaline are the principal non-opaque accessory heavy minerals, with amphibole and rutile present in minor amounts (Table 8).

The white to red-brown sandstone (Figure 44) which may be classified as an orthoquartzite, varies in grain size and degree of grain sorting and rounding. The composition of the sandstone averages 81 percent quartz (61 percent unit quartz, 20 percent polycrystalline quartz, and traces of schistose and recrystallized quartz), 5 percent feldspar (potassium feldspar dominant), 3 percent chert, coarse-grained quartz-feldspar, fine-grained mafic, and fine-grained felsic igneous rock fragments, and 11 percent sericite matrix, chlorite matrix, silica, carbonate and hematite cements, and granulated quartz (Table 7). The principal non-opaque accessory heavy minerals are zircon and apatite, with tourmaline, sphene, garnet, and rutile present in minor amounts (Table 8).

The siltstone appears to be similar in mineralogical content to the sandstone, but with a slightly higher percentage of sericite matrix. Zircon (81 percent) and apatite (19 percent) were again the principal non-opaque accessory heavy minerals found to be present (Table 8).

Provenance and Sedimentation

The pebbles in the basal conglomerate of the Bessemer Formation appear to have been derived from the pre-Keweenawan rocks of the area. The quartz pebbles could have been derived from the quartz veins present
Figure 44. Photomicrograph of sandstone, Bessemer Formation, Locality 4, Whitecap Mountain, Wisconsin. Sample P-12, crossed nicols. Granulated quartz is present between the quartz grains.
<table>
<thead>
<tr>
<th>Location (Exact locations shown in Figure 36)</th>
<th>Locality</th>
<th>Sample</th>
<th>Quartz</th>
<th>Feldspar</th>
<th>Rock Fragments</th>
<th>Cement and Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitate matrix Iron Belt, Wis.</td>
<td>2 P6a</td>
<td>66 15</td>
<td>-</td>
<td>81</td>
<td>2 - x</td>
<td>x x x - 1 x 3</td>
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<tr>
<td>Precipitate matrix Iron Belt, Wis.</td>
<td>2 P6b</td>
<td>33 39</td>
<td>-</td>
<td>72</td>
<td>4 x - x - x - 5</td>
<td>15 5 - - -</td>
</tr>
<tr>
<td>Precipitate matrix average</td>
<td></td>
<td>50 27</td>
<td>-</td>
<td>77</td>
<td>1 - x</td>
<td>x x x - 1 x 4</td>
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<tr>
<td>Sandstone Ironwood, Mich.</td>
<td>1 G1b</td>
<td>62 17</td>
<td>-</td>
<td>79</td>
<td>- - 6 - - 6</td>
<td>9 - 1 - 12 x 13</td>
</tr>
<tr>
<td>Sandstone Iron Belt, Wis.</td>
<td>2 P1</td>
<td>77 10</td>
<td>-</td>
<td>87</td>
<td>x 1 x 2 x x 5</td>
<td>x x x - x - 2</td>
</tr>
<tr>
<td>Sandstone Iron Belt, Wis.</td>
<td>2 P6</td>
<td>42 32</td>
<td>x x 75</td>
<td>-</td>
<td>- - - - - - - -</td>
<td>4 x 1 - x - x 6</td>
</tr>
<tr>
<td>Tabor Lake, Wis.</td>
<td>3 P7</td>
<td>75 15</td>
<td>x - 90</td>
<td>- x - 4</td>
<td>- x x - x - 1</td>
<td>x x - - - x 5 18</td>
</tr>
<tr>
<td>Sandstone Ironwood, Mich.</td>
<td>4 P10</td>
<td>62 21</td>
<td>- 1 84</td>
<td>- 1 - 2</td>
<td>5 x - - x - 6</td>
<td>6 x x - - 1 8</td>
</tr>
<tr>
<td>Sandstone Ironwood, Mich.</td>
<td>4 P12</td>
<td>50 34</td>
<td>- 84</td>
<td>- 4 - 3</td>
<td>7 x x 1 - 1 - 3</td>
<td>x - x - 4 6</td>
</tr>
<tr>
<td>Sandstone Iron Belt, Wis.</td>
<td>5 P13</td>
<td>50 23</td>
<td>- 74</td>
<td>- 3 - 3</td>
<td>1 x x - x - 2</td>
<td>12 2 x - - 4 18</td>
</tr>
<tr>
<td>Sandstone Iron Belt, Wis.</td>
<td>5 P15</td>
<td>72 10</td>
<td>- x 82</td>
<td>- 2 - 2</td>
<td>4 x 1 x - 1 - 3</td>
<td>4 x 1 x - 1 3 10</td>
</tr>
<tr>
<td>Sandstone average</td>
<td></td>
<td>61 20</td>
<td>x x 81</td>
<td>x 1 x 3</td>
<td>2 x x - x x 3</td>
<td>6 1 x x x 3 11</td>
</tr>
</tbody>
</table>

