Polymetamorphic origin of muscovite + cordierite + staurolite + biotite assemblages: implications for the metapelitic petrogenetic grid and for *P–T* paths

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ABSTRACT Metapelites containing muscovite, cordierite, staurolite and biotite (Ms + Crd + St + Bt) are relatively rare but have been reported from a number of low-pressure (andalusite–sillimanite) regional metamorphic terranes. Paradoxically, they do not occur in contact aureoles formed at the same low pressures, raising the question as to whether they represent a stable association. A stable Ms + Crd + St + Bt assemblage implies a stable Ms + Bt + Qtz + Crd + St + Al_2SiO_5 + Chl + H_2O invariant point (IP1), the latter which has precluded construction of a petrogenetic grid for metapelites that reconciles natural phase relations at high and low pressure. Petrogenetic grids calculated from internally consistent thermodynamic databases do not provide a reliable means to evaluate the problem because the grid topology is sensitive to small changes in the thermodynamic data. Topological analysis of invariant point IP1 places strict limits on possible phase equilibria and mineral compositions for metamorphic field gradients at higher and lower pressure than the invariant point. These constraints are then compared with natural data from contact aureoles and reported Ms + Crd + St + Bt occurrences. We find that there are numerous topological, textural and compositional incongruities in reported natural assemblages that lead us to argue that Ms + Crd + St + Bt is either not a stable association or is restricted to such low pressures and Fe-rich compositions that it is rarely if ever developed in natural rocks. Instead, we argue that reported Ms + Crd + St + Bt assemblages are products of polymetamorphism, and, from their textures, are useful indicators of *P–T* paths and tectonothermal processes at low pressure. A number of well-known Ms + Crd + St + Bt occurrences are discussed within this framework, including south-central Maine, the Pyrenees and especially SW Nova Scotia.

Key words: cordierite; metapelite; petrogenetic grid; polymetamorphism; *P–T* paths; staurolite.

INTRODUCTION

Metapelitic mineral assemblages containing all four of the minerals muscovite (Ms), biotite (Bt), cordierite (Crd) and staurolite (St) are some of the most problematic in metamorphic petrology. Although in an overall sense they are rare, they nevertheless have been reported from a number of regional low-pressure (andalusite–sillimanite-type) metamorphic settings. In contrast, the assemblage never occurs in contact aureoles around plutons emplaced in the same pressure range as the regional terranes (Pattison & Tracy, 1991). This paradox raises the question of whether reported Ms + Crd + St + Bt assemblages represent a stable association, the answer to which carries significant implications for metapelitic phase equilibria.

In this paper, we are concerned with Crd + St-bearing mineral assemblages in 'normal' metapelitic rocks containing muscovite, biotite, quartz (Qtz) and a hydrous fluid phase (H_2O) inferred to have been present during times of reaction. These are the 'low-Al pelites' discussed by Spear (1993), and represent by far the most common pelitic bulk compositions. We are not concerned with Al-rich metapelites that do not contain biotite nor with Crd + St-bearing assemblages in K-poor bulk compositions lacking stable muscovite, such as developed in metamorphosed volcanic rocks and volcanically derived sediments. In these rocks, St + Crd has been widely reported as an apparently stable association (e.g. Pirie & Mackasey, 1978; Thurston & Breaks, 1978; Woodsworth, 1979; Percival *et al.*, 1982; Hudson & Harte, 1985; Spear & Rumble, 1986; Spear, 1993).

Ms + Crd + St + Bt assemblages can be represented in the model pelitic system K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O (KFMASH) on AFM diagrams projected from muscovite, quartz and H_2O (Thompson, 1957). Because staurolite is relatively Fe-rich and cordierite is relatively Mg-rich, a Crd + St tie line cuts out a number of possible tie-lines including the Al_2SiO_5 (Als) + Bt tie line (Fig. 1), one of the most common metapelitic sub-assemblages in the

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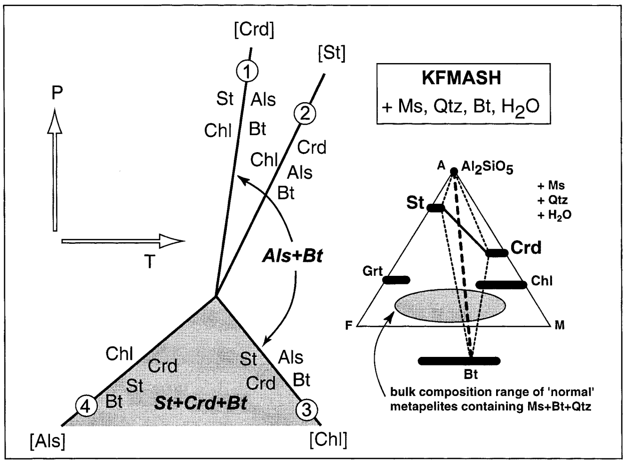


Fig. 1. Arrangement of reactions around the hypothetical Ms + Bt + Qtz + Crd + St + Al_2SiO_5 + Chl + H_2O invariant point (IP1) assuming excess Ms, Qtz, Bt and H_2O. The stability fields for Crd + St + Bt and Al_2SiO_5 + Bt are indicated. The AFM diagram shows the plotting positions of the minerals and the region of bulk composition of concern to this study.

amphibolite facies. A stable Ms + Crd + St + Bt assemblage implies the stability of a KFMASH invariant point involving the phases Ms + Bt + Qtz + Crd + St + Als + chlorite (Chl) + H_2O (IP1) (Fig. 1). The stability field for Ms + Crd + St + Bt is restricted to pressures below the invariant point, whereas the stability field for the common sub-assemblage Ms + Als + Bt is restricted to pressures above the Ms + Crd + St + Bt stability field (Fig. 1). The possible stability of Ms + Crd + St + Bt assemblages and the associated invariant point IP1 has hindered development of a metapelitic petrogenetic grid that reconciles mineral assemblage sequences at low pressures with those at medium and high pressures (Pattison & Tracy, 1991, pp. 154–155).

The primary purpose of this paper is to address the issue of stability versus instability of Ms + Crd + St + Bt assemblages by combining constraints from natural mineral assemblages and thermodynamic modelling. The problem cannot be resolved by thermodynamic modelling alone because calculated reaction topologies (petrogenetic grids) are extremely sensitive to thermodynamic models of the minerals in question, most of which carry large uncertainties in both end-member and mixing parameters. The result is that a wide range of grid topologies is possible within the uncertainties of the thermodynamic data. In examining natural mineral assemblages, we find that analysis of individual occurrences of Ms + Crd + St + Bt in isolation is insufficient to address the problem. Instead, the key to understanding these assemblages comes from considering them in their broader petrological context. Our analysis suggests that, except perhaps for unusual Zn-rich bulk compositions, Ms + Crd + St + Bt is either not a stable association or is restricted to such low pressures and Fe-rich compositions that it is not developed stably as a natural assemblage.

A secondary purpose of the paper is to account for reported occurrences of Ms + Crd + St + Bt. Our analysis suggests that these assemblages indicate polymetamorphism, and, from their textural associations, may place surprisingly strict limits on possible metamorphic *P–T* paths, making them useful indicators of tectonothermal processes at low pressure.

Ms + Bt + Crd + St STABILITY IN PREVIOUS PETROGENETIC GRIDS

Figure 2 shows four published topologies of the Ms + Bt + Qtz + Crd + St + Als + Chl + H_2O invariant point (IP1) and Ms + Crd + St + Bt stability field in the KFMASH metapelitic petrogenetic grid. The reactions pertaining to the stability of Ms + Crd + St + Bt are highlighted in bold, and the Ms + Crd + St + Bt stability field is shaded. Figure 2(a–c) show an Ms + Crd + St + Bt stability field and the associated invariant point IP1, whereas Fig. 2(d) does not.

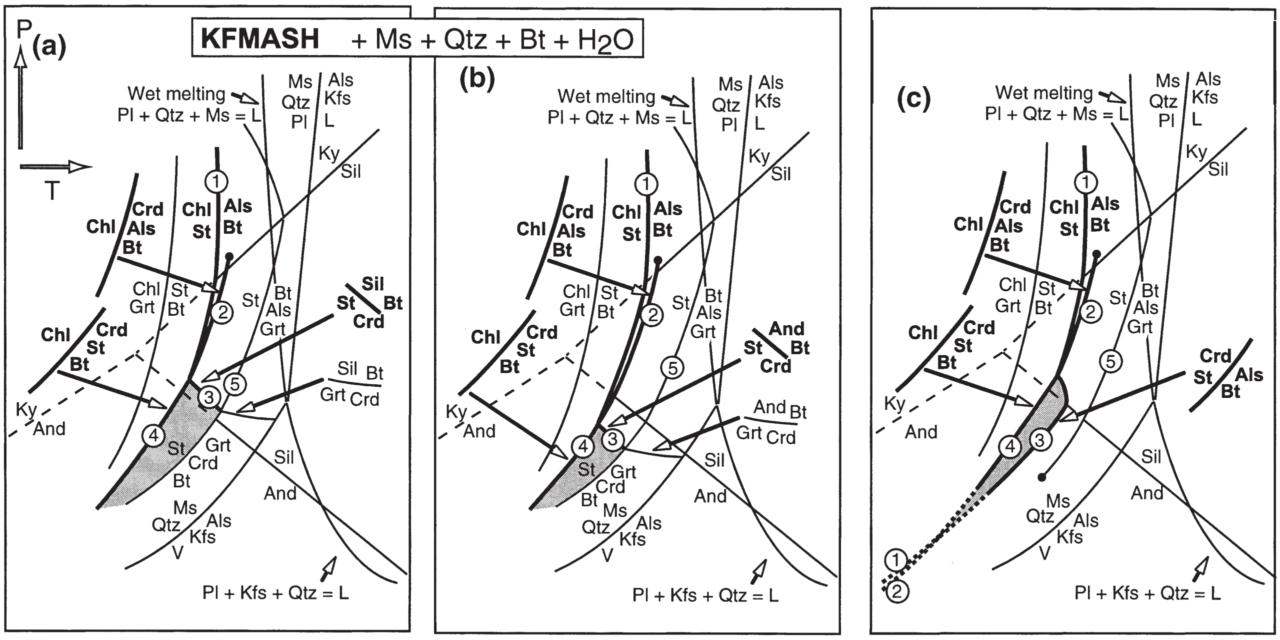
The most common topologies are Fig. 2(a,b), in which IP1 occurs as a stable association between 3.5 and 5.5 kbar (Albee, 1965; Hess, 1969; Thompson, 1976; Kepezhinskas & Khlestov, 1977; Carmichael, 1978; Harte & Hudson, 1979; Davidson *et al.*, 1990; Powell & Holland, 1990; Dymoke & Sandiford, 1992; Reinhardt & Kleemann, 1994; Xu *et al.*, 1994; Froese, 1997). Because several univariant curves emanate from this invariant point, considerable complexity is generated in the low-pressure phase relations, including a controversial low-pressure stability field for Ms + Crd + Grt + Bt (see discussion in Spear & Cheney, 1989 and Pattison & Tracy, 1991). In the topology of Fig. 2(a), in which IP1 lies in the sillimanite (Sil) stability field (Powell & Holland, 1990; Dymoke & Sandiford, 1992; Xu *et al.*, 1994), the stable sub-assemblage Ms + andalusite (And) + Bt is not possible, which contradicts data from many low-pressure settings, both contact and regional (Pattison & Tracy, 1991).

