

PARAGENESIS OF CUMMINGTONITE AND HORNBLLENDE FROM MUURUVESI, FINLAND

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ABSTRACT

Cummingtonite and hornblende occurring in homoaxial intergrowth in an amphibole-bytownite rock were separated and analyzed. Although the separation was not complete, the result is sufficient to show some essential features in the composition of both amphiboles as regards their different ratio $[Mg]:[Mg+Fe]=mg$; in the cummingtonite $mg=0.69$, in the hornblende $mg=0.78$. The variation interval of cummingtonite overlaps that of anthophyllite and, contrary to the statements of earlier investigators, the (Fe, Mg)-amphibole may be dimorphic. The nature of the polymorphism in this and related cases is discussed.

Every student of crystalline rocks probably has seen under the microscope a colorless amphibole in association with common green hornblende, occurring either as irregular spots or grown on the sides or at the ends of the hornblende prisms. The two amphiboles are always in homoaxial intergrowth, i.e. they have axes b and c and the face (010) in common. From analyses of the rocks and of the unhomogeneous amphiboles the colorless amphibole has been concluded to be cummingtonite, and its positive optical character is regarded an optical distinctive feature, though this is not always a reliable criterion. Sometimes anthophyllite occurs instead of or with cummingtonite. In other cases tremolite occurs in a similar manner, but cummingtonite is no doubt most common, being, in the amphibolite facies, the counterpart of hypersthene of the pyroxene-bearing mineral facies.

In his investigation of the gap in the solid solution series between anthophyllite-gedrite and cummingtonite on the one hand, and cummingtonite-grünerite and tremolite-actinolite on the other, Sundius (1933) gives analyses of anthophyllite and tremolite from Edwards, N.Y., in which these two minerals occur together. This, so far as known to me, is the only case where separation of lime-poor amphibole from lime-rich amphibole has been carried out. The separation of cummingtonite from hornblende never seems to have succeeded, although the assemblage of these two amphiboles is of wide occurrence in rocks. During my investigation of the Orijärvi area (Eskola 1914, p. 221), I tried to separate cummingtonite from the green hornblende present in cummingtonite amphibolite at the Orijärvi Mine, but this attempt resulted in failure due to their almost identical density.

Since 1914 I have been looking for more suitable material to separate cummingtonite and hornblende from one and the same rock, but invariably the very fine intergrowth did not encourage renewed attempts.

Finally, a rock was found that seemed worth attempting. It is a hornblende-bytownite rock from east of Jouhtenlampi, Murtolahti, parish of Muuruvesi, district of Kuopio, Finland, described by Wilkman (1938). The rock is millimeter-grained, aplite-like, consisting of tabular crystals of bytownite the interstices of which are filled with unhomogeneous, brown and colorless amphibole with some biotite and iron ore. It is said by Wilkman to form dikes in gneiss.

Wilkman had the rock analyzed by Dr. L. Lokka with the result given in Table 1, 1. Mr. E Helkavaara made another analysis of the rock

TABLE 1. AMPHIBOLE-BYTOWNITE ROCK

	1	2	Average	Mol. numb.	Norm	
SiO ₂	51.18	51.35	51.27	8536	Q	0.72
TiO ₂	0.58	0.47	0.53	66	Or	2.78
Al ₂ O ₃	17.48	17.62	17.55	1722	Ab	15.31
Fe ₂ O ₃	0.23	0.19	0.21	13	An	38.28
FeO	8.62	8.01	8.32	1158		57.09
MnO	0.09	0.01	0.05	7		
MgO	9.12	9.64	9.38	2326	Di 5.67	Wo 2.91
CaO	9.03	9.22	9.13	1628		En 1.78
Na ₂ O	1.93	1.68	1.81	292		Fs 0.98
K ₂ O	0.57	0.42	0.50	53	Hyp 33.89	En 22.16
P ₂ O ₅	0.03	—	0.03	2		Fs 11.73
S	0.31	0.43	0.37	115	Il	1.00
H ₃ O ⁺	0.79	0.76	0.78	433	Mt	0.30
H ₂ O ⁻	0.08	0.08	0.08	—	Pyrrh	1.03
						41.89
<i>d</i>	100.04	99.88 2.908	100.01			98.98

(2). He also separated and analyzed the amphiboles under my supervision. The rock analysis was made in order to check Mr. Helkavaara's mineral analyses by comparing his rock analysis with another analysis of the same rock made by an expert analyst like Dr. Lokka. The agreement is satisfactory in view of the fact that the two analyses were not made on the same sample.

