DESCRIPTION OF THE MENOMINEE QUADRANGLE.

INTRODUCTION.

This account of the geology of the Menominee iron-bearing district of Michigan will be followed by a more detailed report, to appear later as one of the set of monographs issued by the Survey on the iron-ore districts of the Lake Superior region. This folio is based mainly upon field work during 1896 and 1899, but before 1896 the senior author had devoted a considerable amount of time to a general study of the structure of the district. The reason for presenting this account at the present time, rather than later as an abstract of the completed monograph, is the belief that it will be useful to the explorer in developing the resources of the district.

The description here given centers about the accompanying geological map of the district. The only detailed geological maps of the Menominee district that have heretofore been published are those of Brooks and Wright, in the Geology of Wisconsin. Irving published a generalized map of the district, with sections, in his introduction to Dr. George H. Williams's bulletin on the origin of the greenstone-schists of Menominee River (Bulletin No. 62, U. S. Geological Survey, 1890). Wright's map shows the distribution of the greenstone-schists, some of the iron-bearing belts, and the pre-Huronian rocks of the district; Brooks's map shows, in addition to these, the locations of all the ledges of dolomite, slate, quartzite, and other sedimentary rocks met with during his explorations. Brooks also presents a structural sheet illustrating his views as to the sequence of the rock series and the character of the folding. This map was of much use to us in our field work, since it enabled us to make systematic plans for the survey of the district, and directed our attention to many rock ledges that might otherwise have been overlooked.

Many of the large iron-producing companies and many independent explorers are now actively engaged in a search for new ore deposits. Every nook and corner of the Menominee district is being carefully examined in the hope of discovering ore bodies. Old drill holes are being re-examined, abandoned mines are being unwatered, and old ground is being more thoroughly explored. Unfortunately, some of the explorers are apparently ignorant of the results of work already done, and are duplicating this work, thus wasting time and money that might be usefully employed in other directions, while other explorers are working at places which the geology of the district indicates to be unfavorable to the development of ore deposits. On the other hand, considerable belts which our studies point out as favorable places for exploration have been entirely neglected. In spite of the fact, therefore, that the map here presented is not so complete in details as it will be possible to make it, it is thought wise to publish it, in order that the facts represented upon it may, at the very earliest moment, be available to those who are most interested in the development of the district. A more detailed map will be published later in the monographic report, but some time must elapse before the elaborate studies necessary to the production of such a map can be completed. Meanwhile, the present report will suffice to give the main conclusions already reached concerning the districts. It will serve at least to direct exploration toward certain parts of the district that have not heretofore been investigated and to warn against further waste of money in certain other portions, where the conditions preclude a reasonable probability of any return for the investment.

To the mining men of the district many thanks are due for the uniformly courteous treatment that has been accorded the authors. Mine plats and cross sections, records of drill holes, and statements of the results of test pitting have been placed at our disposal, and all these sources have been drawn upon for facts. All inquiries that have been made of mine superintendents and engineers concerning the mines with which they are connected have been carefully considered and, when possible, fully answered by them. Not a single request for information has been denied. To the energetic and courteous mining men of the district, therefore, this folio owes much of the value it may possess.

DESCRIPTIVE GEOLOGY.

Position and extent of the district.—That portion of the Menominee district covered by the accompanying map is bounded on the west by the Menominee River, on the south by the same river and the south line of T. 39 N., Michigan, on the north by the north line of T. 40 N., Michigan, and on the east by the east line of secs. 10, 15, 22, 27, and 34, T. 39 N., R. 28 W., Michigan. The area thus outlined and a small unmapped area to the southeast, extending from the southern limit of the area mapped southward to the Menominee River, constitute a tongue of sedimentary deposits lying between a granite area to the north and a greenstone-schist area to the south. This tongue of sediments is the southernmost of five distinct tongues which extend eastward from the great central area of Huronian deposits in Wisconsin and Michigan. The tongues are separated from one another by areas of granite. The five tongues, beginning with the northernmost, are the Marquette, the Sagola, the Felch Mountain, the Calumet, and the Menominee. (See fig. 1.) Each is structurally a trough of sediments lying between rims of Archean rocks. To the west each of these troughs widens into the broad expanse of Huronian sediments referred to above. To the east all except the Marquette tongue plunge beneath Paleozoic deposits.

At about the line between Rs. 27 and 28 W., the characteristic rocks of the Menominee trough become so deeply buried under later sediments that they can be traced no farther. Lines of magnetic attraction, however, have been obtained still farther east, and these are taken to mean that the Huronian deposits continue for at least a short distance beyond the places where they are last seen on the surface.

The area underlain by the rocks belonging to the Menominee trough is about 125 square miles, entirely within the State of Michigan. In 1899 it shipped 2,348,205 long tons of iron ore, and since the first shipment of ore from the Quinnesec mine, in 1873, the aggregate shipments from all mines to the close of 1899 have amounted to the large total of 20,857,609 tons. The total shipments from the Marquette district to the end of the same year are 56,135,271 long tons; those from the Crystal Falls district, including the Iron River, Felch Mountain, and Calumet areas in Michigan, and the Florence area in Wisconsin, have amounted to 9,902,158 long tons; those from the Gogebic range in Michigan and Wisconsin, to 28,341,340 long tons; those from the Vermilion range in Minnesota, to 13,535,350 long tons; and those from the Mesabi range in the same State, to 23,595,606 long tons. In proportion to its area the Menominee trough has yielded as large a product as any other of the Lake Superior districts with the exception of the Marquette. Since the discovery and development of the Mesabi district the demand for low phosphorus and high silica ores to serve as mixtures for the Mesabi ores has so largely increased that many lean, low phosphorus ore deposits, formerly not marketable, now find a ready sale. The Menominee district can furnish an abundance of this grade of ore, so that it is probable that the importance of the district as a mining center will increase rather than diminish in the future.

The area of sedimentary rocks in the Menominee trough is narrowest in the vicinity of Vulcan, where it measures about 4 miles in width from the contact with the granite on the north to the contact with the greenstone-schists on the Menominee River to the south. To the east the area widens gradually, until in the eastern portion of R. 28 W. its width measures about 7 miles. To the west it also widens gradually, and finally loses its identity as a distinct trough at about the center line of R. 30 W., where it merges, with the Calumet trough, into the wide area of Huronian sediments to the west.

Classification of formations.—The rocks of the Menominee district belong to the Archean, Algonkian, and Paleozoic systems. The oldest series of rocks bordering the Menominee tongue comprises greenstone-schists and granite. These are regarded as Archean. Resting uncomformably upon the Archean rocks are two series of Algonkian sediments, both of which are believed to belong to the Huronian system. These are divisible into a Lower Menominee and an Upper Menominee series, and are separated by an unconformity. The Paleozoic rocks comprise horizontal Cambrian sandstones and Silurian limestones. These occur in patches on the tops of the hills, capping the closely folded and truncated Huronian rocks. Both of the Menominee series are divisible into a number of formations, each representing a time during which the conditions of deposition were approximately uniform. Each of the pre-Cambrian formations has been given a name and is represented on the map by a distinctive color. The following table gives the list of the formations arranged in descending order according to age. The fractional formations, or members of the Vulcan formation, are distinguished in the description, but not on the map.

Table showing the succession of formations in the Menominee district and their relations to general geological systems.

Systems.	Series.		Formations.
Paleozoic	Lower Silurian.	Chazy. Calciferous.	Hermansville limestone.
	Cambrian	Potsdam	Lake Superior sandstone.
	Unconformity.		
Algonkian	Upper Menominee		Hanbury slate.
			Vulcan formation, subdivided into the Curry ore-bearing member, Brier slate, and Traders ore-bearing member.
	Unconformity.		
	Lower Menominee		Negaunee formation.
			Randville dolomite.
			Sturgeon quartzite.
	Unconformity.		
Archean			Granites and gneisses, cut by granite and diabase dikes.
			Quinnesec schists, cut by acid and basic dikes and veins.

The names of the Upper Menominee formations and of the Archean schists are taken from localities in the district. The names of the Lower Menominee formations are those of formations in adjacent districts already reported upon, with which the Menominee formations are believed to be continuous. Beginning at the bottom, the Quinnesec schists are so named because they are typically developed at the Quinnesec Falls, on the Menominee River. The Sturgeon quartzite is so called because this formation in the Menominee district has been traced almost continuously to a like formation in the Crystal Falls district which has been called the Sturgeon quartzite. The dolomite in the Menominee district is called the Randville dolomite because it has been practically connected with the Randville dolomite of the Crystal Falls district.

The Lower Menominee iron formation is called Negaunee because this is the chief Lower Huronian iron-bearing formation of the Marquette district. In the Menominee district, as will be seen, only patches of this formation remain.

In the Upper Menominee series the Vulcan formation is so named because the iron formation occurs in typical development with full succession and fine exposures in the vicinity of the town of Vulcan. The Hanbury slates are thus named because in the vicinity of Lake Hanbury this formation is better exposed than anywhere else in the district.

ARCHEAN SYSTEM.

Two areas of Quinnesec schists.

General description.—Along the Menominee River, to the south of the Huronian rocks, is a complex of dark-green or black basic schists, designated the Quinnesec schists, cut by large dikes of gabbro, diabase, and granite and by smaller dikes and veins of a schistose quartz-porphyry. This will be called the southern area of Quinnesec schists. A second area of Quinnesec schists occurs in the central part of the western end of the trough, but only the eastern end of this area comes within the limits of the maps. It is wedge shaped, widening toward the west. It is surrounded on the north, east, and south sides by the Huronian sediments. To the west it crosses the Menominee River into Wisconsin, where it has not yet been studied in detail. The rocks are greenstone-schists and spheroidal greenstones, cut here and there by basic dikes. This area will be called the western area of Quinnesec schists.

Northern complex.

On the north the Huronian sediments are bordered throughout nearly their entire extent by a complex of granites, gneisses, hornblende-schists, and a few greenstone-schists, all of which are cut by dikes of diabase and dikes and veins of granite. This will be called the northern complex.

Why called Archean.

The Quinnesec schists and the granites and gneisses are placed in the Archean for the following reasons: First, in lithology and structure they have all the complex characters which have been described by the senior author in previous papers and in monographs as typical of the Archean. Moreover, this complex of rocks along the northern side of the Menominee trough underlies unconformably the Lower Huronian series, as elsewhere in the Lake Superior region. The Quinnesec schists underlie the Huronian sediments, but whether they are unconformable below them has not been positively determined, since no contacts have been found. Furthermore, the Quinnesec schists are in every respect identical with similar Archean schists in the Marquette district of Michigan and with the Archean schists in the Vermilion district of Minnesota. Therefore, while it can not be demonstrated beyond question that the Quinnesec schists are pre-Huronian and therefore Archean, this is believed to be highly probable.

QUINNESEC SCHISTS.

Schists along the Menominee River.

Southern area.—The southern area of Quinnesec schists lies along and adjacent to the Menominee River, from the sharp northward bend in the river due west of Iron Mountain to the eastern limit of the mapped area. For this distance the river is bordered by schistose greenstones and various rocks that cut them, except at a few places where rock ledges are absent. The Quinnesec Falls and Sturgeon Falls are on some of the harder ledges of these rocks. Near the Menominee River the rocks of the complex are greenstone-schists, gabbros, diabases, and diorites, cut by dikes of the last three named rocks, by dikes of granite, and by veins of quartz. South of the river, in Wisconsin, at a distance of from half a mile to two miles, is the north side of a large area of granite. This granite sends apophyses into the greenstone-schists, and consequently is of later age. Only the greenstone-schists with their intruded masses come within the limits of the area mapped, therefore only these will be referred to here.

Varieties and relations of schists.

The greenstone-schists comprise chlorite-schists and sericite-schists, schistose diabases, schistose diorites, and schistose and massive gabbros. For the most part, these are arranged in belts striking a little north of west at the Sturgeon Falls, but trending more northerly as one passes up the river, until at the Upper Quinnesec Falls they strike about northwest. In several places the schists are cut by basic dikes whose material is saussuritized gabbro or diorite. At the Horserace Rapids, in secs. 7 and 8, T. 39 N., R. 30 W., the predominant rocks are coarse-grained diorites, some of which are fairly massive and others rather gneissic. In the neighborhood of the Horserace Rapids and of the Upper Quinnesec Falls large quantities of acid rocks are associated with the basic rocks. In some places these are dikes and veins of nearly massive granite, in others beds and dikes of gneissoid granite, and in still other places finely banded and schistose rocks, resembling the Saxon granulites. The last-named rocks occur in bands of different widths, nearly always striking conformably with the schistosity of the greenstones, which is approximately east-west. Wherever the bands exhibit any evidence of schistosity this is always parallel to the foliation of the adjoining greenstone-schist, irrespective of the direction of the band itself. These bands were regarded by Williams as apophyses from the great granite mass of the south, which at the Horserace is only about half a mile distant from the river.

Schists derived from igneous rocks.

From the field relations and microscopical study of the Quinnesec schists and their associated rocks we must conclude that all are igneous in origin. Many of them were lava flows; some were beds of volcanic ashes, or tuffs; others were huge dikes cutting through the bedded deposits. Where subjected to great pressure, such as that which compressed the iron-bearing series into folds, these rocks suffered many changes. Their original constituents were largely recrystallized. The finer-grained rocks, under the influence of the stresses set up in them, became schistose, partly through the granulation of the original components and partly through recrystallization. The particles of some of the newly formed minerals developed with a parallel arrangement, giving a schistosity. The coarse-grained rocks were also made schistose by the same processes, but the grains of these were so much stronger than those of the finer-grained rocks that they were able to resist the deforming agencies more successfully, with the result that their schistosity is much less marked than in the case of the finer-grained materials.

A few small dikes cutting the schists are younger than the latter. They are normal diabases and basalts, identical in composition with some of the rocks cutting through the iron-bearing series.

Western area.—The western area of Quinnesec schists occupies about 5 square miles. It extends from about the center of sec. 15, T. 40 N., R. 30 W., Michigan, to the Menominee River. The normal schists are occasionally cut by altered diabase dikes, but the gabbro dikes and the granite dikes so prominent in the southern schists are entirely absent from them, at any rate so far as they are exposed in Michigan. The Fourfoot Falls are at the southern side of the area, where it crosses the Menominee River, and the old Indian village of Badwater is at its northern limit. The Twin Falls plunge over ledges of the schists.

Schistose and massive greenstones.

The schists are grayish-green, fine-grained greenstones, in which schistosity is nearly everywhere noticeable. In some places the rocks are well-defined schists, with a cleavage almost as perfect as that in slates; but in other places they are nearly massive. On many of the exposures a typical ellipsoidal structure is discernible. The ellipsoids vary in diameter from a few inches to 3 or 4 feet. There is no striking contrast between the material of the ellipsoids and that of the matrix between them. In both cases the rock is a dense grayish greenstone without any distinct textural features. The matrix is usually slightly more schistose than the ellipsoids, but otherwise it is like them. At the Fourfoot Falls the exposures consist of alternating beds of massive, schistose, and slaty rocks, striking about N. 80° W., almost at right angles to the course of the river, and yet these rocks are mostly schistose on the Wisconsin side of the river and mostly massive on the Michigan side. In this respect as in others the western schist area is similar to the southern schist area. The field observations indicate that the western area, like the southern, contains a variety of strongly metamorphosed volcanic rocks.

Schists formerly basic igneous rocks.

The microscopical examination of thin sections shows that some of the rocks in the western area are altered diabases still preserving their characteristic textures. Others are so much changed that their original nature can only be inferred from the character of their alteration products. Some of these appear to have been fine-grained diabases and others perhaps glassy basalts. A few others were originally basic tuffs. All are now aggregates of actinolite, uralite, zoisite, epidote, quartz, and other well-known decomposition products of basic igneous rocks.

Relations to adjacent formation.—There are no contacts visible between the Quinnesec schists and the adjacent Huronian sediments. Exposures of the two series are found in closest proximity on the Menominee River near the Fourfoot Falls. The Chicago and Northwestern Railway bridge crossing the river at this place is built on ledges of the schist. Below the bridge is a long exposure of black slate belonging to the Hanbury formation of the Upper Menominee. The schists and the slates are separated by a distance of about 150 paces, and this interval is occupied by sand and glacial drift. There are, then, no certain data for determining the age of the schists. Since, however, the southern and western schist areas are composed of the same kinds of rocks, since they have the same relations to the Huronian sediments, and since in both cases the rocks have been subjected to approximately the same degree of alteration, the Quinnesec schists of both areas have been placed together in the Archean.

NORTHERN COMPLEX.

Granites, gneisses, and schists.—The abundant rocks in the northern complex are rather fine-grained gneissoid granites and finer-grained banded gneisses. In addition to these there are also present in subordinate quantity a few coarse-grained gneisses, some hornblende-schists, and certain feldspathic greenstone-schists identical with some of the mashed eruptives among the Quinnesec schists. Mica-schists also occur, but they are rare. They are found only in a few exposures in the interior of the Archean area north of the limits of the map. The granites, gneisses, and schists are cut by intrusive coarse-grained and fine-grained basic rocks, by small dikes and veins of pegmatite, and by numerous quartz veins. Some of the hornblende-schists and some of the gneisses appear to be older than most of the granites. Others of the schists are unquestionably mashed intrusives that are younger than some of the granites. The aplites, pegmatites, and some of the basic intrusives are the youngest rocks belonging exclusively in the complex, but even these, since they are not known to cut through the Huronian deposits, are thought to have taken their present position before the sediments were deposited. The latest of all the intrusives are certain coarse-grained massive diabases and gabbros. These rocks not only occur as members of the complex, but are found also in the lower member of the Huronian series, overlying the Archean complex. There is no reason to believe that any of these rocks are metamorphosed sediments. Most of them are clearly igneous in origin.

Varieties of the granites and gneisses.

The massive granites and the gneissoid granites differ from each other in no essential respect. The latter are merely schistose phases of the former. They both embrace medium-grained to fine-grained gray and pink rocks with a granitic texture that sometimes approaches in appearance the texture of some quartzites. The pink or red granites are usually a little coarser grained than the gray ones. In the hand specimen red orthoclase is seen to be the principal constituent. In addition to this there can also be detected a few grains of white feldspar, a large number of quartz grains, and an occasional flake of mica. The gray granites appear almost homogeneous. Here and there through them are stringers and patches of pink granite, but most of the hand specimens are of a nearly uniform dark-gray tint. The gray rock passes into the pink rock by almost imperceptible stages, the differences in the tints of the two end members of the gradation series being due mainly to the color of their feldspathic component.

The banded gneisses consist of alternate bands of pink and gray material, each band having the look of granite. These bands, while appearing to be approximately parallel in the ledges, are found upon close inspection to run parallel to one another for short distances only, and then to anastomose or interlace. The red layers cut across the gray gneiss as though they were veins of granitic material. The only difference that can be discerned between the banded gneisses and the fine-grained gray gneisses cut by red granite veins is that the latter are irregularly injected by the granitic material, while in the former the injections are largely parallel.

Older and younger hornblende-schists.

The hornblende-schists are usually lustrous greenish-black schists with the normal characteristics of such rocks. They are cut by the granites in some places. In other places large blocks are found included in granite. Plainly they are older than the granites, and probably they are the oldest rocks in the northern complex. A second kind of hornblende-schist exists in which the rocks are so related to the granites and gneisses that they must be regarded as dikes. In some places they appear as bands cutting across the banding of the gneisses, and in others as bands conforming in strike and dip with the lighter-colored bands of these rocks. These schists are therefore looked upon as mashed intrusives.

SUMMARY.

From the above brief outline of the Archean rocks it is learned that they are all completely crystalline. Some of them are undoubted igneous masses; others are schists of such a nature that their igneous origin is inferred with little, if any, probability of error. No ordinary sedimentary rocks are found among them. The volcanic tuffs are indeed fragmental, and some of them, possibly, were deposited under water, but of this there is no evidence whatever. They were not formed by the wearing away of a preexisting land surface by the joint action of the air, rivers, and waves, and consequently they are essentially different from the ordinary sediments whose material was derived from land masses through the operation of these agencies. The Archean rocks of the district are thus strongly contrasted with the Huronian rocks described in the following pages.

ALGONKIAN SYSTEM.

General character and definition.—The Algonkian rocks constituting the Menominee trough, though strongly metamorphosed, are recognized as mainly sediments. The greater mass of these sediments is mechanical, clastic textures being still plainly apparent. The iron formations are largely mechanical, but with the mechanical material an important amount of chemical and organic material was deposited, and some of the jaspers of the formation may be wholly chemical or organic. The limestones are chemical or organic sediments. The sedimentary rocks have been intruded by a few coarse-grained and some fine-grained igneous rocks. The latter are now usually schistose. The lowest member of the Algonkian system has at its bottom basal conglomerates, which rest unconformably upon the Archean rocks of the northern complex. These conglomerates may be seen at a number of places along the border of the trough, and notably at the falls of the Sturgeon River.

The members of the system are likewise separated from the overlying Cambrian sandstone by a profound unconformity. The Algonkian rocks are folded; the sandstone is horizontal. The latter thus lies across the truncated ends of the eroded folds. Its lower layer is formed largely of the débris of the more ancient rocks. Hence the Algonkian rocks formed a land surface for a vast period of time before the deposition of the Cambrian sandstones.

