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PRE-CAMBRIAN ROCKS OF THE LAKE SUPERIOR REGION

A REVIEW OF NEWLY DISCOVERED GEOLOGIC FEATURES WITH A REVISED GEOLOGIC MAP

BY

C. K. LEITH, RICHARD J. LUND, AND ANDREW LEITH

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ABSTRACT

Detailed knowledge of the geology of the pre-Cambrian rocks of the Lake Superior region has been greatly augmented since the publication of Monograph 52 by the United States Geological Survey in 1911. The authors have attempted in the present report to assemble as much of this new information as possible, and to give the reader a birdseye view of the geology as seen in the light of all studies made there up to the present time. Detailed descriptions are not presented, and the emphasis is placed upon the major problems of correlation. A revised map of the region, with cross sections, accompanies the report, bringing up to date a knowledge of the areal geology of the region, which otherwise could be gained only by consulting some 150 maps contained in almost as many separate local reports, many of which are unpublished.

Principal changes from the map accompanying Monograph 52 are summarized, the most striking of which, aside from changes resulting from shifts in correlations, are found in Canada, northern Minnesota, and northern Wisconsin—areas which up to 1911 had not received the detailed study which has been given them since that time.

The geologic succession is, in ascending order, (1) the Keewatin series, intruded by the Laurentian granite; (2) the Knife Lake series (which may be Lower Huronian), intruded by the Algoman granite; (3) the Huronian series, including the Lower, Middle, and Upper Huronian groups; (4) the Keweenawan series, intruded by the Killarney granite, the exact age of which is doubtful; and (5) the Cambrian, Ordovician, Cretaceous, and Pleistocene rocks. The series and groups named are separated by unconformities.

New views in respect to correlation of the pre-Cambrian rocks are discussed at length. The most noteworthy of these are (1) the correlation of the major iron-formations of the Mesabi, Gogebic, Marquette, and Menominee ranges as of Negaunee (Middle Huronian) age, and the iron-formations of the Cuyuna, Iron River, Florence, and Crystal Falls districts as of Upper Huronian age; (2) the recognition of the uncertainty surrounding the age of the Knife Lake series, with an inclination to view it as pre-Lower Huronian, but pointing out the distinct possibility of its being Lower Huronian; (3) the recognition and better delimitation of three great periods of granitic intrusion—Laurentian, Algoman, and Killarney—the Laurentian of wide distribution throughout the region, the Algoman confined largely to the north shore of Lake Superior, and the Killarney confined largely to the south shore.

One important change from Monograph 52 is in the use of the terms "Archean" and "Algonkian." In the present report they designate two rock types—a lower or basement group, largely igneous, which is not divisible by the use of normal stratigraphic methods, and an upper group between the basement and the Cambrian, largely sedimentary, and divisible by the use of normal stratigraphic methods. The chronologic significance of the terms, which implied that the †Eparchean intervals of two widely separated districts were equivalent in time, has been abandoned.

The question of the origin of the iron-formations and the subsequent concentration of the iron ores is reviewed, and it is concluded that the theories presented in Monograph 52 are essentially correct. The iron in the iron-formations is thought to be derived principally from volcanic sources and possibly to a lesser extent from weathering; the concentration of the iron ores is due to oxidation and leaching of silica by downward-moving surface water.

A bibliography of literature bearing on the pre-Cambrian geology of the region which has appeared since the manuscript of Monograph 52 was completed, in 1910, concludes the report.

INTRODUCTION

Around Lake Superior, in the States of Michigan, Wisconsin, and Minnesota and the Province of Ontario, is an area of pre-Cambrian rocks representing part of the south margin of the great pre-Cambrian shield of North America. It yields about 85 percent of the iron ore of the United States and 10 percent of its copper. Production in this region is confined to United States territory. The region has produced more than 1,500,000,000 tons of iron ore, and tax commission estimates for Minnesota, Michigan, and Wisconsin show about the same amount in reserve. Extension of known deposits (particularly in depth) and further discoveries will add to this figure. If production continues at the rate established since the World War, exclusive of the present depression, the peak of capacity for production will be passed in perhaps 25 years, after which there will be a falling off due to beginning exhaustion of the Mesabi range of Minnesota, which has been the principal producer. The region has also produced about 4,000,000 tons of metallic copper, but the output of copper is already waning, because of low grade, great depth, and high cost.

Copper mining has continued since 1844 in the Keweenaw district of Michigan. Iron mining began in the Marquette district of Michigan in 1848 and slowly spread over other parts of the region. The Menominee district was opened in 1872, the Crystal Falls, Florence, and Iron River districts in 1880, the Gogebic district in 1884, the Vermilion district in

1885, the Mesabi district in 1891, and the Cuyuna and Baraboo districts in 1903.

The Lake Superior region has been of special interest to students of pre-Cambrian geology because it presents one of the longest and most varied pre-Cambrian successions that have yet been definitely worked out. Its content of valuable iron and copper ores has made possible more intensive and detailed study than has been accorded to large pre-Cambrian areas elsewhere. For over half a century the region has been under continuous investigation by State and Federal surveys of the United States, by Provincial and Dominion surveys of Canada, and by geologic staffs attached to the mining companies.

The United States Geological Survey conducted systematic surveys in the Lake Superior region from 1880 to 1909 and published many reports and maps, culminating in a series of seven monographs. The last of these, Monograph 52, published in 1911, summarized the geology of the region. Since that time the United States Geological Survey has done less systematic work, though three reports have been published—two on the Cuyuna district of Minnesota,[1] in cooperation with the Minnesota Geological Survey, and one on the Keweenaw copper district,[2] based on field work done largely by the Calumet & Hecla Consolidated Copper Co. but extended and completed by the Federal Survey. During the long interval since 1911 State and commercial surveys have added much to the knowledge of the pre-Cambrian of the region. The results of these surveys, however, are in part scattered in numerous publications, and many have not been published at all.

The United States Geological Survey has cooperated in the summary of the new knowledge of the pre-Cambrian geology of the region, as presented in the accompanying map and text, by defraying the cost of base maps and certain expenses of Richard J. Lund and Andrew Leith during 1931–33 and by undertaking the publication of this paper.

The authors have drawn on their own knowledge of the region and have in addition had the cordial cooperation of many Lake Superior geologists and engineers, the State geological surveys, and the Geological Survey of Canada. As a result of this cooperation it has been possible to bring together nearly all of the essential work that has been done, public and private, published and unpublished. Several mining companies have given permission to use the results of surveys made for them. Nearly 150 detailed maps made since 1911, some published and some unpublished, have been used in making up the new general map. Individual acknowledgment would require an unduly long list of names, but the authors here express their appreciation and thanks to the many who have helped to make this summary possible.

No finality can be claimed for the present contribution. There are many gaps in the detailed mapping. Areas have been mapped by different people, at different times, on different scales, and with different interpretations of the geology, with the result that many abrupt changes of classification that do not actually exist in the field are shown by straight-line boundaries on the map. Many local questions of structure, succession, and correlation are still unanswered. In a region as extensive and complicated as this geologists will still find unsolved problems a hundred years from now. The purpose of this paper is to take stock of present knowledge, including contradictory observations and interpretations, and try to express it as well as may be in a generalized map and report. The authors have tried to avoid the temptation to oversimplify or to put the available miscellaneous knowledge into a straight-jacket of rigid correlation, though of course some measure of generalization is necessary to express the available information on the scale adopted for the new map.

PRINCIPAL CHANGES FROM THE OLD MAPPING

Departure from the general scheme as used on the map in Monograph 52 has been made by showing all acidic plutonic rocks by the same color and pattern, the specific ages being shown by letter symbol in those regions only where they are conclusively known. This has been done because of difficulty in differentiating these granitic rocks over extensive areas where they occur, the unknown age in these areas being indicated by the absence of any age symbol.

In several places on the map there will be found straight-line boundaries. Some of these, indicated by heavy black lines, represent fault contacts, but most of them, indicated only by a change in color pattern, signify the limits of detailed surveys, beyond which the different color pattern may indicate undifferentiated formations.

Modifications of correlation in the various iron districts discussed on pages 13–15 will here be passed over with only cursory mention, to avoid repetition.

Areas mapped as "unclassified pre-Cambrian" naturally have been cut down very considerably since the publication of the old map by the extensive work which has been done in these outlying regions, but there still remain large undifferentiated tracts.

Although the region is covered to a considerable extent with glacial deposits, neither the old nor the new map shows these deposits, but the reader who may be interested in studying the relations of the

[1] Harder, E. C., and Johnston, A. W., Notes on the geology and iron ores of the Cuyuna district, Minn.: U.S. Geol. Survey Bull. 660, pp. 1–26, 1918; Preliminary report on the geology of east-central Minnesota, including the Cuyuna iron-ore district: Minnesota Geol. Survey Bull. 15, 178 pp., 1918.

[2] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U.S. Geol. Survey Prof. Paper 144, 238 pp., 1929.

drift to the pre-Cambrian rocks will find in the works of Leverett [3] adequate maps and descriptions of the several drift sheets.

MICHIGAN AND WISCONSIN

South of Lake Superior the boundaries as shown on the geologic maps of Michigan (1916) and Wisconsin (1928) published by the respective State geological surveys have been followed over much of the area, with modifications required by other published or unpublished data made available since their appearance.

The large area in northern Wisconsin previously indicated as "undifferentiated pre-Cambrian" has been eliminated. In its stead are shown either areas of acidic igneous intrusives or areas in which magnetic observations suggest that the occurrence of sedimentary formations of Huronian age is possible. The mapping in the western part of this area is taken from two reports of the Wisconsin Geological and Natural History Survey,[4] and the mapping in the vicinity of the Michigan-Wisconsin boundary southeast of the Gogebic range was revised from the map compiled by R. C. Allen.[5] In this area detailed field work, particularly by the F. I. Carpenter Syndicate, has shown several strong, well-defined magnetic belts with scattered outcrops as supporting evidence, which indicate the existence there of several linear areas of Huronian sedimentary rocks containing iron-formation. These so-called "ranges", extending across the State boundary for varying distances into Wisconsin, named in order from northwest to southeast, are the Marenisco, Turtle, Manitowish, Vieux Desert, and Conover ranges. It is highly probable that the large Upper Huronian slate area of northern Michigan extends across the State line into these various ranges, this possibility being very strongly indicated, if not actually proved, in the Conover district; but until more confirmatory evidence shall have been uncovered it is thought best to follow Allen in classifying these areas as being probably underlain by undifferentiated Huronian sediments. On the map, therefore, the Upper Huronian slates of Michigan are shown fading off gradually into the undifferentiated Huronian sediments of these several districts in Wisconsin.

New detail in mapping of the western Gogebic iron range is taken directly from the recent report by Aldrich.[6] Aside from changes in correlation as discussed on pages 13–14, the new mapping shows abundant fault contacts and a large area of granite of Killarney age just northwest of Mellen, previously mapped as basic intrusive. In Michigan the detail of the part of the Gogebic range between Ironwood and Wakefield comes from the 1916 State geologic map; that of the Wakefield area itself from a map furnished by Pickands, Mather & Co.; the detail in T. 47 N., R. 44 W., from a map contributed by the M. A. Hanna Co.; and that of the area lying in T. 47 N., R. 42 W., from the map of the east end of the Gogebic iron range by Allen and Barrett.[7] The distribution of the Tyler slate (Upper Huronian) is taken from unpublished work of Gordon Atwater for the United States Geological Survey during the summers of 1931 and 1932.

Most of the detail in Iron County, Mich., has been taken from the map published by the Michigan Geological Survey.[8] The principal modifications from that map relate to the distribution of the iron-formation [9] in the Iron River district, which is taken from an unpublished composite map of that district compiled by Stephen Royce; the detail in the Atkins area, north of Iron River, which is taken from work by C. O. Swanson during the summer of 1932; and the changes in mapping of the Saunders area south of Iron River, as well as the change in age of the Paint River belt of greenstone, which are taken from the work of Andrew Leith.

The present map, including the above-mentioned modifications, differs from the map in Monograph 52 in many respects, the most important of which are (1) the elimination of all of the undifferentiated pre-Cambrian area east and southeast of the Crystal Falls "oval" (shown now as Upper Huronian sediments); (2) the addition of a great amount of detail both in and adjacent to the Crystal Falls "oval"; (3) changes in the distribution of the three important greenstone belts lying outside of the "oval", including (*a*) the Paint River belt, extending westward from the city of Crystal Falls, (*b*) the Spread Eagle belt, extending southeastward from Mastodon and Stager, and (*c*) the Pentoga belt, stretching westward and southeastward from the village of Saunders, along the Wisconsin boundary.

The mapping in Florence County, Wis., is a compilation of numerous unpublished reports in the files

[3] Leverett, Frank, Surface geology and agricultural conditions of Michigan: Michigan Geol. and Biol. Survey Pub. 25 (Geol. ser. 2), 223 pp., 1917; Moraines and shore lines of the Lake Superior Basin: U.S. Geol. Survey Prof. Paper 154, pp. 1–72, 1930; Quaternary geology of Minnesota and parts of adjacent States, with contributions by F. W. Sardeson: U.S. Geol. Survey Prof. Paper 161, 149 pp., 1932.

[4] Hotchkiss, W. O., Bean, E. F., and Wheelwright, O. W., Mineral land classification in northwestern Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 44, pl. 1 and township maps for magnetic lines, 1915. Hotchkiss, W. O., Bean, E. F., and Aldrich, H. R., Mineral lands of part of northern Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull 46, pl. 1 and township maps for magnetic lines, 1929.

[5] Allen, R. C., and Barrett, L. P., Contributions to the pre-Cambrian geology of northern Michigan and Wisconsin: Michigan Geol. and Biol. Survey Pub. 18, fig. 1, 1915.

[6] Aldrich, H. R., The geology of the Gogebic iron range of Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 71, pl. 1, 1929.

[7] Allen, R. C., and Barrett, L. P., A revision of the sequence and structure of the pre-Keweenawan formations of the eastern Gogebic iron range: Michigan Geol. and Biol. Survey Pub. 18, fig. 2A, 1915.

[8] Barrett, L. P., Pardee, F. G., and Osgood, W. (compilers), Geological map of Iron County, Michigan Geol. Survey, 1929.

[9] The term "iron-formation" (hyphenated) has been adopted for use in a technical lithologic sense (like "ironstone") in this report, in accordance with the prevalent usage in the Lake Superior region.

of the Wisconsin Geological and Natural History Survey, as modified by recent work by Andrew Leith. There is still much confusion as to the correlation of the greenstones of Florence County and those in Iron County, Mich., mentioned above. Those in the Paint River belt and the Pentoga belt are known to underlie the Michigamme slate, but it is not known whether they are Middle Huronian (Hemlock) or lower Upper Huronian. There seems to be a slight presumption in favor of the latter age, but the evidence is so inconclusive that they are designated on the map "unclassified pre-Cambrian." The Mastodon-Spread Eagle-Lake Antoine greenstone belt is likewise of uncertain age, but owing to the presence of an iron-formation of Middle Huronian type immediately above it near Spread Eagle Lake the belt is designated as doubtfully Middle Huronian. The south belt of the Quinnesec greenstone, first mapped as Keewatin and later in Monograph 52 as late Upper Huronian, is now shown as unclassified pre-Cambrian. It seems to the writers that the evidence is probably in favor of placing the series in the lower part of the Upper Huronian, below the Michigamme slate and above the basal conglomerate, but the evidence is not so conclusive that the old classification of late Upper Huronian or an alternate classification as Middle Huronian can be overlooked.

The quartzite exposed near Keyes Lake is now tentatively assigned to the Lower Huronian, and the iron-formations in contact with it (Little Commonwealth mine and Dunkel areas) are classified as Middle Huronian (Negaunee). The exact relations in this area are at present too obscure for definite conclusion, and the possibility that the quartzite near Keyes Lake is of Goodrich (Upper Huronian) age must be kept in mind. The Breakwater quartzite (named for its occurrence near Breakwater Falls on Pine River, Florence County) is now tentatively assigned to the Goodrich epoch.

