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# PHASE RELATIONS IN CORDIERITE-GARNET-BEARING KINSMAN QUARTZ MONZONITE AND THE ENCLOSING SCHIST, LOVEWELL MOUNTAIN QUADRANGLE, NEW HAMPSHIRE*

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## Abstract

The assemblage biotite-cordierite-garnet-microcline-plagioclase-quartz is found in portions of the large Cardigan pluton of metamorphosed Kinsman quartz monozonite in the east central part of the Lovewell Mountain quadrangle and in the southeastern part of the Sunapee quadrangle, New Hamsphire. Adjacent pelitic schists of the Littleton formation consist largely of the assemblages biotite-garnet-oligoclase-quartz-sillimanite and biotite-garnet-oligoclase-quartz-sillimanite-orthoclase. A graphical phase analysis of these rocks has been made, following the methods of Korzhinskii and Thompson, and using Heald's analyses of biotite, cordierite, and garnet. Mineral assemblages of the kinsman pluton are related to those of the Littleton rocks by the divariant relation:

cordierite+garnet+potassic feldspar=biotite+sillimanite, with quartz and plagioclase present in excess. Thus the pluton and its pelitic wallrocks, though metamorphosed together, are of different metamorphic facies—probably because the pluton was hotter than the wallrock and/or because the chemical potential of water was less in the pluton than in the schist.

## Introduction

The mineral pair cordierite-garnet has been found in pelitic rocks of high metamorphic rank in many localities. Heald (1950, p. 58–60) has described an interesting occurrence of this pair in a portion of the large Cardigan pluton of Kinsman quartz monzonite, here metamorphosed, in the Lovewell Mountain quadrangle, southwestern New Hampshire. Heald (1950, p. 65–67) also gave chemical analyses of coexisting biotite, cordierite, and garnet from this rock. A phase analysis is made in the present paper of the cordierite-garnet-bearing plutonic rock and of its wallrock, the adjacent schist of the Littleton formation, following the methods of Korzhinskii (1959) and Thompson (1957). Mineral assemblages of these two rock masses are represented graphically in Thompson-type ternary plots and in projections of tetrahedral diagrams. These diagrams show that assemblages of rocks of the Kinsman and Littleton formations are mutually incompatible, and may be represented by a divarient reaction.

The geologic map of Fig. 1 shows the southern half of the Cardigan pluton and the enclosing Littleton formation.

## Petrography of the Plutonic Rocks

The Cardigan pluton is exposed for almost 60 miles in a direction slightly east of north, and has a breadth of about 4 to 14 miles (Billings,

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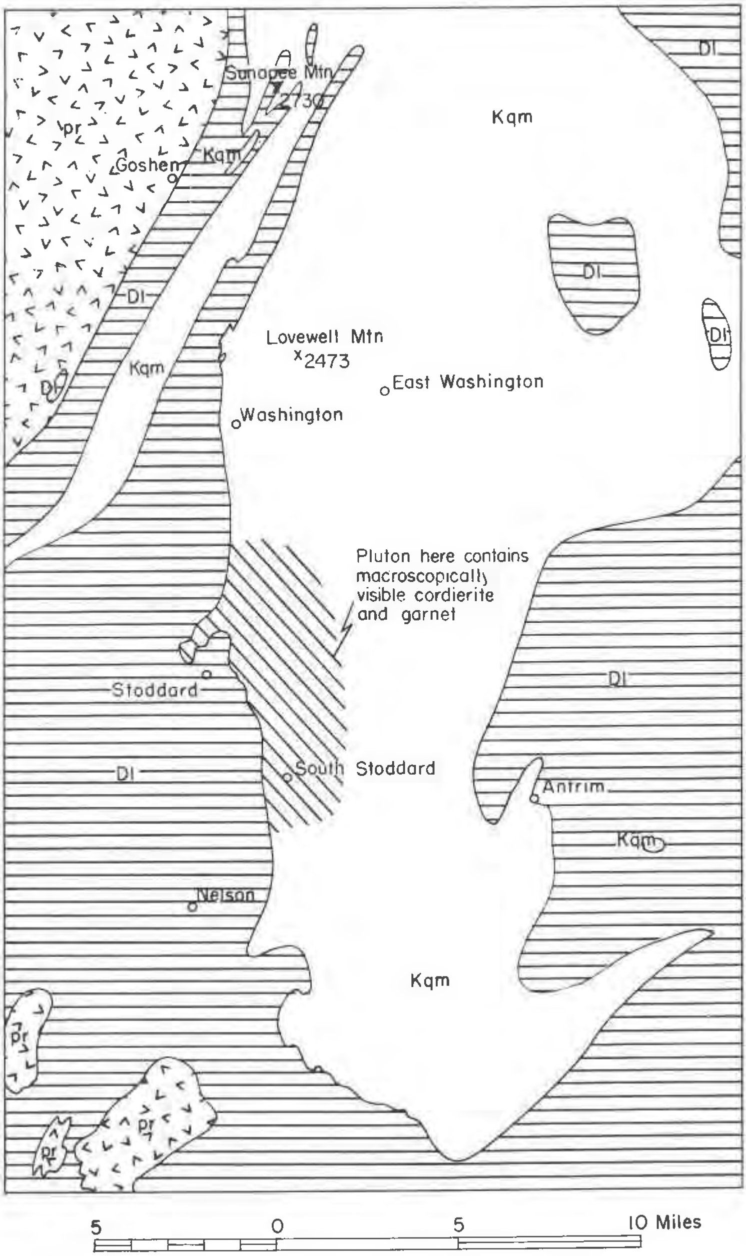


