ART. IV.—*On the Paramorphic Origin of the Hornblende of the Crystalline Rocks of the Northwestern States*; by R. D. IRVING.

THE crystalline rocks of the northwestern States belong to the Archæan formations and to the Keweenaw or Copper-Bearing Series. The hornblende-bearing kinds are distributed among the three general classes of (1) crystalline schists, (2) granites and syenites, and (3) greenstones—the last term being used to cover all the basic massive rocks.

Crystalline schists.—The hornblende-bearing crystalline schists are hornblende-gneisses and hornblende-schists. The hornblende-gneisses are much more abundant in this region than true mica-gneisses, although the latter not unfrequently occur. Transition forms, in which hornblende and mica are associated in all proportions, are more common, however, than kinds without any hornblende. The hornblende-schists are merely more highly lamellar and fine grained varieties than usual of the gneisses into which they grade. These schists present a groundmass of fine particles of quartz, often with some orthoclase, carrying relatively large and generally predominant hornblende grains. Transition forms between the hornblende-schists and true mica-schists (biotite-schists) also occur.

During the last three years I have examined a large number of sections of these hornblendic gneisses and schists, coming from the Flambeau* River region in northwestern Wisconsin, from the upper Wisconsin Valley† in central Wisconsin, from the Menominee River region in northeastern Wisconsin, from the Penokee region‡ of northern Wisconsin, and from the Mississippi Valley in Minnesota. In the larger number of these sections *augite* occurs, either as a prominent accessory, or even as a dominant chief ingredient. Moreover, as was first shown by Mr. C. R. Vanhise, who did most of the work in the examination of the sections from the Wisconsin Valley, both hornblende-gneisses and hornblende-schists graduate into kinds in which *augite* completely replaces the hornblende. Along the Wisconsin River and several of its tributaries in southern Lincoln and western Marathon counties,§ *augite*-gneisses and *augite*-schists are prominent rocks. Even in the mica-gneisses, whenever hornblende appears as an accessory, *augite* is met with also.¶ The hornblende of all these schists is the more common

* Geology of Wisconsin, iv, p. 617.

† "Crystalline Rocks of the Wisconsin Valley," by R. D. Irving and C. R. Vanhise. Geology of Wisconsin, iv, pp. 627-704.

‡ Geology of Wisconsin, iii, pp. 92-99.

§ Geology of Wisconsin, iv, pp. 692-696, 702-707.

¶ Geology of Wisconsin, iv, pp. 628, 631-635, 640-642.

variety, yielding greenish sections, but it shows all gradations from the fibrous forms generally regarded as characteristic of uralite, to large, non-fibrous, strongly cleaved, and deeply colored crystals.

The first to notice augite in any of the northwestern crystal-line schists was Dr. A. Wichman, who in the third volume of the *Geology of Wisconsin* announces its occurrence, in a variety near to sahlite, in the hornblende-schists of the Huronian of the Menominee and Marquette regions of Wisconsin and Michigan.* He also noted its occurrence in a few sections of gneiss and mica-schist. Kalkowsky, however, had already made the same observation on certain European gneisses and mica-schists.† Shortly after the appearance of Wichman's publications I studied the Flambeau River schists above mentioned and found them to be identical with those described by him from the Menominee region, save that in some sections the augite assumes a greater importance. My suspicions were then aroused that all the hornblende of these rocks might be but a paramorphic product of the augite, and when, somewhat later, I came in conjunction with my assistant Mr. Vanhise to study a suite of specimens representing a large area in the Wisconsin Valley, I was on the outlook for evidence on this point. We soon found my suspicions abundantly confirmed, for not only did we find augite occurring almost universally in the hornblendic gneisses and schists of this region, and even wholly replacing the hornblende, as above stated, but a number of sections were observed in which the augite distinctly occurs as cores to the hornblende, which is at times fibrous like uralite, but oftener is without fibrous character.

Granites and Syenites.‡—The granites of this region are in considerable part merely dependencies of the gneisses, but irregular areas of massive granite, plainly of an eruptive nature, also occur. These are sometimes mica-granites, but are also often hornblendic. Nearly all sections yet studied of the latter kind of granite show augite as well as hornblende, and frequently in the shape of cores to the hornblende, which appears not only of the uralitic and ordinary green varieties, but also in the kind known as basaltic, which yields characteristic dark-brown, very deeply absorptive sections.

