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PARTIAL MELTING OF COMMON ROCKS AS A POSSIBLE SOURCE OF CORDIERITE-ANTHOPHYLLITE BEARING ASSEMBLAGES

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ABSTRACT. Cordierite-anthophyllite bearing rocks, with no chemical counterparts among common sedimentary or igneous rocks, have been interpreted by appeal to special circumstances involving changes in composition.

While compositional change is required, the common occurrence of cordierite-anthophyllite bearing rocks in high grade regional metamorphic terranes suggests that there at least a common mode of origin may be sought.

In this environment, partial melting may be anticipated, and removal of melt will usually result in a residuum different in composition from the original rock.

The possibility that these processes may produce cordierite-anthophyllite bearing rocks is investigated by consideration of pertinent phase equilibria in the system Al_2O_3–MgO–K_2O–Na_2O–SiO_2–H_2O and the development of a petrogenetic grid. It is suggested that cordierite-anthophyllite bearing rocks may be formed from such common pre-melting assemblages as potassium feldspar–plagioclase–biotite–sillimanite–quartz and hence from various common protoliths, by partial melting, filter pressing, and recrystallization.

Development of the grid elucidates the possible formation of granitic melts, from assemblages not containing potassium feldspar or muscovite, by incongruent melting of quartz–plagioclase–biotite with or without sillimanite or cordierite.

INTRODUCTION

The origin of cordierite-anthophyllite bearing rocks is commonly difficult to explain in that they do not have chemical counterparts among common sedimentary or igneous rocks. Hence, mechanisms which, in particular, may concentrate Mg and Fe, have been proposed as important in their formation from a variety of protoliths. These include Mg(Fe) metasomatism (Bugge, 1943, p. 99), leaching of lime and alkalis (Bugge, 1943, p. 99), both of these (Eskola, 1914, p. 262), weathering prior to metamorphism (Tilley and Flett, 1929, p. 38), and structural movements during early stages of metamorphism (Tuominen and Mikkola, 1950, p. 67).

However, it is becoming increasingly evident that the association cordierite-anthophyllite (or the closely related gedrite) is not uncommon in regions of high grade regional metamorphism (Montana, Colorado, New England, Minnesota, British Columbia, Southeastern Norway, et cetera), and it is therefore desirable to consider whether this association may be produced from common sedimentary or igneous rocks by processes commonly to be expected in high grade regional metamorphism.

The rocks being considered here are found in migmatitic terranes near or above the second sillimanite isograd. They are schists and gneisses whose assemblages may include, in addition to cordierite and anthophyllite (or gedrite), plagioclase, biotite, garnet, quartz, ilmenite, and magnetite. Assemblages with white mica, potassium feldspar, or sillimanite in addition to some of the above minerals, except anthophyllite,

are common associates. Amphibolites are usually present, with or without cummingtonite, and so are granitic veins, lenses, dikes, or sills, the evidence of whose origin is usually equivocal but much discussed.

The question thus arises, is there operative in such terranes some process whereby change in composition may be effected? From experiments on synthetic and natural systems, as well as from theory, the process of partial melting has been established as viable and is the logical extension of progressive regional metamorphism. (Its efficacy in this context depends, inter alia, on the presence of sufficient water, and one may still debate the extent, as opposed to the occurrence, of the process in nature.) Removal of melt so formed will usually result in a residuum different in composition from the pre-melting protolith.

In this paper, the possibility examined is that a common protolith may give rise to a cordierite-anthophyllite bearing residuum and a melt of granitic composition by partial melting, filter pressing, and recrystallization.

This is done by considering pertinent phase equilibria in the system Al_2O_3–MgO–K_2O–Na_2O–SiO_2–H_2O, the best compromise between simplicity of presentation and complexity of nature. A petrogenetic grid is derived on the basis of Schreinemaker's rules and a minimum of experimental data, and the possibilities apparent from this are discussed. Next, the grid is oriented in pressure-temperature space in a compromise between available data and the assumptions made, and the preliminary conclusions refined. Finally, the effects of some of these assumptions are considered, and an extrapolation to a more realistic iron-bearing system is advanced.

It is emphasized that it is not the thesis that partial melting of common rocks is the only way by which cordierite-anthophyllite bearing assemblages may be produced even in high-grade terranes but rather that this is a possible source of such assemblages.

THE SYSTEM Al_2O_3–MgO–K_2O–Na_2O

In the choice of a pertinent system to show the desired relations, one is restricted to four determining inert components in order to represent phase relations graphically. Such four might be K_2O–Al_2O_3–MgO–FeO (Thompson, 1957), but this has the disadvantage that the relationships of the feldspars to partial melting are not portrayed: we require at least Na_2O in addition to K_2O. This means that either MgO and FeO must be considered isochemical or one or the other omitted. Because cordierite and anthophyllite are dominantly magnesian phases, Al_2O_3, MgO, K_2O, and Na_2O are chosen as the inert components. This choice also eliminates in our initial considerations the oxidation problems which may arise in an iron-bearing system. The complete system which will be considered here is, then, Al_2O_3–MgO–K_2O–Na_2O–SiO_2–H_2O. The pertinent phases which may be discussed in terms of these components are given in table 1, along with other phase compositions and abbreviations used.

TABLE 1

Abbreviation	Phase	Composition
L	Melt	
K′	Melt	$KAlSi_3O_8 \cdot xSiO_2 \cdot yH_2O$
P′	Melt	$NaAlSi_3O_8 \cdot xSiO_2 \cdot yH_2O$
K	Potassium feldspar	$KAlSi_3O_8$
P	Albite	$NaAlSi_3O_8$
B	Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$
C	Mg cordierite	$Mg_2Al_4Si_5O_{18}$
G	Almandine	$Fe_3Al_2Si_3O_{12}$
S	Sillimanite, kyanite, andalusite	Al_2SiO_5
A*	Mg anthophyllite	$Mg_7Si_8O_{22}(OH)_2$
E*	Enstatite	$MgSiO_3$
T*	Talc	$Mg_3Si_4O_{10}(OH)_2$
Q	Quartz	SiO_2
Cor	Corundum	Al_2O_3
Mu	Muscovite	$KAl_2AlSi_3O_{10}(OH)_2$
Fo	Forsterite	Mg_2SiO_4
Ch	Mg chlorite	$(MgAl)_5(AlSi)_2O_5(OH)_4$
	Spinel	$MgAl_2O_4$
	Glaucophane	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$

Note: Where natural assemblages or additional components are specifically considered, the same abbreviations are used for the phases corresponding to the end-members listed above.

* M denotes a magnesian silicate, A, E, or T.

The discussion is simplified by considering only phase relations in assemblages (1) in equilibrium with quartz plus fluid, (2) outside the stability field of quartz-muscovite, and (3) where $P_f = P_{H_2O} = P_s$.

The restrictions allow the omission of Mg chlorite (not stable with quartz above about 680°C according to Fawcett and Yoder, 1966, p. 378; Schreyer, 1968, p. 386) as well as forsterite, corundum, and spinel which are not stable with quartz.

Glaucophane is eliminated from consideration not on the basis of the above restrictions but on the basis that, to the writer's knowledge, it has not been found associated with cordierite-anthophyllite bearing assemblages. However, Ernst (1961) has shown that "glaucophane", quartz, and fluid can coexist in part of the cordierite–anthophyllite–quartz field (in fig. 4, that portion of the field between curves (5) and (6) wherein cordierite is stable), for example at temperatures to 750°C at $P_{H_2O} = 2$kb. Were this so in nature, anthophyllite and albite could not coexist stably (Ernst, 1961, p. 763), but this association is found (Rabbitt, 1948, table 13; Salotti, 1962). The natural assemblages and the experimental data may be reconciled by Ernst's hypothesis (1959, 1963) of two synthetic polymorphs of glaucophane, of which the polymorph with the larger cell volume has no known natural analog. It is this polymorph that has the high temperature and low pressure stability field in the experimental work.

The assumption of $P_f = P_{H_2O} = P_s$, although common in experimental and theoretical work, may not be a good approximation to

reality. Both equalities may be lacking, with significant effects on the phase equilibria involved (see, for example Albee, 1965; Luth, 1967).

Thus, there are three magnesium silicates to be considered (anthophyllite, enstatite, and talc) and one magnesium aluminosilicate (cordierite).

The chemographic relationships between the pertinent phases are shown schematically in figure 1. All these condensed phases, except sillimanite, andalusite, and kyanite, are of variable composition. The relationships shown in figure 1 are used as a first approximation until discussion of the effects of variation in composition (p. 920).

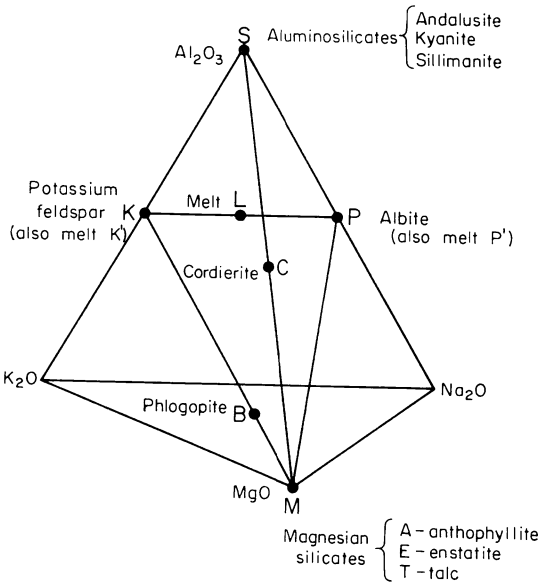


Fig. 1. Chemographic relationships between LKPBCSM in the tetrahedron Al_2O_3–MgO–K_2O–Na_2O, neglecting compositional ranges in liquid or solid solutions.