Table 7. MINERALOGICAL COMPOSITION OF THE BESSONER FORMATION, WISCONSIN
Figures in percent, RF=rock fragment, trace (less than one percent)=x, all mineral types as previously described in Tables 1b, 3b, and 5b.
### Table 8. HEAVY MINERAL DATA, BESSEMER FORMATION, NORTHERN WISCONSIN

Figures in percent, trace (less than one percent) = x, all heavy minerals as previously described in Tables 2b, 4b, & 6b.

<table>
<thead>
<tr>
<th>Location</th>
<th>Locality</th>
<th>Sample</th>
<th>Heavy Mineral Occurrence</th>
<th>Zircon</th>
<th>Tourmaline</th>
<th>Apatite</th>
<th>Amphibole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colloform matrix, Iron Belt, Wisconsin</td>
<td>2</td>
<td>P6</td>
<td>Normal</td>
<td>28</td>
<td>31</td>
<td>63</td>
<td>12</td>
</tr>
<tr>
<td>Sandstone, Ironwood, Michigan</td>
<td>1</td>
<td>G1b</td>
<td>Normal</td>
<td>9</td>
<td>56</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Sandstone, Iron Belt, Wisconsin</td>
<td>2</td>
<td>P1</td>
<td>Normal</td>
<td>13</td>
<td>67</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>Sandstone, Iron Belt, Wisconsin</td>
<td>2</td>
<td>P2</td>
<td>Normal</td>
<td>21</td>
<td>73</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Sandstone, Iron Belt, Wisconsin</td>
<td>2</td>
<td>P3</td>
<td>Normal</td>
<td>24</td>
<td>64</td>
<td>86</td>
<td>2</td>
</tr>
<tr>
<td>Siltstone, Iron Belt, Wisconsin</td>
<td>2</td>
<td>P4</td>
<td>Normal</td>
<td>16</td>
<td>56</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Sandstone, Iron Belt, Wisconsin</td>
<td>2</td>
<td>P5</td>
<td>Normal</td>
<td>17</td>
<td>64</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sandstone Average</td>
<td></td>
<td></td>
<td>Normal</td>
<td>17</td>
<td>65</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3. HEAVY MINERAL DATA, BESSEMER FORMATION, NORTHERN WISCONSIN

Figures in percent, trace (less than one percent) = x, all heavy minerals as previously described in Tables 2b, 4b, & 6b.
in any of the nearby pre-Keweenawan formations. The quartzite, jasper, flint, and iron formation pebbles were probably derived from the Middle Precambrian (Aninikian) Palms and Ironwood Formations now exposed on the nearby Gogebic Iron Range. Lower Precambrian (Archean) metamorphic rocks may have been the source of the gneiss pebbles.

The matrix of the conglomerate was also derived from nearby pre-Keweenawan rocks. The presence of chert fragments in the matrix suggests that banded iron formation, perhaps the Ironwood Formation, was present in the source area. Feldspar and quartz–feldspar rock fragments present in the matrix were probably derived from Middle Precambrian (Penokean) or Lower Precambrian (Archean) granites or gneisses. The polycrystalline quartz in the matrix was possibly derived from the same metamorphic area as the gneiss pebbles. The presence of fine-grained mafic and felsic igneous rock fragments indicates that small amounts of fine-grained igneous rocks, probably lava flows, were also present in the source area.