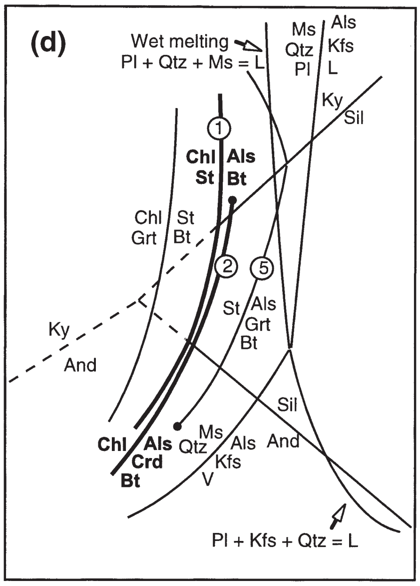
The grids of Hess (1969), Kepezhinskas & Khlestov (1977), Carmichael (1978), Davidson *et al.* (1990), Harte & Hudson (1979) and Froese (1997) maintain the topology of Fig. 2(a) but place IP1 within the andalusite field (Fig. 2b). This topology permits an Ms + And + Bt association at pressures above the implied Ms + Crd + St + Bt stability field. A possible complication in this topology is that predictions from recent thermodynamic data sets (e.g. Spear & Cheney, 1989; Holland & Powell, 1998) suggest that the two reactions which intersect to generate IP1 in the sillimanite stability field:

$$\mathrm{Ms + St + Chl + Qtz = Als + Bt + H_2O} \qquad (1)$$

$$\mathrm{Ms + Chl + Qtz = Crd + Als + Bt + H_2O} \qquad (2)$$

(reaction numbering follows Fig. 2) diverge rather than





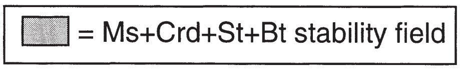


Fig. 2. Published topologies of model KFMASH univariant reactions in the metapelitic petrogenetic grid relevant to invariant point IP1 (see text for discussion). Reactions pertaining to invariant point IP1 (see Fig. 1) are highlighted in bold, and the Ms + Crd + St + Bt stability field is shaded. The solid dot at the end of reaction (2) is its termination in a KMASH invariant point; the solid dot at the end of reaction (5) is its termination in a KFASH invariant point. The dashed lines are the metastable extensions of the Al_2SiO_5 polymorphic transition reactions.
(a) IP1 is stable in the sillimanite field, and reaction (3) intersects reaction (5) to generate a low-pressure Ms + Crd + Grt + Bt stability field. The Ms + Crd + St + Bt field extends into the sillimanite stability field. This is the topology of Powell & Holland (1990), Dymoke & Sandiford (1992) and Xu *et al.* (1994); the topology of Thompson (1976) places invariant point IP1 in the 'zone of uncertainty' for the And = Sil reaction and so may fit either (a) or (b).
(b) Same as (a), except that IP1 and the associated Ms + Crd + St + Bt field are restricted to the andalusite stability field. This is the topology of Hess (1969), Kepezhinskas & Khlestov (1977), Carmichael (1978 and in Davidson *et al.*, 1990), Harte & Hudson (1979) and Froese (1997).
c) IP1 is in the sillimanite stability field, but reaction (3) does not intersect with reaction (5). Instead, reaction (3) inflects across the And = Sil transition such that it re-converges with reaction (4) at low pressure, generating the mirror image of invariant point IP1. The Ms + Crd + St + Bt stability field is an enclosed region between the two invariant points. This is the topology that arises from the January 1997 version of the Spear & Cheney (1989) data set.
(d) There is no stable IP1 and Ms + Crd + St + Bt stability field. Note that in the sillimanite stability field reactions (1) and (2) converge, whereas in the andalusite stability field they diverge. This is the topology of Pattison & Tracy (1991) and Spear & Cheney (1989). The topology of Korikovskii (1979) and the topology arising from the Holland & Powell (1998) data set, although also showing no Ms + Crd + St + Bt stability field, show differences from the above topology (see text).

converge in the andalusite field (see Fig. 2d). Although this implies that IP1 can be stable only in the sillimanite stability field, we suggest that this may not be a robust conclusion because the slopes of these reactions are sensitive to the relatively poorly constrained thermodynamic data for several of the minerals involved (see below).

Figure 2(c) is another variation of Fig. 2(a), in which the reaction

$$Ms + Crd + St + Qtz = Als + Bt + H_2O \quad (3)$$

curves strongly such that it does not intersect the reaction

$$Ms + St + Qtz = Grt + Als + Bt + H_2O \quad (5)$$

to generate a low-pressure Ms + Crd + Grt + Bt stability field as it does in Fig. 2(a,b). The topology of Fig. 2(c) arises from the January 1997 update of the Spear & Cheney (1989) data set. An interesting feature of Fig. 2(c) is that reactions (3) and (4) are inflected across the And = Sil reaction such that they re-converge at low pressures to generate the mirror image of invariant point IP1. The Ms + Crd + St + Bt stability field is therefore an enclosed region bounded by reactions (3) and (4) and the two invariant points. Although this topology in principle allows for Als + Bt to extend into the andalusite stability field, it still implies a significant stability field for Ms + Crd + St + Bt at temperatures below the first appearance of Als + Bt (compare Figs 1 & 2c).

In contrast to the above, Pattison & Harte (1985), Pattison (1989), Spear & Cheney (1989) and Pattison & Tracy (1991) omitted a stability field for Ms + Crd + St + Bt, and therefore invariant point IP1, giving rise to the topology shown in Fig. 2(d). Korikovskii (1979) also omitted an Ms + Crd + St + Bt stability field, but proposed a rather different topology of reactions from those shown in Fig. 2. The most recent version of the Holland & Powell (1998) data set also predicts no stability field for this assemblage in the KFMASH system, although the arrangement of reactants and products for reactions (2) and (5) using their data set is at variance with those shown in Fig. 2(a–d).

LACK OF CONSTRAINTS FROM THERMODYNAMIC MODELLING

Comparison of Fig. 2(d) and Fig. 2(a–c) shows that only subtle changes to the slope and/or position of reactions (1) and (2) are needed to either create or destroy an intersection and thereby generate invariant point IP1 and its associated Ms + Crd + St + Bt stability field. Owing to the relatively poor existing theoretical and experimental constraints on the thermodynamic end-member and mixing properties of the phases involved in these reactions (Crd, St, Chl, Ms, Bt), there is considerable latitude for experimentally permissible thermodynamic models. However, as illustrated in Fig. 2, the topological changes that flow from even small changes to the thermodynamic properties can be extreme. This point is made further by comparing the significantly different topologies of low-pressure metapelitic phase equilibria for different versions of individual thermodynamic data sets: the 1997 version versus the 1989 versions of the Spear & Cheney (1989) data sets, and the 1998 versus 1990 versions of the Holland & Powell (1990, 1998) data sets. In both cases, an Ms + Crd + St + Bt field was predicted using one version of each group's data set, but not the other. Whereas both topologies might be argued to be valid within the uncertainties of the experimental and thermodynamic data, we suggest below that only one topology satisfies nature.

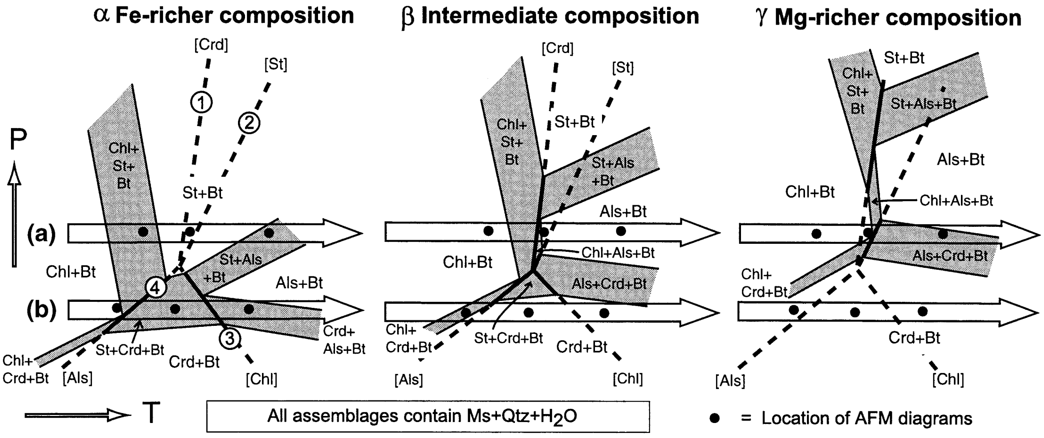
TOPOLOGICAL ANALYSIS OF REACTIONS ASSOCIATED WITH THE Ms + Chl + Qtz + Bt + St + Crd + Al_2SiO_5 + H_2O INVARIANT POINT

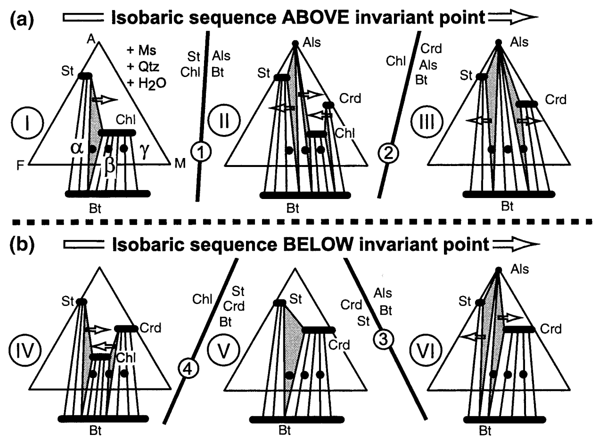
Analysis of the topology of univariant and divariant reactions associated with IP1 is useful in assessing the possible stability of Ms + Crd + St + Bt assemblages. Figure 1 shows schematically the arrangement of KFMASH univariant reactions around the invariant point. The phases muscovite, quartz, biotite and an inferred hydrous vapour phase (H_2O) are assumed to be in excess, resulting in the four reactions illustrated. Addition of Fe–Mg divariant fields to Fig. 1 results in Fig. 3, a series of three *P–T* 'pseudo-sections' (Hensen, 1971) for fixed bulk compositions of differing Mg/(Mg + Fe). Each *P–T* pseudo-section illustrates how the mineral assemblages in that particular bulk composition vary as a function of *P* and *T*. The Fe–Mg divariant fields correspond to continuous Fe–Mg reactions in the model KFMASH system. In Figs 1 and 3, the reactions are oriented schematically from simple entropy/volume considerations, and assume that the order of Fe/Mg in the minerals is as follows: Grt > St > Bt > Chl > Crd (e.g. Spear & Cheney, 1989), with chlorite lying on the Fe-rich side of the Bt–Crd tieline on the AFM diagram (Fig. 1; see discussion in Pattison, 1987, p. 262). The slopes of some of these reactions are poorly constrained, in particular the chlorite-absent reactions, but the conclusions below are unaffected by the exact slopes. Along the univariant reactions considered here, Mg/(Fe + Mg) increases as pressure increases (e.g. Spear & Cheney, 1989; Powell & Holland, 1990).