In the chemographic diagram (fig. 1) several collinearities appear:

1. CSM and KBM. These require little comment: they are due to the use of the simple end-member formulae of table 1. In fact, both may be valid for a wide range of conditions and compositions, witness the rareness of stable associations, magnesian silicate and aluminosilicate, or potassium feldspar and talc or anthophyllite, although potassium feldspar plus hypersthene is well known in charnockites, presumably due to the restriction and elimination of biotite-bearing assemblages.

2. LKP. This is valid for melts on the quartz-feldspar cotectic of the system $KAlSi_3O_8$–$NaAlSi_3O_8$–SiO_2–H_2O. In the system Al_2O_3–K_2O–Na_2O–SiO_2–(H_2O), the first melt in the quaternary volume probably lies slightly to the Al_2O_3 side of the orthoclase–albite–quartz (KPQ) plane (see Tuttle and Bowen, 1958, p. 87). In the present system, then, the melt

(L) should be shown on the Al_2O_3 side of KP and, indeed, within the tetrahedron of figure 1 if melting of phlogopite, cordierite, or a magnesian silicate (B, C, or M) gives rise to an Mg-component in the melt. However, it is a reasonable first approximation that the first liquids formed during partial melting will project very close to KP considering the refractory nature of the other minerals involved (Winkler and von Platen, 1961a, b).

3. LKPBM, KBCSM, and PCSM are coplanar in the simplified system.

THE PRELIMINARY GRID

We now analyze the system (fig. 1) of four components and seven phases (considering but one phase S and one phase M) in terms of invariant and univariant equilibria. On the basis of the chemographic relationships of figure 1, Schreinemakers' rules (Niggli, 1954), and experimental data pertinent to three of the reactions involved (fig. 4), the schematic grid of figure 2 is derived. The full derivation is given in Appendix A.

The seven possible invariant points (or associated bundles) are designated by the phase that does not participate at each: They are, then, [L], [K], [P], et cetera. Univariant equilibria are designated by the phases involved, quartz or fluid being omitted except where a distinction is necessary between equilibria in which they can or cannot participate. Thus, LKP designates an equilibrium between melt, potassium feldspar, and albite with quartz and fluid as possible additional phases. If it is desired to view such equilibria as reactions, then reactants and products can be distinguished from the figures as is done in figure 2B. In addition, univariant equilibria are designated by the phases that do not participate, where this seems desirable, for example [PM] on figure 3.

QUALITATIVE CONCLUSIONS FROM THE PRELIMINARY GRID

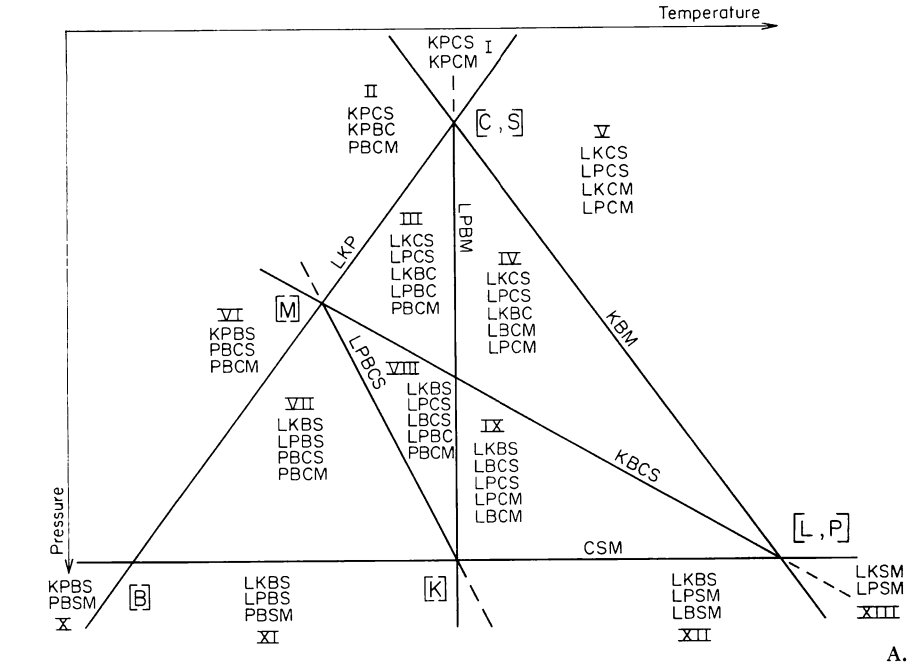
In view of the complications that arise when one attempts to make the grid of figure 2 more precise, it is desirable to outline the possibilities that exist thus far. These preliminary conclusions will be refined in later sections.

If the phase relationship of figure 1 and the grid of figure 2 actually pertained in nature then the following conclusions could be drawn:

1. The association cordierite-magnesian silicate (CM) is possible in the nine facies, I to IX inclusive, within the stability field of cordierite.

2. The production of cordierite-magnesian silicate (CM) from compositions in the volume albite–phlogopite–cordierite–magnesian silicate (PBCM) requires but simple recrystallization under the necessary external conditions.

3. The assemblage potassium feldspar–albite–cordierite–magnesian silicate (KPCM) can occur at temperatures below those at which melt is formed (facies I), due to the breakdown of phlogopite (-quartz) in the assemblages potassium feldspar–albite–phlogopite–cordierite (KPBC) and



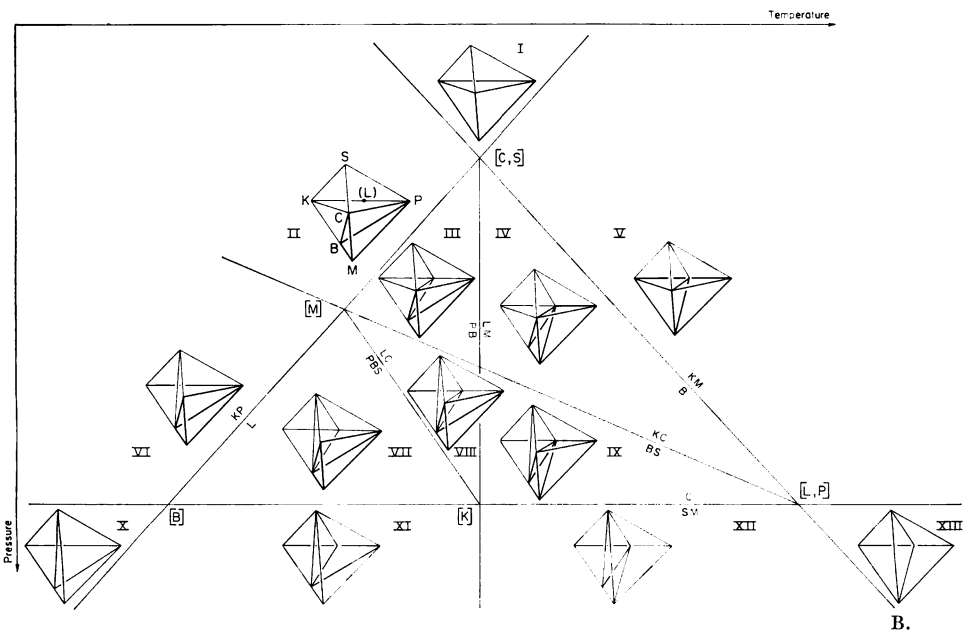


Fig. 2. (A) and (B) Schematic invariant and univariant equilibria between phases indicated in figure 1, with divariant assemblages for each facies region (referred to by Roman numerals). Quartz and fluid are possible additional phases. Volumes heavily outlined are those involving cordierite-magnesian silicate.

albite–phlogopite–cordierite–magnesian silicate (PBCM). Assemblages melt–potassium feldspar–cordierite–magnesian silicate (LKCM) and melt–albite–cordierite–magnesian silicate (LPCM) can occur at temperatures above those at which melt can form (facies V).

4. Of greater interest, largely due to the restrictions on the melt–cordierite–anthophyllite–quartz stability field (see later, fig. 6), are the possibilities of melt–cordierite–magnesian silicate with either phlogopite or albite (LCBM or LPCM) in two facies IV and IX, in the region between LPBM, KBM, and CSM (fig. 2A). If at least part of this region lies within the stability field of cordierite–anthophyllite–quartz, then phlogopite–cordierite–anthophyllite and albite–cordierite– anthophyllite can arise in systems whose compositions lie outside the tetrahedron PBCM (figs. 1 and 2B). This may be illustrated by means of the facies series VI–VII–VIII–IX (fig. 2).