The sandstone is similar to the conglomerate matrix in composition, and appears to have been derived from the same source area. The additional presence of schistose and recrystallized quartz in the sandstone gives further evidence of the presence of metamorphic rocks in the source area. The siltstone is similar to the sandstone and conglomerate matrix in composition, and was probably derived from the same source area.

Heavy mineral analyses indicate that hyacinth, malacan, and normal (Keweenawan) zircon are present in the Bessemer Formation (Table 8). Based on the study of accessory minerals by Tyler, et al. (1940), it may be concluded that rocks of Lower, Middle, and Upper Precambrian age were probably present in the source area.

Paleocurrent analysis of cross-bedding and ripple marks in the
Bessemer Formation (42 measurements) indicates a southwesterly direction of sediment transport, with the source area lying to the northeast (Figure 45). The area to the northeast is now covered by Keweenawan lavas; however, it may be assumed that the pre-Keweenawan formations of the region were exposed to the northeast prior to extrusion of the lava.

A shallow water or beach zone appears to have been the depositional environment of the conglomerate and overlying sandstone. Occasional cross-bedding is present in the conglomerate, while cross-bedding and ripple marks are commonly present in the sandstone. The high percentage of quartz present, as well as the low feldspar and rock fragment content, suggests that the sediments were well-worked prior to deposition. The presence of layers containing well-sorted, well-rounded grains substantiates this suggestion. In addition, a Z-T-R Index of 90 (Hubert, 1962) for the sandstone (Table 8) also indicates a high level of maturity. The siltstone appears to have been derived from the same source area as the sandstone, with the change in grain size probably being the result of a drop in current velocity. The presence of desiccation cracks in the siltstone indicates that the silt was exposed to the air (Krumbein and Sloss, 1963), and thus deposited in very shallow water, perhaps a tidal flat or estuary.

In conclusion, the Bessemer Formation was deposited in a shallow water, near-shore environment, with the well-worked sediment being transported in a southwesterly direction. Deposition of the formation was halted by extrusion of the Keweenawan lavas, which covered both the source area and the deposited sediment.
1. Strike of Ripple Marks
2. Dip Direction of Cross-beds

Figure 45. Paleocurrent Data, Bessemer Formation, Wisconsin and Michigan, 42 measurements.
The Barron Formation of Wisconsin

Stratigraphy and Petrology

The Barron Formation is exposed over a 300 square mile area 65 miles south of Lake Superior in portions of Sawyer, Rusk, and Barron Counties, Wisconsin (Figure 36). The formation is at least 600 feet thick, and consists of quartz-rich sandstone and quartzite, with a basal conglomerate rarely present (Hotchkiss, 1915). The age of the formation is not known with certainty; however, it is believed to be post-Penokean and predate the Keweenawan lava series.

The contact between the Barron Formation and the underlying Lower and Middle Precambrian rocks is an angular unconformity. Small pebbles of slate, iron formation, and quartz are occasionally present in the lower three feet of the formation (Hotchkiss, 1915).

At several locations, the Barron Formation is overlain by sandstone believed to be Upper Cambrian in age (Hotchkiss, 1915). Rounded pebbles and cobbles, or angular blocks of Barron quartzite are present in a yellow sandstone matrix at these locations. Well data indicate the presence of Cambrian sandstone beneath the glacial drift in the surrounding area (Bean, 1949).

Because the contact between the Barron Formation and the Keweenawan lava series is not exposed, the relationship between the two formations is not known. Field relationships suggest that the Barron Formation may be either Lower, Middle, or Upper Keweenawan in age (Hotchkiss, 1915). The limited exposure and the lack of well data have caused the exact correlation of the Barron Formation to remain in question. Recent correlation attempts using seismic studies to locate the subsurface
Barron (Mooney, et al., 1970a; Mooney, et al., 1970b) failed to solve the problem. Because the Barron Formation closely resembles Lower Keweenawan quartzites to the south and west, and does not closely resemble the Upper Keweenawan sandstones to the north, the formation is currently believed to be Lower Keweenawan in age (Hotchkiss and Bean, 1929). The fact that mafic dikes believed to be related to the Keweenawan lava series are known to cut the Barron Formation (Hotchkiss, 1915) also strengthens this correlation.