New detail in the Menominee range is taken from a map compiled by the Oliver Iron Mining Co. Other than the modifications in correlation given on pages 13–14, only minor changes from the old map have been made, including the mapping of numerous faults in the Vulcan iron-formation in the vicinity of the town of Iron Mountain and an extension of this formation some 2 miles to the northwest from the vicinity of the Loretto mine. The outliers of Cambrian sandstone, which are extensively exposed throughout the district, have been omitted because any attempt to show them on a map of this scale would obscure the mapping of the pre-Cambrian geology beneath.

Modifications of the mapping of the Calumet and Felch Mountain troughs, lying consecutively northward from the Menominee district, consist of changes in correlation whereby the iron-formation of these districts, together with the Felch schist immediately underlying it, is now thought to be of Middle Huronian age, rather than Upper Huronian as previously mapped. The detail in the Felch Mountain trough in the vicinity of the village of Metropolitan comes from unpublished work by N. H. Stearn and C. O. Swanson. The narrow tongue of Lower Huronian sediments lying in the granite just north of the Sturgeon River trough is shown on the basis of field work done on separate surveys by Hugh M. Roberts and Andrew Leith.

Revision of the mapping of the Swanzy district, better known as the Gwinn district, in T. 45 N., R. 25 W., is based on the work of Allen.[10] Sediments of both Middle and Upper Huronian age are now shown, only rocks of the latter age having been indicated previously. In addition, numerous faults are shown on the new map, together with an extension of the trough several miles southeastward where the overburden is thicker and more continuous. Rocks of the same type and succession have been found by Allen[11] only a few miles to the east, in the vicinity of Little Lake, Mich.; in Monograph 52 these quartzite and slate inliers were described as of basal Upper Huronian age. The granite in T. 46 N., R. 24 W., and the small area of Middle Huronian sediments in T. 46 N., R. 26 W., are taken from an unpublished map by L. P. Barrett.

Mapping of the Marquette range is based on plate 17 in Monograph 52, as modified in the central and western portions by the work of Swanson[12] and Zinn.[13] The extreme western portion, showing the extension of the several bands of iron-formation some 6 miles west of Lake Michigamme, is taken from the Michigan State geologic map of 1916, already cited. The principal changes from Monograph 52 include the mapping of iron-formation at two separate horizons within the Upper Huronian (Greenwood and Bijiki), together with a much more accurate limitation of the distribution of the Negaunee iron-formation, Clarksburg volcanics, and basic intrusives within that area. In Monograph 52 the possibility of there being iron-bearing rocks at two separate horizons within the Upper Huronian was distinctly recognized, but the work of Swanson and Zinn has definitely proved this fact. The lower iron-formation (Greenwood) lies

[10] Allen, R. C., Correlation and structure of the pre-Cambrian formations of the Gwinn iron-bearing district of Michigan: Michigan Geol. and Biol. Survey Pub. 18, pp. 141–152, map, 1915.

[11] Allen, R. C., and Barrett, L. P., Evidence of the Middle-Upper Huronian unconformity in the quartzite hills at Little Lake, Mich.: Michigan Geol. and Biol. Survey Pub. 18, pp. 153–159, 1915.

[12] Swanson, C. O., Report on the portion of the Marquette range covered by the Michigan Geological Survey in 1929 (unpublished map and mimeographed text).

[13] Zinn, Justin, Report on the portion of the Marquette range between Humboldt and Lake Michigamme covered by the Michigan Geological Survey in 1930 (unpublished map and mimeographed text).

between the Goodrich quartzite and the Clarksburg volcanics, and the upper iron-formation member (Bijiki) lies within the Michigamme slate and above the Clarksburg. Several small portions of the granite fringing the trough on the south are now shown as of post-Huronian (Killarney) age.

Drilling and mining in the Negaunee Basin, the great productive area of the Marquette district, have disclosed much new and interesting information, but the changes in the surface distribution are too small to appear on the scale of the new map. The iron-formation in this basin is now known to have a stratigraphic thickness of more than 1,500 feet, which is over twice that previously known. Also the great masses of diabase intrusive, so abundant in this basin, are now known to consist partly of sills or laccoliths, which were intruded near the top of the iron-formation and which flattened against the massive overlying Goodrich quartzite. Other considerable masses are now recognized as dislocated parts of a great continuous sill that invaded the iron-formation and originally extended through much of the area of the Negaunee Basin.

Revision of the mapping in Baraga County, the Dead River Basin, and the Keewatin belt to the north of the Dead River Basin, comprising the area north and northwest of the Marquette district, is based on an unpublished map by L. P. Barrett. It shows previously unknown fringes of Middle Huronian sediments and iron-formation along the edge of the Laurentian granite, inliers of Middle Huronian sediments and iron-formation within the Upper Huronian slates, and one large and one very small basin of Upper and Middle Huronian sediments within the old Keewatin belt north of the Dead River Basin.

The mapping of Keweenaw Point and vicinity remains practically unchanged, Lane's map [14] having been followed very closely over most of the area. The recent work by Butler and Burbank [15] has added a great quantity of information concerning the district, but in general the changes are too detailed and local to show on a regional map. The sediments lying to the southeast of the middle Keweenawan flows on Keweenaw Point (the †Eastern [16] or Jacobsville sandstone), together with the Bayfield group of sandstones outcropping on Bayfield Peninsula, in northern Wisconsin, are shown on the new map as of upper Keweenawan age, the classification being Paleozoic on the old map. This matter is discussed on page 12.

[14] Lane, A. C., The Keweenaw series of Michigan: Michigan Geol. and Biol. Survey Pub. 6, Geol. ser. 4, pl. 8, 1911.

[15] Butler, B. S., Burbank, W. S., and collaborators, The copper deposits of Michigan: U.S. Geol. Survey Prof. Paper 144, 1929.

[16] A dagger (†) preceding a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the U. S. Geological Survey. Quotation marks, formerly used to indicate abandoned or rejected names, are now used only in the ordinary sense.

An undisputed upper Keweenawan age for the Barron quartzite area to the southwest of the Gogebic iron range, favored by Hotchkiss,[17] has been questioned by H. R. Aldrich in oral communications with the authors. Aldrich favors a Huronian age for this formation, as it was shown on the old map. The new map shows it as doubtful upper Keweenawan.

Geologic boundaries in the Wausau, Stevens Point, and Marshfield area are taken from Weidman's work,[18] as modified by more recent unpublished reports of the Wisconsin Geological and Natural History Survey. Changes in age classification of these areas of pre-Cambrian igneous and sedimentary rocks are discussed on pages 11 and 19.

MINNESOTA

In general, the boundaries in Minnesota are taken from the new geologic map of the State (1932), but with modifications based on other detailed mapping. Changes from the old mapping in northern St. Louis and Koochiching Counties include (1) the westward extension of large areas of Keewatin greenstones and Knife Lake slate for some 50 miles, previously mapped largely as "formation not determined"; (2) the southward extension for a few miles of the area of Knife Lake slate lying to the south of Vermilion Lake (previously mapped as Giants Range granite), and slight changes in the outlines of a few small greenstone belts within this slate area; (3) the mapping of practically all the schist series bordering the Vermilion batholith on the south (except for the extreme southeastern portion) as a member of the Knife Lake series instead of the Ely greenstone as previously shown; and (4) the assignment of the Vermilion batholithic mass of granite containing numerous roof pendants of Knife Lake slate to an Algoman age, rather than Laurentian as described before. Critical evidence in favor of these new interpretations has been set forth at length by Grout.[19] Difficulty was encountered in drawing the contact between the Knife Lake series, as mapped by the Minnesota Geological Survey between Lake of the Woods and Rainy Lake, and the belt of Keewatin greenstones shown north of the Canadian boundary on the map in Monograph 52 and on the new Canadian maps. Decision was finally made to portray this discrepancy by omitting the formation boundary line in this area, allowing each color pattern to continue to the international boundary. The distribution of the Soudan iron-formation in the Vermilion district is taken from

[17] Hotchkiss, W. O., Mineral-land classification showing indications of iron-formation: Wisconsin Geol. and Nat. Hist. Survey Bull. 44, pp. 43–45, 1915.

[18] Weidman, Samuel, Geology of north-central Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 16, pls. 1 and 2, 1907.

[19] Grout, F. F., The geology and magnetite deposits of northern St. Louis County, Minn.: Minnesota Geol. Survey Bull. 21, pp. 9–52, 1926.

the old district map, plate 6 of Monograph 52, rather than from the new State map, because of the greater detail shown on the former. The age of the Knife Lake series is discussed on pages 16–18.

Aside from changes in correlation in the Mesabi and Gunflint districts, described on page 15, there are only minor modifications in the boundaries shown in this area. The detail of the Mesabi is taken from two large-scale maps of the range, one by Grout and Broderick [20] and the other by Gruner.[21] The main change from the old map consists of a continuation of the Virginia slate in a narrow strip between the Duluth gabbro and the Biwabik iron-formation as far north as the Biwabik is mapped without break—namely, to Birch Lake. Previously the slates had been mapped only about 6 miles northeast of the little town of Mesaba. The post-Upper Huronian age of the Embarrass granite,[22] fringing on the north the extreme eastern part of the range, is now considered doubtful. Grout and Broderick [23] discarded this interpretation, favoring an Algoman age for the entire Giants Range batholith; but a recent very detailed study by Richarz [24] has favored the earlier explanation. The locations of small Cretaceous outcrops plastering the Mesabi in a few places are taken from the new State geologic map. The detail of the Gunflint district, showing only minor changes from the old mapping, comes from the work of Broderick.[25]

It was decided to show, in those areas where detailed work has been done, the distribution of the Logan sills, which intrude the Upper Huronian (Rove) slate of northeastern Minnesota and adjoining parts of Canada. These narrow " stringers " of slate and basic intrusives shown on the map in northeastern Minnesota are taken from the recent work of Grout and Schwartz.[26] On the regional map in Monograph 52 these were shown undifferentiated under one symbol.

Recent work on the Keweenawan extrusives and intrusives from Duluth north and northeast to the Canadian border has changed the mapping of the boundaries of these formations considerably in places. The major changes may be summed up as (1) a considerable lessening of the width of the southwestern portion of the long tongue of acidic intrusives (red-rock phase of the Duluth gabbro) lying between T. 55 N., R. 11 W., and T. 62 N., R. 3 W.; (2) the mapping of the rather large area of previously described massive acidic intrusives, essentially in T. 63 N., Rs. 1 and 2 E., 1, 2, and 3 W., as interfingering sheets of acidic and basic intrusives, with basic extrusives; (3) the elimination of the large area of acidic intrusives just north of Grand Marais by mapping it as basic extrusives; and (4) the platting of a long, narrow tongue of Duluth gabbro which continues all the way to the shores of Lake Superior, some 6 miles south of the Canadian border, previously shown as basic extrusives. These revisions are made from the new State geologic map.

The northwestern boundary of the Virginia slate area southwestward from the Mesabi range to the edge of the region mapped is now shown by a change in color pattern without any black formation boundary line, differing in location from that on the recent geologic map of Minnesota in that it bulges around two areas of Algoman granite in the northern part. This is done in order (*a*) to emphasize the possibility and even probability that the slate area and perhaps the Biwabik iron-formation of the Mesabi may curve around considerably to the west into the area previously mapped as " formation not determined " and (*b*) to correct the apparent misconception, which has arisen from the old map, that this line of Algoman intrusions marks the western boundary of the basin in which the Middle and Upper Huronian sediments were deposited.

The north range of the Cuyuna district shows considerable new detail which is taken from a map compiled by Pickands, Mather & Co. Disagreement that has arisen over correlation in this district is discussed on page 15. Mapping of the iron-formation and magnetic lines in the south range of the Cuyuna district is taken from an unpublished map showing magnetic areas and lines of maximum intensity compiled by Carl Zapffe, together with the old district map (Monograph 52, pl. 15), which showed the distribution of magnetic lines southwestward to the Mississippi River.

The distribution of the Keweenawan basic intrusives between Carlton and the Cuyuna district comes from the new State map and plate 14, in Monograph 52. The mapping of acidic intrusives of Killarney age southeast of the Cuyuna district is taken mainly from the old map in Monograph 52 as modified by an unpublished map by C. A. Cheney, Jr. On the new Minnesota map these acidic intrusives, together with the metamorphosed slates between, are all grouped together into one area labeled " granites, gneisses, schists, etc., of post-Archean age." It is thought best, however, to follow the old scheme, inasmuch as the post-

[20] Grout, F. F., and Broderick, T. M., The magnetite deposits of the eastern Mesabi range, Minnesota: Minnesota Geol. Survey Bull. 17, pl. 1, 1919.

[21] Gruner, J. W., Contributions to the geology of the Mesabi range: Minnesota Geol. Survey Bull. 19, pl. 1, 1924.

[22] U.S. Geol. Survey Mon. 43, pp. 186–188, 1903; Mon. 52, p. 178, 1911.

[23] Grout, F. F., and Broderick, T. M., op. cit., pp. 5, 7, 49.

[24] Richarz, Stephen, The metamorphic iron formation of the eastern Mesabi range, Minnesota, and its relation to the Embarrass granite: Jour. Geology, vol. 38, pp. 600–618, 1930.

[25] Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Econ. Geology, vol. 15, pp. 422–452, 1920.

[26] Grout, F. F., and Schwartz, G. M., The geology of the Rove formation and associated intrusives in northeastern Minnesota: Minnesota Geol. Survey Bull. 24, pl. 20, 1933.

Upper Huronian age of these intrusives is generally accepted.

The detail in the southwestern part of the map, showing the distribution of the Cretaceous rocks, the Sioux quartzite, and several areas of undifferentiated pre-Cambrian rocks, is also taken from the new State geologic map.

The age of the belt of sandstones extending southwestward from Duluth between the Virginia slate and the middle Keweenawan flows is indicated as upper Keweenawan after the work of Thwaites [27] in Wisconsin, who found no unconformity between the Bayfield group and the underlying Oronto group, which is definitely upper Keweenawan. Both of these groups extend from Wisconsin into this belt in Minnesota. The boundaries of the formation are taken from the new Minnesota map and are necessarily quite hypothetical over much of the district, because of the heavy drift cover. An account of the controversy regarding the age of these questionable upper Keweenawan red clastic rocks is given on page 12.

CANADA

Revision of the mapping in Canada is based on the following maps, but the correlations for some of them have been changed along general lines indicated on pages 10–20.

Kenora sheet, Ontario, by T. L. Tanton: Canada Geol. Survey Pub. 2270, map 266A, 1933.

Rainy Lake, Ontario, by A. C. Lawson: Canada Geol. Survey Mem. 40, map 98A, 1913.

Iron and copper deposits near Mine Centre, by A. L. Parsons: Ontario Bur. Mines Ann. Rept., vol. 27, pt. 1, 1918.

Sapawe Lake area, by J. E. Hawley: Ontario Dept. Mines Ann. Rept., vol. 36, pt. 6, map 38e, 1929.

Geological sketch map of Steeprock Lake and Sapawe Lake areas, by J. E. Hawley: Ontario Dept. Mines Ann. Rept., vol. 38, pt. 6, p. 14, 1929.

Atikokan iron-bearing district: Canada Mines Branch Pub. 217, maps 340A, 341A, 342A, 343A, 1917.

Eastern part of Matawin iron range, Thunder Bay district, by T. L. Tanton: Canada Geol. Survey Pub. 2069, 1925; Summary Rept. for 1924, pt. C, 1926.

Fort William and Port Arthur sheet, by T. L. Tanton: Canada Geol. Survey Pub. 2141, map 198A, 1928.

Thunder Bay silver area, by T. L. Tanton: Canada Geol. Survey Pub. 2282, map 276A, 1931.

Silver Mountain area, by N. L. Bowen: Ontario Bur. Mines Ann. Rept., vol. 20, pt. 1, 1911.

Maps by J. E. Gill in report on Gunflint iron-bearing formation: Canada Geol. Survey Summary Rept. for 1924, pt. C, 1926.

