not penetrated below the iron formation, and the explorations north of these mines have nowhere exposed the rocks lying beneath the Cambrian sandstone. That the belt continues eastward uninterruptedly through secs. 18, 17, and 16, T. 39 N., R. 28 W., is, however, rendered probable by the fact that two magnetic lines that have their origin in sec. 18, one just north of known exposures of the dolomite and the other to the south of them, can be traced without break into sec. 15 of this township. These indicate that the iron formation continues eastward this far, and since the dolomite is immediately beneath the iron formation, the inference is fair that the dolomite also continues to the same distance.

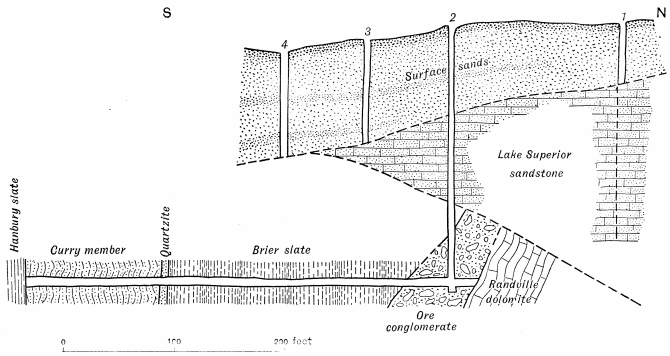


FIG. 16.—Cross section through pits and shafts near the center of sec. 25, T. 40 N., R. 31 W.

The belt occupies a narrow strip of country running a little south of east through the southern portions of secs. 23 and 24, and the northern parts of secs. 26 and 25, T. 40 N., R, 31 W., and through the whole or parts of secs. 30, 29, 28, 27, 31, 32, 33, 34, 35, and 36, T. 40 N., R. 30 W.; secs. 2 and 1, T. 39 N., R. 30 W.; secs. 6, 5, 4, 3, 9, 10, 11, and 12, T. 39 N., R. 29 W.; and secs. 7, 18, 17, and 16, T. 39 N., R. 28 W.

The northern boundary of the belt is in general very indefinite. At several places it can be fairly well determined by exposures, viz, just north of the island in Lake Antoine and south of the Loretto mine, in sec. 7, T. 39 N., R. 28 W., but elsewhere it can not be definitely fixed without recourse to test pits and shafts, because it is deeply buried under the drift or is covered by thick deposits of the Cambrian sandstone. As nearly as can be determined this northern boundary is about as follows: Beginning at the Menominee River, near the east-west quarter line of sec. 23, T. 40 N., R. 31 W., it runs a little south of east to the southwest shore of Lake Antoine where it is crossed by the east line of sec. 30, T. 40 N., R. 30 W. Here it is reported to have been found beneath the surface in drill holes. From this point it continues to the southeast shore of the lake, passing just north of the island and the little knoll opposite its east end. It is mapped as passing around this knoll and running west for a short distance, then turning eastward again and continuing its south-of-east course to a point in the northwest quarter of the southeast quarter of sec. 35, T. 40 N., R. 30 W. The reentrant on the southeast shore of Lake Antoine is based solely on topography. On the little knoll east of the island the dolomite is well exposed. It is known by test pits to occur under the sandstone nearly to the base of the northern slope of the large hill to the south. Between this hill and the knoll is a narrow valley and a swamp. The contrast between it and the hills on both sides is noticeable. Since similar low ground elsewhere is known to be underlain by slates, the assumption is made that this valley is likewise carved from these rocks, and the dolomite is mapped as passing around it. From the point in the southeast quarter of sec. 35, the boundary is again supposed to make a reentrant to the west to correspond to the known salient at Quinnesec on the south side of the belt. From the end of the reentrant the line is drawn straight to about the center of the southeast quarter of sec. 3, T. 39 N., R. 29 W. Except at its eastern portion the boundary here is conjectural. Drill holes have shown the existence of dolomite near the north line of the southwest quarter of the southeast quarter of sec, 35, T. 40 N., R. 30 W., and near the northeast corner of sec. 2, T. 39 N., R. 30 W., and a pit exposes it 500 paces east of this corner in sec. 1. To the east no ledges of any rock older than the sandstone are met until the southeast quarter of sec. 3, T. 39 N., R. 29 W., is reached. Here there is a single small ledge of contorted dolomite, with its folds apparently pitching flat to the west. The boundary line is made to pass around this ledge, then to pass southwestward to the center of the southeast quarter of the southeast quarter of sec. 4 and to turn once more to the east, forming a reentrant to correspond to the dolomite salient on the south side of the belt between the Norway and the Aragon mines. From the apex of this reentrant the boundary line is again drawn straight to about the east quarter post of sec. 11, T. 39 N., R. 29 W. Here it turns northwest to a point 500 paces north of the center of this section and then eastward again skirting the north side of the dolomite ridges that stretch in almost a continuous line from this point to another just south of the Appleton mine, in sec. 7, T. 39 N., R. 28 W. The eastward-extending embayment is necessitated by the presence of 13 or more pits in slates stretching along the north-south center line of the southwest quarter of the northeast quarter of sec. 11. The boundary is assumed to be very near the northernmost ledges in secs. 11 and 12, T. 39 N., R, 29 W., because of the marked change in the topography noted here. The area to the south, known to be underlain by dolomite, possesses an undulating surface broken by numerous ledges, ridges, and hillocks of rock, while that to the north is a low, flat, swampy country in which no ledges of any kind are exposed. The continuation of the boundary eastward to the point where the belt is lost under the thick covering of Paleozoic sediments that stretch from the eastern end of the Menominee trough to Lake Michigan, is placed at a uniform distance south of the magnetic line that begins a little west of the Loretto mine and is traced with fairly good success to about the center of sec. 15, T. 39 N., R. 28 W.

It will be noted that the evidence with respect to the position of the northern border of the dolomite belt is

mainly negative. There are no exposures north of the dolomite and near it that determine the limit of the belt in this direction. The boundary line is drawn close to the northernmost ledges of the dolomite where such ledges, as indicated by the topography, are plainly near the north side of the belt. Between such ledges the boundary is drawn straight except where sinuosities are clearly indicated by their existence in the south boundary. In these cases it is assumed that the belt is folded throughout its entire breadth and that these folds must find expression at its northern boundary. The only sinuosity in the north boundary indicated by the occurrence of rocks other than those belonging in the dolomite series is that extending southeastward into sec. 11, T, 39 N., R. 29 W., and this is indicated only by a row of very old test pits, on the dumps of which slates have been found. The country near this northern boundary has not been explored anywhere to a depth sufficient to reach the rocks underlying the sandstone except by the pits in sec. 11. Natural exposures of other rocks are unknown. From the foregoing it is clear that the position of the northern boundary of the dolomite must of necessity be largely conjectural.

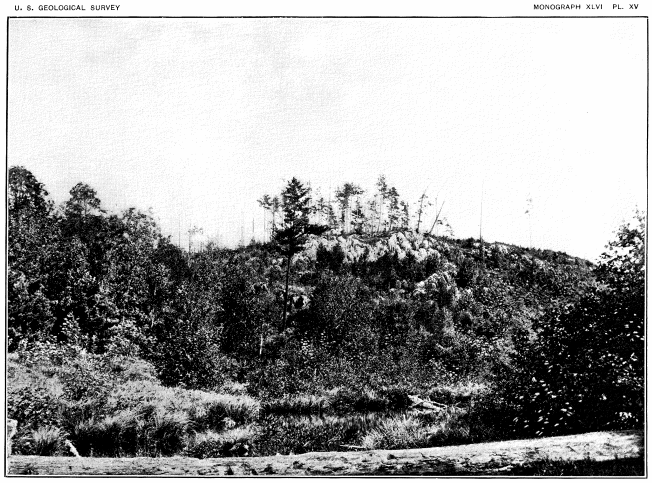
The southern boundary, on the other hand, is rather sharply delimited, not merely by exposures, but also by the underground workings of many of the mines. The evidence is so uniformly distributed along the entire belt that there can be but little doubt that this boundary is very near the position at which it is mapped. The only portions of the boundary that may be considered doubtful are (1) the 2¼ miles between the Menominee River and the old Ludington mine, 500 paces west of the east line of sec. 25, T. 40 N., R. 31 W., and (2) the 3½ miles between the center of sec. 18, T. 39 N., R. 28 W., and the east line of sec 15 in the same town. Along the belt of the iron formation between the Menominee River and the old Ludington mine test pits have been dug, and from some of these drifts have been run to the north. In only one case, viz, near the center of sec. 25, T. 40 N., R. 31 W. (see fig. 16), was any dolomite met with, but in several instances drifts and drill holes penetrated rock that indicates the close proximity of the dolomite formation. A drill hole put down vertically about 1,000 feet east and 420 feet north of the west quarter post of sec. 25 penetrated a cherty quartzite that is usually found at the top of the dolomite formation. At other places the dump heaps show slaty rocks that are usually found near the dolomite, but at only the two points referred to above is there certain evidence that the southern contact of the dolomite is very near. At the eastern end of the district the evidence used in delineating the southern boundary of the belt is the same as that used in fixing its northern boundary. A magnetic line extends from sec. 18, T. 39 N., R. 28 W., continuously to the Breen mine. In sec. 18 the southern boundary of the dolomite is a short distance north of this line. The relative position of the dolomite and the magnetic line is assumed to be the same to the east, and the mapping is in accordance with this view. At Waucedah there is no definite magnetic line, but there are numerous test pits north of the village by which the existence of the lowermost member of the iron formation, with a steep dip to the south, is well established. Since the dolomite elsewhere lies just under this formation, its southern boundary at Waucedah is placed at a distance north of the southern boundary of the northernmost member of the iron formation corresponding to the average width of this formation in those places where its dip is nearly vertical.

In the 14 miles between sec. 25, T. 40 N., R. 31 W., and sec. 18, T. 39 N., R. 28 W., as has been said, the evidence that fixes the position of the dolomite belt is conclusive. The nature of this evidence need not be referred to here, as it is discussed rather fully in connection with the description of the iron-bearing Vulcan formation. The evidence is exhibited on the maps showing the distribution of the rocks in the neighborhood of the various mines.

TOPOGRAPHY.

From the Menominee River as far east as the Sturgeon River the country underlain by the dolomite is a range of high hills (Pl. XIII, *B*), broken only at Iron Mountain, at Quinnesec, at Norway, and at the Sturgeon River by north-south gaps. The slopes of the ridge are comparatively steep on both the north and the south sides, but the northern slope usually merges gradually into the plains lying at its base, while the southern slope in some places terminates in little precipices, well seen east of Quinnesec along the north side of the wagon road leading to Norway (Pl. XV, *A*). These precipices are rough and rugged masses of dolomite (Pl. XV, *B*) or cherty quartzite rising suddenly out of a plain underlain by slates. Their existence is due to differential weathering, the slates having been eroded much more rapidly than the resisting dolomite. Where the dolomite is bordered on the south by the iron formation the slope is gradual, the dolomite occupying its upper portion and the iron-bearing rocks its lower portion.

While the existence of the ridge is no doubt due to the presence of the dolomite, its present height is determined partly by the horizontal Lake Superior sandstone, which caps it almost universally, and gives it an even or gently undulating sky line. Where the sandstone is lacking, i. e., on the lower portions of the ridge, the dolomite outcrops in small, isolated hillocks and groups of ledges. The former are sometimes very steep on all sides, and exceedingly rugged; at other times they are long, narrow, low ridges with gently sloping sides and smooth, rounded tops. In a few places the rock forms low ledges rising only a few inches above the general surface. Between the exposures are deposits of drift. The differences in the character of the topography underlain by the dolomite seem to depend largely on the completeness with which the glacial sands have been removed. If it could all be removed from above the dolomite the country, except where covered by sandstone, would be extremely rough.



A VIEW OF DOLOMITE BLUFFS ON NORTH SIDE OF HIGHWAY FROM QUINNESEC TO NORWAY.

Near point where stream crosses road in sec. 2, T. 39 N., R. 30 W.; about one-fourth mile east of Quinnesec. The cliffs are composed of nearly vertically bedded Randville dolomite, traversed by thin seams of chert parallel to bedding. The plain at the base of the cliffs is underlain by Hanbury slate. The view gives some idea of the rough topography produced by the weathering of the dolomite.

B. NEARER VIEW OF DOLOMITE BLUFF SHOWN IN *A*.

The rough character of the topography is very apparent in this view.

[Plate XV. *A*, View of dolomite bluffs on north side of highway between Quinnesec and Norway; *B*, Nearer view of bluff shown in *A*]

What is true of the present topography of this area is true also of its pre-Potsdam surface. Mining operations in several instances have uncovered the sandstone at considerable depths beneath the present surface. In some cases the rock seems to fill old gorges cut through the dolomite; in other cases it rests against ancient dolomite precipices, and in still other instances it can be seen to rest upon shelving shores, built of this material It is also probable that the transverse gaps referred to as crossing the dolomite ridge at Iron Mountain, Quinnesec, and Norway were once filled with sandstone. While there is by no means sufficient data from which to reconstruct the old topography, it is very clear that the ancient dolomite surface was more rugged than its present surface. Moreover, since the sandstone is found at much lower levels, both north and south of the ridge, than its basal layers on the ridge, it is further plain that the dolomite ridge was in existence in pre-Potsdam time, and that its elevation above the surrounding surface was then not greatly different from its elevation to-day.

LITHOLOGY.

The Randville dolomite consists of a series of beds in which dolomitic layers predominate. With the pure dolomites are associated quartzose dolomites, dolomitic quartzites, argillaceous dolomites, dolomitic slates, cherty quarzites, and talcose schists. Besides these there are present locally, particularly near the ends of folds and along contact zones, dolomitic breccias and conglomerates and cherty quartz breccias.

DOLOMITE AND DOLOMITIC SANDSTONES.

The predominant rock of the series 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. In a few places the rock is a white coarsely crystalline marble, a phase well seen in the ledge 400 paces west of the northeast corner of sec. 14, T. 40 N., R. 30 W.

The lighter-colored, purer dolomites weather with smooth white or very light-pink or light-blue surfaces that are crossed here and there by thin projecting seams. Oftentimes the projecting bands are parallel to the bedding, when they are found to be composed of dolomitic quartzite interbedded with the purer dolomite. In other cases the 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.

The weathered surfaces of the darker-colored dolomites are covered with a thin layer of light-brown sandy substance varying in thickness from a fraction of a millimeter to several millimeters, which indicates the presence of iron in the carbonate, and the existence of quartz grains intermingled with the dolomite. At one place nodular weathering was observed. This was in the large ledge underlying the Lake Superior sandstone in the quarry in the southwest quarter of the southeast quarter of sec. 30, T. 40 N., R. 30 W. Here the dolomite strikes regularly N. 75° W., and dips 78° N, and on its eroded edges the sandstone lies horizontal. Near the contact of the two rocks, the dolomite is filled with nodules that differ slightly in color from the surrounding matrix and thus produce a rock strongly resembling in appearance a conglomerate. No difference can be detected between the texture of the nodules and that of the cementing material. The nodules are slightly harder than the rock in which they lie and perhaps they contain a small percentage of silica leached from the overlying sandstone,

While many of the dolomite beds in the Randville series are practically pure dolomites, others contain a large admixture of sand grains. In some cases dolomite is in excess, in others the principal component is sand with dolomite as a sparse cement. The former have been called quartzose dolomites and the latter dolomitic sandstones. These rocks occur in beds from a few

inches to 20 or more feet in thickness at various horizons in the series, but more frequently near its bottom than elsewhere. The basal beds, which are gradational in character between the underlying Sturgeon quartzite and the overlying dolomitic phases of the Randville series, are almost exclusively dolomitic sandstone. On the fracture surfaces of fresh specimens of the quartzose dolomites the quartz appears as small, round, glistening spots against a dull groundmass of gray, white, or bluish dolomite. The grains are so evenly distributed through the carbonate that at a hasty glance many specimens resemble oolitic limestones. In the most quartzose varieties the rocks are practically quartzites, and their appearance on fresh fractures is not very different from that of normal quartzite. The intermediate phases between these two extremes exhibit naturally intermediate characters. On weathered surfaces the more dolomitic phases are rough and sandy, and of a light- or a dark-brown color. The dolomite has been partly dissolved and in the cavities thus produced quartz has crystallized. A porous, drusy rock results, which is very friable. It resembles closely many calcareous sandstones. The replacement of the dolomite by the silica is not always confined to the exposed surface, but in some instances weathering has proceeded to so great a depth within the rock mass that no specimens can be obtained which do not possess the drusy character.

A few of the quartzose beds associated with the dolomites are nearly pure quartzites that differ in no essential respect from the quartzites of the Sturgeon formation. They are fairly fine-grained rocks with a gray or purplish color. They occur in thin beds rarely more than 2 or 3 inches thick, and are found at any horizon, but more commonly near the base of the dolomitic series.

Under the microscope the purer dolomites are seen to be crystalline aggregates of dolomite exhibiting all the characteristics of this mineral. The larger grains are synthetically twinned, but the smaller ones as a rule are untwinned. The cause of the various shades of color observed in the hand specimens is not recognizable in the thin section, for usually, with the exception of a few grains of ocher and of hematite, no coloring matter of any kind is noticeable in them. It seems necessary, therefore, to regard the color as residing in the carbonates themselves, and not in any impurities present as cementing material between the individual grains, though of course it may be due to a very small quantity of some clay-like interstitial substance. The slides are crossed occasionally by tiny veins of calcite and sometimes by small quartz veins. Little nests of these minerals are also scattered here and there through the mass of the rock.

The lighter colored of the quartzose dolomites are very similar to the purer phases of the rock except that they contain considerable quantities of quartz in grains and little nests, small fragments of plagioclase, and occasionally a few plates of a light-green chlorite that has evidently been derived from some mica. The quartz grains are usually subangular, in a few sections they are sharp edged, and in many they are beautifully rounded sand grains. In a few instances they are distinctly enlarged. These fragmental grains are embedded in a matrix sometimes consisting almost exclusively of the carbonate. In a large number of instances, however, dolomite, calcite, and quartz in grains of equal size are present in approximately equal quantities, composing an aggregate which under low powers of the microscope appears to be thoroughly crystalline. Under high powers the quartz grains are seen to be fragmental and the carbonates to be crystallized about them. Evidently these rocks are mixed dolomitic and clastic sediments that have been partly silicified since their deposition. They mark the transition between the purer dolomites and the rocks that have been called dolomitic sandstones. These present no unusual features. They consist largely of fragmental quartz grains embedded in a crystallized calcitic and dolomitic matrix. Often the carbonates are in such small quantity that the rocks are essentially quartzites, with features closely resembling those of the Sturgeon quartzite.