The norm presents a close approximation to the mode of a norite of the same bulk composition as that of the analyzed rock in which amphiboles take the place of the pyroxenes and, besides some biotite, contain the (Fe, Mg)O in the rock. The composition of the normative plagioclase Ab_{29.8}. In the actual plagioclase were determined $\gamma=1.573$; $\alpha=1.564$,

corresponding to the composition $Ab_{26}An_{74}$. The extinction angle in sections \perp PM is 39° , corresponding to $Ab_{28}An_{72}$.

The intergrowth of the brown and colorless amphiboles is irregular, and the boundaries between them are gradual. Thus it is apparent from thin sections that the amphiboles are unhomogeneous. Decidedly more than a half of the amphibole is cummingtonite, but due to irregular distribution the exact proportions could not be determined. From estimates

TABLE 2. CUMMINGTONITE AND HORNBLLENDE ANALYSES

	Cummingtonite			Hornblende		
	3	3b	3b Mol. numb.	4	4b	4b Mol. numb.
SiO ₂	54.55	54.97	9153	52.41	51.59	8590
TiO ₂	0.20	0.14	18	0.58	0.72	90
Al ₂ O ₃	2.91	2.38	233	6.55	7.95	780
Fe ₂ O ₃	0.19	0.06	4	1.14	1.51	95
FeO	16.37	17.25	2401	10.61	8.41	1170
MnO	0.02	0.02	3	0.01	0.01	1
MgO	21.57	22.11	5484	18.20	16.92	4196
CaO	2.77	1.84	328	8.67	10.95	1953
Na ₂ O	0.33	0.30	48	0.50	0.53	85
K ₂ O	0.13	0.10	11	0.37	0.47	50
H ₂ O+	0.80	0.80	444	0.85	0.87	483
H ₂ O-	0.03	0.03		0.04	0.04	
<i>d</i>	99.87 3.175	100.00		99.93 3.110	99.97	

made I would say that the cummingtonite constitutes between 65 and 75 per cent of the amphiboles.

For the separation of the two amphiboles, first the bytownite was removed by means of bromoform ($d = 2.825$) in which it floated. Then the ore and other possible heavy minerals were removed with Clerici solution of $d = 3.5$, then the solution was slowly diluted to $d = 3.180$. At this density part of the colorless amphibole began to sink, and a considerable portion of it had sunk at $d = 3.171$. The fraction $d = 3.180-3.171$ was submitted to renewed separation at intervals $3.180-3.178$, $3.176-3.174-3.172$. The fractions between $3.178-3.176$ and $3.176-3.174$ were united and separated again. The main part sank between 3.177 and 3.174 . This was taken as the cummingtonite fraction (analysis 3, Table 2).

At continued dilution of the solution a considerable portion of the hornblende was separated between the densities 3.119 and 3.095 . The separation was repeated successively at $d = 3.125-3.120-3.118-3.114$

—3.112—3.110—3.098—3.095—3.090. Microscopic examination showed that the fractions between 3.114 and 3.098 were richest in hornblende. These fractions were united and separated anew. The fraction 3.111—3.110 was collected and washed for analysis as the hornblende fraction (analysis 4).

The cummingtonite is colorless in thin section. The hornblende shows for γ greyish brown, β pale brown, and α yellowish, almost colorless. The angle $\gamma \wedge c$ in both is 20° – 22° , and the dispersion $r < v$. The birefringence is just notably higher in cummingtonite, as appears from the interference colors in homoaxially intergrown crystals. The axial angle in both amphiboles is very large. The hornblende is decidedly negative, whereas $2V$ in the cummingtonite is so nearly 90° that it is hard to tell whether the mineral is negative or positive. Most determinations, however, indicated a positive character.