Animikie iron range, Thunder Bay district, Ontario, by M. A. Hanna Co. (unpublished).

Lead and zinc bearing veins, Dorion Township and vicinity, Thunder Bay district, by T. L. Tanton: Canada Geol. Survey Pub. 1811; Summary Rept. for 1919, pt. E, 1920.

Townships of Dorion and McTavish, district of Thunder Bay, by J. E. Hawley: Ontario Dept. Mines Ann. Rept., vol. 38, pt. 6, map 38f, 1929.

Schreiber-Duck Lake area, by P. E. Hopkins: Ontario Dept. Mines Ann. Rept., vol. 30, pt. 4, map 30a, 1921.

Slate Islands, Lake Superior, by A. L. Parsons: Ontario Bur. Mines Ann. Rept., vol. 27, pt. 1, 1918.

Heron Bay area, by J. E. Thomson: Ontario Dept. Mines Ann. Rept., vol. 40, pt. 2, map 40d, 1931.

Heron Bay-White Lake area, by J. E. Thomson: Ontario Dept. Mines Ann. Rept., vol. 41, pt. 6, map 41j, 1932.

Lake Huron sheet: Canada Geol. Survey Pub. 1553, map 155A, 1929.

Michipicoten area, by W. H. Collins: Canada Geol. Survey Pub. 1972 (Mem. 147, pt. 1), 1925.

Missinaibi area, by E. Thomson: Canada Geol. Survey Pub. 2050 (Mem. 147, pt. 2), 1925.

Oba area, district of Algoma, by J. E. Maynard: Ontario Dept. Mines Ann. Rept., vol. 38, pt. 6, map 38c, 1929.

Mississagi Reserve and Goulais River iron ranges, by E. S. Moore: Ontario Dept. Mines Ann. Rept., vol. 34, pt. 4, map 34d, 1925.

Batchawana area, by E. S. Moore: Ontario Dept. Mines Ann. Rept., vol. 35, pt. 2, map 35b, 1926.

Sault Ste. Marie area, by R. G. McConnell: Ontario Dept. Mines Ann. Rept., vol. 35, pt. 2, map 35a, 1926.

GENERAL SUCCESSION

The pre-Cambrian succession now known includes about 40,000 feet of sediments, at least four major unconformities, three periods of extensive plutonic intrusion, and three periods of mountain building. The record fades out below in a basement complex of igneous and sedimentary rocks and their metamorphic equivalents. Special studies of this complex have from time to time resulted in the separation and better definition of geologic units, and this breaking up is likely to go further, opening new vistas in pre-Cambrian history. The lowermost rocks yet known are like those of later times, except for metamorphism; there is no essential departure from uniformitarianism; and there is nothing to indicate that pre-Cambrian sedimentation may not have begun much earlier than is indicated by the now established record.

The rocks are described below, beginning with those at the top.

CRETACEOUS, ORDOVICIAN, AND CAMBRIAN ROCKS

Soft Cretaceous shales cover the bedrock in the southwestern part of the mapped area, and little-disturbed fossiliferous Ordovician and Upper Cambrian sedimentary rocks mantle the southern periphery of the region and exist in isolated patches within the region. These rocks will not be described in detail, as they are not involved in the problems treated in this paper.

KEWEENAWAN SERIES

Next below the Cambrian, where it is present, is the nonfossiliferous Keweenawan series, consisting of an immense mass, possibly 5 miles thick, of sandstone, with intercalated shales and conglomerates, containing in its lower part large quantities of extrusive lavas and intrusive laccoliths and sills. In degree of

[27] Thwaites, F. T., Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geol. and Nat. Hist. Survey Bull. 25, 1912.

metamorphism its sediments are more like the Cambrian than the underlying series. They have characteristic reddish, yellowish, and purplish colors and exhibit various evidences that they were essentially continental deposits formed under semiarid conditions. Although the lower part of the Keweenawan is tilted in marked unconformity with the Cambrian, its upper part lies nearly if not quite parallel to the Cambrian. Obviously it was deposited mainly in an independent basin before the incursion of the Upper Cambrian sea. Although the Keweenawan is pre-Cambrian in the sense of preceding the Upper Cambrian transgression, having structural and igneous affiliations with the pre-Cambrian, and being nonfossiliferous, it may in part be Cambrian in the sense that its deposition probably continued into the time when Middle and Lower Cambrian sediments were being laid down in approaching Cambrian seas.

On the present map considerable areas of sandstone east and west of Keweenaw Point, formerly mapped as Cambrian, are now mapped as Keweenawan, for reasons stated on page 12. Also the area of granitic intrusives assigned to the Keweenawan has been considerably extended.

HURONIAN SERIES

Unconformably below the Keweenawan are rocks that exhibit an abrupt change in metamorphic character. They are hard and crystalline, locally schistose, have prevailingly gray and green colors, and conspicuously lack the reddish colors of the Keweenawan. They include vitreous quartzite, dolomite, slate, and iron-formation. On the whole they carry evidence of marine deposition, though deposits of shallow water and deltas are also present. Three groups are recognized.

The Upper Huronian group, which is also the thickest and most extensive, consists largely of slate (Virginia, Rove, Tyler (†Copps), and Michigamme (†Hanbury) formations) and occupies the largest area of all the pre-Cambrian sediments of the Lake Superior region. This group carries evidence indicating deltaic deposition. Near its base it locally contains intercalated iron-formation, which contributes a minor part of the iron ores of Lake Superior.

The Upper Huronian contains basic sills and flows of Keweenawan age. South of the Cuyuna district of Minnesota and in northern Wisconsin and Michigan it has also been intruded, with the usual metamorphic results, by plutonic granites, assigned to the Keweenawan epoch. These granites are correlated with the Killarney granite of the north shore of Lake Huron. The principal folding of the Upper Huronian, as well as of the Middle and Lower Huronian, dates from this period.

The Middle Huronian includes the great iron-formation of the Lake Superior region (Biwabik, Ironwood, Negaunee, Vulcan), represented in the Mesabi, Gogebic, Marquette, and Menominee districts and containing by far the greater part of the commercial ore. Conformably below the iron-formation are quartzite and slate (Pokegama, Palms, Ajibik), usually less than 200 feet in thickness but thicker in the Marquette district, which represent the beginning of the period during which this unique iron-formation was deposited.

In part of Michigan a definite unconformity, though with only slight angular discordance, separates the Middle Huronian from the Upper Huronian; but in Minnesota and Ontario this unconformity has not yet been proved, a fact which much complicates any statement of correlation.

The Upper and Middle Huronian groups are widespread over the region, but the unquestioned Lower Huronian rocks are more limited in their distribution. They occur in Michigan and Wisconsin as a rising succession of quartzite (Mesnard, Sturgeon, Sunday), dolomite showing algal textures (Kona, Randville, Bad River), and slate (Wewe), all well assorted and of marine type. These beds lie with definite unconformity, but only slight angular discordance, beneath the overlying sediments. Their correlative east of Lake Superior is supposed to be the Bruce series of Canada, likewise characterized by dolomite with fragmental sediments above and below it.

The term "Knife Lake series" is here adopted for the series in the Vermilion district called "Lower-Middle Huronian" in Monograph 52. Its dominant and characteristic member is composed of banded siliceous slates and graywackes, previously called the "Knife Lake slate." Intercalated with it are many beds of conglomerate, locally named the "Stuntz conglomerate" and the "Ogishke conglomerate", a thin iron-formation called the "Agawa formation", basaltic flows and tuffs, and various intrusives. The series has long been known to students of Lake Superior geology by the name of its dominant member, the "Knife Lake slate." Because of doubt as to its correlation with the Huronian, discussed on succeeding pages, it seems desirable to give it the name in common usage, "Knife Lake", which will identify it geographically and lithologically. It may ultimately be found to be equivalent to the Lower Huronian, but discussion of the problem is much clarified by designating the series by a local name. The Knife Lake sediments seem to be of continental origin. They rest with a well-marked unconformity on Laurentian and Keewatin rocks and underlie with conspicuous angular discordance the Middle Huronian group. They are closely folded, metamorphosed, and intruded by granites of Algoman age. Their position in the stratigraphic sequence corresponds to that of the Lower

Huronian of the south shore, but the contrast in lithology, metamorphism, and folding has raised a question whether they should be classed as Lower Huronian or as an independent pre-Huronian series between the true Huronian and the basement complex. In Monograph 52 these rocks were interpreted as the continental equivalent of the marine Lower Huronian and Middle Huronian sediments of Michigan and Wisconsin, their difference in folding and metamorphism being ascribed to the localization of Algoman granites north of Lake Superior. On the other hand, similar sediments on the Ontario shore of Lake Superior have been classified by Canadian geologists as pre-Huronian. On the present map they are called " Knife Lake series." The alternative interpretations of age are discussed on pages 16–18.

The Timiskaming and Doré series of the Michipicoten and adjacent districts in Canada, northeast of Lake Superior, have similarities of composition and structure to the Knife Lake series of Minnesota and present much the same problem of correlation with the known Huronian series to the south.

BASEMENT COMPLEX (KEEWATIN AND LAURENTIAN SERIES)

Unconformably beneath all the unquestioned Huronian sediments, as well as the Knife Lake series and its correlatives, is a basement complex (Archean of previous reports of the United States Geological Survey), which has much the same group characteristics in all parts of the regions. The oldest rocks of this complex are a great series of basaltic flows (Keewatin) intercalated with thin slate beds and with beds of iron-formation, which are productive only in the Vermilion district of Minnesota. These Keewatin rocks are intruded by granites (Laurentian), of which several types have been discriminated. It is possible even that some of the granites are really post-Laurentian in isolated parts of areas which have been assigned as a whole to the Laurentian.

In the Rainy Lake district of Ontario there is apparently a larger mass of slates within or beneath the Keewatin flows than in other parts of the region. These have been given the local name of " Coutchiching." Some of the supposed Coutchiching of Ontario has been found to be equivalent to the Knife Lake series, which is above the Keewatin, and there is still dispute on structural grounds as to the volume of slates really represented by the Coutchiching.

CORRELATION

Although the main features of the correlation here presented are believed to be based on conclusive evidence, it must be remembered that any correlation of pre-Cambrian areas is limited by lack of fossils and by great variations in metamorphic and structural conditions and in igneous associations. It is handicapped also by the lack of continuity of surface outcrops, due to the covering of glacial drift, Paleozoic sediments, and many lakes, including Lake Superior itself. About the best that can be done in the way of correlation is to call attention to similarities of lithologic types, to similarities in sequence, and to similarities of relations to igneous events. To a person familiar with the field, terms like "Keewatin", " Huronian ", and " Keweenawan " designate fairly definite types of materials and conditions, as well as general positions in the stratigraphic sequence, but in the present state of knowledge such terms cannot be construed as fixing precise equivalence in age.

The several great periods of orogeny and plutonic intrusion have not affected all of the region equally. The first great period of folding and intrusion was the Laurentian, which seems to have been widespread but whose effects have been so obscured by subsequent intrusions that it is conclusively known in only a few localities. The next period, that of the Giants Range or Algoman intrusion and folding, is registered only in the Knife Lake (and equivalent) series north and northeast of the lake, without any known expression to the south. The third period (post-Huronian) affected the Upper Huronian and Keweenawan south and southwest of Lake Superior but left relatively undisturbed the Upper Huronian and Keweenawan in northern Minnesota. The Lake Superior syncline dates mainly from this period. Thus it is that unconformities, when traced through the region, take on quite different structural aspects, and that ancient-looking metamorphic rocks in one locality may be really younger than less metamorphosed rocks elsewhere. Much of the confusion in regard to correlation has arisen from failure to comprehend these facts and particularly from failure to remember that there were three definitely proved periods of plutonic intrusion and orogeny rather than two.

Enough facts are now known to give a student of Lake Superior geology a clear picture of the succession of events for each district, but any attempt to compress these facts into a simple classification applicable to the whole region would involve unproved assumptions or overemphasis on facts of one or another district, at the expense of distortion of perspective. The unconformity above the basement complex has been regarded by the United States Geological Survey as the principal break in the pre-Cambrian and as the dividing line between Archean and Algonkian, as these terms have been used. In Michigan and Wisconsin it is much the most conspicuous unconformity. In Minnesota and Ontario, however, the unconformity, though definitely proved, is overshadowed by the structural discordance at the top of the Knife Lake series. Some of the geologists approaching the region from the north side of Lake Superior have applied the name † "Eparchean interval" to this later unconformity, classifying everything below, including the Knife Lake sediments, as "Archean." This difference of approach, which is reflected in various classifications, tends to obscure the fundamental agreement upon the succession in individual districts.

As the correlation in Monograph 52 of the United States Geological Survey is perhaps the most widely known, this may be used as a basis for indicating changes introduced into the present classification. The term "Upper Huronian (Animikie)" of Monograph 52 is now restricted to the slates of this series in Minnesota and Canada and the Tyler slate (†Copps) of the Gogebic district. It includes as before the Upper Huronian slate of the Marquette and Menominee districts. The immediately underlying iron formations (Biwabik, Ironwood, Negaunee, Vulcan) are now called "Middle Huronian." The Biwabik, Ironwood, and Vulcan were formerly called "Upper Huronian." This change in classification arises mainly from the discovery of the unconformable relation of the iron formations with the overlying slates in the Gogebic and Menominee districts, but it takes into account other considerations arising from studies of recent years. (See pp. 13–15.) The next underlying group is the unquestioned Lower Huronian of Michigan and Wisconsin, unchanged from the previous classification. The Knife Lake series, formerly called "Lower-Middle Huronian", is now mapped separately. The basement complex (Laurentian and Keewatin) of the United States Geological Survey remains the same.

The classification used in this summary is given in the accompanying correlation table.

The terms "Archean" and "Algonkian" are retained, with slightly modified significance to indicate types of rocks and not time. "Algonkian" is used to designate the dominantly sedimentary series, in which stratigraphic methods are possible, between the Cambrian and the basement complex. The term "Archean" is used for the basement complex consisting dominantly of igneous rocks (though containing sediments) in which ordinary stratigraphic methods are not applicable.[28] Such a dual division for most of the Lake Superior region is a reality making desirable the use of some such general descriptive terms. Archean and Algonkian rock types of one region may not be the time equivalents of Archean and Algonkian types in a distant region. There are many other regions in the world where rocks are known to be broadly of Archean or Algonkian types, but where time equivalence cannot be proved. To eliminate the terms entirely would make it impossible to indicate similarities in type without much circumlocution.

[28] Leith, C. K., The pre-Cambrian: Geol. Soc. America Proc. for 1933, pp. 151–179, 1934.

KEWEENAWAN SERIES

Knowledge of the general sequence and structure of the thick series of sediments and igneous rocks included under the term "Keweenawan" shows very little change since the publication of Monograph 52. Normally the series consists of (1) a lower division of thin conglomerates, quartzites, and arkoses on the south shore and a thicker deposit of reddish and white clastic rocks with considerable dolomitic and calcareous material in the vicinity of Black and Nipigon Bays on the north shore; (2) a copper-bearing middle division consisting dominantly of basic lava flows, but with interbedded felsite conglomerates more and more common near the top, into which were intruded large masses of gabbro and related plutonic rocks and minor amounts of granite; and (3) an upper division of reddish clastic sandstone, including shales and conglomerates. The intrusive rocks of the second division may be, in part at least, as late as the rocks of the third division.