Within the Algonkian system there is also an unconformity, corresponding to that in the Marquette district between the Upper Marquette and the Lower Marquette series. This unconformity is not so plainly marked in the Menominee as it is in the Marquette district, but it is nevertheless so plainly indicated that there can be little doubt of its existence. In the Marquette district the unconformity is indicated by a marked discordance between the upper members of the lower series and the lowest members of the upper series, and by the presence of a widespread basal conglomerate in the upper series. In the Menominee district the direct evidence of the unconformity is the presence of a conglomerate or of a coarse quartzite at the base of the upper series containing undoubted fragments of some of the rocks of the lower series. There is also, in addition, indirect evidence of the unconformity in the absence in parts of the district of the lowest and most resistant members of the Algonkian series—the Sturgeon quartzite and the Randville dolomite. The non-existence of the Vulcan formation in parts of the district adjacent to the Randville dolomite and the overlapping of the Vulcan formation by the Hanbury slate at some of these places give further evidence of unconformity. The Algonkian system is therefore divided into a Lower Menominee and an Upper Menominee series, equivalent to the Lower Huronian and the Upper Huronian elsewhere in the Lake Superior region.

LOWER MENOMINEE SERIES.

Succession and distribution.—The Lower Menominee series is divided into three formations. These are, in the order of upward succession, the Sturgeon quartzite, the Randville dolomite, and the Negaunee formation.

Not present on the southern side.

The formations belonging in the Lower Menominee are observed only in the center and on the northern side of the Menominee trough. On the southern side of the trough no evidence of the existence of these formations is obtainable. This may possibly be due to the thick covering of drift that blankets the rocks north of the southern area of Quinnesec schists; but it is thought to be more probable that these formations are actually absent from this portion of the district, since it is hardly credible that two such resistant formations as the Sturgeon quartzite and the Randville dolomite could have been so completely planed down in this particular portion of the area as to leave no projecting ledges above the drift, whereas, in the central and northern portions of the trough they constitute the prominent elevations. If the absence of these formations be confirmed by future explorations, the fact may indicate that they were never deposited on the areas from which they are wanting, or that they were deposited in whole or in part and eroded during Huronian time.

STURGEON QUARTZITE.

Distribution, character, and position.—The Sturgeon quartzite forms a continuous border of bare hills on the southern side of the northern complex. The formation lies between the Archean complex and the northern belt of dolomite. Prominent bluffs of the typical quartzite may be conveniently studied northeast of the Loretto mine.

Basal conglomerate.

At many places at the base of the Sturgeon quartzite there is a conglomerate made up of bowlders and fragments of granites, gneisses, and hornblende-schists, identical with the corresponding rocks in the adjacent Archean complex to the north. The matrix in which these are embedded is in some places a quartzite; in other places it is an arkose composed of the fine-grained débris of granitic rocks. In many places this matrix is schistose, and in these cases a large quantity of a micaceous mineral has been produced by alteration of the feldspar of the original sediment, so that the matrix is now lithologically a sericite-schist.

White vitreous quartzite.

The major portion of the formation consists of massive beds of a very compact, vitreous quartzite, usually white, but occasionally tinted with some shade of pink or green. In its upper portion the cement between the quartz grains is often calcareous. This calcareous constituent increases in quantity as the overlying dolomite is approached, until the rock becomes a calcareous quartzite and finally a quartzose dolomite. The change from the quartzite to the dolomite is thus a transition. This indicates a gradual deepening of the waters during the later part of the Sturgeon epoch.

Southward dipping monocline.

The main belt of the Sturgeon quartzite is a nearly vertical southward-dipping monocline. The outcrop of this monocline varies in strike, thus indicating that cross folding has taken place to some extent. At the western end of the district the quartzite turns northward, wrapping around the Archean complex, and then passing eastward into the area of the Calumet trough. (Fig. 1.) On the turn to

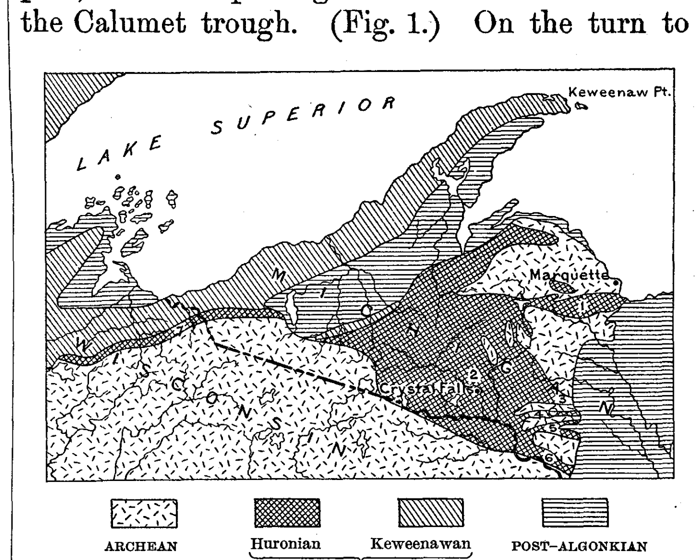

Fig. 1.—Map showing relation of the Menominee district to the other iron-bearing districts of Michigan and Wisconsin. Scale: 1 inch = 60 miles.

1. Marquette district.
2. Crystal Falls district.
3. Sagola area.
4. Felch Mountain area.
5. Calumet area.
6. Menominee district.
7. Penokee district.

the north, several small folds are developed, the synclines of which are now represented by embayments extending eastward into the Archean. (See Structure section BB.) The dips of the quartzite beds may vary a few degrees—25° in one case—from perpendicularity. There are almost as many northern dips toward the granite-gneiss complex as there are southern dips toward the center of the trough.

Two difficulties stand in the way of determining the thickness of the Sturgeon quartzite. The first is the impossibility of deciding how much of the apparent thickness of the many rock layers in a closely folded district, like the Menominee, is due to the duplication of beds in consequence of close folds. The other difficulty is our inability to fix the upper limit of the formation. There is everywhere between the quartzites and the nearest ledges of the overlying dolomite a belt of country without exposures of any kind. If we assume that the southward-facing cliffs which so frequently mark the southern limit of the quartzites are cliffs of differential degradation, that the low ground at the base of the cliffs is underlain by the dolomite formation, and that the exposures are monoclinal, the thickness of the quartzite may be easily calculated at a number of places. At the gorge below the falls of the Sturgeon River is a continuous exposure of conglomerate and quartzite beds about 350 paces in width. For 300 paces the walls of the gorge are in evenly bedded quartzite striking N. 57° W. and dipping 75° to 83° N. An inspection of these beds reveals no indication of folding. The formation in its entire width appears to consist of consecutive beds. The thickness corresponding to this width, calculated at an average dip of 80°, is 915 feet. Approximately the same result is reached from measurements made on the east side of the river a few hundred feet from the river bank. Here the breadth of the formation is 400 paces and its dip 70° N. The corresponding thickness is about 1050 feet. A third calculation, made upon data obtained farther west, gives 1250 feet. It is probable that the Sturgeon quartzite, like sedimentary formations elsewhere, varies in thickness at different places, but it seems safe to assume that the above figures represent a fair average and that its maximum thickness is between 1000 and 1250 feet.

Thickness 900 to 1250 feet.

The Sturgeon quartzite rests unconformably upon the northern complex. This is shown by the character of the lower horizon of the quartzite, which, as already said, is a basal conglomerate. This basal conglomerate contains almost every variety of fragment derivable from the rocks of the northern complex. Some of this material in its original position must have been formed at great depth in the earth. Therefore there was deep-seated denudation of the Archean before the deposition of the quartzite. Upward, the Sturgeon quartzite grades into the Randville dolomite. The nature of the gradation is discussed under the latter heading.

Unconformity below, transition above.

RANDVILLE DOLOMITE.

Distribution, character, and position.—The Randville dolomite occupies three separate belts, whose positions and shapes are determined by the folding to which the formation has been subjected. These will be referred to as the northern, central, and southern belts of dolomite.

The northern belt is south of the belt of Sturgeon quartzite. Only a few exposures are found in this area, but they are so uniformly distributed that the whole belt has been colored for the formation. It is quite possible that in some places erosion has carried away the dolomite and that the Upper Huronian rests immediately upon the quartzite, but in the present state of our knowledge this assumption does not seem justified. The country underlain by the northern belt of dolomite is now the valley of Pine Creek. It is a low plain, covered by sand, which has been partly deposited by the creek and partly by glaciers. It was a valley long before the advent of the glaciers, and there is some evidence indicating that there was a valley in this place even before the deposition of the Cambrian sandstone. The long-continued erosion produced by the Pine Creek drainage has reduced the area to one of low relief. This topography is very different in character from that of the other dolomite areas, which correspond to divides, and thus are elevations rather than depressions.

Northern dolomite belt.

The central belt of dolomite borders the north side of Lake Antoine for a portion of its length, passes eastward between the Cuff and the Indiana mines, and ends at the bluff known as Iron Hill in the east half of sec. 32, T. 40 N., R. 29 W. This belt is well marked by numerous and often large exposures, but, as in the area just described, the exposures are not continuous. On the map the color of the dolomite formation has, however, been made to cover the area between sets of exposures, because we have no evidence that the rock is not at present beneath the soil.

Central dolomite belt.

The southern belt of dolomite extends all the way from the western side of the sandstone bluff west of Iron Mountain to the village of Waucedah, at the eastern end of the mapped area. Where not exposed at the surface the rock has been found in mines and test shafts and pits, so that there is a reasonable certainty that it exists throughout this distance of 16 miles. Where there is any doubt of its existence this is due to a considerable thickness of overlying Lake Superior sandstone. From Iron Mountain as far east as the Sturgeon River the country underlain by the dolomite is a range of high hills broken only at a few points by north-south gaps. On the southern slope of the ridge are the principal producing iron mines of the district. The northern boundary of the southern belt is in general very indefinite. At several places, especially near the transverse gaps referred to above, the northern limit can be fairly well determined by exposures, but elsewhere the country in its neighborhood is so deeply drift covered that the boundary can not be definitely fixed without recourse to test pits and shafts. The southern boundary, on the other hand, is rather sharply delimited, not merely by exposures, but also by the underground workings of many of the mines.

Southern dolomite belt.

Character and variations.—The Randville dolomite is composed of a heterogeneous set of beds in which dolomite is dominant. With the pure dolomites are siliceous dolomites, calcareous quartzites, argillaceous rocks, and cherty quartz rocks. The Randville dolomite, lying upon the Sturgeon quartzite, grades downward into it. The intermediate rock is a calcareous quartzite.

The predominant rock of the Randville dolomite is an almost massive, apparently homogeneous, fine-grained, white, pink, blue, or buff dolomite, occurring in beds from a few inches to many feet in thickness. This is interstratified with beds of siliceous dolomite in which are observable numerous grains of quartz. In many cases on the weathered surfaces of the dolomites are thin projecting bands parallel to the bedding, which the microscope shows to be calcareous quartzite. In other cases projecting bands anastomose or run irregularly over the weathered surfaces, often intersecting the bedding planes of the rock at acute angles. These seams are plainly narrow veins of quartz. Their abundance proves clearly that the dolomites, in spite of their homogeneous appearance, have been extensively fractured and crushed. In many places the crushing has produced a breccia of dolomite fragments in a siliceous matrix. In a few instances the fragments are rounded, so that the rock is a pseudo-conglomerate.

Massive homogeneous dolomite.

The greater part of the argillaceous rocks interstratified with the dolomite is soft, light-gray or dark-gray slate. Another part is typical black slate, still plainly marked by bedding lines. Still other parts are purplish-pink, schistose, argillaceous dolomite. In many instances the thin layers of the purplish-pink slate-like material between massive dolomite beds appear to be largely the selvage of the softer layers of dolomite, rendered schistose by the movement of accommodation between the stronger beds. The cherty quartz rocks are fine grained, drusy in places, and in color white, light red, or dark purple. The darker-colored kinds look very much like some varieties of jaspilite. Under the microscope the cherty quartz rocks seem to be composed almost exclusively of a fine-grained crystalline aggregate of quartz which incloses a few grains of hematite, magnetite, and other iron compounds. Here and there a fragmental quartz grain may be seen, but usually no trace of fragmental constituents can be discerned. These rocks thus appear to be gradation phases between the dolomite and the jaspilites of the Negaunee formation.

Schistose and slaty varieties.

Cherty quartz varieties.

So far as known, none of the beds above described occupy continuously any given horizon in the formation. It appears, however, that the quartzitic dolomites are more frequently near the base of the formation than elsewhere, and that the cherty quartz rocks are often at or near its top. If the cherty quartz rock is a transition between the dolomite and the non-fragmental iron formation, as it is believed to be, its absence at many places is easily accounted for by the erosion that removed the greater part of the Negaunee formation. The erosion at some places ceased at the horizon of the cherty quartz rocks, but at other places continued until it also was removed and the dolomite was reached.

Structurally the northern belt of dolomite is a southward-dipping monocline. The central and southern belts are anticlines. Between the three belts are two synclines. South of the southern belt is a syncline, on the southern limb of which one might expect to find a belt of dolomite. This belt might be anticipated to appear above a belt of Sturgeon quartzite, both overlying the Quinnesec schists of the Menominee River. Apparently, however, the quartzite and limestone were not deposited, or both have been completely removed by erosion during inter-Menominee time, so that the formations of the Upper Menominee series lie upon the greenstone-schists. (See Structure section AA.)

A monocline and two anticlines.

In the anticlinal belts the beds at first sight appear to be isoclinal, but a close examination of the southern belt reveals the existence of a number of minor folds having almost vertical limbs. In the western part of the district the folds are overturned to the south, the axial planes dipping north at high angles. In the central and eastern parts of the district, east of Quinnesec, the minor and major folds have their axial planes steeply inclined to the south. While the minor folds are fairly easily recognizable, it is only on the south side of the southern belt that they become prominent. Here the synclines open out, forming basins in which the ore bodies lie. The small folds, as a rule, pitch west in the western portion of the range and east in the eastern portion. There are exceptions to this rule, but in the majority of instances observed the pitches are as indicated.

Pitch of minor folds.

The attitude of minor folds is, as is well known, an indication of the attitude of the major folds on which they are superimposed. By using this principle, it is concluded that the major anticlines in this district disappear to the east and to the west by plunging beneath the Upper Menominee sediments. Detailed examination of the ends of the anticline north of Lakes Antoine and Fumee seems to show that this belt does actually disappear in this way. The behavior of the ends of the southern anticline can not be described, since both are covered with sandstone and drift. But for this belt, the evidence of the minor folds is fairly conclusive, so that it appears safe to assume that this dolomite plunges below the Upper Menominee rocks.

From the above statements it is clear that, in addition to the major east-west anticlines and synclines that are so prominent in the district, the dolomite formation is also affected by a gentle but large anticlinorium with axis running approximately north-south.

At no place within the area mapped is the dolomite known to be exposed from the bottom to the top. On the northern side of the trough the formation is bordered by the Sturgeon quartzite on the north and the Vulcan formation on the south, but exposures between these limits are so few that we can not be sure that the dolomite occupies the entire breadth.

Thickness indeterminate, 1000 feet or more.

If, however, we assume that in the wider portions of the dolomite belts the entire formation is exposed, we are still unable to estimate its thickness accurately, since we know that it has been subjected to subordinate folding, and we can not determine the exact amount of duplication of beds resulting therefrom.

In the center of sec. 12, T. 39 N., R. 29 W., we find the most continuous set of dolomite exposures in the district. Near the north-south quarter-line the belt is about 3000 feet wide, and has an average dip of 55° S. This corresponds to a breadth of approximately 2450 feet, which must be at least twice the thickness of the formation, since this belt is an anticline. So far as we can learn, there are no minor folds here, so that 1225 feet must be accepted as the greatest possible thickness of the formation exposed at this place. The entire formation, however, does not reach the surface, for the beds in the center of the belt—those at the apex of the anticline, and consequently the lowest members exposed—are not the basal members of the formation. Moreover, while the southern limit of the dolomite is well established by exposures of the Vulcan formation, it is not known whether the contact is at the top of the dolomite or whether some of this rock had been removed by erosion before the deposition of the iron formation. Further, the northern limit of the dolomite belt is not definitely known, for north of the exposures of this dolomite the country is covered with swamps and sand plains.

An estimate of the thickness of the formation based upon the above statement of facts would appear to be too small, because the lower and higher beds of the dolomite are not exposed. However, superimposed upon the major folds, as already pointed out, are many minor folds. To what extent the beds are duplicated by this minor folding it is practically impossible to determine. If one should make calculations so as to obtain a minimum figure, 1000 feet or less could be obtained. If, on the other hand, one were to make calculations on the supposition that all of the isoclinal beds are different layers, an estimate as great as 5000 feet could be obtained. Probably the truth is much nearer the lower figure than the higher. The original thickness of the dolomite is probably somewhere between 1000 and 1500 feet.

The dolomite formation is nowhere seen in actual contact with the Sturgeon quartzite, nor are ledges of the two formations seen in close proximity. It is known, however, that the upper layers of the quartzite are calcareous and that the lower beds of the dolomite are quartzose. The inference seems to be safe that the two formations are conformable, and that they grade into each other through calcareous quartzites.

Conformable gradation into Sturgeon quartzite.

Contacts between the dolomite and the overlying formation are found in many of the mines, but they are nowhere discoverable on the surface. In the little ravine just east of the old Brier Hill mine the dolomite and the lower members of an iron formation are very close together, but their actual contact is covered. The space between the ledges of the two formations is filled with loose fragments, and among these fragments are large pieces of quartzite holding pebbles of jaspilite, quartzite, granite, and other members of the Archean. The presence of the jaspilite fragments in the conglomerate is proof that beneath this rock layer there existed somewhere in the Lower Menominee series an iron formation containing considerable jasper. This formation has now completely or almost completely disappeared, so far as the surface indications show. It is assumed that it has been cut away by erosion, and that its débris furnished the jaspilite fragments in the conglomerate.

Unconformity between Randville and Vulcan formations.

In the mines and the open pits a similar conglomerate or a coarse quartzite is frequently found lying upon the dolomite. Jaspilite fragments can not in all places be detected in it, but they can be observed in so many localities that the only acceptable interpretation of the phenomena is that the dolomite and the quartzite are separated by an unconformity. The contact between the two rocks is sharp. There is no gradation of any kind between them. The dolomite near the contact is usually schistose, so much so that in most cases it is a pure talc-schist. The calcium of the dolomite has been removed and much of it has been deposited in the ore bodies as calcite, while the magnesium has remained in the talc. This talc-schist serves as an impervious lining to many of the folds in which the ore deposits lie, and afforded better conditions for the concentration of the ore material than were afforded by the massive and shattered dolomite underlying the ore formation at various places. The schist was probably formed in connection with movement along the contact plane after the Upper Huronian deposits were

Impervious talc-schist.

laid down, and contemporaneously with the folding and metamorphism that affected both the Lower Menominee and Upper Menominee series. The contact between the schist and the superjacent quartzite is extremely sharp, and in many places the plane of contact is slickensided.

NEGAUNEE FORMATION.

Occurrence and correlation.—The Negaunee iron-bearing formation is believed to occur in only one or two places within the limits of the mapped area. Its identification as one of the formations of the Lower Menominee in this district is partly based upon the fact that the lower layers of the Upper Menominee series are built up very largely of the débris of an iron formation. Whether this formation was exactly equivalent to the Negaunee formation in the Marquette district can not be definitely determined; but it must have rested upon the Randville dolomite and occurred below the Upper Menominee Vulcan formation, which in many places is immediately above the dolomite. This corresponds exactly with the position of the Negaunee formation in the Marquette district. The exposures believed to belong to the Negaunee formation are so few and so small that this formation is not represented on the maps by a separate color but is included under the color for the Vulcan iron-bearing formation. Hence there is no necessity to describe the Negaunee formation in detail in the present paper. The formation is believed to be identical in essential character with the Negaunee formation of the Marquette district. In Structure section AA the formation is supposed to exist, but is indefinitely represented, above the anticline of dolomite in the neighborhood of the Old Cornell mine, in order to account for the huge deposits of conglomerate ore found in the Traders and Clifford pits.

UPPER MENOMINEE SERIES.

Component formations.—All the formations between the unconformity on the top of the Lower Menominee series and the unconformity at the base of the Lake Superior sandstone are placed in the Upper Menominee series. For the purpose of the present folio the series may be divided into two formations: the lower, the Vulcan formation, includes all the known iron-bearing members of the district except the conglomerate beds at the base of the Cambrian; the upper, the Hanbury formation, comprises the great upper slate member of the Menominee series.

VULCAN FORMATION.

Subdivision into members.—The Vulcan iron-bearing formation embraces three members; these are, from the base up, the Traders iron-bearing member, the Brier slate, and the Curry iron-bearing member. In this folio the three members are mapped as a single formation. This is done because the individual members of the formation are not so well exposed that they can everywhere be separately outlined. However, at various places the three members are known to exist and locally they can be separately mapped. It will be necessary briefly to describe each member, since they are lithologically very different. The Traders member is so named because of its typical occurrence at the Traders mine, north of Iron Mountain. The Brier slate is so named because these slates are well exhibited at Brier Hill. The Curry member is so called because the Curry mine is located in this horizon.

Stratigraphic position and distribution.—From the position of the Vulcan formation immediately upon the Lower Menominee beds we would naturally expect the distribution of the ore-bearing formation to be determined by the distribution of the lower series, and as a matter of fact, wherever the Vulcan formation exists it is found immediately above the Randville dolomite member of the Lower Menominee series and below the Hanbury slate. But at some places within the district where we would naturally expect to find the Vulcan formation the dolomite is in immediate contact with the Hanbury slate, or is separated from exposures of the latter formation by intervals so narrow as to show that the Vulcan beds are lacking.

Between Randville and Hanbury formations.

The principal area of the Vulcan formation extends as a belt from 900 to 1300 feet wide along the south side of the southern belt of dolomite for nearly its entire extent. The belt follows the sinuosities of the southern border of the dolomite area rather closely, but it is much wider in the reentrants caused by the pitching synclines of the dolomite than elsewhere. The widening of the formation at these places is of course due to the repetition of beds in consequence of close folding. Along only one stretch, about a mile in length, is the iron formation known to be absent. This is in the west half of sec. 1 and the east half of sec. 2, T. 39 N., R. 30 W., where the Hanbury slate lies upon ledges of the typical dolomite.