In Fig. 3, the three *P–T* pseudosections for different bulk Mg/(Fe + Mg) are for an 'A' value on the AFM diagram below the Grt–Chl tie line (the three bulk compositions are shown as dots in the AFM diagrams in Fig. 4). The arrows in Fig. 3 represent isobaric up-temperature trajectories at pressures above and below invariant point IP1. Figure 4 illustrates schematically how the topology of the AFM diagram changes with increasing temperature along the two isobaric *P–T* trajectories, and shows the evolution of mineral assemblages for each of the three fixed bulk compositions (the *P–T* locations of the AFM diagrams are shown by dots in Fig. 3). Figure 5 shows isobaric $T–X_{Fe–Mg}$ diagrams for the two isobaric *P–T* paths, with the labelled arrows corresponding to the three different bulk compositions in Fig. 3. The locations of the AFM diagrams are shown by the numbered horizontal dotted lines. The *P–T* pseudosections in Fig. 3, the AFM diagrams in Fig. 4 and the $T–X_{Fe–Mg}$ diagrams in Fig. 5 focus on the assemblages of interest to this study, and are not meant to be complete topologies.

Some principal implications of Figs 1–5 are:

1 Ms + Crd + St + Bt is only stable at pressures at or below invariant point IP1 and in relatively Fe-rich





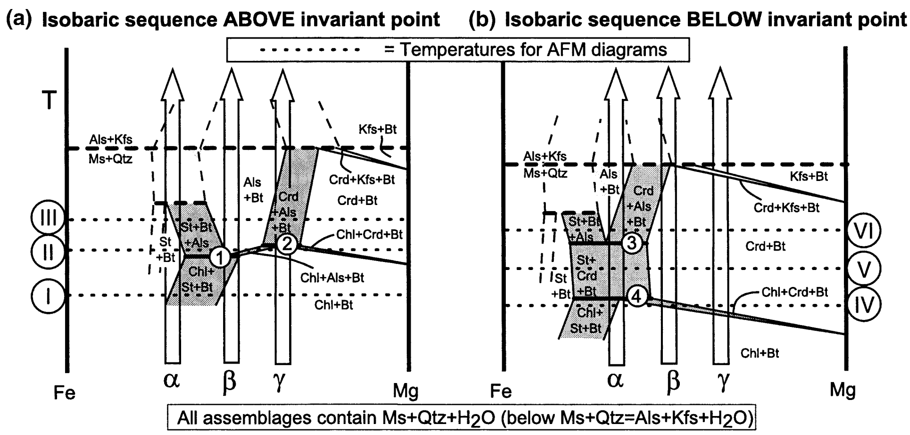


Fig. 3. Schematic *P–T* 'pseudosections' (Hensen, 1971) showing the arrangement of Fe–Mg divariant fields around invariant point IP1 for three different bulk rock Mg/(Mg+Fe) compositions (α, β & γ). The divariant fields correspond to Fe–Mg continuous reactions. The six solid dots in each of the three diagrams represent the *P–T* location of the six AFM diagrams in Fig. 4. The arrows show the locations of two isobaric *P–T* trajectories, one above (a) and one below (b) invariant point IP1. These correspond to the two sequences of AFM diagrams in Fig. 4 and to the two isobaric $T–X_{Fe–Mg}$ diagrams in Fig. 5.

Fig. 4. Series of schematic AFM diagrams showing the progression of assemblages and their compositions for isobaric trajectories above (a) and below (b) invariant point IP1. The AFM diagrams only focus on the assemblages of interest to this study and are not complete AFM topologies. The Roman numerals correspond to the location of the six AFM diagrams in the $T–X_{Fe–Mg}$ diagrams in Fig. 5. The three dots in each AFM diagram represent three different Mg/(Mg+Fe) bulk compositions (α, β & γ), which correspond to the three different *P–T* pseudosections in Fig. 3 and to the three different arrows in the $T–X_{Fe–Mg}$ diagrams in Fig. 5. The small arrows in the AFM diagrams indicate the sense of movement of the three phase triangles (equivalent to Fe–Mg continuous reactions) as temperature increases.

Fig. 5. Schematic $T–X_{Fe–Mg}$ diagrams for isobaric *P–T* trajectories above (a) and below (b) invariant point IP1. The arrows correspond to the three Mg/(Mg+Fe) bulk compositions (α, β & γ) shown in Figs 3 and 4. The labelled dotted lines show the temperatures of the six AFM diagrams in Fig. 4.

bulk compositions, i.e. as Fe-rich as or Fe-richer than the bulk composition in which the invariant point assemblage would be developed (Figs 1 & 3). It occurs as a divariant field bounded by reaction (4) at low temperature and reaction (3) at high temperature.

2 The divariant assemblage Ms + Als + Chl + Bt and univariant assemblage Ms + Chl + Crd + Als + Bt, the latter corresponding to the important univariant reaction Ms + Chl + Qtz = Crd + Als + Bt + H_2O (2), are stable only at pressures at or above invariant point IP1 and for compositions that are as Mg-rich as or Mg-richer than the bulk composition in which the invariant point assemblage would be developed (Fig. 3). Ms + Als + Chl + Bt occurs as a narrow divariant field bounded by reaction (1) at low temperature and reaction (2) at high temperature (Fig. 3c).

3 Different prograde sequences are expected at pressures above and below invariant point IP1, and for different Mg/(Fe + Mg) bulk compositions. For an isobaric prograde path at pressures below the invariant point (Figs 4b & 5b), only relatively Fe-rich compositions will enter the Ms + Crd + St + Bt stability field, the rest developing cordierite without staurolite until higher temperatures are reached. Thus, even though Ms + Crd + St + Bt assemblages are restricted to pressures below the invariant point, they may not be developed at these relatively low pressures if the bulk composition is too Mg-rich. If they are developed, Al_2SiO_5 first occurs upgrade of, and at the expense of, staurolite and cordierite via the univariant reaction Ms + Crd + St + Qtz = Als + Bt + H_2O (3).

4 For an isobaric prograde path at pressures above the invariant point (Figs 4a & 5a), Fe-rich compositions develop Ms + St + Bt ± Als-bearing assemblages, Mg-rich compositions develop Ms + Crd + Als + Bt-bearing assemblages, and a narrow range of intermediate compositions develop assemblages with Ms + Als + Bt alone. Figure 5(a) illustrates the important point that it is not possible, for a given bulk composition, to go from staurolite to cordierite-bearing assemblages, or vice versa, along any prograde path at pressures above the invariant point. This is due to the small Ms + Als + Chl + Bt field which separates Mg-richer cordierite-bearing assemblages from Fe-richer staurolite-bearing assemblages.

EVIDENCE FROM CONTACT AUREOLES

We now compare what is observed in nature with the above constraints, focusing first on low-pressure sequences in contact aureoles, and second on reported Ms + Bt + Crd + St sequences. Pattison & Tracy (1991) emphasized the importance of constraints from contact aureoles around single intrusions for two main reasons: (1) the thermal history is simple (one thermal event), thereby eliminating complications from polymetamorphism such as encountered in many regional low-pressure terranes, and (2) the thermal pulse and decay is relatively rapid (generally <1 Myr), such that the prograde *P–T* path for individual rocks as well as the metamorphic field gradient can be assumed to be sensibly isobaric rather than involving significant variation in both pressure and temperature.

Pattison & Tracy (1991) examined 104 low-pressure (andalusite–sillimanite-type) prograde sequences, of which 64 were contact, 40 regional. They subdivided them into five assemblage sequences or facies series (1a–c, 2a–b) that represent the majority of reported assemblages in the aureoles examined (see Table 1). The compilation in Table 1 indicates that, even within low-pressure And–Sil type sequences, there is a significant pressure-related variation in mineral assemblage sequence. Although bulk compositional variation can account for some of these assemblage variations without appealing to pressure variations (e.g. staurolite in Fe-richer compositions, cordierite in Mg-richer compositions; see Fig. 5), the implied pressure differences are consistent with bulk composition-independent pressure differences related to the intersection of the And = Sil and Ms + Qtz = Als + Kfs reactions. Facies series 1 sequences occur at pressures below the intersection of these two reactions, whereas facies series 2 sequences occur at pressures above this intersection.

In all the aureoles considered by Pattison & Tracy (1991) that are not complicated by polymetamorphism, there is not a single example of an Ms + Crd + St + Bt assemblage, let alone a mappable zone, in a prograde sequence developed from an Ms + Chl + Qtz protolith. Rather, the facies series in Table 1 are consistent with steadily increasing pressure through the topology of Fig. 6, which geometrically is the same as Fig. 3(c) but includes some additional reactions. Fig. 6 implies that the Ms + Crd + St + Bt field and associated invariant point IP1 are either not stable or are restricted to such low pressures and Fe-rich compositions that they are not 'seen' in natural rock compositions.

Table 2 shows Mg/(Mg + Fe) for cordierite and biotite in the assemblage Ms + Chl + Crd + Als + Bt arranged according to the facies series scheme in Table 1. This assemblage corresponds to reaction (2) (Ms + Chl + Qtz = Crd + Als + Bt + H_2O). Overall there is a smoothly decreasing pattern in Mg/(Mg + Fe) in co-existing Crd + Bt as pressure decreases from the kyanite to the sillimanite to the andalusite field, suggesting that metamorphic settings at progressively lower pressures have intersected reaction (2) at progressively Fe-richer compositions. The most Fe-rich values are <0.26 and <0.44, respectively, from the facies series 1c McGerrigle aureole, Quebec. These values provide an upper limit for Mg/(Mg + Fe) in co-existing Crd + Bt in Ms + Crd + St + Bt assemblages, because the Ms + Chl + Crd + Als + Bt assemblage is only stable at pressures above and in more magnesian compositions than invariant point IP1. The data in Table 2 argue against the possibility of a small stability

Table 1. Metapelitic facies series (modified from Pattison & Tracy, 1991).

Facies series	Pressure range (kbar)	Prograde sequence of assemblages*						Number of examples	
								Contact	Regional
1a	1.0–2.0	Crd + Chl	Crd	Crd + Kfs	And + Kfs + Crd	And ± Sil + Kfs + Crd		4	0
1b	2.0–3.0	Crd + Chl	Crd	Crd + Kfs	And ± Sil + Kfs + Crd	Sil(And) + Kfs + Crd		10	3
1c	2.5–3.0	Crd + Chl or And + Chl	Crd or Chl + Crd + And	Crd + And	And ± Sil + Kfs + Crd	Sil(And) + Kfs + Crd		19	4
2a	2.5–3.5	Crd + Chl or And + Chl	Chl + Crd + And or And	Crd + And or And	Sil(And) + Crd or Sil(And)	Sil + Kfs ± Crd		22	13
2b	3.0–4.0	St + Chl	St + And ± Chl or St	St + And or St	St + Sil(And) or St	Sil(And) or Grt + Sil ± St	Sil + Kfs or Grt + Sil + Kfs	10	19
3	4.0–5.5	St + Chl	St + Sil ± Chl or St	St + Sil or St	St + Sil or St	Grt + Sil ± St	Grt + Sil + Kfs	3?	3
4	> 5.5	St + Chl	St + Ky ± Chl or St	St + Ky or St	St + Sil(Ky) or St	Grt + Sil(Ky) ± St	Grt + Sil + Kfs	2	Many

* Assumes starting protolith of Ms + Chl + Qtz ± Bt ± Mn-rich Grt. All assemblages contain Ms + Qtz + Bt ± Grt up to the stability of Al_2SiO_5 + Kfs, except for the higher grade parts of facies series 2–4 in which Grt may be produced from St breakdown. Minerals in brackets are interpreted to have persisted metastably from lower grade.

