[AMERICAN JOURNAL OF SCIENCE, VOL. 254, JULY 1956, P. 413-419]

THE FORMATION OF GORE MOUNTAIN GARNET AND HORNBLENDE AT HIGH TEMPERATURE AND PRESSURE

ROBERT H. WENTORF, JR.

ABSTRACT. Using the "Belt" high-pressure apparatus developed in this laboratory, it was found that garnet forms from Gore Mountain hornblende by loss of water at a temperature of about 1250°C. and a pressure above 27,000 atmospheres. Gore Mountain hornblende forms at about 1200°C. at a pressure of at least 22,000 atmospheres. These findings have interesting geological implications.

INTRODUCTION

Although garnet occurs in many places in the Adirondacks, nowhere does it occur in such interesting forms as at Gore Mountain, near North Creek, New York. According to Krieger (1937), the main body of the mountain is syenite. Of great interest is a deposit of garnet-rich rock which occurs near the top of the mountain, and from which garnet is mined (the Barton Mine). This deposit is a narrow mass about three-quarters of a mile long, east-west, and about 200 feet wide, north-south. It touches syenite on the south, gabbro on the north, and anorthosite at each end. There is some garnet and garnet gneiss in the syenite near the main garnet deposit. The deposit itself contains about 10 percent of garnet crystals from one inch to three feet in diameter, often with dodecahedral faces. The garnets are always fractured, and each is completely enclosed by a shell of dark green hornblende. These hornblende-rimmed garnets are scattered in a groundmass which consists of nearly equal parts of hornblende and andesine, together with smaller amounts of biotite, pyroxene, etc. Often between garnet and hornblende there is a thin whitish film of feldspar and biotite. Buddington (1952) and Levin (1950) have made extensive studies of this garnet deposit.

Figure 1 shows garnet lumps and their rock envelopes, and figure 2 shows the feldspar and biotite at the interface between garnet and hornblende.

Garnet is known to melt at about 1100°C. at one atmosphere and refreeze to minerals or glass of lower density than the garnet. The density of garnet is unusually high for a silicate (3.5 to 4.2), and it seems likely that garnet is formed at high pressure. Workers at the Norton Company have found this to be true. Recently Coes (1955) described the synthesis of several high-pressure minerals, including jadeite, kyanite, pyrope, almandite, andradite, and other pure types of garnet. Nearly all these garnets were synthesized from their constituent oxides and water at 900°C. and 10,000 to 30,000 atmospheres. It is noteworthy that attempts to synthesize garnet at relatively low pressures have not yet been successful (Eitel, 1954).

The chemical composition of Barton Mine garnet is, according to Levin (1950):

SiO_2	39.29%
Al_2O_3	22.12
Fe_2O_3	.78
FeO	19.63

CaO	6.16
MgO	11.18
MnO	.38
H_2O^-	.03
TiO_2	.05
Total	99.62

Thus it is mostly almandite and pyrope.

Hornblende is a mineral of somewhat variable composition. It has a relatively high density (3.2) and contains some water as hydroxyl. Experiments in this laboratory showed that a high pressure is necessary to form hornblende from its melt.

According to Levin (1950), a sample of hornblende from the Barton Mine contained:

SiO_2	43.50%
Al_2O_3	13.15
Fe_2O_3	3.39
FeO	9.38
MgO	14.25
CaO	10.58
Na_2O	2.53
K_2O	.68
H_2O	1.15
H_2O^-	.12
TiO_2	1.12
MnO	.09
F	.30
Total	100.24

A sample of hornblende taken from the hornblende shell around a garnet was analyzed in this laboratory and found to contain:

SiO_2	45.1%
Al_2O_3	14.2
FeO } Fe_2O_3 }	11.7
CaO	9.1
MgO	15.6
Na_2O	3.1
TiO_2	0.9
Total	99.7

It also contained about 1 percent of water as hydroxyl.