In the light-colored phases of the dolomitic sandstones there are no constituents other than those mentioned above, but in the darker-colored phases the proportion of colored components present is quite large. These comprise ochers, magnetite, hematite, rutile, an abundance of small flakes of brownish-green chlorite and spicules of light-green sericite or kaolin, a few prisms of tourmaline and grains of epidote. In other words, these rocks appear to be mixtures of muds, sands, and calcareous deposits that were interstratified with the purer dolomites as a consequence of some local changes in the conditions under which deposition took place. With a decrease in the amount of dolomite present these rocks, like the lighter-colored varieties, pass over into quartzites, which differ from the Sturgeon quartzites in the presence of a large quantity of crystallized quartz and chlorite. The quartz is in large grains that are apparently fragmental and in small grains that appear to have crystallized in situ. The latter form a matrix by which the larger grains and the chlorite are surrounded. Through this matrix are also scattered many small spicules of colorless or light-green sericite, or some other micaceous mineral. Under low powers of the microscope the chlorite appears to be fairly homogeneous, but under high powers it is discovered to be filled with tiny quartz grains and with wisps of a colorless mica. These are bound together by radial and divergent groups of chlorite, the whole forming the flakes noticed under low powers. Between the fibers of the chlorite and occasionally embedded in them are rutile, magnetite, and ocher grains. The character of this chlorite and its associated minerals indicate that they are the decomposition products of a biotite. The quartzites thus appear to be made up largely of quartz sand and a fine mud that has undergone considerable alteration. If dolomite was ever present in them it has been removed by silicification processes.

All specimens of the dolomites, even the least quartzose ones, are crossed by little veins of quartz which, under the microscope, are discovered to consist of crystallized quartz of the same character as the material of the cherty quartz rocks to be described hereafter. The laminæ are usually not thicker than a millimeter, but near the top of the formation they sometimes reach a width of 2 or more inches.

Now and then sections of the dolomite exhibit a schistose structure, in that the grains are all elongated in a common direction. There is no crushing or peripheral granulation observable; hence the elongation must be due to the crystallization of these minerals under the influence of pressure. Adams and Nicolson[a] have recently shown that the cataclastic structure in limestone is not common. On the other hand, they have shown that the structure of schistose marbles is due to the flattening of their constituent grains by twinning and gliding. They have further proved by experiment that the flattening of the grains may be produced by differential pressures at temperatures of 300° to 400°. At this temperature, under pressure, marbles are deformed by flowage, and in this way schistosity is superinduced. The dolomites of the Randville series are closely folded; hence they were in the zone of flowage for these rocks; and were subjected to great pressure at depths that must have had a much higher temperature than that at the surface. The structure of the schistose phase is that which should be expected under the conditions, and is confirmatory of the implied view of Adams and Nicolson that limestones in folded regions should exhibit schistosity, due to flattening of their components as the result of flowage. That the schistosity of the Randville dolomites is not more marked than it is may be due to the fact that they were raised from the zone of flowage to the zone of fracture at the end of Lower Huronian time, and since then have, in large measure, been recrystallized by percolating waters.

[a]Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble Philos Trans. Royal Soc. London, Series A, vol. 95, 1901, p. 363-401.

The quartzose dolomites are more apt to exhibit schistosity than the purer varities. Indeed, nearly all the dolomitic rocks that appear schistose in the hand specimen contain more or less quartz. In the nonquartzose dolomites the schistosity is due to flattening of the dolomite grains. There is no granulation of the components. In the quartzose dolomites, on the other hand, granulation is observed on a comparatively large scale. The larger of their quartzose components have been crushed into quartz mosaics, which may be lenticular in shape or which may possess the general outlines of the original grains from which they were formed. From the ends of the lenticules long tails of a very fine-grained mosaic often extend into the surrounding dolomite, and here and there scattered through the matrix are little irregular masses of the same mosaic that maybe detached portions of shattered grains. Quartz nests are also found in these rocks. These differ from the mosaics in their very irregular outline and in the very much coarser grain of the mineral composing them. The dolomite matrix shows little evidence of crushing. It is an extremely fine-grained crystalline aggregate, containing here and there an embedded quartz grain, and sometimes a few flakes of chlorite, sericite, or other secondary mineral. The schistosity of these rocks is due almost exclusively to the flattening of the quartz grains.

Not all the dolomites were deformed by plastic flowage, however, for many specimens which in the ledge and in the hand specimen appear to be massive, when examined in thin section are found to be minutely brecciated. They consist of dolomite fragments embedded in a matrix of dolomite, calcite, and quartz. Some of the latter mineral is plainly fragmental, but much of it was deposited as little nests of small grains between large crystalloids of calcite and smaller ones of dolomite.

Only one analysis of the dolomites has been made, so far as known, but it probably represents very accurately the composition of the purer kinds. The specimen analyzed was a pink variety from shaft B of the Chapin mine. It was made by Mr. E. E. Brewster, now chemist of the Pewabic mine, who kindly furnished the results for publication. The constituents as determined and the components in the dolomite corresponding to them are as follows:

Analysis of dolomite from Chapin mine.

CaO	30.97 = $CaCO_3$	55.20
MgO	20.48 = $MgCO_3$	42.84
Fe	.80 = $FeCO_3$	1.66
P_2O_5	.05 = Apatite	.11
Al_2O_3	.20 = Al_2O_3	.20
Residue	.73 = Residue (mostly silica)	.73
Total		100.74

The rock is thus an almost normal dolomite of the composition $CaCO_3 + MgCO_3$.

DOLOMITE BRECCIAS AND CONGLOMERATES.

The presence of anastomosing quartz veins in the massive dolomites, the existence of schistosity in many specimens, and the minutely brecciated structure observed in the thin sections of specimens from apparently homogenous beds, indicate that the dolomite series has been deformed under pressure. In most instances this pressure did not express itself in crushing sufficiently marked to be detected in the ledge. But in some places, more particularly at the apices of folds and along contacts with overlying formations where accommodations to stresses resulted in sudden movements, the crushing was so severe that the rock was actually fractured on a large scale, and breccias produced. These consist of sharp-edged and lenticular fragments of dolomite separated from one another by seams and interstitial masses of dolomitic material with which a small quantity of quartz sand is admixed. In some beds the fragments make up the greater portion of the rock mass, as is the case in the cliff at the northeast end of the little valley east of the Aragon mine (see Pl. XVI, *A*). In other beds the interstitial substance is in

greater quantity and the fragments sparse. In the former cast the autoclastic character of the breccia is unquestionable. In the latter case the rock looks very much like a breccia of fragments cemented together by foreign material. This is true of some of the breccia at Iron Hill.

Under the microscope the dolomitic breccias are seen to differ but little from the finely crushed dolomites referred to above (p. 214), except in the greater size of the fragments. These, as has already been described, are mainly angular pieces of dolomite and of the rocks associated with the dolomites. In some instances the matrix surrounding the larger dolomite fragments is made up of small angular fragments of the same rock cemented by an aggregate of large, colorless crystalloids of calcite. The small and the large fragments of the original rock are surrounded by little zones of ocher that seem to have been, deposited upon them before the crystallization of the calcite cement. The rocks are undoubted autoclastic breccias produced from the purer dolomite beds.

In most cases the original rock was a quartzose dolomite, and the resulting breccia consequently contains, in addition to dolomite and calcite, more or less fragmental quartz, the quantity present depending upon the quantity in the original rock. Some of the fragmental quartzes show enlargements, with the added material often extending for considerable distances from the fragmental nuclei into the surrounding carbonates. While much of the dolomite in the matrix may originally have been in clastic grains it is now plainly in forms that have crystallized in situ. The calcite, which is nearly always in comparatively large grains, is clearly newly deposited. Much of the recrystallized carbonates have been deposited as fringes around the fragments of dolomite, which are surrounded by zones composed of many elongated grains lying side by side and forming a radial aggregate completely enveloping the fragmental nucleus.

In some places, particularly in the interstices between the larger fragments, the matrix is schistose, when the dolomite grains are flattened in the plane of schistosity and their twinning lamellae are curved. The breccias in which the schistosity is most marked do not always exhibit this structure in the hand specimens. Usually their embedded fragments can be seen on the weathered surfaces to lie in the matrix with their long axes in a uniform direction, but on the fresh fractures where the fragments can not be distinguished no trace of schistosity can be detected.

PLATE XVI.

FIG. *A*.—BRECCIATED RANDVILLE DOLOMITE. In wall at east end of little gorge running east from the Aragon mine. Fragments and matrix are composed of the same kind of dolomite. Fragments are all sharp edged.

FIG. *B*.—DOLOMITE CONGLOMERATE. At Iron Hill in sec. 32, T. 40 N., R. 29 W. The large fragments are rounded, the smaller ones are angular. Both fragments and matrix are crossed by joint cracks in which cherty quartz has been deposited. The quartz seams now project from the weathered surface. The matrix is more siliceous than the fragments, partly because it contains a thicker network of the quartz seams, and partly because it contains a considerable proportion of sand grains. Consequently surfaces of fragments are depressed. The fragments are, moreover, often surrounded by narrow projecting seams of the cherty quartz. The bedding of the dolomite in the fragments may often be plainly seen.

U. S. GEOLOGICAL SURVEY MONOGRAPH XLVI PL. XVI

A. BRECCIATED RANDVILLE DOLOMITE IN WALL AT EAST END OF LITTLE GORGE RUNNING EAST FROM THE ARAGON MINE.

B. DOLOMITE CONGLOMERATE AT IRON HILL IN SEC. 32, T. 40 N., R. 29 W.

In occasional instances beds are met with in which the inclosed fragments are rounded. The rock then is a definite conglomerate. Some of these occur locally, forming layers lying between thick beds of nearly massive dolomite. The conglomerates of this kind are composed of dolomite pebbles of one color in a dolomitic matrix of another color. They may be intraformational in character, like those described by Walcott[a] in the Paleozoic series of New England, Pennsylvania, Virginia, and elsewhere.

Most of these conglomerates differ from the nonconglomeratic beds with which they are associated only in the possession of fragments. The fragments are almost exclusively dolomite in the beds whose matrix is dolomitic. In those conglomerates in which the matrix is strongly quartzose, the fragments may be dolomite or slate. They are identical in character with the material of neighboring dolomite or slate beds, and the matrix is precisely similar to the material of closely associated quartzose beds. In no case is there anything discoverable in the thin section that contradicts the view that these conglomerates are intraformational beds. Their material is all from nearby sources. There is intermixed with this no foreign material.

A few other conglomerates are very closely allied to the breccias, from which they differ only in the shapes of their fragments. These are rounded or subangular, and are composed exclusively of dolomitic material and quartz—the former predominating. When the matrix contains but little quartz the fragments usually consist of the purer varieties of dolomite; when quartz is abundant in the matrix the fragments are quartzose dolomite. These rocks are clearly autoclastic, their fragments having been rounded by attrition.

[a]The Cambrian rocks of Pennsylvania: Bull. U. S. Geol. Survey No. 134, 1896, p. 34-46.

There is, however, another small group of conglomerates represented almost exclusively by the conglomerate of Iron Hill, the origin of which is completely problematical. In the Iron Hill rock the pebbles are nearly all of dolomite. The few remaining ones are mainly chert, and a very few are quartz or quartzite. They vary in size from those of minute dimensions to others more than a foot in diameter. Pl. XVI, *B* is a reproduction of a photograph of a portion of this conglomerate. The sparse matrix between the pebbles is finely ground up dolomite and chert and small grains of sand. The appearance of the rock suggests strongly that it is a true conglomerate formed from the débris of the underlying dolomite and cherty quartzite beds, but its relations with these beds and with typical breccias are so complicated that no certain conclusion to this effect has been arrived at (see pp. 257-260). If a true conglomerate, it naturally belongs at the base of the formation overlying the dolomite, and is probably Upper Huronian. It is referred to in this place because of its lithological similarity to the other members of the Randville series.

Another conglomerate that may belong with this group occurs near the center of sec. 35, T. 40 N., R. 30 W., on the branch railroad running through this section. It appears to be a true conglomerate, although it is of a different character from that at Iron Hill. Its matrix is a coarse dolomitic or calcareous sandstone, and its pebbles are largely of slate and other argillaceous rocks associated with the dolomites. The rock may, however, be an intraformational conglomerate, like the majority of the conglomerates in the series.

In the conglomerate at Iron Hill the fragments are rounded and very pebble-like. Most of them consist of dolomite or quartz, but some are composed of chert or quartzite. Most of the fragments are surrounded by narrow black borders made up of numerous scales, grains, and small crystals of an opaque substance, intermingled with indefinitely outlined masses of green chloritic material. The same opaque substance surrounds the larger quartz grains in the matrix and is scattered irregularly through some of the components of the groundmass. Just within the borders the rims of the dolomite fragments sometimes show an irregular zone of quartz, as if the dolomite has been corroded by siliceous solutions and a portion of the carbonate had been replaced by silica.

The matrix of the rock is like that of the ordinary breccias. There are a few more fragmental grains of quartz in it, but otherwise the two are similar. At first glance this conglomerate would be pronounced sedimentary in origin, because of the great number of clastic quartz grains in it, but when it is recalled that much of the nonconglomeratic dolomite is quartzose and that the quartz is present in them as distinctly clastic sand grains, the evidence from this component is valueless. Nevertheless, the general appearance of some of the rocks is strongly suggestive of a sedimentary origin. The presence of the quartzite and chert pebbles lends some support to this view.

TALCOSE SCHISTS.

At some places the dolomites, at their contacts with the overlying iron formation, have been entirely changed from their original condition and are now represented by a very different rock, composed largely of talc and serpentine. This talcose rock seems to be limited in its occurrence to those places where shearing must have been at a maximum. It is found in large quantities facing the dolomite underlying the iron formation in the close folds of the Norway and Aragon mines, in less quantities in the same position in the Walpole and Pewabic folds, and often as a thin layer between the dolomite and the basal members of the iron formation in those portions of the district where subordinate folding has not taken place. It occurs, also, as pebbles in the ore and dolomite conglomerate overlying the bedded dolomite in the Norway mine and to some extent in the matrix of this conglomerate.

The rock is soft and unctuous. It is usually of a dark reddish-purple color, mottled with white patches and cut

into prismatic and lenticular masses by three systems of veins, intersecting one another by very acute and very obtuse angles. The rock is thus broken up into a large number of separate portions with long rhomboidal cross sections, all lying in an approximately parallel direction. It therefore possesses as a whole a roughly schistose structure. The material between the veins is generally massive, only incipient schistosity being noted in a few places. Along the walls of the veins, however, differential movement has taken place and slickensides have been produced. The material covering the slickensided surfaces, that causing the white mottling within the rock mass, and the filling of the veins, is all white talc. In the Norway conglomerate the talc rock differs from that just described in that it contains a large quantity of dolomite, intermingled with the talc as small fragments, small crystals, and as druses along little cracks. In the Pewabic mine the rock is lighter in color than commonly, and contains fragmental quartz and other clastic material, probably derived from the upper wall of the shearing zone.

In thin sections the talcose schists do not present any very definite characteristics. A great number of small rounded grains and many crystals of hematite lie in an almost colorless groundmass, which, under crossed nicols, is seen to be made up of small angular grains of quartz and flakes and shreds of micaceous minerals lying in a mass of structureless material which apparently has almost no influence on polarized light. The micaceous minerals are light green in ordinary light and have a small refractive index. Some of the fibers polarize in yellow and reddish tints, and others in the blues and grays of the first order. These are taken to be talc or kaolin and serpentine. The ill-defined mesostasis may be serpentine. Some of the quartz grains have very definite outlines that separate them sharply from the remainder of the rock, but the same mineral is present also in indefinite areas that grade off into the surrounding weakly polarizing material. In these areas the quartz can be detected only by the aid of a mica plate. The distinct grains appear to have a different origin from the indistinct masses, which were probably deposited contemporaneously with the serpentine, talc, and kaolin. Many little veins traverse the sections, and in these there is a predominance of the brightly polarizing talc fibers stained in spots by brown limonite.

A specimen of the rock from the Aragon mine was analyzed by Mr. George Steiger, of the U. S. Geological Survey laboratory. The result of this analysis appears below in column I:

Composition of talcose schist from the Aragon mine.

	I.	Talc.	Serpentine.	Kaolin.	Hematite.	Quartz.	Total.
SiO_2	49.56	19.63	11.13	11.10		7.70	49.56
TiO_2	.60						
Al_2O_3	10.12	.34	.31	9.47			10.12
Fe_2O_3	5.87	.12	.36		5.10		5.58
FeO	.13						
MnO	Trace.	Trace.	Trace.				
BaO	None.						
CaO	.72						
MgO	20.53	10.31	10.32				20.63
K_2O	None.						
Na_2O	None.						
$H_2O-110°$	4.50						
$H_2O+110°$	7.66	1.39	3.64	3.32			8.35
P_2O_5	.04						
CO_2	None.						
Total	99.73	31.79	25.76	23.89	5.10	7.70	94.24

Excluding the Fe_2O_3, which is sufficiently accounted for by the large quantity of hematite in the rock, the essential features of the analysis are the presence of MgO and Al_2O_3 to the practical exclusion of all other constituents except silica and water. The data at hand are not full enough to enable one to calculate with certainty the mineralogical composition of the rock. It is certain, however, that its components are few in number and that they are limited to magnesian and aluminous compounds. If we assume that the MgO is all present in talc and serpentine in equal amounts and that the Al_2O_3 is limited to kaolin, and make the further assumption that the magnesian minerals have the same composition as the corresponding substances deposited in the ores (see p. 390), it is a comparatively simple matter to account for all the constituents enumerated in the analysis. A calculation based on the above assumption shows the rock to be composed of 31.79 per cent talc, 25.76 per cent serpentine, 23.89 per cent kaolin, 7.70 per cent quartz, 5.10 per cent hematite, 0.60 per cent rutile (if the Ti02 is present as rutile needles), 0.42 per cent magnetite, and 0.17 per cent apatite. There remains over unaccounted for only 0.59 per cent CaO, which may well be present in any one of the three principal constituents. The amount of water required to satisfy the demands of this calculation is 0.69 per cent in excess of the amount reported in the analysis of the rock. The calculation, however, is based on the assumption that the serpentine contains 14.08 per cent water (see analysis, p. 390) which is a larger quantity by over 1 per cent than the formula of this mineral requires. Since the determination of this constituent was by loss it is probable that it includes some water driven off at a low temperature.

