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FLATTENED GARNETS IN STRONGLY FOLIATED GNEISSES FROM THE GRENVILLE SERIES OF THE GANONOQUE AREA, ONTARIO

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ABSTRACT

In the Grenville gneisses flattened and elongated almandine garnets occur on the surfaces of foliation, whereas the garnets of adjacent quartz-feldspar layers are rounded and of a smaller size.

Studies of equilibration domains in these gneisses show that chemical communication and therefore diffusion is enhanced along foliation surfaces. It is proposed that differential ease of diffusion of material to and from the site of garnet growth has controlled garnet morphology. Further, the inhibition of diffusion across foliation planes has limited chemical communication between garnets of the foliation surfaces and those in the adjacent layers rich in quartz and feldspar. This effect was observed in the form of adjacent layers containing garnets with contrasting compositions.

INTRODUCTION

During the course of a study of some metamorphic rocks from the Grenville Series of southeast Ontario (Blackburn, 1967), many garnets were noted which displayed a severely elongated and flattened habit. The garnets (almandine) from one of the samples collected (No. 17) were subjected to a thorough petrographic and chemical study which involved the measuring of true garnet sizes, distance between nearest neighbor garnets and concentrations of Fe, Mg, Mn and Ca in each garnet.

Sample 17 was collected on Brier Hill Road, 1.6 miles east of the village of Morton, South Crosby Township. It is a medium-grained, strongly foliated gneiss with quartz, K-feldspar, garnet and biotite as major components observable in hand specimen. Microscopically, the gneiss exhibits an extremely well developed foliation with foliation planes populated, for the most part, with biotite, sillimanite, garnet and cordierite.

Foliation in these gneisses is defined by the interface between layers of different composition and it has been proposed that the foliation surfaces are parallel to, and coincident with, the original bedding planes (Wynne-Edwards, 1959). A lineation is marked by corrugation on the foliation surface and segregation trains of minerals. In the sample studied, trains of segregated sillimanite and garnet define the lineation. The lineation direction parallels the adjacent major and minor fold axes (Wynne-Edwards, 1959).

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Experimental Technique

The original specimen of Sample 17, measuring 9.0×7.5×7.3 cm., was trimmed with a diamond saw to remove any weathered rind. Surfaces were then cut, parallel to (17 | |) and perpendicular to (17 ⊥) the foliation. These thick slices were in turn cut into slabs of roughly the dimensions of a petrographic slide. The slabs thus formed were cemented to petrographic glass slides and the exposed surface ground parallel to the glass base.

A micrometer grinder, capable of allowing the accurate removal of down to 1/1000 inch, was constructed as an adaptation of one used at Iowa State University for the study of oölites (Donald L. Biggs, personal communication, 1966). With the use of a binocular microscope, the centers of all garnets exposed were spotted on a transparent overlay, the coordinates of their centers determined, and the apparent diameters measured by means of an ocular micrometer. Following spectrochemical analysis of the exposed garnets with a laser microprobe as described elsewhere (Blackburn, 1967), the specimen was ground parallel to the initial surface to remove a layer of determined thickness (average = 0.25 mm) and the coordinates and apparent diameters measured again. This process was repeated until enough grains, to delimit a significant population, were measured (a total of nine times). Most of the grains were intersected at least twice and true grain diameters could thus be obtained. The sizes of only about 2 percent of the garnets measured are by estimates on one or more axes.

Shape, Size and Distribution of the Garnets

The almandine garnets of Sample 17, along with those in many of the other gneisses examined, do not exhibit the usual equidimensional habit. Instead, they are flattened in the plane of foliation and many are elongated in the direction of lineation. The observed range in shape was from roughly spherical to ellipsoidal with axial ratios in the order of 4:2:1 as may be seen in Figure 1. The grain size distribution of these garnets was found to be bimodal, as shown in Figure 1, for the garnets of the section cut perpendicular to the foliation. The garnets of the section cut parallel to the foliation show a similar distribution of grain sizes.

The coordinates of the centers of all garnet grains were noted as a routine step in the determinations of true diameters. Using a Fortran IV program for the IBM/360, it was then possible to calculate the distance of each garnet center to the center of the nearest neighbor garnet and test the randomness of distribution of garnets in the two sections. The test for randomness of distribution used was described by Kretz (1966) and regards the garnet centers as a distribution of points in a plane. This method, originally described by Clark and Evans (1964), measures the departure of a distribution from randomness by the method of measuring the distance to the nearest neighbor for each point within the area of study. The value R is a measure of the degree of departure of the observed distribution from a random distribution and is defined in Table 1. R may range from zero for maximum aggregation to unity for random distribution to 2.1491 for a distribution that is evenly and widely spaced as possible.

