

ART. XLIII.—*Upon the Origin of the Mica-Schists and Black Mica-Slates of the Penokee-Gogebic Iron-Bearing Series; by C. R. VAN HISE.*

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THE iron-bearing formation of the Penokee-Gogebic region has been traced from Lake Numakagon in Wisconsin to Lake Gogebic in Michigan, a distance of more than 80 miles. The rock belts of this series traverse the country in a general east-and-west direction. They dip quite uniformly to the northward at an angle usually ranging from 60° to 70°, though occasionally the dip is at a lower angle. They lie unconformably upon a series of schists, gneisses and granites, and are overlain unconformably by the Keweenaw Series.†

At Penokee Gap, Wisconsin, the series is, in round numbers, 13,000 feet thick, of which the upper 11,000 feet are mica-schists and black slates,‡ which thickness is retained to the eastward until Michigan is reached. These upper members have been traced continuously from English Lake (chiefly in Secs. 5 and 8, T. 44 N., R. 3 W., Wis.) to the Black River (Sec. 12, T. 47 N., R. 46 W., Mich.), a distance of more than 40 miles, their course in this distance being north of east, in places as much as 30° north of east (see map).§

The present lithological condition of the upper members of the formation is quite diverse in different localities. The group comprises fine-grained, crystalline mica-schists, black mica-slates, greywackes,|| greywacke-slates and quartzites. The exposures at the eastern extremity of the belt at Black River are red and white feldspathic quartzites. As we proceed westward the exposures found show chloritic greywackes and greywacke-slates. In section 14, T. 46 N., R. 2 E., Wis., the exposures

\* In advance of a full treatment of the subject to be included in a memoir on the Penokee-Gogebic Iron-Bearing Series, by R. D. Irving and C. R. Van Hise.

† This Journal, March, 1885. Divisibility of the Archæan in the Northwest, by R. D. Irving.

‡ Geol. Wis., vol. iii, p. 105.

§ The accompanying map is taken from the article before referred to. For discussion of stratigraphical relations and geographical distribution of the Penokee-Gogebic Series, see the same article, also Geol. Wis., vol. iii, pp. 100-166.

|| The term greywacke is here used in a lithological sense, in accordance with the definition of the term given by Geikie, *Text Book of Geology*, 2d ed., p. 162: "A compact aggregate of rounded or subangular grains of quartz, feldspar, slate, or other minerals, or rocks, cemented by a paste which is usually siliceous, but may be argillaceous, feldspathic, calcareous or anthracitic. Gray, as its name denotes, is its prevailing color; but it passes into brown, brownish purple, and sometimes, where anthracite predominates, into black. The rock is distinguished from ordinary sandstone by its darker hue, its hardness, the variety of its component grains, and above all by the compact cement in which the grains are imbedded."

show biotitic and chloritic greywackes. Continuing westward, the rocks become more and more micaceous, and at Penokee Gap, Wisconsin, they are mostly mica-schists and black mica-slates, although narrow belts of micaceous greywacke are yet found; while the schists at English Lake taken by themselves would probably be considered completely crystalline rocks—as completely crystalline as some mica-schists in the older gneissic formation. These rocks, at present of such widely varying character, microscopic study shows to have been originally in essentially the same condition. All were once, as some are still, completely fragmental rocks composed chiefly of quartz and feldspar, mingled in places with a little clayey matter, perhaps also with a small quantity of fragmental mica and some ferrite. The fragmental feldspar is or was very largely orthoclase, although plagioclase is usually, and in certain localities quite plentifully, found. Measurements of its extinction angles show this plagioclase to be of an acidic character, and it is probably in great part oligoclase. The proportions and magnitudes of the fragments of quartz and feldspar vary in different localities. The quantity of feldspar was apparently considerably greater in the rocks of the western part of the area than in those of the eastern part, i. e., was greater in those rocks which are now mica-schists and mica-slates than in those which have formed the kinds to which the name greywacke is here applied.