A prominent instance of a granite containing hornblende is the coarse-grained rock of Big Bull Falls on the Wisconsin River. The following is quoted from a summary description of the

* *Geology of Wisconsin*, iii, pp. 606, 620, 628, etc.

† *Tschermak's Min. Mittheilungen*, 1875. p. 45.

‡ These terms, as also those applied to the massive rocks below, are used in accordance with the Rosenbusch nomenclature.

microscopic characters of this granite, prepared, after the study of a number of thin sections, by Mr. Vanhise.*

"These rocks are all very much alike in their chief characteristics. The feldspars, which are always a good deal decomposed, are in all cases the dominating constituents. The three species—orthoclase, oligoclase and microcline—are always present, the latter being usually the most abundant one. Apatite is present in all the sections, though varying greatly as to size and number of crystals. It is a constant inclusion in the feldspars, and is also often to be seen in the quartz, diallage and hornblende. The quartz, except in two or three slices, is a subordinate ingredient. Both primary and secondary quartz appear to occur. Apparently primary are the large integral grains filling interstices between the other ingredients; but in some sections a portion of the quartz is arranged within the feldspars in such a way as to suggest its secondary nature or at least its deposition after a certain amount of decomposition had affected the feldspars. The augitic ingredient in most cases is plainly diallage, and all that does not show the characteristic cleavage of diallage is much decomposed. The diallage occurs both independently, and even quite without any associated hornblende in the slice, and also in the shape of cores to uralite or hornblende individuals. It appears probable that all the amphibole is an alteration-product of the diallage. In support of this position are the following facts: The hornblende occurs both as greenish fibrous uralite, enveloping centers of diallage, and also in the shape of ordinary basaltic hornblende without included diallage, and with the characteristic color, cleavage and dichroism. Again, the latter kind of hornblende occurs as a mere border about a diallage center, and from this condition in every stage of replacement up to the complete disappearance of the diallage.† Finally, both uralite and basaltic hornblende are found, not only with a single core of diallage to each crystal, but with several or many spots of the original mineral."

True syenites, that is, massive granular rocks composed of hornblende and orthoclase as chief constituents, seem to be very rare in the Archæan of the northwest. Wichman only has described one or two instances from the Marquette region of Michigan. Among the Keweenawan eruptives, however, there is a peculiar kind of granite-like rock composed chiefly of red feldspars, including a triclinic kind which is apparently near oligoclase, as well as the predominating orthoclase, but in which augite also occurs in subordinate quantity, so that I have else-

* Geol. of Wis., iv, p. 662.

† G. W. Hawes has described and figured a similar relation between augite and basaltic hornblende, in the *Lithology of New Hampshire*, pp. 57, 206; and Plate VII, fig. 1.

where described them under the name of augite-syenite.* In most sections of these rocks quartz is present, and in the more distinctly granite-like kinds may be of a primary nature, but most of it is plainly secondary, or at all events has been deposited after the crystallization and solidification of the rest of the rock. The augite of these rocks is always in very subordinate quantity; it is nearly always very much altered, the more ordinary forms of alteration being to a mass of nearly opaque ferric oxide. In some cases, however, the change has been to a true hornblende or uralite.

Greenstones.—The greenstones of the region in question may be divided as to their mineralogical composition into the four groups of peridotite, gabbro, diabase and diorite; and as to their geological relations, into the three groups of Laurentian,† Huronian and Keweenawan greenstones.

All four of the forms of greenstone mentioned are met with intersecting the older gneisses, much the most common being the diabases. The peridotites, since they never have been found to carry hornblende, do not need to be considered here. Hornblende has, however, been met with in the gabbros and in every case yet studied it is plainly derived from augite or diallage.‡ The diabases include both olivine-free and olivinitic kinds, the sections so far as examined being usually free from hornblende, but whenever this mineral occurs it is always plainly altered augite. The diorites are not common, the only sections thus far examined coming from Rib River in the western part of Marathon county, Wisconsin.§ (N. W. $\frac{1}{4}$, Sec. 26, T. 29, R. 5 E.) These represent a coarse-grained rock which may be seen macroscopically to be composed essentially of dark-green lustrous hornblendes, and large-sized feldspars which often show striations. In a thin section, however, a large number of the hornblendes are seen to contain cores of augite or diallage, often several cores in a single individual.

