THE BIOTITE-CORDIERITE-ALMANDITE SUBFACIES OF THE HORNBLENDE-GRANULITE FACIES

D. DE WAARD
Syracuse University, Syracuse, N.Y., U.S.A.

ABSTRACT

The common, world-wide occurrence of regional-metamorphic quartz-K feldspar-plagioclase-sillimanite-cordierite-biotite-almandite and quartz-K feldspar-plagioclase-cordierite-biotite-almandite-hypersthene assemblages in pelitic gneisses, associated with hypersthene-bearing metabasites, granulites, and charnockites, are characteristic for the newly established biotite-cordierite-almandite subfacies of the hornblende-granulite facies.

Coexistence of reactants and products of the following two reactions is typomorphic for the subfacies:

biotite + sillimanite + quartz ↔ cordierite + almandite + orthoclase + H_2O
biotite + quartz ↔ cordierite + almandite + orthopyroxene + orthoclase + H_2O

Equilibrium is a function of FeO/MgO, P_{H_2O}, P_{load}, and T, and may be considered univariant for an open system, or divariant for a closed, H_2O-deficient system.

The biotite-cordierite-almandite subfacies forms the lower P_{load} (or higher T) portion of the hornblende-granulite facies, bordering on the pyroxene-hornfels facies, and occupying that part of P_{load}-T conditions in which cordierite and almandite are stable in common pelitic rocks. Within this stability field of coexisting cordierite and almandite the biotite-cordierite-almandite subfacies borders at lower P_{H_2O} (or higher T) on the cordierite-almandite subfacies of the pyroxene-granulite facies in which hydrous minerals are absent, and at higher P_{H_2O} (or lower T) on that part of the almandite-amphibolite facies which is characterized by coexisting biotite, cordierite, almandite, and anthophyllite.

INTRODUCTION

Wynne-Edwards & Hay (1963) presented in this magazine valuable chemical information on the coexisting minerals biotite, cordierite, and garnet, which occur in pelitic gneisses associated with charnockitic and granulitic rocks in the Westport area, Ontario. The authors demonstrate that the assemblage is at equilibrium, and they draw attention to the world-wide distribution of biotite-cordierite-garnet gneisses in high-grade metamorphic terranes. Their conclusion is that the association of biotite, cordierite, and garnet characterizes in pelitic rocks a regional metamorphic environment "transitional between those of granulite and high amphibolite facies" which is not defined by the present facies classification.

The occurrence of cordierite as a stable and widespread mineral in certain granulite-facies terranes was noted by Eskola (1939), and the possibility of a subdivision of the granulite facies based upon the presence or absence of cordierite has been suggested by Eskola (1952, 1957), and

Turner & Verhoogen (1960). Recently, the establishment was proposed of a biotite-cordierite-almandite subfacies representing the low P_{load} (or high T) portion of the hornblende-granulite facies*, and a possible cordierite-almandite subfacies of anhydrous assemblages which represents the lower P_{H_2O} (or higher T) conditions of the pyroxene-granulite facies (de Waard, 1965b).

Although there is agreement on the major point, the validity of stable biotite-cordierite-garnet assemblages as an indicator of a certain metamorphic environment, the *ACF* diagram constructed by Wynne-Edwards & Hay differs in some respects from the one proposed by the writer. This paper serves to amplify the writer's point of view by considering seven mineral phases in a six-component system, and to demonstrate the relative P_{load}-P_{H_2O}-T conditions of the new subfacies with respect to those of the four adjoining subfacies.

THE *ACFMK* DIAGRAM

Mineral assemblages of analysed cordierite-garnet gneisses and associated rocks from different high-grade metamorphic terranes of the world are shown in Table 1; the first ten are those from the Westport area. Wynne-Edwards & Hay attempt to demonstrate that the following three-phase assemblages of the *ACF* system can be recognized†: si-al-an si-co-al, and bi-co-al. Accordingly, si-al, co-al, and al-bi joins are shown in the *ACF* diagram.

In the first place it should be remarked that biotite is not properly a phase represented in *ACF*, because K_2O is not a component of this system (eastonitic biotite, when calculated for *ACF*, will plot in the diagram but is then presented as a rock composed of non-potassic phases such as hypersthene and garnet). Furthermore it is evident from Table 1 that cordierite-garnet gneisses have essentially the same mineral assemblage, *viz.*, quartz-K feldspar-plagioclase-sillimanite-cordierite-biotite-almandite. They cannot be divided into distinct groups, and have to be treated as one six-mineral field: or-an-si-co-bi-al, in addition to excess quartz. A co-an tie line must be present in the *ACF* diagram because cordierite and plagioclase coexist in almost all of the cordierite-garnet gneisses, though it may be sparse in several. The *ACF* diagram, as it is constructed here (left triangle in Fig. 1), shows that all of the cordierite-garnet gneisses fall in the an-co-al field.

---

*In order to avoid having subfacies of subfacies it is suggested here to elevate the hornblende and pyroxene-granulite subfacies (Turner, 1958) to the status of facies.

