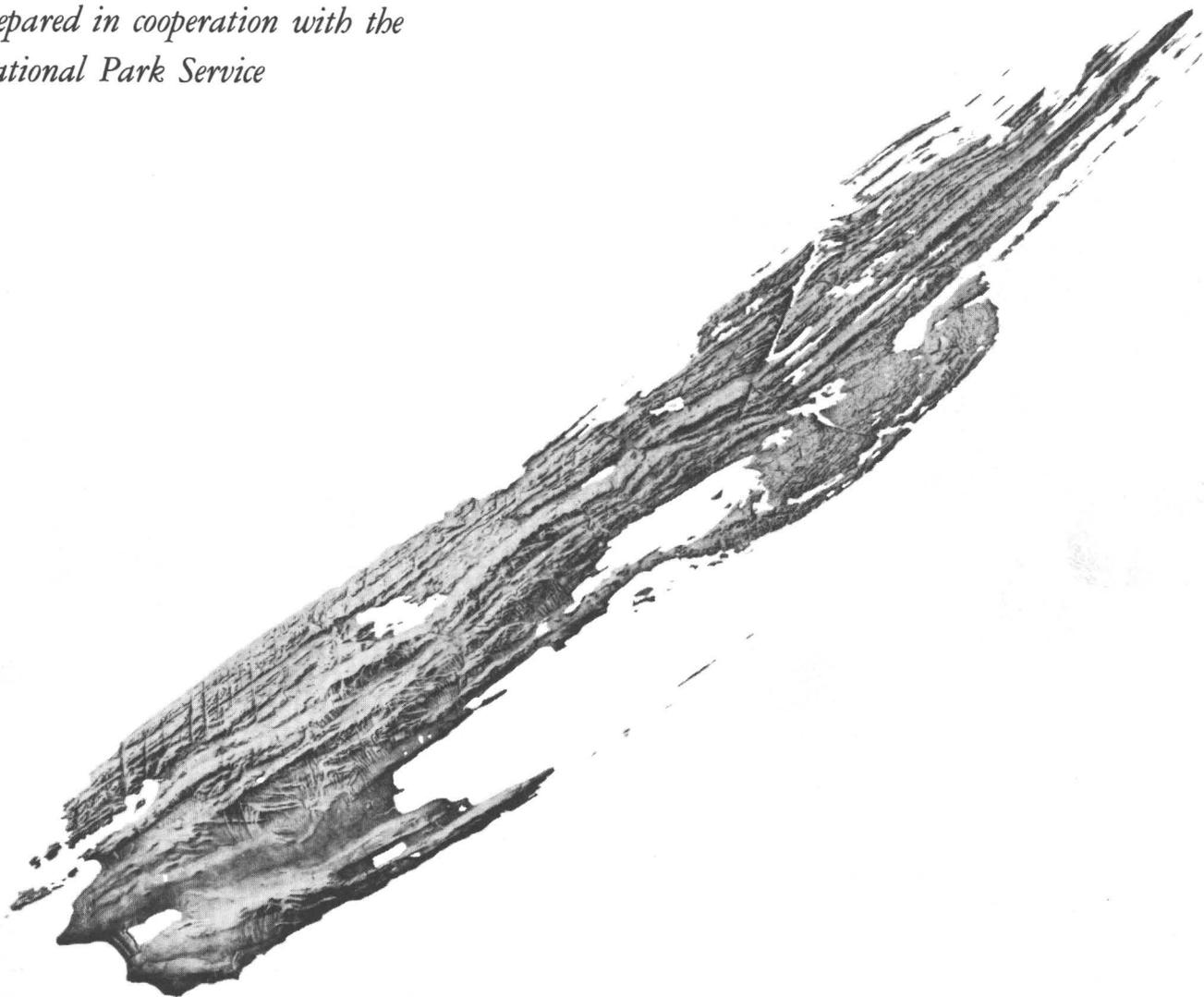


THE COPPER HARBOR CONGLOMERATE (MIDDLE KEWEENAWAN) ON ISLE ROYALE, MICHIGAN, AND ITS REGIONAL IMPLICATIONS

*Prepared in cooperation with the
National Park Service*



The Copper Harbor Conglomerate (Middle Keweenawan) on Isle Royale, Michigan, and its Regional Implications

By ROGER G. WOLFF *and* N. KING HUBER

GEOLOGY OF ISLE ROYALE NATIONAL PARK, MICHIGAN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 754-B

*Prepared in cooperation with
the National Park Service*



UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 72-600388

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock No. 2401-00289

CONTENTS

	Page		Page
Abstract	B1	Copper Harbor Conglomerate on Isle Royale—Continued	
Introduction	1	Lithologic character—Continued	
Scope of study	1	Composition	B7
Acknowledgments	2	Distribution of rock types	8
Copper Harbor Conglomerate on the Keweenaw Peninsula of Michigan	3	Direction of sedimentary transport	10
Copper Harbor Conglomerate on Isle Royale	4	Sedimentary structures as directional indicators ..	10
Location and areal extent	4	Lateral changes in texture and formational thickness as directional indicators	11
Thickness	5	Conglomerate composition as an indicator of source direction	12
Lithologic character	7	Environment of sedimentary accumulation	13
Texture	7	References cited	14

ILLUSTRATIONS

		Page
PLATE	1. Map and structure section of the Copper Harbor Conglomerate on Isle Royale, Michigan	In pocket
FIGURE	1. Sketch map showing generalized distribution of Keweenawan rocks in the Lake Superior region	B2
	2. Chart showing nomenclature for middle and upper Keweenawan rocks of northern Michigan and adjacent parts of Wisconsin	3
	3. Sketch map showing distribution of the Copper Harbor Conglomerate and paleocurrent directions on the Northern Peninsula of Michigan	5
	4. Stratigraphic diagram of the Copper Harbor Conglomerate on Isle Royale from Rainbow Point to Francis Point	6
	5-13. Photographs showing:	
	5. Boulder and cobble conglomerate at Cumberland Point	7
	6. Pebble conglomerate overlying basalt on Hat Island in Malone Bay	9
	7. Sandstone overlying basalt at small cove north of Schooner Island	9
	8. Cobble conglomerate facies and pebble conglomerate facies on west end of Feldtmann Ridge	9
	9. Sandstone facies on Stone House Island	10
	10. Longitudinal section of trough-type crossbedding in sandstone on the southern side of Houghton Ridge	10
	11. Cuspate ripple markings in sandstone on shoreline in sec. 18, T. 63 N., R. 37 W	11
	12. Asymmetric ripple markings in sandstone on shoreline south of Fishermans Home Cove	11
	13. Current-crescent structures in sandstone on shoreline south of Fishermans Home Cove	11
	14. Map of sediment dispersal patterns in the Copper Harbor Conglomerate on Isle Royale	12
	15. Photograph of desiccation cracks in fine-grained sedimentary rock on Menagerie Island	13

TABLES

		Page
TABLE	1. Composition of pebble conglomerate	B8
	2. Composition of coarse to very coarse grained sandstone	8
	3. Composition of very fine to fine grained sandstone	8
	4. Composition of very fine grained sandstones, very coarse grained sandstones, and pebble conglomerates taken from the measured section on Houghton Ridge	10
	5. Relative abundance of sedimentary features in sandstone and pebble conglomerate in the Copper Harbor Conglomerate, Isle Royale	11

GEOLOGY OF ISLE ROYALE NATIONAL PARK, MICHIGAN

**THE COPPER HARBOR CONGLOMERATE (MIDDLE KEWEENAWAN)
ON ISLE ROYALE, MICHIGAN, AND
ITS REGIONAL IMPLICATIONS**

BY ROGER G. WOLFF¹ and N. KING HUBER

ABSTRACT

The Copper Harbor Conglomerate on Isle Royale is the north limb counterpart of the type Copper Harbor Conglomerate exposed on the south limb of the Lake Superior syncline on the Keweenaw Peninsula. In both areas the formation, of middle Keweenawan age, overlies the middle Keweenawan Portage Lake Volcanics and is largely derived from older Keweenawan volcanic source terranes that shed debris into the subsiding Lake Superior basin from opposite sides; for Isle Royale, the source terrane would have been the North Shore Volcanic Group in Minnesota. The deposits appear to be piedmont fan deposits and flood-plain deposits formed under a combination of fluvial and lacustrine conditions.

Various sedimentary features on Isle Royale indicate that the sediments were transported generally eastward, with a range in direction from northeast to southeast. The formation also increases in thickness and in textural and compositional maturity in this direction; it varies from a boulder conglomerate, through a mixture of cobble and pebble conglomerates and sandstone, to sandstone alone. This clastic wedge thickens within a distance of 20 miles from a minimum of 1,500 feet to more than 6,000 feet between stratigraphic marker horizons; the top of the formation is nowhere exposed, however, and the total thickness probably is considerably greater.

The clastic materials in the formation are predominantly derived from older Keweenawan volcanic rocks. Felsic varieties are slightly dominant over mafic varieties. Metamorphic rocks are minor components, and clasts of intrusive igneous rocks appear to be absent. The overall local composition of the formation, chiefly reflecting degree of sediment maturity, is closely related to grain size; rocks of similar grain size have the same composition throughout the formation. Calcite cement is ubiquitous; in the conglomerate and coarse-grained sandstone, it commonly amounts to about 15 percent. As the textures become finer, rock fragments and calcite cement decrease in abundance, whereas quartz, feldspar, and opaque mineral percentages increase.

The felsic and many of the mafic Keweenawan rock types that occur as clasts in the Copper Harbor Conglomerate are not known to occur as flows within the Portage Lake Volcanics on the island. Most of the rock types, however, are known to occur as flows in the North Shore Volcanic Group, which is

stratigraphically lower than the Portage Lake Volcanics and is present in the direction from which the clastic debris was transported. Several lines of evidence suggest the presence of an unconformity between the North Shore Volcanic Group and the Portage Lake Volcanics. Such an unconformity would facilitate the erosion of the North Shore Volcanic Group and the deposition of the erosional debris basinward on top of the Portage Lake Volcanics.

The situation would be analogous to that on the south side of the Lake Superior syncline. There many clasts in the Copper Harbor Conglomerate appear to have been derived from the lowermost Keweenawan volcanic terrane, volcanic rocks of the South Trap Range which underlie the Portage Lake Volcanics.