Occurs south of southern dolomite belt.

On the north side of the southern dolomite belt, in the central or western part of the district, the iron formation has nowhere been found nor has any indication of its presence been detected. Magnetic lines are weak or absent altogether, and no exposures of the Vulcan or other formation have been discovered near the dolomite west of the Loretto mine, except a few slate exposures in pits near the northwest corner of sec. 10, T. 39 N., R. 29 W. Here the slate appears to be in contact, or nearly in contact, with the dolomite, forming the embayment extending into the dolomite area east of Norway, shown on the map. Elsewhere the country bordering the dolomite is thickly drift covered, so that it is not known whether or not it is underlain by a belt of the iron-bearing formation. At the Loretto mine the ore formation exists in an eastward-pitching syncline. From this place it extends eastward along the northern side of the dolomite, as shown by a line of magnetic attractions, to within a short distance of the east end of the area mapped, where the thick deposits of Paleozoic beds prevent further tracing.

Generally absent north of southern dolomite belt.

Loretto mine.

The second important area of the Vulcan formation is that in which the Traders and the Cuff mines are situated. It stretches for about 5 miles along the south side of the central dolomite belt, running north of Lakes Antoine and Fumee, and ending, so far as present information indicates, somewhere about the east line of R. 30 W. Beyond this point for a mile and a half there are no outcrops near the southern boundary of the dolomite, nor have any test pits, so far as our present knowledge goes, uncovered the underlying rock. We are therefore ignorant as to whether or not the ore-bearing formation continues this far. At the east end of the dolomite belt, however, the country has been very thoroughly explored and the underlying rocks have been exposed by pits and trenches. Lean iron-bearing slates are so abundant that the locality is known locally as Iron Hill, but the slates are different from those of the Vulcan formation. These slates are similar to the lean iron-bearing slates discovered at several localities in the Hanbury slate areas. Moreover, a diamond-drill hole recently put down under the pits to within a short distance of the dolomite reveals the existence only of gray slates like those of the Hanbury formation. The contact of the two formations has not been reached by this drill hole, but the interval between the last known position of the slate and the nearest exposure of the dolomite is so narrow that there seems to be no room there for the Vulcan formation. Further, a line of auger borings has been carried from the northernmost exposures of the Hanbury slate north across the swamp to within a few feet of the base of the dolomite cliff, and these revealed only slate. While little confidence should perhaps be placed in the results of these borings, the evidence of the absence of the Vulcan formation and the presence of the Hanbury slate at this place seems so strong that on the map the color of the latter formation has been carried to the very edge of the dolomite area. On the north side of this same dolomite belt the iron formation is known to extend for only a short distance on both sides of the Cuff mine, in the southern portion of sec. 22, T. 40 N., R. 30 W. To the east and the west the country is thickly covered by drift and sandstone, and nothing has been learned of the nature of the underlying rock.

Occurs south of the central dolomite belt.

Lean slates at Iron Hill.

Cuff mine.

The third strip of country in which the iron-bearing beds are to be expected is that which borders the northern dolomite belt. This area, however, is in the valley of Pine Creek. The surface is thickly covered with sand. There is no indication of the character of the underlying rock anywhere west of the Loretto mine except that afforded by a group of pits near the center of sec. 14, T. 40 N., R. 30 W., at the western extremity of the belt. These pits have shown the presence of lean ore associated with cherts, jaspilites, and black slates. The cherts are filled with the "shots and bands" of ore characteristic of the cherts in the Hanbury slate and present to some extent in the jaspilites of the Curry member. In this case the rocks are believed to belong to the Curry horizon.

Occurrence not determined along northern dolomite belt.

In the neighborhood of the Loretto mine the Vulcan formation appears to occupy the entire breadth between the north side of the southernmost belt of dolomite and the south side of the northernmost belt of this rock. A short portion of this distance has not yet been explored, but all that portion which has been opened up by the Loretto and Appleton workings reveals the presence of one or the other members of the Vulcan formation. Of the area east of the Appleton mine nothing is known. The country is here covered with thick deposits of sand and sandstone.

Vicinity of Appleton mine.

The other areas in which the Vulcan formation may occur are those bordering the Quinnesec schists. From the order of succession on the northern side of the Menominee trough, one would expect on the southern side of the trough to find in passing north from the Quinnesec schists of the Menominee River, the following formations: (1) the Sturgeon quartzite, (2) the Randville dolomite, (3) the Vulcan formation, and (4) the Hanbury slate. As a matter of fact, the only rocks exposed near the Quinnesec schists are the Hanbury slates. However, for a belt about a quarter of a mile wide north of the northernmost exposures of the schists no outcrops of any formation have been found. This belt is left doubtful on the map. Since the Sturgeon quartzite and the Randville dolomite are hard, resistant formations, probably much more resistant than the Quinnesec schist, it is thought to be highly probable that these formations do not rest upon the schist. Therefore, if the Hanbury slate does not occupy the doubtful belt, this area is probably underlain by the Vulcan iron-bearing formation. The direction of movement of the glacial drift was from the northeast toward the southwest. The Quinnesec schists occupy high ground, and therefore heavy masses of drift were banked against the northern border of this schist. This is believed to be the explanation of the absence of exposures in this belt. No opinion is expressed as to whether or not the Vulcan formation occupies this belt or a portion of it. Before publishing our final report it is our intention to make a careful magnetic survey of the area of the belt in question, in order, if possible, to ascertain whether this strip of country is probably underlain by the Vulcan formation or the Hanbury slate.

Vulcan formation may occur adjacent to Quinnesec schists.

The situation is nearly similar about the western area of Quinnesec schists. Only two exposures are known as close as 600 feet from the schist ledges. One of these is unquestionably an exposure of Hanbury slate. The other is a ferruginous slate that resembles very closely some of the ferruginous slates of the Hanbury formation. These exposures are both on the southern side of the schist area, and are more than 4 miles apart. Absolutely nothing is known of the geology of the intervening strip of country. Nor is anything known of the belt of country bordering the western schist area on the north. This area is so deeply buried under sand and gravel that we are not even certain that the northern limit of the schists has been correctly outlined. The probabilities are more favorable to the belief that the Quinnesec schists are surrounded by the Hanbury slate than that they are surrounded by a belt of the Vulcan formation. Since, however, there is considerable room for doubt as to the correctness of this view, the belt bordering this area is colored as doubtful on the map, except at the point where it crosses the Menominee River. Here the undoubted Hanbury slate is so near exposures of the schists that there is no room for the Vulcan formation between them.

From the foregoing account of the distribution of the Vulcan formation it will be noticed that the belts of iron-bearing rocks are not continuous. From the stratigraphical relations of the iron-bearing formation, one would expect it to occur as continuous belts surrounding the dolomite anticlines, bordering the south side of the northern dolomite monocline, and bordering the areas of Quinnesec schist. In several places, however, it is seen that these relations do not exist. It is known that in various parts of the district the iron-bearing formation is absent from the position it would naturally be expected to occupy, and that the Hanbury slates, which stratigraphically overlie the ore-bearing strata, are in immediate contact with the dolomite that underlies the Vulcan formation. Furthermore, at least at one place it is known that the slates are exposed in natural ledges at so short a distance from the western area of Quinnesec schists that there would seem to be no possibility of the occurrence of the iron-bearing formation between them. It is probable that the larger parts of the belts mapped as doubtful—the areas in which the underlying rock is unknown—are underlain by the Hanbury slate rather than the Vulcan formation, but it is certain that the Vulcan formation underlies a portion of these areas.

Occurrence of Vulcan formation summarized.

Traders member.—The Traders member of the Vulcan formation consists of a conformable set of beds composed of ferruginous conglomerates, ferruginous quartzites, heavily ferruginous quartzose slates, and iron-ore deposits. On the sections of mine workings these are designated the Traders quartzite, Traders slate, and Traders ore-bearing bed. The conglomerates and quartzites are usually at the base of the member resting upon the Randville dolomite. These vary in thickness from a few inches to 20 feet or more. They contain fragments, usually small but occasionally large, of quartzite, jaspilite, white quartz, and rocks that make up the Archean complex. In many cases, however, the conglomerate contains so much ore and jasper that it is an ore and jasper conglomerate or quartzite, which in some instances is so rich that it is mined. In these cases the matrix is a mass of small grains of hematite, embedded in which are bowlders and pebbles of ore and of jaspilite. The conglomerates and quartzites of this kind are usually schistose. The ore and jaspilite fragments are mashed into lenticular bodies, and the matrix into a mass of thin scales like those characterizing the specular ores of the Marquette district. Typical occurrences of the ore-bearing quartzites and conglomerates may be seen at the open pits of the Traders mine and at the bottom and along the west side of No. 3 pit of the Penn Iron Co., in the SW. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ sec. 9, T. 39 N., R. 29 W.

Several component beds.

The conglomerates and quartzites pass upward into the ferruginous quartzose slates. These consist of alternating layers of heavily ferruginous quartzites, iron oxides, and in some cases jaspilites. The quartzose layers are dark red or purple jasper-like beds, from a fraction of an inch to 18 inches or 2 feet in thickness. Some of them on fresh fractures exhibit the quartzitic texture very plainly. The coarser of them approach ferruginous quartzites. Others, however, resemble very closely a typical jaspilite, which in some cases they are believed to be. These varieties are often mottled by red and purple blotches that appear to be due to the presence of red jaspilite grains in a ferruginous quartzose matrix. In the greater number of instances the mottling is in small elongated areas and the rock possesses an incipient schistosity in the direction of the longer axes of the areas. This phenomenon is the result of mashing, which flattened the jaspilite grains and the smaller components of the quartzose matrix, producing a parallel arrangement of the particles. It is difficult to determine with certainty the relative amounts of the detrital material and true jaspilite which is non-fragmental, but apparently the former is more abundant, and it may be dominant.

Iron ores of the Traders member.

The associated iron oxides usually occur in beds no thicker than the quartzose layers. At various places, however, especially in the basins produced by the folding of the dolomites, they rapidly thicken and replace the quartzose slate along its strike, forming ore deposits, which may be sufficiently large to warrant mining.

The thin-bedded ores are usually gray specular varieties, strongly resembling the Marquette specular ores from the Ishpeming formation. They are schistose rocks, made up of thin plates of hematite arranged in parallel positions. On fractured surfaces along schistose planes, especially when these surfaces have been slightly weathered, there is noticeable a peculiar texture that possesses considerable significance. On such surfaces a distinction can be made out between a fine-grained matrix and numerous comparatively large oval or lenticular areas. The latter give uniform reflection from their entire surfaces, while the matrix reflects from many small surfaces. The appearance thus produced is that of a number of large flattened grains in a groundmass composed of small grains. This texture is characteristic of fragmental sediments.

Conditions of special enrichment.

Where the ore layers thicken they usually take on a different character. They lose their marked specular habit and become more granular. At the same time their color changes to a dark blue or black. The changes from thin beds to thick deposits, and from a gray specular ore to a dark granular one, are noticed to occur particularly in areas of disturbance, such as the ends and troughs of folds, the places where the rocks have been crushed or jointed, etc. In these places the water that is constantly circulating through the rocks has removed silica and deposited hematite. New hematite has built out the plates of the original ore into grains. At the same time it has filled or partly filled with ore the openings that have been produced during the crushing and jointing of the rock. Where the crushing was considerable the ore may present a porous aspect and all joint cracks may be lined with druses of hematite crystals. In other instances the thickening of the ore beds is, in part at least, an original effect and not one due to secondary causes. Some places along the original shore lines were more favorably situated for the accumulation of the ferruginous sediments than others. Here the hematite sands settled in greater abundance than elsewhere and made thick beds. The ore bodies thus produced may pass gradually along the strike into ferruginous quartzose slates, whereas when the change is due to secondary enrichment the passage is comparatively sudden. The ore deposits are thus exceedingly variable in thickness, in some places measuring only a few inches, in others reaching 200 feet or more.

Ferruginous slates.

Like all other fragmental sediments the ores contain a variable quantity of impurities. Much of this impurity consists of quartz grains and of the constituents that are usually found in slates. Sometimes the proportion of such substances is so great that the ores are not marketable. They are then known as slates. The blue or dark-gray slates occurring under the ore at the Clifford pit of the Traders mine are of this character. They are ferruginous sediments in which the proportion of ore grains is not sufficiently great to warrant working.

Brier slate.—The Brier slate lies immediately above the Traders member. The slates are heavy, black, ferruginous, and quartzose, often presenting a very even and fine banding, due sometimes to the presence of layers richer than the average in iron oxides and sometimes merely to the presence of small quantities of pigments. On exposed surfaces the banding is emphasized by slight weathering. Where the weathering has progressed very far, however, red ocher is formed and the slates are stained an almost uniform color. They open along the bedding planes and become very shaly. In this form they yield an abundant talus at the base of all cliff faces in which they are exposed.

Curry member.—The Curry iron-bearing member consists of interbedded jaspilites and ferruginous quartzose slates, with various mixtures of the two, and ore deposits.

Banded nonfragmental rocks; jaspilites.

The jaspilite bands in many cases are in the center of the quartzose slate layers, but occasionally are along one side, and are always parallel to the bedding planes. Both the jaspilites and the ferruginous quartzose slates are dark red or purple. The two can usually, however, be distinguished. The jaspilites are homogeneous rocks, with a flinty fracture and luster. They consist usually of very finely crystalline quartz and hematite, in which much of the iron oxide has a remarkable concretionary structure. Examined under the microscope, some thin sections are found to contain siderite; some, red hematite which has the forms of siderite and is probably secondary to that carbonate. In other cases actinolite occurs in subordinate amount. These jaspilites are very similar to the concretionary ferruginous cherts of the Penokee and Animikie districts, described in Monograph XIX of the United States Geological Survey. The chief difference is that the iron oxide is red hematite rather than brown or somewhat hydrated hematite. They are almost identical with the jaspilite of the Marquette district, described in Monograph XXVIII of the United States Geological Survey, except that the concretionary or oolitic structure is more prevalent in the Curry member than in the similar rocks of the Marquette district.

Fragmental quartzose slates.

The ferruginous quartzose slates consist largely of plainly fragmental quartz. The coarser varieties approach quartzites. Between the grains of fragmental quartz there is finely crystalline quartz and iron oxide. What part of the matrix is truly detrital and what part, like the jaspilite, is non-fragmental in origin it is difficult to say. Between the bands which are plainly true jaspilites and non-detrital and those which are plainly detrital there are all gradations. It is difficult to ascertain whether the fragmental or the non-fragmental material is the more abundant for the entire Curry member, since it is so poorly exposed.

Origin of jaspilite.

In other districts of the Lake Superior region, as has been shown, the jaspilites have developed from an originally cherty iron-bearing carbonate, and there is little doubt that the jaspilites of the Menominee district have the same origin. Independent of the analogy furnished by other districts, the siderite in some of the slides, and pseudomorphs of hematite after siderite in these and other slides, give very strong evidence of their derivation from an oolitic iron-bearing carbonate.

Source of detrital material

The ferruginous quartzose slates are believed to have been derived largely from the erosion of the Lower Menominee series, including the Negaunee formation. But mingled with this detrital material in many cases was apparently a considerable amount of non-fragmental material. There are, therefore, in the Curry member all gradations between clastic and non-clastic sedimentation.

Varieties of iron ore in Curry member.

The iron ore of the Curry member is of two kinds. Generally both kinds are less micaceous than the Traders ore. The first kind of ore is hard, dense, and very flinty. It occurs in very thin layers, separated by equally thin layers of jaspilite. The layers, moreover, do not continue for any great distance with an even thickness, but fray out into thinner, vein-like seams, which run for short distances approximately parallel and then again unite to form a single band. Between the seams of the layers lens-shaped jaspilite occurs.

Sandy iron ores.

The second kind of ore is very different. This often possesses a sandy appearance, as though the ore had mixed with it an appreciable quantity of sand grains, or were itself a mass of small fragments. The beds of this ore are generally thicker than those of the first kind and are much more continuous. The thicker beds are frequently very evenly laminated in dark-gray or black and light-gray bands. The color of the lighter bands is due to the presence of numerous elongated flakes of a nearly white micaceous mineral that may be muscovite or some hydrated decomposition product of this mica.

Conditions of deposit of Curry member.

The ores and siliceous layers in the Curry member of the Vulcan formation are thus divisible into two classes. Into one class fall the dense, black ores and the jaspilites, and into the other the evenly banded sandy ores and ferruginous quartzose slates. The materials of the former appear to have been formed largely by metasomatic changes from an iron-bearing carbonate; those of the latter consist largely of detrital material derived from some older formation. The explanation of the intimate relations of these two kinds of sediments is probably somewhat as follows: The formation originally consisted of ferruginous quartzose sand derived from some older ore-bearing formation (the Negaunee formation) interbedded with cherty iron carbonate and shale, with various mixtures of two or all.

In the course of time the cherty carbonate was changed to hematite, the silica was rearranged (see p. 9), and jaspilite was formed. Where the iron carbonate was in beds of notable thickness the resultant jaspilite is important. Jaspilites also formed in cracks traversing the ferruginous quartzose slates. Some of the new hematite was deposited in thin layers along the bedding planes. Another portion of the newly formed hematite remained or was deposited among the grains of the detrital ores, thus enriching them in the same manner that the Traders ores were enriched, especially in the bottom of the folds and in areas of disturbance. In spite of the enrichment of the Curry member in iron oxide, its ores are not profitably worked at as many places as are those of the Traders member. The ferruginous detritus in the Curry beds is usually not so rich in iron oxide as that found at the Traders horizon. It is more intricately mixed with siliceous sands and is in thinner layers. Where folds exist in the members, furnishing favorable situations for rich deposits, the ore bodies may be large enough and rich enough to warrant mining, but for the greater part of its extent the member yields only lean ores.

Gradation of Traders into Brier.

Relations between the members of the Vulcan formation.—Where no marked disturbances exist between the Traders member and the Brier slates the first grades into the second by diminution of the amount of ferruginous material and by increase in the number and thickness of the quartzose beds. At the same time there is an increase in the proportion of slaty material. When the ferruginous material is much reduced in quantity the Traders ore-bearing bed becomes the Brier slate. This gradation occupies only a very short vertical range, so that the line between the Traders member and the Brier slate is usually determinable within a few feet.

Brecciated zones and ores.

Where marked disturbances have occurred, as in the vicinity of Norway and eastward for several miles, the relations between the two members are very different. Wherever it can be seen the contact between the Traders and Brier members is sharp. In many places the contact seems to be slickensided and often to be a plane of differential movement. At the open pits of the Norway mine and those north of the Curry mine, and between this mine and the West Vulcan, the Traders rocks are in places pseudo-conglomeratic. The Brier slates also may be brecciated. Moreover, the brecciation is not confined to these two members, but the underlying dolomite is at some places likewise brecciated for a short distance beneath its upper surface. The phenomena wherever studied appear to indicate that the relations between the dolomite, the Traders member, and the Brier slates were originally normal—i. e., that the ore-bearing bed is principally detrital material lying upon the dolomite, and that upon the ferruginous material the Brier slates were conformably deposited. At the time of folding slipping occurred along the contact between the Upper Menominee series and the Lower Menominee series and between the Traders and Brier members. The dolomite was brecciated to some extent, the Traders detrital ores were crushed and brecciated, and in several instances the lower portions of the Brier slates were likewise included within the zone of movement and were fractured and brecciated. Later the breccias were enriched by the deposition of hematite and other iron compounds, and both the Traders member and the lower part of the brecciated Brier slates became sufficiently ferruginous to warrant mining. Thus this line of contact is marked by large open pits in the NE. $\frac{1}{4}$ sec. 9, T. 39 N., R. 29 W. The ore belonging to the Traders member was taken from them some years ago. But it was not until the summer of 1899 that the demand for lean ores was so great that the ferruginous quartzose slates could be mined with profit. In this year, however, some of the Norway mine product consisted of this material.

Gradation of Brier into Curry.

The Brier slates pass upward into the Curry member by the diminution of argillaceous material and the introduction of ferruginous material, especially bands of jaspilite. At the same time, the somewhat ferruginous quartzose Brier slates become heavily ferruginous. At one place this transition is seen to occur laterally as well as vertically. No stratigraphic break has been discovered anywhere within the Vulcan formation.

Folds of first and second orders.

Folds of several orders.—The Vulcan formation, where it is known to exist, occupies a position on the upper sides of the dolomite anticlines. Its major folds, or folds of the first order, correspond exactly to the major folds of the Randville dolomite. The folds of the second order correspond also with those of the dolomite. The troughs on the southern side of the southern dolomite area are occupied by the members of the iron-bearing formation.

Folds of third order.

Moreover, within the Vulcan formation are numerous still smaller folds of the third order, which, because of the hardness of the rocks and the perfection of the banding, are well exhibited. These small folds may be observed at nearly every place where mining has progressed to any considerable extent and at many other places where only lean ores have been developed. The folds of the third order pitch in the same direction as those of the second order, on which they are superimposed, but the strikes of their axes may diverge slightly. The minor folds are extremely important guides to the discovery of ore bodies. The folds of the second order determine the general position of the ore bodies, while the folds of the third order determine in many cases their more exact positions within the larger folds. The folded slates of the formation are relatively impervious, and where not shattered often furnished troughs into which the circulating waters were conveyed and the ore deposits formed. In exploring operations it is important to determine the strikes and dips of the axes of the minor folds, not only because they indicate the direction of the pitch and strike of the larger folds, but also because they direct attention to those places at which ore bodies are most apt to exist. This subject is more fully covered in a later section, on the iron-ore deposits.