†The following abbreviations of mineral names are used: qu (quartz), or (K feldspar), an (anorthite), si (sillimanite), co (cordierite), bi (biotite), al (almandite), op (orthopyroxene).

The importance of separating FeO and MgO, lumped in the *F* corner of *ACF*, is properly shown in an *AFM* diagram in which the minerals sillimanite, cordierite, almandite, and orthopyroxene are represented, but not biotite because K_2O, also here, is not a component of this system. In Wynne-Edwards & Hay's *AFM* diagram most of the rock analyses fall in the co-al-bi field instead of in the si-co-al field as may have been expected because sillimanite is present in all but one of the rocks. (Their diagram is in effect a four-component system in which biotite is projected on the *AFM* plane). This failure is partly due to an error in the calculation (subtracting 2CaO from Al_2O_3), but mainly because of the method of calculation which translates the *AFM* components of biotite into non-potassic phases such as cordierite, almandite, and orthopyroxene, and into orthoclase which is eliminated by subtracting the molecular amount of K_2O from Al_2O_3. The only proper method for plotting biotite-bearing rocks in *AFM* in order to show their relationship with coexisting phases, such as sillimanite, cordierite, almandite, and orthopyroxene, is to correct the values of *A*, *F*, and *M* for the amount of biotite in the mode. A less tedious, but also less accurate method, followed here, is to calculate $A = Al_2O_3 - (Na_2O + CaO)$ with the idea that a smaller error is made by leaving in *A* the relatively small amount of Al_2O_3 equivalent to K_2O of K feldspar than by subtracting the fairly large amount of Al_2O_3 equivalent to K_2O of biotite. The *AFM* portion of Fig. 1 shows the analyses of cordierite-garnet gneisses of Table 1 situated in the si-co-al field.

The *AFK* diagram demonstrates the composition of rocks with respect to the minerals K feldspar, sillimanite, cordierite, almandite, orthopyroxene, and biotite. All of the cordierite-garnet gneisses, listed in Table 1, appear to fall in the or-co-al field of the *AFK* portion of diagram, Fig. 1. The mineral assemblages in the Table show, however, that both biotite and K feldspar are present, which is one phase too many for divariant equilibrium (in *AFMK* there are two interfering tetrahedrons: si-co-al-bi, and si-co-al-or). This condition, which is common for the transition from the almandite-amphibolite facies to the pyroxene-granulite facies, may be considered to reflect univariant equilibrium for an open system, or divariant equilibrium for a closed, H_2O-deficient system (de Waard, 1964, 1965a), for the reaction*:

$$(1)\quad \underset{\text{biotite}}{10\ K_2(Fe, Mg)_{5\frac{1}{2}}Al_3Si_{5\frac{1}{2}}O_{20}(OH)_4} + \underset{\text{sillimanite}}{28\ Al_2SiO_5} + \underset{\text{quartz}}{65\ SiO_2} \leftrightarrow$$

$$\underset{\text{cordierite}}{11\ (Fe, Mg)_2Al_4Si_5O_{18}} + \underset{\text{almandite}}{11\ (Fe, Mg)_3Al_2Si_3O_{12}} + \underset{\text{orthoclase}}{20\ KAlSi_3O_8} + 20\ H_2O$$

*To balance the equations simplified mineral compositions have been chosen which fairly closely correspond with those known from high-grade metamorphic terranes.