Detailed descriptions of the type, distribution, and structure of the Keweenawan rocks have been augmented in only minor amount in the last 20 years, with the exception of the following important contributions:

1. With respect to the source of the lavas, which was uncertain at the time of publication of Monograph 52, there now seems to be ample evidence that they were derived from extensive fissures lying near the present center of Lake Superior. From a detailed study of structural features found in the middle Keweenawan rocks on the south shore of Lake Superior, such as bent-pipe amygdules, fanning of the dips (interpreted as indicating flows thinning away from their source), and squeezing up of underlying mud deposits in front of the flows, Hotchkiss[29] has built up the theory that the main center of outflow lay near the present center of the lake and was related to a deep-seated batholithic intrusion. At that time the land must have sloped southward where the southern part of Lake Superior now lies. Cross-bedding of sands interbedded with the flows also points toward a southward slope for this old land surface. As thousands of cubic miles of molten material was drawn through extensive fissures to the north, flowing southward (or up the present dip), the roof gradually collapsed—the tremendous weight of these extruded materials undoubtedly having been an important factor in the break-down—forming eventually the structural basin now occupied by the lake. Butler and Bur-

[29] Hotchkiss, W. O., The Lake Superior geosyncline: Geol. Soc. America Bull., vol. 34, pp. 669–678, 1923.

Correlation of formations in Lake Superior region

System	Series		South shore									Northwest and east shores							
			Keweenaw Point	Gogebic	Marquette	Menominee	Florence	Crystal Falls	Iron River	Felch Mountain	Wausau	Cuyuna	Mesabi	Vermilion	Rainy Lake	Matawin	Thunder Bay	Michipicoten	Soo and Batchawana
	Post-Keweenawan rocks		Unconformity		Upper Cambrian sandstone	Upper Cambrian sandstone		Upper Cambrian sandstone	Ordovician limestone, sandstone, and conglomerate	Upper Cambrian sandstone	Upper Cambrian sandstone	Cretaceous conglomerate	Cretaceous conglomerate and shale						Upper Cambrian sandstone
Pre-Cambrian rocks; Algonkian type	Killarney granite*		Acidic intrusives	Presque Isle granite	Acidic intrusives	Acidic intrusives	Acidic intrusives	Acidic intrusives		Basic and acidic intrusives		Acidic intrusives	Embarrass granite *						Acidic intrusives
Pre-Cambrian rocks; Algonkian type	Keweenawan		Basic intrusives Sandstones, shales, and conglomerates Acidic flows Basic flows	Basic intrusives Sandstones, shales, and conglomerates Acidic flows Basic flows Quartzite and conglomerate Unconformity	Basic intrusives							Basic intrusives	Duluth gabbro	Duluth gabbro	Basic dikes		Logan sills Osler basic flows Sibley clastics and limestone	Diabase dikes Basic flows	Diabase dikes Basic flows
Pre-Cambrian rocks; Algonkian type	Huronian	Upper		Tyler slate	Michigamme slate: Upper slates; Bijiki iron-formation member; Lower slates Clarksburg volcanics Greenwood iron-formation Goodrich quartzite	Michigamme slate (including iron-formation) South belt of Quinnesec greenstone *	Michigamme slate: Upper slates; Iron River iron-formation member; Lower slates South belt of Quinnesec greenstone * Breakwater quartzite *	Michigamme slate: Upper slates; Iron River iron-formation member; Lower slates Paint River belt of greenstone *	Michigamme slate: Upper slates; Iron River iron-formation member; Lower slates Paint River * and Pentoga belts of greenstone *		"Upper sedimentary group." Conglomerates and quartzites	Virginia slate: Upper slates; Deerwood iron-formation member; Lower slates	Virginia slate	Rove slate		Slates	Slates		Cobalt series (late Huronian)
Pre-Cambrian rocks; Algonkian type	Huronian	Middle		Unconformity Basic intrusives and extrusives Ironwood iron-formation Palms quartzite	Negaunee iron-formation Siamo slate Ajibik quartzite	Vulcan iron-formation Greenstones (Lake Antoine region)*	Iron-formation (Little Commonwealth mine area) Greenstones near Spread Eagle Lake *	Negaunee iron-formation Ajibik quartzite Hemlock greenstones		Vulcan iron-formation Felch schist	Acidic intrusives Basic intrusives (Correlation doubtful)		? (unconformity) Biwabik iron-formation Pokegama quartzite	? (unconformity) Gunflint iron-formation			? (unconformity) Iron-formation		
Pre-Cambrian rocks; Algonkian type	Huronian	Lower		Unconformity Bad River dolomite Sunday quartzite	Wewe slate Kona dolomite Mesnard quartzite	Randville dolomite Sturgeon quartzite	Saunders formation (dolomites and quartzites) Quartzite near Keyes Lake*	Randville dolomite Sturgeon quartzite	Saunders formation (dolomites and quartzites)	Randville dolomite Sturgeon quartzite	"Lower sedimentary group." Quartzites, slates, and graywackes								Bruce series, including Soo series (early Huronian)
Pre-Cambrian rocks; Algonkian type	Algoman granite												Unconformity Giants Range granite	Vermilion granite	Algoman granite	Algoman granite	Algoman granite	Algoman granite	
Pre-Cambrian rocks; Algonkian type	Knife Lake (may be Lower Huronian)			Unconformity									Knife Lake slate	Knife Lake slate: Slate; Agawa iron-formation member; Ogishke conglomerate member	Knife Lake slate, including most of schist series mapped by Lawson as Coutchiching	Slaty iron-formation Windigokan(?) conglomerate and slate. Also Tanton's Coutchiching		Doré conglomerate	
Pre-Cambrian rocks; Archean type	Laurentian granite			Granite and granitoid gneiss	Granite, syenite, peridotite Palmer gneiss	Granites and gneisses		Granites and gneisses		Granites and gneisses	Granite gneisses			Granite	Granites and gneisses			Granites and gneisses	Granites and gneisses(?)
Pre-Cambrian rocks; Archean type	Keewatin			Greenstones and green schists	Kitchi schist and Mona schist						Schists (?)		Greenstones, schists, and porphyries	Soudan iron-formation Ely greenstone	Iron-formation Green schists and tuffs Coutchiching schists (?)	Iron-formation Greenstones and green schists		Helen iron-formation Greenstones and tuffs	Iron-formation Greenstones and green schists

NOTE.—The asterisk (*) after a geologic name indicates doubt as to its stratigraphic position.

bank[30] cite further evidence found in Michigan in support of this theory. Observations made by Tanton[31] on the north shore of Lake Superior indicate that the flows in that region were derived from the south, thus corroborating further the theory just outlined. An additional detail has been presented by Aldrich,[32] who suggests that differential tilting, shown by decrease in the present northwesterly dips from 80° near the Montreal River to 30° some 30 miles to the west, may indicate that the main source of the extrusives (and hence the location of the most extensive collapse) was north or northwest of the vicinity of the Montreal River.

Hotchkiss regards the Keweenawan extrusives as the culmination of a long, slow rising of a batholithic magma, beginning in Huronian time. He suggests that the early contributions to the surface were basic lavas associated with silica-iron solutions which may have been the source of the Huronian iron-formation (see p. 21) and that the Keweenawan extrusives carried the copper.

2. Regarding the structure of the Keweenawan rocks, considerable new detail has been added by Butler and Burbank[33] to the knowledge of the faults and minor folds on Keweenaw Point. In addition to giving many new facts describing the nature of the main Keweenaw thrust fault, they present much fresh information regarding the many strike and bedding faults which in earlier years had passed largely unnoticed. In northern Wisconsin Aldrich[34] has contributed many new ideas with respect to the structure of both the Huronian rocks and the Keweenawan lying north of them, in the Gogebic district. He concludes that torsional stresses arising from the differential tilting described above caused the many thrust and cross faults he has shown on his map of that region, some of which are reproduced on the present map.

3. Work by the Wisconsin Geological and Natural History Survey[35] has shown that a rather large mass of granite occurring just west and northwest of Mellen intrudes middle Keweenawan gabbro, anorthosite, and basaltic flows. If this granitic mass can be correlated with other young pre-Cambrian granites in the Lake Superior district—and there seems no reason for not tying them all into one general period of igneous activity—the granites of Killarney age must then be not earlier than late middle Keweenawan, with the possibility that they may even intrude parts of the upper Keweenawan sediments. This younger age is suggested by Butler and Burbank,[36] mainly on the basis of the intrusives which bow up the upper Keweenawan sediments into a dome in the vicinity of the Porcupine Mountains. They conclude, however, that "there is no basis for determining the age of the intrusive rocks more definitely than as Keweenawan or post-Keweenawan."

In the Wausau, Stevens Point, and Marshfield area of north-central Wisconsin the basic and acidic rocks that intrude an older sedimentary series are now shown as of doubtful Killarney age. They were previously mapped as Middle and Lower Huronian respectively, and the older sedimentary series was regarded as of doubtful Lower Huronian age. The younger sedimentary series, previously mapped as of doubtful Middle Huronian age, is now shown as of doubtful upper Keweenawan age. Great difficulty arises in trying to fix the age of these intrusives, because of the uncertainty in correlating the sedimentary series stratigraphically above and below them; but the fact that here, as in the western Gogebic district, basic intrusives are followed by granitic intrusives of fresh aspect as compared to earlier pre-Cambrian intrusives might indicate the possible age correlation shown on the new map. The Wausau district remains, however, a very doubtful problem insofar as its correlation with better-known districts in the Lake Superior region is concerned.

4. Changes in the mapping of Keweenawan extrusives and intrusives in northeastern Minnesota, as outlined on page 6, have been summarized by Grout and Schwartz.[37] Grout's intensive study of the structure and origin of the Duluth gabbro[38] is an important contribution to the literature on that subject.

The most complete description yet given of the Logan sills and related intrusives of northeastern Minnesota has recently been presented by Grout and Schwartz,[39] who conclude that probably the sills are of middle Keweenawan age, some of them having been metamorphosed by the Duluth gabbro and hence earlier.

[30] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U.S. Geol. Survey Prof. Paper 144, p. 26, 1929.

[31] Tanton, T. L., Shore of Lake Superior between Port Arthur and Nipigon: Canada Geol. Survey Summary Rept. for 1919, pt. E, p. 3e, 1920; Fort William and Port Arthur and Thunder Cape map areas, Thunder Bay district, Ontario: Canada Geol. Survey Mem. 167, pp. 64, 86-87, 1931.

[32] Aldrich, H. R. The geology of the Gogebic iron range of Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 71, p. 111, 1929.

[33] Butler, B. S., and Burbank, W. S., op. cit., pp. 48–53.

[34] Aldrich, H. R., op. cit., pp. 113–134.

[35] Aldrich, H. R., op. cit., pp. 119–123; also unpublished notes, reports, etc., on file in the office of the Wisconsin Survey.

[36] Butler, B. S., and Burbank, W. S., op. cit., p. 47.

[37] Grout, F. F., and Schwartz, G. M., Changes in the geologic map of northeastern Minnesota [abstract]: Geol. Soc. America Bull., vol. 38, p. 115, 1927.

[38] Grout, F. F., The pegmatites of the Duluth gabbro: Econ. Geology, vol. 13, pp. 185–197, 1918; The lopolith; an igneous form exemplified by the Duluth gabbro: Am. Jour. Sci., 4th ser., vol. 46, pp. 516–522, 1918; Internal structures of igneous rocks; their significance and origin, with special reference to the Duluth gabbro: Jour. Geology, vol. 26, pp. 439–458, 1918; A type of igneous differentiation: Jour. Geology, vol. 26, pp. 626–658, 1918; Studies for students; origin of the igneous rocks of Minnesota: Jour. Geology, vol. 41, pp. 196–218, 1933.

[39] Grout, F. F., and Schwartz, G. M., The geology of the Rove formation and associated intrusives in northeastern Minnesota: Minnesota Geol. Survey Bull. 24, 1933.

5. Two large areas that were shown on the old map as of Paleozoic (Upper Cambrian) age are now shown as upper Keweenawan. They are the Jacobsville or †Eastern sandstone of the southeastern part of Keweenaw Point and the Bayfield group, occupying Bayfield Peninsula of northern Wisconsin and extending southwestward into eastern Minnesota, where it is recognized as the red clastic series and the Hinckley sandstone. This change is made on the basis of detailed work by Thwaites,[40] who, after his study of the sandstones of the Wisconsin shore of Lake Superior, concluded that "the Bayfield group of sandstones is conformable upon the recognized Upper Keweenawan sediments and is therefore a part of that series."

The Jacobsville sandstone of northern Michigan, which is classified by the Michigan Geological Survey and the United States Geological Survey as Upper Cambrian, is probably correlative with the Bayfield group. W. O. Hotchkiss, in a recent conversation with the senior author, reported the discovery of reddish sandstones of the Jacobsville type lying disconformably beneath sandstones of definite Upper Cambrian age at Grand Island and on the mainland opposite, about 35 miles east of Marquette. Thwaites [41] reports that these red clastic rocks underlie undoubted Upper Cambrian sandstones in deep wells as far south as Escanaba.

The red clastic series of eastern Minnesota, found in deep wells as far south as Iowa, has recently been described by Stauffer,[42] who ascribes a Middle Cambrian age to them on the basis of fossils found in a well boring at Wauconia. Gordon Atwater [43] and F. T. Thwaites [43] state that the formation from which the fossils were obtained is probably the Upper Cambrian Eau Claire shale, which here overlies the red clastic beds and which is not to be correlated with the red clastic outcrops at Hinckley.

The evidence available, then, indicates that there is no marked break in sedimentation between the time of igneous activity of the middle Keweenawan and the time when the uppermost Bayfield unfossiliferous sandstones (hence probably the Jacobsville (†Eastern) and Hinckley sandstones to the east and west respectively) were deposited. A marked break, as reported by Hotchkiss,[43] separated the deposition of the Jacobsville sandstone from that of the Upper Cambrian fossiliferous sandstones. However, as it is impossible to evaluate the time represented by the Grand Island break, the possibility and even probability remains that these sediments of so-called upper Keweenawan age may represent continental deposits in a closed basin during the time that marine sediments of Lower and Middle Cambrian age were being deposited in other parts of the world. Nevertheless, inasmuch as these unfossiliferous red sediments can be traced downward without major break into rocks that are definitely of pre-Cambrian type and orogeny. and as they cannot be traced upward without marked break into fossiliferous Upper Cambrian deposits, it seems best to regard them as of upper Keweenawan age.

6. With respect to the copper deposits of Keweenaw Point, the recent report by Butler and Burbank and their collaborators [44] has added a wealth of material describing the deposits, and has also presented a new hypothesis for their origin.

In Monograph 52 (p. 587) the following outline of the hypothesis of origin of the copper ores of this region was given:

> On the whole the evidence is taken to point to a probable original concentration of copper by hot solutions, largely of juvenile contribution but more or less mixed, necessarily, with meteoric waters, and a later working over of the deposits by waters dominantly of meteoric source. In any case there is a high degree of probability that the associated basic igneous rocks are the source of the copper deposits. The doubt arises only as to the manner of their derivation from these wall rocks—whether they are due to the escape of solutions of a juvenile nature before or during the crystallization of the lavas, or whether on the breaking up of the crystallized rocks by katamorphic alterations the minute portions of copper they contained were concentrated in the deposits. * * *
>
> Was the copper brought in by the extrusive rocks which are interbedded with the sediments, or was it subsequently introduced by intrusives? The evidence available is not conclusive.

The new theory presented in Professional Paper 144 is best summarized by quoting from the outline of the report,[45] as follows:

> The deposits * * * were formed by ascending potential sulphide-bearing solutions which derived their copper from an igneous source, and the reaction of these solutions with the ferric iron of the rocks resulted in the oxidation of the solutions, the reduction of the ferric iron, and the precipitation of native copper.
>
> The theory of deposition by descending waters appears untenable for several reasons. There is, in the first place, no adequate source of the copper, for although copper is present in the traps there is no evidence of its removal. It is difficult, also, to believe that gravity circulation could have been adequate to form the deposits, for the gravity circulation of solutions in the deep levels of the mines is almost nil, and many of the deposits are on the undersides of impermeable barriers. The deposits, moreover, were formed in beds rich in ferric iron and poor in ferrous iron. The ferric iron was partly removed and partly reduced to the ferrous state—a reaction which does not seem likely to occur in the presence of oxidized solutions.

[40] Thwaites, F. T., Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geol. and Nat. Hist. Survey Bull. 25, 1912.