The medium- to thick-bedded, red-brown sandstone (Figure 46) is composed of well-rounded, well-sorted grains. Ripple marks, cross-bedding, and pink to red-brown banding caused by oxidation of iron are present. "Pipestone" or catlinite (aluminous argillite) is sometimes interbedded with the sandstone, and has been quarried by Indians for several hundred years (Marple, 1969).

Modal analyses of three thin sections of the formation indicate an average mineralogical composition of 87 percent quartz (74 percent unit quartz, 13 percent polycrystalline quartz) and 12 percent silica cement. Traces of weathered orthoclase and chert are also present (Table 9). Zircon (97 percent) and tourmaline (3 percent) are the principal non-opaque accessory heavy minerals (Table 10). The sandstone has a Z-T-R Index of 100, and is a pure orthoquartzite.

Provenance and Sedimentation

The Barron Formation appears to have been derived from the pre-Keweenawan rocks of the region. The small scattered pebbles in the lower few feet of the formation indicate that slate and iron formation, possibly the Middle Precambrian Tyler and Ironwood Formations, were
Figure 46. Fifteen foot-high exposure of Barron Formation along Loyal Creek, SW<sub>4</sub>, Sec. 36, T.38N., R.9W., Sawyer County, Wisconsin.
<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Unit Quartz</th>
<th>Polycrystalline Quartz</th>
<th>Total Quartz</th>
<th>Orthoclass</th>
<th>Chert Fragments</th>
<th>Total Grains</th>
<th>Matrix</th>
<th>Silica Cement</th>
<th>Total Cement and Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baraboo Formation, SW, Sec. 28</td>
<td>NF-1</td>
<td>71</td>
<td>13</td>
<td>84</td>
<td>x</td>
<td>84</td>
<td>x</td>
<td>16</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Barron Formation, N.W., Sawyer Co., Wis.</td>
<td>B-1</td>
<td>76</td>
<td>12</td>
<td>88</td>
<td>-</td>
<td>88</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Barron Formation, S.W., Sawyer Co., Wis.</td>
<td>B-3</td>
<td>71</td>
<td>15</td>
<td>86</td>
<td>x</td>
<td>86</td>
<td>x</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Barron Formation, N.W., Sawyer Co., Wis.</td>
<td>B-8</td>
<td>76</td>
<td>12</td>
<td>88</td>
<td>x</td>
<td>88</td>
<td>x</td>
<td>11</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Barron Formation Average</td>
<td></td>
<td>74</td>
<td>13</td>
<td>37</td>
<td>x</td>
<td>37</td>
<td>x</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. MINERALOGICAL COMPOSITION OF THE BARRON AND BARABOO FORMATIONS, WISCONSIN. Figures in percent, trace (less than one percent) = x. All mineral types as previously described in Tables 1b and 2b.
<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Heavy Mineral Percentage of Total Sample</th>
<th>Zircon</th>
<th>Tourmaline</th>
<th>Apatite</th>
<th>2-T-R Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merano Formation, SW, Sec. 29, T.12N., R.9W.</td>
<td>B-1</td>
<td>0.04</td>
<td>94</td>
<td>78</td>
<td>2</td>
<td>94</td>
</tr>
<tr>
<td>Sauk County, Wisconsin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barron Formation, NE, Sec. 13, T.36N., R.8W.</td>
<td>B-3</td>
<td>0.04</td>
<td>94</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Sawyer County, Wisconsin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barron Formation, NW, Sec. 21, T.36N., R.8W.</td>
<td>B-8</td>
<td>0.01</td>
<td>48</td>
<td>50</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Sawyer County, Wisconsin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barron Formation Average</td>
<td></td>
<td>0.03</td>
<td>19</td>
<td>38</td>
<td>40</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 10. HEAVY MINERAL DATA, BARRON AND BARABOO FORMATIONS, WISCONSIN
Figures in percent. Trace (less than one percent)=x. All heavy minerals as described in Tables 2b, 4b, & 6b.
present in the source area. Petrographic analyses indicate that traces of chert and orthoclase are also present. The traces of chert give further evidence for the presence of banded iron formation in the area, while Middle or Lower Precambrian granites are the likely sources for the traces of orthoclase. The polycrystalline quartz was probably derived from the Lower and Middle Precambrian rocks which underlie portions of the formation. The presence of abraded overgrowths on some of the unit quartz grains in the sandstone indicates that quartzite or sandstone was also present in the source area.