FIG. 1. Generalized geologic map of a part of south-western New Hampshire (after Billings, 1955), showing the southern half of the Cardigan pluton of Kinsman quartz monzonite (Kqm), the Devonian Littleton formation (Dl, horizontally ruled), and other plutonic rocks (pr, checked pattern.).

1955). Excellent, detailed descriptions of this rock in the Lovewell Mountain quadrangle and northward Sunapee quadrangle have been given by Heald (1950, p. 58–61) and Chapman (1952, p. 394–397). The pluton in this area is mostly light gray porphyritic granodiorite with tabular megacrysts of perthitic microcline 3 to 12 cm. long. Grains of plagioclase as large as 5 cm. are abundant in much of the rock. The matrix is coarse-grained, subhedral to anhedral, and consists largely of oligoclase or andesine, quartz, and biotite. Small amounts of myrmekite, and retrograde muscovite and chlorite are present. Tiny needles of sillimanite are scattered through the quartz. Magnetite, ilmenite, apatite, zircon, and graphite are accessory. The composition of the Kinsman body in this area ranges from quartz monzonite to quartz diorite, but granodiorite is most abundant. An average of fourteen volumetric modes is given in percentages by Heald (1950, p. 59): oligoclase-andesine 47, quartz 29, microcline microperthite 11, biotite 10, and garnet 2; and an average of nine by Chapman (1952, p. 397): oligoclase-andesine 49, quartz 28, biotite 11, and microcline perthite 7. The variations in bulk composition, however, have little affect on the fabric of the pluton and its mineral assemblages.

Most of the Kinsman quartz monzonite in the Lovewell Mountain quadrangle contains garnet. Cordierite is also a macroscopically visible constituent of the granodiorite in the town of Stoddard and in nearby Antrim and Nelson (Heald, 1950, p. 60), as shown in Fig. 1. Excellent exposures of the porphyritic cordierite-garnet granodiorite may be seen in the road cut on Route 9 from 200 to 300 yards east of Morse Brook. Cordierite forms 3 to 5 per cent of most of the granodiorite, and garnet is present in roughly equal amount but is more widespread in occurrence. The cordierite is partly anhedral, partly subhedral, roughly equant to elongate in outline, 1 to 16 mm. in size, and slightly to wholly altered to muscovite and chlorite. Polysynthetic and sectorial twins and pleochroic haloes about zircons are rare in the cordierite. Garnet is mostly anhedral, equant, 2 to 15 mm. in diameter, and usually slightly altered along fractures to chlorite and biotite. Biotite embays garnet in many instances. Garnet is commonly partly sheathed in biotite.