INTRODUCTION

SCOPE OF STUDY

It has been long proposed (Lane, 1898, p. 56) that part of the Keweenawan Series of the Keweenaw Peninsula (Portage Lake Volcanics² and Copper Harbor Conglomerate) extends beneath the Lake Superior syncline and is exposed again on Isle Royale (fig. 1). The basis for this interpretation is the similarity of the volcanic and sedimentary rock types and of the stratigraphic succession in both areas. The present study supports this conclusion.

The Copper Harbor Conglomerate has been studied by many workers in its type area on the Keweenaw Peninsula, and much data has accumulated regarding its compositional and textural variations, direction of sediment transport, and depositional environment. The only comprehensive geologic study of Isle Royale, that of Lane (1898), places greatest emphasis on the Portage Lake Volcanics because it is the host for native copper mineralization; the Copper Harbor Conglomerate was not studied in detail. Since Lane's study,

²At the request of the Geologic Names Committee of the U.S. Geological Survey and in consultation with workers in the type area (W. S. White written commun., 1972), the formation name Portage Lake Volcanics is used in this report in place of Portage Lake Lava Series in order to bring the formation name into conformity with the Code of Stratigraphic Nomenclature (Am. Comm. on Strat. Nomenclature, 1970, p. 7, 14).

¹Present affiliation, Gulf Oil Corp., P.O. Box 1635, Houston, Texas.

GEOLOGY OF ISLE ROYALE NATIONAL PARK, MICHIGAN

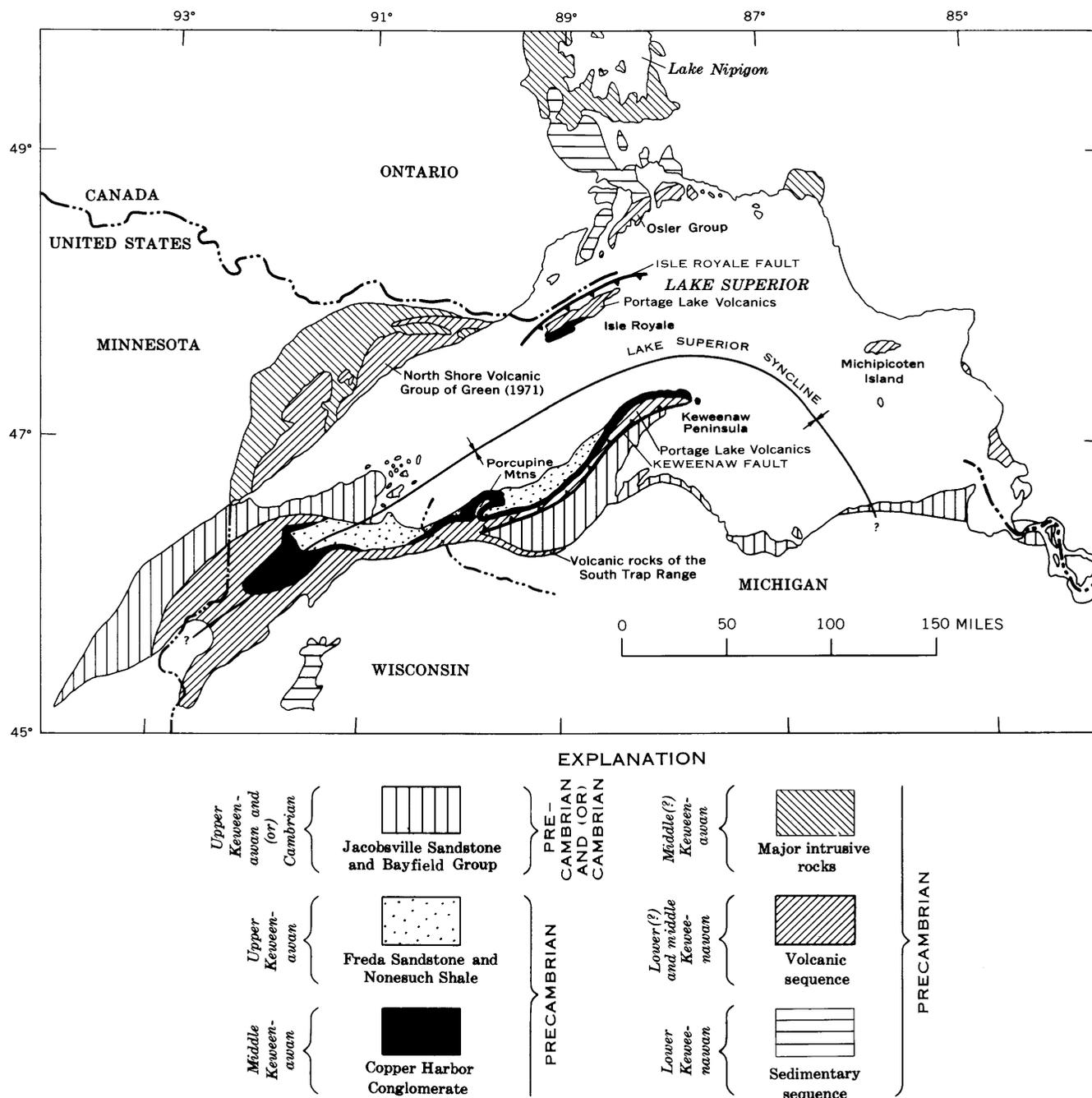


FIGURE 1.—Generalized distribution of Keweenaw rocks in the Lake Superior region. Data from Green (1971), Halls (1966), Irving (1883), White (1966), and White and Wright (1960).

virtually no additional data regarding the Copper Harbor Conglomerate on Isle Royale has been published except for a few measurements on directions of sediment transport (White and Wright, 1960; Hamblin and Horner, 1961).

This study focuses on the nature of the sedimentary rocks above the Portage Lake Volcanics on Isle Royale, provides some basis for their comparison with the Copper Harbor Conglomerate on the south shore

of Lake Superior, and contributes to the understanding of Keweenaw sedimentation in the Lake Superior region.

ACKNOWLEDGMENTS

Wolff studied the Copper Harbor Conglomerate on Isle Royale under the guidance of Professor Campbell Craddock of the University of Wisconsin; he was assisted in the field by Roger Sacia. Wolff is responsible for essentially all of the paleocurrent measure-

ments and data on composition in this report. Financial assistance was provided by the National Science Foundation and the Wisconsin Alumni Research Foundation.

Huber, with the cooperation of the National Park Service, is mapping geologically the entire island; while engaged in studies of the Copper Harbor Conglomerate, he was assisted by David Chivington. Huber's mapping of the Portage Lake Volcanics made possible determination of the approximate base of the Copper Harbor Conglomerate between Sisikiwit Bay and Cumberland Point. Discussions and field visits with John C. Green, Harold A. Hubbard, and Walter S. White, in their respective areas of Keweenaw study, have aided considerably in understanding the regional aspects of Keweenaw geology.

COPPER HARBOR CONGLOMERATE ON THE KEWEENAW PENINSULA OF MICHIGAN

The Copper Harbor Conglomerate, in its type area on the Keweenaw Peninsula of Michigan, was named and defined so as to include a thick sequence of sedimentary rocks, previously separated (in ascending order) into the Great, Middle, and Outer Conglomerates, with intervening lava flows, the Lake Shore Traps (Lane and Seaman, 1907, p. 690-691; Lane, 1911, p. 37-40). On the Keweenaw Peninsula, the Copper Harbor Conglomerate conformably overlies the Portage Lake Volcanics (middle Keweenaw), and locally the two formations interfinger (fig. 2; White and Wright, 1960). The Portage Lake Volcanics consists primarily of lava flows; minor sedimentary rocks, similar to those within the Copper Harbor Conglomerate, are intercalated between flows (hereafter referred to as interflow sedimentary rocks). The transition between the two formations reflects a gradual cessation of volcanic activity and the growing dominance of a sedimentary regime. The Copper Harbor Conglomerate is overlain by the Nonesuch Shale and Freda Sandstone (upper Keweenaw).

Irving (1883) placed the base of what he called the "Upper Division" of the Keweenaw Series at the base of his Outer Conglomerate; this boundary falls within the Copper Harbor Conglomerate as originally defined by Lane and Seaman (1907) and as currently used on the Keweenaw Peninsula. White, Cornwall, and Swanson (1953), in later work, arbitrarily chose to place the base of the upper Keweenaw at the base of the Copper Harbor Conglomerate but failed to discuss this apparent departure from prior usage. Because of confusion arising from this dual usage, White (1972) recently reviewed the difficulties of applying either of these alternative boundaries for the base of the upper Keweenaw and concluded that a third alternative,

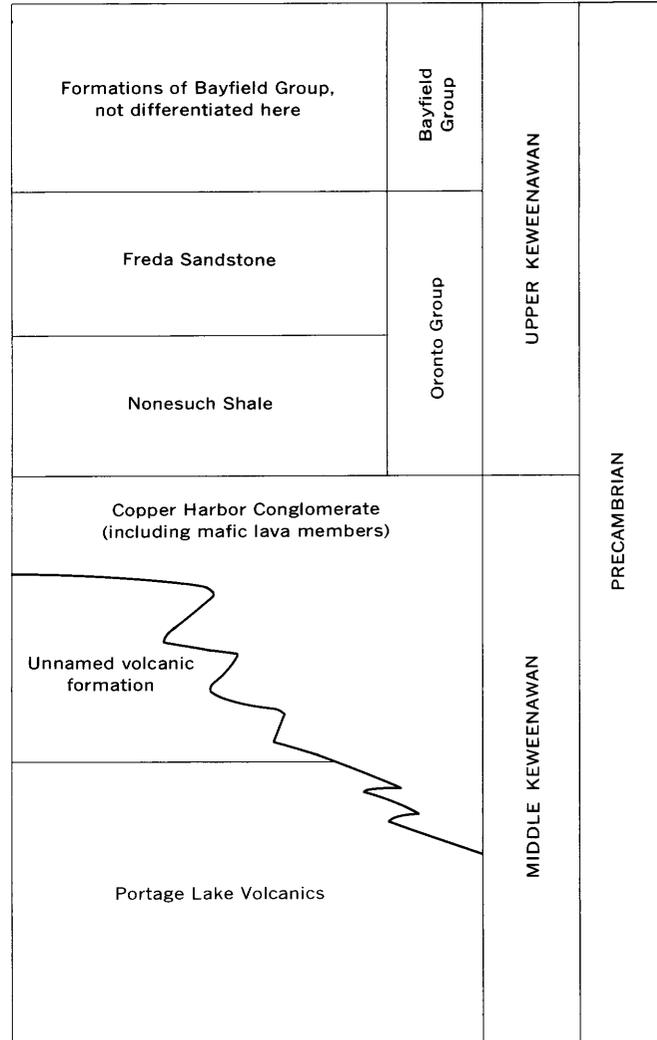


FIGURE 2.—Nomenclature for middle and upper Keweenaw rocks of northern Michigan and adjacent parts of Wisconsin (after White, 1972). The unnamed volcanic formation occurs only in the Porcupine Mountains area (fig. 1).

the top of the Copper Harbor Conglomerate, was, for both theoretical and practical reasons, a more meaningful stratigraphic boundary. He therefore proposed that the top of the Copper Harbor Conglomerate be considered the top of the middle Keweenaw; this usage places the entire Copper Harbor Conglomerate within the middle Keweenaw (fig. 2) and is followed in this report.