Consider the volume KPBS in VI. This is replaced in VII by the two volumes LKBS and LPBS due to development of a melt (L) on the join KP (LKP is forbidden as a divariant assemblage due to assumed presence of quartz in the simple system). In VIII LKBS remains, but LPBS is no longer stable, the corresponding compositional volume being divided between LPCS, LBCS, and LPBC. In facies IX incongruent melting of PB gives rise to the association LM, and thus the volume LPBC of facies VIII is now distributed between the volumes LBCM and LPCM. If L were removed from either of the latter, say, by filter pressing, such that the local bulk composition moved into the volume PBCM, then on equilibrium retrogression, the assemblage PBCM would form and persist if subsolidus retrogression were inhibited. (Retrogression in the presence of melt may be expected to show a close approach to equilibrium, due to enhanced ease of diffusion, and equilibrium assemblages thus produced would not represent the highest pressure-temperature conditions attained during the metamorphism.)

If the relevant magnesian silicate were anthophyllite, then, in this example of a facies series, an assemblage potassium feldspar–albite–phlogopite–aluminosilicate (KPBS) with the requisite bulk composition could give rise to melt–cordierite–anthophyllite with phlogopite or albite (LBCA or LPCA). With sufficient removal of melt and retrogression to subsolidus conditions the assemblage albite–phlogopite–cordierite–anthophyllite (PBCA) could result. Other subsolidus assemblages which could give rise to LBCA or LPCA are potassium feldspar–albite–phlogopite–cordierite (KPBC, II), albite–phlogopite–cordierite–aluminosilicate (PBCS, VI, VII), and albite–phlogopite–aluminosilicate–magnesian silicate (PBSM, X, XI), all with quartz and fluid as possible additional phases.

The requisite compositions in the tetrahedron LPBC (fig. 1) are similar to but simpler than those of common sedimentary rocks in the graywacke range and of some pyroclastic and igneous rocks of granodioritic to quartz dioritic compositions.

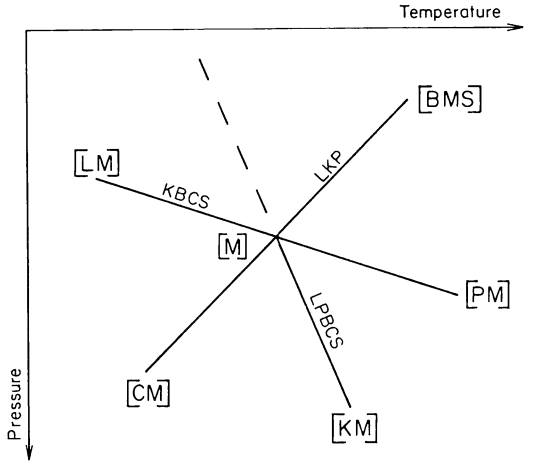


Fig. 3. Schematic univariant equilibria around invariant point [M] of figure 2.

Thus, it is possible that partial melting of common rock compositions, coupled with sufficient removal of melt from the local system, could give rise to cordierite-anthophyllite bearing assemblages.

REFINEMENT OF THE GRID IN PRESSURE-TEMPERATURE SPACE

It is now necessary to inquire whether within the limits of this simple system, melt–cordierite–anthophyllite with or without phlogopite or albite (LBCA or LPCA) may be expected in nature, and if so, what limits may be placed on these assemblages in pressure-temperature space. In this section data on the pertinent reactions of figure 2 as portrayed in figure 4 will be considered, and the grid of figure 2 revised to that of figure 6. The grid of figure 6 is a compromise between the relationships deduced on the basis of simplifying assumptions (fig. 1, p. 910) and existing incomplete experimental data. It is intended to portray the major relationships pertinent to the discussion. Some of the complications known to arise are discussed in later sections (p. 920).

In figure 4 specific magnesian silicates are denoted, quartz is included as an additional phase where permitted, and where K or P in figure 1 would coincide with a liquid composition, that liquid is designated K′ or P′. (For example, K′KQ in fig. 4 designates the cotectic relationships between melt, potassium feldspar, and quartz.)

1. LKPQ: The data for this reaction are taken from Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964). Below about 3.6 kb the reaction no longer corresponds to eutectic melting but to the beginning of melting at the minimum in the quartz-alkali feldspar-vapor system (see p. 920).

2. KBMQ: This is known at low pressures from the work of Yoder and Eugster (1964) and Wones and Eugster (1959). However, once this meets the K′KQ cotectic it is no longer a dehydration reaction: thereafter the pertinent reaction involves a melt. (The assumed relationships

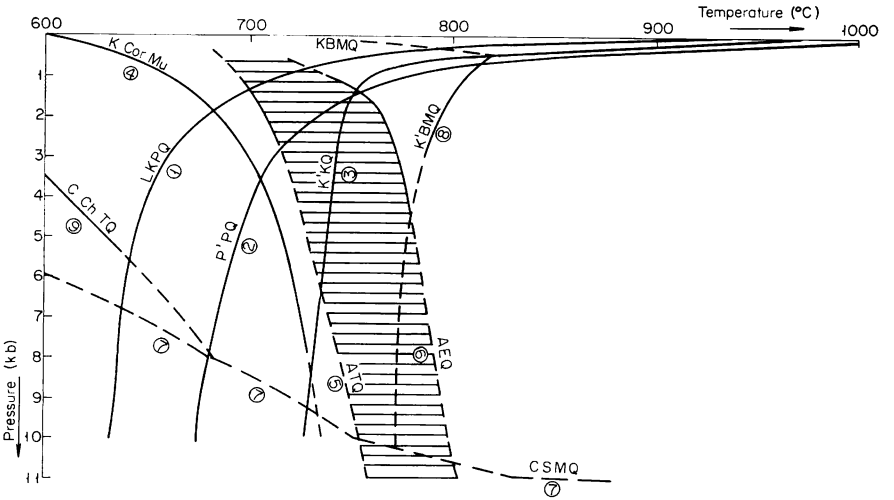


Fig. 4. Experimental data on pertinent univariant equilibria: (1), (2), and (3) Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964); (4) Velde (1964); (5) and (6) Greenwood (1963); (7) Schreyer (1968); (8) Wones and Eugster (1959) and Luth (1967); (9) Fawcett and Yoder (1966). Fluid is a possible additional phase in all assemblages shown.

(1) LKPQ: minimum melting curve for simple granite system; (2) P'PQ: melt-albite-quartz cotectic; (3) K'KQ: melt-potassium feldspar-quartz cotectic; (4) KCor Mu: breakdown curve for muscovite to potassium feldspar and corundum; (5) ATQ: breakdown curve of talc to anthophyllite and quartz; (6) AEQ: breakdown curve of anthophyllite to enstatite and quartz; (7) CSMQ: breakdown curve of cordierite to aluminosilicate, magnesian silicate, and quartz; (8) KBMQ, K'BMQ: breakdown curves of phlogopite and quartz to potassium feldspar or melt, plus enstatite; (9) CChTQ: breakdown curve of quartz and chlorite to talc and cordierite.

Ruled area: stability field of anthophyllite-quartz; ————: defined univariant curve; — — — — —: approximate or extrapolated univariant curve.

in fig. 1 hold for liquids lying between K and P. Once the K'KQ cotectic is attained the effect on this reaction (KBMQ) and on KBCSQ is that of a phase change with degeneracy of the association LKQ. This is because of the coplanarity KBCSM.) This reaction (K'BMQ) is a simple form of the reaction phlogopite + quartz + vapor $\rightleftharpoons$ liquid + enstatite given by Luth (1967, p. 393, reaction 27), and his data will be used and extrapolated here (figs. 4 and 6). For simplicity change in slope due to the transition from enstatite to anthophyllite is not shown.

3. CSMQ: This reaction is a triplet even in the simple system studied. According to Schreyer and Yoder (1960, p. 90-91) and Schreyer (1968, p. 387) CSEQ probably has a shallow (positive?) slope in the vicinity of 10 kb. On entering the anthophyllite and talc (and chlorite) fields at successively lower temperatures the analogous reactions CSAQ and CSTQ (and CSChQ) will have successively more positive slopes (fig. 7). This is in part shown schematically in Schreyer and Yoder (1964, p. 303) and in part in Schreyer's (1968) data on the high pressure termination of the Mg-cordierite field. Schreyer's high pressure termina-

tion is used as an approximation to the reactions CSMQ in this paper (figs. 4 and 6), and this is further discussed on p. 920, 922).