As far as the quartzites, greywackes and greywacke-slates are concerned the microscope shows that they reached their present conditions by processes already fully described by Irving and myself.\* Briefly summarized, these processes included: secondary enlargement of the quartz fragments and in a few cases apparently of the feldspar fragments also; the deposition or formation *in situ* of interstitial finely crystallized quartz; and a chloritic replacement of the feldspars, with consequent separation of silica. In general, the processes by which the mica-schists and black slates have reached their present condition are much the same as the above, with the very important difference that the feldspars instead of altering to chlorite have altered to muscovite and biotite—chiefly the latter—with an accompanying separation of silica; † *the result being the production, from a completely fragmental rock, by metasomatic changes only, of a rock which presents every appearance of complete original crystallization, and which would be ordinarily classed as a genuine crystalline schist.*

\* Bulletin U. S. Geol. Survey, No. 8.

† Lehmann in his work on the "Entstehung der altkrystallinischen Schiefergesteine," demonstrates the formation of abundant secondary biotite and other minerals as accompanying metamorphoses by folding. His work does not state, however, exactly how the biotite developed.

It is important here to recall the chemical changes which occur in the alteration of orthoclase and oligoclase to chlorite, muscovite and biotite. The average content of silica of the following minerals is taken from Dana's System of Mineralogy: orthoclase, 65 per cent; oligoclase, 62 per cent; muscovite, 45 per cent; biotite, 40 per cent; chlorite, 25 to 30 per cent. Evidently where the alterations of orthoclase and oligoclase to muscovite, biotite, and chlorite have taken place so extensively as in the rocks under discussion, it is not difficult to explain the presence of the silica which has enlarged the fragments of quartz, replaced those of feldspar, and separated as independent interstitial quartz. One of these alterations is stated by Tschermak \* to occur as follows: "Wenn man die dreifache Formel des Feldspathes  $3(K_2O, Al_2O_3, 6SiO_2)$  mit jener des daraus entstandenen Glimmers  $K_2O, Al_2O_3, 2SiO_2 + 2(H_2O, Al_2O_3, 2SiO_2)$  vergleicht, so ergibt sich, dass von der ursprünglichen Menge  $6SiO_2$  nur  $2SiO_2$  in die neue Verbindung übergehen und  $4SiO_2$  übrig bleiben." In farther speaking of the alteration of orthoclase to muscovite, Tschermak also observes: "Der neu entstandene Muscovit ist öfters auch von Biotit (Magnesiaglimmer) begleitet."

For the iron of the biotite in the rocks under consideration, it is not difficult to account. Pyrite, marcasite and ferrite are quite widely present in these rocks as accessory constituents. Often the relations of the pyrite or marcasite and biotite (folia of the latter surrounding particles of the former) is such as to lead to the supposition that the former minerals have furnished the iron necessary for the transformation from feldspar to biotite. At all events they indicate a quite sufficient supply of iron.

For a part at least of the magnesium of the biotite, it seems that we must look to some source extraneous to the feldspar fragments; i. e., we must regard it as having been supplied by percolating waters. That calcium-bearing and magnesium-bearing waters have been present in these rocks is evident from the occasional presence of secondary calcite and dolomite. The case is the same as that presented by the replacement of feldspar by chlorite, which has commonly taken place in the greywackes of this and other regions in the Lake Superior country. Analyses of three of the biotite-schists gave an average content of MgO of 2.22 per cent, which if entirely contained in the biotite would correspond to a probable proportion of that mineral of from 10 to 20 per cent.

The change from fragmental quartz-feldspar rocks to quartzites and greywackes in this belt having been produced by metasomatic changes, as indicated above, there is a strong presumption that the mica-schists and slates are of the same origin;

\* Lehrbuch der Mineralogie, Zweite Auflage, page 462.

a presumption which is rendered stronger by the fact that in passing from east to west along the belt the biotite first appears in minute quantities, becomes gradually more plentiful until it equals in quantity the chlorite and farther west grows still more abundant, until, at English Lake, little or no chlorite is found and we have a typical mica-schist.

In the detailed descriptions below given of these micaceous rocks, I begin with one not greatly different from its original condition, and proceed toward those which are more and more completely crystalline. There is a considerable interval as to degree of alteration between each description and the succeeding one, but the gaps cannot be made shorter without unduly extending this paper. In a study of all the sections of the group, some sixty in number, these intervals are closed.