Details regarding the geology of the Copper Harbor Conglomerate on the Keweenaw Peninsula and farther west in Wisconsin are provided by White and Wright (1960), Hite (1968), and White (1971; 1972); Halls (1966) summarizes the regional stratigraphy. The following brief description is based primarily on these sources.

The Copper Harbor Conglomerate crops out in a

discontinuous belt from the east end of the Keweenaw Peninsula westward into Wisconsin (fig. 1). The observed range in thickness in Michigan is about 200 feet to more than 6,000 feet. As the formation is wedge shaped, thickening rapidly to the northwest toward the axis of the Lake Superior syncline, the thickness at any one place depends on the proximity of the place measured to the margin of the depositional basin. And as neither the basin margin nor the outcrop belt is linear, much apparent thickening and thinning is found parallel to the regional strike. The stratigraphy is further complicated in the vicinity of the Porcupine Mountains, where a thick lenticular unit of volcanic rock lies between the Portage Lake Volcanics and the Copper Harbor Conglomerate. There the conglomerate is locally less than 200 feet thick (White and others, 1971; White, 1971, 1972).

The formation consists chiefly of red to brown arkosic conglomerate and sandstone; most of the pebbles are of volcanic origin and predominantly felsic. Metamorphic and granitic rocks are generally very minor constituents (<1 percent). Hite (1968) notes that near the Michigan-Wisconsin border, the relative percentage of metamorphic and granitic clasts as compared with volcanic increases upward in the section. He ascribes this change to a change in provenance, the metamorphic and granitic clasts coming from the Animikean terrane after streams had cut through the lowermost Keweenaw lava flows, the source for the lower part of the Copper Harbor Conglomerate. Boulders and smaller clasts of pre-Keweenaw rocks are also locally abundant in the Copper Harbor Conglomerate on Manitou Island (Cornwall and White, 1955).

The texture of the conglomerate is indicative of high energy conditions. Most of the conglomerate clasts are less than 10 inches in diameter, but boulders more than 2 feet in diameter are present. Modal size is generally in the 2- to 8-inch range. Most clasts are subrounded to well-rounded and bladed or prolate in shape. These pebbles, cobbles, and boulders lie closely packed in a sandy matrix cemented with calcite; near the top of the formation, packing is more open (Hite, 1968). The sandy units are poorly sorted, and the grains are angular to subangular.

White and Wright (1960, p. B6) have recognized a separate "red facies" within the Copper Harbor Conglomerate near the Porcupine Mountains (fig. 1). This unit is a platy fine- to medium-grained sandstone and is redder than the rocks of the formation as a whole.

It has been demonstrated that the general direction of sediment transport for both the Copper Harbor Conglomerate and the interflow conglomerates in the Portage Lake Volcanics was toward the Lake Superior

basin (fig. 3); the source area is thus located to the southeast of the present outcrop belt (White, 1952, 1960; White and Wright, 1960; Hamblin and Horner, 1961). The Copper Harbor Conglomerate, on the Northern Peninsula of Michigan, has been interpreted as a piedmont fan stretching northward away from foothills near the margin of the Lake Superior basin toward an alluvial plain or body of water occupying the center of the basin (White and Wright, 1960; White, 1960, 1971). Hamblin (1961, 1965) has further discussed the regional sedimentary environment and paleogeography of the Lake Superior basin during Keweenaw and subsequent periods; he concludes that a highland extended through northern Michigan and Wisconsin, acting as a source of sediment for the Lake Superior basin from at least late Keweenaw through Late Cambrian (Dresbachian) time.

COPPER HARBOR CONGLOMERATE ON ISLE ROYALE LOCATION AND AREAL EXTENT

Isle Royale is the largest island in an archipelago, all of which is within the boundaries of Isle Royale National Park. The name Isle Royale is often used to refer to the entire archipelago, and this is the sense in which it is used in the title of this report. Within the body of the report, however, the term is also used to refer to the main island. It should be clear in context which meaning is intended. Isle Royale is located in the northwestern part of Lake Superior, 15 miles southeast of the Minnesota-Canadian shoreline and 40 miles northwest of the closest point on the Keweenaw Peninsula (fig. 1). Exposures of Copper Harbor Conglomerate are slightly more than 40 miles apart on opposite sides of the Lake Superior syncline. The island is 45 miles long and about 6 miles wide; the long dimension is parallel to the structural grain.

Approximately four-fifths of Isle Royale is underlain by volcanic flows and minor clastic rocks of the Portage Lake Volcanics, which dip 10° - 20° to the southeast in the vicinity of their contact with the overlying Copper Harbor Conglomerate (Huber, 1973b,c). The Copper Harbor Conglomerate underlies the remaining one-fifth of Isle Royale and is confined to the southwestern part of the archipelago (pl. 1); it dips 5° - 28° to the southeast. The contact between the Copper Harbor Conglomerate and the Portage Lake Volcanics appears to be conformable; the top of the Copper Harbor Conglomerate, however, is not exposed. If the Nonesuch Shale and other formations that overlie the Copper Harbor Conglomerate on the Keweenaw Peninsula are present in the Isle Royale area, they lie beneath Lake Superior to the southeast.

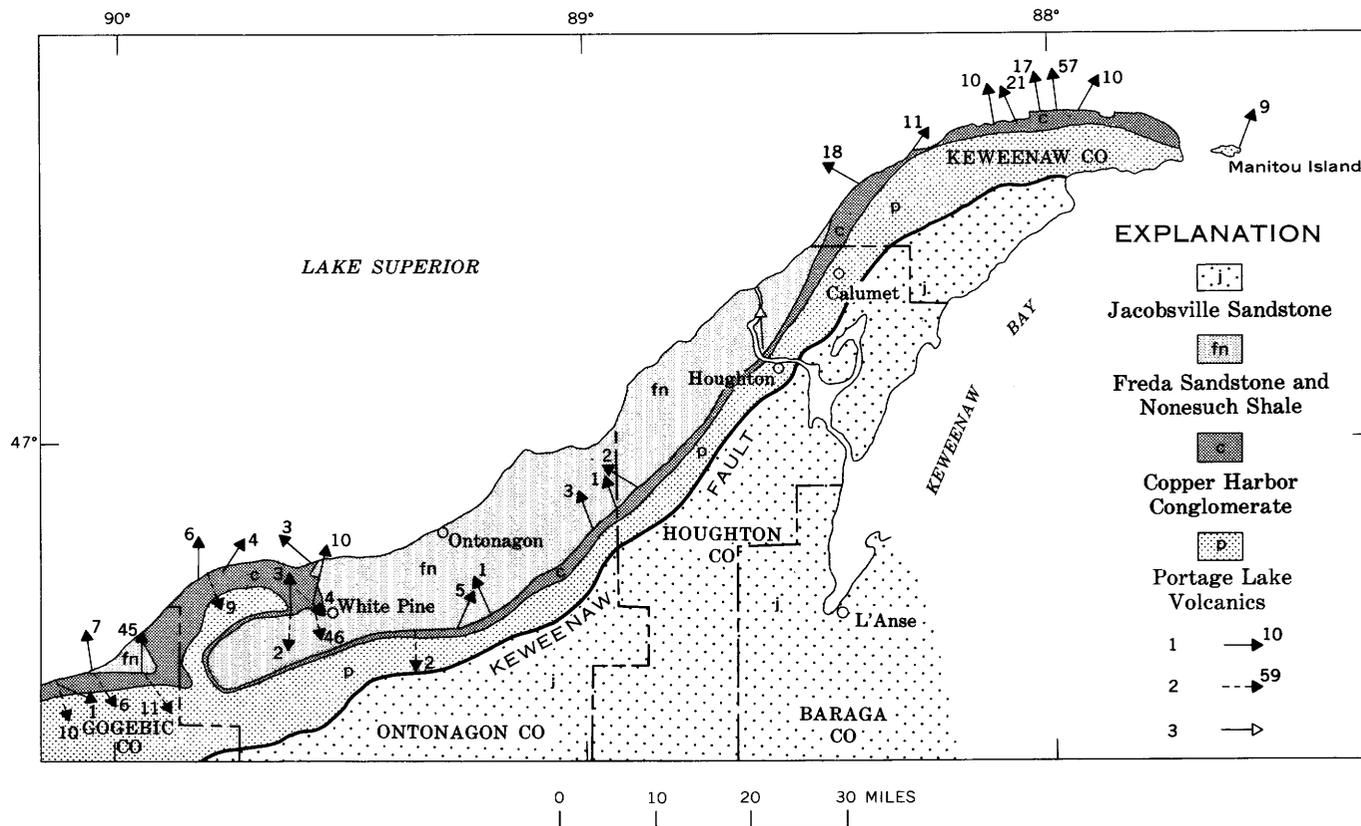


FIGURE 3.—Distribution of the Copper Harbor Conglomerate and paleocurrent directions on the Northern Peninsula of Michigan: 1, average direction of current flow from crossbeds in conglomeratic sandstone. 2, average direction of current flow from crossbeds in “red facies.” 3, direction of current flow indicated by imbrication of pebbles. Number of individual observations included in average is shown by each arrow. Modified from White and Wright (1960).