4. KBCSQ: Data on this reaction are not available, but from the experimental work of Winkler and von Platen (1961a, table 3) and Winkler (1965, p. 202) it is probable that this lies in the vicinity of 675 to 690°C, at less than 2 kb. In experimental anatexis of natural graywackes they report coexisting potassium feldspar–plagioclase–biotite–cordierite–sillimanite–quartz–opaque minerals at 675 to 690°C, P_{H_2O} = 2 kb (compare facies II-VI) and melt–biotite–cordierite–sillimanite–quartz–opaque minerals at 770°C, P_{H_2O} = 2 kb (compare facies VIII

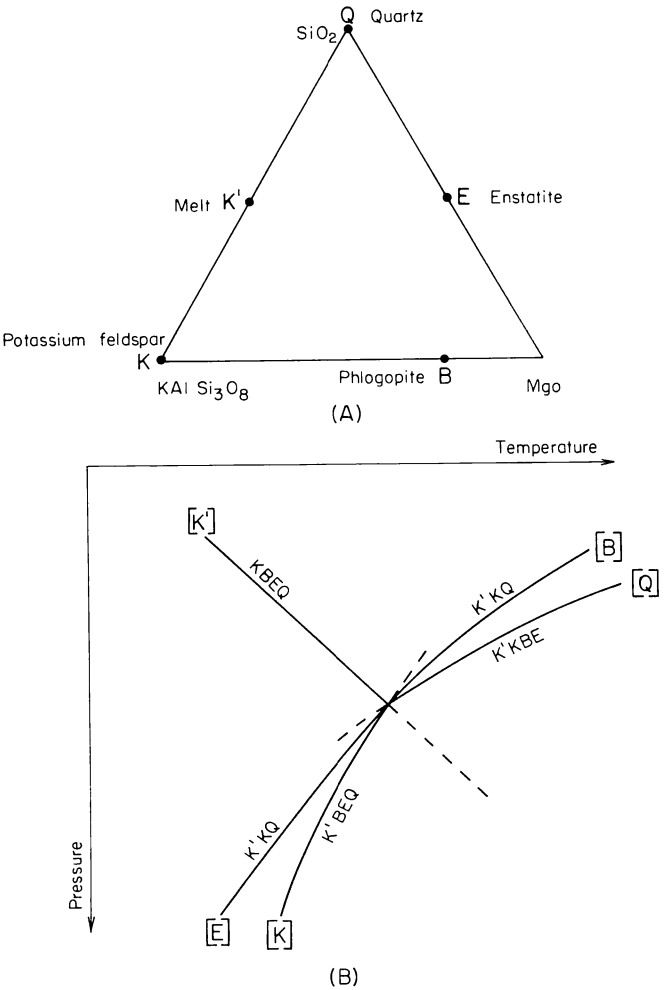


Fig. 5. (A) Chemographic relationships between melt, potassium feldspar, phlogopite, enstatite, and quartz (K'KBEQ) in the system $KAlSi_3O_8$–MgO–SiO_2–(H_2O), projected from H_2O onto the anhydrous plane. (B) Schematic univariant equilibria around the invariant point.

and IX). On the assumption that FeO in their systems decreases the stability field of biotite-sillimanite (see p. 924), the reaction KBCSQ is placed at a lower pressure and higher temperature than their data suggest. As a dehydration reaction with cordierite as a product, the slope in this vicinity is probably shallower than those of most other dehydration reactions at similar pressures due to the high molar volume of cordierite. As with the reaction KBMQ, once the K′KQ cotectic is intersected, KBCSQ is represented by a melting curve, lying between the metastable extension of the dehydration curve and the K′KQ cotectic. It will have a slope less negative than that of K′BMQ, due to the presence of cordierite as a product.

The intersection of KBCSQ and LKPQ defines [M] within limits that are broad but sufficient for the arguments presented here. Furthermore, K′BCSQ, K′BMQ, and CSAQ intersect at point [P]. These relationships are shown in figure 6.

5. LPBCSQ: There are no data available on this reaction, which appears as a melting curve through [M] and [K]. The slope is probably negative, as in most H_2O saturated-melting curves, but less so than usual because of cordierite being a product.

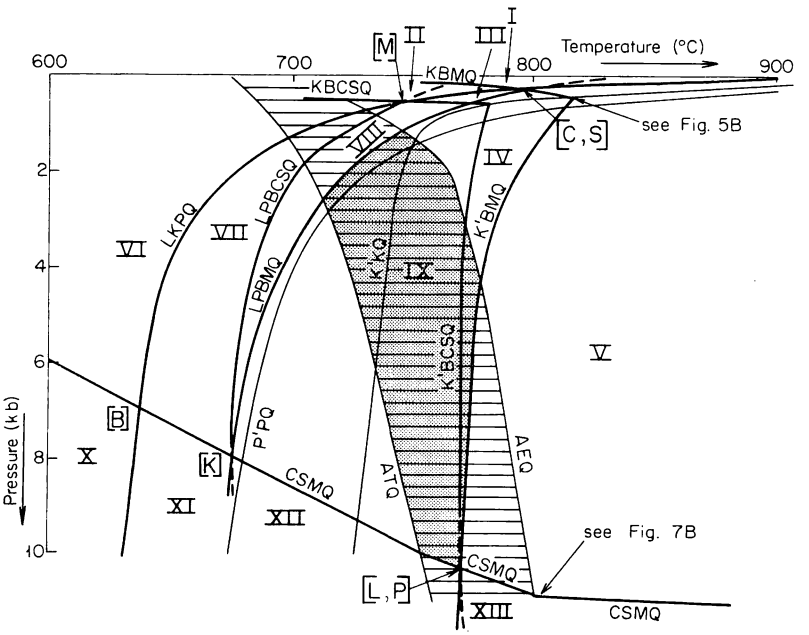


Fig. 6. Semiquantitative revision of figure 2: one solution to the positioning of the grid in pressure-temperature space. Ruled area is the anthophyllite-quartz stability field, stippled area is the field of stability for melt–cordierite–anthophyllite–quartz with or without albite or phlogopite. Fluid is a possible additional phase in all assemblages. Facies are numbered to correspond with figure 2, and divariant assemblages may be ascertained by comparison of figure 2 and figure 6.

For the system of figure 1 to hold, this cannot intersect the P'PQ cotectic. This is perfectly possible and is the case shown in figure 6. If the P'PQ cotectic is intersected then P'BCSQ exists as a divariant assemblage to the right of the cotectic, and the univariant assemblage LPBCSQ is degenerate.

6. LPBMQ: There are no data available on this reaction either. It appears as a melting curve throughout, without cordierite as a product. Hence, the curve may be expected to have a slope more negative than LPBCSQ. The actual slope is dependent on the nature of the magnesian silicate, and the effect of this will be opposite to that due to increasing H_2O in the melt with increasing pressure because of the molar volumes of enstatite, anthophyllite, and talc. These changes in slope are not shown in figure 6.

As with LPBCSQ, for the system to hold, this cannot intersect P'PQ: this is the case shown in figure 6. As before, if P'PQ is in fact intersected, LPBMQ degenerates to the divariant assemblage P'BMQ to the right of P'PQ.

Taking the above arguments into consideration a revised grid is shown in figure 6. It should be emphasized that this is but one solution to the problem of defining the grid in pressure-temperature space compatible with the above data. It would be possible to estimate the slopes of some of the univariant curves (compare Albee, 1965), but this seems unwarranted for the present, considering in particular the lack of knowledge of not only the varying physico-chemical properties of the liquids but even their compositions.

REVISED CONCLUSIONS IN THE LIGHT OF EXPERIMENTAL DATA

In this section it seems unnecessary to consider further the first three preliminary conclusions (p. 912), and only the fourth will be discussed. The question raised therein is whether in this system, melt–cordierite–anthophyllite with or without phlogopite or albite (LBCA or LPCA) may be expected in nature, and if so, under what conditions of pressure and temperature.

In this grid, the reactions LKPQ and KBMQ are sufficiently well known to place [C, S] below 1 kb and in the vicinity of 800°C. The high-pressure boundary of the cordierite-anthophyllite-quartz field is at approximately 10 to 11 kb, and K'BMQ probably intersects this at about 770°C, at [L, P]. Error in the position of [L, P] on CSMQ has obvious effects on the magnitude of the stability field of melt–phlogopite–cordierite–anthophyllite (LBCA) but not on that of melt–cordierite–anthophyllite.

Errors in the positions of [M] and [K] are of secondary importance to this discussion, except with regard to the reaction LPBMQ. If LPBMQ crosses the stability field of cordierite–anthophyllite–quartz, then there will be a stability field for melt–cordierite–anthophyllite with or without albite or phlogopite. This is very probable because the high-pressure, high-temperature termination of the cordierite–anthophyllite–quartz

field lies at a temperature similar to that of [C, S], and LPMBQ is an H_2O-saturated melting curve.

It should be recalled that the grid was developed by consideration of assemblages above the stability field of quartz-muscovite. In figure 6, [B] and [K] are shown as required by the data of Schreyer (1968). Thus [B] and [K] are occluded by at least the quartz-muscovite field. Schreyer and Yoder (1968) suggest a small stability field for yoderite and quartz in the vicinity of 700°C and 10 kb, not shown on figure 6, but if it exists it raises a local complication on CSMQ. These points do not affect the conclusions drawn in this paper.

Thus, from figure 6, there apparently exists a region in pressure-temperature space in which melt–cordierite–anthophyllite with quartz and fluid can be stable. This region would lie within the ruled area of figure 6, between LPMQ and CSAQ. Within this region, in the area stippled in figure 6, melt–albite–cordierite–anthophyllite (LPCA—stable on the low-temperature side of P′PQ) or melt–phlogopite–cordierite–anthophyllite (LBCA) with quartz and fluid could develop from compositions outside the compositional tetrahedron PBCM (fig. 1 and p. 914), that is from systems without high initial magnesium contents and with compositions analogous to those of not uncommon rocks. On removal of sufficient melt and retrogression to subsolidus conditions, the assemblage albite–phlogopite–cordierite–anthophyllite with quartz and fluid could be formed.