Paleocurrent analysis of seven cross-beds in the Barron Formation measured during this study indicates a southerly direction of sediment transport (Figure 47). An analysis of four cross-beds published by Pettijohn (1957a) also indicates a southerly direction of sediment transport. Thus, the sparse paleocurrent data available for the Barron Formation are in agreement.

The high degree of maturity of the formation indicates that the sediments were very well-worked during transportation. The presence of multi-cycle quartz grains suggests that the maturity may be in part due to a previous cycle of transportation and deposition. The presence of cross-bedding and ripple marks suggests deposition in a shallow water, near-shore environment. The Barron Formation appears to have been derived from the pre-Keweenawan rocks to the north, with deposition taking place in a shallow water, near-shore environment, perhaps in a northward-transgressing sea.
1. Dip Direction of Cross-beds

Figure 47. Paleocurrent Data, Barron Formation, Northern Wisconsin, 7 measurements
The Sioux Formation of Southwestern Minnesota

Stratigraphy and Petrology

The Sioux Formation crops out at intervals over an area 180 miles by 35 miles in southwestern Minnesota and adjacent portions of Iowa and South Dakota (Figure 1). The formation, with an estimated thickness of over 5000 feet, consists of up to 62 feet of basal conglomerate overlain by a thick sequence of quartzite containing minor amounts of interbedded mudstone or "pipestone" (aluminous argillite) (Miller, 1961). A potassium-argon date on illite from a mudstone unit near Pipestone, Minnesota, by Goldich, et al. (1961) gives a minimum age of 1.2 billion years for the formation. Goldich, et al. suggest, however, that this age may indicate the time of folding and metamorphism of the formation, rather than the age of deposition.

Near New Ulm, Minnesota, the basal conglomerate of the Sioux Formation unconformably rests upon the Lower Precambrian New Ulm Granite, believed to be equivalent to the Fort Ridgely Granite exposed to the northwest in the Minnesota River Valley. Rounded pebbles, cobbles, and small boulders of quartz, chert, hematitic chert, jasper, and quartzite are present in the conglomerate (Miller, 1961). The matrix of the conglomerate consists of coarse-grained red quartzite, which appears to be identical to the overlying quartzite.

The conglomerate grades upward into a well cross-bedded red quartzite estimated by Miller (1961) to make up over 90 percent of the exposed Sioux Formation. The remaining 10 percent of the Sioux Formation consists of the basal conglomerate, minor conglomeratic layers, and mudstone and catlinite interbedded with the quartzite.
The Baraboo Formation of Wisconsin

Stratigraphy and Petrology

The Baraboo Formation of south-central Wisconsin (Figure 1) is a pink to white-colored quartzite believed to be over 4,000 feet thick (Dalziel and Dott, 1970). The formation is post-Penokean in age, and from rubidium-strontium dates of an underlying rhyolite, and a younger pegmatite dike which cuts the Baraboo, appears to have been deposited between 1.4 and 1.6 billion years ago (Dalziel and Dott, 1970). The Baraboo Formation and several other smaller exposures of quartzite are interpreted by the above authors to be erosional remnants of a large quartzite formation extending from South Dakota to Lake Michigan, and including the Sioux Formation.

The Baraboo Formation is underlain by a rhyolite lava complex believed to be only slightly older in age. A pronounced basal conglomerate is not present in the quartzite; however, pebbly layers containing small pebbles of quartz, jasper, and dark rock fragments are scattered throughout the formation. A 1300 foot-thick slate-argillite sequence appears to conformably overlie the Baraboo Formation.