Small quantities of garnet and cordierite are also present in the Kinsman quartz monzonite in the Sunapee quadrangle (Chapman, 1952, p. 395–396).

The long, sheet-like extension of the pluton that lies southwestward from the east flank of Sunapee Mountain contains only a little garnet and no cordierite (Heald, 1950, p. 61), and is less metamorphosed than the main body of the pluton to the east.

Assemblages in the porphyritic granodiorite, in its inclusions, and in the adjacent Littleton formation were studied in 19 thin sections. Biotite, microcline perthite, plagioclase, and quartz form the usual assemblage in the granodiorite. Cordierite and garnet lie in contact with all of these minerals; however, contacts of these two mafic minerals with microcline perthite are rare because they are partially rimmed with biotite. Thin films of secondary sericite have formed along many of the interfaces between the potassic feldspar and both cordierite and garnet. Thus the assemblage is: biotite-cordierite-garnet-microcline-plagioclase-quartz. Sillimanite needles in quartz and in feldspar are separate from the mafic minerals and thus are not part of the above assemblage. They form a subassemblage microcline-plagioclase-sillimanite.

A small, dark inclusion in the porphyritic granodiorite, collected on Route 9 about 200 yards north of the junction with Route 123, consists of about 4 per cent garnet megacrysts set in a partially muscovitized, massive mosaic of $\frac{1}{4}$ to $\frac{1}{2}$ mm. equant grains of microcline, plagioclase, and cordierite, and chunky tablets of biotite. Sharp contacts of microcline with cordierite and garnet are plentiful in unaltered parts of this rock. The mineral assemblage of this inclusion is identical to that of the enclosing cordierite-garnet granodiorite.

Sillimanite is abundant in some of the inclusions (Heald, 1950, p. 59–60) in the pluton. One inclusion from Route 123, 300 feet east of the Antrim-Nelson town line, consists partly of massive quartz, microcline, plagioclase, garnet, biotite, and cordierite, and partly of irregular lenses of biotite-garnet-sillimanite-quartz schist with pseudomorphs of muscovite and sillimanite after cordierite. Many of the garnets in these lenses are embayed by biotite and sillimanite. These textural relations and the fact that the number of phases if greater than the phase rule allows indicate that this rock is not in equilibrium. This inclusion probably was an assemblage biotite-cordierite-garnet-microcline-plagioclase-quartz, in equilibrium with the granodiorite, that suffered a later, retrogressive alteration in which cordierite, garnet, and microcline partly reacted to biotite, muscovite and sillimanite.

Heald (1950, p. 83–84) has pointed out that the presence of garnet in the Kinsman quartz monzonite is probably due to metamorphism, rather than to assimilation of more mafic rocks. The bulk composition of the garnet-cordierite-bearing granodiorite is essentially the same as that of the garnet-cordierite-free variety, so assimilation may be ruled out. The garnet and cordierite are found only in the central, more intensely metamorphosed portion of the pluton.

The pluton of Kinsman quartz monzonite in the Keene-Brattleboro area, southwesternmost New Hampshire, is only slightly metamorphosed; it contains about 5 to 10 per cent muscovite, only traces of garnet, and no cordierite (Moore, 1949, p. 1642). The components that formed muscovite in the Kinsman pluton near Keene may have entered the minerals cordierite, garnet, and microcline in the Cardigan pluton in the Lovewell Mountain area, according to a reaction such as:

muscovite+biotite=cordierite+garnet+microcline (with quartz in excess). Or, following Heald (1950, p. 84), there may have been a reaction between muscovite and biotite to produce a more magnesian biotite, garnet, and microcline. A balanced reaction between a hypothetical, strictly igneous Kinsman quartz monzonite and its actual metamorphic equivalent, as now found near South Stoddard and vicinity, would probably involve both of the above reactions, but would be more complex.

## Assemblages in the Littleton Formation

The Littleton formation immediately west of the Cardigan pluton is formed of pelitic rocks which have been highly metamorphosed. Potassic feldspar is stable in these rocks. The common assemblages of these rocks are: biotite-garnet-oligoclase-quartz-sillimanite and biotite-garnet-oligoclase-quartz-sillimanite-orthoclase (Heald, 1950, p. 54–55). Biotite and sillimanite are intergrown in these rocks; this mineral pair is not found in the cordierite-garnet granodiorite. Heald found cordierite in only two specimens of this rock (1950, p. 52 and 54); the ratio of FeO:MgO is usually so high that garnet forms, rather than cordierite.