The greenstones or basic massive rocks of the Huronian have been studied microscopically in the Marquette and Menominee regions by Wichman.|| I have myself studied them in the Penoque region of northern Wisconsin, and in the Thunder Bay, Pigeon River region of the north shore of Lake Superior,

* Third Annual Report of the Director of the U. S. Geological Survey, p. 114; also the "Copper-Bearing Rocks of Lake Superior," vol. v, Monographic series of the publications of the U. S. Geol. Survey. This name is unsatisfactory, since the rock is in the main composed of feldspars, usually more or less corroded by quartz. It grades through semi-porphyrific kinds, which might perhaps be called granitic-porphry, into true quartz-porphry. But I am reluctant to coin a new name.

† The term Laurentian is here used provisionally only to cover those gneisses and schists which seem plainly older than the Huronian.

‡ Geol. of Wis., iv, pp. 701, 710, 711.

§ Geol. of Wis., iv, pp. 698, 699.

|| Geol. of Wis., iii, pp. 618, 621-630.

where they occur on a grand scale in what has been called by Hunt the "Animikie Group." This group has been described by Logan, Bell and others as the lower part of the Copper-bearing series, and by Hunt as much newer than the latter series, but it is plainly, as I have elsewhere tried to show,* the exact equivalent of the Huronian of the Penokee region, and of the south shore of Lake Superior generally. In the Huronian of the Menominee-Marquette region the greenstones include all of the four types above named, but the diabases are by far the most important, occurring not only in dike-form, but also in the shape of inter-bedded flows.† Hornblende occurs in some of these diabases as an unimportant accessory, and although Wichman failed to show its paramorphic origin,‡ in the few sections that I have myself seen this mineral is plainly of a secondary nature. In the diorites of this region, however, Wichman found augite crystals more or less completely changed to hornblende.§ Greenstones are rarer in the Penokee Huronian than in that of the Menominee region, and have as yet been only imperfectly studied microscopically, most of the work upon them having been done some years since, before any suspicion of a paramorphic origin for the hornblende was entertained. So far as later investigations have progressed the indications are that the hornblende of these rocks also is secondary.

The greenstones of the Animikie group are displayed in a magnificent way along the shores of Thunder Bay, and inland to the west and north from there, occurring both in dikes and in great interbedded sheets. These greenstones include several varieties of gabbro and several of diabase, which I have elsewhere described.|| Hornblende is not often met with in sections of these rocks, but when occurring seems always to be beyond question secondary.

The Keweenaw greenstones include several varieties of each gabbro and diabase. I have described them in detail elsewhere.¶ Hornblende on the whole is unusual in any of these rocks, but when it occurs it is almost invariably uralite; that is, plainly secondary to augite. In the sections of one unusual variety of gabbro met with in Ashland County, Wisconsin, which I have described as hornblende-gabbro,** in place of the ordinary uralite, or in addition to it, there occurs a deep

* Third Annual Report of the Director of the U. S. Geol. Survey, pp. 159-163. Also "Copper-Bearing Rocks of Lake Superior," pp. 367-386.

† These interbedded diabases of the Huronian have been described by Brooks and others as metamorphic, but there can I think be no question as to their eruptive origin.

‡ Geol. of Wis., iv, p. 607.

§ Geol. of Wis., iii, p. 628.

|| Third Annual Report of the Director of the U. S. Geological Survey, pp. 157-163; also, more completely in my memoir on the Copper-Bearing Rocks of Lake Superior.

¶ op. cit.

** Copper-Bearing Rocks of Lake Superior, pp. 56-58.

brown intensely absorptive basaltic hornblende. Pumpelly first described this rock in the third volume of the *Geology of Wisconsin*, under the name of augite-diorite,* this name being given because he regarded the hornblende as primary and the rock as intermediate between diabase and diorite. In the same volume I suggested that the hornblende was secondary and that the rock was merely an altered gabbro.† This opinion I find sustained by a re-examination of Pumpelly's sections, and by the study of a number of new sections. The hornblende is found in every stage of growth from an augite crystal, with a slight border of hornblende, to a completed crystal without trace of augite.

Thus, after an examination of about a thousand thin sections representing the crystalline schists, acid eruptives and basic eruptives of a region some four hundred miles in length by 300 in width, and of three distinct geological systems, I have found no hornblende that is not either clearly, or very probably, secondary to augite.

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