Minute folds.

In addition to the three orders of folds above referred to, there may in many places be discovered still smaller folds. These are superimposed on the folds of the third order in the same way in which the latter are superimposed on the folds of the second order. On exposed surfaces the folds of the higher orders appear as a series of crinklings or flutings, with heights of from one-quarter inch to 5 or 6 inches from trough to crest. Even in the troughs of these minute folds, under favorable circumstances, iron ore was deposited, especially where crushing and brecciating took place in connection with the folding.

Wherever folding is observed within the iron-bearing formation it is noticeable that it is best preserved in the siliceous bands. The iron-ore layers between the siliceous layers, while yielding to the stresses that produced the folding, were mashed and sheared and became schistose. Where the compressing forces were very powerful a slaty cleavage developed in both the iron-ore and the siliceous layers. In the siliceous layers this is the only secondary structure observed, while in the ores there is present in addition a schistose structure nearly parallel to the bedding plane, unless this has been obliterated by the deposition of new ore material.

Determinations of thickness.—A number of sections offer opportunities for determining the thickness of the separate members of the Vulcan formation, but only a few present opportunities for determining its total thickness. All along the south side of the southern dolomite belt, from the Aragon mine eastward to the Sturgeon River, the iron-bearing formation stretches as a narrow belt which for much of the distance appears to be without important folds. At several places mining operations have afforded excellent sections from the base of the productive portion of the Curry member, to the top of the Curry member, and at a few places the sections extend downward to the top of the Randville dolomite. At Brier Hill, where practically the whole formation can be seen on the surface, its thickness is about 600 feet. At the Curry shaft No. 2 it is 700 feet thick, and at the Aragon mine its thickness is about 675 feet.

Total thickness 600-700 feet.

At a number of sections the thickness of the individual members comprising the formation is easily measured. The Brier slates have been measured at seven places, yielding results between 100 and 360 feet. Five of these measurements fall between 320 and 360 feet. Eight measurements of the Curry member have given results varying between 100 and 225 feet. Six of these fall between 160 and 225 feet. Measurements of the Traders member have yielded no such concordant results. In the first place, its thickness probably varies widely, as should be expected of a formation composed largely of detrital deposits formed near a shore line. Moreover, only a few sections reach as low as the dolomite. Hence, the exact position of the contact between this rock and the iron-bearing formation must be guessed at. Only three measurements have been made from the known top of the dolomite to the known top of the Traders member. These give 170 feet, 85 feet, and 155 feet.

Thickness of separate members.

The opportunities for accurate determinations of the thickness of the Vulcan formation in the southern iron-bearing belt west of Norway and in the central iron-bearing belt north of Lake Antoine are very poor. In both of these areas folding is more prominent than it is in the southern belt east of Norway, and where folding is not prominent exposures are lacking. In the Pewabic mine a measured section along a drift in the first level under shaft No. 1 gave 232 feet for the Traders member and 265 feet for the Brier slates. At the Traders mine 195 feet of the Traders member are exposed, and the interval between the top of this member and the supposed position of the base of the Hanbury slate corresponds to a thickness of 480 feet for the Brier and Curry members. At the Indiana mine the measured thickness of the entire Vulcan formation is about 550 feet.

Thickness in southern and central belts.

An interesting feature of these figures appears when we compare the estimated thickness of the Brier and the Curry members with the total thickness of the two. In almost every case where the estimated thickness of either of these members falls below the average of all the measurements for that member the thickness of the other formation exceeds the average, and the total of the two is fairly constant. Thus, whereas seven estimates of the thickness of the Brier slates vary between 240 feet and 360 feet, and eight estimates for the Curry member vary between 112 feet and 225 feet, measurements of the total thickness of the two vary only between 400 and 530 feet. The apparent greater variation in thickness of each of the members than the two combined may be partly explained as due to the gradation between the two and the consequent difficulty of fixing upon the exact place at which one ends and the other begins.

Relative variations of thickness.

From a careful consideration of the figures given above and a few others that are not here recorded, it is estimated that the average thickness of the Vulcan formation is approximately 650 feet, divided as follows: Traders member, 150 feet; Brier slates, 330 feet; Curry member, 170 feet: i. e., the two ore-bearing members combined about equal in thickness the intervening slates. It is conceded, however, that the Traders member departs considerably from this average and that the total thickness of the formation varies accordingly.

Relations between the Vulcan formation and the adjacent formations.—The Vulcan iron-bearing formation, except in very limited areas, rests upon the Randville dolomite. In a few places it appears to rest upon the Negaunee iron-bearing formation. If the Vulcan formation exists in the doubtful areas adjacent to the Quinnesec schist, it there rests upon that schist.

Where the Vulcan formation rests upon the Randville dolomite the lower layers of the upper formation appear to lie conformably upon the older one, with an extremely sharp line of definition between them. In some places the upper part of the Randville formation is a dolomite. In other places it is a talc-schist derived from the dolomite. Where the Vulcan formation rests on the dolomite or talc-schist its basal member is either a quartzite which often contains ore and jaspilite fragments, or an ore and jasper conglomerate containing large and small pebbles of ore. These fragments must have been derived from an older iron formation that originally rested upon the dolomite, but which was eroded at the time the Traders member was laid down. In one case, at least, the dolomite itself yielded bowlders to the overlying beds, for on the seventh and eighth levels of the Chapin mine, at a point just south of the "C" shaft, several large rounded fragments of the dolomite were found embedded in the iron-bearing formation. If there was originally a slight discordance in bedding between the two formations it has been obliterated by the movements along the contact plane that took place during the folding of the district and the production of the talc-schist. The Traders member thus appears to be conformable in attitude, though not continuous in time, with the underlying dolomite, which remained practically undisturbed during the long interval which succeeded its deposition and preceded the deposition of the Traders member.

Time gap between Vulcan and Randville.

Where the Vulcan formation rests upon the Negaunee formation discrimination between the two is difficult. However, close observation shows that at the contact plane the non-clastic jaspilite characteristic of the Negaunee formation disappears and the red or purple quartzose slates characteristic of the Traders member of the Vulcan formation appear. Furthermore, the hard, dense ores of the Negaunee formation are different from the fragmental and micaceous ores of the Traders member. The exact boundaries between the two can be determined only after a careful microscopical examination has been made of thin sections cut from specimens taken at short intervals across the strike.

Vulcan and Negaunee distinguished with difficulty.

The relations between the Vulcan formation and the overlying Hanbury slates are those of conformity. The contact is usually very sharp. No difficulty is experienced in defining the upper limit of the iron-bearing formation. The slates, however, are often so very schistose on the upper side of the contact that their bedding planes can not be recognized. The bedding of the iron-bearing formation, on the other hand, is still almost perfectly preserved, and is parallel to the contact.

Vulcan and Hanbury are conformable.

The relations between the Hanbury slate and the subjacent formations other than the Vulcan formation should perhaps logically be considered under the Hanbury slate rather than in this connection. However, these relations are so connected with the relations of the Vulcan formation that the subject is here introduced. A further reason for this treatment is that the relations of the Hanbury slate have an important bearing upon the possible distribution of the beds of the Vulcan formation, which carry the iron ores.

At only one point has the actual contact between the Randville dolomite and Hanbury slate been seen. This is in a trench about 10 feet long near the east line of sec. 2, T. 39 N., R. 30 W., a few rods west of the Bryngelson shaft, in graphite-slates. A careful examination of the relations between the dolomite and slate was made with special reference to their bearing upon unconformity and faulting. We found that the dolomite projects slightly into the slates half way up the exposed portion of the contact, and recedes from them both above and below this point. The surface of the dolomite is minutely irregular, small projections and reentrants occurring throughout the entire line of contact. The slates, which are strongly graphitic, are interlaminated with cherty bands. They contain small fragments of the dolomite, and are badly shattered. A slate breccia is thus formed, which might be a fault breccia or a brecciated conglomerate. There can be no doubt that there has been movement along the contact zone, for the bedding of the slate has been much disturbed for a distance of 8 feet or more from the dolomite. Whether or not the movement was along a fault plane which cut out the Vulcan formation was not determinable from the exposures. The dolomite along the contact plane is not slickensided, nor is the rock near the contact greatly mashed, so far as could be observed. This may be thought to indicate that the movement was of slight magnitude, and that it was more in the nature of a differential movement of the slates near the contact than of faulting across the beds. If the absence of the iron-bearing beds between the Hanbury slate and the dolomite is due to overlapping of the slates rather than to faulting, the lower layers of the slate should be coarse detritus, since the relation of the slates to the underlying rocks are those of a younger sedimentary series to an older series, upon which the younger series is unconformable. The breccia between the slate and the dolomite referred to above may be a mashed conglomerate of this kind, but of this we can not be sure.

Hanbury and Randville near Bryngelson shaft.

At Iron Hill, in sec. 32, T. 40 N., R. 29 W. the Hanbury slate is believed to lie immediately upon the Randville dolomite. No contact between the two is seen. The dolomite ends in a number of small knobs having steep faces toward the south. At the bases of the little cliffs is a swamp about 300 feet wide, and on the opposite side of the swamp, on the north slope of a slight elevation, are several exposures of slate. The intervening swamp area has been tested at a number of places by auger borings, as has already been related, and has been found to be underlain by slates.

Hanbury and Randville at Iron Hill.

The uppermost layers of the dolomite formation consist of white cherts, and these are beautifully brecciated. Above these in some places lies a conglomerate containing numerous large rounded bowlders of dolomite, subangular fragments of chert, and an occasional pebble of quartzite, in a matrix composed mainly of dolomite and chert débris. Many of the pebbles are mashed and faulted, thus showing that the district was deformed after the conglomerate was laid down. When the conglomerate is traced eastward to the end of the set of dolomite ledges the relations between this rock and the chert are found to be very complicated. The conglomerate apparently grades into a breccia, and this in places is between beds of dolomite or layers of the chert. At one place the conglomerate looks as though it were a breccia formed by crushing of the chert and dolomite; at other places it appears to be a layer of true conglomerate between layers of massive dolomite; and in other places it strongly resembles a conglomerate composed of fragments of the dolomite and chert lying above the dolomite. The conglomerate may be an intraformational conglomerate (one originally produced during the deposition of the formation, and therefore an integral part of it), whose complex relations to the remainder of the Randville dolomite are due to crushing and close folding; or, on the other hand, it may be a true conglomerate at the base of the Hanbury slate, made to appear like an intraformational conglomerate by repeated close folding at the end of an eastward-pitching anticline on which are superposed several minor folds. The latter is thought to be the probable explanation. If this be correct, the difference in composition of the conglomerate from the normal slates is explained by its being the first deposit along a shore-line composed of dolomites and cherts. But the relations of the various rocks at this place are so exceedingly complicated that no unprejudiced observer would be willing to declare without reservation that the conglomerate is not a member of the dolomite formation, rather than the basal member of the Hanbury slate.

Explanation of the distribution and relations of the Vulcan and Hanbury formations to the underlying formations.—Two possible explanations have occurred to us to account for the facts of distribution of the Vulcan and Hanbury formations, their relations to the adjacent formations, and the character of their basal members—faulting and unconformity.

For a time it was thought that faulting near the contact plane between the Hanbury slate and the older rocks might explain the phenomena. Thus the absence of the Vulcan formation east of Quinnesec could be explained by the hypothesis that the Hanbury slates had been thrust over the lower formation of the Upper Menominee series so as to rest upon the Randville dolomite. The absence of the Vulcan formation between the Hanbury slate and the dolomite at Iron Hill might be similarly explained, only here it would be necessary to believe that after the faulting occurred close folding took place, else the manner in which the Hanbury slate wraps around the eastern end of the central belt of dolomite would be inexplicable.

Hanbury slates possibly faulted against older formations; probably not.

There are undoubted minor faults in the Menominee district, but most of them are extremely small, that in the Pewabic mine being the only one of sufficient magnitude to be mapped on the mine plats (see fig. 3). Moreover, it is clear that certain crushed zones of the Traders and Brier beds near Vulcan are due to faulting. Further, there have been marked movements of accommodation between the different formations at their contacts, which might be called faulting. In all of these instances, however, the faults are local, and in none of them is the displacement of the faulted beds great. These few minor faults, which are easily recognized, certainly would not warrant the assumption of such numerous and extraordinary faults as would be necessary to explain the relations above described. Furthermore, the faulting theory does not explain the conglomeratic and quartzitic character of the Vulcan formation where it is in contact with the Randville dolomite and the Negaunee formation, nor does it explain the apparent conglomerates at the base of the Hanbury slate.

The second explanation which suggested itself to us is that there is an unconformity between the Lower Menominee and the Upper Menominee, such as obtains elsewhere between the Upper Huronian and the Lower Huronian in the Lake Superior region. The order of events producing the unconformity must have been somewhat as follows: After the deposition of the Lower Huronian series, consisting of the Sturgeon quartzite, the Randville dolomite, and the Negaunee iron formation, the area was raised above the sea. Denudation continued for a long time. Upon the southern side of the Menominee trough these formations, if deposited, were entirely removed. In the central and northern portion of the district denudation extended to a sufficient depth to remove the Negaunee formation in the larger part of the area, and to cut into the Randville dolomite over much of the area. Probably the folding accompanying this uplift and erosion was very moderate.

Hanbury slates and Vulcan formation probably deposited unconformably on older rocks.

After erosion had long continued, there was slow subsidence of the Lower Menominee land. During the early stages of the encroachment of the sea upon the land the Vulcan formation was laid down. As shown by the character of this formation, it consists largely of detrital oreformation material. This was derived from the Lower Menominee Negaunee formation, which has nearly all disappeared. However, at the end of Vulcan time the sea had not yet wholly overridden the land, for at some places certainly, and perhaps for extensive areas, the Vulcan formation is not present. After Vulcan time the Hanbury slate was deposited. In places where the Lower Menominee series was not below the sea at the beginning of Hanbury time the Hanbury slate rests directly upon the lower series, as, for instance, east of Quinnesec and at Iron Hill.

The theory of unconformity thus fully and satisfactory explains every fact of distribution and every known relation between the Upper Menominee, Lower Menominee, and Archean. The presence of a great quantity of detrital ores and the quartzites and ore and jasper conglomerates near the base of the Vulcan formation is fully explained. The absence of the Vulcan formation in various parts of the district also presents no difficulty, these being areas which were still above the sea during Vulcan time. The gradual approach of the base of the Hanbury slates to the lower formation at such places and the presence of conglomerates at the base of the Hanbury slates are likewise made clear. Therefore, with great confidence, we hold to the second explanation—that of unconformity between the Lower Menominee and the Upper Menominee series, with a gradual advance of the Upper Menominee sea, the deposits of which slowly overlapped the earlier deposits and gradually buried the higher lands of the Lower Menominee series. There are therefore in this district all the evidences of a great unconformity between the Upper Menominee and Lower Menominee found in the Huronian of the Marquette district and other districts of the Lake Superior region, except that of marked discordance in strike and dip between the upper and lower series. This lack of discordance does not in the least invalidate the conclusion that a great time gap separates the two series. It has been shown by the senior author that an apparently minor unconformity may mark as great a time interval as the most startling discordance. The relations of the two series in the Menominee district are very similar to those existing in the Penokee district between the cherty limestone of the Lower Huronian and the Upper Huronian quartz-slate member.

THE IRON-ORE DEPOSITS.

Ore-bearing horizons.

General relations.—The iron ores of the Menominee district occur in two members, from the base upward as follows: (1) The Traders member of the Vulcan formation, and (2) the Curry member of the Vulcan formation. The iron ores may occur at any horizon within these members. However, other things being equal, they are more likely to occur at lower and higher horizons than at middle horizons in each of the members, but a number of the large ore bodies extend entirely across the members in which they occur.

Ore deposits in impervious pitching troughs.

It will be explained that the iron-ore deposits occur at places where downward-moving waters are converged. Of these places, pitching troughs with impervious basements are the most important. Therefore, the iron-ore deposits of large size rest upon relatively impervious formations, which are in such positions as to constitute pitching troughs. A pitching trough may be made (*a*) by the dolomite formation underlying the Traders member of the Vulcan formations, (*b*) by a slate constituting the lower part of the Traders member, and (*c*) by the Brier slate between the Traders and Curry members of the Vulcan formation. The dolomite formation is especially likely to furnish an impervious basement where its upper horizon has been transformed into a talc-schist, as a consequence of folding and shearing between the formations.

Ore deposits at contacts of different members.

While all the larger iron-ore bodies are confined to the pitching troughs with impervious basements of dolomite or slate, smaller ore deposits occur at contacts between the different members. These contacts are favorable places for the concentration of ore, because they are horizons along which important slipping or differential movement has occurred during the folding of the district. Wherever a set of beds are folded there must be differential movement among them. This is well illustrated by the slipping of the leaves of a flexible book over one another when the book is bent. In nature the contact planes between formations of different characters are always planes of weakness, hence at such places the major movements take place. These movements are sure to make the formations porous and thus produce main channels of percolating water; hence the frequent presence of ore bodies at the contact planes.

Ore deposits in crushed zones.

Still smaller ore deposits are found where faulting has occurred or where close plication has brecciated the Vulcan formation. Such movements furnish zones or areas where percolating waters are converged into trunk channels and thus favor the concentration of the iron oxide.

The combination of two or all of these conditions is more favorable than any one of them. Where the conditions are such as to combine pitching troughs with impervious basements, contact planes between formations, and faulting or brecciation, ore deposits of the first magnitude may be expected.

Relative importance of conditions.

Such are the conditions at the great mines in the district. However, in the search for an ore deposit, the first of the favorable conditions—a pitching trough with an impervious basement—is the dominant consideration. It can not be too strongly insisted that the essential condition for the development of a large iron-ore body in the Lake Superior region is the production in some way of a pitching trough which is relatively impervious. Where the pitching, impervious troughs are large and continuous, as at the Chapin, Pewabic, and Aragon mines (see figs. 3 to 7), the ore deposits are almost sure to be large. Where the pitching troughs are small, irregular, or broken, the ore deposits are likely to be small.

At first sight the forms of the ore deposits might be thought to be exceedingly irregular, but when the above relations are understood they seem to have orderly forms. A main mass of ore is likely to be at the bottom of a trough, but from this main mass a considerable belt of ore may follow along the limbs of the trough to a much higher altitude than in the center of the trough. The ore bodies in cross sections thus frequently constitute a U which is very thick at the bottom, the center of the U being occupied by the iron formation which has not been transformed to ore.

Details of occurrence.—In this folio it is not our intention to discuss each mine in detail. Individual mines are considered only so far as they illustrate the manner of occurrence of the ores. The present purpose is briefly to discuss the different forms and relations of the ores, in order to determine the principles controlling their deposition and to guide future prospecting. The selection of mines for figures is based upon the excellence with which they illustrate the principles of occurrence, rather than upon their relative importance.

Ores occur in three belts.

The iron ores now being exploited are confined to three belts: (1) The more numerous and important deposits are found in the belt of iron-bearing formation extending from Iron Mountain to Waucedah, south of the southern belt of dolomite; (2) iron ores are being or have been worked north, south, and west of the central belt of dolomite; (3) iron ores are being mined east of the locality where the northern and southern belts of dolomite unite.

Ore deposits and folds in the southern belt.

1. It has already been explained that the southern belt of dolomite is an anticlinorium. Further, it has been pointed out that superimposed upon this major fold are folds of higher orders. The occurrences of the ore deposits in the Vulcan formation south of this belt of dolomite are closely related to the subordinate folds in the dolomite. The folds of the second order superimposed upon the major fold are a series of very close plications, which, for the western part of the district, plunge steeply to the west. The result of these plications is to produce a number of westward-pitching synclinal troughs directly underlain by the dolomite or by the slates of the Traders member. As the result of this folding, the surface outcrop of the southern boundary of the dolomite has a notched-like distribution, producing bays in the dolomite. The iron-bearing formation occupies the bays which open out to the west into the main belt of the Vulcan formation, each bay being surrounded on the north, south, and east by the dolomite.

Chapin, Millie, Walpole, and Pewabic mines.

Beginning at the west, the first and most important set of folds of the second order are those adjacent to Iron Mountain. Here are two important folds, superimposed upon which are folds of the third order. The western produces the troughs in which the Chapin, Millie, and Walpole mines are located. The eastern fold produces the trough in which the Pewabic mine is located. The western trough is especially complicated, it being really composed of two minor troughs or folds of the third order, with an intervening anticline, and even these folds have folds of a higher order superimposed upon them. If one were to follow a geographical order, beginning at the west, the Chapin mine should be first mentioned, but the interpretation of the occurrence of the ore at the Chapin depends upon the facts furnished by the Walpole and Pewabic. They are therefore first considered.