Muscovite occurs in the Kinsman and Littleton assemblages only as a retrograde mineral. It is not known if this mineral is stable under the conditions of the main metamorphism. The pair sillimanite+sodic microcline (or orthoclase) is stable, and the related pair muscovite+plagioclase is not. Below its breakdown muscovite may be stable with both sillimanite and microcline (or orthoclase) that is more sodic than the muscovite (Dr. James B. Thompson, Jr., oral communication, 1960). The pair, sillimanite+sodic microcline (or orthoclase), may separate, in a compositional sense, the assemblages muscovite-sodic microcline (or orthoclase)-sillimanite and soda-saturated microcline (or orthoclase)-sodic plagioclase-sillimanite. The rocks described here contain the latter assemblage, and the possibility remains that muscovite would be stable under these same external conditions in rocks of generally similar composition except with higher ratios of $K_2O:Na_2O$.

## Graphical Representation of Assemblages

These assemblages of the Kinsman quartz monzonite and the Littleton formation may be represented graphically. The rocks are considered systems of eight essential components: $Al_2O_3$, $CaO$, $FeO$, $H_2O$, $K_2O$, $MgO$, $Na_2O$, and $SiO_2$. With the condition that quartz be present in excess, the component $SiO_2$ is also present in excess, and need not be directly represented in compositional plots of the system. This method has been developed by Korzhinskii (1959, p. 66–71) and Thompson (1957).

Most of the CaO of these rocks is found in the ubiquitous plagioclase. The garnet contains only 1.13 weight per cent of CaO (Heald, 1950, p. 64), and so the effect of this component is neglected. Similarly, much of the $Na_2O$ is present in plagioclase. However, appreciable amounts of soda are present in the microcline of the Kinsman quartz monzonite and in the orthoclase of the Littleton formation: two representative analyses by Heald (1950, p. 63) showed 14 mole per cent of albite in the former and 21 mole per cent in the latter. In this analysis microcline and orthoclase are plotted as $KAlSi_3O_8$ for convenience, but it should be kept in mind that these feldspars actually are sodic and of compositions stable with oligoclase-andesine.

The small molar ratios of $Fe_2O_3$:FeO in these rocks (Heald, 1950, p. 77, 84; Chapman, 1952, p. 389) give only trace amounts of magnetite; and so the effects of $Fe_2O_3$ in the system are also neglected. The temperature, pressure, and chemical potential of $H_2O$ are assumed to have had nearly constant values during formation of the assemblages. Thus each of these rock units may be represented by the components $Al_2O_3$, FeO, $K_2O$, and MgO, with the phases quartz and oligoclase-andesine present in excess, and at given conditions of nearly constant temperature, pressure, and chemical potential of $H_2O$. The temperature and chemical potential of $H_2O$ in the schist apparently were different from those in the granodiorite; this point is discussed below.

In the terminology of Korzhinskii (1959, p. 71) $Al_2O_3$, FeO, $K_2O$ and MgO are inert components, and $H_2O$ is a perfectly mobile component. $SiO_2$ is an excess component. The $Na_2O$ and CaO may be considered together as a single excess component in the ratio that they are found in the plagioclase, if one neglects their entrance into the potassic feldspar and garnet.

Four variables may be plotted in a tetrahedron, or one of the variables may be held constant and the remaining three plotted in a two-dimensional projection similar to that given by Thompson (1957). Both a direct perspective view of the tetrahedron and the method of Thompson will be given here.