The proportion of the various components demanded to satisfy the principal mineral constituents are given in the columns above under appropriate headings. To the sum under the column headed “Total” there should be added 6.28, which represents the hygroscopic water, the quantities of magnetite, rutile, and apatite calculated as present in the rock, and the excess of CaO indicated by the analysis, and there should be deducted from this sum 0.69, representing the calculated excess of combined water present in the serpentine, talc, and kaolin above that found by the analysis. The result of these processes will correspond with the sum of the

constituents determined as being present in the sample analyzed.

The composition of the schist as given above corresponds very well with the conclusions derived from a study of its thin sections so far as the nature of its constituents is concerned. In most sections, however, the talc appears to be in less amount than the above calculation would indicate, and the serpentine (if the feebly polarizing matrix is composed of this mineral) in greater amount. However, variations in the quantities of these two minerals assumed to be present would effect only the proportion of free silica in the calculation, an increase in the quantity of serpentine causing a corresponding increase in the calculated proportion of the free quartz. The essential features of the chemical and optical study are the same. The rock is composed mainly of talc, serpentine, kaolin, quartz, and hematite. Whether it was derived directly from dolomite or whether it was originally a fragmental rock composed largely of dolomitic débris can not now be told, as all of its original components, except possibly a few quartz grains, have been replaced by secondary minerals that were in all probability deposited from the same kinds of solutions that elsewhere in the ore bodies deposited talc, serpentine, and quartz. The presence of kaolin in the schist may be looked upon as evidence that the original rock was a sediment, but this is only a surmise, as the waters that deposited the talc and serpentine may have brought with them aluminous salts.

If the rock were originally a portion of the dolomite its alteration into talc necessitated the removal of the calcium carbonate and the replacement of the carbon dioxide of the magnesium carbonate by silica. The dissolved calcium carbonate was carried off and some of it was deposited as calcite in the ores and along watercourses (see p. 387). Some of the magnesium carbonate was also carried off in solution. It now appears as dolomite in the ores and another portion, changed to silicates, occurs as deposits of serpentine and talc (see pp. 389-390). The remaining magnesian silicates, together with the impurities originally existing in the dolomite and others contributed by the water, constitute the impure talcose rock. The conditions favoring its production appear to be movement in a shearing zone attended by chemical action brought about by percolating water. These conditions are most perfectly provided for in the pitching subordinate folds occupied by the ore deposits and in the steeply dipping surfaces of contact planes between two formations. To a minor degree the conditions also prevail along fault planes, and it is noticeable that along slickensided surfaces of such fault planes in the dolomite talc is also found.

Because of its impervious character, troughs lined with the talc-schist afford especially favorable situations for the deposition of ore bodies.

ARGILLACEOUS ROCKS.

The argillaceous members of the dolomite series are not abundant. They consist of a few rocks interbedded with the dolomites and dolomitic quartzites at various horizons in layers varying from the fraction of an inch to several feet in thickness. Together with thin beds of quartzite, they also constitute definite congeries of beds that appear to be somewhere near the top of the series. Sometimes the slaty beds in these groups are as much as 40 feet in thickness, but usually the aggregate is made up of alternations of quartzites and slaty rocks in layers not more than 5 or 10 feet thick. The slaty rocks are best exposed along the railroad running through sec. 35, T. 40 N., R. 30 W., and in the ledges south of the center of sec. 12, T. 39 N., R. 29 W.

Most of the slates are soft, light-gray or dark-gray, schistose rocks, some of which resemble very closely some phases of sericite-schists. Others are typical black slates, still plainly marked by bedding lines. These are rare and, so far as known, are confined to the set of interbedded slates and quartzites referred to above as constituting a definite portion of the dolomite series near its top. All the argillaceous rocks except the black slates contain considerable dolomitic material.

In addition to these slates, thin seams of an argillaceous dolomite, with a schistose structure and a purplish-pink color, often occur between massive beds of dolomite. In many instances they appear to be merely the selvages of softer layers of the dolomite rendered schistose by the movements of accommodation between stronger beds. Others may actually represent thin beds of argillaceous material deposited between beds of purer dolomite.

A third group of argillaceous rocks should be referred to here, though the slates may belong at the base of the overlying formation. These are red, white, light-purple, or light-gray, fine-grained, often fissile, calcareous shales, with a dull luster on fresh fracture surfaces. The rocks are known only from test pits and drill holes. They usually occupy an extremely narrow belt between well-defined dolomite and well-characterized members of the overlying iron formation. Their relations with the contiguous rocks have not been seen; consequently their exact position has not been definitely determined. In the coarser varieties quartz grains are easily distinguishable. These rocks may be built up of the detritus of the dolomite series and consequently may be the basal layers of the Upper Huronian beds. On the other hand, they may be integral portions of the Randville series at some distance from its top that have in some places been made to appear at the top of the series by the removal of overlying beds during the inter-Huronian erosion period. In any event, wherever they are found they always mark the near proximity of the contact between the dolomite series and the overlying Vulcan formation.

None of these slates present any features of peculiar interest from a microscopical point of view. The black and the gray slates are like the siliceous slates of the

Hanbury formation, to be discussed later (see pp. 463-464), and the sericite phases are like corresponding phases in the Hanbury series.

The white and light-purple slates between the dolomite and the Vulcan formation are composed of small quartz grains, small flakes of chlorite, a few larger ones of muscovite, granules and irregular masses of ocher, and innumerable tiny plates of a light-green or colorless mineral that resembles kaolin. This kaolinitic substance is included in all the other constituents, and forms, together with some secondary quartz, an aggregate by which the other components are surrounded. Some dolomite and calcite are also present in little nests, but not in any considerable quantity. A few rutile needles, irregular grains of zircon, and an occasional group of small epidote grains are also universally present. The color of the pink dates is due to a great number of very small round granules and tiny dust-like particles of hematite and limonite that are scattered indiscriminately through all the other constituents.

The characteristic features of these slates which distinguish them from the younger slates in the district are the abundance of kaolin in them and the absence of any large quantity of sericite and chlorite.

CHERTY QUARTZ ROCKS.

The cherty quartz rocks are found only at the top of the Randville formation and never elsewhere in the series. They are fine-grained, vitreous, or saccharoidal, in places drusy, massive, siliceous rocks with a white, gray, pink, red, or dark-purple color. Because they are composed partly of quartz grains and partly of chemically deposited silica they have been called cherty quartz rocks. The red and purple varieties resemble very closely some of the jaspilites in the iron formation. They all weather with a smooth, polished surface much like that of some of the most exposed ledges of the Sturgeon quartzites. They occur at only a few localities, always overlying normal dolomite. Their best developments are at Iron Hill, in sec. 32, T. 40 N., R. 29 W., and in the cliff north of the Commonwealth pit or the new Keel Ridge mine, in sec. 32, T. 40 N., R. 30 W. (see pp. 261-263).

Wherever found the rock is crossed by quartz veins that sometimes run for short distances in parallel directions and then anastomose, and at other times anastomose irregularly over all exposed surfaces, cutting the rock up into parts, producing a breccia. In other instances the rock is fractured, and the fragments thus produced are cemented by a mixture of fragmental and chemically deposited silica. The breccias produced by both methods are practically identical. They consist of sharply angular fragments of one color in a matrix of some other color. Both matrix and fragments have essentially the same composition and the same texture, though the texture of the matrix in some specimens may be a little coarser than that of the inclosed fragments. In some places it is also drusy through the solution of some constituent and the deposition of quartz in the walls of the cavities thus formed.

The presence of the cherty quartz rocks at some places and their absence from others is accounted for by the supposition that they were once continuous over the dolomite, and that the erosion that marked the interval between Lower Huronian and Upper Huronian times cut down irregularly into the Randville series, in some places removing only the upper layers of the cherts and at other places removing the entire deposit. Their almost universal brecciated character may be due to the fact that they occur along a contact zone where movements of accommodation that must have attended the folding of the district were naturally accentuated and to the further fact that because of their brittle character the cherty rocks yielded to stresses more easily by fracture than by shearing.

In natural light, under low powers of the microscope, the more massive phases of the cherty quartzites appear as very light-yellow, transparent homogeneous rocks speckled by little clumps of a dark-yellow substance, which under high powers is resolved into masses of ocher, and dusted with little opaque dots, which on stronger magnification are seen to be grains of hematite. In polarized light the sections become very fine-grained aggregates of interlocking quartz grains, cut here and there by veins of quartz, and containing occasionally little areas of the same mineral in which the grains are several times the size of those in the surrounding aggregate. Very small flakes of a colorless micaceous mineral are scattered here and there through the aggregates. In one or two sections calcite or dolomite is abundant. It is in very small rounded grains embedded in the quartz and in irregular masses apparently interlocking with the quartz grains. Occasionally there is a grain of quartz present in the slide which looks as though it might be fragmental, but usually no traces of clastic characters can be detected in any of the components. Here and there in the midst of the fine-grained aggregate round and irregularly shaped areas of quartz mosaics are met with that may perhaps mark the positions of large grains in an original sediment. The structure of the mosaic is always much coarser than that of the main portion of the rock mass, and often many of its constituent grains are crossed by strain shadows.

Like the cherts in the Gogebic district, those in the Menominee district are markedly brecciated. Reference has already been made to the abundance of brecciated forms in the descriptions of the macroscopic features of the rocks. When examined in thin section it is soon noted that many of the specimens which appear in the ledge to be completely homogeneous are in fact made up of fragments in a well-defined matrix. The brecciated structure is almost universal. The fragments are mainly sharp edged and range in size from those of microscopic dimensions to those several inches across. Sometimes the distinction between fragments and matrix is difficult to make, since the material of the two is similar in composition and in the coarseness of texture. Usually,

however, they are distinguished by differences in color due to the presence in them of hematite, ocher, and magnetite grains, chlorite, and sericite, or kaolin flakes, rand certain indefinite greenish and brownish stains in different amounts. Occasionally the fragments are darker colored than the matrix, but usually the reverse is the case. The snow-white varieties so characteristic of the Gogebic cherts occur only as fragments in the Randville breccias. There is also frequently noted a difference in texture between the fragments and the inclosing matrix. In the fragments the texture is very fine, but in the matrix it is often quite coarse. Often the coarsest texture is in a zone immediately surrounding the fragments. These coarsest portions may be traced continuously into stringers extending into the fragments and often separating them into several portions. Usually the stringers are extremely narrow, but sometimes they are rather wide. They cross the fragments in all directions, constituting the quartz filaments and veins noticed in the hand specimens.

In some specimens the filaments also cross the material of the matrix, and sometimes little irregular areas of the coarsely textured aggregate occur in the midst of the finer-textured aggregates, as though they represented cross and oblique sections through tiny quartz veins. In still other cases the coarse quartz grains form little round areas composed of a central grain surrounded by a zone of grains radially arranged around the nucleal grain. In short, the rocks look as though they may originally have been nearly homogeneous cherts, containing here and there a fragmental quartz grain, which were subsequently very thoroughly shattered and then healed by infiltrated quartz. Moreover, they seem to have been subjected to thorough silicification, so that it is doubtful if in some sections any of the original rock material remains. Sections which in natural light show plainly the presence of fragments in a matrix, between crossed nicols appear as a nearly homogeneous mosaic of small quartz grains of uniform size and character, interrupted here and there by lines of coarser mosaics, marking the positions of quartz veins.

CONCLUSIONS FROM MICROSCOPICAL STUDY AND COMPARISON WITH SIMILAR ROCKS IN THE MARQUETTE AND GOGEBIC DISTRICTS.

The microscopical features of these cherty quartz rocks are nearly identical with those of the cherts associated with the limestone in the Gogebic district, except that forms composed of individualized quartz grains, with crystal outlines, have not been seen among the Menominee rocks. The concretionary structure that Irving and Van Hise[a] detected among the Gogebic cherts also seems to be lacking in the Menominee ones, but this may be due to the few specimens that have been seen that are free from brecciation. In the breccias a concretionary arrangement of the quartz is sometimes suggested in the groundmass surrounding the fragments, and occasionally in the fragments themselves, but the suggestion is a very obscure one.

[a]Irving, P. D., and Van Hise, C. P., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 132-133, and Pl. XVI, figs. 2, 3, 4.

The principal conclusion deduced from the study of the cherty quartzites is to the effect that they may be regarded as intermediate forms linking the dolomites beneath them with the jaspilites of the Negaunee formation that must at some time have existed above them. While we have no specimens of the Negaunee formation from this district, except in the form of small pebbles in the basal conglomerate of the Upper Huronian, in the Marquette district the Negaunee formation is well exhibited,[a] and its cherts and jaspilites have been carefully studied.

The Randville cherts are found to have many of the features of these rocks, and may well be transition phases between them and the underlying dolomites. The latter are in many instances silicified, and in some instances are so much so that they might well be described as cherty dolomite. However, these cherty forms are not as common in the Menominee district as they are in the Marquette district.[b] Otherwise the dolomites and cherts of the two districts are very similar, and the words used by Van Hise in describing those of the Kona formation in the Marquette district might almost equally well be used in the descriptions of the dolomite and cherts of the Randville series in the Menominee district. If lithological features are of any value as criteria upon which to base conclusions as to the stratigraphical continuity of formations in sedimentary basins situated in the same general geological province, then the identity of character between the dolomite and cherts in the Gogebic, Marquette, and Menominee districts must mean that they are at the same geological horizon, although their continuity on the surface is interrupted by wide stretches of younger sediments.

[a]Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan, with atlas, including a chapter on the Republic trough by H. L. Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 370-371.

[b]Ibid., pp. 248-249.

ORIGIN OF THE DOLOMITES AND CHERTY QUARTZ ROCKS.

From the statements above made concerning the character of the dolomites and cherts, it is evident that their origin must be the same as the origin of the corresponding rocks in the Gogebic and Marquette districts. Irving and Van Hise[a] have discussed the origin of the Grogebic rocks, and have reached the conclusion that there is no definite proof as to whether the dolomite is of chemical or of organic origin, but that many geologists would assert that the very nature of the rock precludes the possibility of its having been produced by other than life agencies. Where there are no fossils, as in these dolomites, it is at best a matter of opinion as to their origin, but in making up a judgment upon this point the organic beds of chert of later times associated with limestones and the beds of iron carbonate and

carbonaceous material in higher horizons of the series are facts to be taken into account. While not expressing any definite opinion as to the origin of the dolomites, the impression left by the discussion is that they might well be looked upon as organic deposits.

As for the cherts, they declare that—

The vein-like character of a part of the chert implies that the silica has been rearranged to some extent, or partially introduced subsequently to the deposition of the main body of the belt. The deposition of similar cherty carbonates of great thickness is definitely known to occur in the Carboniferous and Permian[b] periods. The chert is here probably all of organic origin. Whether the chert in the limestones under discussion is an organic or a chemical substance it is impossible to say; but it is certain that in later time we have the exact analogue of the deposits described, which are definitely known to be organic deposits.

It appears that the chert of the limestone belt, whether original or secondary, had in the main reached its present condition before the accumulation of the immediately overlying formation. That the chert has been rearranged to a greater or less extent since its deposition, and that in the cracks infiltrating solutions have brought additional silica, is more than probable.

Again in summarizing their conclusions they state:[c]

The chert and limestone are water-deposited sediments; whether chemical or organic is uncertain, but it is not improbable that they are partly or wholly the latter. However, if this is the case, the silica has subsequently changed to the mineral form [quartz], and has been extensively rearranged, while the limestone has become dolomitized.

[a]Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 140-141.

[b]Hinde, G. J., On the organic origin of the chert in the Carboniferous limestone series of Iceland, and its similarity to that in the corresponding strata in North Wales and Yorkshire: Geol. Mag., London, new series, decade 3, vol. 4, pp. 435-446. Also on the chert and siliceous schists of the Permo-Carboniferous strata of Spitzbergen, and on the characters of the sponges therefrom, which have been described by Dr. R. von Dunikowski: Idem, vol. 5, pp. 241-251.

[c]Mon. U. S. Geol. Survey, vol. 19, 1892, p. 142.

These words are so entirely applicable to the Randville cherts and dolomites that they have been quoted here, partly as a summary of the conclusions that must be arrived at after studying these rocks, and partly to emphasize the fact that what is true of the dolomite formation in the Gogebic district is true also of the corresponding formation in the Menominee district. The two formations are almost identical in all their characteristics. There can be little doubt that they represent dissevered parts of a formation that once extended continuously over both districts.

FOLDING.

A knowledge of the folds of the Randville dolomite is the key to the knowledge of the folding of the entire series of Algonkian rocks in the district. Moreover, the distribution of the folds determines the distribution of the productive ore bodies, as will be shown later. Consequently it is necessary to study the folding of this formation with some minuteness in order that a better understanding may be had of the conditions which have made the district of such economic importance.

The formation, as can easily be discerned from its mapped distribution (Pl. IX), occurs in two anticlines and three synclines in the western portion of the district and two synclines and one anticline in its eastern portion. Structurally the northern belt of dolomite is a southward-dipping monocline. The central and southern belts are anticlines. Between the belts are synclines. South of the southern belt is a syncline, on the southern limb of which one would expect to find a belt of dolomite. This belt might be expected 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 map and structure section AA, Pl. IX).

MAJOR FOLDING.

From the mapped distribution of the dolomite formation (Pl. IX) and its relations to the iron formation (see p. 251), it is clear that the central and southern belts are two anticlines with axes striking a little north of west, connected with one another by a syncline, and that a syncline also connects the central belt with the northern one.

In the central belt the northern and southern borders of the formation are known accurately only in the neighborhood of the Indiana mine. Just south of the Cuff mine shaft the dip of the dolomite is about 25° N. At the Indiana mine, near the southern border of the belt, the dip of the upper contact of the dolomite is south at an angle of about 60°, but, if the evidence of drill holes is to be relied upon, the dip flattens at greater depths. West of the Cuff mine are a number of ledges situated near the center of the belt whose bedding, as well as can be determined, is vertical. Thus the dips in this, the only portion of the central belt that can be examined across the strike from its southern to its northern contacts, are in accordance with the view that the belt is structurally an anticline.