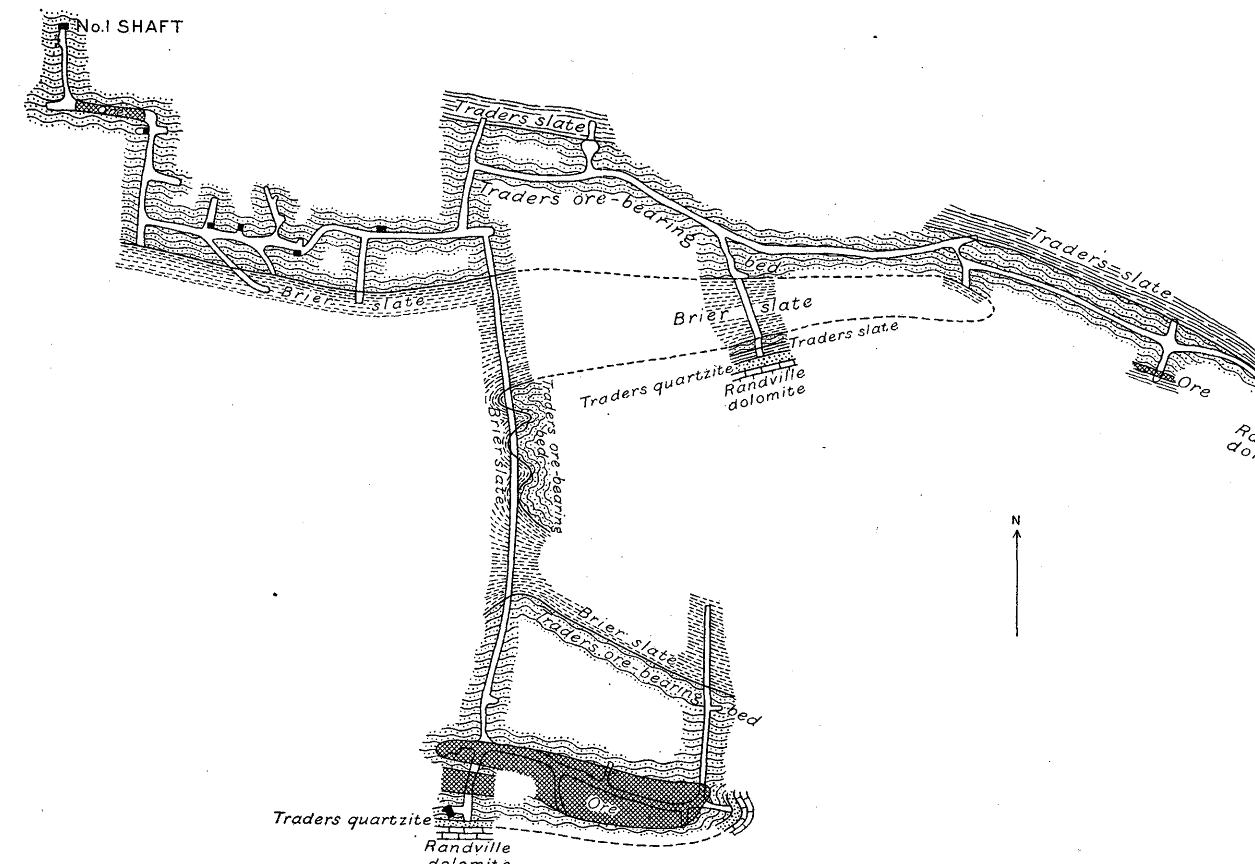

Fig. 2.—Horizontal section of the Walpole mine at the third level. Scale: 1 inch = 250 feet.

The Walpole has a north and a south ore deposit (fig. 2). These ore bodies occur in subordinate synclines, separated by an intermediate anticline. These synclines and the anticline together constitute the east end of the western important fold of the second order. The northern deposit of the Walpole is an excellent illustration of a steep, pitching trough, which is bottomed by slate and limestone and is bounded to the north, east, and south by the same rocks. The fold is here so close that the iron-bearing member on the south limb has all but been pinched out. The southern ore body is just as clearly a westward-pitching syncline. The workings of the Walpole mine beautifully illustrate the relation and succession of formations from the limestone to the Brier slate in places where the folding is of a very complicated character.

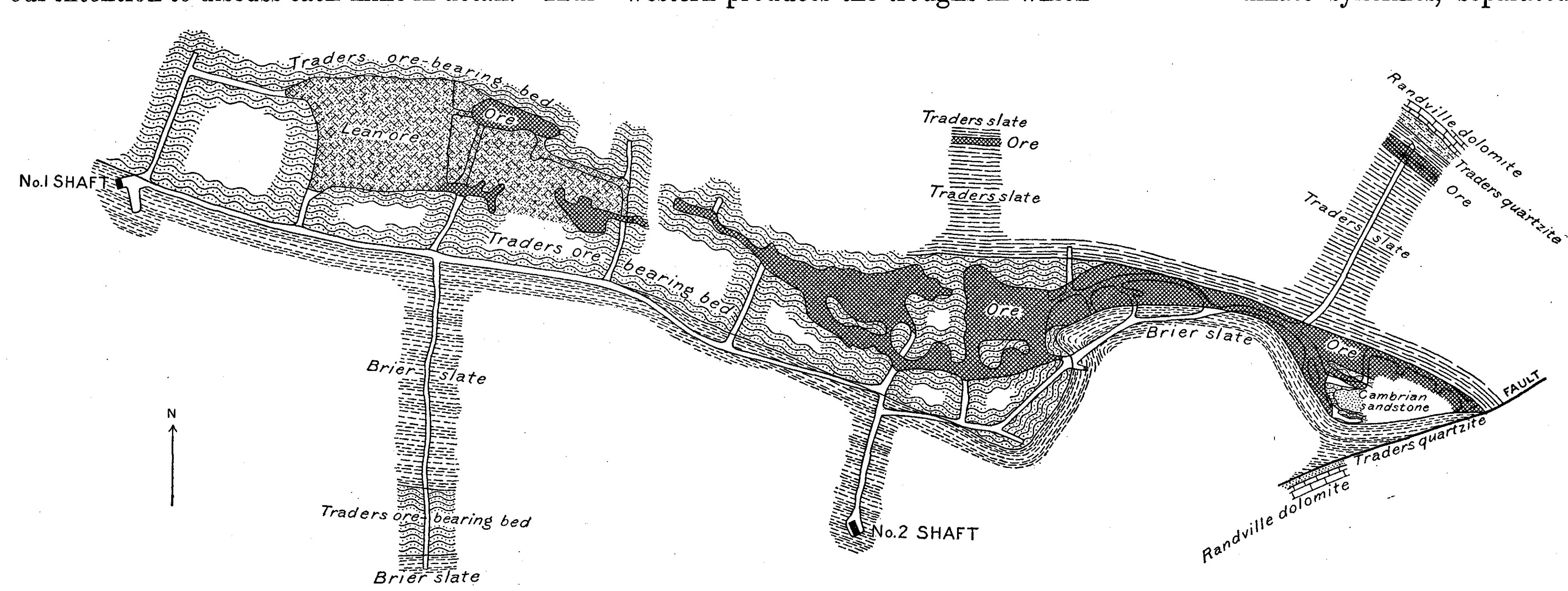

Fig. 3.—Horizontal section of the Pewabic mine at the third level. Scale: 1 inch = 250 feet.

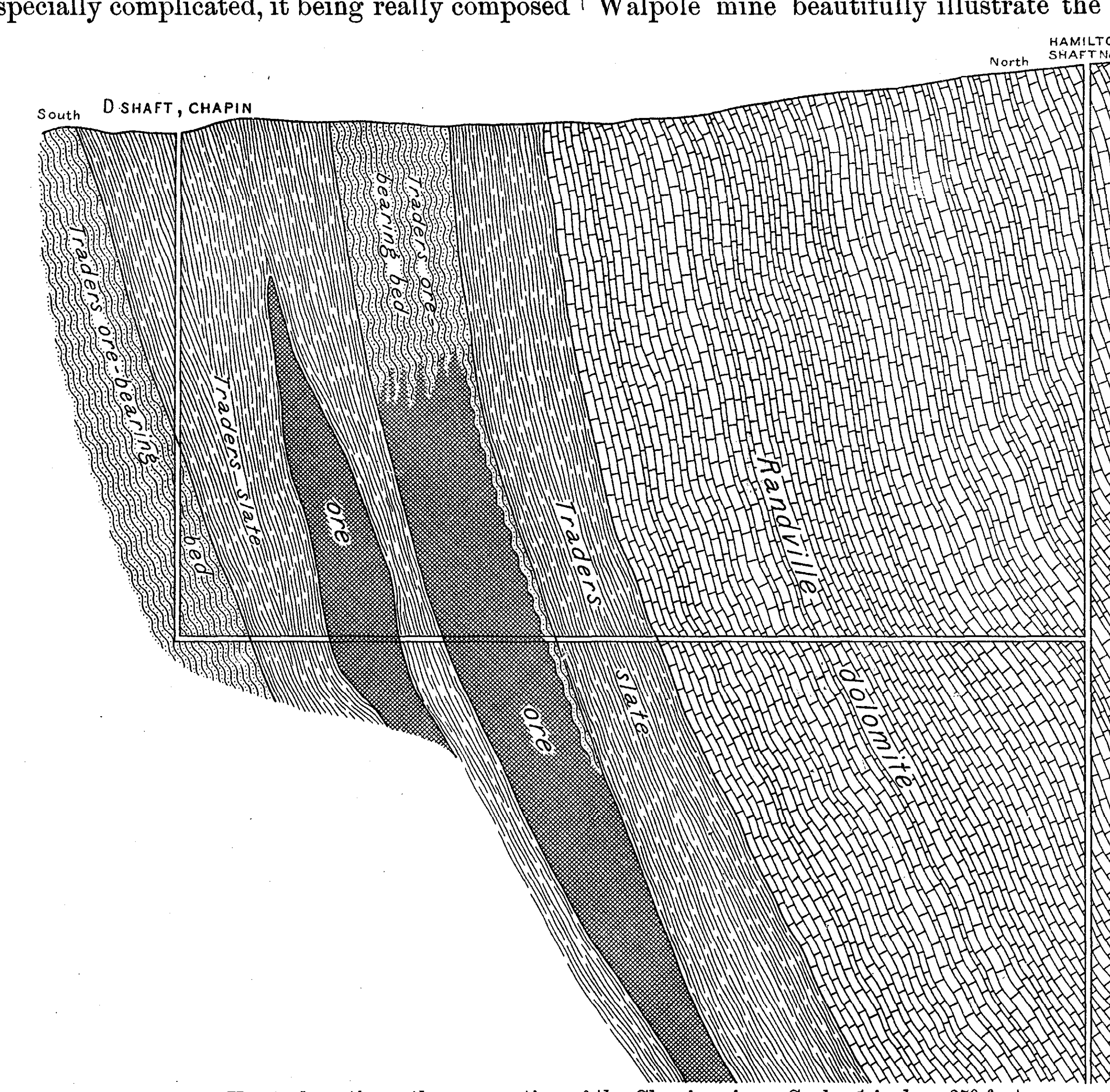

Fig. 4.—Vertical north-south cross section of the Chapin mine. Scale: 1 inch = 250 feet.

The Pewabic mine is a single, closely appressed, synclinal fold (fig. 3). The slate and dolomite are here again found on the north, east, south, and bottom of the ore body. Here, however, on the south limb of the fold the ore-bearing member does not appear between the dolomite and the Brier slate. It has therefore been squeezed out by the very great pressure, or else slight faulting has taken place. A crosscut north in the first level from the Traders ore-bearing bed to the limestone shows several repetitions of the foot-wall slates, the quartzite, and the iron-bearing members, these being found in narrow belts. The reduplications are regarded as due to very close subordinate folding.

At the present time the workings of the Chapin mine have not extended sufficiently far to show beyond question the relations of the ore bodies (fig. 4). As yet they have not been connected with the ore deposits of the Walpole in such a manner as to show the continuity of the Walpole folds with those of the Chapin. However, two main belts of ore have been developed at the Chapin, and it is believed that these two belts will be found to correspond with the two closely appressed, westward-pitching folds of the Walpole. North of the northern ore body is a succession of slates, quartzites, and thin belts of iron-bearing formation similar to that south of the Pewabic mine. Immediately north of this ore body is a slate similar to that of the Walpole and Pewabic. Slate also occurs between the two ore bodies. Further, slate bounds the southern lens of ore on the south. South of this slate is iron-bearing formation, and south of this are slates and quartzites. There is every reason to believe that when the workings extend sufficiently deep the ore bodies will be found to be underlain by slate also, as well as bounded by slate on the north and south. The south ore lens at the cross section given is bounded by slate above as well as below. The explanation of this anomaly is probably that the compression was so severe that the center of the soft syncline of ore at the top was actually pinched out, the slate on each side of the ore coming together.

It is impossible at present to be absolutely sure as to the horizon at which the great lenses of ore of the Chapin belong. Since, however, the relations of the ore bodies to the surrounding rocks at the Chapin are parallel in many particulars to the occurrences at the Walpole mine, it is thought that the two ore belts belong to the Traders member of the iron-bearing formation, that member being repeated by close folding. According to this explanation, each of the two ore lenses would constitute an isoclinal syncline, and the slates between them would be anticlines; also the slate between the southern lens of ore and the southern belt of iron-bearing formations would be an anticline. This would fix the southern iron-bearing belt, in which no ore bodies have been found, as Traders. The slates and quartzites south of this would be Brier. Therefore, the southern belt of iron-bearing formation is regarded as a monocline rather than a syncline. Thus is explained the apparent absence of ore bodies in it. Where Iron Mountain belongs, which gives its name to the locality, is somewhat uncertain, but in all probability a portion of it is a continuation of the southern belt of iron-bearing formation found underground.

If the above be the correct explanation of the structure, the Chapin mine presents a case of isoclinal folding, the strata of which are reduplicated three times, not to mention the minor duplications north of the northern lens of ore. While it is freely admitted that as yet this interpretation is not proved, it is the one which upon the whole appears to correspond most closely with the facts. The two lenses of ore would correspond to the two embayments in the outcrop of dolomite east of the Walpole mine. The isoclinal folds at the Chapin mine are overturned, the axial planes dip to the north, and the dolomite belonging structurally below the Vulcan formation really rests upon it with a steep dip, about 80° at the surface, but bending so as to be as low as 70° deep in the mine. For a long time it was a question with the miners which of the two formations was geologically the higher. However, the occurrence of undoubted dolomite bowlders in the Traders member, and the continuity of the dolomite from the vicinity of Iron Mountain to the east end of the district, have shown beyond question that the dolomite is the lower formation. With the possible exception of the Quinnesec, the Chapin mine shows the most in ense folding known in the districts, the structure being, in short, a set of isoclinal overturned folds.

The Millie mine is not sufficiently developed to enable us to make definite statements as to the relations of this ore deposit, but the probability is strong that it belongs to the Traders member of the Vulcan formation.

Quinnesec and Cundy mines.

The next important point to the east of the Pewabic mine where ore is produced is at Quinnesec. The Quinnesec ore body is probably a somewhat narrow, closely appressed fold. The dolomite and the talc-schists at this locality apparently overlie the ore, the dip being about 70° to the north. The ore is bounded by the talc-schists on the north and by slates on the south. South of these slates is iron-bearing formation. The ore in longitudinal section passes into iron-bearing formation both to the east and to the west, and if there is a pitching trough here it does not clearly appear. However, the sharp embayment in the dolomite immediately adjacent renders it highly probable that a pitching trough really exists. South of the old Quinnesec is the Cundy mine, but as yet developments have not gone far enough to show the relations of the ore body.

Norway and Aragon mines.

Another very important producing ore center is at Norway, where are found the Norway and Aragon mines. Here are two important folds in the dolomite, both opening out to the west as at Iron Mountain. The first gives the Norway mine and the second the Aragon mine. The relations may be particularly well seen at the open pits and the drifts of the Norway. Here is a pitching trough which is being mined for ore, bounded on both the north and the south by the limestone. The fold is so important as to bring the dolomite very near the surface (fig. 5). Between the dolomite and the ore is a certain amount of ferruginous and siliceous slate, which, until the demands for low grade, non-phosphoric ores arose, could not be mined, but during the last summer a large amount of this lean material was exploited.

The Aragon mine gives, perhaps, the clearest illustration of the principle of the formation of ore in pitching troughs on impervious basements furnished by the district. Just east of the Aragon mine is a sharp embayment in the dolomite, which may be beautifully seen above ground, an amphitheater of limestone entirely surrounding the low land occupied by the iron-bearing formation. A short distance to the west of this embayment the Aragon body was discovered. Where first found it was at the top of the Traders member of the ore formation, just below the bottom of the Brier slate (see fig. 6). At this time no one could have predicted that this ore body is really related to the impervious talc-schists of the dolomite below. However, as mining continued, the ore deposit gradually and irregularly widened, and at the fifth level assumed definite relations to the dolomite. From the fifth level downward this relation has continued, the main mass of the ore body being found at the apex of the trough, and long arms of ore extending up along both limbs of the fold, but especially along the main dolomite wall to the north (see fig. 7). This occurrence is especially interesting, since the ore deposit was found steadily to increase in size as it assumed definite relations to the underlying pitching trough. At the high levels, where it did not have a definite impervious basement furnished by the dolomite formation, it was comparatively small. As soon as it had assumed, at lower levels, definite relations to that trough it became a large ore body, and has continued to increase in size to the present depth, now reached at the eighth level, where the relations of the ore to the pitching trough are perfectly illustrated (see figs. 7 and 8).

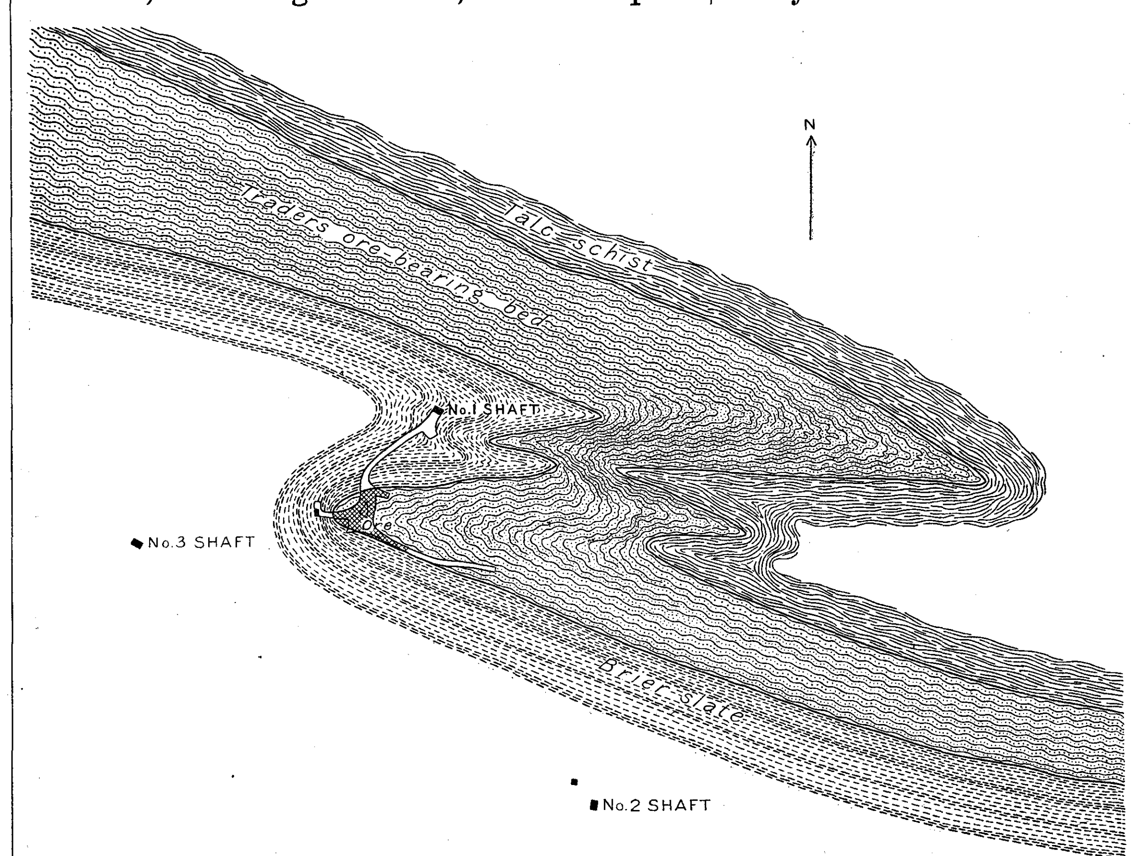

Fig. 6.—Horizontal section of the Aragon mine at the first level. Scale: 1 inch = 250 feet.

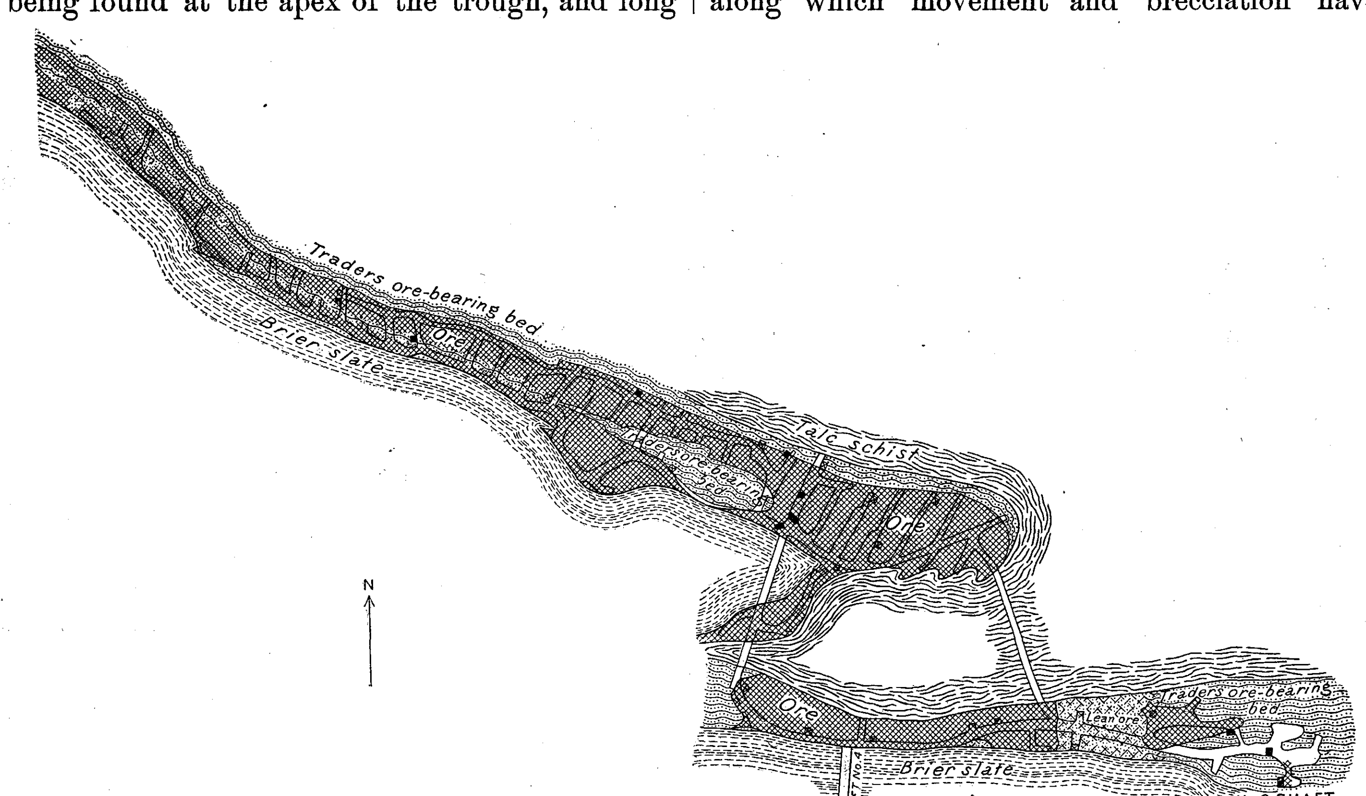

Fig. 7.—Horizontal section of the Aragon mine at the eighth level. Scale: 1 inch = 250 feet.