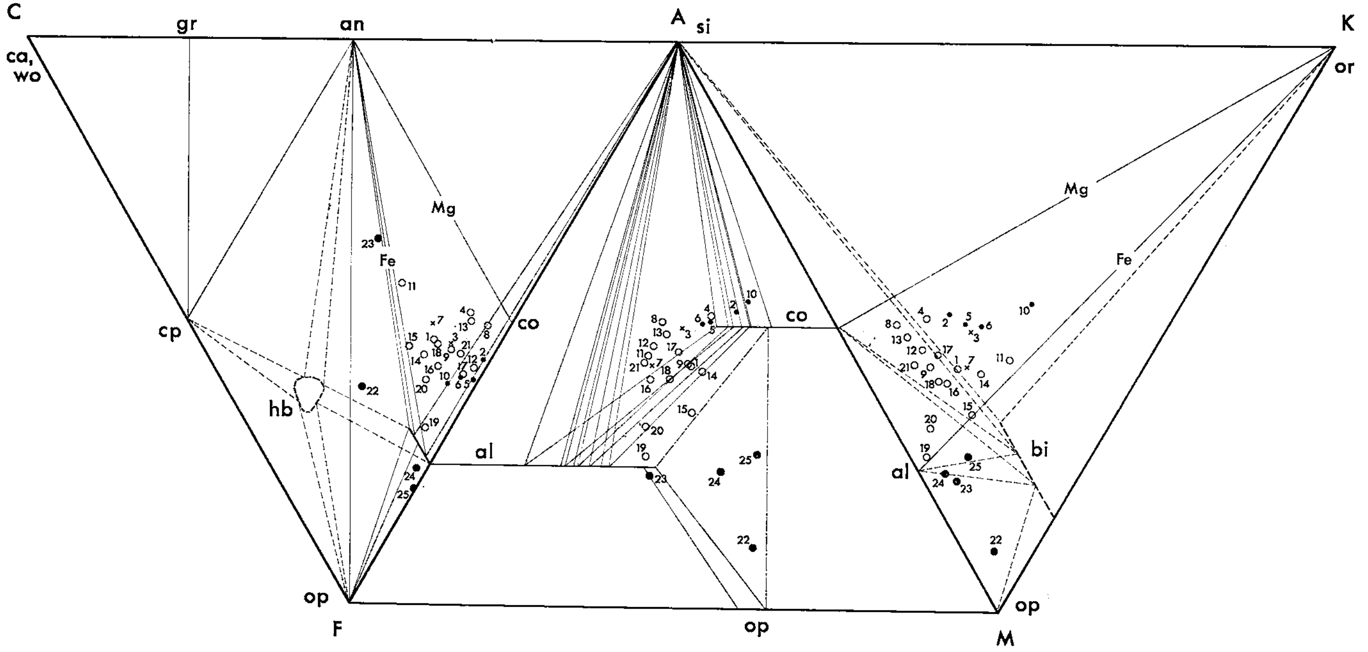


FIG. 1. *ACFMK* diagram for the biotite-cordierite-almandite subfacies illustrating the mineral assemblages of pelitic rocks. Legend: open circle, biotite-cordierite-garnet gneiss; cross, biotite-garnet gneiss; small dot, biotite-cordierite gneiss; large dot, hypersthene-bearing cordierite-garnet or garnet gneiss. Dashed tie lines and mineral phases represent the upper almandite-amphibolite facies; intersecting full-drawn tie lines represent the pyroxene-granulite facies.

TABLE 1. MINERAL ASSEMBLAGES OF BIOTITE-CORDIERITE-GARNET GNEISSES AND ASSOCIATED ROCKS

	Mineral assemblage									FeO/FeO+MgO			
No.	qu	or	ab	an	si	co	bi	al	An%	rock	co	bi	al
1	x	x	x	x	x	x	x	x		45.7	29.6	45.8	67.4
2	x	x	x	.	x	x	x	–		30.2	20.4	34.5	
3	x	x	x	x	x	–	x	x		48.1		50.4	67.4
4	x	x	x	x	x	x	x	x		38.5	34.0	50.2	69.9
5	x	x	x	.	–	x	x	–		39.0	26.8	43.1	
6	x	x	x	.	x	x	x	–		41.7	27.1	52.5	
7	x	x	x	x	x	–	x	x		56.4		48.2	65.0
8	x	x	–	–	x	x	x	x		54.1		54.3	70.7
9	x	x	x	x	x	x	x	x		46.2			
10	x	x	x	x	x	x	x	–		25.8			
11	x	x	x	x	x	x	x	x	34	57.6	37.1	53.4	80.8
12	x	x	x	x	x	x	x	x	28	56.4			
13	x	x	x	x	x	x	x	x	30–40	52.6	32.1	45.8	72.4
14	x	x	x	x	x	x	x	x	18	42.9			
15	x	x	x	x	–	x	x	x	23	46.0			
16	x	x	x	x	–	x	x	x	28	56.4			
17	x	x	x	x	x	x	x	x	20	49.2			73.4
18	x	x	x	x	x	x	x	x	23	51.8			
19	x	.	.	.	–	x	x	x		56.0			
20	x	x	x	x	x	x	x	x	40	56.5	27.0		63.2
21	x	–	x	x	x	x	x	x	30	58.6			
no.	qu	or	ab	an	co	bi	al	op	An%	rock	co	al	op
22	–	–	x	x	–	x	x	x		36.3		54.0	35.8
23	x	–	x	x	–	–	x	x		58.5		56.1	40.0
24	–	–	x	x	x	x	x	x	15	40.7			
25	x	–	–	–	x	x	x	x		32.7			

Legend: x present, . present in very small amounts, – absent or not reported. FeO of rocks reduced by TiO_2 to compensate for ore. Location and source: (1) Southeastern Ontario, Wynne-Edwards & Hay (1963), no. H-29; (2) ibid., no. H-60; (3) ibid., no. H-66; (4) ibid., no. H-70; (5) ibid., no. H-90; (6) ibid., no. H-105; (7) ibid., no. H-126; (8) ibid., no. WE-4-58; (9) ibid., no. WE-10-57; (10) ibid., no. WE-17-57; (11) Southwestern New Hampshire, Heald (1950), no. LM1; (12) ibid., no. LM6; (13) Sturbridge, Massachusetts, Barker (1962); (14) Southwestern Finland, Hietanen (1943), Table 3, no. 1; (15) ibid., no. 2; (16) ibid., no. 3; (17) South Finland, Parras (1958), Table 2, no. 53; (18) ibid., no. 57; (19) Lapland, North Finland, Eskola (1952), Table 2, no. 11; (20) ibid., no. 12; (21) South Coast, Western Australia, Clarke, Phillips, & Prider (1954), Table III, no. A, quoted from Simpson (1951), p. 105; (22) Lapland, North Finland, Eskola (1952), Table 1, no. 9; (23) ibid., no. 10; (24) Dangin, Western Australia, Prider (1945), Table III, no. 20481; (25) Mysore, South India, Radhakrishna (1954), Table I, no. 2.