EFFECT OF COMPOSITIONAL VARIATIONS WITHIN THE SYSTEM

All the phases involved in figure 1, except the aluminosilicates, may show considerable variation in composition, therefore, extensive two-phase and three-phase fields are to be expected. Most important and least known are variations in the composition of L, as has been indicated in several contexts above, and which will be considered again in the next section. Obviously in reality the composition of L is not constant across the grid: an increasingly large volume in figure 1 will be occupied by liquid as melting progresses.

Consideration of solid solution between the alkali feldspars necessitates modification of the relationships discussed. This will be done while retaining the other assumptions of figure 1 and page 910. The alkali feldspar critical curve passes through about 700°C at 2 kb with a slope of about 15°C/kb (W. C. Luth, personal commun., 1968). Thus [S] is no longer strictly an invariant point but an indifferent point on the minimum melting curve ("LKPQ") where it meets the curves LPssBMQ and LKssBMQ (where Pss and Kss are respectively albite-rich and orthoclase-rich feldspars). At this point the composition of the feldspar involved in all three reactions becomes the same and so does the composition of the liquid. The reaction LKssBMQ terminates where K′KQ and KBMQ intersect. Similarly [M] may be an indifferent point on the minimum melting curve where it meets LPssBCSQ and LKssBCSQ, the latter terminating at the intersection of K′KQ and

KBCSQ. Obviously, in the subsolidus region, KP is forbidden above the critical curve.

At temperatures above the melt-potassium feldspar-quartz cotectic (K'KQ) the coexistence of all three phases is obviously forbidden and similarly with regard to the melt–albite–quartz cotectic (P'PQ). This restricts the stability fields of assemblages involving melt and feldspar (fig. 2A), and care should be taken in comparing figures 2 and 6.

It may be that the assemblage PBCA(Q) could be derived from sodic assemblages KPBC(Q) without intervention of melt, by virtue of the change in plagioclase coexisting with potassium feldspar to more potassic compositions with rise in temperature (A. L. Albee, personal commun., 1967). This would result in a diminution of the volume KPBC and passage of appropriate bulk compositions into the volume PBC

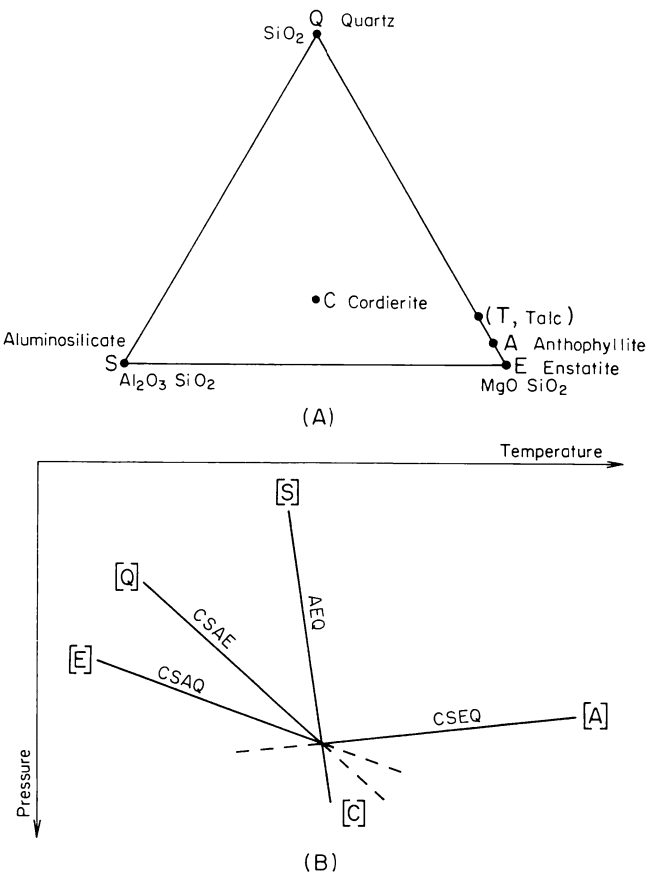


Fig. 7. (A) Chemographic relationships between cordierite, aluminosilicate, anthophyllite, enstatite, talc, and quartz, (CSAETQ) in the system Al_2O_3–MgO–SiO_2–H_2O, projected from H_2O to the anhydrous plane. (B) Schematic univariant equilibria around invariant point [T] in this system.

and perhaps into the volume PBCA. However, a greater range in original bulk compositions may yield PBCA(Q) if removal of melt is possible.

It was assumed that talc, orthoamphibole, and orthopyroxene are aluminum free: this is an approximation which will now be considered. It is possible that increasing aluminum content raises the stability limits of these minerals to higher temperatures. For example, the stability limit of talc at approximately 11 kb may be raised from about 760°C to about 830°C (compare Greenwood, 1963, p. 332; and Schreyer, 1968 p. 388). Aluminous talc has been synthesized at 11 kb, 750°C and 800°C, and 12 kb, 800°C, in particular, and gedrite at 11 kb, 850°C and 900°C (Schreyer, 1968). Schreyer (p. 389) states that "reactions have not been reversed and it is therefore not clear whether the gedrites are stable phases under the conditions of synthesis. . . ." If the data on talc, however, are substantially correct in this region, then reaction ATQ (fig. 6) may still represent the limit of the anthophyllite-quartz field but not the lower limit of cordierite–orthoamphibole–quartz. This assemblage would be formed only after an analogous reaction eliminating the Al–talc–cordierite tie line, probably Al–talc + cordierite $\rightleftharpoons$ gedrite + quartz. To the extent that this reaction differs from ATQ, the field for melt–cordierite–orthoamphibole–quartz will be altered. It is quite possible from existing data that this field may be reduced to pressures lower than about 5 kb rather than 11 kb as suggested in figure 6.

The high temperature stability limit of gedrite + quartz is not known yet, but similar considerations affect the transition from cordierite–gedrite–quartz to cordierite–Al–enstatite quartz, the former assemblage possibly being stable above AEQ (fig. 6) and limited by gedrite + quartz $\rightleftharpoons$ Al–enstatite + cordierite.

EFFECTS OF DEGENERACIES IN THE SYSTEM

The degeneracies KBM and CSM within the system have already been commented upon sufficiently (p. 911). However, further comment on LKPQ may be of value.

As stated on p. 911, a truer representation would place L close to KP in the plane KPS of figure 1, permitting a divariant association LKP and disrupting the coplanarity LKPBM, thus also permitting LPBM as an additional divariant assemblage. Further, the place of the univariant association LPBM would be taken by LKBCM and LPBSM.

This situation is hardly more complicated than the degenerate case discussed. It implies that isobarically a quaternary cotectic LKPSQ exists close to the "ternary" granite minimum in the system Al_2O_3–K_2O–Na_2O–SiO_2–(H_2O), whence with slight rise in temperature one of the solid phases would be eliminated, presumably K or P, giving rise to LKSQ or LPSQ, and thereafter the relationships are sufficiently well protrayed in the degenerate system.

As noted previously (p. 911) the composition of the lowest temperature melt may lie within the KPSM tetrahedron of figure 1. (Winkler and von Platen, 1961a and b). It is probable that a composition projecting

close to the feldspar join but with alumina in excess of the 1:1 ratio (Na + K) :Al and a small amount of magnesia is geologically pertinent (Luth, personal commun., 1968) that is, a composition within the volumes KPCS and KPBS. Retaining the previous assumptions (p. 910), except for this change in the position of L, one may develop a consistent grid, figure 8, which may help in illuminating the stability relations of figure 2, and be a closer approximation to reality.

It may be noted that now the incongruent melting of albite and phlogopite (PB) to liquid and magnesian silicate (LM) may involve cordierite or sillimanite. Thus liquid–albite–phlogopite–magnesian silicate (LPBM) becomes another possible divariant assemblage which may yield albite–phlogopite–cordierite–magnesian silicate (PBCM) with removal of liquid and retrogression to subsolidus conditions. The range of compositions which could yield this assemblage is increased by an amount correlative to that by which L is removed from the feldspar join.

Further discussion of this non-degenerate case is given in Appendix B.