THICKNESS

The thickness of the Copper Harbor Conglomerate on Isle Royale is difficult to estimate because (1) the base of the formation, concealed beneath surficial materials for most of its length, is impossible to locate accurately; (2) the top of the formation, concealed beneath Lake Superior is nowhere exposed; and (3) the attitudes of strata are uncertain in the extensive covered areas. Nevertheless, useful approximations can be made.

East of Hay Bay the base of the Copper Harbor Conglomerate can be located reasonably well. From Hay Bay west to the head of Siskiwit Bay, the contact can be projected on the basis of topographic expression of the immediately underlying lava flows; from that area west to Cumberland Point, however, projection on the basis of topography is impossible as large areas are swamp or are covered by glacial debris (Huber, 1973c). In this western area, the location of the basal contact that is shown on plate 1 was calculated by measuring stratigraphically upward from marker horizons within the uppermost 1,000 feet of the Portage Lake Volcanics. (The marker horizons are

recognized in a few scattered outcrops and in a diamond drill hole logged by Lane (1898, hole no. 11).) These calculations assume a relatively uniform thickness for the upper part of the Portage Lake Volcanics and a uniform dip or rate of change of dip in covered areas between outcrops of the Portage Lake Volcanics and the Copper Harbor Conglomerate. Errors derived from non-uniform thickness are believed to be small and those derived from dip are difficult to evaluate. The total changes in dip from one formation to the other in this area are small; this fact suggests that errors from this source also may be relatively small.

Differential resistance to erosion of many horizons within the Copper Harbor Conglomerate has resulted in the development of a linear ridge and valley topography in the outcrop areas. Although this ridge and valley structure is more subdued and less continuous than that in areas underlain by the Portage Lake Volcanics, it is sufficiently well developed to permit one to trace some individual horizons for several miles or more. One such horizon, which makes up the southern coastline from Fishermans Home Cove to about 2 miles west of Attwood Beach, has been used as an

upper datum plane for estimating thicknesses for at least part of the Copper Harbor Conglomerate. Other less continuous or less well controlled horizons within the formation provide additional data on the nature of lateral thickness changes.

Stratigraphic thicknesses have been graphically calculated for seven sections across the Copper Harbor Conglomerate between Rainbow Point and Francis Point. A stratigraphic diagram based on these data (fig. 4) indicates a fourfold increase in thickness (1,480–5,450 feet) from west to east along a 12-mile length of outcrop. For a section 8 miles farther east in the vicinity of Long Island and Malone Bay an estimate of approximately 6,000 feet may be obtained by assuming a uniform rate of change of dip between opposite ends of the section where known dips are quite different and there is a large gap in data. This calculation is subject to greater errors than the others, but it does suggest the possibility that the thickness of the section continues to increase in an easterly direction, but at a much lower rate than along the Rainbow Point–Houghton Ridge segment.

One other possible complication in determining stratigraphic thicknesses for the Copper Harbor Conglomerate should be considered briefly. Lane (1898, p. 54–56) postulated a major high-angle fault, more or less parallel with the strike of the rocks, through the covered interval between Rainbow Cove and Siskiwit

Bay. The duplication of stratigraphic section that such an interpretation requires would have a sizable effect on thickness calculations. This interpretation was based to a large extent on his belief that apparent inconsistencies in attitudes of strata between outcrops of similar rock types on opposite sides of Rainbow Cove indicated a structural disturbance between them and on his speculation that the conglomerate on Cumberland Point on the north side of Rainbow Cove might indeed be the same horizon as that exposed on Rainbow Point to the south and on Feldtmann Ridge. As additional support, he cited the large differences in attitudes between sandstone outcrops on opposite sides of the east end of Siskiwit Bay. He also believed that except by such a fault there was no accounting for the seemingly anomalous prominence of Point Houghton, which is underlain by sedimentary rocks that are not exceptionally resistant to erosion and generally underlie lowlands. Prominent ridges underlain by rocks of the Copper Harbor Conglomerate, however, also occur on the Keweenaw Peninsula, as at Mount Lookout and Brockway Nose, where there is no evidence for fault control of their development (Cornwall, 1954a, b).

The apparent structural inconsistencies can be explained partly by the now-recognized wedge shape of the formation and partly by differential warping related to flexures on the generally monoclinial struc-

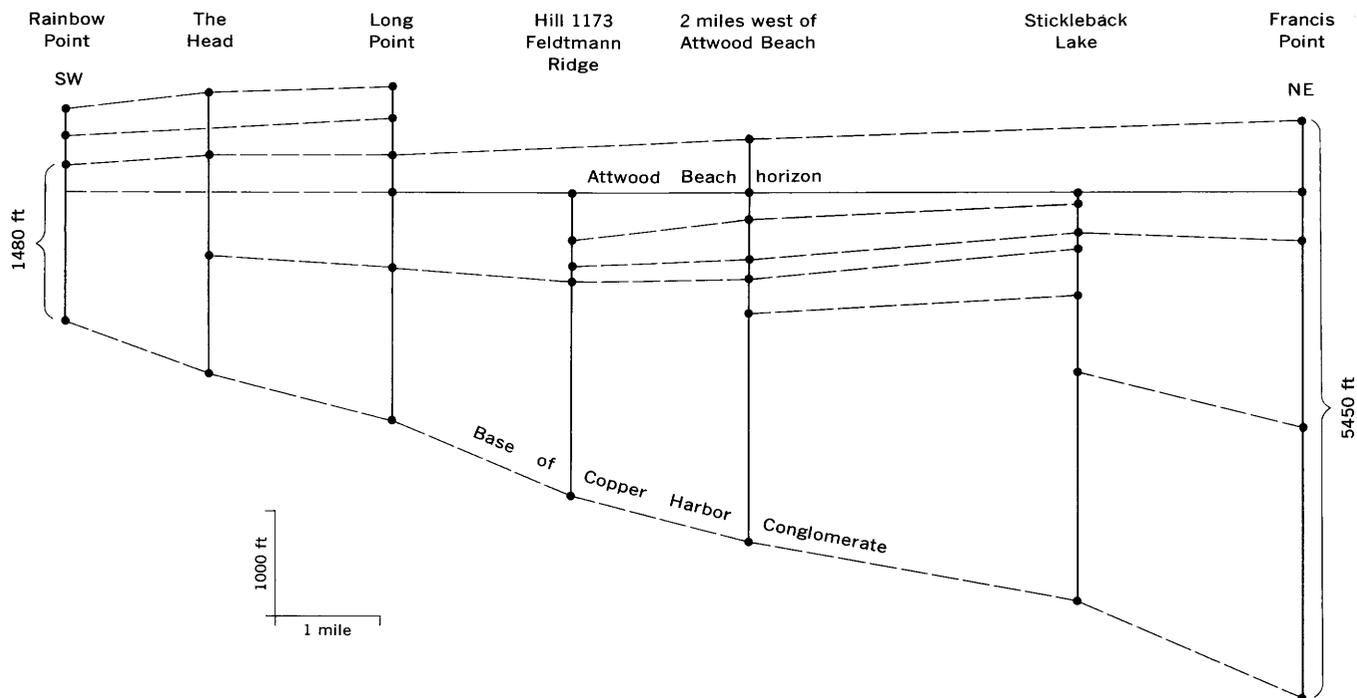


FIGURE 4.—Stratigraphic diagram of the Copper Harbor Conglomerate on Isle Royale from Rainbow Point (SW.) to Francis Point (NE.). Dashed lines connect points on more resistant, ridge-forming horizons traceable on aerial photographs.

ture of the island. Such flexures in the sedimentary sequence are suggested by geophysical data from just southeast of the island (Halls and West, 1971, p. 619–621). As the postulated fault is not required to explain the geologic relations, we have not allowed for any stratigraphic duplication in making our thickness calculations.

LITHOLOGIC CHARACTER

Alternating beds of sandstone and conglomerate with varying textural characteristics are typical of the Copper Harbor Conglomerate on Isle Royale as well as on the Keweenaw Peninsula. The three major rock types are sandstone, pebble conglomerate, and boulder and cobble conglomerate. Within these major groups clast size varies widely, the material ranging from clay-sized particles to boulders larger than 2 feet in diameter. Texture and composition are closely related throughout the formation, the finer grained rocks being compositionally more mature. Conglomerate near the top of the exposed section is similar to conglomerate at the base; the sandstones show a like similarity, even though separated by large stratigraphic intervals. Because of this, general lithologic descriptions can be made for the formation as a whole prior to considering internal variations and specific localities.

Bedding thicknesses vary considerably. Most of the conglomerate beds are between 1 and 3 feet thick; the sandstone beds between $\frac{1}{4}$ inch and 6 inches thick. Clast size descriptions follow Wentworth (1922): pebbles, between $\frac{3}{16}$ inch (4 mm) and $2\frac{1}{2}$ inch (64 mm) in maximum dimension; cobbles, between $2\frac{1}{2}$ inch and 10 inches (256 mm); boulders, greater than 10 inches.

TEXTURE

The conglomerate clasts are subangular to rounded with prolate, bladed, and equant shapes. The maximum dimension of most clasts is between 2 and 8 inches although many are larger, and at least one is 2 feet in diameter (fig. 5). Both the larger clasts and the matrix are poorly sorted, and a complete size gradation commonly exists from fine matrix to conglomerate clasts. The components are generally loosely packed; calcite cement fills most of the spaces between grains.

Sandstone textures are very fine to very coarse grained, and a complete gradation within these ranges may occur in a single bed. Vertical changes in grain size are both abrupt and gradational. Grains are prolate, equant, and bladelike; most grains are angular to subrounded. The degree of sorting generally increases with decrease in grain size, the very fine- and fine-grained sandstones being fairly well sorted, the medium- and coarse-grained sandstones poorly sorted.