The reaction represents the breakdown of biotite in systems with excess alumina and silica, *i.e.*, in common, sillimanite-bearing, pelitic rocks. The development of coexisting cordierite and almandite, as opposed to that of cordierite or almandite alone, is a function of P_{load}-T conditions and FeO/MgO ratios of rocks. The left-hand side of the reaction represents the almandite-amphibolite facies, characterized by coexisting biotite and sillimanite, and expressed by the dashed tie line in *AFK* of Fig. 1. The right-hand side represents the anhydrous assemblage of the pyroxene-granulite facies, demonstrated by the full-drawn tie lines co-or and al-or in Fig. 1. The combination of reactants and products of the reaction characterizes the hornblende-granulite facies, *i.e.*, the combination si-bi-co-al-or in this particular case.

The total number of coexisting minerals demonstrated by the plots of cordierite-garnet gneisses in Fig. 1, *ACF*: an-co-al, *AFM*: si-co-al, and *AFK*: bi-co-al-or, results in the six-phase assemblage or-an-si-bi-co-al which, in addition to quartz, are the minerals most commonly represented in the mode.

In pelitic rocks deficient in alumina the following reaction takes place instead of, and presumably at higher T (or lower P_{H_2O}) conditions than reaction (1):

$$(2)\quad \underset{\text{biotite}}{6\,K_2(Fe,\,Mg)_{5\frac{1}{2}}Al_3Si_{5\frac{1}{2}}O_{20}(OH)_4} + \underset{\text{quartz}}{39\,SiO_2} \leftrightarrow \underset{\text{cordierite}}{(Fe,\,Mg)_2Al_4Si_5O_{18}} +$$

$$\underset{\text{almandite}}{(Fe,\,Mg)_3Al_2Si_3O_{12}} + \underset{\text{orthopyroxene}}{28\,(Fe,\,Mg)SiO_3} + \underset{\text{orthoclase}}{12\,KAlSi_3O_8} + 12\,H_2O$$

Four hypersthene-bearing rocks (22–25), associated with cordierite-garnet gneisses, have been plotted in Fig. 1 to demonstrate the composition of this adjoining six-phase field, *ACF*: an-al-op, *AFM*: co-al-op, and *AFK*: bi-or-al-op, which combines to qu-or-an-co-bi-al-op as the maximum number of minerals present in the mode.

THE BIOTITE-CORDIERITE-ALMANDITE SUBFACIES

The five-component system *ACFMK*, shown for the biotite-cordierite-almandite subfacies in Fig. 1, is an attempt to illustrate fields of five (six in this case) mineral phases which can be visualized three-dimensionally in two stages by combining any two of the three triangles to four-component tetrahedrons. *AFK* and *AFM* are faces of the *AFMK* tetrahedron in which can be seen the si-co-al-or field in full-drawn tie lines, and the si-co-al-bi field in dashed tie lines. *ACF* and *AFM* form two faces of the *ACFM* tetrahedron which includes the si-co-al-an field.

In common rock types the following mineral assemblages may be expected:

(a) qu-or-an-si-co-bi-al
(b) qu-or-an-co-bi-al-op
(c) qu-or-an-bi-hb-op
(d) qu-or-an-hb-op-cp
(e) qu-an-bi-al-hb-op

Assemblages (a) and (b), depending on the alumina content of the rock, are found interlayered in pelitic gneisses. Associated charnockites contain assemblage (c) or (d), depending on the alumina-lime ratio of the rock. Assemblages (d) and (e) occur in basic layers which are common in charnockitic and pelitic rock units. The combination of hypersthene and hydrous minerals in assemblages (b), (c), (d), and (e) is characteristic for the hornblende-granulite facies. Assemblages (c), (d), and (e) may occur in both the biotite-cordierite-almandite and the hornblende-orthopyroxene-plagioclase subfacies (see below). Assemblages (a) and (b) are typical for the biotite-cordierite-almandite subfacies.