The southern belt over much of its extent presents the appearance of a uniform succession of isoclinal beds—i. e., it appears as a monocline. In its western portion near the Chapin mine the dips of the beds exposed on the surface are uniformly at high angles to the north.

Farther east, in the neighborhood of the line between secs. 32 and 33, T. 40 N., R. 30 W., they are high to the south. In the longitude of Quinnesec they are high to the north in the southern half of the belt and high to the south in its northern half. East of this longitude the dips are uniformly to the south except where minor folds are encountered, but the angle of dip becomes flatter and flatter as we proceed eastward. Near the Sturgeon River it rarely exceeds 55°.

Consideration of these dips indicates that the southern anticline is a very closely compressed fold with a warped axial plane. At its western end this plane is overturned to the south; a little farther east it is overturned to the north; in the longitude of Quinnesec the fold appears to be fan shaped, and at its eastern end it is again overturned to the north.

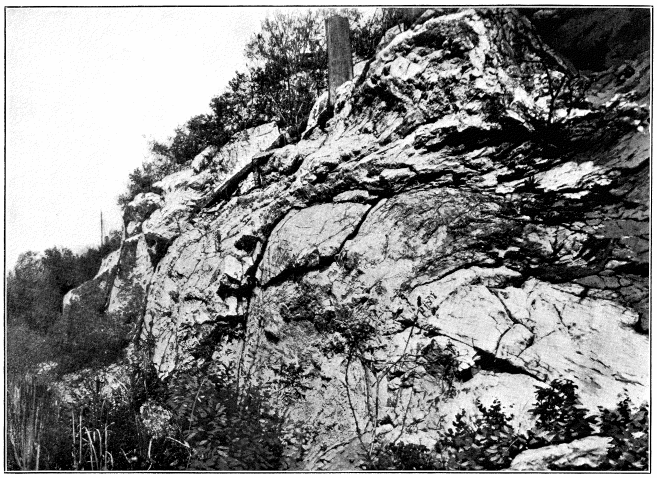
CROSS FOLDING.

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, and the sudden disappearances of the southern belt toward the west points to a similar conclusion with respect to its termination in this direction.

The most easterly exposures of the central belt are at Iron Hill in sec. 32, T. 40 N., R. 29 W. Most of the width of the belt in this neighborhood is covered by the Lake Superior sandstone, but at the southwest margin of the sandstone covering abundant exposures of the dolomites occur. Their bedding is very distinct, with a definite strike N. 50° to 60° W. This strike projected southeast war dly would carry the dolomite into a well-characterized area of ferruginous chert and slates. These slates and cherts are above the dolomite, hence the latter rock must plunge under them on its line of strike. Corroborative evidence for this conclusion is found in the fact that the easternmost exposure of the dolomite formation consists of dolomitic cherts. These rocks not only limit the normal dolomite to the east, but they are found also wrapping around the end of the hill and appearing again in the southeast side and along the southern side of the dolomite exposures (see Pl. XVII, *A*). Where its relations to the normal dolomite can be seen, the chert clearly overlies the latter. In other portions of the district where it is exposed, it is likewise seen to be above the normal dolomite. Since, then, the uppermost layers of the dolomite formation at Iron Hill are the last to disappear to the east, the formation must be terminated by an eastward-plunging anticline.

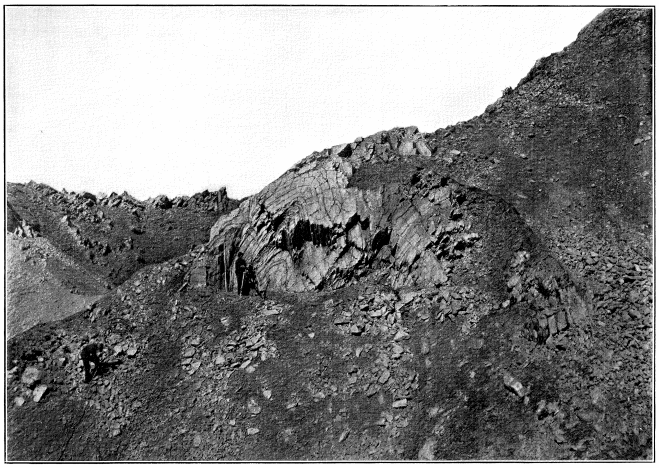
At the west end of the belt the conditions are very unfavorable for determining the method of its disappearance in this direction. The westernmost place to which the formation is known to extend is in the tunnel and drill hole near the quarter post between secs. 20 and 21, T. 40 N., R. 30 W., on the south side of the great hill overlooking Lake Antoine. This hill, like nearly all of the other higher elevations in the district, is covered with sandstone, so that the areal distribution of the dolomite in this neighborhood can not be determined. The west and northwest slopes of the hill, however, are broken by the mining and exploration pits of the Cornell, the Traders, and Clifford mines, so that the extension of the dolomite in this direction is impossible. Moreover, the magnetic observations in sec. 20 indicate that this section is underlain by a broad area of the iron-formation rocks. These facts seem to show that the west end of the central dolomite belt, like its east end, must terminate in an anticline which, in this case, pitches to the west.

U. S. GEOLOGICAL SURVEY MONOGRAPH XLVI PL. XVII



A. FOLD IN CHERT AT IRON HILL IN SEC. 32, T. 40 N., R. 29 W.

The underlying rock is a conglomerate dolomite like that shown in Pl. XVI, *B*. The overlying chert is brecciated.



B. SMALL FOLDS IN TRADERS JASPILITE, WEST SIDE OF CLIFFORD PIT, TRADERS MINE.

The rocks are brecciated, but folds can nevertheless be plainly recognized in them. In the view one anticline and one syncline can easily be made out.

[Plate XVII. *A*, Fold in chert at Iron Hill; *B*, folds in Traders jaspilite, west side of Clifford pit, Traders mine]

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. The westernmost point at which the dolomite is known to occur is near the center of sec. 25, T. 40 N., R. 31 W., where it was reached by a drift running about 50 feet north from the bottom of a shaft located 150 feet southwest of the center of the section (fig. 16). The dolomite lies to the north of a slate and ore formation and is overlain unconformably by the Lake Superior sandstone. The dip of the dolomite is apparently to the south, but the surface on which the sandstone was deposited slopes to the north. Unfortunately we are here, as at other important places,

met by the sandstone covering which completely hides from view the relations of the rocks beneath it. From the magnetic observations made on the west slope of the hill and in the valley of the Menominee at the base of this slope it appears that the iron formation occupies a large part of the area between the hill and the river and nearly surrounds its west end. At its east end the southern belt is covered completely by Paleozoic beds, so that the manner of its disappearance with respect to the Upper Huronian sediments is not known.

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.

MINOR FOLDING.

THE NORTHERN BELT.

In the northern belt minor folding, if it exists, can not be discovered except at the extreme western end, where the belt makes the turn northward into the Calumet trough (see p. 189). The area occupied by the belt is included within the valley of Pine Creek. Throughout nearly its entire extent the rock is buried beneath the valley sands. The few exposures belonging to it exhibit no evidence of folding.

THE CENTRAL BELT.

In the central belt the exposures are almost uniformly low, massive ledges, in which strikes and dips are not always easy to obtain. Where observations were taken the strike is invariably in the direction of the trend of the belt. West of the Cuff mine the dips are practically vertical, and the belt appears to be isoclinal. East of the Indiana mine the dips are usually 70° to 80° S. But here only the southern side of the belt is open to inspection, since the northern side is buried under sandstone. At the Cuff mine test pits show that the northern boundary of the dolomite swings suddenly to the north, and a dolomite ledge exposed at the southwest end of the open pit east of the shaft strikes east-west and dips 45° N. There is here plainly a small subordinate anticline (fig. 17).

At Iron Hill, at the eastern extremity of the belt, there is also clear evidence of minor folding. Near the east quarter post of sec. 32, T. 40 N., R. 29 W., are two small knolls of dolomitic chert separated by a small valley. The rock in the northern knoll dips 75° to 90° S. Across the valley, and at a distance of only about 50 feet, the rock on the northern side of the southern ledge dips 45° N. On the southern side of the same knoll the dip is 45° S. The dips of the beds in the great ledges of dolomite farther south are 85° to 86° S. There are here, then, at least one minor syncline and two anticlines, superimposed on the major anticline that gives rise to the belt (see map, Pl. XLII).

The southern boundary of the dolomite in places terminates in little cliffs. One of these is situated 500 paces west of the east line of the section. The face of the cliff consists of white cherty quartzite, under which is a much-jointed, conglomeratic or brecciated dolomite. A side view of the cliff (see Pl. XVII, *A*) shows the chert extending vertically up its face to the top and then suddenly bending northward and becoming horizontal and covering the dolomite with a distinct layer which finally disappears under the soil. The photograph also shows plainly that not only does the chert roll over the dolomite but that it is further folded into crumples of small dimensions. The intensity of the folding at this place is also indicated by the brecciated character of the chert. Here the folding is no doubt connected with the existence of the pitching anticline which carries the dolomite beneath the Hanbury slates.

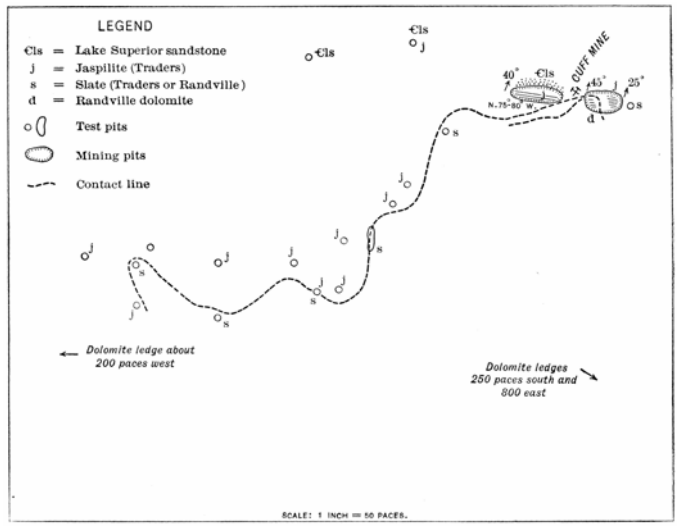


FIG. 17.—Sketch plan of Cuff mine and vicinity.

THE SOUTHERN BELT.

MARGINAL FOLDS.

The southern belt appears to be practically isoclinal throughout nearly its entire exposed extent. Nevertheless close folding may be observed in a number of places. Minor folding is abundantly exhibited on the south side of the formation, where it is in contact with the overlying iron formation. The numerous synclines found here afforded suitable conditions for the concentration of the ores, and it is in them that the larger mines are situated. The mining operations have brought to our knowledge the underground relations of the two formations so fully that the nature of the folds in them has been made very clear. The most important ones may be named from the mines occupying them as follows: The Walpole, the Pewabic, the Quinnesec, the Norway, the Aragon, and the West Vulcan. All of these are closely compressed folds pitching to the west at angles varying between 25° and 80°, usually becoming flatter at greater and greater depths. The western folds are overturned to the south and the eastern ones to the north. The axial planes of the Walpole and the Pewabic folds dip about 70° N. and that of the Quinnesec fold 60° in the same direction, while the Norway fold dips 70° S., the Aragon fold 60° S., and the West Vulcan fold is

nearly vertical. Although these folds are discussed rather fully in connection with the description of the ore deposits, a brief summary of the evidence upon which their recognition is based may conveniently be given in this place.

Walpole fold.—The most westerly fold whose existence is made certain by mining operations is that in which the Chapin, Millie, and the Walpole ore deposits are found. This is not anywhere to be seen on the surface, since the Lake Superior sandstone and the loose materials of the drift cover all the ground in its vicinity. The existence of the fold, however, is well established by the underground working of the Walpole mine, the old shaft (No. 1) of this mine being on its north limb, and the southern, or No. 2, shaft on its southern limb (fig. 34). The dolomite has not been met with in No. 1 shaft, and no crosscuts have been driven to the north from this shaft to locate it. About 550 feet to the west, however, is the A shaft of the Chapin mine, and 110 feet north of this on the surface is the southern limit of the dolomite. The dolomite is again met with at the east end of the third level of the Walpole, at a point 1,625 feet east and 525 feet south of the shaft. Just before reaching the dolomite the drift encountered a light-colored slate known to occur elsewhere at the base of the Traders formation. This rock, varying somewhat in appearance, but nevertheless essentially the same in composition, is disclosed again at several points at the ends of crosscuts running north from the main drift. The dolomite is immediately behind this. The Traders slate is again found at the end of a south crosscut at 1,425 feet east and 475 feet south of the shaft, and the same slate, underlain by a narrow bed of quartzite (Traders quartzite), back of which is the dolomite, occurs again 900 feet east and 425 feet south of the shaft. These exposures outline a narrow syncline of dolomite pitching to the west. No. 2 shaft is a little over 1,000 feet south of shaft No 1. South of it on the third level the quartzite that is so frequently associated with the dolomite again appears, and at a point 375 feet east of the shaft the east end of a drift terminates in the same rock. No other indications of the presence of the dolomite are met with on the third level, but in a long crosscut running north from the southern shaft and connecting it with the workings of the northern shaft, at a place midway between the two, three belts of ore-bearing material are uncovered, like the material lying above the Traders slate and quartzite elsewhere in the mine. The inference is plain that the dolomite lies a short distance to the east of this crosscut, and that its border is crenulated. Further, it is evident that the dolomite must form an anticline between the syncline in which the workings of the northern shaft are developed and another syncline partly outlined by the exposures in the workings of the southern shaft. The Walpole fold is thus composed of two synclines and an intermediate anticline. The folds pitch to the west and dip to the north.

Pewabic fold.—The Pewabic fold, like the Walpole fold, has been developed solely by underground work (fig. 35). Dolomite was reached at the end of a crosscut running a little east of north from No. 1 shaft of the Pewabic mine, at the first level, and at a distance of 870 feet from the shaft. This point is about 1,250 feet east and about 150 feet south of the Walpole shaft No. 2, just south of which, as was stated in the preceding paragraph, dolomite was found. There is then an anticline of this rock between the Walpole and the Pewabic basins. The latter basin is further outlined by the discovery of dolomite by means of two drill holes put in to the north and the south from the east end of the third level of the Pewabic mine, and a third hole driven to the south from the drift extending southward from the same level, about 500 feet east of shaft No. 1. Normal dolomite was not encountered in this drill hole, but the drill ended in the Traders quartzite, which is found only in close association with this rock. On the sixth level, however, a hole drilled in the same direction reached the dolomite. The east end of the fold is complicated by a fault the exact character of which has not been worked out. By these explorations it is shown that the iron formation of the Pewabic mine and the rocks associated with them lie in a syncline of the dolomite which widens to the west. The mining operations show that the pitch is to the west and the dip of the fold to the north.

Quinnesec fold.—The underground workings of the Quinnesec and the Cundy mines have not yet reached the typical dolomite on either side of the ore formation, though its presence north of the Quinnesec pit is indicated by the nature of the rocks met with. The principal evidence we have of the existence of a fold here is found on the surface (Pl. XXX). Near the corner, between secs. 34 and 35, T. 40 N., R, 30 W., and secs. 2 and 3, T. 39 N., R. 30 W., is a large ledge of well-bedded dolomite with a dip of 80° S. and a strike N. 70° W. This dolomite, if continued along its strike, would pass through the large open pit of the Quinnesec mine, in which the ore formation is well exposed. Exposures of the dolomite occur as far west as the road running north to the Indiana mine, and it is found again in the Quinnesec public well, situated about 750 feet west of the corner. The strike of the dolomite beds projected beyond this point would carry them south of the Quinnesec mine into an area dotted with ledges and test pits in the jaspers and slates of the iron formation.

North of the well there are no exposures of the dolomite for 300 paces (about 780 feet), though a drill hole put down about 525 feet east of the Quinnesec shaft disclosed the rock under the surface about 250 feet south of the southernmost exposure. North of this drill hole exposures are found at short intervals for 1,000 feet, and then at greater intervals for 2,500 feet beyond. The beds in the southern ledges strike from 3° to 8° north of west and dip nearly vertically.

Between the well that marks the westernmost point at which the dolomite has been found south of the mine and the next most southern occurrence of the same rock is a valley 530 feet wide in which no exposures of any kind are found. Artificial openings, however, show that the valley is occupied by the slates and other rocks of

the iron formation. The displacement of the dolomite is thus a little over 500 feet. A glance at the geological map (Pl. XXX) will make these relations plain. This displacement must be due either to a fault trending a little east of north or to a syncline pitching west. Since there is no direct evidence of a fault at this place, nor in the dolomite beds almost continuously exposed a short distance east of the section line, and since faults of important dimensions are not common elsewhere in the district, it is concluded that the displacement must be due to folding. The dolomite ledge near the corner is at the crest of an anticline. The dolomite north of the mine is the south side of another anticline, and the interval between is occupied by a synclinal trough filled with iron formation rocks.

Norway fold.—The folds in which the Norway and the Aragon mines are situated are as well known as any others in the district because of their extensive exploration by mining operations. On the surface a ledge of dolomite exists near the corner between secs. 4, 5, 8, and 9, and four other ledges of the same rock are exposed northeast of this one, i. e., in the southeast quarter of the southeast quarter of see. 4, T. 39 N., R. 29 W. (see Pl. XXXI). On the north, south, and west of these exposures the iron formation is known to occur. There is, consequently, an anticline of dolomite between the northern area of the iron formation, which is the basin of the Norway deposits, and the southern area, in which the Aragon deposits lie. The two folds—the Norway and the Aragon—are comparable with the Walpole-Pewabic folds farther west. The analogy is all the more striking since the Norway fold, like the Walpole, is a double syncline pitching to the west.

The northern side of the Norway syncline is quite sharply delimited on the surface by a number of dolomite exposures stretching for a distance of about 1,400 feet along a line running about N. 77° W. immediately north of the great open pits of the Norway and Perkins mines.

