COMPOSITIONAL GRADIENT IN INTERSTITIAL HORNBLENDE FROM A NORWEGIAN GARNET WEBSTERITE

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Hornblende formed at the grain boundaries between pyrope, diopside, and enstatite of a Norwegian garnet websterite exhibits concentration gradient. The pattern of the concentration gradient is explained by the material flow through the interstitial hornblende, by which local equilibrium is reached among hornblende and anhydrous minerals.

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The texture and the genesis of symplectite and its conversion to hornblende in Norwegian eclogitic rocks have been discussed by several authors, notably Eskola (1921), Wikström (1970), and Mysen (1972). During the examination of the chemistry of a garnet websterite from Norway, we noticed a remarkable compositional gradient within interstitial hornblende formed between anhydrous minerals. The chemical features of the interstitial hornblende will be described below together with a discussion on its genesis.

Petrography

The sample studied is a garnet websterite from Norway. It was presented to us by Dr. H. S. Yoder, who gave the following notes on its occurrence: 'Eclogite collected by Eskola on a farm at Lien, Almklovdalen, Sunnmøre, Norway'. Eskola (1921) referred to an eclogite collected near a farm at Lien as being enclosed in dunite and mentioned that bimineralic eclogite passes into garnet-diopside-enstatite rock. The rock consists essentially of pyrope, diopside, and enstatite with subordinate amounts of rutile, sphene, and hornblende. Wet chemical analyses of pyrope and diopside are shown in Table 1, and microprobe analysis of enstatite in Table 2. The pyrope, diopside, and enstatite are coarse-grained and the interstices between them are filled by hornblende. The anhydrous minerals are stained and show wavy extinction, but the hornblende does not. The texture of the rock is sketched in Fig. 1. The hornblende is pale green in colour, forming an aggregate of small grains. Symplectite does not occur and this may be due to the paucity of the jadeite component in the diopside (Wikström 1971).

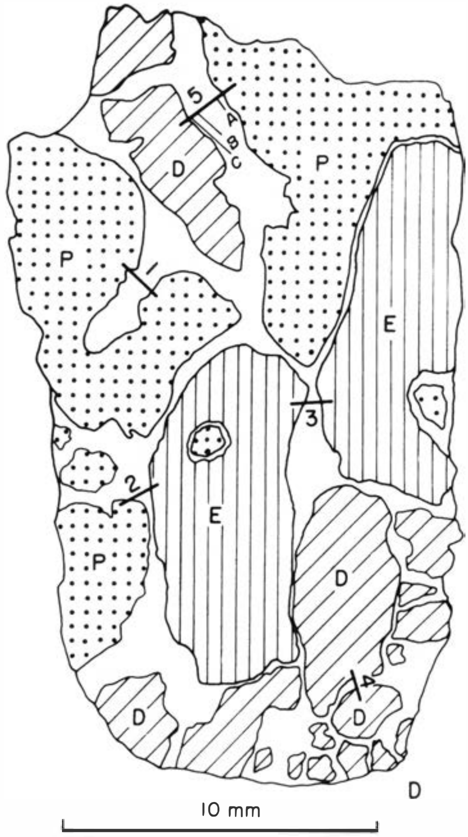

Fig. 1. A diagram of the thin section. The numbered lines shows the paths of electron microprobe analysis. P: pyrope, D: diopside, E: enstatite.

The hornblende sometimes contains minute acicular lamellae, which have lower refractive indices than the hornblende and are arranged parallel to the crystallographic c-axis. Rounded minute grains, probably garnet, are sometimes observed in the hornblende. Generally, hornblende is free from inclusions. Anhydrous minerals are generally clear except along the cracks. The rims of the diopside are sometimes clouded by minute unidentified minerals. For the anhydrous minerals, distinct zonal structure in regard to Fe and Mn has not been detected either by activation autoradiography (Banno et al. 1970) or by the electron-probe microanalyser.

The compositional profiles of hornblende between various pairs of anhydrous minerals are shown in Fig. 2 – the numbers show the paths described in Fig. 1. The composition gradient within hornblende is most clearly seen in Al_2O_3 and SiO_2, but is almost absent for CaO. For hornblende developed between pyrope and diopside and showing a clear compositional gradient, the variations of FeO and MgO are also shown. Hornblende was analysed on the three spots, A, B, and C, on path 5 by electron-probe microanalyser, Hitachi model XMA 5A, using natural kaersutite as