EXPERIMENTAL

From a look at the garnetiferous hornblende of Gore Mountain, it seemed possible that the garnet could have formed out of the surrounding hornblende

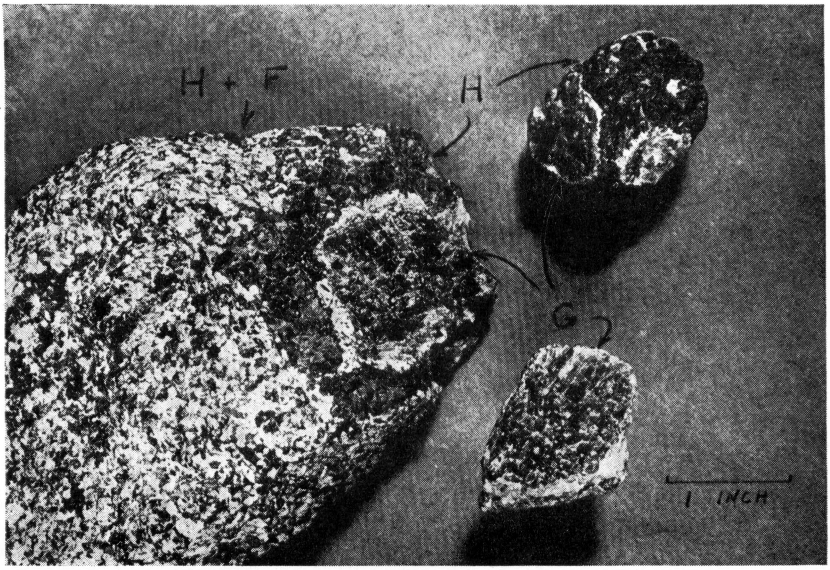

Fig. 1. Gore Mountain garnet rock, 2/3 natural size.
G: Garnet; H: Hornblende; H and F: Hornblende and Feldspar.

at high pressure; the remaining water, silica, alumina, and sodium partly diffused away into the surrounding rock and partly remained at the garnet-hornblende interface to form biotite and feldspar.

Excellent high-pressure and high-temperature equipment capable of testing this hypothesis exists in this laboratory. The experiments that follow were performed in the "Belt" apparatus of Dr. H. T. Hall. This is a pressure vessel containing a capsule with a working volume of about 0.1 ml. The temperature of the capsule is known to within 50°C. from the electrical power used to heat it.

For example, consider an experiment showing the formation of garnet from hornblende. Powdered hornblende was tamped into a metal capsule. (Metal was used because it reacts with water at high pressure and temperature to form hydrogen which escapes from the capsule. Unless water is removed from hornblende, no garnet will form.) The capsule was subjected to a pressure of about 35,000 atmospheres while it was heated to 1450°C., held there a few minutes, slowly cooled (6 minutes) to about 1150°C., and cooled rapidly to 25°C. The pressure was released and the capsule was broken apart and examined under the microscope. Garnet dodecahedra from 2 to 20 microns in diameter were visible, together with hornblende and a little feldspar and biotite. X-ray powder diffraction patterns were made of the products of such an experiment and also of natural hornblende and natural garnet from Gore Mountain. These photographs showed that the hornblende contained hornblende and a little andradite, the natural garnet contained almandite and pyrope, and the products of the experiment contained all the above minerals with unidentifiable traces of others.

As another experiment, consider the growth of large garnet crystals in a temperature gradient. A mixture of powdered garnet and hornblende was tamped into a graphite capsule and exposed to a pressure of 35,000 atmospheres. (Graphite was used because it has a high melting point and is inert

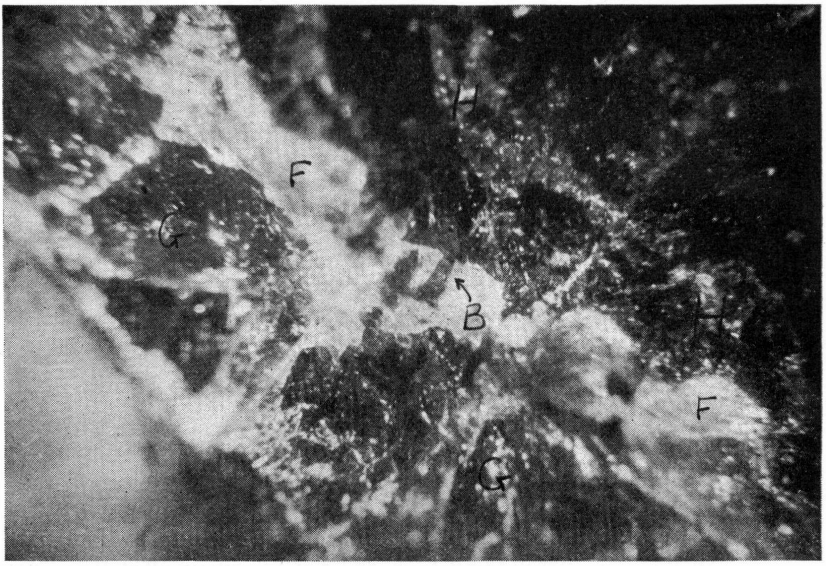

Fig. 2. Photomicrograph of interface between garnet and hornblende in Gore Mountain garnet rock, × 24.