The south limb of the fold is indicated by the exposures in the southeast quarter of sec. 4, already referred to. To the east of the mine the country for some distance is sand covered, and there are no pits nor mine openings that yield information as to the nature of the underlying rock. Consequently the eastern limit of the fold can not be designated with any close degree of accuracy. A diamond drill located about 1,000 feet north of the south quarter post of sec. 4, however, encountered dolomite. Since this hole is nearly on the strike of the iron formation as exposed in the Norway and the Perkins pits, it is plain that this must terminate to the east before the position of the drill hole is reached.

In the underground workings of the Norway mine the syncline is beautifully disclosed, and it is by means of the mine explorations that we discover the syncline to be compound. At a number of places drifts and shafts have penetrated the dolomite or the slates that lie immediately above it. On the north side of the mine the upper contact of the dolomite dips south at angles varying between 45° and 65°. At the bottom of the mine the dips are flat for short distances and then on the south side of the ore basin they become northerly at steep angles (see sections on Pl. XXXII and fig. 18). The anticline thus formed nowhere reaches the surface, though its apex sometimes reaches a height of 100 feet or more above the bottom of the syncline. On the south side of the anticline the dolomite falls rapidly to the south and rises again in the anticline separating the Norway and the Aragon ore basins. This southern portion of the Norway fold, which may be designated as the Cyclops syncline, has not yet been thoroughly explored, but we know that its north side at one place dips 60° S.

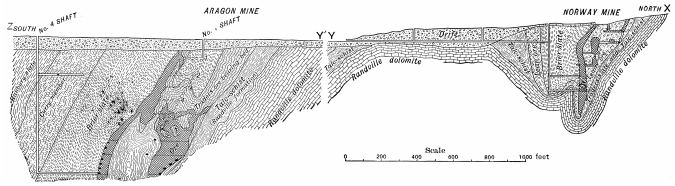


FIG. 18.—Vertical north-south cross section of the Norway and Aragon mines. Section along XY-YZ in Pl. XXXI.

An inspection of the cross sections of the Norway syncline will show that it differs from the more westerly folds in that its axial plane is either vertical or has a high dip to the south. The character of the Cyclops syncline in this respect is not known, although it probably also dips southward. The Norway fold must be a double east-west syncline, pitching to the west and in general dipping slightly to the south.

But the fold is not simply a pair of westward-plunging synclines. It is also gently folded along a north-south axis. A longitudinal section through the Norway pit (fig. 19) shows the dolomite rising under No. 8 shaft as a flat ridge and sloping down into valleys to the east and the west. It has been followed to the east until it again begins to rise in an anticline, but has not been traced to the surface. To the west it has been followed only sufficiently far to show that the dip of its upper contact is westward beyond the point at which it is flat.

Aragon fold.—The anticline of dolomite near the corner of secs. 4, 5, 8, and 9, already referred to, separates the Norway fold on its northern side from a southern fold in which lies the ore body of the Aragon mine. Although not developed on the surface, this fold has been so thoroughly explored by the lower workings of the Aragon mine that the minutest details of its structure at these depths are known. Like the Norway fold, the Aragon fold is also double, consisting of two synclines with an anticline between (see fig. 18). The northern syncline is, however, much larger than the southern one, which, measured from the crest of the anticline north of it, is only 100 feet in depth. The northern syncline is narrow, but its depth exceeds 800 feet. Both synclines are overturned to the north, the dip of their axial planes being about 70° S. Typical dolomite is rarely observed in the mine workings, but in its place is a talc-schist into which the dolomite seems to be altered on and near its contact with the overlying rocks. If this schist is an

altered product of the dolomite, its contact with the overlying rocks delimits the dolomite syncline.

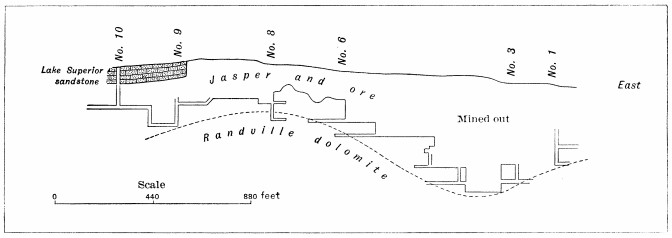


FIG. 19.—Longitudinal section through the Norway pit, showing position of dolomite beneath the ore. Only the bottoms of the shafts and lowermost galleries are shown.

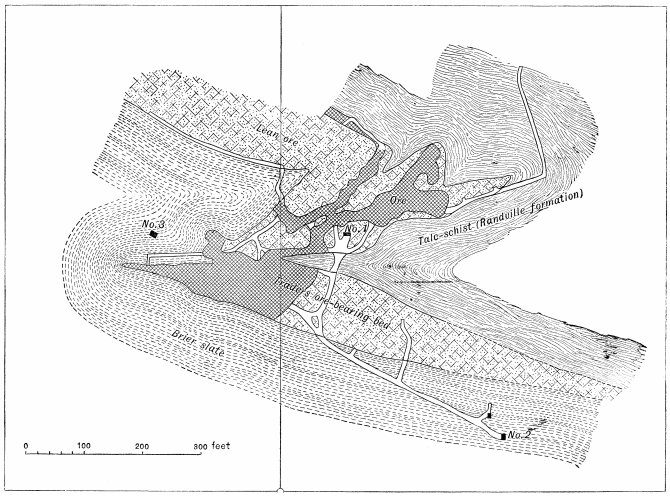


FIG. 20.—Horizontal section of the Aragon mine at the fifth level.

The plan of the fifth level of the mine exhibits a good horizontal section through the northern syncline and the anticline separating this fold from the southern one (see fig. 20). The plan of the sixth level (see fig. 21) shows in addition an apparently isolated mass of talc-schist, separated by ore from a more northerly mass of the same rock, which is plainly a lower portion of the anticline cut on the fifth level. On the seventh and lower levels this mass is found to be joined with the main portion of the schist, and the intervening ore has disappeared. The isolated area of schist on the sixth level is thus a section through the upper portion of a dome-shaped mass of the schists that is united with the schist to the north and that to the east by synclines.

Projecting upward the contact of the schist with the iron formation north of No. 1 shaft, along a line whose direction corresponds to the average dip of this contact below the fifth level, we find the north side of the northern syncline reaching the rock surface about 75 feet below the top of the drift covering at a point about 400 feet south of the north section line of sec. 9. The southern side of the fold does not reach the surface. Its top, that is, the apex of the anticline, is at a depth of about 375 feet. To the west it is deeper, and to the east it becomes shallower.

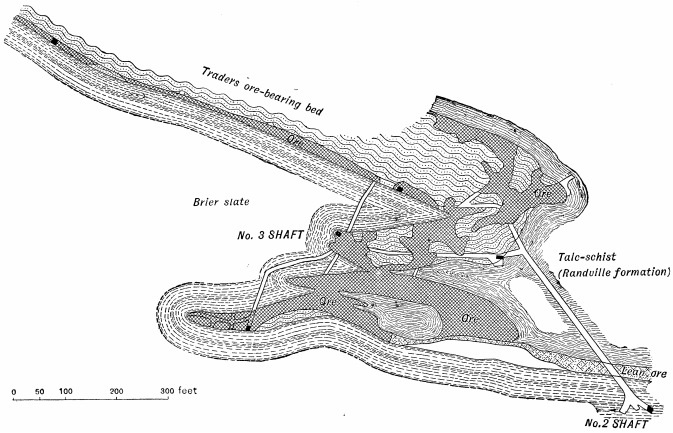


FIG. 21.—Horizontal section of the Aragon mine at the sixth level.

The southern fold, as has been said, has a vertical dimension of only about 80 feet. Its northern limb is formed by the anticline just referred to. Its southern limb is formed by another anticline, whose apex is about 120 feet south of that of the more northerly one and a few feet lower. The relation of these anticlines and synclines are well shown on the cross sections of the mine reproduced in fig. 18 and Pl. XXXII.

In attempting to define the eastern extension of the Aragon folds on the surface we are met by the same difficulties as were encountered in attempting to define the eastern end of the Norway fold. At about 750 feet east of No. 1 shaft, however, a series of great ledges of dolomite begins and runs eastward continuously for over 1,000 feet (see Pl. XXXIII). Hence the fold can not extend farther in this direction. The projection of the trough of the syncline along its pitch, as calculated from its known position on the fifth and sixth levels of the mine, would bring it to the surface at just about the west end of these exposures.

In the discussions of the folds of the Aragon mine no reference has been made to the small folds imposed upon the larger ones. If the Aragon synclines are secondary folds, these smaller ones are tertiary. Upon these, in some places, folds of the fourth order are known to occur, but they have not been carefully enough worked out to warrant platting. The tertiary folds are well seen on the sides of the syncline shown in the plan of the fifth level of the mine (see fig. 20). This is the northern syncline. On the plats of some of the other levels tertiary folds are also indicated, but nowhere else are they as strikingly exhibited as on the maps of the fifth level.

West Vulcan fold.—East of the Aragon mine the southern margin of the dolomite belt is covered by thick beds of the Lake Superior sandstone, except at a very few widely scattered points. Moreover, the mining operations have disclosed the dolomite in only a few places within the underground workings. Therefore no definite folds of the dolomite series have been recognized in this portion of the belt. There are, however, abundant indications that such folds exist.

In contact with the dolomite and south of it is the belt of the iron-bearing Vulcan formation. In this several folds have been discovered by explorations for ore. In the western portions of the district, where both the dolomite and the iron formation are exposed, the former is seen to behave like the latter. Where this is folded the underlying dolomite is likewise folded, and the folds possess the same character as those of the overlying rocks. If the two formations behave in the same way in the eastern portion of the belt, and there is no reason to suppose that they do not, there must be several minor folds on the margin of the dolomite between the Aragon mine and Waucedah. The best defined of the folds in the iron formation has been developed near the west quarter post of sec. 10, T. 39 N., R. 29 W., on the surface, and in the West Vulcan mine underground (see figs. 45-50). The plan of this fold on the surface is shown on Pl. XXXIV. Its axis pitches nearly west and its axial plane probably dips nearly vertically. The corresponding fold in the dolomite to the north must have approximately the same pitch and dip. It is, however, covered by the Cambrian sandstone, and consequently is not visible. Its position on the surface must be somewhere near the center of the section.

Other secondary folds at the southern margin.—Another fold within the iron formation has been observed west of No. 3 shaft of the East Vulcan mine in the southwest portion of sec. 11, T. 39 N., R. 29 W. (Pl. XXXV), and within the workings of this shaft and No. 4 shaft of the same mine farther east (figs. 51-53). This fold, however, is known to exist only in the upper members of the Vulcan formation. Its presence in the lower member has not yet been recognized, and consequently it is not certain that the dolomite which is still lower in the succession was involved in the folding.

There are no other folds indicated along the southern margin of the southern dolomite belt, though they may exist. The country east of the East Vulcan mine has not been thoroughly explored, and until explorations are sufficiently numerous to delineate the margin of the dolomite area with a close degree of accuracy it will be impossible to declare whether folds exist in it or not.

Secondary folds at the northern margin.—The recognition of the existence of secondary folds along the northern border of the southern dolomite belt is dependent on the distribution of the dolomite with respect to the overlying rocks. The mapping of this distribution exhibits the fact that the dolomite contact in several places is marked by embayments (see pp. 205-206), which can only be explained as due to crumpling into synclines and anticlines. Corroborative evidence that such crumpling does exist at some of these places is afforded by the attitude of the dolomite beds at the apices of the assumed folds. The most notable instances of this kind of evidence are found in sec. 35, T. 40 N., R. 30 W., and sec. 3, T. 39 N., R. 29 W. Near the center of sec. 35, just east of the apex of a supposed anticline, a number of exposures occur along both sides of the branch of the Chicago and Northwestern Railway that connects with the main line east of Quinnesec (see Pl. XXXIX). The ledges consist of beds of quartzose and normal dolomite, which in places are distinctly schistose. In many instances the schistosity is parallel to the bedding, both having a strike of N. 70° to 85° W., and a dip of 78° to 80° N. to 70° S., but in several instances the bedding and the schistosity are at variance. The latter is more pronounced, but close examination of the ledges will always reveal the former. Often the two structures will be found to coincide, but in many cases the schistosity will be seen to cut the bedding at varying angles up to 90°. North-south strikes are sometimes observed and dips of 35° to 45° W. The platting of these indicates the existence of small folds at these points with a pitch of 30° to 40° W. Thus is corroborated the view that a fold of greater magnitude exists in the dolomite at this place.

In the southeast quarter of sec. 3, T. 39 N., R. 29 W., is a single exposure of dolomite, the bedding and schistosity of which are not coincident. The beds are much crumpled and the little folds seem to have a low pitch to the west. The location of the exposure is at the apex of the assumed anticline opposite the Norway syncline in the south side of the belt. Its presence adds plausibility to the mapping of a fold at this place.

In sec. 11, T. 39 N., R. 29 W., the presence of a marginal fold is also indicated by the existence of slates within the area, which, in the absence of a fold, would be occupied by dolomite. This is the only evidence of the presence of the fold in this place.

INTERIOR FOLDS.

In the interior of the dolomite areas indications of close folding are but rarely met with, and when seen the folds are not sufficiently characterized to warrant safe conclusions as to their exact nature. Moreover, it is only in the southern belt that they are exhibited. At several places in the interior of this belt the dips and strikes over small areas are in different directions, thus showing the presence of folds of some kind.

One of the places at which folding may be observed is at the west end of the hill north of the Chapin mine. Here a large ledge is exposed at from 670 to 780 paces west and from 560 to 650 paces north of the southeast corner of sec. 30, T. 40 N., R. 30 W. As a whole the layers composing the ledge are evenly bedded with a strike N. 74° W., and a dip 85° to 87° N., but some of the beds, consisting of thin layers of dolomite and quartzite, are folded within themselves into numerous sharp anticlines and synclines following each other in rapid succession. The axes of the folds plunge almost vertically to the north.

In the large ledges north and east of Quinnesec folding is common (see Pl. XXXIX). The beds in some places are crossed by faults with throws of a few inches to a few feet. In other places the rock is much fractured and all traces of bedding have been obliterated. In the southeast quarter of sec. 34, northeast of the Quinnesec

mine, distinct crumplings are noted. In a few instances the beds strike nearly north. At one place a strike of N. 25° W. was measured, but this is maintained for only a short distance. The normal strike is N. 70° to 80° W.

In other portions of the belt the beds are for the most part very uniform in their strikes and for a given area also in their dips. These are for the most part nearly vertical, but occasionally, near the borders of all the belts, dips as low as 37° have been observed, and in one case a dip of 25° was measured, but in these instances the low dips are local phenomena, for the beds in neighboring ledges have high dips. These rapid local variations in dips indicate close folding, but since the strikes are maintained with a uniform direction the exact character of the folding is not discernible.

THICKNESS.

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.

If, however, we assume that in the wider portions of the belt 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.

It is only in the southern area that data can be obtained for estimating even approximately the thickness of the formation. The width of the exposed portion of this belt is about 4,000 feet, measured across the strike of the beds north of the Quinnesec mine. The dips vary from 88° N. to 70° S. Assuming the dips to average 80° S., and the formation to be folded into a simple anticline, the corresponding thickness would be 1,900 feet. This estimate is, however, of little value, since, on the one hand, we can not know what proportion that part of the formation which is here exposed bears to the entire formation, nor can we, on the other hand, estimate the amount of thickening due to minor folding. That the entire formation is not exposed from bottom to top is evident from the fact that the contact with the underlying Sturgeon quartzite is not seen. Moreover, the layers of chert that are believed to be characteristic of the upper horizons of the formation are likewise absent, probably as the result of the erosion that took place between Lower and Upper Menominee time. In view of these facts alone, the estimate given above would seem to be too small. But minor folding must exist in this area. The variations in the strikes and dips of the dolomite beds northeast of Quinnesec have already been referred to as indicative of folding. Moreover, the existence of a syncline in the belt just east of the section under discussion (see pp. 239-240) has been mentioned. This syncline is so near the present section that its influence must extend to it, and an apparent thickening of the formation must be the result. How great the reduplication of beds due to these folds is can not be determined, but it is clear that the estimate given is higher than it should be were the formations not affected by them. Whether the estimate would be increased or diminished by the elimination of the doubtful elements from the discussion is entirely unknown.

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 3,000 feet wide and has an average dip of 55° S. This corresponds to a breadth of approximately 2,450 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 1,225 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 imposible to determine. The difficulties here are practically the same as were met with in the attempt to calculate the thickness of the formation in the Quinnesec section. Although the data are more complete in these two sections than anywhere else in the entire district, there is still a great deal to be demanded before the calculations based upon them can be accepted as possessing a close degree of accuracy. If one should make calculations so as to obtain a minimum figure, 1,000 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 in the sections are different layers, an estimate as great as 5,000 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 1,000 and 1,500 feet.

RELATIONS TO ADJACENT FORMATIONS.

Relations to underlying Sturgeon quartzite.—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 three dolomite ledges nearest to the quartzite are as follows: One in the northeast quarter of sec. 33, T. 40 N., R. 29 W.; one on the south bank of the Sturgeon River, near the center of sec. 8, T. 39 N., R. 28 W.; and the third in the northeast quarter of sec. 3, T. 40 N., R. 30 W. None of these ledges are so near the quartzite that they can be said to represent undoubted transition phases between the two formations. They unquestionably indicate the character of the transition, however, for all three ledges are near the base of the dolomite series, and all three are composed largely or exclusively of quartzose dolomites. The westernmost ledge has already been described in some detail (see p. 193). That in sec, 33 is compact in the interior and drusy on the surface. The easternmost ledge is friable and sandy. The inference seems to be safe that the two formations grade into one another through dolomitic quartzites or quartzitic dolomites, and therefore that they are conformable.

Relations to overlying Negaunee formation.—While there is no evidence that any of the Negaunee formation now occurs in the Menominee district, there is abundant evidence that it occurred above the dolomite before the erosion interval that separates the Lower Menominee and the Upper Menominee series. In most places the erosion not only removed the Negaunee formation, but it also cut down into the Randville series, and in most places removed its upper portions. In a few places above the normal dolomite there still remain beds of cherty quartzite, sometimes brecciated, but at other times nonbrecciated, and distinctly bedded. The nature of the cherty quartzite suggests the idea that it may represent a transition between the dolomite beneath it to an iron formation that may have been immediately above it. In its macroscopic, as well as its microscopic character, the cherty rock resembles some phases of the jaspilites associated with the ores of the Marquette district. The pebbles in the conglomerates that prove the former existence of the Negaunee formation in the Menominee district show that the iron formation in this district was identical with the corresponding formation so well developed in the Marquette district. While conclusive evidence of the fact is lacking, nevertheless it is probable that the formation which in this report has been called the Randville formation graded into the now absent Negaunee formation through these cherts. It is possible that had a considerable quantity of the iron formation remained for study the line between this formation and the underlying dolomite series would be found more naturally to belong between the dolomite and the cherty quartzite than at the top of the latter rock, which would then belong at the base of the Negaunee formation as the lowest portion of a jaspilite member.