Probable mineral assemblages of muscovite-bearing schists of the sillimanite zone have been graphically represented by Thompson (1957, p. 856). Starting with temperature, pressure, and chemical potential of $H_2O$ given, and with quartz present in excess, he made a projection in the tetrahedron $Al_2O_3$-FeO-$K_2O$-MgO from the muscovite point to the plane $Al_2O_3$-FeO-MgO. Thus a diagram of phases stable with both muscovite

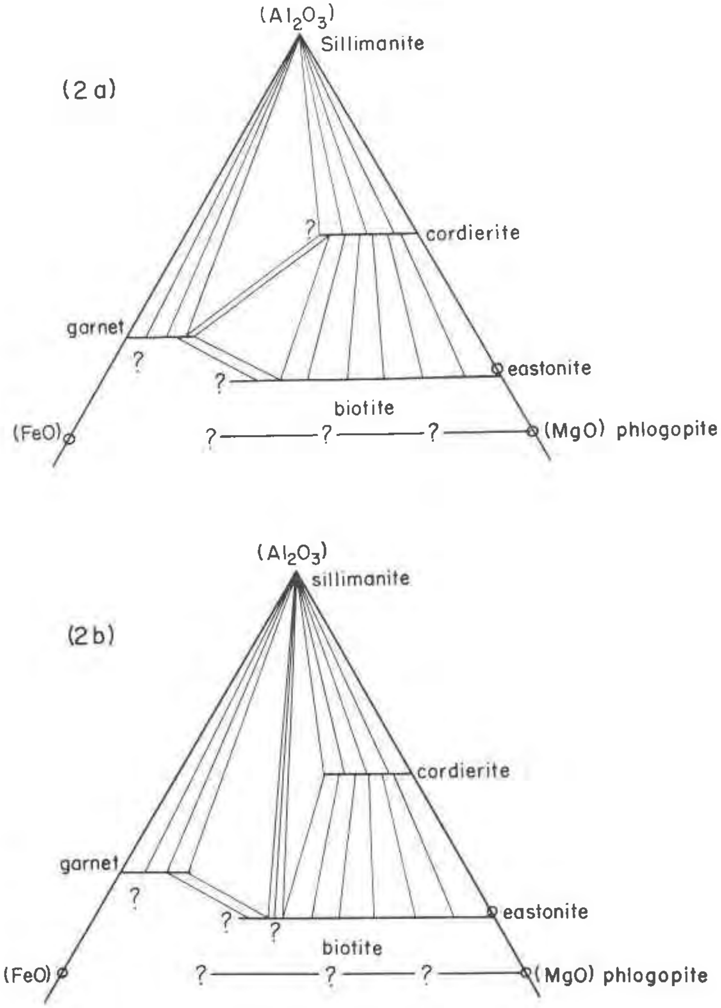


FIG. 2. Minerals stable with quartz, oligoclase-andesine, and potassic feldspar at constant temperature, pressure, and chemical potential of $H_2O$ in: (*a*) cordierite-garnet-bearing Kinsman quartz monzonite, and (*b*) Littleton formation east of the orthoclase isograd. Extent of biotite field and relations near FeO corner not known. The lines in biotite-cordierite field are schematic.

and quartz was made. A similar projection, from the point for potassic feldspar, may be made for the muscovite-free rocks described above. The two diagrams of Fig. 2 are obtained; that for the cordierite-garnet-bearing granodiorite is determined from the assemblage biotite-cordierite-garnet-microcline (-quartz-plagioclase), using Heald's analyses (1950, p. 64–67) of the three mafic silicates; and that for the Littleton formation by the two biotite-sillimanite-bearing assemblages given above.

Figure *2b* does not show the potentially important potash feldspar-free assemblage biotite-cordierite-garnet-sillimanite (plagioclase-quartz) which would be expected in rocks with less $K_2O$ than the schists of the Littleton formation. This assemblage occurs at Sturbridge, Massachusetts, and is being studied by the author. To show this assemblage and its relation to those of Fig. *2a*, two perspectives of the tetrahedron $Al_2O_3$-FeO-$K_2O$-MgO are given in Fig. 3. The region bounded by the five compositions sillimanite, sodic microcline or orthoclase, ferrous cordierite, magnesian almandine, and biotite contains five possible four-phase regions. Two are shown in Fig. *3a*.

cordierite-garnet-potassic feldspar-sillimanite,
and cordierite-garnet-potassic feldspar-biotite;

and they are separated by the three-phase region:

cordierite-garnet-potassic feldspar.