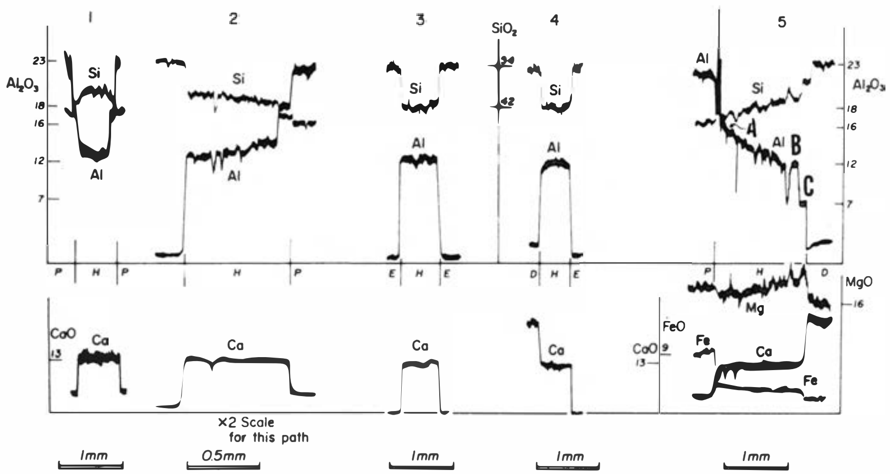

Fig. 2. Composition profiles along the paths shown in Fig. 1. P: pyrope, D: diopside, E: enstatite, H: hornblende.

standard with 15Kv acceleration voltage and 0.03 micro ampere specimen current with the results shown in Table 2. The concentration scale shown in Fig. 2 must be taken as an approximate measure.

Discussion

Hornblende formation clearly postdated that of the anhydrous minerals and was accompanied by the introduction of water from the outside of the system. Judging from a fairly high Na_2O in the hornblende and low Na_2O in the diopside (2.7 and 1.2 wt. %, respectively), Na_2O may also have been

Table 1. Wet chemical analyses of pyrope and diopside.

	Pyrope	Diopside
SiO_2	40.98	54.08
TiO_2	0.05	0.08
Al_2O_3	22.97	2.72
Fe_2O_3	3.84	0.85
FeO	6.09	0.90
MnO	0.49	0.04
MgO	19.91	17.70
CaO	4.88	21.79
Na_2O	0.05	1.23
K_2O	<0.03	0.03
Cr_2O_3	1.30	0.70
H_2O+	0.0	0.38
H_2O-	0.00	0.08
Total	100.59	100.58

Analyst H. Haramura.

Table 2. Electron microprobe analysis of enstatite and hornblende.

	Enstatite	Hornblende A	Hornblende B	Hornblende C	"Bulk"***
SiO_2	58.1	42.8	46.5	50.0	48.6
TiO_2	0.03	0.2	0.2	0.2	
Al_2O_3	0.94	16.6	12.0	7.1	11.6
FeO*	4.5	3.8	2.3	2.4	6.5
MnO	0.09	0.10	0.10	0.10	
MgO	36.8	18.6	22.0	22.0	20.6
CaO	0.13	11.9	11.5	12.7	12.0
Na_2O	0.0	2.8	2.7	2.7	
Cr_2O_3	0.27	1.4	1.3	0.6	
Total	100.86	98.2**	98.6**	97.8**	

* Total Fe as FeO
** Water-free total
*** Mixture of 45 % pyrope 45 % diopside and 10 % enstatite.

supplied from outside the system. As for other components, it is hard to decide if metasomatism was necessary to form hornblende. Wikström (1970) and Lappin (1974) also mentioned that Na_2O was mobile during the symplectite formation.

From Fig. 2, it is seen that the most common Al_2O_3 content of hornblende is 12 % and that this value is close to the Al_2O_3 content of the bulk of the rock (Table 2). The presence of a minimum (or maximum) in the section normal to the hornblende area can be explained by assuming a material flow in the midst of the hornblende area. We will construct a two-stage model to explain this. At first when the formation of hornblende started, migration of Al_2O_3 was very limited because of its very low diffusion coefficient in pore solution or in hornblende. At this stage, hornblende between two pyrope grains contained 18 wt. % of Al_2O_3 and that between