The relations of the dolomite with this rock would thus become significant. So far as has been observed in the few cases where contacts have been seen, the dolomite and the nonbrecciated phases of the cherty quartzite are conformable. The contact between the two is in some cases sharp, a well-defined layer of chert resting directly upon dolomite. In other cases the two rocks seem to grade by interlaminations. This seems to be the condition just north of the Norway pit, where near the top of the dolomite at this place a few alterations of the typical carbonate with a red cherty quartzite occur, and where occasionally what look like veins of the latter rock penetrate the underlying rock. There are no definite cherty beds of any great thickness above the dolomite at this place, though the chert seems to be most prevalent in the uppermost of the exposed horizons.

The shattered and jointed character of the autoclastic breccias makes it exceedingly difficult to discern the true relations of these phases of the rock to the dolomite with which they are in contact, though there seems to be little doubt that they are also conformable with the underlying rock. No place has been seen where the cherty breccias are in direct contact with the members of the underlying formation, except at Iron Hill, where the cherts are associated with a dolomite conglomerate. But at this place the relations are so exceedingly complicated that little can be learned from them (see p. 256).

Relations to basal member of the Upper Huronian.—Contacts between the dolomite and the overlying formation of the Upper Huronian 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 dolomites and the slates on either side of the contact plane strike N. 81° W., and dip 65° S., and no evidence of discordance between them can be discovered. However, 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 Archeau. 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.

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 phenomenon 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 talc-schist. The schist was probably formed in connection with movement along the contact plane after the Upper Huronian deposits were 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.

In those places where the basal member of the iron formation is not a coarse quartzite, it is usually a bedded red slate; or more nearly a schist composed of small grains of quartz and considerable dolomite and sometimes talc. Alternate bands are composed of layers in which dolomite and talc are predominant and those in which siliceous material predominates. The contacts between the schist and the rocks on both sides of it are usually covered. At the open pit of the Indiana mine this rock is represented by a fine-grained pink and gray slate that lies between the dolomite to the north and the iron formation to the south. The rock may be seen in the north wall of the pit, but its contact with the dolomite is covered. Drill holes in the vicinity of the mine which encountered the slate passed through about 25 feet of it directly into the dolomite. In the records this slate is spoken of as a "broken slate" formation, by which it is inferred that the rock is either brecciated or conglomeratic. If the latter, it is confirmatory evidence of an unconformity between the dolomite and the bottom of the iron formation.

At the Norway open pit and in the pits in the northeast quarter sec. 9, T. 39 N., R. 29 W., the original relations existing between the dolomite and the overlying iron formation have been greatly obscured by deformations due to movement. The overlying iron formation is a coarse schistose conglomerate or breccia composed of fragments of dolomite, slates, and ore, in a matrix composed of the same substances subsequently enriched by the deposition of ferruginous material. Many of the fragments are angular, others are rounded. In some instances the brecciated bands may be seen to cut diagonally across unbrecciated layers of the same composition, indicating that the former is autoclastic in origin (see Pl. XXI, *B*). The more conglomeratic phases are usually richer in dolomitic fragments than are the brecciated phases. Their material is more varied in character and their inclosed fragments more pebble-like. In all its aspects the rock much resembles a sedimentary conglomerate. But it is also brecciated. Large-sized angular fragments of the rock are here and there scattered through a conglomeratic matrix of the same composition as the fragments.

The rock underlying these brecciated ones is either a talcose schist, or slate, or a quartzose dolomite. In each case this rock also is brecciated, the included fragments and the inclosing matrix being of the same composition. There is in some localities a gradation between these underlying rocks and the rocks lying above them, while in other places the line of division between them is well defined. Often there has been extensive movement along this crushed zone, as indicated by the schistosity of both breccias. This has resulted in a very irregular contact between the two, causing the relations between them to be so obscure that they are difficult to decipher. The only probable explanation of the facts observed seems to be that the conglomeratic rock is a true conglomerate which was deposited on the eroded surface of the dolomite and then, together with the underlying rock, was brecciated and rendered schistose by the accommodation movements along the contact plane that took place when the district was folded. If this view is correct, the presence of the conglomerate above the dolomite is further evidence of an unconformity between the dolomite series and the overlying iron formation.

Relations to other formations.—The relations existing between the dolomite and the contiguous formations younger than the base of the iron formation will be discussed in connection with the descriptions of these formations (pp. 361 and 366).

INTERESTING LOCALITIES.

Although the dolomite series is for the most part covered by the Lake Superior sandstone, there are many places where excellent exposures can be studied. These are mainly in the area of the southern belt and generally near the transverse gaps that have been described as crossing the belt at several places, or on the southern slope of the ridge of hills north of the line of the most important mines. Though no continuous section across the entire formation has been seen, nevertheless it is thought that practically all of its beds from bottom to top are exposed at different places.

IN THE NORTHERN BELT.

Northeast quarter of sec. 3, T. 40 N., R. 30 W.—The only exposures of the northern belt that are at all extensive are those in the northeast quarter of sec. 3, T. 40 N., R. 30 W., and those in the northeast quarter of sec. 14 in the same town. The former have already been described in connection with the description of the near-by exposures of Sturgeon quartzites (see p. 193).

Northeast quarter of sec. 14, T. 40 N., R. 30 W.—Near the north quarter post of sec. 14, T. 40 N., R. 30 W., four distinct ledges outcrop on the south slope of the valley of the stream that empties into Pine Creek at Hamilton and Merryman's camp No. 6. They occur along a line trending about southwest, and, taken together, they exhibit a cross section of the formation about 800 feet in length. The northernmost ledge, which is on the north line of the section, 250 paces east of the quarter post, is a massive, white, crystalline, dolomitic marble without noticeable strike or dip. About 75 paces east and the same distance southwest are two other ledges in which the rock is a dolomitic quartzite, likewise without distinct strike or dip. The southernmost ledge, about 100 paces east and 225 paces south of the quarter post is a fine-grained, nearly pure white quartz rock that strikes N. 75° W. and dips 75° N. It is indistinctly marked by pink and light-gray bands that apparently indicate bedding, and is traversed by a great profusion of quartz veins. In some places it is cellular or drusy. On a fresh fracture the luster is dull and resinous and quite unlike the vitreous luster of the Sturgeon quartzites. The rock is a fairly good type of the cherty quartz rocks occurring at the top

of the Randville formation. The exposure is interesting as indicating the near proximity of the upper boundary of the dolomite formation.

IN THE CENTRAL BELT.

In the area of the central belt the only exposures of note are those just west of the Cuff mine, in the southwest quarter of sec. 22, T. 40 N., R. 30 W., and those at Iron Hill, in sec. 32, T. 40 N., R. 29 W.

Southwest quarter of sec. 22, T. 40 N., R. 30 W.—In the southern portion of the southwest quarter of sec. 22, T. 40 N., R. 29 W., and the neighboring portion of sec. 21 are six isolated little knobs of typical dolomite, forming together a ridge of ledges extending for about half a mile along the north side of the road from Lake Antoine to the Cuff mine. Some of the ledges are in sight of the road. These appear as rough knobs partially covered with trees and bushes. Others are buried in scrubby second growth and are invisible from short distances. The exposures are interesting mainly as illustrative of the massive character of much of the dolomite and as evidence of the existence of the Randville formation between the Cuff mine and the Indiana mine. The rock in the ledges is a massive pink or gray dolomite, heavily bedded, with indistinct bedding structure striking about N. 70° to 80° W. and dipping vertically. The exposures are traversed by gaping cracks or hollows where weathering has opened up the bedding planes, and by cross gashes opened up along joint cracks. Their surfaces are therefore rough and rugged, with projecting portions separated by hollows.

Iron Hill.—The central belt of dolomite terminates on the surface in the southeast quarter of sec. 32, T. 40 N., R. 29 W., where dolomites, cherts, breccias, and conglomerates occur in such relations as to suggest the presence of an eastward-pitching anticline with superimposed minor folds. The exposures at this place have already been referred to several times on preceding pages (pp. 219-220, and 234 and Pl. XVI, *B*, Pl. XVII, *A*, and Pl. XLII). They are easily reached from Norway by the road running north around the east end of the Norway open pit.

The ledges constitute a little plateau overlooking a swamp to the south and southeast. The southern limit of this plateau is a steep slope broken at four places by projecting buttresses of rock with precipitous fronts ranging from 15 to 20 feet high. On the top of the plateau the exposures are all of one kind except at the eastern end. Together they form practically a continuous ledge about a quarter of a mile long and from 200 feet to 500 feet wide, extending in a direction N. 60° W. The main portion of the ledges is a well-bedded, light-gray or dark-gray dolomite dipping nearly vertically and striking N. 50° to 60° W. Interbedded with this are a few thin layers of a very schistose quartzose dolomite. North and west of the ledges the ground rises toward a low hill underlain by the Lake Superior sandstone with a basal layer of conglomerate, which can be well seen at several places on the east of the dolomite along the eastern slope of the plateau and in the valley at its eastern base. On the slope the sandstone conglomerate occurs as patches lying upon a cherty quartz rock and a chert breccia in such a way as to permit of no doubt that it is unconformably above them. Although this rock in many places consists largely of cherty and dolomitic fragments in a cherty and dolomitic matrix, it nevertheless grades upward into a horizontally bedded rock with the characteristics of the normal Cambrian sand rock. The rocks beneath this conglomerate, while in many places possessing the same general appearance as the latter, are a little more compact. They moreover show abundant evidences of folding and are cut by joint cracks and penetrated by quartz veins, both of which features are lacking from the sandstone conglomerate. Farther up on the slope cherts are well exposed in a number of small ledges. In some ledges the rock is a fine-grained, pink, homogeneous quartzite indistinctly bedded and folded into definite folds. Most of the ledges, however, especially those to the south, consist of a cherty breccia composed of sharp-edged fragments of a white chert lying in a pink or red matrix composed of small grains of the same white chert in an extremely fine-grained siliceous groundmass that looks not unlike a red felsite. This chert breccia may be seen in places to lie upon the dolomite. It also occurs as patches plastering the faces of the little cliffs overlooking the swamp to the south and as layers a foot or two thick coating these cliffs and bending up over them (see Pl. XVII, *A*). The main rock in the cliffs is a dolomite conglomerate which differs from the chert breccia in the nature of its pebbles and also in the character of its groundmass. The rock is dark gray in color when viewed in the ledge. Its matrix is an almost black cherty dolomite with intermingled quartz grains, cut by tiny veins of calcite and quartz. In this are numerous pebbles of all shapes and sizes, the largest 20 inches in diameter. The majority are elongated and lie with their larger dimensions in approximately the same direction, though variations from this position are very numerous. Most of them consist of dolomites; the remaining ones are mainly white chert, though a very few consist of quartz or quartzite. Many of the dolomite pebbles still retain their bedding lines, and these run in all directions across the pebbles irrespective of their elongation, though naturally, in the greater number of cases, the bedding and elongation are parallel. Both pebbles and matrix alike are traversed by many fractures that have been cemented by quartz, forming veins which now stand up as tiny projecting ridges intersecting one another diagonally. Some of these may be seen in Pl. XVI, *B*. The main fracture lines intersect one another at angles of 40° and 140°, the acute angles opening in a direction a little to the east of north, about 20°, and to the west of south, and the obtuse ones nearly east and west. Since the beds are probably folded and the apex of the folds strike about N. 60° W., and pitch steeply to the east, the direction of the joints and their angular relations correspond very closely to the directions which they should have according to the discussions of Van Hise.[a] On the horizontal surfaces of some ledges a third

set of joints may be observed that appear as a series of fine parallel cracks nearly bisecting the obtuse angles of the two main sets. This series in direction nearly coincides with the strike of the beds as observed in other ledges. Along the main-joint cracks minor displacements have often taken place and the rock within a small fraction of an inch on both sides of the fractures has been sheared. Moreover, many of the pebbles are mashed and faulted, thus showing that the district was deformed after the conglomerate was laid down.

In the ledges forming the cliffs the conglomerate appears to overlie the chert breccia in some places, but in others the reverse condition obtains. In the eastern ledges, as has been stated, the breccia is usually above the bedded dolomite. In one of these ledges, however, the chert breccia is interbanded with beds of massive dolomite. Although the breccia in the eastern ledges and the conglomerate in the southern and western ledges appear to be very different rocks, if one begins at the east and traces carefully the breccia, step by step, in the successive ledges, he must be struck with the fact that the breccia fragments become more and more rounded as he proceeds westward, and the rock assumes more and more the character of a conglomerate, until finally the typical conglomerate is reached. No line of demarcation between the two rocks can be detected, but the one seems to grade imperceptibly into the other. This observation suggests the possibility that the conglomerate is an autoclastic rock and that its conglomeratic character is due to the easy attrition of the dolomite pebbles as compared with the difficult attrition of the chert fragments in the breccia. At one place toward the east end of the hill a conglomerate band is between solid ledges of dolomite, and is in such a position as to indicate that it cuts diagonally across the bedding of the nonconglomeratic rock.

[a]Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1894, pp. 651-654 and 671-672.

These relations between the dolomite, the chert breccia, and the conglomerate are exceedingly complicated. The attempt to interpret them leads to one or the other of the following conclusions: (1) The conglomerate may be a true sedimentary intraformational conglomerate whose complex relations to the remainder of the Randville dolomite are due to the crushing and close folding to which the series at this place has been subjected; (2) the conglomerate, like the breccia, may be an autoclastic rock formed by crushing and abrasion of the autoclastic fragments which in the case of the breccia, because of their hardness, retained their sharp-edged forms; or (3) 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 the eastward-pitching anticline which terminates the dolomite belt. Since several minor folds are superimposed on the anticline the conglomerate would naturally be folded in between the underlying dolomite, and upon erosion would appear as an intraformational conglomerate. In this case the chert breccia would have to be considered a sedimentary rock. The difference in the character between it and the conglomerate might be due to the fact that the former was deposited against a shore composed of chert and the latter against a dolomite shore line from which the overlying chert had been removed by erosion. The Hanbury slate—an Upper Huronian formation— borders the dolomite to the south and the east, though its contact with the dolomite is not visible. The normal Hanbury slate is a typical gray argillaceous rock quite different in composition from the conglomerate and breccia, but this difference is easily explained by the latter rocks being the first deposits along a shore line composed of dolomite and chert.

While the third view is the one that seems most satisfactory to explain the phenomena, nevertheless there are a few facts that are not explained by it. The presence of a band of conglomerate cutting diagonally across several dolomite beds is explained best by the second view. If the breccia and the conglomerate do not actually grade into one another as they have been described to do, it is possible that the breccia is an autoclastic rock and the conglomerate the basal member of the Hanbury series. The inability to distinguish a line of demarcation between them may well be due to exceedingly close folding and a welding together of the two rocks where they are in contact. No unprejudiced observer, however, after reviewing the facts impartially, would be willing to declare without reservation that the conglomerate is not a member of the dolomite formation; nevertheless, after repeated visits to the ledges and careful examination of them, it seems most plausible to regard the conglomerate as the basal member of the Hanbury formation and the breccia as an autoclastic rock formed from the uppermost (cherty) members of the dolomite formation by the fracturing that accompanied close folding. That the whole series of deposits in this place was indeed fractured is shown by the numerous quartz veins that traverse them, but since these veins cut indifferently all the rocks, the conglomerate as well as the massive dolomites, and the pebbles in the conglomerate as well as its matrix, this fracturing must have taken place after the conglomerates were laid down. It is conceivable, of course, that before the conglomerate was made, an earlier fracturing took place and that its effects are preserved in the breccias.

IN THE SOUTHERN BELT.

In the southern belt of dolomite the opportunities for the study of the formation are exceptionally good. Exposures are fairly abundant, and, though limited very largely to the south side of the belt, they exhibit the character of the formation in all its phases. Some of the most interesting groups of exposures are those discussed in the following paragraphs. There are many others in addition to those described that are worth study, but these represent all the phases of the formation, and, besides, they are easily accessible.

Southeast side of Lake Antoine.—The ledges on the southeast side of Lake Antoine are best reached by the road from Iron Mountain that passes along the south side of the lake. They form a little hillock on the east and south sides of the road almost due east of the little island in the southern portion of the lake.

The rocks outcropping on the top and along the south slope of this hillock are well-bedded dolomites and dolomitic quartzites, the latter often exhibiting cross bedding. The surfaces of the ledges are roughly corrugated. The dolomite, weathering more rapidly than the quartzite, forms the hollows of the corrugations, while the quartzite forms the ridges. All the beds dip vertically and strike N. 71° to 75° W. The predominant dolomite is a bluish-gray rock, containing here and there a grain of quartz. It is cut by small veins of quartz, and others of a mixture of quartz and dolomite. On a fresh fracture surface the rock is fine grained, homogeneous, and entirely massive. On the light-brown weathered surface, however, many very distinct oval grains of quartz are apparent, scattered indiscriminately through the rock in particles measuring a millimeter in their longest diameters, which are nearly always in the plane of the rock's bedding. Moreover, the rock appears distinctly schistose through the presence of a great number of very thin seams of argillaceous dolomite, which run parallel to the bedding for short distances and then disappear, their places being taken by other seams starting near the terminations of the first ones and disappearing in turn a centimeter or so beyond their starting points. The effect of these seams, which are approximately parallel, but which sometimes make very acute angles with one another, is to break the surface up into a number of elongated areas, some of which are flat rhombs, thus producing an appearance of schistosity. There is no evidence of shearing in the dolomite. The phenomenon just described is probably a direct result of sedimentation.