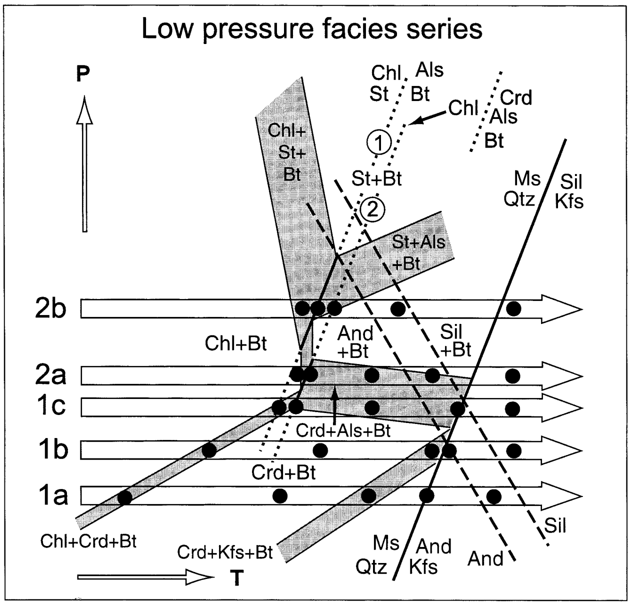


Fig. 6. Schematic topology of KFMASH univariant reactions and divariant fields (the latter corresponding to Fe–Mg continuous reactions) for an arbitrary Mg/(Mg + Fe) bulk composition, assuming no stability field for Ms + Crd + St + Bt. Isobaric trajectories corresponding to Pattison & Tracy's (1991) five low-pressure facies series (see Table 1) are represented by the labelled arrows. Dots correspond to individual assemblages listed in Table 1. Topologically this diagram is like that of Fig. 3(c), although we do not wish to imply that the bulk composition is unusually Mg-rich.

field for Ms + Crd + St + Bt such as that shown in Fig. 2(c), because there are no significant compositional 'gaps' in the reaction (2) assemblage between which such a field could fit (see also other arguments below).

FEATURES OF REPORTED OCCURRENCES OF Ms + Bt + Crd + St

Despite the indications from contact aureoles that Ms + Crd + St + Bt may not be a stable association, or one of restricted stability, this assemblage has nevertheless been reported from a number of low-pressure regional settings. Reported occurrences of Ms + Bt + Crd + St fall roughly into three groups:

1 as assemblages within low-pressure Crd + And-type settings in which the host rocks to the low-pressure overprint were St ± Grt ± Als regional assemblages (e.g. Errol aureole, Maine: Green, 1963; Omey aureole, Ireland: Ferguson & Harvey, 1978; Betic-Rif area, Pyrenees: Garcia-Casco & Torres-Raldon, in press)

2 as relatively rare, isolated assemblages in low-pressure regional settings (e.g. Buchan, Scotland: Hudson, 1980; Mt Lofty, Australia: Sandiford *et al.*, 1990; Finland: Tuisku & Laajoki, 1990; Saxonian Massif: Reinhardt & Kleeman, 1994), and

3 as apparent metamorphic zones in a relatively small number of regional low-pressure settings, including parts of the French and Spanish Pyrenees (Zwart, 1962; Guitard, 1965; Verhoef *et al.*, 1984; de Bresser *et al.*, 1986; Kriegsman *et al.*, 1989; Pouget, 1991), the southern Massif Central, France (Thompson & Bard, 1982), south-central Maine (Osberg, 1968, 1971; Ferry, 1980; Novak & Holdaway, 1981; Holdaway *et al.*, 1982), south-western Nova Scotia (Hope, 1987; Hwang, 1990; Raeside & Jamieson, 1992; Peskleway, 1996) and parts of the Slave province, North-west Territories (e.g. Ramsay & Kamineni, 1977).

Neglecting the obviously polymetamorphic occurrences, we note the following commonalities.

1 The metamorphic sequences are part of regional, low-pressure (And–Sil type) metamorphic terranes. The metamorphism is spatially associated with several

Table 2. Variation in Mg/(Mg+Fe) of Crd and Bt in Ms+Chl+Crd+Al_2SiO_5+Bt assemblages as a function of facies series.

Location	Facies series*	Assemblage†	Biotite Mg/(Mg+Fe)	Cordierite Mg/(Mg+Fe)	Assemblages downgrade of Chl+Crd+And†	First occurrence of Sil in sequence
McGerrigle	C, 1c	Chl+Crd+And	0.26–0.33	0.44–0.49	Crd+Chl, And+Chl	No Sil
Onawa	C, 1c	Chl+Crd+And	0.32–0.33	0.47	Crd+Chl, And+Chl	Above And+Kfs-in
Tono	C, 1c	Chl+Crd+And	0.40–0.41	0.54	And+Chl	Above And+Kfs-in
Bugaboo	C, 1c	Chl+Crd+And	≤0.41	≤0.56	Crd+Chl, And+Chl	Above And+Kfs-in
Cupsuptic	C, 2a	Chl+Crd+And	0.39–0.42	0.56–0.58	Crd+Chl	Below Sil+Kfs-in
S. Nevada	R, 2a	And	≥0.44	≥0.58?	And+Chl	Below Sil+Kfs-in
Panamint	R, 2b	Chl+Crd+And	0.52–0.55	0.65–0.67	Crd+Chl, And+Chl	Below Sil+Kfs-in
Rangeley	R, 3	Chl+Crd, Crd+Sil	≤0.76	≤0.82–0.84	Crd+Chl	Below Sil+Kfs-in
Truchas	R, 4?	Chl+Crd+Ky	0.71–0.73	0.85–0.86	No data	Below Sil+Kfs-in
Whetstone Lake	R, 4	Chl+Crd, Crd+Ky	≤0.86	≤0.95	Crd+Chl	Below Sil+Kfs-in

* R, regional; C, contact.
† All assemblages contain Ms+Qtz+Bt±Grt.
References: McGerrigle; Van Bosse & Williams-Jones, 1988; Onawa: Symmes & Ferry, 1995; Tono: Okuyama-Kusunose, 1993; Bugaboo: Pattison & Jones, 1993; Debuhr, unpublished; Cupsuptic: Ryerson, 1979; S. Nevada: Best & Weiss, 1964; Panamint: Labotka, 1981; Rangeley: Guidotti *et al*.. 1975; Guidotti & Cheney, unpublished; Truchas: Grambling, 1981; Whetstone Lake: Carmichael *et al*., 1978.

generations of intrusions (e.g. south-central Maine, SW Nova Scotia) and/or migmatitic gneiss complexes (Pyrenees).

2 Ms+Crd+St+Bt assemblages may have a patchy distribution within a given metamorphic setting. Such localities include the Augusta area, Maine (Fig. 7; fig. 1 of Holdaway et *al*., 1982), SW Nova Scotia (Fig. 8), Buchan area, Scotland (fig. 1 of Hudson, 1980), and parts of the Pyrenees (fig. 1 of Guitard, 1965 and fig. 2 of Pouget, 1991). This patchiness reflects either the sporadic occurrence of staurolite in predominantly And+Crd-bearing rocks (e.g. Kriegsman *et al*., 1989; Pouget, 1991), or the sporadic occurrence of late porphyroblastic cordierite in predominantly St±And-bearing rocks (e.g. Figs 7 & 8).

3 A common map pattern of apparent prograde mineral assemblage zones is (Ms+Qtz+Bt in excess):

$$\text{St } or \text{ St+And} \rightarrow \text{St+And+Crd}$$

This sequence, termed the 'Pyreneean sequence' by Hietanen (1967) and Hess (1969), is based on Zwart's classic study in the Bosost area (Zwart, 1962), and pertains to the Slave and Mount Lofty areas. Figure 7 illustrates an example of this apparent isograd sequence from the Augusta area of Maine, and Fig. 8 shows the distribution of mineral assemblages in SW Nova Scotia, some parts of which show this sequence. In the Bosost area, a Ms+And+Crd+Bt zone occurs above the apparent Ms+St+And+Crd+Bt zone. In other areas in the Pyrenees (e.g. Guitard, 1965; Verhoef *et al*., 1984; Kriegsman *et al*., 1989) and in the Buchan area of Scotland (Read, 1952; Hudson, 1980), Ms+Crd+St+Bt-bearing assemblages occur within what are mapped as And+Crd and Sil zones. In the Massif Central (Thompson & Bard, 1982), the apparent metamorphic zonal sequence is (Ms+Bt+Qtz in excess):

$$\text{Crd} \rightarrow \text{Crd+St} \rightarrow \text{Crd+St+And} \rightarrow \text{Crd+St+And+Sil}$$

In general, the distribution of mineral assemblages and thus the metamorphic zones associated with Ms+Crd+St+Bt±Als occurrences appear to be complex and/or irregular (Guitard, 1965; Holdaway

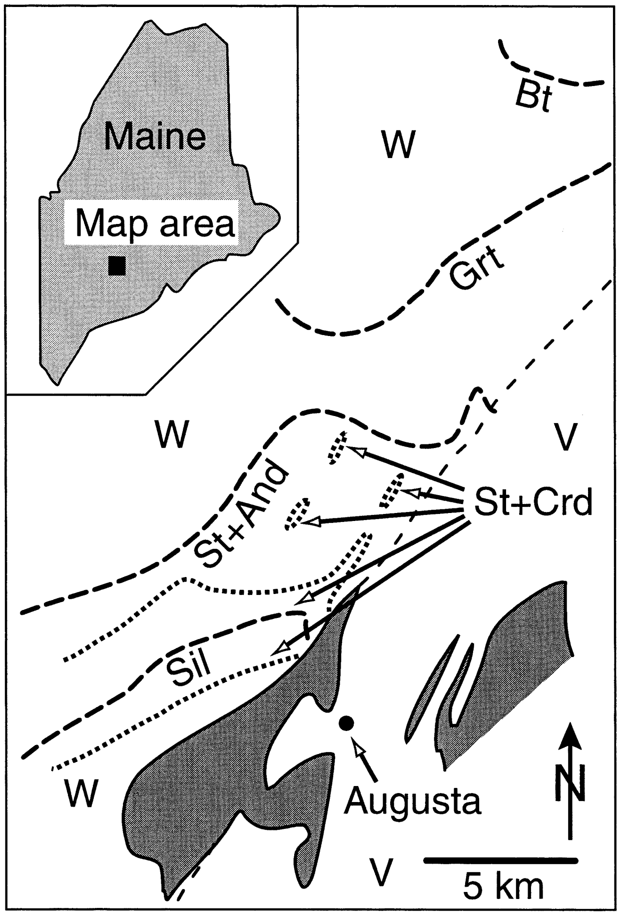


Fig. 7. Map of principal isograds (dashed lines) in Ms+Bt+Qtz±Grt-bearing rocks in the Augusta area, Maine (based on Fig. 1 of Ferry, 1980). The St+And isograd corresponds to the first appearance of St or And; rocks containing both minerals are common upgrade of the isograd. The dotted lines bound occurrences of Crd+St-bearing assemblages, many of which also contain And±Sil. The lowest grade occurrences of St+Crd assemblages are within the St+And zone, whereas the highest grade occurrences are 2–3 km upgrade of the sillimanite isograd (see fig. 1 of Osberg, 1974). W, pelitic Waterville Formation. V, calcareous Vassalboro Formation. Quartz monzonite stocks are shown in the grey ornament.