The next important group of mines along the southern belt are those adjacent to Vulcan, including the Vulcan, East Vulcan, West Vulcan, and Curry. Here important plication of the dolomite is not noted, and the occurrence of the ore is somewhat different from the deposits in the vicinity of Norway and Iron Mountain.

Vulcan and Curry mines.

Ore has been mined in both the Traders and the Curry member of the Vulcan formation. Indeed, it is from the Curry mine that the term Curry member is taken. The ore of the lower horizon now being exploited occurs immediately below the Brier slates, at the top of the Traders member. The ore of the higher horizon occurs in the Curry member between the Brier slates and the Hanbury slate, extending from one to the other (see figs. 9 and 10). Development has not as yet gone far enough to show whether minor folds occur in these slates, as the result of which pitching troughs will be found. However, the three contacts of the two iron-bearing horizons with the Brier and Hanbury slates are planes along which movement and brecciation have occurred, and therefore where percolating waters have been active. These ore bodies have a considerable longitudinal extent, but as yet have not shown great width. The southern deposit of the West Vulcan shows very well the relation between sharp folding, and therefore brecciation, and differential movement between the iron-bearing member and Brier and Hanbury slates. Here, at the east end of the mine, is a very sharp fold in the slate and iron-bearing member (see fig. 9). The Traders member, where ore was first mined in this vicinity, shows beautifully the effect of sharp plication and brecciation of the ore-bearing formation. Here was a continuous zone of movement. As a result, an almost continuous narrow belt of ore was concentrated, which has been mined for some distance along the strike of the rocks, the position of the removed ore being marked by a long row of open pits. The positions of the ore deposits in the vicinity of Vulcan, therefore, fully correspond to the general principles laid down. They occur at places of differential movement between different formations or members, where, therefore, circulating, downward-moving waters were effective; but

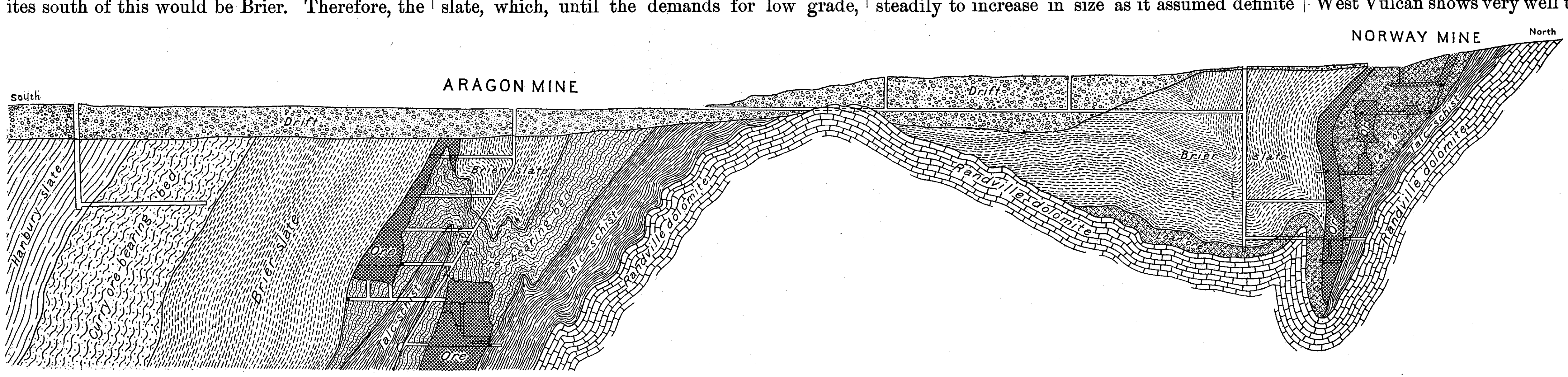

Fig. 5.—Vertical north-south cross section of the Norway and Aragon mines. Scale: 1 inch = 250 feet.

wide ore bodies have not yet been developed, apparently because impervious basements are still lacking.

Waucedah mine.

East of the East Vulcan mine the dolomite formation appears to extend as a continuous straight belt to the eastern end of the district, no subordinate folds being indicated by reentrants in the southern border of the dolomite. Corresponding with this, no ore bodies have yet been discovered except at Waucedah, where a comparatively small deposit of ore has been found. It is by no means certain that plications of the dolomite between East Vulcan and Waucedah, furnishing pitching troughs, do not occur, but if they exist the outcrops are not sufficient to indicate them.

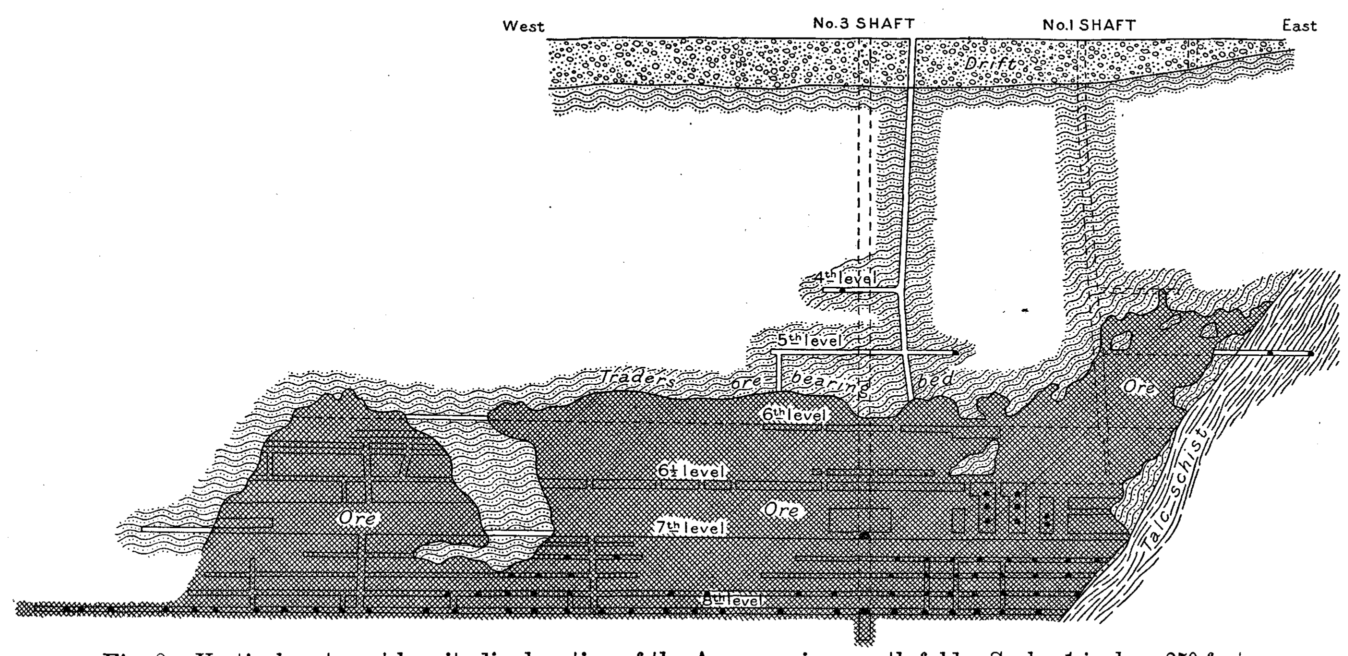

Fig. 8.—Vertical east-west longitudinal section of the Aragon mine, north fold. Scale: 1 inch = 250 feet.

Traders and Cuff mines.

2. Passing now to the second belt of the Vulcan formation, that adjacent to the central belt of dolomite, the only mines which are at present worked are the Traders and Cuff. The Traders mine is near the west end of the ore-bearing formation, which in this vicinity constitutes a westward-plunging anticlinorium. However, there is a subordinate synclinorium in the anticline, as a result of which the Hanbury slate makes a plicated eastward reentrant angle. It is in this westward-pitching synclinorium that the concentration of the Traders ore has taken place. The foot wall is a heavily ferruginous slate, which, however, differs sufficiently from the profitable ore to present a relatively impervious basement. But this syncline is not nearly so sharply defined as are the synclinoria which contain the larger ore deposits on the southern belt of the Vulcan formation. As a consequence of this, probably, the ore is rather high in silica. The percolating waters have not been sufficiently converged to remove this constituent to the extent to which it was dissolved in the better-defined troughs (see pp. 7–8). The special causes which have produced a concentration of ore at the Cuff mine have not been ascertained, but there is probably here also a fold in the dolomite.

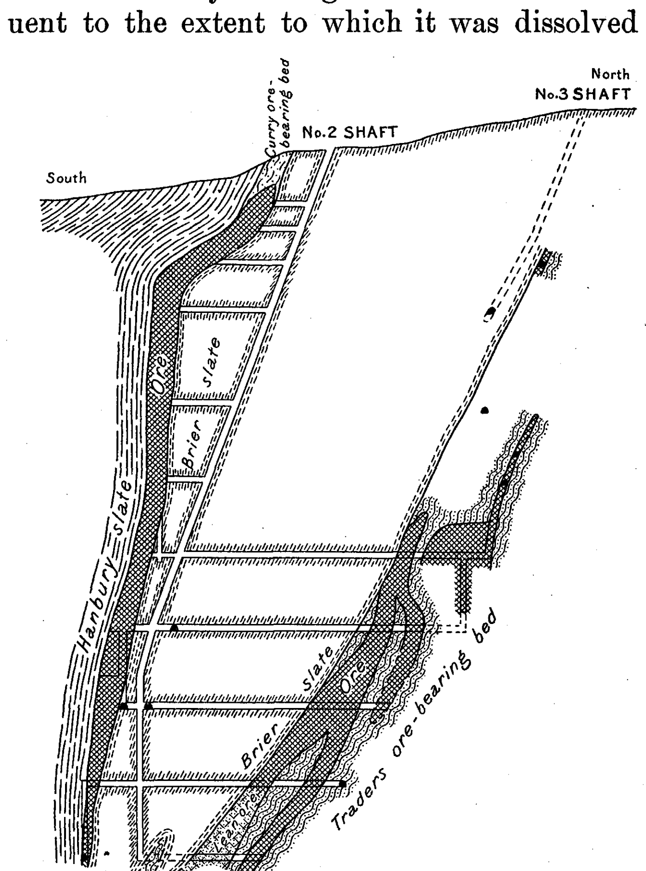

Fig. 10.—Vertical north-south cross section of the West Vulcan mine. Scale: 1 inch = 250 feet.

Loretto and Appleton mines.

3. The only remaining important ore-producing locality is that adjacent to Loretto, where are found the Loretto mine and the Appleton shaft. Here the northern and central belts of dolomite probably join (see map), giving continuous dolomite from the Sturgeon quartzite on the north to the southern iron-bearing belt on the south. East of this bridge of dolomite, beween the northern and southern belts of dolomite, is the Vulcan iron formation. To the west of the bridge are possibly the Vulcan iron formation and certainly the Hanbury slates. It is therefore clear that a cross anticline here exists which brings to or near the surface the dolomite that to the east and west is buried beneath the surface. Hence it follows that the structure adjacent to the Loretto is that of an eastward-plunging syncline, the dolomite being to the north, to the south, and to the west. In every essential respect the structure is therefore the same as that where the large ore bodies occur in the southern iron belt, except that the fold at the Loretto is much open. The character of this syncline is beautifully shown by the horizontal outline of the ore body (see fig. 11). The outer limit of the ore makes a broad U which opens out to the east, the bottom of the U being to the west. The cross section of the main ore deposit also makes a wide U, the southern limb of which passes into a sharp subordinate anticline (fig. 12). In the center of the syncline slate caps the ore. Moreover, the longitudinal section of the mine is also a syncline (fig. 13). As a consequence lean material is found east of this slate. This material passes into ore under the slate capping and is found under the drift west of the slate. The failure of the rock to change to ore is apparently due to a subordinate cross anticline, which has prevented the convergence of downward-moving currents of water, and therefore the transformation of the rock into ore has not taken place. No better illustration of an ore body in a trough on an impervious basement could be desired than that furnished by the Loretto mine.

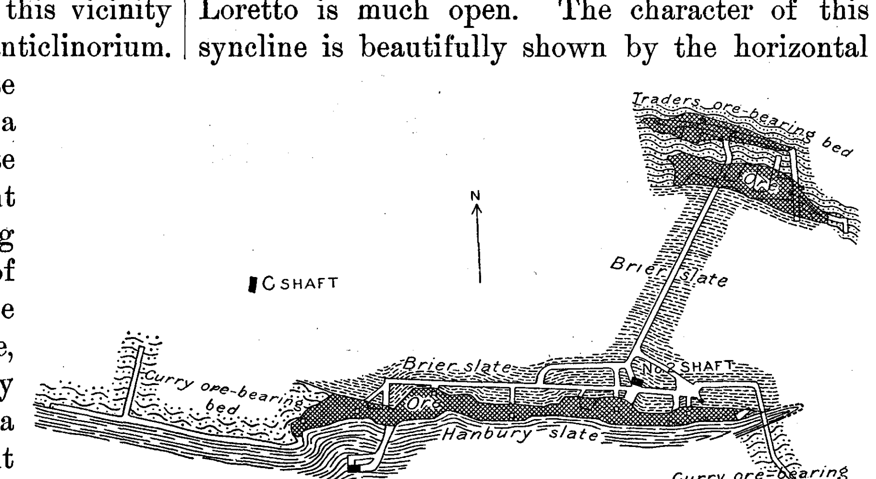

Fig. 9.—Horizontal section of the West Vulcan mine at the eighth level. Scale: 1 inch = 250 feet.

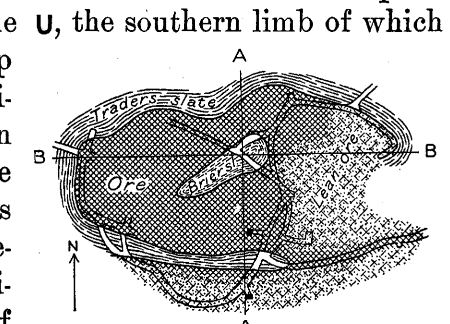

Fig. 11.—Horizontal section of the Loretto mine at the first level. Scale: 1 inch = 250 feet.

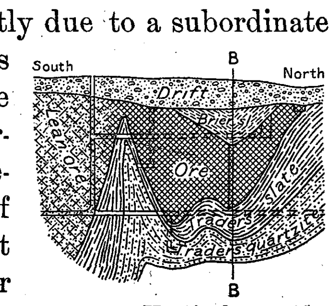

Fig. 12.—Vertical north-south cross section of the Loretto mine. Scale: 1 inch = 250 feet.

Development of ore deposits.—We are now prepared to consider briefly the process by which the ore bodies developed. It has been seen that without exception the large ore deposits of the district have the following characters: (1) They are above an impervious basement; (2) this impervious basement is in a pitching trough; and (3) the ore formation in the pitching trough is much broken. Smaller deposits occur without pitching troughs at contacts, fault planes, and at sharp folds, where the iron formation is broken.

Ores deposited in pitching troughs by descending waters.

These relations of the ore deposits to the troughs (see figs. 2 to 8 and 11 to 13) are such as to show clearly that the iron ores must have been deposited in their present position after the troughs were formed. No igneous or sedimentary rock as originally produced has such forms as those exhibited by most of the ore bodies. They clearly are not altogether original sedimentary rocks, such as the iron-bearing formation as a whole is, but the iron-ore deposits grade into the other rocks of the Vulcan formation. The ore bodies clearly are not igneous rocks. No igneous rocks ever grade by imperceptible stages into sedimentary rocks such as the various members of the iron-bearing formation, nor do igneous rocks ever have such uniformly definite relations to troughs. If the iron ores were deposited in their present position after the troughs were formed, as the foregoing facts seem to show beyond question, they must have been produced by the work of underground circulating waters.

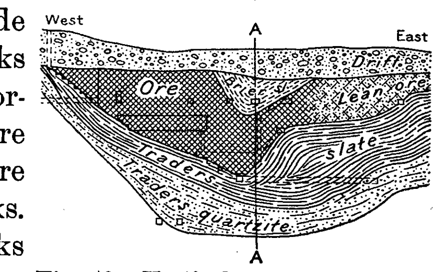

Fig. 13.—Vertical east-west longitudinal section of the Loretto mine. Scale: 1 inch = 250 feet.

The question next arises as to whether these waters were ascending or descending. The positions of the ores in pitching troughs bottomed by impervious basements rather than in pitching arches topped by impervious cover are conclusive evidence that the ores were concentrated by descending rather than by ascending water. Descending waters would be converged by pitching troughs with impervious basements, whereas ascending waters would be converged in pitching arches having impervious roofs.

In this connection it is also to be noted that the ores are usually a more or less hydrated hematite—that is, they belong to the class of hydrated and oxidized ores. The products therefore accumulated under conditions favorable to oxidation and hydration, and if secondary concentrates, must have been precipitated by water bearing oxygen. Such waters are usually descending, hence the character of the deposits makes it probable that the waters producing the ores were descending rather than ascending.

Process of concentration of the iron ores.

The next question to be considered is the chemical process of concentration of the ores at places where waters from different sources are converged. This process has been fully described by the senior author in Monographs XIX and XXVIII of the United States Geological Survey. In this folio the statement will be summarized.

Source of the iron was iron carbonate.

A part of the iron oxide of the ore bodies was deposited in its present position as an original sediment, which may since have been chemically changed; that is to say, some of it may have been deposited as iron carbonate and later transformed to iron oxide in situ. Another part is iron oxide secondarily deposited, by which the originally lean material has been enriched, forming an ore body. The process of enrichment involved concentration of the iron from a source capable of yielding it, convergence of solutions carrying it into trunk channels, and conditions favorable to its chemical precipitation. The source of the iron for the enrichment of the ores is believed to have been mainly iron carbonate. In spite of the fact that the iron-bearing members of the Vulcan formation are largely fragmental and contain but an insignificant amount of residual iron carbonate, it is probable that originally mingled with this material was much iron-bearing carbonate. The jaspilites which constitute a considerable portion of the formation have elsewhere in the Lake Superior region been genetically connected with iron-bearing carbonates, and there is every reason for believing that they have had a similar origin in the Menominee district. Indeed, the processes of change are shown to some extent in the few specimens where iron carbonate is still found. The iron carbonate within the Vulcan formation was originally, therefore, probably somewhat abundant. If iron-bearing carbonate was plentiful, the concentration of the ores at the particular places where they occur may be fully explained. However, we are not restricted to the iron carbonate of this formation as a source of the iron for the solutions. The Hanbury slate still contains a considerable amount of iron carbonate, from which there have been developed within the slates small bodies of chert, jasper, and iron ore. While no workable ore deposits have been found in the Hanbury slate, the siderite there present may have played an important role in the production of the iron-ore deposits in the Vulcan formation.

The iron carbonates in the Hanbury formation are more abundant at low horizons than at high horizons—that is, are more plentiful adjacent to the Vulcan formation. The foregoing facts render it highly probable that percolating waters within the Hanbury formation took up iron carbonate, passed down into the Vulcan formation, and thus contributed iron-bearing solutions for the enrichment of the ore bodies.

Chemical and mechanical conditions of precipitation.

The chemical reactions depend upon the mingling of waters containing oxygen with those containing iron carbonate. The waters following circuitous routes, and especially those passing through the Hanbury slate, had their oxygen abstracted by the iron carbonate in an early stage of their journey. In this way the limonite and hematite of the Hanbury slate developed. The waters from which the oxygen was taken took into solution unaltered iron carbonates and finally were converged in the Vulcan formation along the sides and the bottoms of the pitching troughs, or in other places where there were trunk channels. Water more directly from the surface, and especially that passing only through the Vulcan formation, which contained little iron carbonate, at least in the later stages of the process, retained its oxygen. The waters bearing iron carbonate and oxygen were thus commingled. The result was the precipitation of iron oxide. Furthermore, the great quantity of downward-moving water, converged into the troughs, took silica into solution and transported it elsewhere, and thus abstracted this deleterious element, its place being taken by the deposited iron oxide.