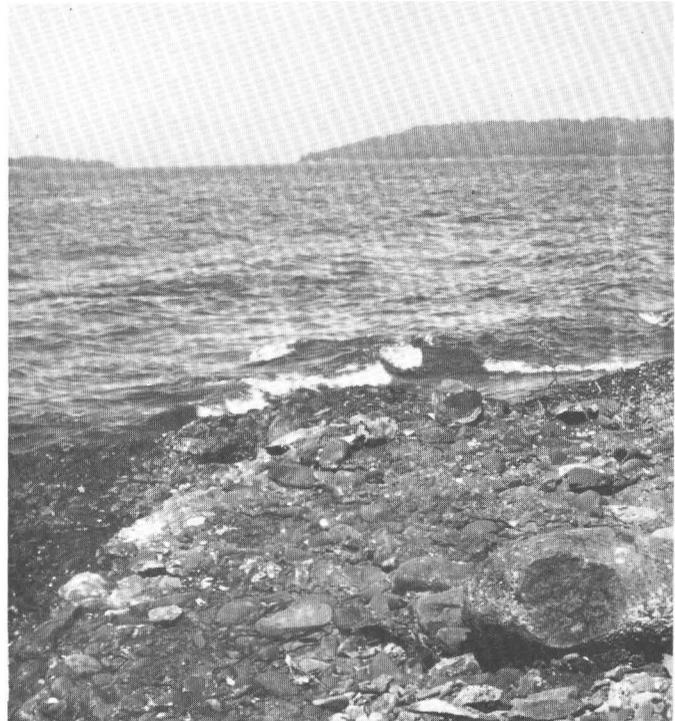


FIGURE 5.—At the western end of Isle Royale at Cumberland Point, the basal part of the Copper Harbor Conglomerate is a coarse boulder and cobble conglomerate. Large boulder in foreground is 2 feet in diameter.

Most fine-grained sandstones are tightly packed and contain less calcite cement than the coarser sandstones with their more open framework.

Siltstone beds, which are very highly jointed and have a darker red color than the coarser grained rocks, are poorly sorted, owing mainly to a bimodal size distribution with many larger quartz and feldspar grains in finer silty matrix. Very thin shale layers, commonly displaying desiccation cracks, are abundant locally.

COMPOSITION

The boulders, cobbles, and pebbles throughout the Copper Harbor Conglomerate are chiefly derived from volcanic rocks, including basalt, andesite, trachyte, latite, quartz latite, and rhyolite. Such volcanic rock fragments usually make up 50–75 percent of the conglomerate, including the finer matrix. Sedimentary rock clasts (claystone and arkosic sandstone) and metamorphic rock clasts (quartzite) make up 0–5 percent of the conglomerate, but usually less than 2–3 percent.

Three types of quartz grains (unstrained, undulatory, and polycrystalline) together make up less than 10 percent of the matrix of the conglomerate beds. Potassium feldspar and plagioclase generally amount to less than 5 percent each; in a given rock, one may be more abundant than the other. Both quartz and

feldspar are less abundant in the coarser conglomerates than in the finer ones. Opaque minerals range between 0 and 9 percent.

The percentage of interstitial calcite increases with increasing grain size, and in some specimens calcite makes up as much as 25 percent of the rock. In most specimens, however, this constituent is between 5 and 15 percent of the rock. Other cementing materials present are ferric oxide, silica, and laumontite.

The average composition of five samples of pebble conglomerate is given in table 1.

TABLE 1.—*Composition of pebble conglomerate*
[Five samples average grain size <1 inch; 300-plus point counts per sample]

Constituent	Percentage	
	Range	Average
Rock fragments:		
Felsic volcanic	21.9–43.7	35.4
Mafic volcanic	22.7–34.3	27.5
Sedimentary (shale and sandstone) .....	.3– 3.5	1.4
Metamorphic (quartzite)	Trace– 1.3	.8
Mineral grains:		
Unstrained quartz	1.9– 6.1	3.9
Opaque .....	.9– 8.1	3.8
Plagioclase	1.5– 5.9	3.6
Potassium feldspar .....	.6– 7.1	2.8
Undulatory quartz .....	.6– 3.5	1.5
Polycrystalline quartz .....	.6– 1.9	1.2
Others (epidote, pyroxene, zeolites)	1.6– 2.3	1.9
Cement:		
Calcite	9.8–23.3	16.2

In the sandstones, volcanic rock fragments make up from 0 to more than 50 percent of the rock, depending on the grain size. The abundance of these rock fragments decreases uniformly from the very coarse-grained to the very fine grained sandstones. Sedimentary and metamorphic rock fragments make up less than 3 percent of most sandstones; some beds contain abundant shale chips, probably derived from the immediately underlying strata.

Quartz grains increase from about 10 percent in the coarse-grained rocks to nearly 50 percent in the fine-grained ones. Unstrained quartz is slightly more abundant than undulatory quartz, and the polycrys-

TABLE 2.—*Composition of coarse to very coarse grained sandstone*
[Twelve samples; 300-plus point counts per sample]

Constituent	Percentage	
	Range	Average
Rock fragments:		
Felsic volcanic	12.3–45.2	31.4
Mafic volcanic	12.3–36.9	26.9
Sedimentary (shale and sandstone) .....	.0– 3.2	1.1
Metamorphic (quartzite)	Trace– 2.3	.6
Mineral grains:		
Plagioclase	2.3–11.6	7.4
Unstrained quartz	1.6–18.1	6.3
Opaque .....	.3–11.6	4.6
Potassium feldspar .....	.9–11.6	4.0
Undulatory quartz .....	.9– 6.1	3.2
Polycrystalline quartz .....	.3– 6.1	1.1
Others (epidote, pyroxene, zeolites) .....	.3– 3.2	1.7
Cement:		
Calcite .....	.3–22.3	11.7

TABLE 3.—*Composition of very fine to fine-grained sandstone*
[Ten samples; 300-plus point counts per sample]

Constituent	Percentage	
	Range	Average
Rock fragments:		
Felsic volcanic	0.0– 3.2	1.3
Mafic volcanic .....	.0– 1.6	.9
Sedimentary (shale and sandstone) .....	.0– 4.2	.8
Metamorphic (quartzite) .....	.0– .3	Trace
Mineral grains:		
Unstrained quartz	28.1–46.2	36.8
Undulatory quartz	11.9–24.2	19.0
Potassium feldspar	4.8–22.9	16.2
Plagioclase .....	.6–20.6	8.0
Opaque	4.8–11.0	6.6
Others (epidote, pyroxene, zeolites)	2.9– 5.4	4.1
Polycrystalline quartz .....	.0– .9	.4
Cement:		
Calcite	1.9– 8.7	5.9

talline variety generally amounts to only 1–2 percent. Potassium feldspar is usually less than 10 percent and commonly 5–7 percent; the plagioclase percentages are about 5 percent greater. Magnetite is by far the dominant opaque mineral; it ranges from 2 to 30 percent, and where most abundant, is concentrated in layers parallel to the bedding. Calcite cement constitutes as much as 20 percent of the sandstones.

The average composition of coarse- and fine-grained sandstones is indicated in tables 2 and 3.

The composition of the siltstones is more difficult to determine; 60–70 percent of these rocks consists of material so fine that it is not easily identifiable with the petrographic microscope. Staining the feldspars helped somewhat in their identification. Owing to recrystallization and alteration, it is also difficult to distinguish matrix material from cement. Much of the fine material is clay, which commonly occurs as shale fragments; some fine material is probably extremely fine quartz and feldspar. Larger quartz and feldspar grains are also present; the quartz amounts to about 15 percent of the total composition of the rock, the feldspars 10 percent or less. Volcanic clasts and opaque minerals are present in small amounts.

DISTRIBUTION OF ROCK TYPES

Even though there is a major gap in the exposed section because of the lack of outcrops in the swampy lowland between Rainbow Cove and Siskiwit Bay and, of course, in Siskiwit Bay itself, data from existing outcrops are sufficient to demonstrate a major facies change from west to east. This facies change, indicated by a decrease in clastic fragment size and an increase in textural and compositional maturity — predominantly coarse conglomerate in the west and sandstone in the east, is shown in a very general way by the geologic map (pl. 1). On plate 1 the different map units are based upon average clast size.

This lateral facies change can be clearly recognized at several horizons within the formation as well as in



FIGURE 6.—Near the middle of Isle Royale on Hat Island in Malone Bay, the basal part of the Copper Harbor Conglomerate is a few feet of pebble conglomerate which overlies the rock of the Portage Lake Volcanics. Exposed patches of amygdaloidal basalt (flat-appearing surface above hammer) are overlain by pebble conglomerate (rough surface near hammer).

the overall gross change. At Cumberland Point, a minimum of several hundred feet of coarse boulder conglomerate lies at the base of the formation. Eastward toward Malone Bay, the basal rock becomes a cobble and then a pebble conglomerate (fig. 6), and at Hat Island only a few feet of fine pebble conglomerate separates a thick section of sandstone from underlying volcanic rock of the Portage Lake Volcanics. Farther east, in a small cove north of Schooner Island in sec. 33, T. 65 N., R. 35 W. (fig. 7), and on a small island at the entrance to Vodrey Harbor, the conglomerate has phased out and sandstone rests directly upon the volcanic rock. There are no outcrops of Copper Harbor Conglomerate east of Vodrey Harbor, although the



FIGURE 7.—East of Malone Bay at a small cove north of Schooner Island, the basal part of the Copper Harbor Conglomerate is a sandstone which overlies the basalt of the Portage Lake Volcanics.

basal contact must be near the shore for many miles eastward along the island coast.

One of the most dramatic and best exposed displays of the facies sequence making up the Copper Harbor Conglomerate is exhibited by the backbone of Feldtmann and Houghton Ridges and the Siskiwit Island chain. Not only can one see here the change from coarse conglomerate on Feldtmann Ridge in the west (fig. 8) to sandstone on the island chain (fig. 9), but on Houghton Ridge, between the two extremes, one can also see the vertical variations in rock type brought about by the interfingering of beds representing different clast sizes and sedimentation energy levels, as illustrated in the cross section on plate 1. A series of samples collected across Houghton Ridge shows that the only consistent compositional changes are related to changes in grain size (table 4); there is no evidence for a vertical compositional trend.