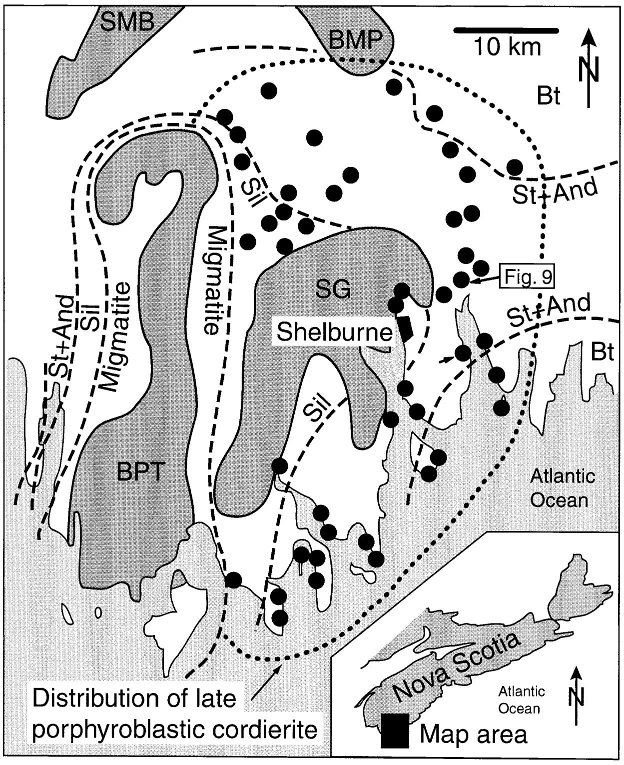


Fig. 8. Map of the Shelburne area, SW Nova Scotia (based on figs 3 and 4 of Raeside & Jamieson, 1992 and figs 4 and 5 of Peskleway, 1996). Isograds are shown in dashed lines. St locally appears without And below the St + And isograd. Occurrences of late porphyroblastic cordierite (solid dots) are contained within the dotted line. BPT, Barrington Passage Tonalite. SG, Shelburne Granite. SMB, South Mountain Batholith. BMP, Balm Mountain Pluton.

et al., 1982; Verhoef *et al.*, 1984; de Bresser *et al.*, 1986; Kriegsman *et al.*, 1989; Pouget, 1991; Raeside & Jamieson, 1992).

4 Staurolite is typically early texturally, and cordierite is late. This situation pertains to most of the occurrences listed above. Examples of rocks from SW Nova Scotia showing this relationship are shown in Fig. 9(a–d). Andalusite, which is commonly present in Ms + Crd + St + Bt-bearing assemblages, tends to be later than staurolite and earlier than, or of ambiguous timing relative, to cordierite (Fig. 9b,e; Peskleway, 1996). Sandiford (personal communication) reports a rare counter-example from Petrel Cove, Mount Lofty Ranges, Australia, in which staurolite is late relative to And + Crd. In a number of Ms + Crd + St + Bt ± And assemblages, microtextures indicate a protracted and sometimes complex history of mineral growth and deformation events (e.g. Ramsay & Kamineni, 1977; Thompson & Bard, 1982; Verhoef *et al.*, 1984; de Bresser *et al.*, 1986; Kriegsman *et al.*, 1989; Pouget, 1991).

5 The first occurrence of sillimanite invariably occurs upgrade of andalusite and downgrade of Ms + Qtz = Als + Kfs (e.g. Figs 7 & 8). This indicates moderate rather than low pressures (i.e. facies series 2 rather than facies series 1; see Table 1).

6 Ms + Crd + St + Bt-bearing assemblages typically contain more AFM phases than expected, leading to anomalously low variance (e.g. univariant and invariant) assemblages. It is not unusual for assemblages to contain Crd + St + Chl + Grt + And ± Sil ± Ky in addition to Ms + Qtz + Bt (e.g. Zwart, 1962; Holdaway *et al.*, 1982; Thompson & Bard, 1982; de Bresser *et al.*, 1986; Raeside & Jamieson, 1992). Even allowing for the stabilization of garnet by Mn, a retrograde origin for chlorite, and relic metastability for kyanite and perhaps sillimanite, a common assemblage in all of the above terranes is Ms + Crd + St + And + Bt. This assemblage may be widely and irregularly developed over significant areas in the above terranes (Figs 7 & 8).

7 Ms + Crd + St + Bt ± And assemblages are relatively magnesian. Table 3 lists compositional data of cordierite, biotite and staurolite from these assemblages from several localities. The ranges of Mg/(Mg + Fe) of cordierite, biotite and staurolite, respectively, are 0.42–0.71, 0.58–0.82 and 0.13–0.25.

PROBLEMATIC ASPECTS OF Ms + Crd + St + Bt OCCURRENCES

Inability to reconcile assemblage sequences in a single prograde path

The common prograde mineral assemblage sequence (metamorphic field gradient) described in point 3 and illustrated in Fig. 7 cannot be developed along any single prograde *P–T* path for a given bulk composition. We assume that the metamorphic field gradient is similar to the *P–T* path of individual rocks in the sequence and is approximately isobaric, as concluded by De Yoreo *et al.* (1991) in their compilation and thermal modelling of low-*P*/high-*T* metamorphic belts.

Referring to Figs 3–5, if the reported Ms + Crd + St + Bt associations are stable, they imply *P–T* conditions below invariant point IP1. However, in a prograde sequence below IP1, St + Crd must occur downgrade of St + And, the opposite to what is seen. Alternatively, if one accepts the documented progression from the staurolite zone to the St + And zone (the common facies series 2b progression of Pattison & Tracy, 1991; see Table 1), there is no way to proceed upgrade to a St + Crd + And zone from the St + And zone unless there is a change in the bulk composition.

Inconsistency of textures with predicted reaction relations

Prograde *P–T* paths of individual rocks through different sequences of reactions will result in a predictable sequence of mineral consumption and/or

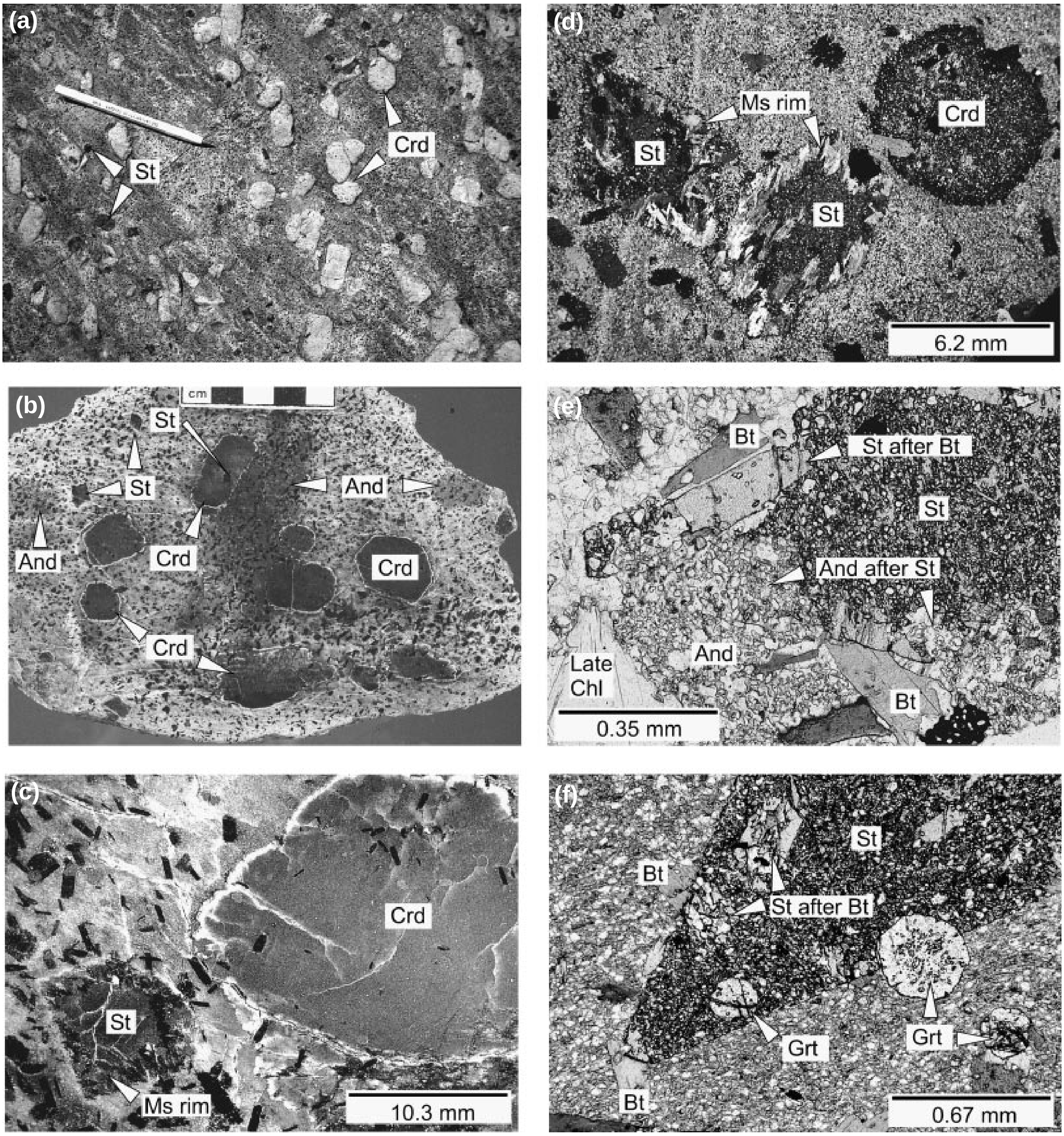


Fig. 9. Photographs of rocks and thin sections from an outcrop near Jordan Falls, SW Nova Scotia (see Fig. 8 for location of outcrop).
(a) Outcrop surface showing distribution of Crd and St porphyroblasts in a biotite-speckled, fine grained Ms + Qtz + Bt + Grt matrix. The Crd occurs in vaguely rectangular and hexagonal patches (cf. Raeside & Jamieson, 1992). Several Crd porphyroblasts contain St as inclusions. And is also present in the outcrop but is not visible in this photograph. Length of pen is 14 cm.
(b) Polished slab of rock from the outcrop in (a) showing the distribution and texture of St, And and Crd porphyroblasts in a biotite-speckled Ms + Qtz + Bt + Grt matrix. St occurs as euhedral brown crystals, sometimes with Ms-rich rims, and may be included in Crd and And porphyroblasts. And occurs in large, pale, anhedral poikiloblastic crystals with diffuse margins. Crd occurs in anhedral to subhedral, occasionally pseudohexagonal, crystals that are developed in both the matrix and in And crystals. The light-coloured margins on the Crd crystals are due to pinitization. Whereas And porphyroblasts may contain abundant biotite crystals as inclusions, Crd porphyroblasts contain few biotite inclusions and may be surrounded by a biotite-depleted halo.
(c) Close-up of another polished rock slab from the outcrop in (a), showing a euhedral St grain partially pseudomorphed by coarse muscovite, and a large, inclusion-poor Crd porphyroblast surrounded by a biotite-depleted halo.

growth, which can be compared with the observed timing of mineral growth from microstructures. A prograde path (below IP1) that leads to the formation of an Ms + Crd + St + Bt + And assemblage implies passage through univariant reaction (4) (Ms + Chl + Qtz = St + Crd + Bt + H_2O) followed by reaction (3) (Ms + Crd + St + Qtz = And + Bt + H_2O) (see Figs 1 & 5b). The expected timing of mineral formation from such a sequence will be staurolite and cordierite early, and andalusite late, with andalusite forming at the expense of cordierite and staurolite. However, in many natural examples of this assemblage (e.g. SW Nova Scotia, Maine), cordierite is the latest mineral to form, overgrowing and in some cases forming pseudomorphs after earlier staurolite and andalusite (Fig. 9). Andalusite overgrows and may be pseudomorphous after staurolite, but is itself most commonly overgrown or replaced by cordierite (e.g. Raeside & Jamieson, 1992; Peskleway, 1996) (Fig. 9). These textures indicate a *P–T* path involving sequential growth of staurolite, andalusite and cordierite. Although the sequence staurolite followed by andalusite can be explained in an isobaric prograde *P–T* path above invariant point IP1 (see Fig. 5a), the late growth of cordierite requires decompression (see below).