G: Garnet, H: Hornblende; F: Feldspar; B: Biotite.

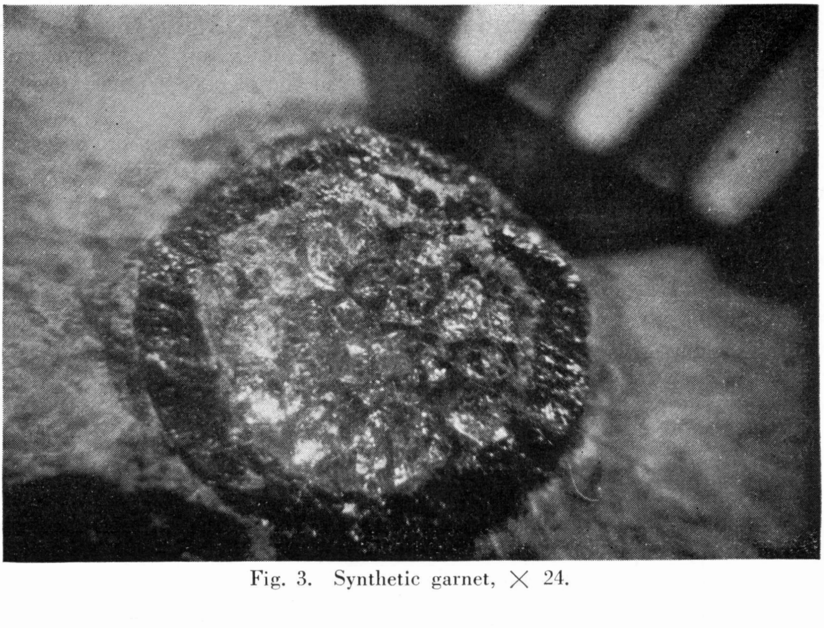

Fig. 3. Synthetic garnet, × 24.

to these minerals.) The capsule was heated at 1400°C. for about 5 minutes, cooled to 1200°C. in 10 minutes, then cooled rapidly to 25°C. The pressure was released and the capsule was broken up for examination. Here one found that the cooler ends of the capsule contained several dozen yellow garnet crystals embedded in a fragile matrix. Figure 3 is a photomicrograph of these garnets. An edge of a millimeter scale is visible for comparison. Toward the midlength of the capsule were no garnets, but instead a mixture of powdery hornblende and lumps of a yellow hydrated glass which puffed up on heating to 1000°C.

As yet another typical experiment, consider the formation of hornblende from garnet and water. Crushed garnet was tamped into a graphite capsule and moistened with water. The capsule was subjected to 35,000 atmospheres pressure and heated at 1400°C. for about 6 minutes, cooled to 1150°C. in 13 minutes, then cooled rapidly to 25°C. The pressure was released and the capsule was examined. At its bottom end appeared a fragment of synthetic garnet about 1 mm square embedded in a crumbly glass. In the midlength of the capsule were many fragments of synthetic hornblende about 20 to 100 microns in diameter. Since the garnet contains very little alkali, the hornblende made from it must be mostly the alkali-poor variety.

SUMMARY

After about forty experiments along these lines it was possible to assemble the following facts about the formation of garnet and hornblende.

1. At temperatures between 1200 and 1300°C. and pressures between 27,000 and at least 40,000 atmospheres a complex equilibrium exists:

$$\text{Melt, Hornblende} \rightleftarrows \text{Melt, Water, Garnet, Biotite, Feldspar}$$

A change of pressure between 27,000 and 40,000 atmospheres does not change the equilibrium much. As the temperature is lowered from 1400°C. garnet crystallizes first at about 1250°C. Thus it forms in regular crystals and grows in the cool end of a capsule. Unless water is removed from hornblende no garnet will form. Below 1150°C. the melt is essentially frozen, and no formation or destruction of hornblende can be noticed in half an hour at 35,000 atmospheres. The effect of pressure above 40,000 atmospheres on the equilibrium was not studied.