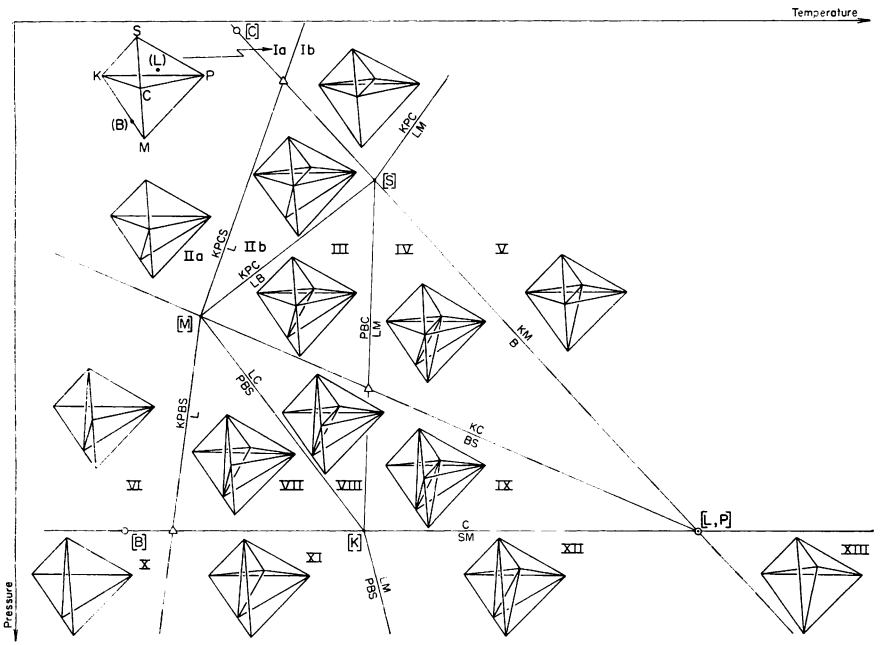


Fig. 8. Schematic invariant and univariant equilibria between phases indicated in figure 1, except that L is removed to a quaternary position in the volumes KPBS and KPCS (p. 922). Divariant assemblages are indicated graphically for each facies region (referred to by Roman numerals). Quartz and fluid are possible additional phases. • stable invariant point; o metastable invariant point; △ intersection of univariant curves not generating an invariant point.

EFFECTS OF OTHER COMPONENTS ON THE TOPOLOGY

1. CaO: In the phases under consideration CaO would be largely restricted to plagioclase and liquid. Introduction of CaO as an additional component would permit the existence of a divariant association LKPQ and a larger stability range for melt–plagioclase–quartz. This would alleviate the problem (p. 918) of possible intersection of P'PQ by LPBCSQ or LPBMQ and extend the stability fields for assemblages LPCS, LPCM, and LPSM. With sufficiently high CaO content new phases such as calcic amphibole or calcic pyroxene may be expected: this lies outside the scope of the present paper.

2. FeO: FeO principally enters biotite, cordierite, anthophyllite, enstatite, and talc in the system considered. Increased annite component in biotite decreases the maximum stability of the quartz-biotite association (Wones and Eugster, 1959). FeO in cordierite apparently lowers the stability field to pressures below about 3 kb for Fe-cordierite (Richardson, 1968, p. 401). Possibly addition of FeO lower the temperatures of the quartz-anthophyllite field and of the reactions LPBMQ, LPBCSQ, and KBCSQ, but this is uncertain. Overall one would anticipate lowering of the temperature range over which melt–cordierite–anthophyllite can occur toward the granite minimum LKPQ and a decrease in the pressure range over which this assemblage can occur.

Considering the appearance of new phases, obviously garnet is a potential phase with increased FeO. Were the FeO content sufficient and the stability of cordierite exceeded, (for example, Chinner, 1959), the chemographic relations (fig. 1) and qualitative grid (fig. 2) would be similar to those for the analogous FeO system, with almandine in place of cordierite, and FeO in place of MgO.

For intermediate FeO–MgO compositions where garnet and cordierite can coexist, the above analysis is inadequate.

In this case there is an additional determining inert component and an additional phase in the system. With five determining inert components, graphical representation becomes impractical. However, some of the relationships can be visualized by consideration of the system Al_2O_3–MgO–FeO–K_2O–SiO_2–H_2O under the same conditions as before, quartz in excess, $P_f = P_{H_2O} =$ Ps. The critical phases involved are thus LKBCGSM, that is, seven.

L and K, to a first approximation, can be considered equivalent in the chemographic relationships shown in figure 9. In this figure, it is assumed that the FeO/MgO ratio is similar in the magnesian silicates and biotite, greater in garnet, and less in cordierite (Albee, 1965; Himmelburg and Phinney, 1967; Grant and Weiblen, in press).

Under these conditions one invariant point exists, with three univariant lines radiating from it (one represents the degeneracy CGSM, the other, the assumed degeneracy KBM) as shown in figure 9. Although data on these reactions are minimal, the orientation shown in qualitatively correct. This invariant point is analogous to [L, P] in the Al_2O_3–MgO–K_2O–Na_2O system and probably lies at a pressure and a tempera-

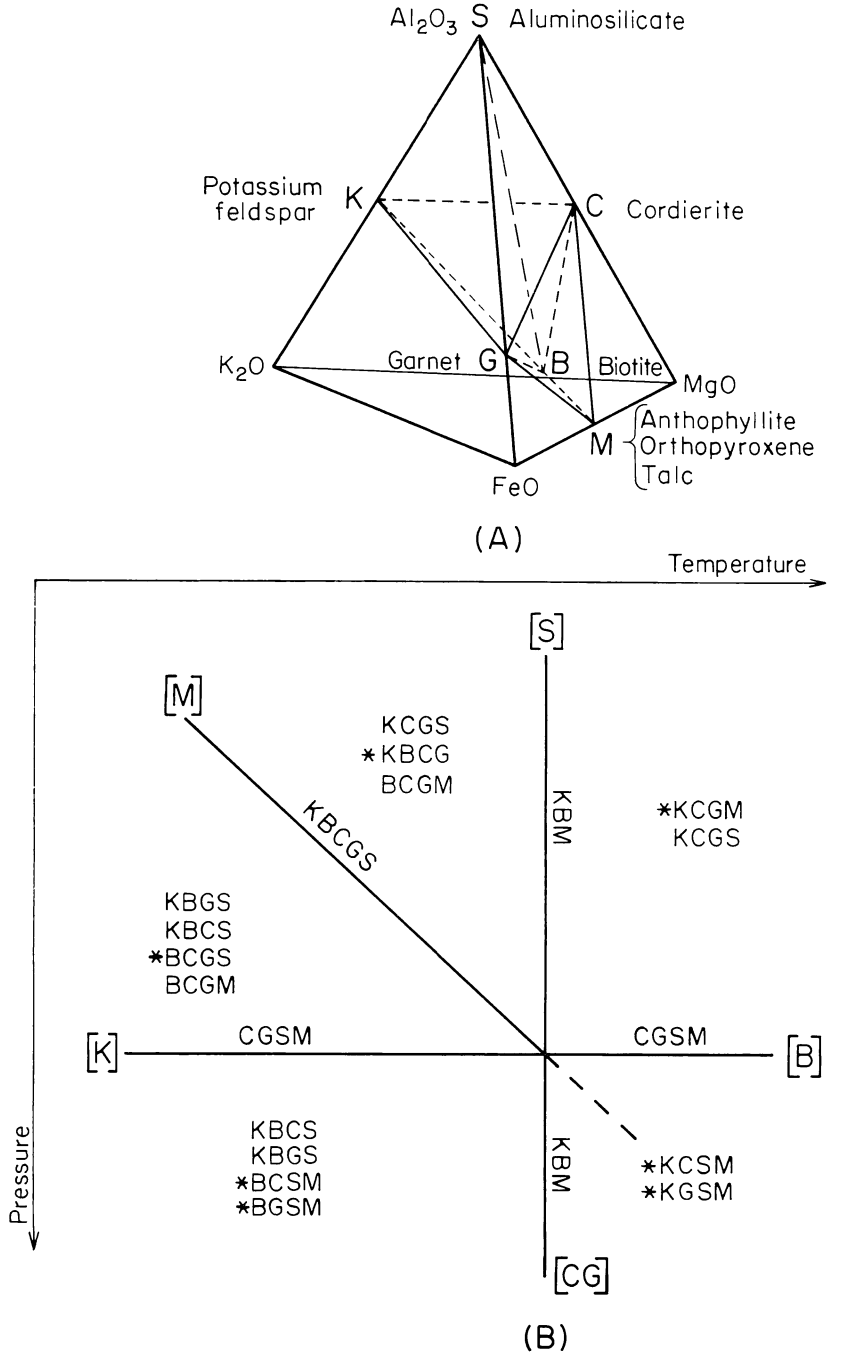


Fig. 9. (A) Chemographic relationships between potassium feldspar, biotite, cordierite, garnet, aluminosilicate, and magnesian silicate, (KBCGSM), neglecting solid solution, in the system Al_2O_3–MgO–FeO–K_2O–(SiO_2)–(H_2O). (B) Schematic univariant equilibria around the invariant point corresponding to the association of the above six phases, with divariant assemblages for each facies region (diagnostic assemblages designted thus: *BCGS). Quartz and fluid are possible additional phases in all assemblages.

ture lower than that of [L, P], considering the effect of FeO on the stability of biotite-quartz and the further restriction that CGSM must lie within the cordierite field. Probably at the conditions of the invariant point the reactions involving K will be represented by melting curves, but, as before, below the K′KQ cotectic these will be replaced by dehydration curves.

No anthophyllite-bearing assemblages necessarily to the right of KBM or below CGSM in figure 9B are known to the writer (except for BGSM, reported by Rabbitt, 1948, table 13), but assemblages falling on either side of KBCGS are known, and possibly common, for example, Sims (written commun.), Grant (in progress), Bugge (1943). (The colinearity KBM assumed above does not affect the existence of the facies on either side of KBCGS.)

By comparison of figure 9 with figure 6, it is suggested that the assemblage biotite–corderite–garnet–anthophyllite (albite, quartz) BCGA (PQ) may be derived from partial melting, filter pressing, and recrystallization in a manner analogous to the derivation of albite–phlogopite–cordierite–anthophyllite–quartz PBCA(Q).