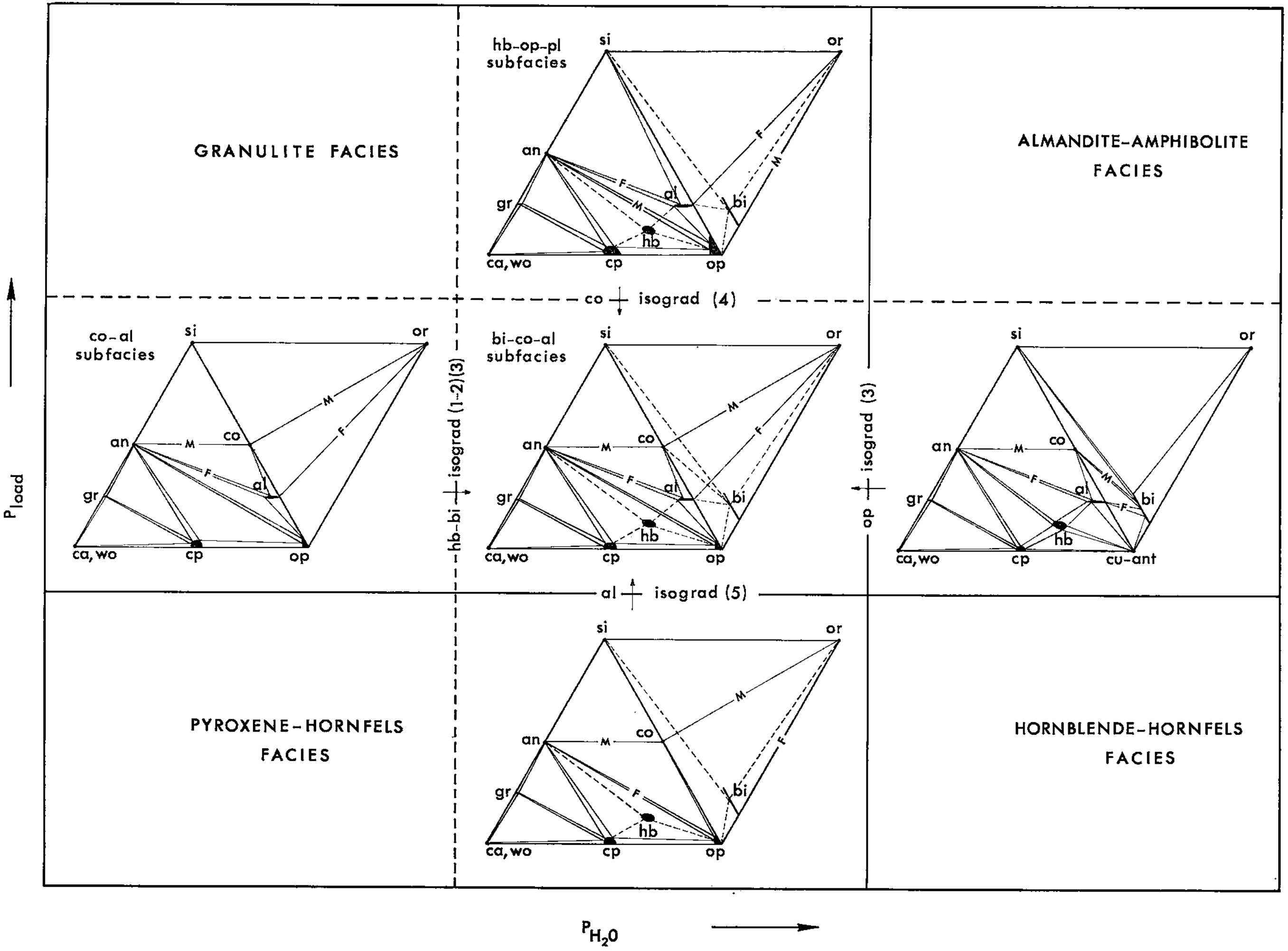
The relationships between the biotite-cordierite-almandite subfacies and adjoining subfacies is shown in diagram, Fig. 2, as a function of P_{load}, P_{H_2O}, and T. Because P and T have opposing effects on the boundary reactions the three variables can be reduced to the two pressures which are inversely related to T. The transition from one subfacies to another may thus be produced also under similar P conditions by a change of T in the opposite sense from a change of P. The biotite-cordierite-almandite subfacies occupies the low P_{load} (or high T) field of the hornblende-granulite facies, borders at higher P_{load} (or lower T) on the hornblende-orthopyroxene-plagioclase subfacies, and at lower P_{load} (or higher T) on the pyroxene-hornfels facies. At lower P_{H_2O} (or higher T) it adjoins the cordierite-almandite subfacies of the pyroxene-granulite facies, and at higher P_{H_2O} (or lower T) a cordierite-garnet-containing subfacies which represents the low P_{load}, low P_{H_2O}, or high T portion of almandite-amphibolite-facies environments.