The remaining three assemblages are shown in Fig. 3b:

biotite-cordierite-potassic feldspar-sillimanite,
biotite-garnet-potassic feldspar-sillimanite,
and biotite-cordierite-garnet-sillimanite;

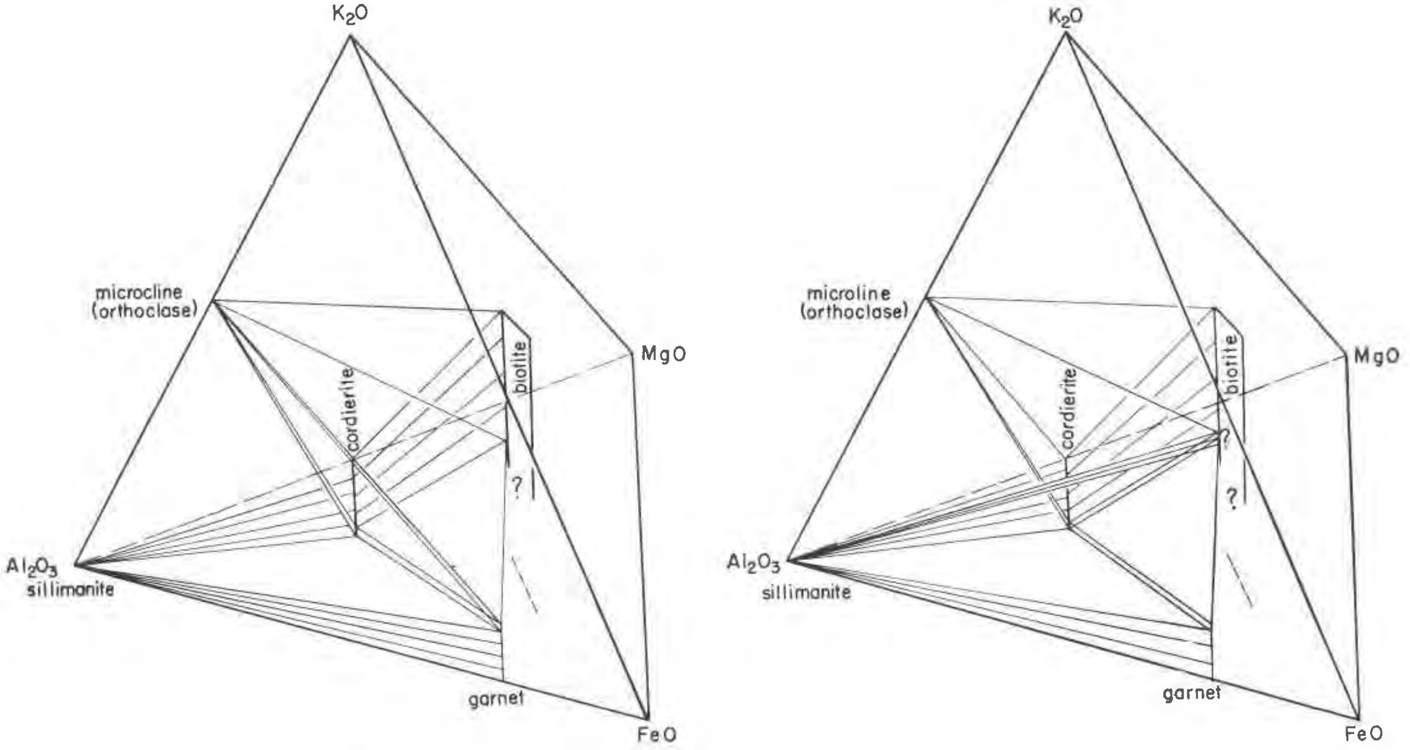
and are separated by the three-phase fields:

biotite-potassic feldspar-sillimanite,
biotite-cordierite-sillimanite,
and biotite-garnet-sillimanite.

Compositions of minerals in the three-phase fields are related by tie planes, which are analogous to tie lines of two-dimensional diagrams. These five regions intersect in a small volume, where a general divariant reaction, approximating the transition from Figs. *2a* and *3a* to Figs. *2b* and *3b*, takes place:

cordierite+garnet+potassic feldspar=biotite+sillimanite (with quartz in excess and the chemical potential of $H_2O$ externally determined). This abrupt type of reaction has been called a discontinuity in facies by Thompson (1957, p. 856).