The separation was incomplete. According to a counting of the grains under the microscope the hornblende fraction would contain 21 per cent cummingtonite, but as the colored grains are more conspicuous than the colorless ones, the amount is probably greater, and was taken as 25 per cent. The cummingtonite was considerably purer, though grains of hornblende could be seen in it. Many of the colorless grains were speckled with pigment-like iron ore. The amount of hornblende in the cummingtonite portion was taken as 10 per cent. The analyses thus do not give exactly the compositions of these amphiboles. As, however, the materials contained only two amphiboles, it is possible to compute the composition of both kinds with closer approximation by stepwise eliminating the one and the other amphibole from the analytical figures, as described below.

From the original analysis of hornblende (Table 2, 4) 25 per cent cummingtonite (analysis 3) were subtracted. Thereafter 10 per cent of the residual figures, recalculated to 100 per cent and called analysis 4a (not quoted), were subtracted from analysis 3 and the residue was recalculated to 100 per cent (3b). This is the corrected analysis of the cummingtonite. Likewise 25 per cent of the percentage figures of 3b were subtracted from analysis 4. The residue, recalculated to 100 per cent, is quoted under 4b as the corrected analysis of the hornblende. The elimination could be continued in the same way, but as a trial showed that 3c, 4c, etc. would be practically identical with 3b, 4b, the calculation was not carried farther.

As may be seen from the molecular numbers, the figures under 3b and 4b agree fairly well with the Warren formulas for cummingtonite and hornblende, excepting the percentages of H_2O which are too low. Of course these figures can not be used for calculation of the amphibole formulas, as the factors 0.25 and 0.1 were based upon crude estimates only. Moreover, none of the two amphiboles was homogeneous, as ap-

pears from the facts that the intensity of the brown color in the hornblende varied, also in different parts of a grain, and that the density of the cummingtonite partly overlapped that of the hornblende.

It might be possible to achieve a better separation of the two amphiboles, e.g. by means of a magnetic separator and centrifuge. The analyses here published, however, give for the present purpose enough information as to the distribution of elements in conjugated lime-rich and lime-poor amphiboles. In the cummingtonite $[Mg]:[Mg+Fe]=mg=0.69$, in the hornblende $mg=0.78$. The hornblende, moreover, has taken up much more TiO_2 , Al_2O_3 , Fe_2O_3 , Na_2O and K_2O in its structure, whereas the percentage of MnO is small in both. Furthermore the cummingtonite contains some Al_2O_3 and CaO .

Sundius (1933) claims that cummingtonite and anthophyllite represent different parts of the solid solution series between Fe- and Mg-amphiboles, and that a gap of a few per cent exists in the series from the ratio 60 per cent Mg-silicate upwards, the anthophyllite containing more Mg-silicate and the cummingtonite more Fe-silicate. The gedrites, however, may be richer in Fe-silicate, up to $c:a$ 87 per cent, but instead they contain considerable amounts of alumina and ferric oxide. Sundius concludes that a content of Al_2O_3 and Fe_2O_3 of over 6 or 9 mol. per cent changes the monoclinic amphibole into the rhombic modification.

Rabbitt (1948) proposes, without stating the reason, that the name gedrite should be dropped and classifying the aluminous varieties with the anthophyllites, he extends the field of orthorhombic amphiboles up to ca. 75 mol. per cent Fe-silicate. On the Mg-silicate side he draws the boundary of the cummingtonite field at the same point as Sundius, though he remarks that the cummingtonite field may possibly be extended towards the Mg-corner on account of the cummingtonite from Sutherland, described by Collins (1942). It may be noted that the latter amphibole, in which $mg=0.68$, contains 5.02 per cent Al_2O_3 and therefore should not be given as much consideration as normal cummingtonites which are much poorer in alumina.

The cummingtonite from Muuruvesi is conclusive, showing $mg=0.69$ and less than 2.91 per cent Al_2O_3 . This is the most important result of the present study. It is not the only example of such amphiboles known so far. In my Orijärvi work (Eskola 1914) I gave an analysis of an amphibole from cummingtonite amphibolite at the Julin Shaft, Orijärvi, with 30 per cent hornblende, showing $mg=0.68$, well above the solid solution limit according to Sundius.