As a function of P_{H_2O}-T the boundary between the biotite-cordierite-almandite subfacies and the upper almandite-amphibolite facies may be defined by reactions (1) and (2). In view of the more general applicability, however, the boundary is better defined by the following reaction which involves the typomorphic assemblages of both the almandite-amphibolite facies and the pyroxene-granulite facies:

$$(3)\quad \underset{\text{hornblende}}{NaCa_2(Fe,Mg)_4Al_3Si_6O_{22}(OH)_2} + \underset{\text{almandite}}{(Fe,Mg)_3Al_2Si_3O_{12}} + \underset{\text{quartz}}{5\,SiO_2} \leftrightarrow$$

$$\underset{\text{orthopyroxene}}{7\,(Fe,Mg)SiO_3} + \underset{\text{plagioclase}}{NaAlSi_3O_8 + 2\,CaAl_2Si_2O_8} + H_2O$$

According to the reaction the boundary between the almandite-amphibolite facies and the hornblende-granulite facies is delineated in the field by the first appearance of hypersthene in basic rock types, and the boundary between the hornblende-granulite facies and the pyroxene-granulite facies, ideally, by the last occurrence of hornblende in these rocks. It should be noted that reactions (1), (2), and (3) may well be


GRANULITE FACIES
ALMANDITE-AMPHIBOLITE FACIES
PYROXENE-HORNFELS FACIES
HORNBLENDE-HORNFELS FACIES
hb-op-pl subfacies
co-al subfacies
bi-co-al subfacies
co ┼ isograd (4)
al ┼ isograd (5)
hb-bi ┼ isograd (1-2)(3)
op ┼ isograd (3)
si
or
an
gr
ca, wo
cp
op
co
al
bi
hb
cu-ant
M
F
P_{load}
P_{H_2O}

expected to take place at different P_{H_2O}-T conditions, and that these conditions for each reaction are influenced by cation ratios of the rock.

The biotite-cordierite-almandite subfacies is distinguished from the hornblende-orthopyroxene-plagioclase subfacies by the appearance of cordierite in pelitic rocks (*e.g.*, Scheumann, 1925; Scheumann & Huckenholz, 1961). The boundary reaction which limits the stability fields of coexisting femic minerals as a function of FeO/MgO ratios, P_{load}, and T may be conveniently expressed in phases of the *AFM* system as follows:

$$\text{(4)}\qquad \mathrm{si + al + op} \begin{array}{l} \diagup\ \mathrm{si + co' + al'} \\ \text{—}\ \mathrm{co'' + al''} \\ \diagdown\ \mathrm{co''' + al''' + op'''} \end{array}$$

The boundary between the two subfacies is delineated in the field by a cordierite isograd which has coexisting cordierite and almandite in pelitic rocks on one side and a consistent absence of cordierite in sillimanite-biotite-garnet gneisses on the other.

The low P_{load} (or high T) boundary of the biotite-cordierite-almandite subfacies, and of the hornblende-granulite facies, is marked by the disappearance of almandite in the pyroxene-hornfels facies (*e.g.*, Wheeler, 1955):

$$\text{(5)}\qquad \begin{array}{l} \mathrm{si + co + al}\ \diagdown \\ \mathrm{co' + al'}\ \rightarrow \\ \mathrm{co'' + al'' + op''}\ \diagup \end{array} \mathrm{si + co''' + op'''}$$

The coexistence of biotite, cordierite, and hypersthene characterizes the pyroxene-hornfels facies.

The biotite-cordierite-almandite subfacies thus occupies a portion of P_{load}-T environments in which the stability fields of cordierite and almandite in pelitic assemblages overlap. The subdivision of this cordierite-almandite field, as shown in Fig. 2, is based upon P_{H_2O}-T-controlled dehydration reactions, giving rise to adjoining cordierite-almandite-containing subfacies in the pyroxene-granulite and almandite-amphibolite facies.

Regional distribution and common occurrence amply evidence the existence of cordierite-almandite-bearing subfacies. Rocks of the biotite-cordierite-almandite subfacies, distinguished by bi-co-al-or and bi-co-al-op-containing assemblages, occur on a regional scale and commonly

---

FIG. 2. Relationships between metamorphic environments of the biotite-cordierite-almandite subfacies and adjoining subfacies presented as a P_{load}-P_{H_2O}-T controlled, H_2O-deficient system for rocks with excess SiO_2 (T and P_{load} or P_{H_2O} have opposing effects on the boundary reactions). Subfacies are represented by *ACF-AFK* diagrams in which tie lines marked *F* and *M* indicate the effect of FeO/MgO on the assemblage.

associated with hypersthene-bearing metabasites, granulites, and charnockites, *e.g.*, in Ontario, Canada (Wynne-Edwards & Hay, 1963) and in the adjoining northwestern Adirondacks (Smyth & Buddington, 1926), in western Greenland (Ramberg, 1949), South Norway (Bugge, 1943), South Finland (Hietanen, 1943, 1947; Parras, 1946, 1958), Lapland (Eskola, 1952), Arctic Russia (Rabkin & Ravich, 1960; Bondarenko, 1964), the Aldan Shield in Siberia (Marakushev, 1964), Mysore and Madras States in South India (Iyer, 1929; Rama Rao, 1945), Ceylon (Cooray, 1963), Western Australia (Prider, 1945, 1958), Central Australia (Wilson, 1960), South Australia (Andrews, 1922; Binns, 1964), and Antarctica (Stillwell, 1918; Tilley, 1940; McCarthy & Trail, 1963).