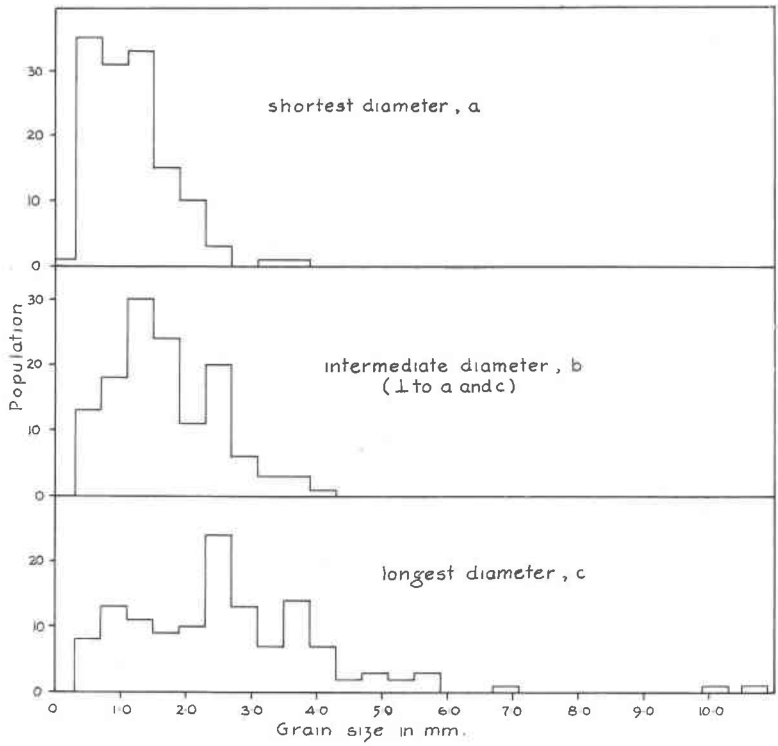

FIG. 1. The distribution of garnet axial diameters in Section 17 ⊥ cut perpendicular to the foliation.

The results from the measurements on Sections 17 || and 17 ⊥ are given in Table 1. The values of R show that the distributions of garnets in Sections 17 || and 17 ⊥ were very nearly random with a possible slight aggregation. This is in good agreement with the macroscopic observations of these sections in which the garnet appears to aggregate locally in trains in the lineation and foliation traces.

The difference in the shape and size of the garnets is related to the differing mineralogy of the alternating rock folia. The garnets of the quartz-feldspar layers are equidimensional and range from about 0.1 to 2.5 mm in diameter. They are closely associated with quartz, K-feldspar, plagioclase and sillimanite. Biotite is present in these layers but is scattered and seems to have no definite relationship to garnet.

However, the garnets located in the strongly biotitic foliation planes are almost always elongated and flattened and are closely associated in space with sillimanite, cordierite and K-feldspar. Sillimanite was ob-

TABLE 1

	Section 17 ⊥	Section 17 ∥
A = area in mm² of section	2675.5	6328.1
N = number of grains measured	141	243
ρ = grain density = N/A	0.0527	0.0384
Σr = sum of distances to the nearest neighboring garnet	263.655	555.336
r_a = mean distance to nearest neighbor garnet	2.044	2.373
r_e = mean distance to nearest neighbor garnet expected in a random distribution of the same density = $1/2\sqrt{\rho}$	2.179	2.552
R = measure of departure from randomness of distribution = r_a/r_e	0.938	0.930

served to be very abundant in the plane of foliation where no garnet was present. The modal concentration of sillimanite upon reaching a garnet face decreased sharply although some grains were still observed to pass directly through the garnet. Biotite was observed to act in the same manner but inclusions of biotite within garnet were scarce. K-feldspar and quartz were also observed as inclusions in the garnets. The flattened garnets were mantled by cordierite, K-feldspar and quartz. A photograph