Incongruities between the zonal sequence of mineral assemblage zones and microtextural evidence for timing of mineral growth

This situation contrasts with that in the contact metamorphic prograde sequences described above, in which available textural evidence for timing of mineral growth and/or consumption generally fits with the sequence of mineral assemblage zones (i.e. lower-grade assemblages appear to be the precursors to higher-grade mineral assemblages). In SW Nova Scotia, cordierite is late texturally in all sub-migmatitic rocks, even though it may occur spatially at lower grade than St + And-bearing assemblages (e.g. NE corner of Fig. 8) (Raeside & Jamieson, 1992; Peskleway, 1996). In the Massif Central, Thompson & Bard (1982) noted that despite the apparent zonal sequence noted in point 3 above, in which cordierite occurs spatially at the lowest grade, microtextural evidence showed that staurolite, garnet and kyanite pre-dated andalusite and cordierite. Similar examples have been described from the Pyrenees by de Bresser *et al.* (1986) and Gibson (1992).

Inconsistency in pressure between contact aureole sequences and Ms + Crd + St + Bt sequences

All sequences containing Ms + Bt + Crd + St develop sillimanite upgrade of andalusite and downgrade of the terminal reaction of muscovite (Ms + Qtz = Kfs + Als). Unless the metamorphic field gradient is atypically steep (cf. De Yoreo *et al.*, 1991), with marked increase in *P* and *T*, this implies that the Ms + Crd + St + Bt stability field, and therefore invariant point IP1, must lie in the andalusite stability field at pressures above the intersection of And = Sil and Ms + Qtz = Kfs + Als (Fig. 10). This contradicts evidence from numerous facies series 1 aureoles (e.g. Onawa, Bugaboo, McGerrigle; Table 2) in which the prograde progression passes through model univariant reaction (2) (Ms + Chl + Qtz = Crd + Als + Bt + H_2O). Because reaction (2) is stable only at pressures above invariant point IP1, this implies that IP1 can only lie at pressures below the intersection of And = Sil and Ms + Qtz = Kfs + Als (Fig. 10), the opposite inference from the Ms + Bt + Crd + St sequences.

Inconsistency in mineral compositions

Cordierite and biotite in Ms + Crd + St + Bt assemblages are more Mg-rich than they are in Ms + Crd + And + Bt ± Chl assemblages from several well-documented low-pressure settings (compare Tables 2 & 3). This contradicts the topological constraints of Figs 1–5, which show that Ms + Crd + St + Bt assemblages, which are restricted to pressures below invariant point IP1, should be more Fe-rich than Ms + Crd + And + Bt assemblages, which are restricted to pressures above IP1. The Mg/(Mg + Fe) ratios for cordierite and biotite in Ms + Crd + St + Bt ± And assemblages are approximately the same as they are in Ms + And + Crd + Bt ± Chl assemblages from facies series 2b.

Too many AFM phases

The phase rule variance for most Ms + Crd + St + Bt assemblages is consistently and unusually low (univariance and invariance is common), even allowing for stabilization of some minerals by minor components. The most common assemblage, Ms + Crd + St + And + Bt, may occur over broad areas (e.g. Maine, SW

Fig. 9 *(Cont'd)*

(d) Photomicrograph of the rock in (b) showing a Crd porphyroblast adjacent to two St grains partially pseudomorphed by coarse Ms.
(e) Photomicrograph of another rock from the outcrop in (a) showing the partial pseudomorphing of St by And. The St grain occurs on the margin of a large, enveloping And poikiloblast which extends past the bottom of the photomicrograph.
(f) Photomicrograph of the same rock as in (e), showing a euhedral St poikiloblast in a fine grained Ms + Qtz matrix. Grt occurs as porphyroblasts in the matrix and as inclusions in St. Biotite porphyroblasts are partly to totally pseudomorphed by St.

Table 3. Compositional parameters of Crd, St and Bt in $Ms+Crd+St+Bt\pm Al_2SiO_5$ assemblages.

Location	Assemblage*	Number of samples analysed	Biotite Mg/(Fe+Mg)	Cordierite Mg/(Fe+Mg)	Cordierite Mn/(Mn+Fe+Mg)	Staurolite Mg/(Fe+Mg)	Staurolite Mn/(Fe+Mg+Mn+Zn)	Staurolite Zn/(Fe+Mg+Mn+Zn)
Shelburne	Grt±And±Sil(±Chl)	13	0.42–0.58	0.58–0.72	0.01–0.03	0.14–0.25	0.01–0.06	0.04–0.13
Mean values			0.50	0.66	0.02	0.20	0.03	0.07
Bosost	And+Sil+Grt	1	0.48	0.61	0.02	0.13	0.03	0.00
Augusta–O71	Grt±And(+Chl)	6	0.48–0.51	0.64–0.66	0.02–0.03	0.20	0.03–0.04	n/a
Augusta–NH81	And+Sil+Grt(+Chl)	1	0.55	0.70	0.01	0.20	0.02	0.05
Rangeley	±And±Grt(±Chl)	2	0.53–0.55	0.65–0.68	0.02	0.16–0.21	0.03	0.02–0.03
Mt. Lofty	And+Sil	1	0.53	0.69	n/a	0.20	n/a	n/a
Finland	Grt	1	0.71	0.82	0.02	0.25	0.05	0.03

* All assemblages contain St+Crd+Ms+Qtz+Bt. Minerals in brackets are secondary. n/a, not available.

References: Shelburne: Peskleway, 1996; Bosost: Pouget, 1991; Augusta: Osberg, 1971; Novak & Holdaway, 1981; Rangeley: Henry, 1981; Mt. Lofty: Sandiford *et al.*, 1990; Finland: Tuisku & Laajoki, 1990.

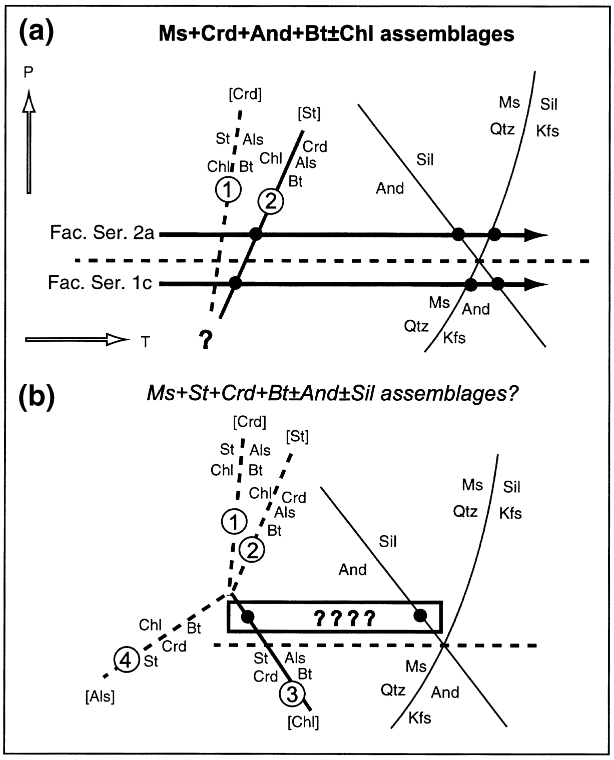


Fig. 10. Conflicting petrological evidence for the possible location of invariant point IP1.
(a) Prograde sequences in numerous contact aureoles go through $Chl=Crd+And+Bt$ (reaction 2), including some from facies series 1 in which $Ms+Qtz$ breaks down to $And+Kfs$. Invariant point IP1 must therefore lie at pressures lower than the intersection of $And=Sil$ and $Ms+Qtz=Al_2SiO_5+Kfs+H_2O$.
(b) All reported $Crd+St+Bt\pm Al_2SiO_5$ assemblages come from prograde sequences in which Sil first appears downgrade of the $Ms+Qtz$ breakdown, implying that invariant point IP1 must lie at pressures higher than the intersection of $And=Sil$ and $Ms+Qtz=Al_2SiO_5+Kfs+H_2O$.

Nova Scotia, Pyrenees), an unexpected pattern for an ostensibly univariant assemblage (see discussion in Holdaway *et al.*, 1982 and below).

POSSIBLE EXPLANATIONS FOR REPORTED OCCURRENCES OF Ms+Bt+Crd+St

Misinterpretation of assemblages

Misinterpretation of late muscovite

Muscovite, like chlorite, is ubiquitous as an alteration product of staurolite, cordierite and Al_2SiO_5 minerals. Misinterpretation of late-formed or alteration-related muscovite is a significant problem in K-poor metasediments lacking stable muscovite because St+Crd is possible as a stable association in these rocks (Percival *et al.*, 1982; Hudson & Harte, 1985; Spear & Rumble, 1986; Spear, 1993). Special attention must therefore be paid to the spatial associations and texture of modally minor amounts of muscovite in rocks that contain both staurolite and cordierite. Sandiford (personal communication) has described a rock from Petrel Cove in the Mount Lofty Ranges, Australia, that contains Ms+Crd+St+And+Bt, but the muscovite is a late reaction product that is not in equilibrium with the cordierite and andalusite.

Mixing of compositional domains

Metapelitic rocks commonly display millimetre to centimetre scale bands of differing composition. Failure to recognize separate domains within individual metapelitic rocks or thin sections may lead to mixing of mineral assemblages from the separate domains. For example, an Mg-richer cordierite-bearing layer adjacent to an Fe-richer staurolite-bearing layer might be misinterpreted as an apparent Ms+Crd+St+Bt assemblage.

Extra components

The two most likely components that will expand the stability field of Ms+Crd+St+Bt are Mn, which may occur in both cordierite and staurolite, and Zn in staurolite. Table 2 lists the measured Mn and Zn contents of cordierite and staurolite from

Ms + Crd + St + Bt localities. Mn/(Mg + Fe + Mn + Zn) in cordierite is generally low, averaging 0.02. Mn/(Mg + Fe + Mn + Zn) in staurolite averages 0.03, ranging from 0.01 to 0.06. Zn/(Mg + Fe + Mn + Zn) in staurolite averages about 0.05, ranging from 0.01 to 0.13.