The massive quartzite of the Baraboo Formation ranges from pink to white in color, and contains abundant cross-bedding and ripple marks. The medium- to coarse-grained quartzite is composed of well-sorted, well-rounded, sand-sized grains. Color-banding caused by the presence of iron oxides is often found in the quartzite. Fine-grained phyllitic and micaceous layers are occasionally present in the upper portion of the formation.

A thin section made from a sample of quartzite collected near
influenced by the local tectonic events which immediately preceded Keweenawan lava extrusion in each area. Because the paleocurrent directions indicated by the sedimentary structures in each of these formations shows sediment transport away from what was to be the Keweenawan Basin, the area of Keweenawan volcanic activity was apparently uplifted just prior to the outbreak of volcanism.

Correlation of the Lower Keweenawan Sandstones

Until recent studies of paleomagnetism in the Keweenawan rocks of the Lake Superior Region were undertaken, relative age correlations of Keweenawan rocks in different areas of the region was difficult. All dated Keweenawan igneous rocks gave the same age, approximately 1.1 billion years. Detailed studies of the paleomagnetism of the Keweenawan rocks have provided a new time line which allows better resolution in comparing the ages of Keweenawan rocks.

Studies by Books (1968, 1970), DuBois (1962), and Palmer (1968, 1970) have indicated the presence of two reversals in the earth's magnetic field during Keweenawan time. Such a polarity change occurs over the entire earth at the same time, and thus may be used as an absolute time line. The oldest Keweenawan rocks formed during a period of normal polarity. These rocks are overlain by a group of rocks formed during a period of reversed polarity. The younger (Middle and Upper) Keweenawan rocks which overlie this group formed during a period of normal polarity. Thus there are three divisions of polarity in Keweenawan rocks of the Lake Superior Region which may be used to make relative age correlations.

A summary of age correlations for the Lake Superior Keweenawan based on paleomagnetic studies is shown in Figure 48. On the South Shore, the
Bessemer Formation and a portion of the overlying South Range lavas were deposited during the early period of normal polarization. On the North Shore in Ontario, the lower portion of the Sibley Formation was deposited during this period. Unfortunately, no paleomagnetic data are yet available for the Puckwunge Formation. From the available data, however, it can be seen that the Bessemer Formation and the lower Sibley Formation are probably of the same general age, and that Keweenawan igneous activity appears to have begun earlier on the South Shore than on the North Shore. It is very probable that the Puckwunge Formation is correlative with the Sibley Formation (see above), and was deposited during this same time interval.

The period of reversed polarity allows further correlations of Keweenawan rocks in the Lake Superior Region. On the South Shore, igneous activity continued with extrusion of the bulk of the South Range lavas. In northeastern Minnesota, the lower portion of the North Shore Volcanic Group was extruded. Because of lack of data, it is not known if deposition of the Puckwunge Formation occurred during this time period, or was restricted to the previous period of normal polarity. In Ontario, the upper portion of the Sibley Formation, and the Osler Series of sediments and lava flows were deposited during this period of reversed polarity.

The younger group of normally polarized rocks provides additional correlation of the Keweenawan in the Lake Superior Region. On the South Shore, the Portage Lake lavas were extruded, while in northeastern Minnesota, the bulk of the North Shore Volcanic Group was extruded. In Ontario, extrusion of the Osler lavas may have continued; however, insufficient paleomagnetic data are available for positive correlation.
The results of these paleomagnetic studies have provided a means for age correlation in the Keweenawan. However, more sample collecting and polarity determinations need to be done. The paleomagnetics of the Lower Keweenawan sedimentary rocks and lava flows at Nopeming, near Duluth, the Puckwunge Formation of northeastern Minnesota, and the upper portion of the Osler lavas should be studied. In addition, the possibility of correlating the Barron, Baraboo, and Sioux Formations by use of paleomagnetism should not be overlooked.

SUMMARY AND CONCLUSIONS

A summary chart of the Lower Keweenawan sedimentary formations is presented in Table II. This table lists some of the similarities and variations found in these formations.