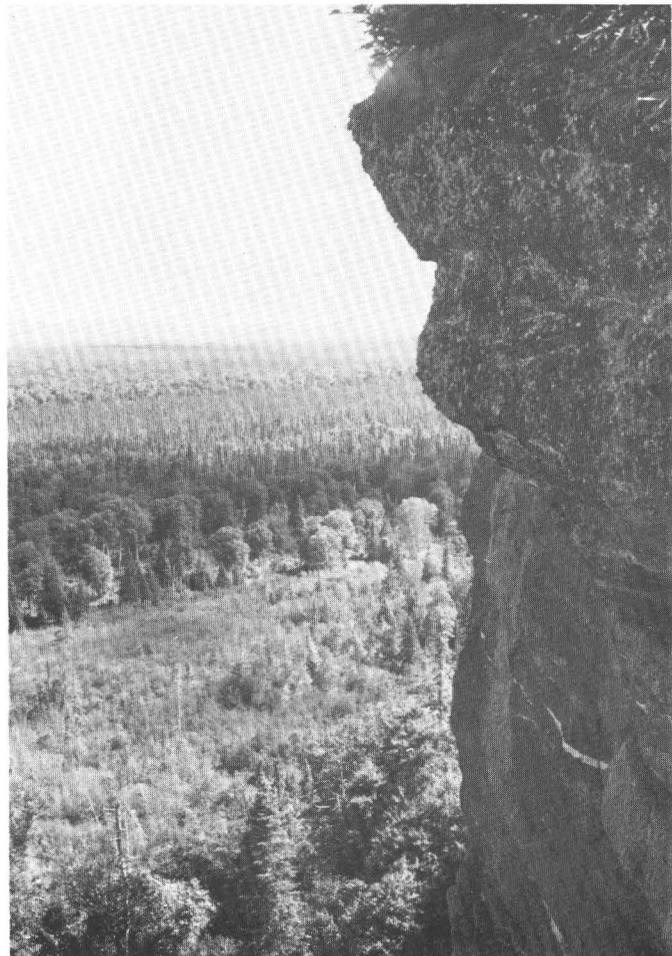


FIGURE 8.—Cobble conglomerate facies (upper) and pebble conglomerate facies (lower) of the Copper Harbor Conglomerate on the west end of Feldtmann Ridge.



FIGURE 9.—Sandstone facies of the Copper Harbor Conglomerate on Stone House Island.



FIGURE 10.—Longitudinal section of trough-type crossbedding in sandstone on the southern side of Houghton Ridge.

TABLE 4.—Composition of very fine grained sandstones, very coarse grained sandstones, and pebble conglomerates taken from the measured section on Houghton Ridge
[Specimen numbers indicate relative position with lowest number lowest in section. See plate 1 for locations]

Specimen No.	Very fine grained sandstones						Very coarse grained sandstones						Pebble conglomerates				
	4	6	7	11	18	28	12	15	18	22	24	27	5	16	30	31	32
MV	0.3	0.6	0.9	Trace	0.9	0.0	30.7	36.9	35.5	35.6	23.9	21.7	22.7	34.3	28.2	22.9	29.4
FV	.9	.6	.9	0.9	.6	.0	31.8	38.8	31.7	33.6	24.2	39.6	43.7	39.9	37.2	21.9	34.6
SF	4.2	.3	.0	Trace	.0	.0	.0	.9	.6	.9	1.6	Trace	.9	.3	1.9	3.5	.3
MF	.0	.0	.3	.0	Trace	.0	.6	Trace	2.3	Trace	.6	.3	.9	.3	1.3	1.3	Trace
UQ	46.2	39.7	42.3	36.5	32.4	28.1	4.8	3.5	3.9	4.5	4.5	1.6	1.9	2.9	4.2	6.1	4.2
UnQ	21.6	16.2	18.8	24.2	23.2	11.9	4.8	1.6	1.9	1.3	2.9	1.9	.9	.6	1.3	3.5	1.3
PQ	.6	.6	.6	.0	.9	.0	.3	.6	.9	.6	1.6	1.3	1.3	1.9	.6	1.3	.9
PF	4.8	15.5	12.9	23.3	18.5	22.9	1.6	1.6	.9	.9	3.9	4.5	7.1	.6	1.6	2.9	1.9
PIF	5.5	8.4	5.2	5.5	6.1	20.6	9.0	11.6	5.4	6.8	10.0	2.3	2.9	5.9	1.9	2.9	4.5
O	6.6	6.8	8.1	5.2	5.8	6.6	6.1	2.3	1.3	5.2	7.1	1.6	1.3	1.6	.9	8.1	7.1
Ca	6.1	6.8	5.5	1.9	8.4	4.5	9.4	1.3	15.3	9.7	17.1	22.3	14.8	9.8	19.0	23.3	14.2
Other	3.2	4.5	4.5	3.5	3.2	5.4	.9	.9	.3	.9	2.6	2.9	1.6	1.9	1.9	2.3	1.6

NOTE.—Abbreviations:

MV. mafic volcanic rock fragments
FV. felsic volcanic rock fragments
SF. sedimentary rock fragments (shale and sandstones)
MF. metamorphic rock fragments

UQ. unstrained quartz grains
UnQ. undulatory quartz grains
PQ. polycrystalline quartz grains
PF. potassium feldspar grains

PIF. plagioclase grains
O. opaque grains
Ca. Calcite cement
Others. epidote, pyroxene, zeolites

DIRECTION OF SEDIMENTARY TRANSPORT

The direction of sedimentary transport of the Copper Harbor Conglomerate on Isle Royale was determined from (1) the orientation of current-formed sedimentary structures such as crossbedding, primary current lineations, and ripple markings; (2) lateral changes in coarseness and thickness of the formation; and (3) conglomerate boulder and cobble composition. Textures, bedding types, and sedimentary structures suggest that streamflow was responsible for transporting and depositing the sandstones and conglomerates of this formation.

SEDIMENTARY STRUCTURES AS DIRECTIONAL INDICATORS

Sedimentary structures that yield directional information include trough-type crossbedding (fig. 10), microcross-laminations (rib-and-furrow structure), ripple markings (figs. 11 and 12), primary current lineations, and current crescents (fig. 13) (Pettijohn and Potter, 1964; Potter and Pettijohn, 1963). Analysis of the relative abundance of these structures on Isle Royale, given in table 5, shows that trough-type cross-

beds occur in both sandstone and pebble conglomerate beds and that all other sedimentary structures are confined to the sandstones. Most data on these structures are from a narrow belt parallel to the strike of the beds along the southern shoreline where sandstones are well exposed by wave action.

The data collected consist of 273 paleocurrent measurements. Measurements of trough crossbeds, rib-and-furrow structures, ripple marks, and current crescents indicate current directions (arrows on fig. 14), whereas measurements of primary current lineations indicate only current trend (one of two opposite directions—straight lines on fig. 14). Half of the data are from structures with discrete directions, but it is encouraging that the measurements of current trend are parallel to these and therefore can be assigned the single directional property with reasonable confidence. Each arrow or line plotted on the sediment dispersal map represents the arithmetic mean of the azimuthal readings from the unit sample area (township-range section). The average number of readings per square-mile section is twelve.

TABLE 5.—Relative abundance of sedimentary features in sandstone and pebble conglomerate in the Copper Harbor Conglomerate, Isle Royale

[A, abundant; C, common; R, trace to rare;, probably does not occur]

Sedimentary features	Sandstone	Pebble conglomerate
Trough cross-stratification	C-A	C-A
Planar cross-stratification	R-C	R
Ripple stratification	C-A	.....
Graded bedding	R-C	C
Asymmetrical ripple markings	C	.....
Symmetrical ripple markings	C	.....
Flat-topped ripple markings	R	.....
Interference ripple markings	R	.....
Cuspate ripple markings	R	.....
Rib-and-furrow structures	C-A	.....
Primary current lineations	A	.....
Dessication cracks	C	.....
Raindrop impressions	R	.....
Channels	R	R
Current-crescent structures	R-C	.....
Heavy mineral concentrations	R-C	R

These same data have been used to construct rose diagrams of current direction, with class intervals of 30°. They have been plotted in four groups (fig. 14) along the strike of the formation. Standard deviations of the measurements are small; the maximum is 40° for an individual group and 55° for all 273 determinations. The diagrams show that most currents flowed southeastward, but in the Houghton Ridge area and on the Siskiwit Island chain the currents flowed eastward to northeastward. These findings are in good agreement with those of Hamblin and Horner (1961), whose data consisted of 80 readings taken along the southeastern shore.

LATERAL CHANGES IN TEXTURE AND FORMATIONAL THICKNESS AS DIRECTIONAL INDICATORS

The demonstrated decrease in average clast size, increase in textural and compositional maturity, and increase in thickness of the formation from west to east suggest transport of material in a general easterly

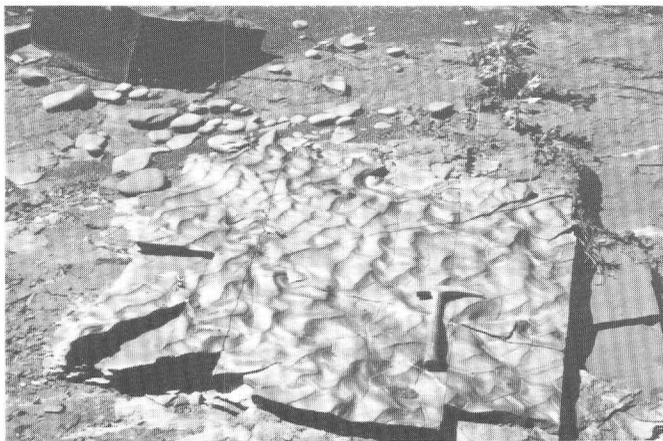


FIGURE 11.—Cuspate ripple markings in sandstone on shoreline in sec. 18, T. 63 N., R. 37 W.

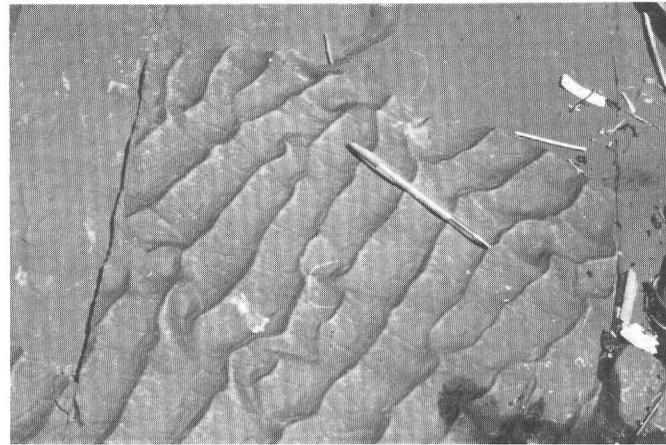


FIGURE 12.—Asymmetric ripple markings in sandstone on shoreline south of Fishermans Home Cove.

direction, consistent with the data supplied by paleocurrent analysis.