[41] Thwaites, F. T., Well logs in the northern peninsula of Michigan showing the Cambrian section: Michigan Acad. Sci. Papers, vol. 19, pp. 413–426, 1933.

[42] Stauffer, C. R., Age of the red clastic series of Minnesota: Geol. Soc. America Bull., vol. 38, pp. 469–477, 1927. See also discussion by A. C. Lane.

[43] Personal communication.

[44] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U.S. Geol. Survey Prof. Paper 144, 1929.

[45] Idem, p. xii.

NOTE

More recent work by Atwater and Clement[1] in northwestern Wisconsin and northeastern Minnesota has established the presence of a great structural and erosional unconformity between the lowest Upper Cambrian sandstone and the uppermost Keweenawan, the Bayfield group. Evaluation of the significance of this structural and erosional break indicates that the uppermost Keweenawan of the Lake Superior region should be considered pre-Cambrian, not only in type but in reference to geologic time.

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[1] Atwater, G. I., and Clement, G. M., Relation of the pre-Cambrian and the Cambrian in the upper Mississippi Valley (unpublished).

In the ascensional hypothesis it is assumed that the copper solutions originated in the underlying Duluth gabbro and that they either entered the lode-forming layers directly where the downward extensions of these layers were in contact with the magma or passed from the magma to the places of deposition by way of fissures. Solutions thus originating must have been highly heated, in the early stages gaseous, and under great pressure, and they could therefore easily make their way along fissures and permeable layers.

The principal facts that cause the authors to favor this hypothesis are that the solutions became concentrated and deposited ore on the under sides of barriers and that they were reducing in character—they carried sulphides, and they deposited native copper in beds rich in ferric iron, which they partly reduced or removed.

Oxidation of the flow tops, described in great detail, was accomplished in part by weathering of the surfaces between outflows but mainly within the cooling molten masses by rising gases, principally steam and carbon dioxide.

NEW CORRELATION OF THE UPPER AND MIDDLE HURONIAN GROUPS

MICHIGAN AND WISCONSIN

On the map accompanying Monograph 52 the Middle Huronian, including the Negaunee iron-formation and its equivalents, was recognized only in the Marquette and Sturgeon districts. The iron-formations in the remaining districts of Michigan were all classed as Upper Huronian, with the Middle Huronian missing. On the present map the Middle Huronian has been extended to include the iron-formation of the Gogebic, Gwinn, Felch, Calumet, and Menominee districts and a part of the iron-formation in the Crystal Falls district. The Upper Huronian has been restricted to the upper slate formations of the various districts, including the iron-formation contained within the slates in the Iron River, Crystal Falls, Florence, Menominee, and Marenisco districts. The Upper Huronian, as so defined for these districts, now corresponds with the Upper Huronian of the Marquette district, where the classification has not been changed.

The reason for this change is primarily the discovery of an unconformity between the slates of these areas and the underlying iron-formation, corresponding to the long-known unconformity between the Negaunee formation and the overlying Upper Huronian group of the Marquette district. This unconformity is well exhibited in the Copps area of the eastern Gogebic range, from which it is traced westward through the Gogebic district with less certain indications. It is also very well shown in the Red Rock, Hemlock, and Michigan mines of the Crystal Falls district and can be seen in diamond-drill cores along the same horizon south of these mines, in the Crystal Falls district. It is less certainly known in the Penn mine of the Menominee district.

The clearest evidence of unconformity has been found in the Hemlock and Michigan mines of the Crystal Falls district, where a truncated fold in the underlying Middle Huronian group is blanketed by a coarse conglomerate at the base of the upper group. The presence of this conglomerate has now been demonstrated by intermittent exploration along a belt nearly 10 miles in extent.

In the Copps district of the eastern Gogebic range a great conglomerate was found by Allen and Barrett[46] at the base of the upper slate (Tyler slate), called locally †" Copps slate." This conglomerate carries abundant granite pebbles but also a few pebbles of greenstone, quartz, chert, and more rarely quartzite. Toward the west the granite pebbles disappear and other varieties, including jasper, increase in number.

In the Copps area granite was found intrusive into the Middle Huronian, and it was supposed that this granite furnished the granite pebbles to the conglomerate. Allen and Barrett therefore regarded the conglomerate as evidence of a great break between the overlying slates and the Ironwood iron-formation. On this basis they presented a new correlation of the Huronian formations.[47] Subsequent work has shown that granite of two ages is present in this area, much the larger part being Laurentian or pre-Huronian, and a comparatively small part (the Presque Isle granite) being intrusive into the Middle Huronian Palms and Ironwood formations and the Upper Huronian Tyler slate. The granite pebbles in the conglomerate member of the Tyler are now regarded as having come from the earlier granite. Although the new concept of the age of the granite lessens the time significance of the break between the Tyler slate and the underlying iron-formation in this particular locality, the unconformity does exist and has now been traced over a much broader area.

Recent work by Atwater has shown that when the unconformity is followed westward from the conglomerate member of the Tyler slate in the Copps area the slate formation is found to overlie successively younger beds, and the conglomerate is found to include pebbles of hematite, chert, and ferruginous chert, probably derived from the immediately underlying rocks, and to assume the general character of the conglomerate included in the beds in the central part of the Gogebic district described by Hotchkiss in 1919 as the Pabst member. These beds constitute the basal member of the Tyler slate of this part of the area, and their base bevels the underlying iron-formation.

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[46] Allen, R. C., and Barrett, L. P., A revision of the sequence and structure of the pre-Keweenawan formations of the eastern Gogebic iron range of Michigan: Michigan Geol. Survey Pub. 18, pp. 33–64, 1915.

[47] Idem, p. 36.

When the Copps unconformity was first found, it was thought that the overlying slates represented a series later than the Tyler slate of the central and western parts of the Gogebic district, and the term †"Copps" was therefore applied to them. At that time the unconformity below the Tyler was not recognized, and the Tyler slate was placed in the Middle Huronian with the Ironwood iron-formation. Since then it has been rather conclusively demonstrated that the †Copps and the Tyler are the same. The gradation from the granite-boulder conglomerate of the †Copps westward to a conglomerate lithologically similar to that in Hotchkiss' Pabst member is good evidence for this correlation. The slate and graywacke, which occur in both the †Copps and the Tyler formations, are distinctly of Upper Huronian type, and a group of hand specimens from either formation can readily be distinguished from any of the slates in the Lower and Middle Huronian of this region. They also conform to the type of slates and graywackes present in the Upper Huronian of the other Lake Superior districts. Chert occurs in both the †Copps and Tyler slates, notably in the bed of the Black River north of the Eureka mine and above the base of the †Copps north of the old Copps mine. Associated with the chert horizons are beds of carbonate, much of which is siderite. Highly ferruginous slates and quartzites characterize the lower portions of both formations, and black carbonaceous slates similar to those in the Upper Huronian of the Marquette district are also present near the base of the Tyler and the †Copps formations. The term "Tyler" is therefore applied to the entire Upper Huronian of the Gogebic district.

In the Menominee district crosscuts from the iron-formation into the overlying Michigamme (†Hanbury) slates, as well as drill holes cutting the same horizon, have shown the existence of a conglomerate separated from the iron-formation by a thin band of slate conformable with the iron-formation. That this conglomerate so long escaped detection is due to the fact that nearly all the underground workings on the range stopped when they reached the conformable hanging-wall slate. It was assumed that this slate was Michigamme, and that the Michigamme and Vulcan formations were conformable. It now appears that the unconformity does not occur directly at the contact of the iron-formation but at a slightly higher horizon. As yet the conglomerate has been cut in only a few places, and much shearing along the contact obscures the relations, with the result that the identification of the unconformity in the Menominee district is not in itself positive enough to warrant a change in the classification, but the finding of the unconformity at similar horizons elsewhere, together with other considerations named later, makes its presence in the Menominee district seem highly probable.

Other evidence favoring the new correlation is the considerable degree of areal continuity of the known Middle Huronian (Negaunee) iron-formation in its extensions and repetitions south and west of the Marquette district through the Gwinn, Sturgeon, Felch, Calumet, Menominee, and Crystal Falls districts. Its continuity of lithologic type through this area has long been recognized, and the earlier geologists classified the iron-formation of these districts as equivalent to the Negaunee of the Marquette district. When the United States Geological Survey took up its detailed mapping in these districts, however, it was unable to find any break between this formation and the overlying Upper Huronian slates, which also have areal continuity through all the districts; and very reluctantly it was decided, therefore, to class the iron-formation as Upper Huronian.

The new correlation affords a better accord in sequence of series in the several districts. Classification of the principal iron-formations of the Gogebic, Menominee, Crystal Falls, and adjacent districts as Upper Huronian required the assumption that the Middle Huronian, as represented in the Marquette district, was completely absent over all this area. The Lower Huronian is very much alike in all these districts and presents no problem in correlation. The triple division of the Huronian into similar lithologic types is now apparent throughout the Michigan ranges, in the Wisconsin end of the Gogebic range, and, as described in another place, possibly in Minnesota.

Particularly to be noted is the evidence afforded by the character of the iron-formations themselves. The iron-formations now classed as Middle Huronian, equivalent to the Negaunee, are all similar in lithology and thickness and are extensive formations with so much areal continuity that they can be regarded with reasonable certainty as once having constituted a blanket covering the entire region. To assign parts of this formerly continuous iron-formation to the Upper Huronian, as was previously done, implied the repetition of a period of unusual sedimentation. In view of the unique features of the Lake Superior iron-formations as compared with those of later geologic time, it would be a remarkable coincidence indeed if the conditions under which they were laid down had been repeated so exactly.

The iron-formations found in the Upper Huronian occur as thinner and less continuous beds in the slate. They are also marked by a uniformly high phosphorus content and in many places carry manganese. When altered, they produce high-phosphorus ores having general characteristics by which they can be easily distinguished from all the ores in the Middle Huronian iron-formation. An additional criterion is the general absence of specularite in the Upper Huronian.

MINNESOTA

One of the most obvious facts in Lake Superior geology is the similarity of the Biwabik iron-formation of the Mesabi district of Minnesota to the Ironwood iron-formation of the Gogebic range in Michigan. The Biwabik dips south under Lake Superior at a very low angle; the Ironwood dips north under the same basin at a high angle. Both of them are underlain conformably by thin quartzites, and both are overlain by thick masses of slates of similar lithology. Both nearly parallel the synclinal Keweenawan rocks immediately overlying them. If, therefore, there is an unconformity between the Ironwood formation and the overlying slates (Tyler) of Michigan, there is strong reason for expecting the discovery of a similar unconformity between the Biwabik formation and the overlying Virginia formation of Minnesota. Certain small beds of conglomerate near the base of the Virginia slate and an apparent beveling of the members of the iron-formation by the slate have been noted in the western part of the Mesabi range and have been construed by Wolff[48] and others as furnishing evidence of the probable existence of this unconformity; but Grout, Leith, and others do not regard this evidence as in itself sufficient. On the other hand, they do not regard the absence of discovered evidence of such an unconformity as proof that it does not exist. The long delay in discovering such evidence in Michigan through several decades of study by many geologists is enough to make anyone chary of asserting that such an unconformity will not be found in Minnesota. Some of the conglomerates may mark an unconformity, and the absence of the upper beds of the iron-formation in part of the Mesabi district may be ascribed to beveling, but until more evidence is discovered it is considered best to describe this unconformity as probable but still unproved. The critical zones are thickly drift-covered throughout, mine workings do not extend into them but are usually stopped before reaching the slate, and comparatively few drill holes have crossed them. Such drilling as has been done in these zones, furthermore, was to a large extent done 20 to 30 years ago, when there was no thought of a possible unconformity and when thin or obscure conglomerates or slight discordance, of the kind that may well characterize such an unconformity, might easily have been overlooked.

[48] Wolff, J. F., Recent geologic developments on the Mesabi iron range, Minnesota: Am. Inst. Min. and Met. Eng. Bull. 118, p. 1786, 1916; also personal communication.

The correlation of the upper slate in Minnesota with that of Michigan is favored by its lithologic character, its evidence of probable delta origin, its great mass and area, and its included iron-formation in the Cuyuna range, having the high phosphorus and manganese content that is characteristic of the iron formations in the upper slates in the Iron River, Crystal Falls, and Marquette districts of Michigan. It would be a remarkable coincidence indeed if all these characteristics were repeated in formations of different ages, lying in both areas above an iron-formation that in character, structure, and general position in the geologic sequence can be so definitely correlated.

There is still a possibility that the Deerwood iron-formation member of the Cuyuna district may prove to be the equivalent of the Biwabik iron-formation of the Mesabi district, as suggested by the fact that in a few places a thin quartzite very much like the Pokegama quartzite at the base of the Biwabik has been found at the base of the Deerwood. Wolff[49] maintains that the subdivision of the Deerwood beds corresponds with that of the Biwabik formation. However, other observers do not regard either of these bits of evidence as conclusive. If the quartzite is truly basal to the series, one would expect, in a closely folded district such as the Cuyuna, considerable outcrops of unconformably underlying formations, like those in the Mesabi, as well as evidence of unconformity between the quartzite and its basement. No such outcrop or evidence of unconformity has been found. The underlying materials, as shown by drilling, are green schists of doubtful origin, which in lithology cannot be distinguished from many schists within the Upper Huronian of the Cuyuna district. The similarity of sequence of beds in the iron-formation with that in the Mesabi district, emphasized by Wolff, has so many exceptions and qualifications that it fails to be convincing. Finally, there is the general fact that in its high phosphorus and manganese content the iron-formation of the Cuyuna district contrasts markedly with that of the Mesabi, whereas it shows marked similarity to the iron-formations known to occur in the upper slates in Michigan.

On the new Lake Superior map, therefore, the Virginia slate of the Mesabi and Cuyuna districts, with the contained iron-formations, is classed as Upper Huronian, and the Biwabik iron-formation, with the immediately underlying Pokegama quartzite, is classed as Middle Huronian. This correlation seems to the authors the logical expression of the preponderance of evidence.

[49] Wolff, J. F., Correlation of Mesabi and Cuyuna iron ranges: Skillings Min. Review, vol. 7, no. 45, pp. 1, 4, March 29, 1919.

AGE OF THE KNIFE LAKE SERIES AND ITS EQUIVALENTS

RELATIONS TO THE UNQUESTIONED HURONIAN ROCKS

The age of the rocks here called "Knife Lake" and similar series occurring northwest and north of Lake Superior in Minnesota and Ontario is yet in doubt. In Monograph 52 these rocks were called "Lower-Middle Huronian", but doubtful elements in this correlation were pointed out. On the present map these rocks are mapped separately. Evidence bearing on their age is summarized below.

The Knife Lake series of the Vermilion district and its equivalents along the international boundary rest unconformably upon a basement of Keewatin and Laurentian rocks, are closely folded, are intruded and metamorphosed by granites of Algoman age, and together with the granites are peneplaned to a remarkably flat surface. On this surface rest the Middle and Upper Huronian and the Keweenawan, which have suffered but little deformation other than a slight tilting to the south, toward the axis of the Lake Superior syncline. No occurrence of the Knife Lake series has been found anywhere south of the north margin of the late Huronian and Keweenawan rocks to the northwest of Lake Superior. These rocks are therefore known only to rest unconformably upon the Keewatin and Laurentian and unconformably below the Middle Huronian.