We may state, therefore, that the fields of variation in the composition of cummingtonite and anthophyllite overlap at least within a range between the mg -values 69 and 60. This means that among the monoclinic and orthorhombic ferromagnesian amphiboles there exist examples

exactly identical in composition. Therefore, Sundius' claim that cummingtonite and anthophyllite never present the relation of dimorphism, has to be modified. The same is the case with Rabbitt's conclusion that the anthophyllite and the cummingtonite series are not isodimorphous.

In some cases anthophyllite (or gedrite) and cummingtonite, when occurring together, are very different in composition. Such was the case in the garnet-gedrite-cummingtonite amphibolite from Isopää, Kalvola, Finland (Eskola 1936). In other cases, however, the monoclinic and rhombic amphiboles, in all probability, are identical in composition. This is especially the case when both are intergrown in the manner of laths twinned on {100}, as in many rocks from the Orijärvi area (Eskola 1914). A photomicrograph is in that memoir reproduced as plate V). No difference in refringence nor any other property can be detected except those dependent upon the different symmetry, the monoclinic laths showing oblique and the rhombic ones straight extinction. In this case, therefore, the dimorphism of the (Fe, Mg)-amphiboles would seem to be as close as that of the potash feldspar, with orthoclase and microcline, which seem to be identical in composition and all other respects except geometric symmetry. If Sundius' statement were right, cummingtonite and anthophyllite in such twin-like intergrowths would have different mg-values and different densities, so they could be separated one from the other. This will be worth an attempt!

I have (1936, p. 483) characterized the dimorphism in the (Fe, Mg)-amphiboles, supposing an identical composition for cummingtonite and anthophyllite, in the following words:

"This kind of intergrowth, so extraordinarily similar to the twinning of the monoclinic amphibole, really would suggest a picture of their crystal structure somewhat like the following: Compare the silicon-oxygen bands of the amphibole with a group of soldiers standing in parallel rows. So long as all the rows are looking in the same direction they represent the monoclinic modification, but if every second row be commanded right about turn they will form an orthorhombic grouping. This would be equivalent to polysymmetry."

In the results of *x*-ray investigation of the structures concerned I cannot see anything that would materially contradict this rough model.

In most assemblages of anthophyllite and cummingtonite, however, these undoubtedly are different in composition. The differences are controlled by definite rules, the cummingtonite being especially richer in Ca and Fe and the anthophyllite in (Al, Fe)³⁺ and Mg, while an identical composition is also possible. In other words, the diadochy (Strunz), or the ability of mutual replacement of the cations in both forms is different. The question is, whether the degree of diadochy of the cations is merely influenced by the coordination which obviously changes when two monoclinic unit cells turn over into one rhombic by doubling (Warren and Modell 1930). This apparently may be the case, as the lattice-energy

thereby must change. Thus we may understand the relations in many such groups of crystal species in which two isomorphous series stand more or less strictly in an isodimorphic relation one to the other, and the vectorial properties (e.g. the optical ones) of the more symmetric modification can be derived from those of the less symmetric modification by means of the well-known Mallard equations, starting from the assumption that the one form represents submicroscopic polysynthetic twins of the other form. Further examples of such pairs of series are microcline and orthoclase, clinoenstatite and enstatite, clinozoisite and zoisite. The degree of isodimorphism is, of course, most perfect in such cases in which little or no isomorphous replacement of the cations takes place, as in the feldspars. Every mineralogist will at once see the different behavior concerning diadochy in the series mentioned.

Returning to the main subject of this paper it seems apparent from general petrographic experience that it is mostly cummingtonite and not anthophyllite that occurs in paragenesis with hornblende. Why? A natural explanation is that the monoclinic lattice of hornblende can only induce the crystallization of monoclinic (Fe, Mg)-amphibole. In its composition the latter may perhaps always be somewhat richer in iron than the hornblende, as we found in the present case, but it will vary according to the mg-ratio in the rock. It will be useful to have cummingtonite and hornblende separated and analyzed from many different rocks in which they occur together. At the same time it will be advisable to separate as many different fractions of both mineral species as possible. In this way only will it be possible to establish the succession of different members of the amphibole group, the variations of which no doubt will be very sensitive indicators of the conditions of origin and the laws of the metamorphic crystallization of the rocks.

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