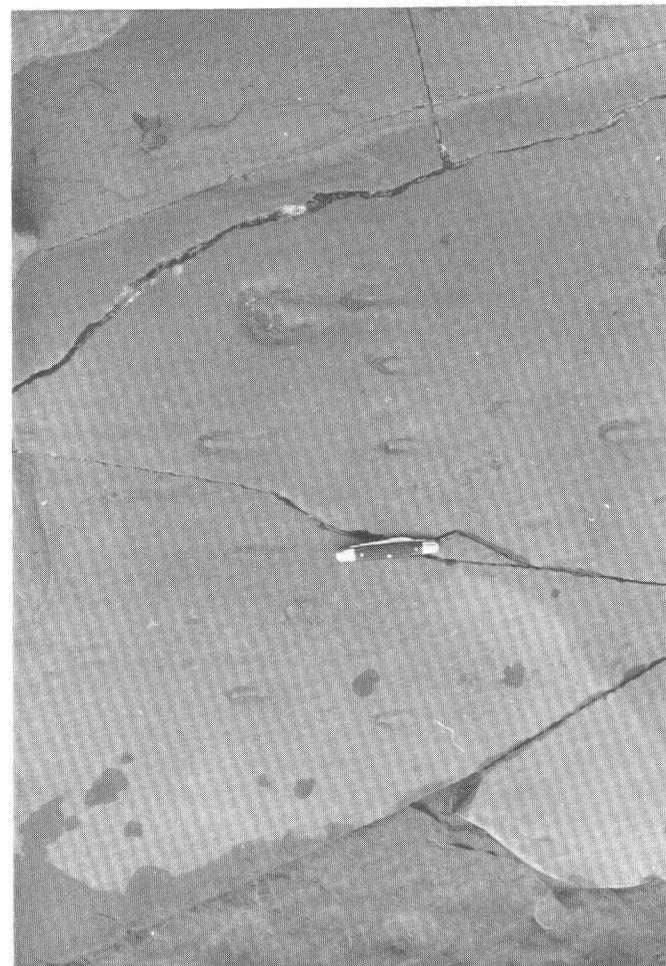


FIGURE 13.—Current-crescent structures in sandstone on shoreline south of Fishermans Home Cove.

CONGLOMERATE COMPOSITION AS AN INDICATOR OF SOURCE DIRECTION

More than one hundred boulders and cobbles were sampled from the conglomerates and later identified more accurately in the laboratory. With the exception of a minor amount of sandstone, conglomerate, and quartzite clasts, all clasts are of volcanic rocks covering a wide range in composition from basalt to rhyolite. No intrusive igneous clasts were noted. Most of the matrix material of the conglomerate could have been derived from volcanic rocks.

The low degree of metamorphism and lack of schistosity of the volcanic clasts is typical of Keweenaw volcanic rocks and unlike any pre-Keweenaw volcanic rocks in the Lake Superior region. The Keweenaw volcanic sequence itself is the most likely source for the clastic debris in both the interflow conglomerates of the Portage Lake Volcanics and the overlying Copper Harbor Conglomerate.

Felsites and some of the textural varieties of mafic volcanic fragments that occur as clasts in the Copper Harbor Conglomerate are not found in flows in the exposed section of the Portage Lake Volcanics on Isle Royale, although Lane (1898, p. 94) does report a diamond drill hole with record of a felsite, which is about 6,200 feet stratigraphically below the top of the lava series. Similarly, although small bodies of intru-

sive and extrusive felsite are present in the Portage Lake Volcanics on the Keweenaw Peninsula, they are not sufficiently abundant to have supplied the felsic, clastic debris of the Copper Harbor Conglomerate there.

Abundant felsitic volcanic rocks do occur in the lowermost part of the Keweenaw flow sequence in the North Shore Volcanic Group of Grout, Sharp, and Schwartz (1959) and Green (1968; 1971) in Minnesota. A few of the textural types of mafic volcanic rocks found as clasts in the Copper Harbor Conglomerate on Isle Royale have not been reported from the North Shore Volcanic Group, but because the outcrops are not continuous, they could well be present. Similarly, recent work by Hubbard (1968b; 1972) indicates that while many Copper Harbor Conglomerate pebble types are not present in the Portage Lake Volcanics in westernmost Michigan, nearly all volcanic types are present in older Keweenaw flows that form the so-called South Trap Range (White and others, 1971) and predate the Portage Lake Volcanics in that area. For this and other reasons, he has proposed an unconformity within the total Keweenaw volcanic sequence (Hubbard, 1968a). Such an unconformity would permit an older Keweenaw sequence of volcanic rocks to be eroded to provide clastic debris for the intraformational conglomerates in the middle

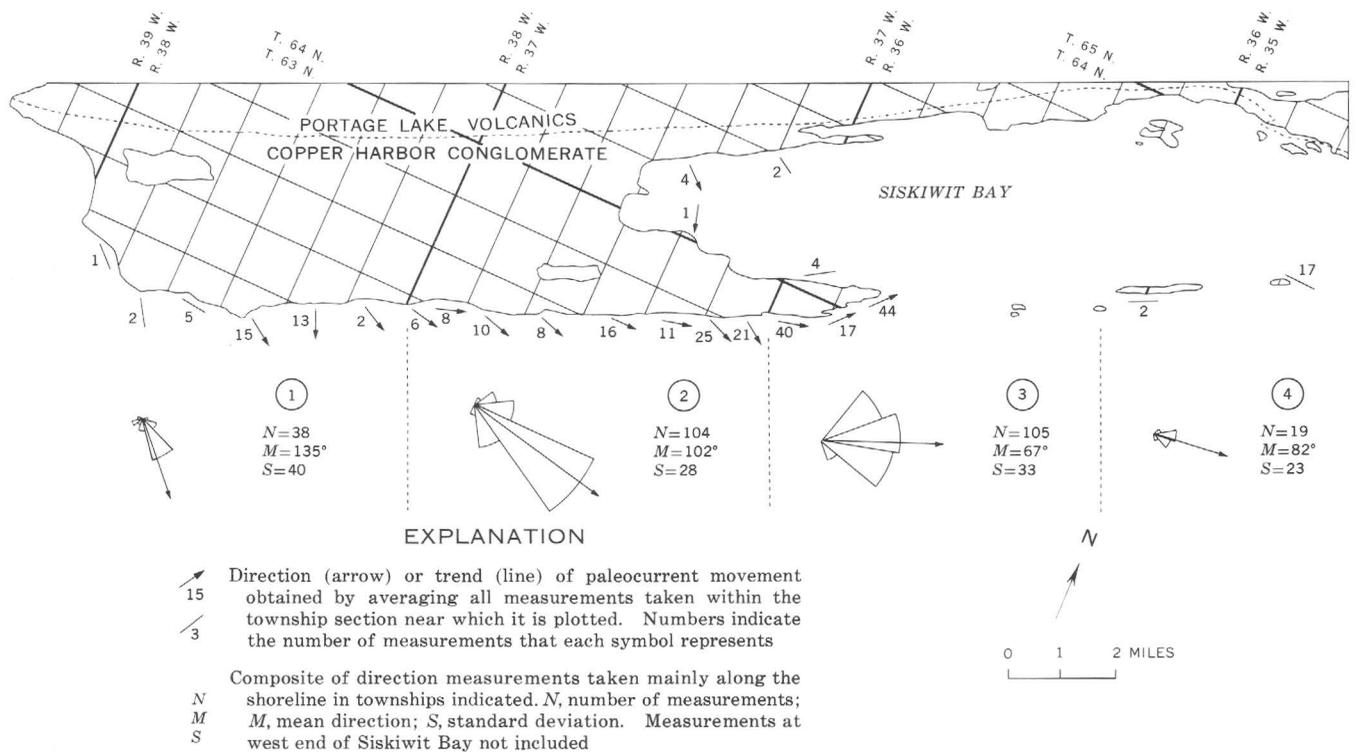


FIGURE 14.—Sediment dispersal patterns in the Copper Harbor Conglomerate on Isle Royale.

Keweenaw Portage Lake Volcanics and the overlying Copper Harbor Conglomerate.

Paleomagnetic studies by DuBois (1962), Books (1968, 1972), and Palmer (1970) have shown that the only zone of reversed magnetic polarity within the Keweenaw volcanic sequence occurs within the lowermost group in western Michigan and within the lower part of the North Shore Volcanic Group in Minnesota, thereby strengthening the correlation of rocks on opposite sides of Lake Superior. By analogy, then, an unconformity can be postulated between the North Shore Volcanic Group and the Portage Lake Volcanics on Isle Royale similar to that suggested for the volcanic rocks of the South Trap Range and the Portage Lake Volcanics on the south side of the lake. The North Shore Volcanic Group would then not only provide a source terrane of appropriate composition but such an unconformity would also allow for erosion of that source terrane while deposition of the interflow sediments of the Portage Lake Volcanics and of the Copper Harbor Conglomerate present on Isle Royale took place. The North Shore Volcanic Group does not necessarily provide a unique source for the clastic material, as similar material may exist within the Keweenaw volcanic rocks of the Osler Group in Canada (fig. 1), but a likely source present in the direction indicated as the source by other criteria is helpful.

Although all evidence indicates that the North Shore Volcanic Group is stratigraphically older than the Portage Lake Volcanics on Isle Royale, interpretations other than the postulated unconformity are possible. It is possible that the North Shore Volcanic Group may have been tectonically uplifted at the western margin of the depositional basin while in the central part of the basin volcanic activity continued with the eruption of the Portage Lake Volcanics and the later deposition of the Copper Harbor Conglomerate. Alternatively, it is also possible that the North Shore Volcanic Group and the Portage Lake Volcanics may have formed in separate tectonic basins isolated from each other, rather than in a single large basin, as has been suggested for some of the Keweenaw volcanic sequences on the south side of the basin (White and others, 1971). Each of these structural settings would permit erosion of the North Shore Volcanic Group to provide clastic debris for the interflow conglomerates in the Portage Lake Volcanics and for the Copper Harbor Conglomerate.