South of Lake Superior the Knife Lake series is absent. The Upper, Middle, and known Lower Huronian rocks rest unconformably upon a basement complex composed of Keewatin and Laurentian greenstones and granites. Together with parts of the overlying Keweenawan they have been folded, intruded by late granites (of Killarney age), and peneplaned prior to the deposition of the Upper Cambrian sediments. So far as its position in the column is concerned, therefore, the Knife Lake series corresponds to the Lower Huronian. It contrasts with the unquestioned Lower Huronian of the south shore in that it is of a continental rather than a marine type. It contrasts also in its close folding and intense metamorphism, which is due to the fact that it is intruded by granites of Algoman age, which are absent from the unquestioned Lower Huronian areas of the south shore. For this reason the unconformity above the Knife Lake series is a striking one, more conspicuous than the one at its base. Some investigators have emphasized the unconformity above the Knife Lake series as a primary basis of classification, have stated that it represents an †Eparchean interval, and have been inclined to correlate it with the unconformity at the base of the unquestioned Lower Huronian of the south shore, which shows an equally great structural discordance, there said to represent the †Eparchean interval. If the unconformities are so correlated the Knife Lake series is pre-Huronian. The hypothesis of pre-Huronian age of the Knife Lake series, however, meets several objections. The fact that no sediments of this age are found below the unquestioned Lower Huronian on the south shore is difficult to explain in view of the large exposed areas of other pre-Huronian rocks (Keewatin and Laurentian) in Michigan and Wisconsin. It is necessary to assume either that they were never deposited south of Lake Superior, or that they were completely swept away by erosion prior to the deposition of the Huronian series. It seems unlikely that erosion could have accomplished such a result, and traces of infolded synclines of the Knife Lake series would probably have been left in this closely folded terrane. It therefore seems highly improbable that the Knife Lake series was ever deposited south of Lake Superior. Whether it is Huronian or pre-Huronian, it seems to be confined to the northern subprovince of the region. It may represent the continental deposits accumulated at the same time as the marine Lower Huronian sediments of the south shore, or it may be earlier.

The only place north of Lake Superior where there are sediments suggestive of the Lower Huronian is at Steep Rock Lake, where there are algal limestones, conglomerates, basic lavas, and obscure green schists, separated by an interval of about 2 miles from the Seine series of Canada Geological Survey reports, which is included in the present mapping as a part of the Knife Lake series. All are agreed that the two series were formed under different environments and are probably not of the same age, but faults obscure the true relations, and it is not yet possible to reach a final conclusion as to their relative ages.[50] This locality seems likely, however, to contain the key to the problem.

So far as the evidence available from the north and south shores of Lake Superior is concerned, there seems to be little choice between the hypotheses of Huronian or pre-Huronian age.

Northeast of Lake Superior, in portions of Ontario covered only partly by the accompanying map, the problem is a similar one. In these areas there are old sediments resembling the Knife Lake type, which are variously called "Doré", "Pontiac", "Timiskaming", or merely "pre-Huronian" and which are here referred to as "Timiskaming." They rest unconformably on Keewatin and Laurentian rocks. They are intruded by Algoman granites, are closely folded and metamorphosed, and are beveled by a great peneplain. This early pre-Cambrian sequence is similar to that in the Knife Lake area northwest of Lake Superior, though separated from it by considerable

[50] Hawley, J. E., "Seine" or "Coutchiching": Jour. Geology, vol. 38, pp. 521–547, 1930.

stretches of granite of unknown age or of unmapped territory.

In parts of the region the post-Algoman peneplain, beveling Timiskaming sediments, is overlain by sediments classed as Huronian. The late Huronian consists of a thick terrestrial deposit (Cobalt series of Canada Geological Survey reports), underlain without much structural discordance by the Bruce series, which is the lower part of the original Huronian series of Logan and Murray. This series is in turn divided into two and possibly three parts by minor disconformities. The lowest group of the Bruce series corresponds lithologically with the Lower Huronian of Michigan, particularly in its content of dolomite. Much of the Bruce series is of marine type, as contrasted with the terrestrial type of the Cobalt series. It happens, however, that only the Cobalt series has been found resting on the part of the peneplain carrying Timiskaming sediments, and that where the Bruce series intervenes between the Cobalt series and the underlying peneplain, Timiskaming sediments have thus far not been identified.

The Timiskaming sediments are therefore known to antedate the Cobalt series, but that they antedate the Bruce or Lower Huronian to the south is not established by direct observation. A pre-Bruce correlation depends on the assumption that the conspicuous unconformity between the Cobalt and Timiskaming series is the same as that between the Bruce and its basement complex. To put the problem in a different way, it depends on the assumption that the basement complex under the Bruce contains Algoman granite, which is later than the Timiskaming sediments, as well as Laurentian or pre-Timiskaming granite.

The problem of the age of the Timiskaming series is still further obscured by the doubt that exists as to the age of its possible correlative, the Sudbury series, occurring east of the area covered by the accompanying map and not heretofore mentioned. The Sudbury series is similar in lithologic and metamorphic character to the Timiskaming series. It underlies the Bruce series with apparent unconformity in some places and with apparent conformity in others. Whether as a whole it lies above or below the pre-Bruce unconformity is not yet proved.

The Canadian geologists have almost uniformly favored the pre-Huronian correlation of the Knife Lake and Timiskaming sediments. In preparing the new map of the Lake Superior region, it has been the purpose of the authors, so far as possible, where correlations are doubtful, to use noncommittal terms that will not obscure general agreement as to facts. On the present map the rocks of the Knife Lake region are called "Knife Lake series," without definite assignment of age. They are of a different type of sedimentation from the unquestioned Lower Huronian rocks. In the absence of proved age relations it seems undesirable that terms like "Huronian" should be extended to include beds representing contrasting types of sedimentation. It seems equally undesirable to call the Knife Lake series "pre-Huronian," which implies that it is older that the †Eparchean interval. Such grouping obscures the unconformity known to exist at its base, above the true basement complex. If it should prove to antedate the Huronian, it should be given a name that would separate it from the basement complex, and not a name as inclusive as "pre-Huronian," which covers the basement complex as well.

The reader should be skeptical of emphatic assertions, which have unfortunately become too frequent in the literature, that the precise age of these sediments has been proved. All that has been proved in any district is that they are earlier than the later Huronian rocks and later than the Laurentian granite. The Knife Lake series may be Lower Huronian; it may be pre-Huronian (implying that it antedates the †Eparchean interval); or it may be intermediate in age.

RELATIONS TO THE KEEWATIN SERIES

In the Rainy Lake district and its eastward extensions certain sediments of Knife Lake type have been mapped by Lawson and his successors as pre-Keewatin and given a separate name, "Coutchiching". There has been much controversy about the thickness and extent of the Coutchiching sediments in this territory. Most of the mapping following Lawson's has considerably reduced the area and volume of sediments called "Coutchiching", but a late regional map by Tanton extends that term much farther than ever before to include great areas regarded by the present authors and others as equivalent to the Knife Lake series. Tanton makes no claim that all of his present Coutchiching has been proved to antedate the Keewatin but has used the term as a blanket designation of old sediments.

The problem is far from settled. The rocks are closely folded, and the structural problem of determining what sediments lie above greenstone flows and what below, or what flows belong with the Keewatin and what flows may be post-Keewatin, is a very difficult one. Faulting along contacts between Keewatin greenstones and sediments of the Knife Lake type has commonly obscured the relations between them. In the Vermilion district of Minnesota, where the Knife Lake series has been mapped in most detail, Keewatin sediments (principally iron-formation, but including slates and tuffs) have been recognized, but none have been shown to be definitely pre-Keewatin. Even here, however, because of the difficulty of the structural problem, it is entirely possible that some of the sediments may be found to be really pre-Keewatin.

In Manitoba, northwest of Lake Superior, many more or less isolated areas of pre-Cambrian rocks have been reported as containing much the same assemblage, and here also there have been differences of opinion as to the amounts of sediments to be assigned to post-Keewatin and pre-Keewatin ages.

Bruce[51] has bracketed all the sediments of Knife Lake and Coutchiching type through the general region northwest of Lake Superior as parts of a great delta, which he has called the "Coutchiching delta." This simple grouping calls attention to common features of the sedimentation before, during, and after the Keewatin flows, over a wide area and conveniently covers the frequently obscure relations of sediments and flows. It does not, however, take care of the great unconformity, representing a long time interval, plutonic intrusion, mountain building, and erosion, known to exist at many points between the Knife Lake series and the Keewatin-Laurentian basement.

Almost the same problem reappears in connection with the Doré-Pontiac-Timiskaming sediments northeast of Lake Superior. In some areas they have been regarded as in part pre-Keewatin, or at least older than certain flows of a Keewatin type. However, where they have been most closely studied, in the Michipicoten district and the Larder Lake, Porcupine, and Kirkland Lake gold belt, they have been found to rest with a definite unconformity on a basement of Keewatin or Laurentian type.

The Keewatin rocks are mainly surface flows. They are known to be interbedded with sediments, and there is no inherent reason why they should not have been deposited on sediments. It is quite possible that future work will show that a part of the rocks of the Knife Lake type are definitely pre-Keewatin, and, if the volume of such sediments is found to be large enough, it may warrant general use of the term "Coutchiching" to indicate a separate pre-Keewatin series. As yet, however, the volume of pre-Keewatin sediments definitely established is very small. No unconformity has been found between them and the overlying Keewatin, and there has been no proof that they are anything but interbedded sediments in the Keewatin, like those already abundantly known. For these reasons, and especially for the reason that the supposed pre-Keewatin sediments occupy so very small an area, no attempt has been made to show them on the present map, all being classed as Keewatin, Knife Lake, or undifferentiated Keewatin and Knife Lake.

THREE PERIODS OF GRANITIC INTRUSION

In Monograph 52 granite intrusives of three periods were recognized—(1) the Laurentian granites, intrusive into the Keewatin; (2) the Giants Range and equivalent granites (subsequently named "Algoman" by Lawson), intrusive into the Knife Lake slate and equivalent rocks of Minnesota and Canada; and (3) granites intrusive into the Upper Huronian south and west of the Menominee district and near the Cuyuna district of Minnesota, which were classed, doubtfully, as Keweenawan. For the last-named granites the term "Killarney" is now used. The present map shows several changes in the mapping and classification of the granites, with the general result that the area of granites assigned to the Laurentian is decreased, while that of the granites assigned to the two later periods is increased.

MINNESOTA

In the Vermilion range of Minnesota the granites of Vermilion, Burntside, and Basswood Lakes, formerly classed as Laurentian, are now mapped as Algoman, meaning intrusive into the Knife Lake series, in accordance with the interpretation of Grout,[52] of the Minnesota Geological Survey, who in recent years has studied these granites in detail. The main evidence for the former classification of these granites as Laurentian was the abundance of acidic pebbles in the conglomerate at the base of the Knife Lake series. These are dominantly of a porphyry type, obviously implying derivation from the nearby basement porphyry intrusives in the Keewatin, but there are also a few granite pebbles. Formerly it was assumed that the known Laurentian porphyries were simply phases of the adjacent granite intrusives, but more intensive study shows that they probably are not and that to a large extent the granites intruded the Knife Lake sediments, producing extensive metamorphic changes. In short, the evidence of metamorphism in the sediments at the contacts is now believed to outweigh the existence of a few granite pebbles in the conglomerate. The presence of granite pebbles in the conglomerate indicates that sizable granitic intrusives of Laurentian age were present in this area, but they cannot be identified as such.

The only granite batholith of northern Minnesota now left in the Laurentian is the Saganaga granite. Here the evidence of unconformity with the Knife Lake sediments is conclusive, for the pebbles in the basal conglomerate have clearly come from the Saganaga granite, and there is no evidence that the granite metamorphosed the sediments.

On the map of the Mesabi district in Monograph 52 one small area of granite, the Embarrass granite, was mapped as intrusive into the Middle Huronian iron-

[51] Bruce, E. L., Coutchiching delta: Geol. Soc. America Bull., vol. 38, pp. 771–781, 1927.

[52] Grout, F. F., The Vermilion batholith of Minnesota: Jour. Geology, vol. 33, pp. 467–487, 1925; The geology and magnetite deposits of northern St. Louis County, Minn.: Minnesota Geol. Survey Bull. 21, 1926; Ages and differentiation series of the batholiths near the Minnesota-Ontario boundary: Geol. Soc. America Bull., vol. 40, pp. 791–809, 1929.

formation at the east end of the Mesabi range. Since then Grout and Broderick [53] have restudied the contact in this area and have concluded that the granite is of the same age as the Giants Range granite—that is, Algoman. This conclusion is not agreed to by Richarz,[54] who concurs with the view presented in Monograph 52, that the metamorphic effects at the contact indicate intrusive relations. The question of the degree of metamorphism effected by the granite is somewhat obscured by the general metamorphism of the rocks at that end of the Mesabi district by the overlying Duluth gabbro. A few small intrusive dikes of granite cut the Middle Huronian iron-formation farther west, and there are also acidic flows and dikes in the Keweenawan of Minnesota, so there is nothing inherently improbable in the intrusive nature of the Embarrass granite. However, it seems safe to assume that the mass of granite intrusive into the Middle Huronian of the Mesabi district is relatively small, because it has not disturbed the gentle southward dips of the sedimentary series in the manner that might be expected from a considerable batholithic mass. On the present map this granite is indicated as doubtfully of Killarney age. The granites at Little Falls and Mille Lacs, south of the Cuyuna range, are intrusive into the Virginia slate and are therefore mapped as Killarney.

The Algoman granites of Minnesota are intrusive into the Knife Lake series and lie unconformably below the Middle Huronian. It is not known whether the Knife Lake series is equivalent to the unquestioned Lower Huronian or whether it is pre-Huronian (see pp. 16–17), and for this reason also the exact age of the Algoman granite cannot be fixed. It may be later than Lower Huronian, or it may be pre-Huronian.

WISCONSIN AND MICHIGAN

It is now known that considerable parts of the great area in northern Wisconsin formerly classed as undifferentiated pre-Cambrian are underlain by granite which is intrusive into the later Huronian sediments. The evidence is best developed in northeastern Wisconsin and adjacent parts of northern Michigan, in the Marenisco, Turtle, Vieux Desert, and Conover districts, as described by Allen and Barrett.[55] The granites of the Florence district were known to be intrusive into the Upper Huronian and were so mapped in Monograph 52. West of these districts, in northern Wisconsin, abundant granites of post-Huronian age are believed to exist by Hotchkiss,[56] who mapped this area for the Wisconsin Geological and Natural History Survey. However, much of the area of northern Wisconsin is thickly drift-covered, exposures are few, and conclusions must be based on drill cores, on evidence of contact metamorphism, and on the existence of many magnetic belts showing a probable continuation of the conditions existing in northeastern Wisconsin to the north-central part of the State. It is quite possible that Laurentian and even Algoman granites are also present in this territory.

In north-central Wisconsin, in the vicinity of Wausau, the basement complex of granite gneisses and schists is still shown as Laurentian. Overlying these (probably unconformably, although no exposures of the actual contacts have been found) is a series of quartzites, conglomerates, and graywackes that are intruded by a large series of igneous rocks ranging from basic peridotites, gabbros, and diorites to granites and syenites, of which the more basic are the earlier. These rocks are shown on the present map as of doubtful Killarney age, with the lower sedimentary group classed as undifferentiated Huronian. A fact rather suggestive of Killarney age is that intrusives of this age in other parts of the Lake Superior region (notably the western Gogebic district) likewise rather commonly include types ranging from basic to acidic. Lying unconformably on this series of igneous intrusives is an upper sedimentary group of conglomerates and quartzites, which is shown on the present map as uppermost Keweenawan with a question mark. Correlation of the sedimentary rocks as well as the igneous rocks in this area is still extremely doubtful.

In the Gogebic range of Michigan all the granites bordering the south side of the range were formerly mapped as Laurentian, but in the eastern part of the range, in the vicinity of the Presque Isle River, parts of this granite, called the Presque Isle granite by Allen and Barrett, are known to have intruded and extensively metamorphosed the Middle Huronian iron-formation and quartzite and to a lesser extent to have intruded the basal Upper Huronian slate of this area. The existence of abundant granite boulders in the conglomerate at the base of the Upper Huronian in the Copps area, together with the known intrusions of granite into the Middle Huronian of this area, led Allen and Barrett to the conclusion that the Presque Isle granite was intrusive into the Middle Huronian but not into the Upper Huronian. Further work has developed the fact that a part of the granite of this area is Laurentian, that this part furnished the pebbles

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[53] Grout, F. F., and Broderick, T. M., The magnetite deposits of the eastern Mesabi range, Minnesota: Minnesota Geol. Survey Bull. 17, p. 49, 1919.