CONCLUSIONS

Consideration of the problem of development of cordierite-anthophyllite bearing assemblages in the system Al_2O_3–MgO–K_2O–Na_2O–SiO_2–H_2O, with quartz potentially present in all assemblages and $P_f = P_{H_2O} = Ps$, and the other assumptions of figure 1 (except for the restrictions initially imposed on solid solution in the alkali feldspars and magnesian silicates) leads to the following conclusions. In these "anthophyllite" includes gedritic compositions, "potassium feldspar" denotes orthoclase-rich feldspar, and "albite" denotes albite-rich feldspar.

1. The association corderite–anthophyllite–quartz can occur in those facies whose fields overlap the area bounded by talc (+cordierite) $\rightleftharpoons$ anthophyllite + quartz and anthophyllite + quartz $\rightleftharpoons$ orthopyroxene (+cordierite) and cordierite $\rightleftharpoons$ anthophyllite + aluminosilicate + quartz (compare ATQ, AEQ, and CSMQ in fig. 6).

2. The assemblage albite–phlogopite–cordierite–anthophyllite (PBCA) is restricted to facies on the low-temperature side of LPBMQ in the above area. Attainment of this assemblage by compositions initially in the volume PBCM (fig. 1) requires but simple recrystallization under the necessary external conditions.

3. The assemblages potassium feldspar–albite–cordierite–magnesian silicate (KPCM, facies I) and melt-potassium feldspar–cordierite–magnesian silicate LKCM, facies V) are probably developed only in the enstatite field at low pressures and high temperatures, where the first assemblage would contain but one alkali feldspar and the second is restricted by the melt–potassium–feldspar quartz cotectic, K′KQ.

4. Of greater significance in the present context is the apparent presence of a stability field for melt–cordierite–anthophyllite with albite (below the melt–albite–quartz cotectic P′PQ) or phlogopite (LPCA or

LBCA) in that region of the cordierite–anthophyllite–quartz field at temperatures above the incongruent melting of albite and phlogopite (compare LPBMQ, fig. 6) and below the incongruent melting of phlogopite and quartz, (compare K'BMQ in fig. 6) that is between approximately 700°C to 800°C and 1 to 10 kb. This region is stippled in figure 6. The high-pressure limit on this field may have to be decreased drastically (perhaps to 5 or 6 kb) depending upon the effects of aluminum substitution in talc and anthophyllite.

Compositions that may attain these assemblages (LPCA or LBCA) but that lie outside the volume PBCM are those in the volume LPBC (fig. 1). Under high-temperature subsolidus conditions, this volume includes compositions with possible assemblages:

potassium feldspar–albite–phlogopite–cordierite (KPBC)
potassium feldspar–albite–phlogopite–aluminosilicate (KPBS)
albite–phlogopite–cordierite–aluminosilicate (PBCS)
albite–phlogopite–aluminosilicate–magnesian silicate (PBSM)

Thus, partial melting of these assemblages may give rise to melt–cordierite–anthophyllite with albite or phlogopite (LPCA or LBCA). Filter pressing of the melt will then leave residual assemblages cordierite-anthophyllite with albite or phlogopite, with the possibility of albite–phlogopite–cordierite–anthophyllite (PBCA) forming if the melt is but partially removed and if equilibrium crystallization is maintained back into subsolidus conditions.

The above conclusions apply to a simple and artifically circumscribed system, for which the grid of figure 2 is warranted and for which the grid of figure 6 is a compromise with available experimental data. What are important, then, are the topology of figure 2 and the probability, shown in figure 6, of an extensive region in which melt–cordierite–anthophyllite–quartz may be stable with or without albite or phlogopite.

It seems reasonable to extrapolate from this to natural occurrences, with CaO and FeO contents such that no new phases are introduced, and wherein the liquid may be of quaternary composition as suggested on p. 922 (giving rise to the possible fifth assemblage below).

This extrapolation implies that partial melting of rocks, especially metamorphosed sediments in the graywacke compositional range and to a lesser extent some pyroclastic and igneous rocks of granodioritic to quartz dioritic compositions, with high temperature subsolidus assemblages:

potassium feldspar–plagioclase–biotite–cordierite (KPBC)
potassium feldspar–plagioclase–biotite–aluminosilicate (KPBS)
plagioclase–biotite–cordierite–aluminosilicate (PBCS)
plagioclase–biotite–aluminosilicate–magnesium silicate (PBSM)
potassium feldspar–plagioclase–cordierite–aluminosilicate (KPCS)

all with quartz, can give rise at higher temperatures to a granitic melt and a residual assemblage plagioclase–biotite–cordierite–anthophyllite–quartz (PBCAQ) on partial removal of the melt and crystallization back

to subsolidus conditions. Note that a cordierite-anthophyllite bearing assemblage can form from a high-temperature subsolidus assemblage lacking either mineral.

If FeO/MgO is sufficiently high to allow garnet as an additional phase, then by comparison of the systems Al_2O_3–MgO–FeO–K_2O–SiO_2–H_2O and Al_2O_3–MgO–K_2O–Na_2O–SiO_2–H_2O, it is further suggested that the assemblage plagioclase – biotite – cordierite – garnet – anthophyllite – quartz (PBCGAQ) may be formed from similar rocks by the processes of partial melting, filter pressing, and recrystallization.

A granitic melt can form from an assemblage lacking potassium feldspar or muscovite (von Platen, 1965). On the basis of the grid (fig. 6) it is seen that, in this simple system, such a melt could arise by incongruent melting of quartz–albite–phlogopite with or without sillimanite (LPBCSQ or LPBMQ) at temperatures in the vicinity of 700°C. If a quaternary melt is considered as in figure 8, then cordierite may be consumed in the incongruent melting: the place of LPBMQ is taken by LPBCMQ and LPBSMQ (p. 923).

In the development of residual assemblages (such as PBCAQ in this case) in association with a melt, an unusually close approach to equilibrium during retrogression may be expected because of the probable ease of diffusion via the melt. Indeed, this may be even more true for diffusion via an associated aqueous fluid phase, or one formed or enhanced on crystallization of the melt. If so, the residual assemblages may not be equated with conditions at the highest temperature (and pressure) attained during the event. In appropriate mineral pairs, bulk composition, and sample sizes, partition data may show increasing rather than decreasing fractionation suggesting crystallization with falling temperature. This could arise, for instance, in a certain rock and mineral pair in which equilibration occurred on more and more confined local scales (Grant and Weiblen, 1968).

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ADDENDUM

A review of partition data on natural potassium feldspar–biotite–cordierite–aluminosilicate assemblages suggests that KBCSQ may not represent the low-pressure, high-temperature limit of biotite–aluminosilicate–quartz. If this is so, KBCSQ (fig. 6) could lie at higher pressures and lower temperatures than indicated (without altering the conclusions drawn here).

Appendix A

Derivation of the schematic grid, figure 2

We are concerned with four determining inert components and seven phases, considering but one phase S and one phase M, involving these four components. (Whether S is sillimanite, andalusite, or kyanite, and whether M is talc, anthophyllite, or enstatite do not affect the qualitative arguments here.) This yields seven invariant points at which six of the seven phases may coexist. From each invariant point radiate a maximum of six univariant reaction lines on which a maximum of five of the seven phases may coexist, separating fields in which not more than four of the seven phases may coexist. The actual univariant reactions are determined by the chemographic relationships fixed in figure 1. The sequence of reactions round an invariant point is determined by Schreinemakers' rules (see Niggli, 1954). The absolute slopes of the reaction lines, the sense of the sequences, and the metastability or stability are unknown at this stage.

Because of the coplanar relations between five phases LKPBM, the bundles [C] and [S] coincide, and the reactions involved in both are independent of C or S. Similarly KBCSM are coplanar, and [L] and [P] coincide. Because all four of these invariant points, [C], [S], [L], and [P], involve five rather than six phases and because each set of five phases can be described in terms of three determining inert components, a maximum of only five univariant lines diverge from each. Moreover, two degeneracies occur in each case, resulting in only three different univariant lines in each bundle (figs. 2A and 2B).

It is not possible from theory alone to construct the topology of the complete grid unambiguously. However it is possible to do so by considering, in addition, available data pertinent to three of the reactions involved.

The data (fig. 4) on LKPQ, KBMQ, and K'BMQ (see p. 915) and CSMQ are used to approximate LKP, KBM, and CSM. These relationships define the relative positions of [C,S] [L,P], and [B] in pressure-temperature space and, further, the directions and relative stabilities of LPBM and KBCS, as shown in figure 2A. These latter, by their intersections with CSM and LKP respectively, define the relative positions of the two remaining invariant points [K] and [M] and hence the relative position of LPBCS. Furthermore, the stable part of LPBCS must be within the triangle bounded by the univariant lines LKP, KBM, and CSM, as shown.

Thus, the relative positions of the bundles in pressure-temperature space and the relative slopes of the six univariant reactions are known qualitatively. It remains to decide on the stability or metastability of each bundle.