(1.) *Muscovitic and Biotitic Greywacke.*—Macroscopically this rock is gray-colored, medium-grained, and massive. It breaks with a conchoidal fracture. Under the microscope large fragments of quartz and feldspar, with the alteration-products and replacement products of the latter, compose the rock. The grains of quartz are enlarged and consequently minutely angular, although still retaining their general roundish forms. Much of the feldspar is quite fresh, many individuals showing no alteration further than a slight kaolinization. Other feldspar fragments, however, include each many grains of quartz, or a single large, reticulating quartz individual and numerous flakes of muscovite and biotite. Here the quartz, muscovite and biotite are plainly replacements and alteration-products of the feldspar. In some cases this alteration has proceeded so far as to leave but irregular, partly replaced and altered cores of feldspar which are entirely surrounded with the secondary quartz, muscovite and biotite. Again, in other places, the original rounded outlines of the feldspars are distinct, the replacements and alterations having occurred in spots through the grains. The finer-grained parts of the rock are composed of quartz, a portion of which is elastic; of feldspar—the proportion being smaller than in the coarser parts; and of biotite and muscovite. The mica is here clearly also, to a very large extent, secondary to feldspar, while there is little doubt that the small remaining fraction of the mica is of the same origin. Scattered through the finer portions of the section are numerous small particles of a black substance which is taken to be partly altered pyrite or marcasite, and perhaps also partly carbonaceous material.

(2.) *Biotitic Greywacke.*—Macroscopically this rock differs from (1) only in being of a darker gray color; and under the microscope also it is much the same except that the micaceous alteration of the feldspars has been carried farther. Well rounded fragments of quartz and feldspar with the secondary

products of the latter compose most of the section. A few of the grains of quartz are finely complex, and nearly all of them are enlarged by renewed growths. The alteration of feldspar to biotite is nicely shown. The freshest of the feldspar grains are surrounded by and more or less deeply penetrated by secondary biotite. These grains yet retain their well-rounded forms. However, in many cases, the original outlines of the grains of feldspar are lost. Often the entire surfaces of the feldspars include very numerous particles of the biotite, there remaining through such areas, here and there, little spots of feldspar which act as a unit in each area. With a low power such areas appear to be roundish aggregates of biotite. It is only with a higher power that the remaining feldspar and its true relations to the biotite are discovered. The rather sparse matrix of the rock does not differ materially from the matrix of (1).

(3.) *Biotite-schist*.—Macroscopically this rock is mottled dark-gray and black, fine-grained, and quite massive, showing roundish cleavage-areas. Under the microscope the cleavage-areas seen macroscopically are found to be well-rounded, partly-altered feldspars. These feldspars are set in a ground-mass which consists of intimately mingled grains of quartz and small brown folia of biotite with a considerable quantity of ferrite. The partial decomposition of the feldspar has resulted in the formation of very numerous small folia of biotite and a few larger ones of muscovite. In places also the feldspar is replaced by quartz. In each of the feldspar areas the secondary mica is found most plentifully at or near the exteriors of the grains, although in almost every case the alteration has proceeded to a greater or less degree quite to the center. In the matrix of the rock it is quite impossible to determine what part, if any, of the quartz is fragmental. The biotite of the matrix is in part plainly secondary to feldspar and is precisely like that found in the larger feldspars. The folia are deep brown and very strongly dichroic, and therefore probably bear a large percentage of iron. The feldspar plainly shows this rock to have been fragmental, and the alteration of feldspar to both biotite and muscovite upon a large scale is most beautifully shown. The large quantity of dark brown and black ferrite has doubtless furnished the iron required for the formation of the biotite. The peculiar spotted appearance of the section, viewed without the microscope, gives a clear idea, when taken in connection with its appearance under the microscope, of the processes by which the rock reached its present condition.