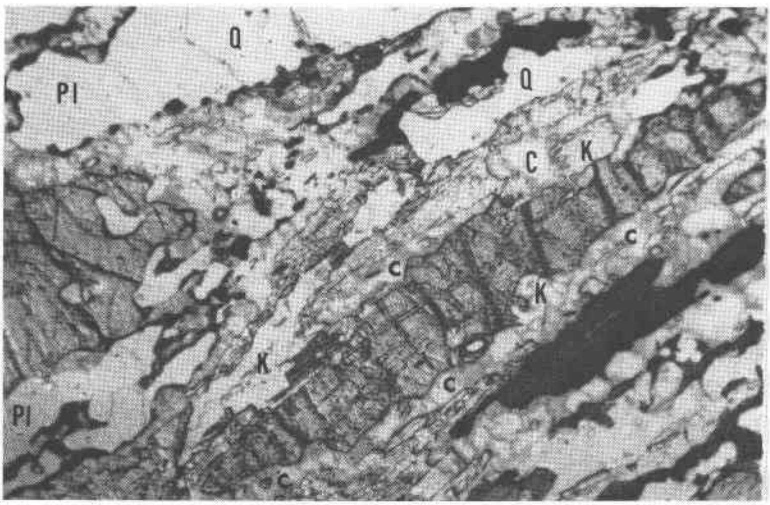

FIG. 2. Photomicrograph of a typical flattened garnet in Sample 17. The section is cut perpendicular to the foliation and approximately parallel to the lineation direction. The close association of cordierite (C), K-feldspar (K) and the unequidimensional garnet should be noted. Sillimanite needles may be observed passing uninterrupted through the garnet. Plane light. Magnification is close to 33×.

of a typical flat garnet is given in Figure 2. In most cases, the chemistry of the garnets in the foliation planes was distinctly different from that of those in the adjacent quartz-feldspar layers, on the order of a few millimeters away (Blackburn, 1967).

Figure 3 shows the spatial distribution of several garnets in section 17 ⊥, *i.e.*, cut perpendicular to the foliation. The atomic fraction of Mg for each of the garnets is also shown. The spatial distributions of Fe, Mn and Ca in the garnets illustrated in Figure 3 show similar patterns. Chemical communication and equilibration along the trace of the foliation plane is much better developed than across the same trace. The garnets associated with cordierite in the foliation surfaces have a higher almandine proportion and less calcium, in agreement with the analyses given by Wynne-Edwards and Hay (1963).

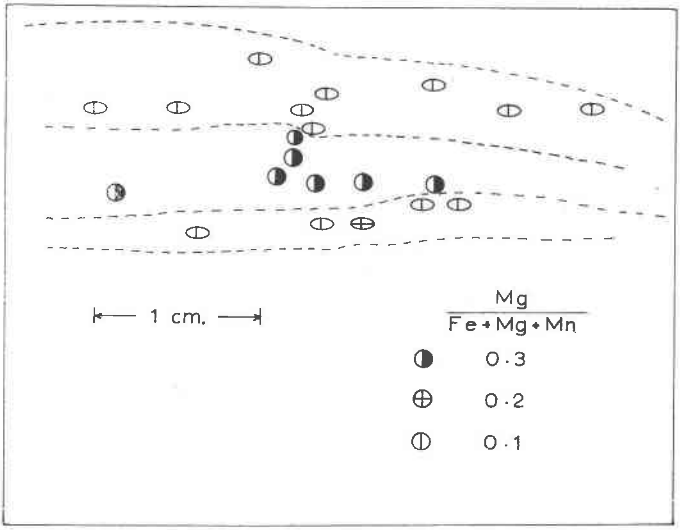

FIG. 3. The spatial distribution of garnets in an area of Section 17 ⊥. The garnets within foliation planes are shown as ellipses; those within the quartz-feldspar layer are shown as circles. The garnets within the foliation surfaces are actually unequidimensional being flattened in the foliation plane and often elongated parallel to the lineation direction.

Discussion

Gresens (1966) describes flattened spessartite garnets within muscovite books in the Kiawa Pegmatite of New Mexico. Further, he found large irregular anhedral spessartite masses in the albite-rich portions of the rock. Gresens describes the garnet within the muscovite books as flattened in the *c* direction and proposes that these flattened garnets nucleated and grew within the muscovite and, after DeVore (1959), that minimum interfacial free energy acted as a control on the morphology of the garnets. An analogous situation of flattened garnets within muscovite crystals from the Deer Park Mine, Spruce Pine, North Carolina, has been brought to the authors' attention by Professor W. R. Brown (pers. comm., 1967). This occurrence shows garnets (spessartite ?) severely flattened with dominant dodecahedral faces parallel to the (001) direction of the muscovite.

Two further possibilities come to mind with respect to the origin of the flattened and often elongated garnets of the present study.

1. The garnets nucleated and grew, within the foliation plane by an exchange reaction with biotite and cordierite, as normal spherical to subspherical grains. Later tectonic deformation caused the garnets to assume their present form.

2. The garnets nucleating and growing on the foliation surface grew as pseudomorphs after biotite or had their growths controlled by the foliation surface and the increased diffusivity along such a surface.

The first possibility is eliminated on the basis that the orientation of sillimanite needles in the foliation planes is undisturbed, some unbroken needles passing directly through a garnet. Further, the optical properties of the garnets in question show no anisotropic effects. It is thus considered highly unlikely that the unequidimensional garnets formed by tectonic deformation.