ENVIRONMENT OF SEDIMENTARY ACCUMULATION

Source areas for the debris in the Copper Harbor Conglomerate were on opposite sides of the Lake

Superior syncline, and the major sediment transport directions were generally toward the axis of the syncline. The relative abundance of various sedimentary features in the formation on Isle Royale (table 5) best fits that summarized for a fluvial environment by Picard (1967), and the coarser facies are characteristic of alluvial fan deposits (Bull, 1972). These features, together with lateral changes in texture and compositional maturity, suggest a piedmont fan deposit grading outward into a flood-plain deposit. Although some sedimentary features in the finer grained rocks, such as crossbeds and ripple marks, indicate that they were deposited in bodies of standing water, the abundance of desiccation cracks (fig. 15) and occasional raindrop impressions indicate that such bodies of water were ephemeral. Other more permanent bodies of water may have existed in the central part of the Lake Superior syncline.

A depositional environment such as this has been proposed by White and Wright (1960) for the Copper Harbor Conglomerate on the Keweenaw Peninsula. The Isle Royale study not only supports their interpretation, but provides an exceptional illustration of the transition from fan deposits to flood-plain deposits over a distance of more than 20 miles along the general direction of sedimentary transport.

White (1960) has clearly demonstrated that the Lake Superior syncline was subsiding during alternating eruption of the lava flows and deposition of the interflow sediments of the middle Keweenaw Portage Lake Volcanics. Presumably, the subsidence continued into at least part of the subsequent Keweenaw, for the deposition of the Copper Harbor Conglomerate indicates the gradual demise of volcanic activity without any radical changes in the depositional environment. In fact, on the Keweenaw Peninsula a few last surges of volcanic activity are



FIGURE 15.—Desiccation cracks in fine-grained sedimentary rock on Menagerie Island.

represented by flows within the Copper Harbor Conglomerate (refer to Cornwall, 1955; White and Wright, 1960); one group of flows is only 300 feet below the top of the formation (White and others, 1953). The wedge-shaped depositional geometry of the Copper Harbor Conglomerate on Isle Royale is related to continuing subsidence of the Lake Superior basin.

White's analysis (1960), which indicates periodic reversals of slope between flows and interflow sediments, further indicates rather low gradients for the streams that deposited the Copper Harbor Conglomerate. Hamblin and Horner (1961, p. 210) suggested that the small standard deviation in orientation of current structures and the coarse texture of the sediments on Isle Royale indicate streams with straight courses and steep gradients. These sedimentary features, however, may well be compatible with quite low gradients under the prevegetation hydrologic conditions that existed during the Precambrian. As Schumm (1968, p. 1585) recently pointed out, "before the appearance of significant plant cover, denudation and runoff rates were high and floods were large, and coarse sediments were spread over piedmont areas even in humid climates." These processes would also help explain the extensive sheetlike nature of the interflow conglomerates.

REFERENCES CITED

- American Commission on Stratigraphic Nomenclature, 1970, Code of stratigraphic nomenclature: Tulsa, Okla., Am. Assoc. Petroleum Geol., 19 p.
- Books, K. G., 1968, Magnetization of the lowermost Keweenaw lava flows in the Lake Superior area, *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600-D, p. D248-D254.
- , 1972, Paleomagnetism of some Lake Superior Keweenaw rocks: U.S. Geol. Survey Prof. Paper 760, 42 p.
- Bull, W. B., 1972, Recognition of alluvial-fan deposits in the stratigraphic record, *in* Rigby, J. K., and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 16, p. 63-83.
- Cornwall, H. R., 1954a, Bedrock geology of the Delaware quadrangle, Michigan: U.S. Geol. Survey Geol. Quad. Map GQ-51, scale 1:24,000.
- , 1954b, Bedrock geology of the Lake Medora quadrangle, Michigan: U.S. Geol. Survey Geol. Quad. Map GQ-52, scale 1:24,000.
- , 1955, Bedrock geology of the Fort Wilkins quadrangle, Michigan: U.S. Geol. Survey Geol. Quad. Map GQ-74, scale 1:24,000.
- Cornwall, H. R. and White, W. S., 1955, Bedrock geology of the Manitou Island quadrangle, Michigan: U.S. Geol. Survey Geol. Quad. Map GQ-73, scale 1:24,000.
- DuBois, P. M., 1962, Palaeomagnetism and correlation of Keweenaw rocks: Canada Geol. Survey Bull. 71, p. 1-75.
- Green, J. C., 1968, Varieties of flows in the North Shore Volcanic Group, Minnesota [abs.], *in* Inst. Lake Superior Geology, 14th Ann., 1968, Tech. Sess. Abs.: Superior, Wis., Wisconsin State Univ., p. 52-53.
- , 1971, The North Shore Volcanic Group, *in* Inst. Lake Superior Geology, 17th Ann., 1971, Tech. Sess. Abs. and Field Guides: Duluth, Minn., Univ. Minnesota, Duluth, p. 73-96.
- Grout, F. F., Sharp, R. P., and Schwartz, G. M., 1959, The geology of Cook County, Minnesota: Minnesota Geol. Survey Bull. 39, 163 p.
- Halls, H. C., 1966, A review of the Keweenaw geology of the Lake Superior region, *in* The earth beneath the continents - A volume of geophysical studies in honor of Merle A. Tuve: Am. Geophys. Union Geophys. Mon. 10 (Natl. Acad. Sci. - Natl. Research Council Pub. 1467), p. 3-27.
- Halls, H. C., and West, G. F., 1971, A seismic refraction survey in Lake Superior: Canadian Jour. Earth Sci., v. 8, p. 610-630.
- Hamblin, W. K., 1961, Paleogeographic evolution of the Lake Superior region from Late Keweenaw to Late Cambrian time: Geol. Soc. America Bull., v. 72, no. 1, p. 1-18.
- , 1965, Basement control of Keweenaw and Cambrian sedimentation in Lake Superior region: Am. Assoc. Petroleum Geologists Bull., v. 49, no. 7, p. 950-958.
- Hamblin, W. K., and Horner, W. J., 1961, Sources of the Keweenaw Conglomerates of northern Michigan: Jour. Geology, v. 69, p. 204-211.
- Hite, D. M., 1968, Sedimentology of the upper Keweenaw sequence of northern Wisconsin and adjacent Michigan: Wisconsin Univ., Madison, Ph. D. thesis, 236 p.
- Hubbard, H. A., 1968a, Stratigraphic relationships of some Keweenaw rocks of Michigan and Wisconsin [abs.], *in* Inst. Lake Superior Geology, 14th Ann., 1968, Tech. Sess. Abs: Superior, Wis., Wisconsin State Univ., p. 35-37.
- , 1968b, Stratigraphy and structure of some Keweenaw rocks, Michigan: U.S. Geol. Survey open-file report, 12 p.
- , 1972, Source of pebbles of volcanic rocks in the middle and upper Keweenaw conglomerates of northern Michigan: Jour. Geology, v. 80, p. 627-629.
- Huber, N. K., 1973a, Glacial and postglacial geologic history of Isle Royale National Park, Michigan: U.S. Geol. Survey Prof. Paper 754-A, p. A1-A15.
- , 1973b, The Portage Lake Volcanics (middle Keweenaw) on Isle Royale, Michigan: U.S. Geol. Survey Prof. Paper 754-C (in press).
- , 1973c, Geologic map of Isle Royale National Park, Keweenaw County, Michigan: U.S. Geol. Survey Misc. Geol. Inv. Map I-796, scale 1:62,500 (in press).
- Irving, R. D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geol. Survey Mon. 5, 464 p.
- Lane, A. C., 1898, Geological report on Isle Royale, Michigan: Michigan Geol. Survey Rept., v. 6, pt. 1, 281 p.
- , 1911, The Keweenaw Series of Michigan: Michigan Geol. and Biol. Survey Pub. 6; Geol. Ser. 4, 2 v., 983 p.
- Lane, A. C., and Seaman, A. E., 1907, Notes on the geological section of Michigan: Part I. The Pre-Ordovician: Jour. Geology, v. 15, no. 7, p. 680-695.

- Palmer, H. C., 1970, Paleomagnetism and correlation of some Middle Keweenaw rocks, Lake Superior: *Canadian Jour. Earth Sci.*, v. 7, no. 6, p. 1410-1436.
- Pettijohn, F. J., and Potter, P. E., 1964, Atlas and glossary of primary sedimentary structures: New York, Harper and Row, 718 p.
- Picard, M. D., 1967, Stratigraphy and depositional environments of the Red Peak Member of the Chugwater Formation (Triassic), west-central Wyoming: *Wyoming Univ. Contr. Geology*, v. 6, no. 1, p. 39-67.
- Potter, P. E., and Pettijohn, F. J., 1963, Paleocurrents and basin analysis: New York, Academic Press, 296 p.
- Schumm, S. A., 1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: *Geol. Soc. America Bull.*, v. 79, no. 11, p. 1573-1588.
- Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: *Jour. Geology*, v. 30, no. 5, p. 377-392.
- White, W. S., 1952, Imbrication and initial dip in a Keweenaw conglomerate bed: *Jour. Sed. Petrology*, v. 22, no. 4, p. 189-199.
- , 1960, The Keweenaw lavas of Lake Superior, an example of flood basalts: *Am. Jour. Sci., Bradley Volume*, v. 258-A, p. A367-A374.
- , 1966, Tectonics of the Keweenaw Basin, western Lake Superior region: U.S. Geol. Survey Prof. Paper 524-E, p. E1-E23.
- , 1971, Geologic setting of the Michigan Copper District, in *Guidebook for field conference, Michigan Copper District*, Sept. 30-Oct. 2, 1971: Houghton, Mich., Michigan Tech. Univ. Press, p. 3-17.
- , 1972, The base of the upper Keweenaw, Michigan and Wisconsin: U.S. Geol. Survey Bull. 1354-F, p. F1-F23.
- White, W. S., Brooks, E. R., Hubbard, H. A., Johnson, R. F., and Wilband, J. T., 1971, Keweenaw stratigraphy of westernmost Michigan [abs.], in *Inst. Lake Superior Geology, 17th Ann., 1971, Tech. Sess. Abs. and Field Guides: Duluth, Minn., Univ. Minnesota, Duluth*, p. 71-72.
- White, W. S., Cornwall, H. R., and Swanson, R. W., 1953, Bedrock geology of the Ahmeek quadrangle, Michigan: U.S. Geol. Survey Geol. Quad. Map GQ-27, scale 1:24,000.
- White, W. S., and Wright, J. C., 1960, Lithofacies of the Copper Harbor Conglomerate, northern Michigan, in *Geological Survey research 1960: U.S. Geol. Survey Prof. Paper 400-B*, p. B5-B8.