Interbedded with the gray dolomite is a lighter-colored one of a pinkish-gray tint, that differs from the gray variety only in color and in the presence of a few more quartz grains. The dolomitic quartzite is evidently only a very quartzose phase of the dolomite. It forms beds from 1 inch to 2 feet in thickness between beds of the dolomite. Often these are so very quartzose that the rock weathers with a surface almost identical with that of the Sturgeon quartzite. These ledges are interesting as exhibiting the best illustration of the interlaminations of dolomitic and quartzose beds observed in the district.

Southeast quarter of sec. 32 and southwest quarter of sec. 35, T. 40 N., R. 30 W.—The upper cherty members of the dolomite series are well shown in the large ledges occurring in the southeast quarter of sec. 32, and the southwest quarter of sec. 33, T. 40 N., R. 30 W., south and southwest of the Pewabic ore pit near the east quarter post of sec. 32 (Pls. XXIX and XXXVIII).

Through this area a number of hillocks of dolomite occur, forming a little plateau whose south escarpment consists of little cliffs faced with a porous, mottled red and white, drusy and saccharoidal quartz rock, crossed by numerous narrow streaks of a darker red color and gashed by short, irregular crevices. No bedding can be discovered in the quartz rock, but on the plateau a little back from the edge of the cliff dolomite occurs with a well-defined strike N. 66° W., and an almost vertical dip. The narrow dark-red streaks that traverse the quartz rock run in approximately parallel directions. They seem to be tiny veins of quartz that occupy crevices parallel to the bedding planes. In places the cracks which they occupy widen out and hollows are formed, the walls of which are covered with druses of tiny quartz crystals. Often the veins anastomose, cut across the portions of the rock included between two parallel veins, and separate it into isolated portions that look like fragments derived from a preexisting rock. Near the top of the cliff the vein material predominates over the fragments, causing the rock to resemble a typical breccia composed of sharp-edged white chert and fine-grained quartzite fragments in a dark-red quartzite matrix. In other places, probably where movement within the rock mass has separated fragments, crushed some and caused others to assume new positions, quite different from their original ones, the rock resembles a basal breccia or conglomerate of the Lake Superior sandstone, from which it can be distinguished only by the coarser grain of the latter rock and the greater drusiness of the former. At the top of the cliff and a little back from its face the two rocks are in contact, the sandstone breccia overlying the cherty quartz breccia. Even when so near together, it is not always possible to discriminate between the two. From the base of the sandstone breccia veins and dikes of sandstone extend down for some little distance into the cherty rock. Back from the edge of the cliff, for a width of 100 paces or more, the dolomite is well exposed in an almost continuous ledge of a pink and gray fine-grained massive rock, cut by the usual quartz veins. The dips and strikes vary somewhat in different portions of the ledge, but the general strike is N. 66° W. for the southern portion of the exposure and N. 80° W. for the northern part. The dip remains nearly constant. Where good observation can be made it is about 85° to 87° S.

Farther east the dolomite is exposed in a number of smaller ledges that rise above the general surface of the country in little hillocks. Here the strike bends a little farther to the west and the dip in some places is as low as 37° S. The tops of the hillocks in several instances, both in secs. 32 and 33, are covered with remnants of the basal Lake Superior conglomerate, which to the north is replaced by the usual sandstone that nearly everywhere caps the high ridge lying north of the belt of mines along the main line of the railroad. This conglomerate, or, in some places, more properly breccia, is made up of many angular fragments of quartzite in a red sandy matrix, which in some instances is highly calcareous. At the Pewabic pit it consists of many bowlders of a high-grade iron ore embedded in a sandstone matrix which differs from the ordinary sandstone simply in being admixed with considerable finely comminuted ore. At several places within and

near the pit the conglomerate can be seen resting unconformably upon the underlying dolomite, with its horizontal beds capping the upturned beds of the dolomite and filling all the many irregularities of its surface.

North and northeast of Quinnesec.—Another interesting group of exposures is in secs. 2 and 3, T. 39 N., R. 30 W., and secs. 34 and 35, T. 40 N., R. 30 W., north and northeast of Quinnesec. The most instructing ledges are easily reached from the wagon road between Quinnesec and Norway and from the branch of the Chicago and Northwestern Railway running through secs. 2 and 35. These exposures have already been referred to several times in previous pages (see pp. 239-240, and Pl. XV, *A* and *B*, and Pl. XXXIX).

Just north of the Norway wagon road, east of Quinnesec and parallel to it, an almost bare ledge extends for a quarter of a mile, forming a series of rough knobs with nearly precipitous south sides (see Pl. XV, *A* and *B*). The rock of these knobs is a heavily bedded light-gray, fine-grained, and usually massive dolomite, striking N. 70° W. and dipping 70° to 80° S. It is banded with the usual quartzose dolomite layers, and is cut by small irregular quartz veins.

To the north and northwest of this are other ledges of smaller dimensions in which the rock is similar. The strike, however, is more nearly east and west, and the dip is much higher, sometimes being vertical or even slightly inclined to the north. The color of the rock also changes to dark gray, pink, or red. Here and there the beds show strong evidence of compression in the existence of a well-marked schistosity. Usually the schistosity escapes detection because it is parallel to the bedding, but in the ledge 200 paces north, 25 to 150 paces east of the southwest corner of sec. 35 the schistosity is inclined to the bedding at 15°, so that the two structures are easily differentiated. The strike of the bedding in this ledge is N. 70° W. and that of the schistosity is N. 55° W.

In the southeast quarter of sec. 34 there are also ledges in which the strike of the bedding and the schistosity depart even more from parallelism. In all these instances it is usually the bedding that is disturbed, the schistosity striking nearly uniformly in a direction N. 55° to 70° W., while the strike of the bedding varies between this direction and due north. Here, too, and in the neighboring portion of sec. 35, there are many exposures in which minor faulting of a few inches to a few feet is noticeable and some ledges in which the dolomite is much fractured and all traces of its original bedding are lost. These disturbances are plainly connected with the great fold at Quinnesec (see p. 239), since in other portions of the district at a distance from known folds disturbances of this kind are lacking.

The exposures along the branch railroad exhibit one of the best sections across the formation anywhere met with in the district. In length it measures a little over three-quarters of a mile. If the view with respect to the structure advanced in previous pages (see p. 239) is correct, the section cuts a broad anticline to the south, a narrower one to the north, and a narrow syncline between these. The rocks of the southern half of the southern syncline are described in the preceding paragraphs. Those of the remainder of the section are somewhat different from these, and are described in the following paragraphs. The difference is probably due to the fact that the northern portion of the section is through the upper portions of the formation while its southern part is across lower portions, the upper members having been removed by erosion during inter-Huronian time.

The exposures along the railroad embrace a dozen or more ledges, some small and some large, lying on both sides of the right of way. Those in sec. 2 and in the southeast quarter of the southwest quarter of sec. 35 are mainly even-bedded massive and schistose dolomites like those described above. In some places the roadbed passes through solid ledges in open cuts that exhibit beautifully the massive character of the rock. At the stream crossing about 400 feet north of the south line of sec. 35 the exposures are particularly good, since in addition to the railroad cut there is here a natural section made by the stream which tumbles through a little gorge in a series of small cataracts and rapids. In all its essential features the dolomite here is like that to the south. It is banded by thin parallel seams of argillaceous dolomite, that extend from the weathered surfaces as little projecting ridges, and is cut by the usual quartz veins. The strike is N. 85° W., and the dip is 85° S. North of the stream the road traverses a swamp which drill holes show to be underlain by Lake Superior sandstone lying above dolomite.

North of the swamp, toward the center of sec. 35, exposures again begin, and extend north almost continuously on both sides of the road for a distance of about 800 feet. The ledges are usually small and flat on the east side of the road and somewhat larger and more knob like on the western side. There is no regularity in the succession of beds exposed, though slates and conglomerates predominate toward the south and dolomites toward the north. Traveling northward, and examining the ledges now on one side and now on the other side of the roadbed, we find first a series of black slates, dolomitic quartzites and conglomerates, and pink dolomites, followed by interbedded gray slates and dolomites, and finally a succession of thick beds of bluish-gray dolomite.

The black slates, quartzites, conglomerates, and dolomites are definitely interbedded. The slates are dark-gray, almost black, rocks with thin laminæ preserving the bedding very perfectly. The cleavage is parallel to the bedding, which strikes about N. 70° W. North of the slate ledges are others in which the interbanded quartzites and dolomites are well exposed. The quartzites are rather coarse-grained pink varieties composed largely of intermingled quartz grains and crystalline dolomite. Their beds, varying in thickness from a few inches to 2 feet, weather with a dark-red color

and a rough porous surface. In them are occasional fragments of dolomite, of a dark-gray, fine-grained rock resembling chert in its general appearance, and of a white or light-colored schist that looks something like the light-colored slates associated with the dolomites farther north. In a few ledges the fragments are so abundant that the rock may be denominated a conglomerate. From the relations of the conglomerate to the quartzites and the dolomite, it is clear that it can mark no important stratigraphic break in the series. It is intraformational. The dolomite interstratified with the quartzites and conglomerates is also pink in color. On fresh fractures the principal difference noted between the first two rocks named is the finer grain of the dolomite and less abundance of quartz grains in it. Quartz is present, however, but only in small grains and in no great quantity. The weathered surface of the dolomite is depressed below that of the quartzite and its texture is much more finely granular. Ledges in which both rocks occur have therefore a corrugated surface made up of projecting bands of a coarsely granular structure alternating with depressed bands of a finely granular structure.

Farther north slates again appear. These, however, are unlike the dark slates to the south. They are usually light gray, more or less schistose rocks containing considerable dolomite, constituting beds from a few inches to 50 feet in thickness. In all their essential features they resemble very closely the slates associated with the Kona dolomite in the Marquette district.[a] None of the wider beds are composed exclusively of slate. There are always interlaminated with this rock thin seams of dolomite, but the slate predominates. Alternating with the beds composed principally of slates are others composed exclusively of dolomite. As we proceed northward we find the dolomite becoming more prominent, the northernmost ledges consisting exclusively of this rock. The dolomites in this portion of the section are schistose bluish-gray varieties interlaminated with thin layers of a more siliceous phase that projects above the general surfaces of the ledges as dark-red ridges no thicker than sheets of wrapping paper. In many places the ridges are crinkled and closely folded, while the dolomite between them seems to be quite devoid of any evidences of minor contortions. The schistosity of the dolomite strikes N. 70° to 80° W. and dips 70° to 80° S.; i. e., it is concordant with that of the rock elsewhere throughout this portion of the district. In some ledges the bedding and schistosity strike and dip in the same directions, but in most exposures the two structures intersect each other at greatly varying angles, the strike of the bedding changing rapidly within short distances. In the two small ledges on opposite sides of the roadbed at the northern end of the section definite folds pitching to the west are plainly apparent. In the ledge on the west side of the road the schistosity strikes N. 85° W. and dips 78° to 80° N. This is the most prominent structure and the one most easily discerned in the ledge. Close inspection will show, however, that the little projecting quartzose layers referred to above do not always run in this direction, but that, on the contrary, they frequently depart from it very widely, the variation in the two directions sometimes amounting to 90°. Since these bands mark the bedding, it becomes plain that while the two structures, bedding and schistosity, coincide in some places, in others they are distinct, and the difference is due to the variation in the bedding. An inspection of the bedding shows a fold pitching to the west at an angle of 35° to 40°, which accounts completely for the discrepancies noted in the two structures. On the east side of the road a similar condition obtains, except that the strike of the schistosity is N. 70° W. and its dip 70° S., and the pitch of the fold 30° to 40° W. The presence of minor folding at this place has been used as an argument in favor of the existence of a larger fold in the series (see p. 247).

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 244-245, 259-260.

Northwest quarter of sec. 9, T. 39 N., R 29 W.—The south half of this quarter section is underlain by the iron-bearing Upper Menominee beds and by Hanbury slates. In its north half are magnificent exposures of the dolomite formation, showing nearly all of its phases, except some of the slaty ones. Just east of the Aragon shaft No. 1 is the mouth of a little gully about 130 paces wide (see Pl. XXXIII), which extends a few degrees south of east for about a quarter of a mile. Its north side and east end are bounded by high and almost precipitous ledges of dolomite and its south side by a low ridge of jaspilite and quartzite belonging with the Vulcan iron formation. The latter will be described in another place (p. 435). The floor of the gully is flat and even. It is now occupied as a little garden patch, but was evidently once more or less swampy. It is probably underlain in part at least by talcose schists. The cliffs on the north side of the valley rise abruptly from the valley floor to a height of about 50 feet, forming the south side of a little range of rough hills which separate this valley from the great plain that extends eastward from the open pits of the Norway and Perkins mines. The hills are nearly bare of vegetation, but a light covering of soil obscures the relations of the rocks to a considerable extent. Bedded and brecciated dolomites, brecciated cherts, and a few light-colored slates constitute the principal rock types exposed. For the most part the distinctly bedded rocks strike about N. 65° W. and dip between 40° and 50° S., but at the eastern and western ends of the range the rocks are in plunging folds that naturally cause rapid variations in strikes and dips. In many ledges, moreover, even where the dolomite lavers have a uniform strike, the slates interbedded with these are deformed into many little folds.

In the little hillock at the west end of the ridge the folding is very pronounced. On the top of the hillock dolomites and slates are well exposed, with strikes varying between N. 88° E. and N. 70° W. and dips between 30° and 45° S. Small folds are abundant in the slates, and several larger ones affect the slates and dolomites alike. On the east side of the exposed surface these pitch to the west and on the west side they pitch to the east.

Southeast of this exposure is another one forming a westward-facing bluff. In this the strike of the dolomite beds varies from north on the northwest side of the cliff through N. 45° W. to N. 70° W. on its south side. The dip varies between 25° and 80° SW. At this place there is evidently a fold pitching fairly steeply to the west. At its apex, i. e., between the points at which the strikes are north and northwest, the rock is shattered and a well-marked dolomite-breccia has developed.

From the south side of this bluff dolomites extend eastward with a uniform strike of about N. 70° W. and a dip of about 40° to 50° for about 500 paces, forming the line of little cliffs bordering the north side of the valley. Similar rocks with the same strikes and dip likewise constitute the north slope of the ridge. The top of the ridge consists of chert. This begins at a point between the two little hillocks above referred to as exhibiting folds, and stretches as an almost continuous ledge the entire length of the ridge and finally disappears under the soil. On both sides it is flanked by the dolomite forming the north and the south slopes of the ridge. The chert appears on fresh surfaces as a fine-grained rock mottled with gray, red, blue, and white streaks, and cut by short cracks the walls of which are coated by druses of tiny quartz crystals. On surfaces that have been exposed to the weather a brecciated structure becomes very apparent and the irregular mottling observed on the fresh surfaces is seen to be due to the presence of white and bluish-gray fragments cemented together by a reddish groundmass. Nearly all the chert in these hills seems to be brecciated in this way. The brecciation does not appear to bear any definite relation to the axes of folds. Although best exhibited where folds are recognizable in the associated dolomites, it is by no means limited to these positions. Here as elsewhere the chert seems to be characterized by the brecciated structure, as though its brittleness caused it to yield to compressing stresses more easily by fracture than by flowage even when confined between dolomite beds that were deformed by flowage exclusively.

At the east end of the ridge the relations of cherts and dolomites again become complicated. From the northeast corner of the main valley, where the cliffs bordering its north side meet those bordering its east end, two little side valleys or ravines extend northward. The more westerly one affords an excellent section through the ridge at a point where the folding seems to be the most complicated—indeed it appears that the ravine is a consequence of the folding. The west side of the ravine is a bluff exposing a sharp fold in dolomites overturned to the north and pitching to the east. On its south face, overlooking the main valley, the dolomite has the normal strike, N. 70° W., and a dip of 40° S. Passing northward along the edge of the bluff, however, the strike is observed to swing to the east, and then to become northeast, north, and northwest, successively, and finally to resume a direction on the north side of the hill parallel to that observed on its south side, i. e., N. 70° W. Where the strike is approximately north, i. e., at the point which may be supposed to be in the axis of the fold, the dip is 30° N. On the north limb of the fold the dip corresponds to that on the south limb, viz, 40° S.

Beyond this fold, on the top of the ridge, even-bedded dolomites with the usual strike and dip are again exposed in a large ledge, and in contact with them to the east appear equally large exposures of the chert. The dolomite is apparently the continuation of the beds flanking the north side of the chert band on top of the ridge to the west. The chert, on the other hand, seems to be a distinct bed, quite independent of the beds on the top of the ridge, though it may possibly be the same bed repeated by folding or faulting. This chert extends practically continuously for about 150 paces to the southeast, and is in contact on its south side with bedded dolomite and dolomitic and cherty breccias. On its west side its contact is with the dolomite forming the north slope of the ridge, as already mentioned. This contact is extremely sharp. It cuts diagonally across the bedding of the dolomite, so that the chert rests directly upon the truncated layers of this rock. From the relations of the chert to the dolomite elsewhere it is plain that the two rocks are not separated by an unconformity, nor is it probable that the chert in this instance occurs as a vein in the dolomite. The phenomenon is best explained as due to the presence of a little fault along the contact line. On the east wall of the little ravine, opposite the exposures just described, are others of the same character. Dolomitic breccias are particularly well developed here, the picture reproduced in Pl. XVI, *A*, exhibiting the appearance of one of them, in which the fragments and matrix are practically all dolomite. On the top of the bluff the breccia can be seen to be interbedded with nonbrecciated dolomites. Evidence of folding is as marked on this wall of the ravine as on the western wall, but the exposures are not as continuous, and consequently the character of the folding can not be as well worked out. It is probable that the folds pitch to the west. Since the dip in the dolomite beds immediately to the north of the breccia figured (Pl. XVI, *A*) is to the north and that in the bed to the south is southerly, it is possible that the brecciated band is situated along the axis of the fold. However, in other portions of the hills smaller exposures of the same kind of breccias are frequently met with in which the relations to folding are not so plain. It is true that in almost all these cases departures from the normal dips and strikes may be observed, but it is not always certain, or even probable, that the breccias mark the axis of the folds.

From the distribution of the folds and of the breccias, and from the relations of the latter to the former, as well as the relations of the cherts to the dolomites it would seem that the dolomite series in this range of hills is affected by a close east-west folding and a more open north-south folding, with occasionally subordinate faulting. The chert is apparently interbedded with the dolomite near but not at the top of the series. That this folding is connected with that which gave rise to the Norway and Aragon ore basins can admit of no doubt.