Incorporation of Zn only into staurolite means that invariant point IP1 (and hence the stability field for Ms + Crd + St + Bt) will be displaced up-pressure along the staurolite-absent reaction (2) (see Fig. 1). Incorporation of Mn into both cordierite and staurolite means that IP1 will be displaced up pressure along staurolite-absent reaction (2) and cordierite-absent reaction (1), respectively, according to the amount of Mn in each phase.

To estimate the effect of these extra components on the stability field of Ms + Crd + St + Bt, a stable point invariant point IP1 was created at 4.5 kbar, 595 °C using the thermodynamic data set of Spear & Cheney (1989; January 1997 update), although it is emphasized that we do not think that the invariant point actually occurs here. Because the cordierite- and staurolite-absent reactions are so close together and are nearly parallel (Fig. 2), for simplicity we have assumed that the combined Mn and Zn in cordierite and staurolite all reside in staurolite. The invariant point was displaced for (Mn + Zn)/(Fe + Mg + Mn + Zn) values in staurolite of 0.05, 0.10 and 0.15, which cover the measured range of Mn and Zn contents in Table 3. For simplicity we assumed ideal mixing. The pressure of invariant point IP1 is raised from 4.5 kbar in the Mn + Zn-free system to 4.9, 5.3 and 5.7 kbar, respectively. This modest expansion of the Ms + Crd + St + Bt stability field is a maximum and will be offset by substitution of Mn and Fe^{3+} in chlorite and Mn, Ti, Fe^{3+} and F in biotite, and perhaps other minor element substitutions. Thus, for most of the natural examples listed in Table 3, in which the combined Mn and Zn content of cordierite and staurolite is relatively small, there is not a sufficient expansion of the Ms + Crd + St + Bt stability field for this mechanism to offer a general solution to the problematic aspects of these assemblages.

Variable a_{H_2O}

Variable fluid composition may also affect the stability of Ms + Crd + St + Bt assemblages (e.g. Osberg, 1971; Henry, 1981). Reduction in a_{H_2O} displaces invariant point IP1 along the H_2O-absent reaction, which according to the data set of Spear & Cheney (1989; January 1997 update) is towards lower temperature and pressure. This sense of displacement is the opposite to what is needed to reconcile Ms + Crd + St + Bt assemblages with the other natural data because it displaces the Ms + Crd + St + Bt stability field to lower rather than higher pressure.

Reduced a_{H_2O} has the additional effect of shrinking a possible Ms + Crd + St + Bt stability field (topology of Fig. 2c) to the point that it disappears at an a_{H_2O} value of *c*. 0.7. This opens the possibility that Ms + Crd + St + Bt assemblages might be stable under conditions of high a_{H2O} whereas Ms + And + Bt ± Crd ± Chl assemblages might be stable at the same *P–T* conditions under conditions of low a_{H_2O}, possibly accounting for the two apparently incompatible assemblages occurring at similar pressures.

We consider significantly reduced a_{H_2O} to be unlikely during the growth of mineral assemblages in metapelites because the reactions involved are dehydration reactions. Maintaining significantly reduced a_{H_2O} throughout the time of reaction would imply an efficient means to continually dilute and/or remove the water-rich fluid being produced within the pores and channels of the dehydrating rock. A more viable mechanism to reduce a_{H_2O} may be represented by graphitic rocks, in which graphite reacts with the H_2O released from dehydration to produce C-O-H-bearing fluid species, thereby lowering a_{H_2O} (Ohmoto & Kerrick, 1977; Pattison, 1989; Connolly & Cesare, 1993). If graphite did have a significant effect, one might expect a pattern in which Ms + Crd + St + Bt ± And assemblages are found preferentially in graphite-free rocks and Ms + And + Bt ± Crd ± Chl assemblages are found preferentially in graphitic rocks. However, there are numerous examples of non-graphitic Ms + And + Bt ± Crd ± Chl assemblages (e.g. Bugaboo aureole, British Columbia), and graphite presence is implied at least some of the Ms + Crd + St + Bt assemblages from Maine (Novak & Holdaway, 1981; p. 53). In summary, we feel that reduced a_{H_2O} does not provide an adequate explanation for the problematic aspects of Ms + Crd + St + Bt assemblages.

Polymetamorphism

The final possible explanation for natural Ms + Crd + St + Bt assemblages is that they are products of polymetamorphism. By polymetamorphism we mean unstable persistence of minerals formed from an earlier set of *P–T* conditions into the stability field of a later, different mineral assemblage formed at different *P–T* conditions. Texturally, this would be manifested as partial conversion of the earlier assemblage to the later assemblage.

Figure 11 illustrates a number of *P–T* paths by which an Ms + Crd + St + Bt association could be developed, assuming a rock of a given Mg/(Mg + Fe) ratio (see Figs 3–5 and associated discussion). Implicit in Fig. 11 is that the topology of Figs 2(d) and 6 are correct. Although Fig. 11 is schematic, the topology is robust.

The *P–T* paths are drawn to satisfy the common observation from microtextures that staurolite is generally early and cordierite generally late. The essential feature of the *P–T* paths in Fig. 11 is that the only way to produce Ms + Crd + St + Bt assemblages that satisfy the above timing of mineral growth is to

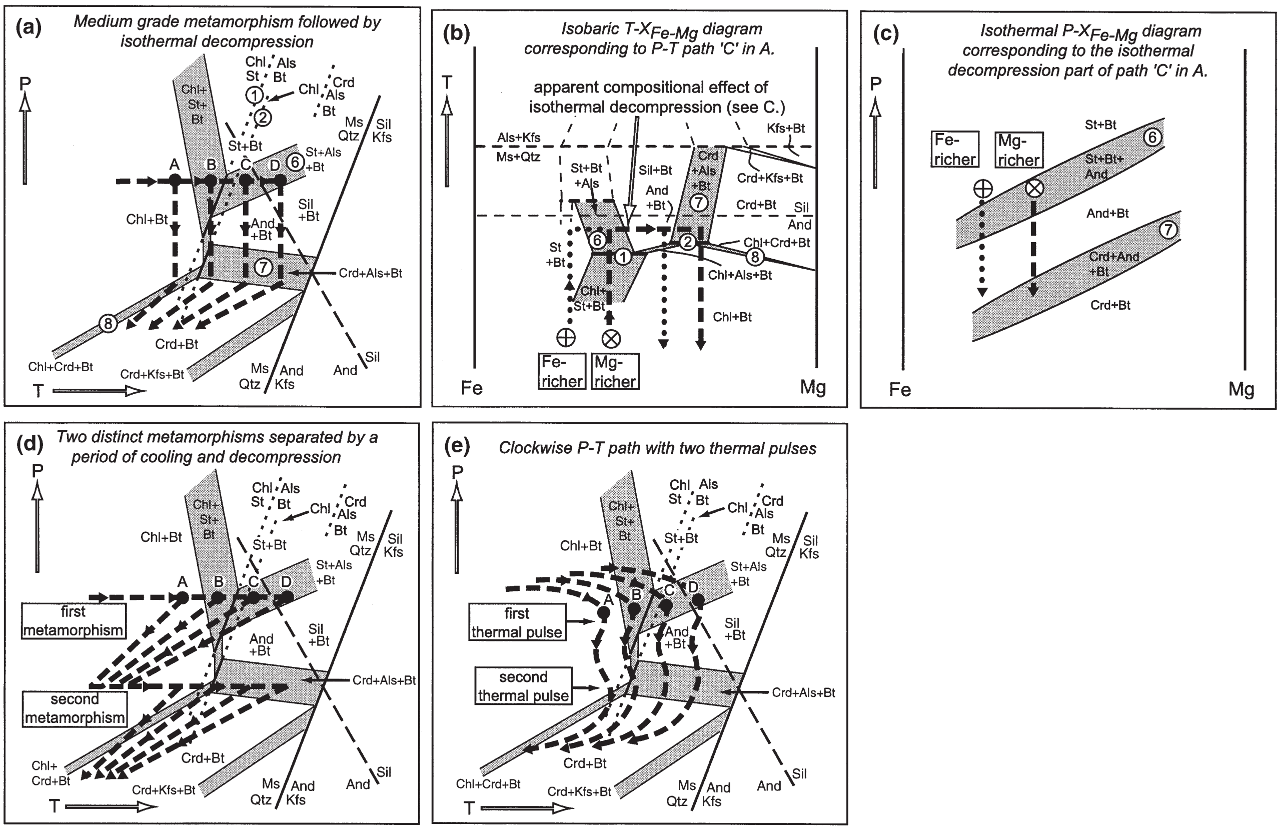


Fig. 11. Schematic $P–T$ paths, $T–X_{Fe–Mg}$ diagram and $P–X_{Fe–Mg}$ diagram that could account for development of Ms + Crd + St + Bt assemblages by polymetamorphism (see text for discussion). The topology of the $P–T$ diagrams in (a,) (d) & (e) is that of Fig. 6; the topology of the $T–X_{Fe–Mg}$ diagram in (b) is that of Fig. 5(b). Letters A–D represent assemblages of the Chl (A), St (B), St + And (C) and St + Sil (D) zones of a medium-pressure metamorphic event.

(a) Isothermal decompression follows medium-pressure prograde metamorphism, leading to development of a low-pressure Crd ± And overprint on assemblages from the medium-pressure metamorphism.

(b) Isobaric $T–X_{Fe–Mg}$ diagram showing the apparent compositional effect of isothermal decompression on a St + And assemblage (C) from the medium pressure metamorphism (dashed lines) (see (c) and text for discussion). Decompression allows St + And-bearing assemblages to enter the And + Crd stability field. The dotted line shows the evolution of an Fe-richer St-bearing sample at the same grade; even though the rock experiences the same amount of decompression, the rock is too Fe-rich to enter the And + Crd stability field (see (c)).

(c) Isothermal $P–X_{Fe–Mg}$ diagram showing how mineral assemblages of different bulk composition may develop different overprinting assemblages in response to the same amount of isothermal decompression (refer to (a) & (b)). Whereas decompression may result in the Mg-richer St + And-bearing assemblage entering the And + Crd stability field, the Fe-richer St-bearing assemblage may not.

(d) An early medium-pressure metamorphism results in the development of an St–And sequence. The rocks cool down prior to being affected by a late low-pressure thermal event. This situation could apply to any early metamorphism that is overprinted by a later low-pressure thermal event.

(e) An early medium-pressure metamorphism results in the development of an St–And sequence. The rocks undergo decompression with minor cooling, and are shortly afterwards affected by another thermal pulse at lower pressure.

have an earlier higher pressure staurolite-bearing assemblage overprinted by a lower pressure cordierite-bearing assemblage. A $P–T$ path involving overprinting of a low-P cordierite-bearing mineral assemblage by a higher-P staurolite-bearing assemblage could also produce an Ms + Crd + St + Bt assemblage, but the timing of mineral growth would be the opposite to that commonly observed.

Figure 11(a) illustrates simplified $P–T$ paths for rocks from four metamorphic zones in an idealized facies series 2b sequence (e.g. SW Nova Scotia, Fig. 8; Augusta area of Maine, Fig. 7): Chl (A), St (B), St + And (C) and St + Sil ± And (D) (all with Ms + Qtz + Bt ± Grt). We assume simple isothermal decompression to conditions of cordierite stability.