If the second possibility is assumed correct, the processes and reactions which have taken place must be examined with care since Atherton (1965, p. 191–193) believes that, in most cases, there is no direct pseudomorphous, prograde growth of one index mineral from another. However, let the reasonable assumption be made that biotite existed before the garnet formed, or at least was present in its early stages of nucleation. Under these circumstances, the nucleation of garnet would take place at a position in the rock where the garnet components were readily available, probably in, on, or very near biotite crystals.

As the garnet grows, it must draw component material from the surrounding biotite by an exchange reaction, possibly the following where garnet is becoming more iron-rich and the biotite more magnesian,

$$\underset{\text{biotite}}{K(Mg, Fe, Mn)_3(Al, Si_3)O_{10}(OH)_2} + \underset{\text{sillimanite}}{Al_2SiO_5} + \underset{\text{quartz}}{2SiO_2} \rightleftharpoons \underset{\text{garnet}}{(Mg, Fe, Mn)_3Al_2Si_3O_{12}} + \underset{\text{K-feldspar}}{KAlSi_3O_8} + H_2O \quad (1)$$

At a specific temperature, the rate of growth of garnet will depend on the proximity and abundance of garnet components and the ease of diffusivity of components to and from the site of growth. In this light, one might expect that if nucleation of garnet took place along planes or lines of increased ion mobility, the garnets would grow more rapidly and to a greater size in these directions and the chemical communication between adjacent biotite and garnet grains would be enhanced. Further, the domain of chemical equilibration would take on an ellipsoidal shape with its long axis parallel to the foliation and lineation direction, the medium axis parallel to foliation and perpendicular to lineation and the short axis perpendicular to foliation and lineation. This is exactly what was observed in a study of the spatial extent of equilibration (Blackburn, 1967). Details of this study will be published elsewhere.

It is suggested then that the flattened, elongated garnets observed in this study nucleated within, or on, biotite grains. The garnets then grew by incorporating material from the adjacent biotite. Further growth was enhanced by increased mobility of components along the foliation surface and lineation direction while growth in the direction perpendicular to the foliation was inhibited because of a lesser diffusivity in this direction. The resulting garnet need not be pseudomorphous after a single biotite grain, although in many cases observed in these gneisses, this remains a distinct possibility.

If the diffusion rates across foliation surfaces are inhibited as proposed above, then equilibration between adjacent gneissic layers will also be affected and the biotites and garnets of adjacent layers may show contrasting compositions. Then the first reaction given above, may hold true in the quartz-feldspar-sillimanite-biotite layers while a reaction such as,

$$\underset{\text{biotite}}{10K_2(Fe, Mg)_{5.5}Al_3Si_{5.5}O_{20}(OH)_4} + \underset{\text{silimanite}}{23Al_2SiO_5} + \underset{\text{quartz}}{65SiO_2} \rightleftharpoons \underset{\text{cordierite}}{11(Fe, Mg)_2Al_4Si_5O_{18}} + \underset{\text{garnet}}{11(Fe, Mg)_3Al_2Si_3O_{12}} + \underset{\text{K-feldspar}}{20KAlSi_3O_8} + 20H_2O$$

given by de Waard (1966) may be in operation in the biotite-sillimanite-quartz assemblages of the foliation surfaces. It should be noted here that the close association of cordierite and K-feldspar with the garnet grains on foliation surfaces, coupled with the modal concentration changes of biotite, sillimanite and garnet along these same surfaces, gives supporting evidence for the validity of the second reaction. Wynne-Edwards and Hay (1963) have pointed out that the occurrence of coexisting garnet and cordierite is dependent on the CaO content of the rock as well as its FeO/MgO ratio. They find that in rocks containing no free plagioclase, biotite and cordierite were present with no garnet. As the CaO content increases, cordierite-garnet assemblages are stable. Further rise in the lime content affords cordierite-free, garnet-bearing gneisses. This is entirely in accord with petrographic evidence from this study. The quartz-feldspar rich layers contained garnet and biotite but no cordierite. All the cordierite was concentrated along the foliation surfaces where it was closely associated with garnet, biotite, sillimanite and K-feldspar. No plagioclase was evident in these planes.

It may be true that prograde reactions of the type discussed above are not operative during the crystallization of index minerals (Yoder, 1955; Atherton, 1965) and the main crystallization of index minerals takes place after dehydration of the rocks and the distribution of isotherms. It is certainly possible that reactions involving chlorite, muscovite or other low-grade and even nonmetamorphic minerals could be substituted for the reactions given above. Again, however, the reaction products are dependent for the most part on the composition of the rock and the above arguments are applicable.

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