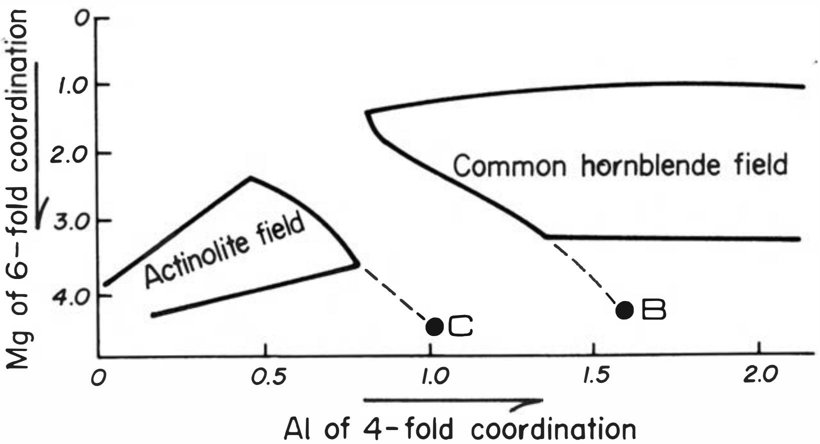

Fig. 3. Compositions of hornblende on both side of the composition gap at pyrope-diopside boundary plotted on a Shido's diagram.

two pyroxene grains 7 - 12 % Al_2O_3, and a concentration gradient was set up between them. We assume that water and Na_2O migrated freely within the rock. As local equilibrium was maintained throughout the whole process, lateral migration of Al_2O_3 can take place only at the middle of the hornblende area. With time, the middle of the hornblende area tended to have 12 % of Al_2O_3, which is the average Al_2O_3 content of the host rock (Table 2). In this way, material transfer maintaining local equilibrium can explain the formation of the compositional profiles shown in Fig. 2. It is also inferred that the hornblende formation took place at a time when the pyrope and pyroxenes were not in mutual equilibrium, because otherwise pyrope and pyroxenes should have coexisted with homogeneous hornblende. Addition of water to the eclogitic assemblage alone cannot form heterogeneous hornblende.

Hornblende is chemically heterogeneous and its nature may be best described in terms of approximate wt. % of Al_2O_3. The area of hornblende in Fig. 1 is actually composed of many small grains, measuring about 0.01 mm. It was not possible to determine if each hornblende grain is chemically homogeneous or not, but an overall chemical gradient is conspicuous. Apart from a few discontinuities, which will be discussed later, the Al_2O_3 content varies continuously. Hornblende in contact with the anhydrous minerals has a unique Al_2O_3 content depending upon the species of the latter. Thus, hornblende in contact with pyrope always has 16 to 18 wt. % of Al_2O_3 and that with enstatite 12 % Al_2O_3. The Al_2O_3 content at the contact with diopside is 12 % when the latter has 2.0 % Al_2O_3 and it is 7 % when the latter has 1.3 % Al_2O_3. In the latter case, where the margin of the diopside has 1.3 % Al_2O_3, the main part of the diopside still contains 2 % Al_2O_3, thereby producing a slight concentration gradient of Al_2O_3 in the diopside, too. These observations show that local equilibrium is reached in the hornblende and diopside as well as across the interfaces between hornblende and anhydrous minerals. Therefore, when hornblende is formed between pyrope and diopside, the hornblende has to maintain a concentration gradient of Al_2O_3 from 16 - 18 % at the contact with pyrope, to 7 % at that with diopside. In return, the presence of such a gradient shows that Al_2O_3 of hornblende was supplied from garnet and flowed towards diopside. However, hornblendes formed between two pyropes and between two pyroxenes have minimum and maximum Al_2O_3, respectively, at the middle of the hornblende area. The presence of such a minimum (or maximum) cannot be explained by local equilibrium alone.

There is another interesting feature worthy of mention in the composition profiles shown in Fig. 2. This is the compositional gaps seen in hornblendes developed between pyrope and diopside, and between two pyrope grains. As is shown in Fig. 3, the compositions of the hornblendes with 12 and 7 wt. % Al_2O_3 (analysis B and C in Table 2) plot on both sides of the miscibility gap between actinolite and hornblende, as suggested by Shido (1958, fig. 8). If this gap represents the actinolite-hornblende gap, the continuity of the chemical potential of Al_2O_3 required in local equilibrium model is satisfied. However, as to the gap between 14 and 17 wt. % Al_2O_3, we can find in Leak's catalogue of calciferous amphiboles (1968) hornblendes with Al_2O_3 in this range and they include hornblende formed at low temperature.

A possible, but not yet confirmed, interpretation of the existence of the compositional gap in the Al_2O_3-rich side is that garnet was first surrounded by very Al_2O_3-rich hornblende, and when lateral migration of materials took place, there developed an unstable grain boundary at some parts of the interstices, but a continuous gradient at others. At the unstable grain boundary, Al_2O_3-rich hornblende dissolved into the pore solution, from which developed less aluminous hornblende. The interpretation of the observed compositional gaps, including the one between actinolite and hornblende, has to await future study.

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