2. Between 22,000 and 27,000 atmospheres, garnet will not form from molten hornblende, and one finds the capsule filled with recrystallized hornblende. If the melt is cooled too quickly, there forms a clear yellow glass containing dendrites, mostly of hornblende. The clear glass shows no crystallinity in an X-ray powder diffraction pattern.

3. Between 15,000 and 22,000 atmospheres the hornblende melt solidifies to a complex mixture of hypersthene, pyroxene, and other unidentifiable minerals, according to an X-ray diffraction pattern. If the melt is cooled faster than 20°C. per minute, only glass forms.

4. A mixture of Gore Mountain garnet and the feldspar-hornblende-biotite rock forming the mass of the mountain solidifies to a brown glass below a pressure of about 27,000 atmospheres. At pressures between 27,000

and 40,000 atmospheres garnet forms from such a melt at about 1200°C., together with brown and yellow glass. The melt could not be cooled slowly enough to obtain crystals instead of glass.

5. Large crystals of garnet can be grown at pressures between 27,000 and 40,000 atmospheres. The raw material for the melt can be made up of garnet and hornblende, or garnet and Gore Mountain rock, or garnet and water. The garnets form at the cool end of the capsule. The largest garnet grown so far was about 1 mm in diameter. Its size was limited by the size of the capsule.

6. The andesine-hornblende mixture in which the hornblende-surrounded garnets are found melts about 50° lower than the hornblende alone. No garnet forms from this melt unless water is removed from it while the pressure exceeds 27,000 atmospheres.

7. If a hornblende melt is cooled slowly at 22,000 atmospheres, there forms a mixture of glass and hornblende. If a hornblende melt is cooled at the same rate at 27,000 atmospheres, nearly all hornblende is formed with very little glass. Certainly viscosity rises with pressure, so that if diffusion limited crystal growth one would expect fewer, smaller crystals at the higher pressure. But at the higher pressure there is a greater free energy difference between glass and hornblende, and this, not diffusion, must control the rate of crystal growth.

Again, it is possible to grow well formed 20-micron garnets from hornblende by cooling from 1350°C. to 1100°C. in 30 seconds. This implies a relatively fluid melt, almost like water, for the time available to grow the garnets is about 15 seconds.

It is interesting that these silicate melts have such low viscosities at such high pressures. By way of comparison, some molten, nearly anhydrous volcanic lavas have viscosities about 100 times that of honey, and Bridgman found that the viscosity of hexane increases thirty-fold when the pressure on it is increased from 1 to 8000 atmospheres at 30°C. Such comparisons illustrate the solvent powers of water.

DISCUSSION

It is tempting to suppose that the garnet of Gore Mountain formed under conditions similar to those in the laboratory, and some arguments exist favoring this hypothesis. However, many gaps remain in our knowledge about this mineral system; the most serious of these are the combined effects of low temperature (400-600°C.) and long time (months or years). Perhaps under such conditions garnet could form at low pressures of a few thousand atmospheres. Until this mineral system is thoroughly explored, the genesis of the garnet of Gore Mountain must remain uncertain.

Perhaps from a study of the pressure-temperature dependence of the garnet-hornblende equilibrium it will be possible to set a lower pressure limit below which garnet cannot form even at 100°C. Whether such a pressure-temperature equilibrium line can be followed sufficiently far depends on the as yet unknown rate of approach to equilibrium in such a system. Further studies are planned along these lines.

References

Buddington, A. F., 1952, Chemical petrology of some metamorphosed Adirondack gabbroic, syenitic, and quartz syenitic rocks: Am. Jour. Sci., Bowen v., p. 37-84.

Coes, Loring, Jr., 1955, High pressure minerals: Am. Ceramic Soc. Jour., v. 38, p. 298. (Also, Silica Symposium, Rutgers University, June 4, 1954.)

Eitel, W., 1954, The physical chemistry of the silicates: Chicago, Univ. Chicago Press.

Hall, H. T., The "Belt" ultra high-pressure, high-temperature apparatus: (to be published).

Krieger, M. H., 1937, Geology of the Thirteenth Lake quadrangle: New York State Mus. Bull. 308.

Levin, S. B., 1950, Genesis of some Adirondack garnet deposits: Geol. Soc. America Bull., v. 61, p. 519-565.

General Electric Research Laboratory
Schenectady, New York