The cliffs at the east end of the main ravine consist exclusively of well-bedded dolomites striking uniformly about N. 65° W. and dipping 35° to 40° S. At the extreme southeast corner of the ravine the strike becomes more nearly east-west (N. 85° W.) and the dip higher (50°). To the east and to the west of this exposure are several pits in iron-formation material which are just a trifle south of the projection of the strike of the southernmost portion of the ledge. This fact indicates that the ledge is very near the contact of the dolomite formation with the iron-bearing Vulcan formation. No direct contact is observable, but by digging into the little gully that runs down the cliff on the south side of the dolomite exposure large loose pieces of a white quartzite conglomerate containing numerous jasper fragments may be picked from the soil. The abundance of these fragments and the fact that they comprise the only kinds found in this place point to the conclusion that the ledge from which they were separated is but a short distance beneath and that the rock marks an unconformity between the dolomite and the overlying iron formation.

Secs. 12 and 13., T. 39 N., R. 29 W.—The most extensive exposures of the dolomite series is in the group of hills and hillocks in the valley of the Sturgeon River, secs. 12 and 13, T. 39 N., R. 29 W. The ledges are almost bare of vegetation, and therefore present exceptionally favorable opportunities for study. Those in sec. 13 are near the north quarter post of the section, just north of the wagon road from Vulcan to Loretto, on the south side of a high hill, the top of which in all probability is covered with the Lake Superior sandstone (see Pl. XLI). A walk of a quarter of a mile due north will bring one to the principal group of ledges, lying between the front of the hill just referred to and the track of the Escanaba and Iron Mountain Railroad (Chicago and Northwestern), one-fourth mile farther north. Most of the ledges are small, flat exposures, but here and there a little hillock rises from the valley floor, and on the south side of the railroad a very large, bare, smooth knob lifts its top about 75 feet almost vertically above the rails. It is an almost solid ledge of dolomite, but at its eastern end, where its slope is gradual, the rock is covered with drift material. This large ledge and the smaller ones to the south afford an almost continuous exposure of the series for a distance of about 600 paces across its strike. The distance from the southernmost ledge, near the wagon road, to the northernmost one, in the center of sec. 12, on the side of the railroad track, is about 3,100 feet.

From the center of the section the ledges extend eastward toward the lower portions of the Sturgeon Valley, where they are buried beneath thick deposits of sands. On the east side of the river, however, the rocks of the series again emerge from beneath the sands and outcrop in a number of small hills in the northeast quarter of sec. 13, T. 39 N., R. 29 W., and in the southwest quarter of sec. 7 and the north half of sec. 18, in T. 39 N., R. 28 W. A network of roads radiating from the bridge across the Sturgeon on the main road from Loretto to Waucedah passes between the outcrops and approaches many of them so closely that they may be examined from the seat of a carriage. These outcrops are not as interesting as those on the west side of the river, however, as they consist almost uniformly of a heavy-bedded, almost massive dolomite, striking and dipping in uniform directions.

The southernmost dolomite ledge in sec. 13 is situated about 200 paces south of the north quarter post of the section and about 75 paces north of a deep shaft in the iron formation, from which a large quantity of poor ore has been taken. The ledge is made up of alternating bands of pink and dark reddish-brown dolomite striking N. 85° E. and dipping 70° S. The lighter-colored bands are divided into layers by very thin seams of darker color, and are traversed by little joint cracks and fault planes. In many places the fine bedding lines show distinct contortions, which, however, are not observable in the broader bands. In other words, while the broad bands of dolomite have a uniform strike and dip throughout the ledge, they exhibit within themselves complex minor corrugations. In some instances the corrugations are so sharp that the contorted bands are actually fractured and the rock becomes a breccia.

Another ledge just east of the quarter post is a more typical dolomite breccia than that just described. On the weathered surface angular fragments of pink dolomite and others with rounded edges are seen to be separated from one another by stringers and small triangular patches of a dark-colored sandy nature. Where the rock is not brecciated it is contorted in the most complex way. Evidently a breccia of this kind was formed by mechanical means after the rock itself had been laid down as a series of alternating layers of dolomite and dolomitic quartzite.

The ledges in the northern portion of the south half of sec. 12 are composed of interbedded dolomites, dolomitic quartzites, and slates. In the southernmost ledge, on the north-south quarter line of the section, for instance, are to be found a 15-foot bed of dark, pinkish-gray, thin-bedded dolomitic quartzite, interlaminated with thin bands of a bluish-gray slate, a bed of purple dolomite 12 feet thick, interbanded with thin seams of a light-gray slate, a 7-foot bed of coarse dolomitic quartzite containing thin beds of dolomite, a band of dolomite and slate 25 feet wide, 10 feet of quartzite, and 10 feet of dolomite. The bedding of all these rocks strikes N. 65° to 70° W. and dips 45° to 52° S.

As we pass northward the sandstones and slates become less prominent and the dolomites more abundant. The hill next north of the ledge described in the last paragraph is composed of interlaminated dolomite and thin beds of slate. The rocks strike as in the ledge to the south, but the dips vary from 50° S. to nearly horizontal. The steeper dips occur on the slopes of the hill and the flat ones on top. In places, however, on the top the layers are closely folded into sharp little folds, pitching very steeply, the westernmost ones to the west and the easternmost ones to the east.

North of this hillock only thick-bedded dolomites appear. These rocks form the large hill already referred to as being south of the railroad track in the center of the section. Bedding lines with a dip of 45° S. can be observed on the southern side of the hill. As we pass north over the hill the dolomite becomes more and more massive until on the ridge no distinct strikes nor dips are noticeable. On the cliff overhanging the track, however, the dip is vertical in one place and at its east end there is an exposure with a dip to the south. North of this ledge there are no exposures for some distance. The outlook from the top of the hill is over a swamp, bordered on the north by a steep sand slope leading upward to a sand plateau.

This section afforded the data for the best estimate of the thickness of the Randville formation that was obtained.

NEGAUNEE FORMATION.

The identification of an iron-bearing formation in the Lower Menominee series corresponding to the Negaunee formation of the Lower Marquette series in the Marquette and Felch Mountain districts is based mainly on the fact that the lower layers of the Upper Menominee series contain fragments of jasper and ore that must have been derived from an older series. Whether the formation that yielded these fragments was exactly equivalent to the Negaunee formation in the Marquette district or not 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, for jaspilites are not known in the Archean rocks surrounding the Menominee trough nor in the Huronian beds below the top of the Randville formation. The position of this supposed formation in the Menominee district corresponds exactly with that of the Negaunee formation in the Marquette district. No distinctive name has been given it in the Menominee district, because of the impossibility of deciding positively whether or not there are any remnants of it now exposed on the surface. It must, however, be referred to in any discussion on the geology of the district, because only on the assumption of its presence can be explained some of the deposits of ore and jasper in the Upper Menominee series.

The jaspilites described in the immediately succeeding pages, while probably members of the Vulcan formation of the Upper Menominee series, are nevertheless somewhat different in their lithological features from the other jaspilites of the formation, and very like those in the Negaunee formation in the Marquette district. They are also very similar to the jasper in the pebbles of the coarse quartzite at the base of the Vulcan beds, and therefore must be similar to the jaspilites that furnished these pebbles. For these reasons they are discussed at greater length than their areal importance in the district would otherwise warrant, and not because it is believed that they are actually remnants of Negaunee beds that have escaped erosion. The Negaunee jaspilites were like these in all essential respects, and so the latter may serve to illustrate the features of the former.

DISTRIBUTION.

Remnants of the Negaunee formation may exist in the Aragon mine, the Pewabic mine, and some of the other mines of the district, but of this we have no definite knowledge, as the mining plats can not discriminate between two iron formations so nearly alike in their macroscopical features as are those of the supposed Negaunee and the Vulcan formations. The exposures above referred to, consisting of a jaspilite similar to that which furnished the pebbles to the basal conglomerate in the Upper Menominee series, lie in a narrow belt bordering the south side of the Randville dolomite area near the center of sec. 9, T. 39 N., R. 29 W. (see map, Pl. XXXIII). This belt is outlined by three test pits, a ledge, and several large abandoned mining pits. It begins a short distance east of the shaft of the old Brier Hill mine, embraces the north portion of the large, flat exposure lying a few degrees north of east of Curry shaft No. 2, and ends, so far as observed, at the northwest corner of the old mining pit No. 3 in the center of the southeast quarter of the northwest quarter of sec. 9.

LITHOLOGY.

The rocks from the narrow belt of iron formation just mentioned comprise even-banded beds of jasper and ore which have a range in thickness from the fraction of an inch to three inches or more. The jasper, which is of a dark purplish-red color, is very fine grained. It has a flinty texture and a completely homogeneous aspect. Here and there it is cut by little cracks lined with small plates of brilliant hematite. Sometimes the rock is faulted and hematite has penetrated between the faulted surfaces. The ore interlaminated with the jasper is a hard, dense, finely granular hematite, often possessing a slaty cleavage, but rarely exhibiting a specular character. It is sometimes spangled with tiny, brilliantly reflecting crystals of hematite, that appear to be due to infiltration, and sometimes it contains a small quantity of minute magnetite crystals. While some of the ore bands are homogeneous throughout, most of them when examined carefully are observed to be made up of interlaminations of very thin layers of ore and jasper. The contact between the hematite and the jasper layers is usually sharp and even, and often the rock will split more easily along this contact plane than anywhere else. Frequently, however, there is a gradation between the layers, the jasper near the ore bands becoming more and more thickly impregnated with hematite until it is apparently replaced entirely by the iron oxide. The ore layers, like the jasper beds, are traversed by cracks lined by hematite crystals, producing bright, glistening streaks across the dull surface of the ore. Both ore and jasper are cut by tiny veins of quartz.

In natural light sections of the jasper appear to be composed of a uniform aggregate of colorless quartz grains elongated in a common direction, which is parallel

to the bedding, crystals and aggregates of crystals of blood-red hematite, a few small flakes of some micaceous mineral, and an abundance of hematite dust particles. Their most noticeable structural feature is the presence of numerous little oval masses or lenses arranged in lines that are parallel to the bedding. The lenses are all elongated in this same direction, and are separated from one another by a groundmass without distinctive structure other than the schistosity due to the elongation of the quartz grains. The lenticular areas are composed of the same kind of quartz-hematite aggregate as that composing the ground-mass in which they lie. The distinguishing characteristics that mark them off from the surrounding material are a greater richness in hematite crystals and sometimes a difference in the coarseness of grain of their quartzose component as compared with that of the groundmass quartz. Moreover, in some instances the ore in the lenses is in a different form from that of the ore in the groundmass. The former is frequently in rods that may be the cross sections of flat rhombohedra, while the latter is in plumper crystals, whose cross sections are more nearly square. In many instances, also, the presence of the lenses is emphasized by the fact that there is an accumulation of ore particles near their peripheries which seems to mark their outlines very distinctly.

Between crossed nicols the sections break up into an almost uniform mosaic of interlocking quartz grains, many of which exhibit strain shadows. The hematite grains occur indiscriminately between the quartzes, and inclosed within them. No distinction can be noted between the quartz of the lenses and that of the groundmass, except that occasionally the latter is a little coarser than the former. There is no sharp line of demarcation between the two. The mosaic, in most instances, seems to continue uninterruptedly from lens to groundmass, and many grains seem to lie partly within the lens and partly without. The mosaic is plainly a crystalline aggregate; no trace of a fragmental grain can anywhere be detected in it.

It is extremely difficult to reconstruct the original character of the rock. The lenses may be regarded either as mashed jasper fragments that lay in a finer-grained quartzite, or as having been originally concretionary masses in a cherty sediment, such as gave rise to the jaspilites of the Penokee district and those belonging in the Negaunee formation of the Marquette district. Whatever the original character of the rock, it has been so completely silicified that definite traces of its structure have disappeared. From the fact, however, that in a silicified quartzite the fragmental cores of quartz to which the new quartz was added can in almost all cases be detected, whereas none have been recognized in the jaspers under discussion, it is concluded that the rock can not have been a quartzite made up partly of jasper fragments. From analogy with the Penokee and Marquette jaspilites, and because the rocks are like many of the concretionary jaspilites from these districts, except that they are more squeezed, it is thought that the lenses noted in the Menominee jaspers may be mashed concretions and the jaspers themselves may be silicified rocks comprised largely of ferruginous carbonates or of greenalite.[a]

[a]These lenses are identical in every respect with those pictured by Leith in The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, Pl. XV, *C* and *D*, and regarded by him as being altered greenalite grains.

While the deformation of the jaspers is due principally to mashing, nevertheless there has been some crushing. A few quartz veins cut through them in several directions, most commonly in a direction nearly perpendicular to the schistosity. A few tiny veins filled with hematite are detected and some of the little lenses are broken into pieces and faulted. These phenomena were evidently produced subsequent to the mashing and the resulting schistosity.

The ore bands associated with the jasper differ from the latter mainly in the presence of a much greater quantity of hematite. This is usually in long, irregularly shaped stringers running parallel to the bedding. The stringers consist of open aggregates of crystals united at a few points only and of masses made up of crystals fused together compactly. Occasionally these rod-like aggregates are in curved lines, as though they originally surrounded a waterworn grain or a concretion. The relation of the hematite to the quartz is difficult to determine, but from the fact that the former is idiomorphic with respect to the latter wherever the two are in contact, and the further fact that toward the ends of the ore aggregates individual crystals of the hematite are to be seen embedded in quartz grains, it is concluded that most, if not all, the hematite is older than the quartz. The relations between the ore and the quartz are exactly the same as those existing in the ferruginous cherts of the Negaunee formation in the Marquette district where "there is no apparent concentration of the iron oxides between the quartz grains, but they occur concentrated in laminæ or as separate flecks included in the grains of quartz just as though they were all in their present positions before the silica began to crystallize."[a]

[a]Mon. U. S. Geol. Survey, vol. 28, 1897, p. 370.

RELATIONS TO ADJACENT FORMATIONS.

The contacts of the jaspilites with the underlying rocks are covered. The relations of the Negaunee-like jaspilites with others that are unquestionably members of the Upper Menominee series are well seen in the ledge east of Curry shaft No. 2. On the north side of the ledge the jaspilites are of the character described above. On the south side they are more nearly like the jaspilites characterizing some portions of the Traders member of the Vulcan formation. The jasper layers particularly are more granular and less vitreous than those to the north, and they are frequently mottled with little oval spots of a bright-red color. The northern jasper is dull red and breaks with a conchoidal fracture. The southern jasper, while red on the weathered surface, is darker on the fresh fracture, and has a grayish-purple color. Moreover, it breaks with an uneven, fragmental aspect,

the surface being roughened by little projecting splinters with a white color and a granular texture. All the rocks strike uniformly N. 85° W. and dip 82° S. at the west end of the exposure, and strike N. 70° W. and dip 60° S. at its east end. At the two extremities of the ledge, north and south, the differences in the aspects of the jaspers are easily recognized, but as its central line is approached the difficulty of discriminating between them becomes greater, and finally in the middle of the ledge it becomes impossible to distinguish any difference between them. There is certainly no distinguishable unconformity between them and no bed of conglomerate that might mark an erosion interval. To all appearances the beds form a conformable series.

On the northwest side of pit No. 3, about 350 feet northeast of the eastern edge of the ledge, the same kind of flinty jasper is found. Here it is at the base of a series of conformable beds forming the wall of the pit. The upper layers are distinctly quartzites, containing abundant fragments of jasper interlaminated with layers of lean ore, some of which apparently contain large bowlders of ore (see Pl. XXII, *A*). Above the lowermost distinctly fragmental quartzites there axe no beds of the cherty-looking jaspers. These are confined to the part of the series below the quartzite. The base of the series is not visible, however, so that it is not known whether beds containing fragmental jasper occur again below the cherty jasper beds or whether these latter are actually beneath the entire fragmental series.

CONCLUSIONS FROM FOREGOING STUDY.

It is clear that there is no structural evidence to indicate that the jaspilites under consideration are members of the Lower Menominee series and represent an iron formation corresponding to the iron-bearing Negaunee formation in the Marquette and Felch Mountain districts. The only evidence that bears on the case is lithological. The jaspilites are different in appearance from most of the jaspilites of Upper Menominee age, and in their composition and texture are similar to the jaspilites of Negaunee age in other districts. So far as has been noted they contain no fragmental material, but, on the other hand, they seem to have an oolitic structure. Since they are beneath beds that are certainly members of the lowest iron formation in the Upper Menominee series, it might be concluded that they represent a small portion of the iron-bearing Lower Menominee formation which has yielded so much material to the overlying iron-bearing Upper Menominee formation. There are other considerations, however, which tend to cast doubt on this conclusion. If the jaspilites are Negaunee in age, the immediately underlying rocks should be the cherty upper members of the dolomite formation. The absence of these cherts seems to demand the assumption of an erosion interval between the jaspilites and the dolomite formation of sufficient duration to allow of the entire removal of the cherts. If this assumption is a correct one, it would necessitate the placing of the jaspilites in the Upper Menominee series with the Traders member of the Vulcan formation. It is not certain, however, that the chert was ever a uniform layer overlying the dolomite and coextensive with it, in spite of the fact that wherever found it is at or near the top of the formation. Of course, if it never existed in this place its absence indicates nothing with respect to the age of the jaspilites.

It is almost impossible to reconcile the absence of an unconformity between these jaspilites and the overlying jaspilites of the Vulcan formation with the view that the two jaspilites belong to two different series. In many places it might be difficult to recognize such an unconformity, even if present, because of the fact that the contact between the Lower and the Upper Menominee series was a zone of accommodation along which the original relations between the beds in contact were often obliterated by shearing. In the present instance, however, where the two jaspilites strike and dip uniformly, there has been no marked disturbance of the beds, and, in spite of this fact, no evidence of an unconformity between them can be detected. Indeed, the two varieties of jaspilites grade into one another like the beds of a single formation.

In a word, while the evidence that has thus far been adduced as bearing upon the age of the cherty jaspilites is not entirely conclusive, it seems to point to the fact that they are parts of the Traders member of the Vulcan formation. They are recognized, however, as being, on the whole, different lithologically from the characteristic jaspilites of the Traders member, although in the open pit of the Quinnesec mine and at one or two other places in the district there are beds that look very much like the jaspilites considered here. These beds are above the quartzite which contains fragments of jasper, and so are unquestionably younger than Negaunee.