The cordierite-almandite subfacies, characterized by the absence of hydrous minerals in cordierite-garnet assemblages, occurs in the Egersund area, southwestern Norway (Michot, 1957, 1960). The cordierite-almandite-containing portion of the almandite-amphibolite facies, distinguished by the absence of hypersthene, and the presence of anthophyllite in cordierite-garnet gneisses and in associated rocks, is found, *e.g.*, in Ontario, Canada (Pye, 1957), South Norway (Bugge, 1943), South Finland (Tuominen & Mikkola, 1950), and Western Australia (Johnstone, 1950).

P-T conditions of the cordierite-almandite-containing subfacies are transitional into those of the pyroxene-hornfels and hornblende-hornfels facies, approximately where the vaguely separated environments of regional and contact metamorphism meet. Because of these transitional P-T conditions the subfacies, which are defined by their mineral assemblages and not by their geologic occurrence, may be found in both regional and contact-metamorphic environments. The biotite-cordierite-almandite subfacies occurs predominantly in regional-metamorphic setting, but it is also represented in some contact-metamorphic aureoles, and in intermediate cases it is found on a limited scale in and around plutonic domes, such as the bi-co-al-or-gneiss occurrences in New England (Heald, 1950; Barker, 1961, 1962), which may represent local upward bulges in regional-metamorphic isograd surfaces. An example of the presence of the biotite-cordierite-almandite subfacies in contact-metamorphic aureoles is the occurrence of bi-co-al-or hornfelses, which developed from medium-grade regional-metamorphic schists, adjacent to the Lochnagar granodioritic intrusions in Scotland (Chinner, 1962).

REFERENCES

Andrews, E. C. (1922): The geology of the Broken Hill District, *Mem. Geol. Surv. New South Wales, Geol.*, **8**, 432 pp.

BARKER, F. (1961): Phase relations in cordierite-garnet-bearing Kinsman quartz monzonite and enclosing schist, Lovewell Mountain quadrangle, New Hampshire, *Am. Min.*, **46**, 1166–1176.

——— (1962): Cordierite-garnet gneiss and associated microcline-rich pegmatite at Sturbridge, Massachusetts and Union, Connecticut, *Am. Min.*, **47**, 907–918.

BINNS, R. A. (1964): Zones of progressive regional metamorphism in the Willyama Complex, Broken Hill District, New South Wales, *J. Geol. Soc. Australia*, **11**, 281–330.

BONDARENKO, L. P. (1964): The granulites and the charnockites of the central part of the Kola Peninsula, *XXII Int. Geol. Congress, Reports of the Soviet geologists, Problem 13, Charnockites, Moscow, 13–31.*

BUGGE, J. A. W. (1943): Geological and petrographical investigations in the Kongsberg-Bamble formation, *Norges Geol. Unders.*, **160**, 150 pp.

CHINNER, G. A. (1962): Almandine in thermal aureoles, *J. Petrology*, **3**, 316–340.

CLARKE, E. DE C., PHILLIPS, H. T., & PRIDER, R. T. (1954): The Pre-Cambrian geology of part of the South Coast of Western Australia, *J. Roy. Soc. Western Australia*, **38**, 1–64.

COORAY, P. G. (1963): The charnockites of Ceylon—a review, *Geol. Soc. India, Symposium on charnockites, Abstracts*, p. 1.

DE WAARD, D. (1964): Mineral assemblages and metamorphic subfacies in the granulite-facies terrane of the Little Moose Mountain syncline, south-central Adirondack highlands, *Proc. Kon. Ned. Akad. Wetensch., Amsterdam*, B. **67**, 344–362.

——— (1965a): The occurrence of garnet in the granulite-facies terrane of the Adirondack highlands, *J. Petrology*, **6**, 165–191.

——— (1965b): A proposed subdivision of the granulite facies, *Am. J. Sci.*, **263**, 455–461.

ESKOLA, P. (1939): Die metamorphen Gesteine, In: Barth, T. F. W., Correns, C. W., & Eskola, P., *Die Entstehung der Gesteine*, Springer, Berlin, 263–407.

——— (1952): On the granulites of Lapland, *Am. J. Sci., Bowen vol.* 133–171.

——— (1957): On the mineral facies of charnockites, *J. Madras Univ.*, B. **27**, 101–119.

HEALD, M. T. (1950): Structure and petrology of the Lovewell Mountain quadrangle, New Hampshire, *Geol. Soc. Am. Bull.*, **61**, 43–89.

HIETANEN, A. (1943): Ueber das Grundgebirge des Kalantigebietes im südwestlichen Finnland, *Bull. Comm. Géol. Finlande*, **130**, 105 pp.

——— (1947): Archean geology of the Turku district in southwestern Finland, *Geol. Soc. Am. Bull.*, **58**, 1019–1084.

IYER, L. A. N. (1929): A study of the calc-gneisses, scapolite-gneisses, and cordierite-garnet-sillimanite-rocks of Coimbatore, Madras Presidency; with comparison to other similar occurrences in India, *Mineral. Mag.*, **22**, 121–135.

JOHNSTONE, M. H. (1950): The geology of the Hamersley Siding area, *J. Roy. Soc. Western Australia*, **36**, 45–75.