[54] Richarz, Stephen, The metamorphic iron formation of the eastern Mesabi range, Minnesota, and its relation to the Embarras granite: Jour. Geology, vol. 38, pp. 600–618, 1930.

[55] Allen, R. C., and Barrett, L. P., Contributions to the pre-Cambrian geology of northern Michigan and Wisconsin: Michigan Geol. and Biol. Survey Pub. 18, Geol. ser. 15, pp. 65–139, 1915.

[56] Hotchkiss, W. O., Mineral land classification, showing indications of iron formation in parts of Ashland, Bayfield, Washburn, Sawyer, Price, Oneida, Forest, Rusk, Barron, and Chippewa Counties: Wisconsin Geol. and Nat. Hist. Survey Bull. 44, pp. 53–54, 1915. Hotchkiss, W. O., and Bean, E. F., Mineral lands of part of northern Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 46, pp. 35–36, 1929.

to the conglomerate at the base of the Upper Huronian Tyler slate, and that it was a later granite that intruded the Middle and Upper Huronian of this area. Because of the lack of exposures it is not yet possible to map the boundaries between the older and later granites of this area.

Granite regarded as a differentiate of Keweenawan anorthosite masses intrudes the Upper Huronian slate and middle Keweenawan flows in the western part of the Gogebic district, near Mellen, Wis.

Along the southern margin of the Marquette district of Michigan, in the vicinity of Champion and Palmer, part of the granite formerly classed as Laurentian is now known to have intruded and metamorphosed the Huronian sediments, though elsewhere along the south side of the Marquette district the granite is clearly older than the Huronian sediments, as shown by the pebble content of the basal conglomerate and the lack of metamorphism. Other isolated observations[57] south of the Marquette district show that parts of the granite previously mapped as Laurentian have intrusive relations to the Huronian. Among these may be cited granite dikes in the Felch district that change to a finer grained texture in approaching the Huronian.

The known unconformity between the lowest Huronian sediments and the underlying granite and the fact that granite only locally cuts these sediments are regarded as proof that the main mass of granite is Laurentian and that the later or Killarney granite is represented only by minor amounts of intrusives.

In general the best-known granite of Killarney age in Michigan and Wisconsin is confined mainly to northeastern Wisconsin and to the nearby parts of Michigan west of the Iron River district, but it is quite possible that the granite may extend pretty well across northern Wisconsin. Whether this is one main batholith with offshoots or two or more batholiths is not yet known.

NORTH SHORE OF LAKE SUPERIOR

The Algoman granites, so widely developed in northern Minnesota, have their counterparts at various points along the north and northeast shores of Lake Superior as far east as the Michipicoten district. They cut sediments of the Knife Lake type. Here and there they are found well to the north in Ontario, but how far they may extend in that direction is not known. Where sediments of the Knife Lake type are not present it is impossible to distinguish between the Algoman and Laurentian granites; so presumably some, or even a large part, of the area mapped by the Canadians as Algoman granite may be Laurentian.

EAST SHORE OF LAKE SUPERIOR

Mapping of the Michipicoten district by Collins and Quirke[58] shows the granite to be mainly of Algoman instead of Laurentian age, as formerly mapped. Several small areas of granite, however, are definitely known to be pre-sedimentary and therefore Laurentian.

Much of the large area between the Michipicoten region and the Soo is underlain by granite. To the south this granite is known to underlie the Huronian series, and it therefore appears as Laurentian on our map. Information is not yet available which makes it possible to draw the line between Laurentian and Algoman granites for the main part of this area. Collins,[59] in his map of this portion of Ontario, classes it all as Algoman, on the basis of its intrusive relation to sediments in the Michipicoten district and the assumption that it is substantially a unit mass as far south as the original Huronian district. On the present map the age of the granite is indicated by symbols only on the north and south.

GENERAL COMMENTS

In review, then, granite batholiths of Laurentian age are shown both north and south of Lake Superior. Batholiths of the next period, the Algoman, are confined to a zone paralleling the Lake Superior axis on the north. The last of the granites, of Killarney age, is not found north of the Cuyuna range, except for the questionable Embarrass granite, and there is no disturbance in the late Keweenawan and Huronian rocks there to indicate its possible presence. It is confined on the whole to a zone paralleling the axis of the Lake Superior syncline on the south, where its intrusion is doubtless to be correlated with the folding of the Huronian and Keweenawan of that zone. As to the age of this late granite, it is known to cut the latest of the Huronian sediments, and the folding which it accompanied affected at least a part of the Keweenawan series. Still further, small quantities of granite are known to be intrusive into the Keweenawan series, as near Mellen, on the western Gogebic range. It is therefore believed that the granite is of late Keweenawan age. If it were earlier, one would expect to find more evidence of orogenic disturbance in the Upper Huronian before the deposition of the Keweenawan series south of Lake Superior.

The evidence of three periods of granitic intrusion and orogeny is now generally recognized by students

[57] Lamey, C. A., Granite intrusions in the Huronian formations of northern Michigan: Jour. Geology, vol. 39, pp. 288–295, 1931. Swanson, C. O., Report on the portion of the Marquette range covered by the Michigan Geological Survey in 1929 (mimeographed), Michigan Geol. Survey, 1930. Zinn, Justin, Report on the portion of the Marquette range between Humboldt and Lake Michigamme covered by the Michigan Geological Survey in 1930 (mimeographed), Michigan Geol. Survey, 1931.

[58] Collins, W. H., Quirke, T. T., and Thomson, Ellis, Michipicoten iron ranges: Canada Geol. Survey Mem. 147, map 1972, 1926.

[59] Collins, W. H., Lake Huron sheet: Canada Geol. Survey Pub. 1553, map 155A, 1929.

of Lake Superior geology, but there is still wide divergence of opinion as to the classification of particular areas of granite, especially where these are far removed from known contacts with sedimentary horizon markers. For this reason all granites are shown by the same color on the map, and symbols are introduced only in places where the authors are reasonably sure of the classification.

The principal differences of opinion relate to the mapping and age of the Algoman granites. As already noted, these are known to be later than the Knife Lake series and earlier than Middle Huronian, but until it is definitely known whether Knife Lake is pre-Huronian or Lower Huronian, it is impossible to say whether the Algoman is pre-Huronian or later than Lower Huronian. No Knife Lake sediments are known beneath the unquestioned Lower Huronian—a fact which means that the granites below the Lower Huronian might be called either "Algoman" or "Laurentian." Collins has called such granites on the north shore of Lake Huron "Algoman." In the present mapping all such granites are called "Laurentian." This is done for the reason that the term "Laurentian" as defined and used by the United States Geological Survey and by the International Geological Committee is confined to granites below the lowest Huronian. This usage has been followed during the 50 years of mapping of the region by the United States Geological Survey. The absence of any sediments of Knife Lake type makes it impossible to prove that any of the granites are of Algoman age. The authors think that the present state of knowledge can be best expressed by retaining the term "Laurentian" for the known pre-Lower Huronian granites, until the vexing problem of the relations of the Knife Lake series to the unquestioned Lower Huronian can be solved. At present the authors can see little likelihood of final solution of this problem.

ORIGIN OF THE IRON-FORMATIONS

DIFFERENT HYPOTHESES

The iron-formations of the Lake Superior region, like those in the pre-Cambrian elsewhere, represent a type and scale of sedimentation not known in post-Cambrian time. They now consist mainly of well-oxidized banded jaspers and ferruginous cherts. Before oxidation they contained, in addition to jasper, large masses of banded siliceous iron carbonate and greenalite rocks. Large parts of the iron-formations have been anamorphosed into banded quartz-amphibole-magnetite rocks under the influence of igneous intrusion. The principal iron-formations reach 800 feet in maximum thickness. In recent years drilling in the Negaunee Basin of the Marquette district has shown a local maximum thickness of over 1,500 feet. The total area of iron-formations now exposed at the rock surface is about 225 square miles. All are agreed that the iron-formations are chemical or in small part biochemical sediments, but there is difference of opinion as to the source of the solutions.

The dominant early hypothesis of origin was that the material of the iron-formations was derived from the weathering and erosion of old land surfaces and deposited in nearby basins or seas of shallow water. Exceptions were the hypotheses of Wadsworth and Winchell, which ascribed the iron-formations to igneous sources. The authors of Monograph 52 had long accepted the prevalent hypothesis of derivation of these formations by ordinary processes of weathering, but in that monograph they abandoned it as applying to a part of the iron-formations and presented evidence to show that direct and indirect contributions from contemporaneous lavas were probably instrumental in the deposition of some of these formations. This evidence consisted not only in the general association of the iron-formations with lavas in time and place, but in quantitative studies of weathering processes, which seemed to show that such processes are incapable of producing iron-formations on so large a scale. Although such processes can produce bog, lake, and similar deposits, mostly unbanded, at no place in the world are they producing the peculiar banded iron and silica deposits of the Lake Superior type. Furthermore, nowhere in the world have geologic columns shown iron-formations of this kind and scale except in the pre-Cambrian, and it is to be assumed that the geologic column in one place or another is likely to reflect all varieties of conditions of sedimentation and weathering. Many similar iron-formations in the pre-Cambrian of other parts of the world are known to be likewise associated with contemporaneous basic igneous rocks.

Since the publication of Monograph 52 studies of this question have been continued by various investigators, and the conclusions reached have shown the same wide range between weathering and igneous contributions as the source of the iron-bearing solutions to the original sediments.

Gruner,[60] in 1922, with reference to the Biwabik iron-formation of the Mesabi range of Minnesota, concluded:

> During Upper Huronian time there existed large land areas in North America, which were covered largely with greenstone and basalts. It is probable that fresh extrusive rocks and volcanic tuff and ash were deposited on parts of the land, as well as in the sea basins then existing. The climate of the continent was humid and probably tropical or subtropical. Vegetation of a low form was abundant and aided in the rapid decay of the rocks. Under these conditions iron, which usually is one of the most stable elements

[60] Gruner, J. W., The origin of sedimentary iron-formations: Econ. Geology, vol. 17, pp. 459–460, 1922.

in weathering, went into solution to a large extent, but only in waters with organic colloids was it stable for any length of time in the zone of oxidation. Silica was also dissolved on a large scale. Both iron and silica were carried to the sea by rivers rich in organic matter. * * *. A part of the silica contained in the taconite may have been contributed to the sea directly by magmatic springs or hot submarine lava flows. We do not believe, however, that much iron had this origin.

Collins,[61] in 1926, presented his conclusions about the iron-formation of the Michipicoten district, northeast of Lake Superior. There the formation consists of three members—a lower siderite member, a middle pyrite member, and an upper banded silica member. He found abundant evidence that at least the two lower members directly replaced the associated igneous rocks. His conclusion follows:

The three features—irregular lamination, brecciation at the time of deposition, and early conversion of siderite into iron oxide—suggest flowing water and exposure to the air rather than deposition under the seal of a large body of standing water. Apparently the iron-formations were formed by ascending heated mineralized waters at many loci in a land area of great volcanic activity. These loci ranged in area from a few yards to 7 or 8 miles in major horizontal extent, and they are to be found throughout the vertical range of the volcanic complex. The heated waters were mineralized with carbon dioxide, iron, silica, and sulphur compounds at least. They permeated the volcanic rocks and converted them, to a maximum depth of nearly 250 feet, into carbonates and sulphides. In so doing they were protected from atmospheric oxidizing influences. At the surface they probably spread out in depressions and by evaporation and cooling precipitated their content of silica and such carbonate as was not deposited below ground. It is not absolutely certain that the banded silica deposits were formed above ground, but the stratified arrangement of the silica and iron compounds forming them and their great horizontal extent as compared with their thickness seem to require this postulate. In some cases these waters may have collected in pools and even extensive ponds, but the lenticular banding, brecciation, and substitution of hematite or magnetite for siderite in other cases seems to imply during part of the time thin and irregular flow over a surface intermittently exposed to the air. In some such manner hundreds of feet of banded silica were built, and in one of several conceivable ways a laminated structure resembling fine sedimentary bedding was imparted to it. Eventually the iron-formation thus formed in a valley or other depression was covered by a flow of ellipsoidal greenstone or other lava, terminating the process at this place, only to have it begun again in some other place at the new surface.

The subordinate beds of banded silica, which in a few cases are found within the carbonate member or at its base, and the subordinate alternations of banded silica and pyrite or carbonate seen in many of the iron-formations seem on first consideration to contradict this theory of origin of the iron-formations. However, in a region of active volcanism and rugged topography, it is quite likely that layers of lava or rock debris would become spread over the growing iron-formations from time to time, only to be covered up by later deposits of banded silica and converted into pyrite or carbonate by the mineralized waters, thereby producing minor repetitions or complications in the succession of banded silica, pyrite, and carbonate.

The conditions here visualized have probably a close modern counterpart in the volcanic regions of Iceland, Alaska, and Yellowstone Park, where geysers and hot springs are depositing silica at the surface and no doubt causing extensive chemical alteration in the rocks through which they ascend. It seems well within the realm of probability that the loci of the Michipicoten iron-formations were in early pre-Cambrian time the scene of volcanic hot-spring activity on a grand scale.

[61] Collins, W. H., Quirke, T. T., and Thomson, Ellis, Michipicoten iron ranges: Canada Geol. Survey Mem. 147, pp. 75–76, 1926.

Gill,[62] in 1927, studied the origin of the Gunflint iron-formation of Minnesota, which is the eastward extension of the Mesabi range, and concluded:

During the Animikie period continental weathering proceeded much as it does today. A landmass of low or moderate relief in a temperate or tropical climate was subjected to deep decay. Among other substances, iron and silica were carried to the sea by rivers, principally as colloids stabilized by protective agents. The usual clastic sediments were deposited near the river mouths, but the sols retained their stability long enough to be carried relatively long distances by off-shore currents to areas of shallow or moderate depth, in which fine suspended particles were deposited rarely and only during brief periods. These conditions, maintained for a much longer time than in most other periods in the earth's history, resulted in the formation of an exceptionally thick series of sediments consisting almost wholly of iron compounds and silica.

Volcanism occurred, particularly during the latter half of the iron-formation period. Some silica and iron may have been contributed directly by magnetic springs or by submarine lava flows, but the total quantity supplied in this way is believed to be relatively small.

In a study of the Gogebic range of Wisconsin Aldrich,[63] in 1929, concluded:

There can be no doubt about its chemical sedimentary origin, but among the long list of sediments there is hardly a one which in any essential respects strongly resembles the Ironwood, excepting the other iron formations of similar age.

The main difficulty lies with the very uncommon composition. Here is a formation obviously formed as a chemical precipitate in a body of water on the surface of the earth and therefore one which would be the passive product of surficial environment. However, a very comprehensive study of surficial processes has revealed no circumstances under which a solution of these two substances, silica and iron, may be mutually segregated from the other elements of ordinary rocks and in such enormous quantities. The uniform habit of iron and silica in surface processes is to part company—that is, one is removed and the other remains insoluble and fixed.

The escape from this difficulty has been seen only in the concentration of the silica and iron in an extrasurficial environment. In short, these materials were created in solution by a subsurface environment—a magma. This turn to magmatic sources is compelled not alone by the elimination of more immediate sources. Wherever similar formations occur there are ample evidences of magmatic activity if not contemporaneously at the surface, at least imminently below surface, for not long subsequent to the deposition there is

[62] Gill, J. E., Origin of the Gunflint iron-bearing formation: Econ. Geology, vol. 22, pp. 726–727, 1927.

[63] Aldrich, H. R., The Geology of the Gogebic iron range of Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 71, pp. 143–144, 1929.

surface volcanism. In the present case it is but a matter of observation that on the Michigan end there was contemporary volcanism throughout Upper Huronian time, as shown by intercalated tuffs and surface flows. Furthermore, in Keweenawan time the whole vicinity was deeply and completely buried by 5 miles of lava flows. The reservoir of this lava could not have been far below the surface even in Ironwood time.