Therefore the iron oxide of an ore body consists in part of iron compounds originally deposited in situ and in part of iron brought in by underground waters. Which of the two constituents of the iron ore, the original material or that added by underground water, upon the average is more abundant it is impossible to say. In some cases it is almost certain that the original detrital iron oxide is the more abundant, and in other cases that the material added by underground water is more abundant; but in all cases it may be said that were it not for the secondary enrichment by underground waters through the addition of iron oxide and the abstraction of silica the material would not be iron ore. The evidence of this lies in the fact that the ore bodies are universally confined to the places where underground waters have been converged into trunk channels. In order that this process should have produced the large ore bodies, it is necessary that it should have continued for a long period during progressive denudation. Many of the large ore bodies known in the district somewhere reach the surface. The secondary material now found near the surface is largely derived from the Vulcan and Hanbury formations, which were once at higher levels, but which since have been removed by erosion.

Examination of areas in which Vulcan formation is not known.

Future prospecting.—Upon the maps the area given as iron-bearing formation is very conservatively represented. The area mapped as Vulcan formation is certainly underlain by rocks there belonging. The long belts of doubtful material adjacent to the northern and central belts of dolomite and along the northern side of the southern belt of dolomite may be underlain in whole or in part by the Vulcan formation. These belts are not given the color of any of the rock formations because the glacial deposits completely cover the subjacent rocks. The same is true in reference to the doubtful belts adjacent to the Quinnesec schist areas. The iron-bearing formation is known to exist south of the west end of northern dolomite. It is highly probable that the iron formation extends for some distance to the east and west of the area which is definitely known to belong to the Vulcan formation, but how far it is impossible to state.

The belts in which the Vulcan formation may possibly exist should all be subjected to a close magnetic survey with dial compass and dip needle. For the most part, the iron-bearing formation of the Menominee district is not strongly magnetic, but it is generally somewhat so, and it is thought to be probable that a sufficiently close magnetic survey will determine whether or not the iron-bearing formation has any considerable extent in these areas. After magnetic surveys have been made, if indications of ore-bearing formations are found in various areas, these should be further examined by judicious test pitting.

Favorable positions to prospect in the Vulcan formation.

Where the iron formation is known to exist, the rules for explorations are very clear. All, or nearly all, of the ore deposits yet discovered somewhere approach very close to the surface. Moreover, at the surface these are found at the contacts of the different formations or at the contact of the members of the Vulcan formation. Hence it is clear that explorations should follow very closely the contact lines of the various lithological units. There are, therefore, five horizons along which search ought to be made: (*a*) the top of the Randville dolomite; (*b*) the top of the Quinnesec schists, provided an iron formation is found adjacent to those schists; (*c*) the contact of the Traders member with the Brier slates; (*d*) the contact of the Curry member with the Brier slates; and (*e*) the contact of the Curry member with the Hanbury slate. Where the contacts are plicated, giving embayments, these are especially good places to look for ore, for here pitching troughs may be expected. The reentrant embayments of the Randville dolomite have already been sufficiently emphasized and, above all, in and adjacent to such embayments along the strike are the most favorable places for prospecting; but it should be noted that an ore body, the main part of which rests upon the dolomite, may be first discovered along the contact between the Traders member and the Brier slates, as in the case of the Aragon mine (see figs. 6 and 7). The iron-bearing formation adjacent to plications of the bounding formations or the intermediate belt of slate should be very closely examined, whether the plications seem to mark anticlines or synclines, for where subordinate anticlines are found synclines are likely to be adjacent. This again is well illustrated by the Aragon, which was found just below a little anticline of the Brier slate.

As a specific instance where exploration is warranted, we may consider the southern iron-bearing belt between Vulcan and Waucedah. Here the southern outline of the Randville dolomite should be represented on a large-scale map with the utmost care. If natural exposures are not adequate for this, the first step in exploration is to determine this outline by pits through the drift, which need not extend into the rock. When the dolomite is outlined, if embayments are found these are places for elaborate exploration. The embayments may open out to the east or to the west. The areas for exploration are along the strikes of the rocks in the directions in which the embayments open. The distance from the head of an embayment to which explorations ought to extend should be determined by studying the relations of the ore deposits of the Chapin, Walpole, Pewabic, Norway, and Aragon mines to the associated limestone embayments.

Explorations along the contacts of other belts of the iron-bearing members with the adjacent formations should follow a similar course.

If the foregoing directions are followed it is believed that the explorer will not unnecessarily waste money in exploring unfavorable localities, and will be more likely to have his labor rewarded than by any other method of procedure.

THE HANBURY SLATE.

Distribution and character.—The Hanbury slate occurs mainly in three large belts constituting valleys which correspond with synclines between the older rocks. It occupies nearly all the low ground in the Menominee trough, forming a plain broken only by heaps of glacial material deposited upon it, by the protrusions of a few hillocks composed of the harder slates, or by equally resistant greenstones. Since the main part of the Menominee trough is a westward-pitching synclinorium the slate areas are narrowest at the east, and gradually widen toward the west. The northern belt is divided into two portions by the western area of Quinnesec schists. The northern part turns northwest and leaves the Menominee district at the northern limit of the mapped area, while the southern portion coalesces with the middle belt and crosses the Menominee River into Wisconsin. East of Iron Hill the two northern belts again coalesce and extend as a single belt to the Sturgeon River. Near the longitude of Waucedah all the slates disappear to the east beneath the Paleozoic beds.

Occupies low ground in three belts.

General character.

The formation comprises black and gray clay slates, gray calcareous slates, graphite slates, graywackes, thin beds of quartzite, occasional beds of ferruginous dolomite, and rarer bodies of ferruginous chert and iron oxide. The formation is cut by dikes of schistose greenstones, and in one or two places sheets of the same rock have been intruded between the sedimentary beds. The predominant rocks of the formation are the gray clay slates and the calcareous slates. The latter are more abundant in the lower portions of the formation and the former in the upper portions. The exact vertical relations of the two rocks have not been made out, because of the scarcity of exposures and the very intricate folding to which they have been subjected. The clay slates are normal argillaceous slates, in which there is always more or less ferruginous matter. Where exposed to the weather they are light in color and have a shaly character. Muscovite then becomes prominent. Their iron components are decomposed to red ocherous compounds. Where most altered the rocks are light-red sericite-slates or shales. Where the slates contain small quantities of calcareous components their weathering is somewhat different. They tend to bleach to a very pale-green or white color and to become porous through the loss of their calcareous cement. The ferruginous components oxidize, forming red ocher, and this lies in an irregular pattern on the light-colored background. The result of these changes is a red and white, or pale-green, mottled, friable slate, known locally as "calico slate."

Varieties of clay slate.

Calcareous ferruginous slate.

By the addition of calcareous material the argillaceous slates pass into the calcareous slates. These sometimes contain as much as 50 per cent of calcite or other carbonate as a cement. With an increase in the carbonate the slates lose their slaty character, become more massive, and finally pass into beds of dolomite measuring from a few inches to 20 feet in thickness. Upon weathered surfaces both the dolomite and the calcareous slates are often coated with a skin of brown ocherous limonite, which in the case of some of the massive dolomites reaches a thickness of an inch or more. Much of the limonite is pseudomorphous after siderite. These facts show that the dolomites are sideritic, and that the siderite has partly decomposed, producing limonite.

Ferruginous chert and iron-oxide.

The ferruginous cherts and iron oxides are not known to be present in the Hanbury slate in large quantity. Indeed, they are usually only locally developed in association with the sideritic dolomites and calcareous slates where these have been severely crushed or folded. The source of the iron oxides is clearly iron-bearing carbonate in the calcareous slates and the dolomites. The cherts are white or yellow massive rocks with finely granular texture. They occur as thin seams and veins traversing the slates and dolomites, and as thin beds interlaminated with the thicker beds of the last-named rocks.

Wherever the cherts occur there is usually found also a greater or less quantity of some iron oxide. Sometimes this occurs as small veins of pure hematite cutting through the cherts, sometimes as coatings of hematite on the walls of cracks traversing the slates, sometimes as small vugs inclosed in shattered cherts, sometimes as druses covering the walls of the cavities in an extremely porous chert, sometimes in distinct bands interlaminated with bands of graywacke or quartzite, and sometimes in the form of a mixture of oxides and hydroxides impregnating slaty material. In short, the iron oxides occur in all forms characteristic of deposits precipitated from percolating waters. The slates impregnated with ferruginous matter are naturally dark red. Where but slightly ferruginous they still plainly exhibit their true character. When, however, the proportion of the iron oxides is large, but few traces of the original slate remain and the rock resembles a slaty ocher.

Secondary banding.

At one place in the slate area near the south quarter post of sec. 21, T. 39 N., R. 28 W., the banding of the material obtained from a deep shaft appears on the weathered surfaces to be as even and as well defined as the banding of the ores and ferruginous quartzose slates of the Curry member. Close inspection of the hand specimens, however, especially where made on fresh fracture surfaces, shows that the resemblance to the Curry rock is illusory. The banded rock is mainly a graywacke interlaminated here and there with layers of slate. A set of cracks cuts the graywacke parallel to its bedding planes, and along these the percolating waters found ready passage. An earthy hematite was deposited in the cracks and in the rock mass adjacent to them, thus producing bands of ore material separated by belts of the graywacke in which there was little deposition of ore.

Graphite slates, quartzites, and graywackes.

The graphite slates are black, very fissile, thinly laminated rocks. They appear to be limited to the lower portions of the Hanbury slate. At any rate, they have been seen only in association with the underlying Curry member, and at horizons a few hundred feet above the base of the slate formation, but they do not everywhere occur at the base of the formation. The graphite slates appear to grade laterally into the normal gray slates, of which they seem to be local modifications. The graywackes and quartzites of the Hanbury slate are normal rocks of their kind, requiring no special description. They both occur in comparatively thin beds, more frequently in the lower part of the formation than in the upper portion. The quartzites are more abundant than the graywackes, but neither are common.

Three major synclines.

Folding and secondary structure.—The major folding of the Hanbury slate corresponds with that of the underlying formations. Along a north-south cross section there are three major synclines, the major anticlines having been eroded save at the ends of the central dolomite belt and at the east end of the western area of Quinnesec schist. At these places the slates should present plunging anticlines. The exposures are not sufficiently good to confirm this inference.

Strikes and pitches of minor folds.

Within the major synclines the slates are crowded together in many close folds, here pitching in one direction and there in another. No system has been discovered in the minor folds, chiefly perhaps because outcrops are so scarce. On one or two of the hillocks on which exposures are fairly plentiful it was observed that, as a rule, the little folds at the east ends of the hillocks pitch to the east and those on the west ends to the west, at angles varying between 20° and 45°. These hillocks thus constitute open cross anticlines with approximately north-south axes. The east-west folds, on the other hand, are extremely close folds. Frequently on ledges that show cross sections 10 or 12 feet across, several small anticlines or synclines may be plainly seen, so closely appressed that the dips of their opposite limbs vary but a few degrees. Frequently, too, the folds are overturned so that the dips of the limbs are in the same direction. On horizontal exposures these close folds are very difficult, if not impossible, to detect, so that in many cases the closely folded beds appear to be consecutive. The strikes of the folds are usually a little north of west, and consequently the strike of the bedding is approximately in the same direction, and this is also the direction of trend of the Menominee trough. Departures from this strike are noticeable in many instances, but the variations are not great except in a few restricted areas where the pitch due to cross folding is marked. Small folds with dimensions of an inch or two are present everywhere. These often cause flutings and puckerings of the strata to such an extent that even approximate strikes and dips can not be obtained. In some places lens-shaped deposits of quartz have been found between the layers of the slate at the apices of the little anticlines and in the troughs of the little synclines.

Cleavage and jointing.

The strong north-south compression of the slate beds, producing the close east-west folds, also impressed upon all the weaker members of the slate formations a perfect slaty cleavage with a nearly east-west strike and a dip that varies but a few degrees on either side of the vertical. In addition to this cleavage there was also often produced a set of fracture planes or joints at right angles to the cleavage. These latter intersect the rocks at approximately equal intervals of several inches. In some places they are bordered by narrow shear zones in which the total displacement of the slate beds is an inch or more. On flat horizontal surfaces two sets of these joints are sometimes seen cutting each other at acute angles, and about each slight faulting has occurred. All of the phenomena presented by the slates indicate that they were subjected to powerful north-south stresses acting nearly at right angles to the axis of the Menominee trough and producing the close east-west folds, the cleavage, and the jointing; and that at the same time they were influenced by less powerful east-west stresses acting along the axis of the troughs, and producing the open north-south cross folds.

Direction of stresses.

Thickness.—No approximately correct estimate of the thickness of the Hanbury slate is at present possible. The similarity of the beds and their reduplication in consequence of the close folding render it impossible to determine what proportion of the apparent thickness of the formation is due to folding and what proportion is due to successive deposits. There can be no doubt that the Hanbury slate is much thicker than any of the other formations in the district, but that it is as thick as the corresponding formation in the Penokee district—12,000 feet—is not probable. Indeed, it is extremely doubtful whether its maximum thickness is more than 2000 or 3000 feet.

Relations to Paleozoic strata.—The relations of the Hanbury slate to the underlying Vulcan formation, the Randville dolomite, and the Archean schists have already been fully discussed. The relations of the formation to the overlying Paleozoic sediments are those of a much deformed, closely folded, highly tilted set of beds to a set of undisturbed horizontal deposits laid down upon them. No actual contacts of the two have been seen, but from the nature of the structural differences exhibited by them there is no doubt as to the existence of a profound unconformity between the two. During the interval represented by the break the Upper Huronian beds were raised above the sea, closely folded, deeply eroded, and again lowered beneath the water's surface.

Possible iron-ore deposits.—From very early times in the exploration of the Menominee district, speculation has been rife as to the possibility of discovering workable ore deposits in the great slate area between the Chicago and Northwestern Railway and the southern area of Quinnesec schists. The discovery of valuable ore beds at Commonwealth and Florence, in Wisconsin, in slates resembling those of the Hanbury formation, has given rise to the belief in many minds that similar ores will sometime be found in the slates east of the Menominee River. That so few explorations have been made in this area is explained by the fact that few clues have been available to guide the explorer in locating drills and test pits. Exposures are scarce, and the mantle of drift is so thick that explorations can not be intelligently undertaken; even if ore bodies exist they would be very difficult to find. At seven or eight places within the slate area, however, groups of test pits have been sunk, and from these lean ores have been obtained. (See map for locations.) In some cases the material is only ferruginous

Small deposits of lean ore found.

slate, and in other instances it appears to be red ocher. In a few cases, however, mixtures of chert and iron oxide have been found that resemble some of the mixed cherts and ores from the Michigamme slates of the Marquette district. Thus far nothing has been discovered that would lead to the belief that large ore bodies exist at any of these places. But, notwithstanding the unfavorable results reached by explorations, the conclusion that no ore bodies exist in the slate areas should not be assumed. The slates have been pierced at only a few places, and at these places there has unquestionably been deposited some ore material. That ore bodies of workable size have not been discovered may be due to the fact that the explorations were not made in situations that presented conditions favorable to the deposition of the ores, or it may be due to the absence of sufficient ferruginous material in the slates to furnish large quantities of iron ore.

Under the lithology of the Hanbury slate reference was made to the presence of iron carbonates in the calcareous slates and dolomites in the lower portion of the formation and to their alteration products. Under favorable conditions this carbonate has partially or completely changed into oxide. That this change has taken place is proved by pseudomorphs of limonite after siderite and by heavily ferruginous slates uncovered by the test pits. The gradation of ferruginous dolomite into ferruginous chert in an exposure on the north face of the hillock in the SE. $\frac{1}{4}$ sec. 7, T. 39 N., R. 29 W., is suggestive that ore deposits also may possibly have developed. In the Penokee and Crystal Falls districts lean iron-bearing carbonates in slates are known to have been the source of materials constituting the ore-bearing formations.

How to prospect Hanbury slates.

Before locating exploring plants the ground should be closely examined with a view to securing the most favorable sites. If possible, the following conditions should be met by the sites selected. First, since the ore material is derived from iron carbonates, and these are known to exist only in the dolomites, cherts, and calcareous slates, the explorations should be confined to areas known to be underlain by these rocks, which when exposed to the weather may be identified by the coating of limonite that covers their weathered surface. Second, the most favorable situations for ore concentration are the troughs of pitching synclines with impervious bottoms. Hence search should be made for pitching folds. If such folds can be found, and it can further be determined that the folding involves beds of argillaceous slates or other impervious rocks, these furnish conditions favorable for ore concentration. Third, in the Crystal Falls district carbonaceous shales are often associated with the ore bodies, and in the Menominee district graphitic slates are often associated with the Curry ores, some of the material of which is almost certainly original. Therefore, if situations can be found where carbonaceous slates occur in pitching synclines below rocks containing iron carbonate the conditions may be regarded as exceptionally favorable for the accumulation of ore deposits. Fourth, percolating waters are the agents of the process of concentration; consequently localities at which the rock masses have been shattered, thus affording easy passage to the water, are places particularly desirable for testing. In a set of slates as closely folded as are the Hanbury there may somewhere be found places where the conditions outlined are fulfilled, and in such places ore bodies will be found, if they exist anywhere in the slate area.

Thus it appears that although no ore bodies of value have thus far been discovered in the slates, the possibilities of the formation have not by any means been exhausted. A more extensive exploration of the slate formation is perhaps warranted before the field is finally abandoned as worthless.

PALEOZOIC SYSTEM.

Limited areas of Paleozoic sediments in horizontal sheets are found to lie on the eroded edges of the Huronian and Archean rocks. The Paleozoic rocks may be divided into two formations. The lower beds are mainly red sandstone, which are known in the region as the Lake Superior sandstone. The upper beds are porous arenaceous limestone, identified by Rominger as corresponding to the Chazy and Calciferous formations of the Eastern States. This is designated the Hermansville limestone on the accompanying map. The sandstones and limestones were at one time spread continuously over the entire Menominee district. To the east of the district they still cover all the older rocks. West of Waucedah, however, they have been generally eroded from the valleys, leaving remnants as isolated patches on the tops of the higher hills.

LAKE SUPERIOR SANDSTONE.

Character and relations.—The Lake Superior sandstone, according to Rominger, consists of a lower portion partly cemented by an iron oxide and consequently red in color, and an upper portion in which the cement is partly calcareous and the color white. The total thickness is estimated at 300 feet. Although Rominger states that there is no record of any recognizable fossils from the sandstone, he nevertheless, because of its position beneath the limestones, correlates it with the Potsdam of New York. Since the publication of Rominger's report several pieces of the sandstone have been obtained, which according to reliable authority came from the ledge through which one of the Pewabic mine shafts, near Iron Mountain, was driven. These contain numerous fragments of fossils, some of which were determined by Walcott as "the heads of small trilobites, probably *Dicellocephalus misa;* also fragments of a large species of Dicellocephalus." According to Walcott, "These indicate the upper Cambrian horizon of the Mississippi Valley section."

The relations of the sandstone to the underlying formations are always practically the same. Whether on the tops of hills or in the depressions between the hills, the horizontal beds of the younger rock always rest unconformably upon the upturned and truncated layers of the older series. Moreover, the basal layers of the sandstone always contain a great deal of material derived from the immediately subjacent formations. Where the underlying rocks are those belonging to the Vulcan formation the basal member of the sandstone is an ore and jasper conglomerate, composed of huge rounded bowlders of ore and large sharp-edged fragments of ferruginous quartzose slate and jasper in a matrix consisting of quartzose sand, numerous small pebbles and fragments of ore-formation materials, quartzite, and occasional pebbles of white quartz, of granite, or of other members of the Archean. Some of these conglomerates are exceedingly handsome. In a few instances the proportion of ferruginous material is so great that they have been utilized as sources of iron ore. A deposit of this kind was formerly worked by the operators of the Quinnesec mine, and another has recently been worked by the Pewabic company. The latter was reached by the open pit in the SE. $\frac{1}{4}$ sec. 32, T. 40 N., R. 30 W., known as the Pewabic pit. Although the immediately underlying rock here is dolomite, the amount of iron ore is so great that the company operating the pit felt warranted in erecting concentrating works on the property for the separation of the ore from the sandstone. In the summer of 1898 the yield of ore from the concentrator was 5000 tons.

LOWER SILURIAN LIMESTONE.

The general character of the Hermansville limestone "is that of a coarse-grained sandstone, with abundant calcareous cement, in alternation with pure dolomite or sometimes oolitic beds." The limestone may be seen near the top of the hill east of Iron Mountain, on the bluff northeast of Norway, and at several places on the hills north of Waucedah. Its maximum thickness, according to Rominger, is about 100 feet, but this maximum is rarely reached in the Menominee district. Only a few fossils have been reported from it. Rominger states that it has yielded a few fragments of molluscan shells. To these may now be added a broken Orthoceras, a fragment resembling a piece of a Cyrtoceras, a gasteropod, and several other fragmentary forms found in the top layer on the bluff northeast of Norway.

OUTLINE OF GEOLOGIC HISTORY.

RÉSUMÉ OF FORMATIONS.

Before giving a brief outline of the history of the district, it may be well to recall the general succession of formations and their distribution. The district is bordered by areas of Archean schists and granites. The Huronian sediments of the district are in a trough between these older rocks. Structurally this trough is a synclinorium, composed of several important anticlines and synclines. The Lower Menominee series comprises 1050 to 1250 feet of quartzites and conglomerates that have been called the Sturgeon quartzite, 1000 to 1500 feet of dolomites, with subordinate amounts of calcareous slate and chert, designated the Randville dolomite, and small patches of the Negaunee iron-bearing formation. The Upper Menominee series comprises the Vulcan formation, 650 feet thick, and the Hanbury slate. The Vulcan formation includes three members, the Traders iron-bearing member, consisting largely of detrital ores, but having basal members of quartzite and conglomerate; the Brier member, composed of ferruginous and siliceous slates; and the Curry member, consisting of quartzites, ferruginous quartzose slates, jaspilites, and ores. The Hanbury slate is mainly argillaceous, but in places is calcareous and includes small beds of dolomite and ferruginous chert.