MARAKUSHEV, A. A. (1964): Some mineral facies of metamorphic rocks poor in calcium, *XXII Int. Geol. Congress, Reports of the Soviet geologists, Problem 13, Charnockites, Moscow*, 54–75.

MCCARTHY, W. R. & TRAIL, D. S. (1963): The high-grade metamorphic rocks of the Mac-Robertson Land and Kemp Land coast, *Bur. Min. Resour. Aust., Rec.*, 1963/144, 9 pp.

MICHOT, P. (1957): Phénomènes géologiques dans la catazone profonde, *Geol. Rundschau*, **46**, 147–173.

——— (1960): La géologie de la catazone: le problème des anorthosites, la palingenèse basique et la tectonique catazonale dans le Rogaland méridional, (Norvège méridionale), *XXI Int. Geol. Congress, Guidebook g*, 54 pp.

PARRAS, K. (1946): On the coarse-grained garnet-cordierite gneisses of South and South-West Finland, *Bull. Comm. Géol. Finlande*, **138**, 1–7.

——— (1958): On the charnockites in the light of a highly metamorphic rock complex in southwestern Finland, *Bull. Comm. Géol. Finlande*, **181**, 137 pp.

PRIDER, R. T. (1945): Charnockitic and related cordierite-bearing rocks from Dangin, Western Australia, *Geol. Mag.*, **82**, 145–172.

——— (1958): The granulites and associated rocks of Galena, Western Australia, *Australasian Inst. Mining & Metall., Stillwell Anniversary vol.*, 189–211.

PYE, E. G. (1957): Geology of the Manitouwadge area, *Ontario Dept. Mines, Ann. Rept.*, **66**, pt. 8, 114 pp.

RABKIN, M. I. & RAVICH, M. G. (1960): The Precambrian of the Soviet Arctic, in: *Geology of the Arctic*, G. O. Raasch, ed., Univ. Toronto Press, Toronto, 18–30.

RADHAKRISHNA, B. P. (1954): On the nature of certain cordierite bearing granulites bordering the Closepet granites of Mysore, *Mysore Geol. Dept. Bull.*, **21**, 1–25.

RAMA RAO, B. (1945): The charnockite rocks of Mysore (Southern India), *Mysore Geol. Dept. Bull.*, **18**, 199 pp.

RAMBERG, H. (1949): The facies classification of rocks: a clue to the origin of quartzo-feldspathic massifs and veins, *J. Geol.*, **57**, 18–54.

SCHEUMANN, K. H. (1925): Die gesteins- und mineralfazielle Stellung der Metakieselschiefergruppe der südlichen Randzone des sächsischen Granulitgebirges, *Abh. Math.-Phys. Kl. Sächs. Akd. Wiss.*, **39**, 3–44.

——— & HUCKENHOLZ, G. (1961): Die Cordieritgneise und Granatgneise des sächsischen Granulitgebirges, *N. Jb. Miner., Abh.*, **96**, 131–161.

SIMPSON, E. S. (1951): *Minerals of Western Australia*, vol. 2, W. H. Wyatt, Perth, 675 pp.

SMYTH, C. H. & BUDDINGTON, A. F. (1926): Geology of the Lake Bonaparte quadrangle, *New York State Mus. Bull.*, **269**, 106 pp.

STILLWELL, F. L. (1918): The metamorphic rocks of Adelie Land, *Australasian Antarctic Expedition, 1911–1914, Scient. Rep.*, A, **3**, pt. 1, 1–230.

TILLEY, C. E. (1940): A group of gneisses (sillimanitic and cordieritic) from the moraines at Cape Denison, *Australasian Antarctic Expedition, 1911–1914, Scient. Rep.*, A, **4**, pt. 10, 339–344.

TUOMINEN, H. V. & MIKKOLA, T. (1950): Metamorphic Mg-Fe enrichment in the Orijärvi region as related to folding, *Bull. Comm. Géol. Finlande*, **150**, 67–92.

TURNER, F. J. (1958): Mineral assemblages of individual metamorphic facies, In: Fyfe, W. S., Turner, F. J., & Verhoogen, J., Metamorphic reactions and metamorphic facies, *Geol. Soc. Am. Mem.*, **73**, 199–239.

——— & VERHOOGEN, J. (1960): *Igneous and metamorphic petrology*, 2nd ed., McGraw-Hill, New York, 694 pp.

WHEELER, E. P. (1955): Adamellite intrusive north of Davis Inlet, Labrador, *Geol. Soc. Am. Bull.*, **66**, 1031–1060.

WILSON, A. F. (1960): The charnockitic granites and associated granites of Central Australia, *Trans. Roy. Soc. S. Aust.*, **83**, 37–76.

WYNNE-EDWARDS, H. R. & HAY, P. W. (1963): Coexisting cordierite and garnet in regionally metamorphosed rocks from the Westport area, Ontario. *Can. Mineral.*, **7**, 453–478.

Manuscript received June 23, 1965, emended December 12, 1965