The magmatic origin of the silica and iron which makes up the Ironwood is therefore believed to meet the requirements of the formation. It is not possible to indicate the exact method by which this transfer of material from the depths to the surface was accomplished, but it is necessary to accept one or both of two possibilities. Either the silica and iron were dissolved in a solution and the solution was poured into this surface basin, or there were deliveries of molten lava at the surface, and sea water or meteoric waters extracted the silica and iron salts from these hot masses.

In 1929 Moore and Maynard [64] studied the solution, transportation, and precipitation of iron and silica with reference to the origin of iron-formations generally. In applying these conclusions to the pre-Cambrian banded iron-formations, including those of Lake Superior, they stated:

> Assuming an abundance of organic matter in pre-Cambrian formations, it is possible for cold water to have extracted and transported sufficient iron and silica from the great areas of igneous rocks exposed in pre-Cambrian time to build up large deposits of banded iron and silica. The iron would be dissolved and carried as a ferric oxide hydrosol and the silicas as colloidal silica, the two being stabilized by organic matter which kept them from mutually precipitating one another until thrown down by the electrolytes in the sea. The banding in the deposits, as shown by experiment, could be due to the differential rate of precipitation of the iron and silica combined with the influence of seasonal changes causing varying quantities of these substances to be brought into the basin of deposition at different periods throughout the year. * * *
>
> The senior writer has for years adhered to the idea that practically all the pre-Cambrian iron-formations have been formed as the result of normal processes of weathering and chemical sedimentation. However, field work in recent years, followed by the laboratory experiments herein described, have led to a belief in Leith's contention that hot waters have played a more important role in the deposition of the highly siliceous formations associated with igneous rocks than was formerly admitted.

IRON BACTERIA AND ALGAE

It is now well established that iron bacteria deposit iron in considerable quantities. Definite evidence has been found in spring, bog, and lake deposits. Gruner [65] reports the existence of evidence of bacteria in the Mesabi and Vermilion ranges. However, Hawley [66] was able to produce similar forms by purely chemical means. Algal structures exist in the lower few feet of the Biwabik formation of the Mesabi district—a fact which has been interpreted as favoring the conclusion that bacteria played a part in its deposition. There is no a priori reason for believing that bacteria may not have played a considerable part in the deposition of the iron-formations. On the other hand, the direct evidence for such an agency is not convincing, and from the beginning there has been no difficulty in explaining how iron and silica could be precipitated from solution by chemical agencies. The real problem is how such vast quantities of iron were brought into solution, not how they were precipitated.

CONCLUSION

Study of the origin of the iron-formations since publication of Monograph 52 has not appreciably modified the conclusion therein reached—namely, that both weathering and igneous processes have played a part in bringing the iron salts together and that both chemical and organic processes have caused their precipitation. The quantitative ranges of the different processes are still conjectural. Points of view and emphasis are determined more or less by the particular area studied, and the region shows so wide a variety of conditions that differences in perspective among the different investigators are not surprising. No one is yet qualified to make flat assertions as to origin that will apply to all parts of the region.

The great and as yet unsolved problem is why and how these materials came into solution in so great concentration and on so vast a scale. Where formations of banded iron and silica, containing almost no other sedimentary materials, have been produced with a thickness of 600 to 1,500 feet and areas of thousands of square miles, the effective processes, whether of weathering or of igneous contribution, must have been on a scale without counterpart in any process observed today.

The conclusion cannot be avoided that the iron-formations of the pre-Cambrian, not only of the Lake Superior region but of the world, were the unique result of some special combination of conditions that has not since been repeated.

OXIDATION OF THE IRON-FORMATION AND CONCENTRATION TO ORE

AGENCY INVOLVED

There is general agreement that large parts of the Lake Superior iron-formations were originally ferrous minerals, mainly siderite and greenalite, interbedded with silica and with some layers of original ferric oxide. The exposed parts of the formations, amounting to about 225 square miles, where not previously anamorphosed into amphibole-magnetite rocks, are now mainly oxidized to jasper, ferruginous slate, and

[64] Moore, E. S., and Maynard, J. E., Solution, transportation, and precipitation of iron and silica: Econ. Geology, vol. 24, pp. 524–525, 1929.

[65] Gruner, J. W., The origin of sedimentary iron formations: Econ. Geology, vol. 17, pp. 417–421, 439–440, 457–458, 1922.

[66] Hawley, J. E., An evaluation of the evidence of life in the Archean: Jour. Geology, vol. 34, pp. 441–461, 1926.

ferruginous chert. The original ferrous portions of the formations are found only in scattered remnants, usually far beneath the surface, in places protected by a variety of special conditions from surface oxidation. Over considerable areas in the Marquette and Crystal Falls districts of Michigan the mantle of oxides over the carbonates is thin and discontinuous.

The concentration of Lake Superior iron-formations to iron ore has consisted of the oxidation of such of the original compounds as were ferrous and the leaching out of vast quantities of silica. In the producing districts about 6 percent of the area of the iron-formations, exclusive of anamorphic phases, has been altered to ore. The general relations of the ores to present and past erosion surfaces and to structural basins seem to demonstrate the agency of meteoric waters.

This conclusion has served as a basis for all the exploration and development work yet done in the Lake Superior region. It has been presented in detail in several of the United States Geological Survey monographs on individual districts and was summarized and restated in Monograph 52. Since that time further mining and exploration have added to the available information, requiring some restatement of the hypothesis but essentially confirming it.

In view of the old tradition as to the insolubility of silica under ordinary weathering conditions, it is not surprising that some geologists have found difficulty in accepting the conclusion that weathering agencies are adequate to accomplish the vast amount of leaching of silica necessary to account for the ores, and because of this difficulty Gruner [67] has offered the hypothesis that the Lake Superior iron ores owe their concentration to hydrothermal solutions emanating in the main from Keweenawan basic intrusives, and in the Vermilion district to earlier acidic intrusives. He finds from laboratory experiment that oxidation and leaching of silica are greatly accelerated by moderately high temperatures (200° to 300° C.). He points out supposed shortcomings of the currently accepted hypothesis of leaching by surficial weathering. He cites local relations of ores with igneous rocks, the local presence of supposedly hot-water minerals in the ore, and local structural details which seem to him to favor the idea of ascending hot solutions rather than descending solutions from the surface.

This hot-water hypothesis has attracted wide attention, but few geologists familiar with the field find the cited evidence convincing. Although many apparently confirmatory details may be cited, as might be expected in a region that has been subjected to so great a variety of metamorphic and structural processes, none of the facts yet presented can be construed as valid evidence against the prevalent hypothesis of concentration by surface waters. In another place the senior author [68] has discussed in some detail the specific evidence offered by Gruner, and this argument will not be repeated here. In this summary report it seems better to restate the hypothesis of the concentration of iron ores by waters from the surface, to cover some features disclosed in developments of recent years. Indirectly this restatement will meet some of the main arguments advanced to favor the activity of hot solutions from igneous rocks below.

[67] Gruner, J. W., Hydrothermal oxidation and leaching experiments: their bearing on the origin of Lake Superior hermatite-limonite ores: Econ. Geology, vol. 25, pp. 697–719, 837–867, 1930; The Soudan formation and a new suggestion as to the origin of the Vermilion iron ores: Econ. Geology, vol. 21, pp. 629–644, 1926.

RESTATEMENT OF PROCESSES OF ORE CONCENTRATION

Mining began at or near the present erosion surface, and for a long time little ore was known deeper than 1,000 feet. In this distance many ore bodies were bottomed. It was natural, therefore, that early ideas of the ore concentration should relate to the present erosion surface. Even yet there is a good deal of confused thinking on this subject. When development disclosed ore bodies extending to greater depths, it became clear that they could hardly be explained by oxidation under present conditions, where the water table is seldom more than 100 feet below the surface, and more attention was paid to evidence fixing the time of concentration and the conditions existing at that time. Several periods of possible concentration are known in the different districts.

1. The iron-formation of the Keewatin was exposed to weathering (*a*) in the period preceding the deposition of the Knife Lake series, (*b*) after the Algoman revolution and before the deposition of the Middle Huronian of the Mesabi district and its equivalents, (*c*) in the period of erosion of the Upper Huronian and prior to the Keweenawan deposition, (*d*) in the period following the Keweenawan and prior to the Cambrian. The only commercial ore bodies in the Keewatin are in the Vermilion district, where the record ends with the post-Algoman erosion and where evidences of later erosion cycles are not recorded. The metamorphic history here is complex, but the evidence seems to indicate concentration both preceding and following the deposition of the Knife Lake series. Whichever it was, the depth of concentration yet known below the present surface is sufficiently shallow to be accounted for by concentration from either of these old surfaces.

2. At the end of the Negaunee epoch (Middle Huronian) in the Marquette district and at equivalent horizons in the Crystal Falls and Menominee districts the iron-formation was exposed and surficially concen-

[68] Leith, C. K., Secondary concentration of Lake Superior iron ores: Econ. Geology, vol. 26, pp. 274–288, 1931.

trated over considerable areas, as shown by the nature of the overlying conglomerate, which carries boulders both of ore and of oxidized formation. The hard ore of the Marquette district was initially concentrated at this time, though it has since undergone metamorphic changes and perhaps additional concentration. This old erosion surface in most places dips steeply with reference to the present surface and has been followed to a maximum depth of nearly 3,000 feet at the Republic mine. There seems to be no theoretical reason why ore bodies on this old surface should not go indefinitely deeper. In the Crystal Falls and Menominee districts the post-Negaunee surface only locally exposed the iron-formation, more or less slate being left as a capping, and in these districts no ore bodies can be definitely ascribed to this old surface.

New ideas of correlation presented in this report class the iron-formation of the Gogebic and Mesabi districts as of the same age as the Negaunee formation of the Marquette district, but as yet an unconformity between the iron-formation and the overlying slates has been proved only in the Gogebic district. In the Mesabi district no adequate evidence has yet been found.

3. In the Gogebic range the erosion preceding the Keweenawan deposition beveled the iron-formation in the Sunday Lake area and farther east, and the boulders in the basal conglomerate of the Keweenawan show that there was some concentration at this time. This probably was a factor in the concentration of the Brotherton, Sunday Lake, and Castile ore bodies, but not of the ore bodies in the main producing part of the range, to the west. There the pre-Keweenawan erosion did not expose the iron-formation, which remained blanketed with a thick mass of slate. In Minnesota any Keweenawan surface beds that may have covered the Cuyuna, Vermilion, and Mesabi districts have been stripped away, leaving no evidence for or against surface concentration during the pre-Keweenawan erosion interval.

4. By far the larger part of the Lake Superior iron ore, including practically all the soft ore, was concentrated in the post-Keweenawan period of erosion that preceded the deposition of the Cambrian sediments. There is no positive evidence that the parts of the iron-formations carrying most of the soft ores were ever before exposed to erosion. Basal conglomerates of the Cambrian carry abundant boulders of fully concentrated ore. The erosion surface on which they rest records one of the most striking examples of long-continued and deep erosion known in geologic history. During this time all the great folds of the pre-Cambrian were truncated. Restoration of these folds shows mountainous conditions, where surface waters must have had a head comparable with that existing in mountainous regions of today, where oxidizing solutions are known to penetrate to far greater depths than they do in the Lake Superior country. Furthermore, this period is known, from the character of the Keweenawan sediments, to have been one of a semiarid climate under which the water table must have been far below the surface.

Each of the earlier erosion surfaces described in the foregoing paragraphs was beveled by the later ones. Each time oxidation and leaching of silica created porous zones, which were utilized by waters from later surfaces. Such predisposition to concentration was undoubtedly an important factor in the efficacy of the great concentration of post-Keweenawan time.

These reconstructed conditions (which were substantially outlined over 20 years ago [69]) seem to be adequate to explain concentration by surficial waters to any depths yet known. However, recent exploration has showed that one of the Gogebic deposits extends down to 3,000 feet from the pre-Cambrian erosion surface, with the end not yet in sight. This ore may be related to the post-Negaunee erosion surface described under paragraph 2, above, but the evidence of this unconformity is not yet conclusive. If the unconformity does not exist, then the ore must be related to the post-Keweenawan erosion surface. This calls for a review of the conditions existing in the post-Keweenawan erosion epoch to explain how oxidizing and leaching waters from the surface could penetrate to so great a distance. This is apparently beyond the depth of oxidation known today in any of the semiarid mountainous regions of the West, where the depth of oxidation is presumably a maximum. However, existing information in mountainous regions is mainly confined to a few mining districts, and the ultimate possibilities have perhaps not yet been disclosed. If a depth of 3,000 feet proves to be beyond the reach of penetration of the surface waters in a mountainous semiarid period, modification of the hypothesis here presented may become necessary. Concentration may have begun early in the period of Keweenawan tilting and continued during the Keweenawan folding, with the downward migration of the erosion plane, but under the influence of temperatures higher than normal, owing to the slow cooling of the thick blanket of Keweenawan lavas and its associated intrusives. Ore bodies so formed, before the tilting was complete, would be rotated by the further tilting, thus reaching a greater vertical depth. Geologic and physical evidences are multiplying that igneous rocks of such mass cool very slowly, raising the question whether an inheritance of heat from this source may have accelerated the leaching of silica from the ores by ordinary surface waters through a

[69] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U.S. Geol. Survey Mon. 52, pp. 557–560, 1911.

very long period. This might help to explain the fact that so much of the concentration took place before Cambrian time and so little since. The process is the same in kind before and since, but the striking difference in degree has heretofore been taken as just another evidence of the immense length of time represented by the erosion interval preceding the Cambrian.

Although higher temperature will accelerate the process of concentration, it still fails to account for the hydraulics of such deep flow. Waters are ordinarily ponded and stagnant at such depths. For the exceptionally deep ore bodies the possibility has been considered that there may have been unusually deep and direct channels, both for inlet and outlet of waters, that might have carried active artesian circulation far below the normal water table, as in the case of a stream carried in an inverted pipe elbow. Several years ago James Thompson, one of the successful explorers of the Gogebic range and the discoverer of the deep Newport ore body, worked on the assumption that the ore body might continue eastward down the pitch to a depth of 2 miles or more, until intersected by a cross fault known in the vicinity of Bessemer, which would serve as the outlet. It is difficult to prove or disprove such a hypothesis on theoretical grounds, and the deep ore bodies in question have not been developed far enough to show whether or not such outlets to the surface exist. If an unconformity exists between the iron-formation and the overlying slates, which is possible, as already indicated, this would afford a porous zone of easy flow. It should be noted, also, that so far as concentration occurred before the Keweenawan tilting was complete, the ore was nearer the surface than today—a fact which would make it easier to accept the idea of artesian circulation with cross faults as outlets.

In the Marquette district soft ore has been found by drilling to a depth of 3,000 feet below the surface. This ore lies along the extension of the Negaunee mine and contiguous ore bodies that connect directly with the surface, and it seems likely that direct surface connection with the ore in the drill hole will eventually be demonstrated. The iron-formation was exposed to weathering before the deposition of the Goodrich quartzite, which is the bottom of the next overlying (Upper Huronian) group. It was also exposed in post-Keweenawan time, and there are various lines of evidence that this was the time of the formation of the soft ores of this district. There is no evidence to indicate whether or not the district was covered by surface flows of the Keweenawan, but intrusives of supposed Keweenawan age are abundant. As in the case of the deep ore of the Gogebic range, it is not certain that this ore was beneath the range of active artesian circulation of cold waters from the surface, either in pre-Goodrich time or during the long period of peneplanation that preceded the Cambrian. But again it is possible that the waters from the surface were warmed and that the process was well started before the Keweenawan folding was complete, when the deep concentration now known was much nearer the surface.

In conclusion, the general hypothesis of concentration of the iron ores by downward-moving waters from the surface, as presented in Monograph 52, still seems to be adequate to cover the great body of facts yet known, and it is too early to say how far additional qualifications are necessary to explain the few exceptionally deep concentrations that have been found. The problem has a direct practical bearing on estimates of the future Lake Superior mines, and it has been receiving close attention for years from geologists concerned in the detailed study of these mines.

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