Consider bundles [M] and [K]. These are linked by the stable portion of the non-degenerate reaction LPBCS and hence [M] and [K] are simultaneously stable (Korzhinskii, 1959, p. 131). Next, consider the arrangement of stable and metastable univariant lines radiating from [M], shown in figure 3. Here, resulting from the degeneracy of KBCS, [L] and [P] lie on the stable extension of [PM] and on the metastable extension of [LM]. The corresponding possible assemblages are:

[L]—KPBCSM	[LM]—KPBCS
[P]—LKBCSM	[PM]—LKBCS

[L] contains an assemblage stable only to the left of [M] and hence is metastable. [P] contains an assemblage stable to the right of [M] and hence is stable.

Similarly, from the double degeneracy of LKP, [S] is stable, [C] and [B] are metastable. [C] coincides with the stable invariant point [S], and [B] coincides with an intersection of stable segments of degenerate univariant lines.

Appendix B

Comments on the schematic grid with a non-degenerate liquid, figure 8

The change in the position of L (p. 922) removes the colinearity LKP and the coplanarity LKPBM. It does not affect the univariant equilibrium KBCS (obviously these four remain coplanar) nor the invariant points [L] and [P].

As before (see App A) if [M] is stable, [K], [P], and [S] are stable, and [B], [C], and [L] are metastable. In the present case, [B] corresponds to the intersection of the metastable extensions of [BM] and [BS] on the degenerate univariant line CSM. Similarly, [C] corresponds to the intersection of the metastable extensions of [KC] and [CM] on the degenerate univariant line KBM. As before [L] is metastable: the corresponding invariant association LPBCSM is forbidden by several incongruent melting relationships to the left of [L, P].

The major differences in univariant and divariant equilibria between figures 2 and 8 are:

1. LKP is replaced in figure 8 by four discrete non-degenerate univariant equilibria, each involving two phases in addition to L, K, and P. (The intersections of LKPBS and CSM, LKPCS and KBM do not represent invariant points.)

2. LPBM is replaced on figure 8 by two discrete non-degenerate univariant equilibria involving an additional phase.

3. Divariant assemblages LKP plus B, C, S, or M are permitted in several facies in figure 8.

4. LPBM is a possible divariant assemblage in facies IV, IX, and XII of figure 8. (The divariant assemblages noted in (3) and (4) are the only new ones introduced.)

It must be emphasized again that in reality the composition of L is not constant across the grid. In particular, once the minimum melting curve for the simple granite system (LKPQ in figs. 4 and 6) is attained, LKP is no longer a possible association in quartz bearing assemblages. If, as seems probable, the four univariant lines LKPBS, LKPCS, LKPBC, and LKPCM are close to the minimum melting curve for the simple granite system but lie at lower temperatures, then the divariant assemblages LKPB, LKPC, LKPS, and LKPM will have very restricted stability fields. The non-degenerate case (fig. 8) suggests that, in quartz-bearing systems, the incongruent melting of albite and phlogopite (PB) to liquid and magnesian silicate (LM) may in fact involve cordierite or sillimanite. This does not significantly alter the conclusions based on the degenerate case (figs. 2 and 6, p. 920) with regard to the production of cordierite-anthophyllite bearing assemblages. One needs to note simply that part of the volume in facies IV and IX previously occupied by LPCM and LBCM is in this case occupied by LPBM. With sufficient removal of melt from this assemblage and appropriate retrogression into subsolidus conditions, the assemblage PBCM could again be formed. The range of compositions which could yield this assemblage is increased by an amount correlative with that by which L is removed from the feldspar join.

References

Albee, A. L., 1965, A petrogenetic grid for the Fe-Mg silicates of pelitic schists: Am. Jour. Sci., v. 263, p. 512-536.

Bugge, J. A. W., 1943, Geological and petrographical investigations in the Kongsberg-Bamble formation: Norges. Geol. Undersökelse, no. 160, 150 p.

Chinner, G. A., 1959, Garnet-cordierite parageneses: Carnegie Inst. Washington Year Book 58, p. 112-113.

Ernst, W. G., 1959, Alkali amphiboles: Carnegie Inst. Washington Year Book 58, p. 121-126.

———— 1961, Stability relations of glaucophane: Am. Jour. Sci., v. 259, p. 735-765.

———— 1963, Petrogenesis of glaucophane schists: Jour. Petrology, v. 4, p. 1-30.

Eskola, Pentti, 1914, On the petrology of the Orijarvi region in southwestern Finland: Finlande comm. géol. Bull., no. 40, p. 1-277.

Fawcett, J. J., and Yoder, H. S. Jr., 1966, Phase relationships of chlorites in the system MgO–Al_2O_3–SiO_2–H_2O: Am. Mineralogist, v. 51, p. 353-380.

Grant, J. A., and Weiblen, P. W., 1968, Distribution of iron and magnesium in garnet-biotite pairs in high-grade metamorphic rocks [abs]: Geol. Soc. America Spec. Paper 115, p. 80-81.

Greenwood, H. J., 1961, The system $NaAlSi_3O_8$–H_2O–argon: total pressure and water pressure in metamorphism: Jour. Geophys. Research, v. 66, p. 3923-3946.

———— 1963, The synthesis and stability of anthophyllite: Jour. Petrology, v. 4, p. 317-351.

Himmelburg, G. R., and Phinney, W. C., 1967, Granulite facies metamorphism, Granite Falls-Montevideo area, Minnesota: Jour. Petrology, v. 8, p. 325-348.

Luth, W. C., 1967, Studies in the system $KAlSiO_4$–Mg_2SiO_4–SiO_2–H_2O: I, Inferred phase relations and petrologic applications: Jour. Petrology, v. 8, p. 372-416.

Luth, W. C., Jahns, R. H., and Tuttle, O. F., 1964, The granite system at pressures of 4 to 10 kilobars: Jour. Geophys. Research, v. 69, no. 4, p. 759-773.

Niggli, P., 1954, Rocks and mineral deposits: San Francisco, W. H. Freeman and Co., 559 p.

Rabbitt, J. C., 1948, A new study of the anthophyllite series: Am. Mineralogist, v. 33, p. 263-323.

Richardson, S. W., 1968, The stability of Fe-staurolite and quartz: Carnegie Inst. Washington Year Book 66, p. 398-402.

Salotti, C. A., 1962, Anthophyllite within the albite-epidote hornfels facies, Fremont County, Colorado: Am. Mineralogist, v. 47, p. 1055-1066.

Schreyer, W. F., 1968, A reconnaissance study of the system MgO–Al_2O_3–SiO_2–H_2O at pressures between 10 and 25 kb: Carnegie Inst. Washington Year Book 66, p. 380-392.

Schreyer, W. F., and Yoder, H. S. Jr., 1959, Cordierite-water system: Carnegie Inst. Washington Year Book 58, p. 100-104.

———— 1960, Instability of anhydrous Mg-cordierite at high pressures: Carnegie Inst. Washington Year Book 59, p. 90-91.

———— 1964, The system Mg-cordierite-H_2O and related rocks: Neues Jahrb. Mineralogie, Abh., v. 101, p. 271-342.

———— 1968, Yoderite: synthesis, stability, and interpretation of its natural occurrence: Carnegie Inst. Washington Year Book 66, p. 376-380.

Thompson, J. B., Jr., 1957, The graphical analysis of mineral assemblages in pelitic schists: Am. Mineralogist, v. 42, p. 842-858.

Tilley, C. E. and Flett, J. S., 1929, Hornfelses from Kenidjack, Cornwall: Great Britain Geol. Survey Summ. Prog., pt. II, p. 24-41.

Touminen, H. V. and Mikkola, T., 1950, Metamorphic Mg-Fe enrichment in the Orijarvi area as related to folding: Finlande comm. géol. Bull., no. 150, p. 67-92.

Tuttle, O. F. and Bowen, N. L., 1958, Origin of granite in the light of experimental studies: Geol. Soc. America Mem. 74, 153 p.

Velde, B., 1964, Upper stability of muscovite: Carnegie Inst. Washington Year Book 63, p. 141-142.

von Platen, H., 1965, Experimental anatexis and genesis of migmatites, *in* Controls of Metamorphism: Geol. Jour. Spec. Issue no. 1, p. 203-218.

Winkler, H. G. F., 1965, Petrogenesis of metamorphic rocks: New York, Springer-Verlag, Inc., 220 p.

Winkler, H. G. F., and von Platen, H., 1961a, Experimentelle Gesteinsmetamorphose; IV, Bildung anatektischer Schmelzen aus metamorphisierten Grauwacken: Geochim. et Cosmochim. Acta., v. 24, p. 48-69.

———— 1961b, Experimentelle Gesteinsmetamorphose; V, Experimentelle anatektische Schmelzen und ihre petrogenetische Bedeutung: Geochim. et Cosmochim. Acta, v. 24, p. 250-259.

Wones, D. R., and Eugster, H. P., 1959, Biotites on the join phlogopite-annite: Carnegie Inst. Washington Year Book 58, p. 127-132.

———— 1965, Stability of biotite: experiment, theory and application: Am. Mineralogist, v. 50, p. 1228-1272.

Yoder, H. S., Jr., and Eugster, H. P., 1954, Phlogopite synthesis and stability range: Geochim. et Cosmochim. Acta., v. 6, p. 157-185.

———— 1955, Synthetic and natural muscovites: Geochim et Cosmochim. Acta., v. 8, p. 225-280.