The Puckwunge Formation of northeastern Minnesota is an orthoquartzite intermittently exposed for 25 miles beneath the lower flows of the Keweenawan North Shore Volcanic Group. A conglomerate believed to be a basal conglomerate contains pebbles and cobbles of pre-Keweenawan rocks of the area, and is exposed at two locations. The conglomerate is overlain by a quartz-rich sandstone composed of well-sorted, well-rounded grains. This sandstone is disconformably overlain by Keweenawan lava flows. Analysis of cross-bedding and ripple marks in the conglomerate and sandstone indicate the presence of currents flowing toward the southeast during deposition. The Puckwunge Formation appears to have been deposited in a high-energy, near-shore, shallow water environment, with the sediment having been derived from the pre-Keweenawan rocks to the northwest.

The Puckwunge Formation is inferred to be correlative with the near-
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness</th>
<th>Rock Type</th>
<th>Percent of Cores Analysed</th>
<th>Z-F-R Index or Heavy Mineral Analyses</th>
<th>Depositional Environment</th>
<th>Paleocurrent</th>
<th>No. of Paleocurrent Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Osler</td>
<td>200</td>
<td>lithic sandstone</td>
<td>-</td>
<td>-0</td>
<td>shallow water, low energy</td>
<td>←</td>
<td>0</td>
</tr>
<tr>
<td>Sibley</td>
<td>600</td>
<td>orthoquartzite, mudstone</td>
<td>95 3 87 4</td>
<td></td>
<td>shallow water, near-shore, high-energy</td>
<td>↓</td>
<td>14</td>
</tr>
<tr>
<td>Puckwunge</td>
<td>300</td>
<td>orthoquartzite</td>
<td>91 18 80 9</td>
<td>&quot;</td>
<td></td>
<td>↓</td>
<td>56</td>
</tr>
<tr>
<td>&quot;Nopeming&quot;</td>
<td>28</td>
<td>orthoquartzite, metasiltstone</td>
<td>98 9 86 5</td>
<td>&quot;</td>
<td></td>
<td>↑</td>
<td>22</td>
</tr>
<tr>
<td>Bessemer</td>
<td>300</td>
<td>orthoquartzite, siltstone</td>
<td>91 10 90 7</td>
<td>&quot;</td>
<td></td>
<td>↓</td>
<td>42</td>
</tr>
<tr>
<td>Barron</td>
<td>600</td>
<td>orthoquartzite, mudstone</td>
<td>97 3 100 3</td>
<td>&quot;</td>
<td></td>
<td>↓</td>
<td>7</td>
</tr>
<tr>
<td>Sioux</td>
<td>5000</td>
<td>orthoquartzite, mudstone</td>
<td>- 0 - 0</td>
<td>&quot;</td>
<td></td>
<td>↓</td>
<td>0</td>
</tr>
<tr>
<td>Baraboo</td>
<td>4000</td>
<td>orthoquartzite, mudstone</td>
<td>95 1 99 1</td>
<td>&quot;</td>
<td></td>
<td>↓</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 11. Summary Chart, Lower Keweenawan Formations, Lake Superior Region. The number of paleocurrent indicators measured, and the number of modal analyses and heavy mineral analyses conducted in this study are shown.
by Sibley Formation along strike to the northeast in Ontario. The basal conglomerate of the Sibley disconformably overlies the Middle Precambrian Rove Formation. The lithologies represented by the rounded pebbles, cobbles, and small boulders in the conglomerate are present in the nearby pre-Keweenawan rocks. A massive white, quartz-rich sandstone containing well-rounded, well-sorted grains overlies the conglomerate. The sandstone is in turn overlain by a mudstone sequence. Analysis of cross-bedding and ripple marks in the sandstone indicates that a southerly direction of sediment transport existed during deposition of the Sibley. The conglomerate and sandstone appear to have been deposited in a high-energy, shallow water environment.