The conclusion is drawn that the Cardigan pluton was not in facies equilibrium with the immediately enclosing schists of the Littleton formation, and that these rock masses are related by the equation of the previous paragraph. The pattern of regional metamorphism suggests that the assemblage of the Kinsman quartz monzonite is of higher metamorphic grade than that of the adjacent schist. It is probable that the



(3a)

(3b)

FIG. 3. Phase relations in part of the system $Al_2O_3$-FeO-$K_2O$-MgO, with quartz and oligoclase-andesine in excess, and at constant temperature, pressure, and chemical potential of $H_2O$. (*a*) (left) Cordierite-garnet-bearing Kinsman quartz monozonite. (b) (right) Littleton formation east of the orthoclase isograd. Some of the tie lines garnet-potassic feldspar are omitted for clarity.

plutonic rock was hotter than the schist, or that its chemical potential of $H_2O$ was lower than that of the schist, or both, and that these gradients of temperature and/or chemical potential of $H_2O$ were existent during the peak of metamorphism. In other words the more restricted range of biotite in the granodiorite, as compared with its range in the schist, is a reflection of conditions that favor formation of anhydrous phases. If the granodiorite had been metamorphosed at still higher temperatures or lower chemical potentials of $H_2O$ one might expect the biotite to have been altered to hypersthene and potassic feldspar.

## Similar Occurrences

Assemblages similar to those described above were found by Korzhinskii (1936) in metasedimentary rocks of the Southern Baikalia region, southeastern Siberia. His analysis is similar to the writer's, as would be expected; unfortunately his work was not known to the writer until the above paper was completed. Korzhinskii (1936, p. 279) found four stages of equilibrium with assemblages:

I

alm-bio-fay-hyp
alm-or -bio-hyp
alm-or -cdt-hyp
alm-or -cdt-sil

II

alm-bio-fay-hyp
alm-bio-cdt-hyp
bio-or -cdt-hyp
alm-bio-or -cdt
alm-or -cdt-sil

III

alm-bio-fay-hyp
alm-bio-cdt-hyp
alm-bio-cdt-sil
alm-bio-or -sil
bio-cdt-or -sil

IV

alm-bio-gr?-hyp
alm-bio-cdt-hyp
alm-bio-cdt-sil, and
alm-bio-or -sil, and

(Abbreviations are: alm—almandine, and—andalusite, bio—biotite, cdt—cordierite, fay—fayalite, gr—grunerite, hyp—hypersthene, or—orthoclase, sil—sillimanite).

Each assemblage is stable with quartz, magnetite, apatite, zircon, phyrrhotite, and graphite. Plagioclase and rutile are stable with all assemblages except those containing fayalite. Stage I is stable at the highest temperature, II and III at intermediate temperatures, and IV at the lowest temperature. Korzhinskii gives a number of the reactions that take place between one stage and another, including the one given by the author. Assemblages of the Kinsman quartz monzonite are in Korzhinskii's stage II, and those of the Littleton formation in stage III, with the important difference that anthophyllite would be stable for highly mafic compositions in the New Hampshire area, rather than hypersthene.

A metamorphic reaction similar to that given has been postulated for rocks in southwestern Finland. Pehrman (1936) suggested that biotite-cordierite-garnet-microcline-oligoclase-quartz gneiss at Åbo has been transformed to cordierite-garnet-bearing granite by the reaction:

biotite + sillimanite + quartz = cordierite + potassic + feldspar + water.

Analyses of biotite from the gneiss and of cordierite and garnet from the granite are given (1936, p. 16–19); the ratios of FeO:(Fe+MgO) are 0.37 for biotite, 0.16 for cordierite, and 0.70 for garnet (neglecting 1 mole per cent of grossularite end member). In Pehrman's reaction the biotite and cordierite should have the same ratio of FeO:(FeO+MgO); the fact that they are different necessitates the presence of another mafic mineral in the reaction, which probably is garnet.

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