(4.) *Muscovitic Biotite-Schist*.—Macroscopically this rock is very fine-grained, grayish and quartzose, with very fine mica flakes visible. Under the microscope the thin section shows a fine grained ground-mass of quartz and feldspar in which are

abundant muscovite and biotite. Many of the large quartz grains include numerous folia of mica. The feldspar areas include quartz and both muscovite and biotite. This section, by itself, if not examined closely would be taken to be of a completely crystalline mica-schist in which the interlocking and mutual inclusions of the different minerals are of the most intricate kind. But, like the other mica-schists of the Penokee series, it is an ordinary clastic rock in which the metasomatic changes have gone very far. The large areas of quartz, including folia of mica, are in the places of feldspar fragments. As the feldspar has altered to mica the excess of silica has separated as quartz. Frequently the alteration of a single feldspar has resulted in the formation of a single ramifying individual of quartz, with several or many included folia of mica, mingled with which are detached remnants of the feldspar. In other cases the decomposition of a feldspar has resulted in the formation of many grains of quartz as well as numerous folia of mica. In yet other cases the feldspar areas have not altered to such extent as described above. In almost every case the rounded exteriors of the clastic grains are lost, but irregular areas of considerable size often remain considerable, which include but few folia of biotite or little replacing quartz, or both.

(5.) *Muscovitic Biotite-Schist*.—Macroscopically this rock is fine-grained to aphanitic, and dark grayish black, with rather distinct lamination. Under the microscope the sections show a rather fine-grained, apparently completely crystalline, typical mica schist. The ground-mass consists chiefly of quartz, mingled with which is feldspar, both orthoclase and plagioclase. Biotite in rather small, well-defined folia of quite uniform size is very plentiful. Muscovite is much less abundant. That all the mica is a secondary product cannot be proved from the sections from this locality taken by themselves. A portion of it is, however, certainly of this nature. Many grains of feldspar are partly surrounded and cut by folia of mica, while many of the larger particles of feldspar contain throughout their areas numerous folia of mica which in magnitude and appearance are exactly like the mass of the biotite in the rock. Quite numerous black grains and crystals of a mineral which is taken to be pyrite are seen, which are included alike in the quartz, feldspar and mica.

The rocks above described thus furnish us with a graded series, from the slightly altered greywackes to the crystalline mica-schists. There are many similar mica-schists in other parts of the Lake Superior region which there is good reason to think have had a similar origin; but those wide-spread mica-schists associated with the older gneisses are not now referred to.

The micaceous alteration of feldspars has also been very important in the production of various black mica-slates of the Penokee series. Macroscopically these slates are all exceedingly fine-grained and finely laminated, cleaving readily along the planes of lamination. In color they vary from dark gray to black. A lens shows many of them to contain numerous small particles of pyrite. Very numerous roundish black areas are contained in the fine-grained, gray material in many of the specimens. These areas in some cases show distinct cleavage surfaces and are taken to be large fragmental particles. In other cases they are dull and break without giving cleavage surfaces, while in yet other specimens these darker spots are not found at all.

Under the microscope the rocks which have the mottled appearance described above consist of two parts, a finely crystalline matrix, and coarse, well rounded fragmental feldspars, which are always altered to a greater or less extent. This alteration is to biotite and quartz, many small folia of biotite and grains of quartz always being found in a single feldspar individual. Every gradation of this change is seen, from grains of feldspar which contain but little biotite and quartz to those in which the remaining feldspar is just sufficient in quantity to enable one to perceive that the detached particles are parts of a common individual. Doubtless also the alteration to biotite and quartz has often been carried out completely. Accompanying the biotite thus secondary to the feldspar, is much black, opaque, partly-altered pyrite in minute particles. The black, roundish spots seen macroscopically are evidently the partly-altered feldspar fragments. The degree of this alteration as determined by microscopic study corresponds exactly with the appearance of the rock as seen in the various hand-specimens. In the specimens in which the feldspar areas are well outlined and show clearly marked cleavage surfaces, the biotitic and quartzose alteration has taken place to but a small extent. In the specimens in which the feldspars are obscurely outlined and which lack cleavage the alteration has extended very far. The matrices of these rocks and the sections of those not containing large grains of feldspar are composed of intimately mingled quartz, feldspar, biotite and pyrite, with perhaps a little organic matter.\* A portion of the quartz is certainly fragmental, as is evidenced by a secondary enlargement. The biotite is all believed to be due to the alteration of feldspar, much of it certainly being of this nature. The matrices of the different sections vary in coarseness and in the relative proportions of the various mineral constituents, but are alike in all essential points.

\* Geol. Wis., vol. iii, p. 136.