The Sibley Formation is disconformably overlain by the Osler Formation which consists of sedimentary rocks and lava flows. The twelve-foot-thick basal conglomerate of the Osler Formation disconformably rests upon the Sibley Formation. The conglomerate contains rounded pebbles, cobbles, and boulders of the underlying Sibley and pre-Keweenawan rocks of the area. Two hundred feet of sandstone and interbedded red mudstone overlie the conglomerate. The sandstone and mudstone are similar in character to those of the underlying Sibley Formation, and appear to have been deposited in a similar environment. In contrast to the Puckwunge Formation which is disconformably overlain by lava flows, the uppermost sedimentary rocks of the Osler Formation are conformably overlain by Keweenawan lava flows.

At Nopeming, Minnesota, near Duluth, 28 feet of quartzite and interbedded conglomerate and metasiltstone are exposed beneath Keweenawan lava flows. The conglomerate contains well-rounded pebbles of quartz and quartzite in a quartzite matrix. The dominant lithology is quartzite; however, metasiltstone containing occasional grains of basaltic material
is interbedded with the quartzite just below the overlying lava flows. The lava flows conformably overlie the sedimentary rocks, with no significant lapse in deposition having taken place. The sedimentary rocks, which overlie the Middle Precambrian Thomson Formation with an angular unconformity, were derived from pre-Keweenawan rocks of the region, and deposited in a high-energy, near-shore environment by currents flowing toward the north.

The Bessener Formation is intermittently exposed beneath Keweenawan lava flows along a 55-mile stretch in northern Michigan and Wisconsin. A basal conglomerate containing rounded pebbles and cobbles of pre-Keweenawan rocks of the area disconformably rests upon the Middle Precambrian Tyler Formation. The conglomerate is overlain by a white to brown, cross-bedded, quartz-rich sandstone, containing occasional interbedded layers of siltstone. As is the case in the Otter Formation and at Nopeming, Keweenawan lava flows conformably overlie the sandstone.

Several quartzites of lower Upper Precambrian (Keweenawan) age are exposed just south of the Lake Superior Region. The Barron and Baraboo Formations of Wisconsin, and the Sioux Formation of Minnesota are very similar to each other in lithology, composition, and depositional environment, and appear to be correlative. These formations appear to have been deposited during the transgression of a sea into the region during Lower Keweenawan time.

The Puckwunge and Sibley Formations north of Lake Superior, and the Barron, Baraboo, and Sioux Formations south of Lake Superior appear to have been deposited prior to the beginning of Keweenawan volcanism in their depositional areas. The very mature character of these sediments indicates that the region was tectonically stable during the
interval between the Penokean Event and the outbreak of Keweenawan igneous activity.

Deposition of several other Lower Keweenawan sandstones, however, appears to have been interrupted by the outpouring of Keweenawan lavas. The Osler Formation of Ontario, the Lower Keweenawan sedimentary rocks at Nopeming, Minnesota, and the Bessener Formation of Michigan and Wisconsin belong in this classification. These formations are each conformably overlain by lava flows, with the extrusion of the flows apparently ending sedimentary deposition in each area. Because volcanic detritus is only present in very minor amounts, the principal sources of sediment apparently lay outside the area of volcanic activity.

Superposition, radiometric dating, and correlation by use of a reversal of the earth's magnetic field allow a tentative chronologic framework to be set up for sedimentary deposition in the Lake Superior Region during Lower Keweenawan time (Table 12). The Baraboo, Sioux, and Barron Formations were apparently the first formations deposited, as a sea transgressed northward into the region. As the sea slowly transgressed farther to the north, deposition of the Bessener, Puckwunge, and Sibley Formations took place. As extrusion of the Keweenawan lavas began on the South Shore, deposition of the Bessener Formation ended, while deposition of the Sibley and Puckwunge Formations continued in the north. As the Keweenawan igneous activity spread northward, the Osler Formation was deposited. Because of lack of paleomagnetic data, the exact correlation of the "Nopeming Formation" is not known. Until more paleomagnetic and geochronologic data are available to firmly prove or disprove these correlations, this depositional sequence should be considered tentative.
Table 12. Correlation Chart, Lower Keweenawan Formations of the Lake Superior Region
REFERENCES


_________, 1970, Written communication to J. C. Green.