SUCCESSION OF EVENTS.

Archean.—The history of the Archean rocks is an extraordinary complex one, which will not here be analyzed. It is sufficient to say that the ancient Quinnesec schist, wholly of igneous and largely of volcanic origin, was intruded in a most complex fashion by various igneous rocks, of which granite was the most abundant. This complex of rocks went through a long series of epeirogenic and orogenic movements, with attendant metamorphism and deep denudation, before Algonkian time.

Lower Menominee deposition.—By transgression of the sea, due to subsidence of the land or rise of the sea, or both, the Menominee district was finally covered by water, and Lower Menominee Algonkian deposition began. Originally the sediments were laid down as a set of approximately horizontal beds on a basement composed of Archean rocks similar to, if not identical with, the material constituting the rims of the trough. The first deposit of the advancing sea was the basal conglomerate of the Sturgeon quartzite. Following this conglomerate was a thick layer of sandstone, which later was consolidated into quartzite. The deposition of a considerable thickness of sand shows that the district must have continued to subside during Sturgeon time. Apparently toward the end of the Sturgeon epoch the water became too deep for sandstone formation, and the non-clastic sediments of the Randville dolomite were deposited. These are now cherty crystalline dolomites and marbles, but there is every reason to believe that the original form of the material was an ordinary siliceous limestone. The time represented by the Randville dolomite was probably long, for the thickness of limestones deposited was 1000 feet or more. Possibly as a result of upbuilding with shallowing of the sea, or other unknown conditions, the carbonates being deposited changed in character and bore a large amount of iron. At this time the cherty iron-bearing carbonates were produced. Later these were transformed into the ferruginous cherts and jaspilites of the Negaunee formation. Whether or not later formations were deposited during Lower Menominee time upon the Negaunee formation is uncertain.

The formations of the Lower Menominee series were certainly deposited over a considerable area in the Menominee district, and the equivalents of these formations were deposited north of the Menominee district in the Crystal Falls and Marquette districts. Whether or not the Lower Menominee formations were deposited upon the Quinnesec schists is uncertain. It is possible that the Quinnesec schists were land areas during a large part of Lower Menominee time, and that the iron for the Negaunee formation was derived from these heavily ferruginous rocks within and bordering the district mapped. The apparent entire absence of the Lower Menominee formations about the western area of Quinnesec schist is difficult to understand. The most plausible explanation for this area, and possibly for the southern area, is that the Lower Menominee formations were there deposited and were subsequently removed by erosion. These formations, resting upon the Quinnesec schists, might have been composed of softer material than the resistant formations adjacent to the granite area on the north side of the trough, and therefore may have been more easily erodible.

In any case it is highly probably that the different formations were not deposited in uniformly thick layers throughout the district. If all the formations, or the lower ones, were not deposited upon the Quinnesec schist, each higher stratum overlapped the one next below it in passing toward the land areas of Quinnesec rocks.

Inter-Menominee unconformity.—Following the long-continued deposition of Lower Menominee time the district was raised above the sea. Apparently this uplift was accompanied by only very gentle folding. The reason for this belief lies in the apparent conformity of strike and dip of the Upper and Lower Menominee series. However, it is explained in another connection that such an erosion interval, with no great discordance in strike and dip, may mark a very great hiatus, and such is believed to have been the case in the Menominee district. The evidence is not found in the Menominee area, but in other areas south of Lake Superior; for instance, the Marquette district, where the inter-Huronian orogenic movements and denudation were of a most profound character. As soon as the Menominee area rose above the water erosion began, and continued until all but remnants of the Negaunee formation was removed through the central and northern parts of the district, and probably also all of the Lower Menominee formations which existed were eroded from the part of the district adjacent to the Quinnesec schist. However, as has already been said, these schist areas may have been above water during much of Lower Menominee time, in which case it would not be necessary to suppose that denudation removed the Lower Menominee formations.

Upper Menominee deposition.—During the later stages of the inter-Menominee denudation the sea again gradually overrode the district. Evidently at this time the area was uneven, though not mountainous, for the first formation laid down by the Upper Menominee sea does not extend over the entire district. These first deposits constitute the Traders iron-bearing member of the Vulcan formation. The material of which this member is composed was largely derived from the Negaunee iron-bearing formation, although material was furnished by other formations. Therefore the basal layers are composed of quartzites and conglomerates, the bowlders and smaller detritus of which consist largely of iron oxide and jasper, with some quartzite and dolomite. Since these bowlders could have come only from a land mass, it is certain that the Lower Menominee beds at this time had already been consolidated and were at least partly above the sea. Following the deposition of the basal, somewhat coarse clastic member of the Vulcan formation, there came a time of relative quiescence, during which the muds that afterward solidified into the Brier slate were laid down. Following the deposition of the Brier slate the mingled fragmental and non-fragmental sediments of the Curry member were deposited, the latter consisting largely of iron-bearing carbonate. At the end of the time of the deposition of the Vulcan formation—that is, at the close of the deposition of the Curry iron-bearing member—the sea had not as yet spread over all of the district. The area covered has not been accurately determined, and the Vulcan formation may have a wider distribution than that shown upon the map, but it is certain that the sea had not covered the entire district, and that some areas were still land, especially those occupied by the hard, resistant dolomite. This is shown by the fact that the Hanbury slate, the next deposit of the advancing sea, at various places rests directly upon the Randville dolomite, there being no intermediate belt of Vulcan formation. The deposition of the Hanbury slate required a long time, during which the physical conditions varied, for mingled with the ordinary slates are subordinate amounts of calcareous slate, dolomite, and chert, marking brief stages of partial or complete non-fragmental sedimentation.

Folding and metamorphism.—Following the deposition of Upper Menominee time the district was again raised above the sea and was subjected to very great orogenic forces. The major compressing force was nearly north-south. As a result of compression in this direction the areal extent of the mass of Menominee sediments was shortened considerably, probably as much as one-half. Consequent on this folding two great anticlinoria formed, bordering the northern and southern sides of the area, and a great central synclinorium constituting the Menominee trough proper. The northern and southern anticlinoria naturally expose the oldest, or Archean, rocks. The intermediate synclinorium is occupied by the Huronian sediments. This central synclinorium consists of three synclines and two anticlines. Superimposed on these folds of the first order is a set of folds of the second order, on these a set of folds of the third order, and on these folds of higher orders, to those of microscopic dimensions. The major folds of the Menominee synclinorium are illustrated by the anticlines of dolomite; the folds of the second order by the synclines of the Vulcan formation, in which such mines as the Walpole, Pewabic, and Aragon occur; the folds of the third order by the two separate ore deposits of the Walpole. From an economic point of view, therefore, it is necessary to take into account at least the three major orders of folds.

In addition to the intense north-south compression there was very strong compression in an approximately east-west direction, or, to speak more exactly, parallel to the direction of the trough. This compression produced folds at right angles to the longitudinal folds, so that the east-west folds of the various orders have a pitch. In some cases this pitch is comparatively slight, but in other cases it is very steep, as high as 40°, 50°, 60°, or even 70° or more. It is therefore clear that the east-west compression was of great importance. While the north-south compression produced the subordinate synclines holding the ore bodies, the east-west compression gives these folds a pitch and thus supplies the chief final condition for the production of the ore deposits.

During the uplifting and folding of the rocks of the Menominee series the harder formations were fractured in a most complicated fashion and all were profoundly metamorphosed. The sandstones were transformed to quartzites, the limestones to crystalline dolomite or marble, the iron-bearing formation to ferruginous slates, jaspilites, and ores, the muds to slates.

Post-Huronian unconformity.—Contemporary with the uplifting and folding of the district, which must have produced mountain masses, denudation was steadily going on. It was during this complex series of transformations that iron oxide was concentrated in the pitching troughs and the ore deposits were produced. The period of post-Huronian folding and erosion occupied the great length of time represented in other parts of the Lake Superior region by the unconformity between the Upper Huronian and the Keweenawan, the formation of the entire Keweenawan series, and the great unconformity between the Keweenawan and the Cambrian.

The Paleozoic deposition.—During the later stages of this great period of denudation the Cambrian transgression was slowly making its way in North America from the southeast toward the northwest. Finally the Cambrian sea reached the Menominee district, but not until upper Cambrian time. At this time the topography of the Menominee area was rough, even bluffy. The Cambrian deposits filled the depressions in the pre-existing rocks and capped even the highest hills of the district. Where the sandstone lies adjacent to or upon the Vulcan formation the basal member of the Cambrian contains quantities of iron-ore pebbles, and where the topography furnished depressions for concentration of the heavy material these beds are so strongly ferruginous as to furnish detrital iron ores. Sandstone deposition continued to the end of the Cambrian period, at which time the water had become sufficiently deep for limestones to be deposited, and at this stage of the history the Hermansville limestone was laid down. Whether Paleozoic rocks later than the Hermansville limestone were deposited in the Lake Superior region is uncertain.

Post-Paleozoic history.—Following the Paleozoic period of deposition the area was again elevated above the sea, and then another long period of denudation began. So far as known, this erosion period continued until late in Cretaceous time. Possibly later Cretaceous sediments were laid down over the Menominee areas; but in any case, following Cretaceous time the region was again raised above the sea, and so far as we know, denudation has since continued. Nearly all of the Silurian limestone has now been removed from the district, and only a subordinate amount of the Cambrian sandstone remains capping the higher hills and filling the depressions in some of the subordinate valleys. During this period of erosion the present topography of the district was largely produced. To what extent this topography follows the pre-Cambrian topography can not be determined, but apparently the pre-Cambrian topography has had an important influence upon present topography. As the result of the removal of the greater part of the Paleozoic rocks, the Huronian and Archean rocks were again brought to the surface. The final important episodes in the history of the Menominee district were the successive advances of the North American ice sheet, which modified the topography of the district by erosion and by deposition. The glacial deposits constitute a mantle which subsequent river erosion has only partially succeeded in removing, and which has prevented fully satisfactory determination of the distribution of the Vulcan and other formations.

Descending succession in the Penokee, Marquette, Crystal Falls, and Menominee districts.

Penokee District.	Marquette District.	Crystal Falls District.	Menominee District.
Lake Superior sandstone.	Lake Superior sandstone.	Lake Superior sandstone.	Lake Superior sandstone.
(Unconformity.) Keweenaw series. (Unconformity.)	(Unconformity.)	(Unconformity.)	(Unconformity.)
Upper Huronian.	*Upper Huronian.*	*Upper Huronian.*	*Upper Huronian.*
1. Upper slate member.	1. Michigamme formation (locally replaced by Clarksburg volcanic formation). One might divide the Michigamme sedimentary formation into three members: (*a*) Upper slate member.	1. Michigamme formation; consists of three members equivalent to those of the Marquette district, but 2 and 3 given below can be separated in mapping only in the southern part of the district.	1. Hanbury slate, bearing in lower portion calcareous slates, etc., containing siderite.
2. Iron-bearing member. (In east part of the district volcanic fragmentals are associated with 1 and 2.)	(*b*) Iron-bearing member.	2. Groveland iron-bearing formation in southern part of district.	2. Vulcan formation, consisting in descending order of— (*a*) Curry iron-bearing member.
3. Quartz-slate member, having— (*a*) A thin belt of quartzite at its top; (*b*) A main belt of slate below; and (*c*) A thin belt of quartzite at its bottom at various localities.	(*c*) Lower slate member. 2. Ishpeming formation of quartzites and detrital ores, and the Bijiki schists in western part of district.	3. Mansfield slate.	(*b*) Brier slate. (*c*) Traders iron-bearing member.
(Unconformity.)	(Unconformity.)	(Unconformity.)	(Unconformity.)
Lower Huronian.	*Lower Huronian.*	*Lower Huronian.*	*Lower Huronian.*
(Evidence of the former existence of an iron-bearing member above the cherty limestones is seen in the presence of ore and jaspilite grains in basal portion of Quartz-slate member.) 1. Cherty limestone member.	1. Negaunee iron-bearing formation. 2. Siamo slates, containing interstratified amygdaloids. 3. Ajibik quartzite. 4. Wewe slate. 5. Kona dolomite.	1. Negaunee iron-bearing formation in northeastern part of district. 2. Hemlock volcanic formation. 3. Randville dolomite.	1. Negaunee iron-bearing formation. 2. Randville dolomite.
	6. Mesnard quartzite.	4. Sturgeon quartzite.	3. Sturgeon quartzite.
(Unconformity.)	(Unconformity.)	(Unconformity.)	(Unconformity.)
Archean.	*Archean.*	*Archean.*	*Archean.*

CORELLATION WITH OTHER DISTRICTS.

In the table above, the successions of the Penokee, Marquette, and Crystal Falls districts south of Lake Superior are compared with the succession in the Menominee district. Formations or sets of formations which are believed to be equivalent in age are placed opposite one another. The table does not include the iron-bearing districts north of Lake Superior, since it is not thought advisable in this folio to take up the discussion of the correlation of the various formations of the Menominee with those of the more remote iron-bearing districts of the Lake Superior region.

In the table it will be noted, by comparing the column given for the Crystal Falls district with that contained in Monograph XXXVI of the United States Geological Survey, that the succession has been somewhat changed. When the monograph was published it was supposed that the Groveland iron formation and the Mansfield slate of the southern part of the district belong in the Lower Huronian; but the work in the Menominee district shows beyond reasonable question that these formations, which have a comparatively small areal extent in the Crystal Falls district, really belong in the Upper Huronian.

Discrepancies in columns.—In the four districts the correlation of the series placed opposite one another and separated by the unconformities, and the correlation of the unconformities, may be regarded as practically certain; also the correlation of individual members within the parallel series has in many cases a very high degree of probability. However, an examination of the table shows various discrepancies. These discrepancies are due in a given case to one or more of the following causes:

During the time a series or formation was being deposited throughout all or a part of one district, all or a part of another district was still undergoing erosion. As the sea advanced overlap resulted. The extreme illustration of this case is furnished by the great Keweenawan series in the Penokee district, which is entirely absent in the Marquette, Crystal Falls, and Menominee districts. It appears that the unconformity at the base of the Cambrian in these three districts stands as the time equivalent of the Keweenawan series and the two great unconformities above and below this series. The Penokee district furnishes an illustration of an absent member in the Huronian series, due to the fact that the district was a land area, while the other districts were at least partly under water. In the Penokee district, below the Cherty limestone member of the Lower Huronian no thick quartzite formation is found equivalent to the quartzites below the dolomites in the other districts. Therefore the limestone in the Penokee district overlaps the lower quartzite. A case of overlap within a district is furnished by the Hanbury slate of the Menominee district, which overlaps the Vulcan formation at various places.

The inter-Huronian erosion cut to different depths in the different districts, as a consequence of which formations of the Lower Huronian may have been largely removed in one district and may have been comparatively untouched in another. This case is well illustrated by the Penokee district, where all the Lower Huronian formations above the Cherty limestone were removed before the Upper Huronian transgression. To some extent the case is also illustrated by the Menominee district, where only remnants of the Negaunee iron-bearing formation remain.

A formation may have a greater vertical range in one district than in another; the conditions may have remained uniform in one district, and therefore deposits of the same kind continued, while the conditions changed in another district, and therefore more than one formation was deposited. This case is illustrated by the Randville dolomite of the Menominee district, which appears to occupy the time required for the deposition of the dolomite in the Crystal Falls and Marquette districts, and also that required for the deposition of the volcanic and fragmental formations between the dolomite and the Negaunee iron formations. The order of formations in the Upper Huronian might at first thought be regarded as very different in the various districts. However, if one reduces the order of succession to a general statement it is as follows: (1) an upper fragmental slate member; (2) an iron-bearing member, largely non-detrital; and (3) a lower fragmental member which consists of quartzites, slates, and, at its base in some districts, large quantities of fragmental iron-formation material.

In all the districts the upper fragmental member is represented; in the Penokee by the great upper slate member, in the Marquette by an equally great upper slate member, in the Crystal Falls by the entire Michigamme formation, and in the Menominee by the Hanbury slate.

The largely non-detrital, iron-bearing member is also represented in all of the four districts. In the Penokee district it is a continuous, almost completely non-fragmental formation, which extends from the western part of the district nearly to the eastern end. In the extreme eastern part of the district the formation is broken up by a great volume of contemporaneous volcanic rocks. In the Marquette district the non-detrital iron-bearing member is not found as a continuous formation, but is represented by subordinate belts of iron-bearing formation which, here and there, bear ore bodies. These are plainly at a persistent horizon corresponding very nearly in position to the iron-bearing member of the Penokee district. In the Crystal Falls district the iron-bearing member is represented by the Groveland iron-bearing formation, which in the Felch Mountain tongue is only partly non-clastic, but which in the Mansfield and Amasa areas appears to be wholly non-clastic. In the Menominee district this iron-bearing horizon is represented by the Curry member, which is apparently largely non-clastic, but which has with it a considerable amount of non-clastic material.

The lower fragmental member of the Upper Huronian, as one would suppose, is the most variable in the different districts, since this is the basal formation. In the Penokee district it consists of three different belts—a thin quartzite on top, a main slate belt in the middle, and a thin quartzite and conglomerate at the bottom. The upper and lower of these belts are so thin that they have been placed with the slate in mapping. At the bottom of this member no detrital iron ores are found. This is due to the complete removal of the Negaunee formation by erosion before the encroachment of the Upper Huronian sea. In other words, the Penokee district was a land area until the Negaunee formation was wholly removed. In the Marquette district the lower detrital member is represented by the lower part of the Michigamme slate, by the Ishpeming quartzite with detrital ores at its base, and, in the western part of the district, by the Bijiki schist. In the Crystal Falls district the lower formation is represented by the Mansfield slate. This does not show detrital ores at its base, nor does it have a quartzite at its base, as in the Penokee and Marquette districts. The absence of the detrital ores in the district is due to the same cause as in the Penokee district, viz., it was a land area until the Negaunee formation was entirely removed. The absence of a quartzite at the base of the section was doubtless due to the fact that it rests upon a dolomite rather than upon hard siliceous formations, as does the lower member in the Penokee and Marquette districts. In the Menominee district the lower member is represented by the Brier slate and the Traders iron-bearing member. Here the detrital ores appear because of the encroachment of the sea before the Negaunee iron-bearing formation was removed. However, thick beds of quartzite are generally absent, and this is explained in the same manner as in the Crystal Falls district—that is, the formation was deposited upon a dolomite rather than upon siliceous formations.

If it were possible to map in each of the four districts each member which is recognized, the apparent discrepancies in the succession of the Upper Huronian would be much less prominent. Indeed, where volcanic rocks are absent the succession would be found to correspond almost exactly. However, a given formation would be very important in one district and comparatively unimportant in another. Moreover, where vulcanism has disturbed the succession, as in the eastern end of the Penokee district and in the Crystal Falls district, the orderly succession is not readily recognized.

The discrepancies of the successions in the Lower Huronian series are greater than those in the Upper Huronian. As already noted, in the Penokee district all the members above the Cherty limestone were removed during the time of inter-Huronian erosion. In the Menominee district the Negaunee formation was all but removed at the erosion period. In the Menominee district only one formation, the Randville dolomite, has been discriminated between the Negaunee formation and the Sturgeon quartzite; whereas in the Marquette district four formations, the Siamo slate, Ajibik quartzite, Wewe slate, and Kona dolomite, are found; and in the Crystal Falls district two, the Hemlock volcanic formation and the Randville dolomite. The formations which are present in the Marquette and Crystal Falls districts and are not found in the Menominee district are all clastic and volcanic formations. The inference is that in the Menominee district quiescent physical conditions favorable to limestone deposition were long continued. The Randville dolomite was there laid down during the time of the deposition of the limestone formations and the fragmental and volcanic sediments between the limestone and the Negaunee formations in the Crystal Falls and Marquette districts. This is shown to be highly probable by the relations within the Crystal Falls district. In the eastern part of that district the Randville dolomite is a thick formation, and there no volcanics are found, whereas in the western part of the district the limestone deposit is very thin and there is a great volcanic formation standing in an equivalent position. In the Marquette district, also, changing physical conditions combined with volcanism explain the deposition of the clastic sediments and volcanic formations between the Kona dolomite and the Negaunee iron formation.

The attempt to correlate the various formations of the two Huronians series in the four different iron-bearing districts south of Lake Superior shows very significantly that the geologic history of pre-Cambrian time was extraordinarily complex. From Archean to Cambrian time, in the Marquette, Crystal Falls, and Menominee districts, the areas three times emerged from the sea and were three times overridden by the sea. In the Penokee district there was a fourth emergence and transgression of the sea. The epeirogenic or land-making movements were accompanied by orogenic movements, or mountain growths, of varying power, but some of them exceedingly intense. In Huronian time, in all the districts except the Menominee, there were important and long-continued periods of volcanism. The great events of Keweenawan time are only mentioned, since they do not particularly concern the Menominee district. The erosive forces at periods when the districts were land areas found rocks of very different characters. Here they were resistant, there easily denuded. As a consequence, when the sea encroached at the close of Archean, Lower Huronian, and Upper Huronian times, the country in detail was very irregular—was in fact bluffy, but not mountainous. Therefore certain areas were covered by the sea, while other immediately adjacent areas were above the water and were being actively eroded. As a consequence of all these complex conditions we have unconformity, overlap, changes in the characters of contemporaneous sediments along the strike and across the strike, disturbances in the successions due to volcanism, close folding and attendant metamorphism, and all of these phenomena in a region which is largely covered by glacial drift.

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