On decompression, rocks from the chlorite zone (A) will either show no mineralogical change or, if decompression was large enough, develop cordierite by passage through the model divariant reaction:

$$Ms + Chl + Qtz = Crd + Bt + H_2O \quad (8)$$

Rocks from the staurolite zone (B) that still contained chlorite could remain unchanged or develop cordierite by the same reaction, resulting in an Ms + Crd + St + Bt association. Rocks from the St ± And zone (C) that decompressed would pass first through the reaction:

$$Ms + St + Qtz = And + Bt + H_2O \quad (6)$$

producing andalusite after staurolite, and then pass through the reaction:

$$And + Bt + Qtz + H_2O = Ms + Crd \quad (7)$$

producing cordierite after andalusite. Rocks from the St + Sil ± And zone (D) would probably show similar textures to those from the St ± And zone.

Figure 11(b,c) illustrates in an isobaric $T–X_{Fe–Mg}$ diagram and isothermal $P–X_{Fe–Mg}$ diagram, respectively, how decompression may allow a rock that initially developed a St + And assemblage (C) to develop late cordierite (see heavy dashed lines). In the isobaric $T–X_{Fe–Mg}$ diagram in Fig. 11(b), the apparent compositional effect of decompression is for the minerals to cross more and more Fe-rich isopleths, thereby passing from the St + And field to the And field and then to the And + Crd field. This effect is shown explicitly in the isothermal $P–X_{Fe–Mg}$ diagram in Fig. 11(c).

In order to produce co-existing Ms + Crd + St + Bt ± And by this path, some staurolite must persist unstably as 'relics' into the cordierite stability field (e.g. reaction (7)) despite earlier passage through staurolite-consuming reaction (6). Such a situation may pertain if the temperature stays uniform or falls during decompression, resulting in unfavourable reaction kinetics for staurolite consumption. Unstable persistence of staurolite 'relics' during decompression most likely accounts for Ms + Crd + St + Bt assemblages from the Betic-Rif area of the Pyrenees, in which staurolite from an earlier high-pressure event was partially replaced by coronal cordierite in a low-pressure overprint (Garcia-Casco & Torres-Raldon, in press).

Figure 11(a–c) accounts well for rocks in which the sequence of mineral growth is staurolite followed by andalusite followed by cordierite (e.g. Fig. 9a,b,e). In Ms + Crd + St + Bt + And rocks from SW Nova Scotia, instability of staurolite may be indicated by partial replacement by coarse muscovite (Fig. 9c,d). Reaction (7), in addition to accounting for the growth of cordierite after andalusite, may also account for the zone of depletion of biotite around newly formed cordierite crystals (Fig. 9b,c).

Summary

Our analysis suggests that polymetamorphism best explains the problematic aspects of most Ms + Crd + St + Bt assemblages, including:

1 too many AFM phases;
2 lack of textural equilibrium between AFM minerals;
3 inability to reconcile apparent Ms + Crd + St + Bt assemblage sequences in any single prograde path;
4 incongruity between mineral growth sequences observed from microtextures and the expected mineral growth sequence from the spatial distribution of metamorphic minerals;
5 inconsistency of topological constraints between contact aureole sequences and apparent Ms + Crd + St + Bt sequences;
6 inconsistency of mineral compositions with topological constraints; and
7 occurrence of Ms + Crd + St + Bt assemblages in areas of multiple intrusions where overlapping thermal events may be expected.

Although individual occurrences of a stable Ms + Crd + St + Bt assemblage might develop in unusually Zn-rich metapelites, we consider these to be exceptions. Thus, the topology favoured is illustrated in Figs 2(d) and 6, in which invariant point IP1 and an associated Ms + Crd + St + Bt field are not stable at all, or are stable at such low pressure and for such Fe-rich compositions that they may not develop in natural rocks. Evidence in favour of the actual instability of the assemblage is the predicted lack of convergence of reactions (1) and (2) needed to create IP1 in the andalusite field (Fig. 2 and associated discussion).

P–T PATHS AND TECTONOTHERMAL PROCESSES IMPLIED BY Ms + Crd + St + Bt OCCURRENCES

Textural analysis of Ms + Crd + St + Bt assemblages allows their *P–T* history to be inferred. Most Ms + Crd + St + Bt assemblages have textures indicating that staurolite formed early and cordierite late, so the discussion below focuses on these, although other textures may imply different *P–T* paths. Because the only type of *P–T* path that can explain early staurolite and late cordierite involves decompression, these assemblages provide potentially valuable insight into tectonothermal processes at low pressure. Well-known Ms + Crd + St + Bt occurrences from the literature are discussed in terms of different tectonothermal settings.

Contact metamorphic overprinting of regional metamorphic rocks

Figure 11(d) shows a situation in which there are two distinct metamorphic events, one (staurolite-bearing) at higher pressure and the second (cordierite-bearing) at lower pressure, separated by a significant period of cooling and decompression. The isobaric heating path shown in Fig. 11(d) for the earlier higher-pressure event is only one of many possible *P–T* paths. An example of such a situation would be contact metamorphic overprinting of an earlier regional St ± Grt ± Als metamorphism, such as may have occurred to produce the Ms + Crd + St + Bt-bearing assemblages in the Errol aureole, Maine (Green, 1963) and the Omey aureole, Ireland (Ferguson & Harvey, 1978).

Thermal and structural doming: Bosost area, Pyrenees

Figure 11(a) involves prograde metamorphism at moderate depths followed by decompression without significant cooling. This situation might pertain to rocks in tectonothermal domes (e.g. gneiss domes) that are uplifted relatively rapidly from depth, such as has been described in a number of areas in the French and Spanish Pyrenees (e.g. Verhoef *et al*., 1984; Pouget, 1991).

Pouget (1991) re-examined the geological evolution of the Bosost area of the Central Pyrenees made famous in the classic study of Zwart (1962). In contrast to Zwart (1962), who interpreted the abundant Ms + St + And + Crd + Bt assemblages in the area to be a stable prograde metamorphic zone around a single-event thermal culmination, Pouget (1991) argued from microtextures and *P–T* work that the assemblages represent a progressive evolution from early medium-pressure metamorphism, characterized by St + Grt-bearing assemblages at mid-grade and anatectic migmatites at high grade, to a low-pressure metamorphic overprint characterized by And + Crd. In Pouget's model, the migmatitic rocks and their mantle of St + Grt-bearing metamorphic rocks moved upwards diapirically, resulting in a thermal front that migrated outwards into the surrounding lower-pressure metasediments. In some areas, this resulted in the development of andalusite and cordierite beyond the limits of the St + Grt-bearing medium-pressure rocks. This interpretation may also explain the apparent paradox noted by Thompson & Bard (1982), de Bresser *et al*. (1986) and Gibson (1992), in which the expected sequence of mineral growth from the distribution of metamorphic minerals did not agree with the sequence deduced from microtextures.

Overlapping thermal effects of intrusions emplaced at different levels in regional low-pressure terranes: SW Nova Scotia

Figure 11(e) illustrates a situation involving essentially a single clockwise *P–T* path in which there is more than one thermal pulse, with the time period between thermal pulses short enough that the rocks did not cool significantly but long enough to allow for some decompression. Such a situation might pertain to regions in which multiple intrusions are emplaced in relatively close proximity over a short period of time, resulting in overprinting thermal pulses in a generally elevated thermal regime. Examples of regions where this sequence of events may have occurred include the Augusta area of Maine (see discussion in Novak & Holdaway, 1981 and Holdaway *et al*., 1982), the Aston region of the Pyrenees (Verhoef *et al*., 1984) and SW Nova Scotia.

The discussion below focuses on the SW Nova Scotia locality (Figs 8 & 9) because of its spectacular outcrops and the large amount of work that has been done there (e.g. Hope, 1987; Hwang, 1990; Raeside & Jamieson, 1992; Peskleway, 1996 and references therein). Late porphyroblastic cordierite occurs sporadically but widely as an additional phase in rocks from biotite grade to sillimanite grade in what otherwise appears to be a normal facies series 2b (St–And) sequence (Fig. 9). Whereas the isograd patterns rises towards the Barrington Passage Tonalite, a second major intrusion, the Shelburne Granite, is emplaced across this metamorphic sequence. If a boundary is drawn around the occurrences of late porphyroblastic cordierite (Fig. 9), these define a roughly concentric pattern around the Shelburne Granite, suggesting that the Shelburne Granite may have provided a later thermal and/or fluid pulse resulting in the sporadic development of late cordierite across the earlier metamorphic sequence. This interpretation implies first that the Shelburne Granite is later than the facies series 2b metamorphic event, and second that there was sufficient uplift between the earlier metamorphism and the emplacement of the Shelburne Granite to result in a change from St–And (facies series 2b) to Crd–And (facies series 1c or 2a) assemblages. Despite the conspicuous change in mineral assemblage, the pressure decrease associated with this change might be rather small, as little as 0.5–1.0 kbar (= *c*. 2–3 km) (Pattison & Tracy, 1991; see Table 1).

A problematic aspect of this interpretation is accounting for the patchy development of the cordierite. The extent of replacement of an earlier St ± And-bearing assemblage by a later Crd ± And-bearing assemblage will be influenced by a number of factors, including relative temperatures of overprinting thermal events, bulk composition of the rocks and availability of water during decompression. In some areas of the Pyrenees (e.g. Kriegsman *et al*., 1989; Pouget, 1991), staurolite becomes increasingly relict with respect to And + Crd-bearing assemblages as a function of grade, suggesting that as the peak temperatures of the lower-pressure metamorphism equalled and then exceeded those of the earlier metamorphism, the earlier staurolite-bearing assemblage was increasingly obliterated. In contrast, in SW Nova Scotia, the sporadic development of cordierite as an additional phase in rocks that may show the same mineral assemblage, grain size and textures as rocks without late cordierite (Raeside & Jamieson, 1992) suggests that the temperature of the lower-pressure overprint did not exceed those of the earlier prograde sequence.

Peskleway (1996) noted that there was a weak positive correlation between the presence of late porphyroblastic cordierite and Mg content of the rocks. Figure 11(b,c) provides a possible explanation for this observation by showing the evolution of two different bulk compositions, one Fe-richer, the other Mg-richer. The Mg-richer assemblage develops St + And at the peak of the earlier event, and on decompression passes from the St + And + Bt field to the And + Bt field and finally to the Crd + And + Bt field, potentially giving rise to a Ms + St + And +

Crd + Bt assemblage in which the staurolite and perhaps andalusite are unstably persisting relics. The Fe-richer assemblage develops staurolite at the peak of the earlier event, but on decompression never reaches the cordierite stability field because it is too Fe-rich.

The presence or absence of water during decompression may have affected the development of late cordierite in two ways: in its role as a reactant phase, and as a catalyst. Owing to the significant water content of cordierite, cordierite-producing reactions such as And + Bt + Qtz + H_2O = Crd + Ms (7) and St + Bt + Qtz + H_2O = Crd + Ms are hydration reactions. These reactions would not proceed if there were no free water present in the rocks during decompression. As a catalyst, water increases metamorphic reaction kinetics by several orders of magnitude (Rubie, 1986) and might determine whether a given reaction proceeds, especially decompression reactions that occur isothermally or during falling temperature. Because these two effects work in combination, the patchy development of late cordierite in SW Nova Scotia may partly reflect zones where fluid infiltration occurred during decompression.

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