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Metamorphism of an Early Palaeozoic continental margin, western Baie Verte Peninsula, Newfoundland

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ABSTRACT Metamorphic mineral assemblages and textures from Early Palaeozoic continental margin rocks in north-western Newfoundland indicate that different structural levels have contrasting metamorphic histories. Rocks of the East Pond Metamorphic Suite, which represent the older, structurally lower level of the margin, experienced an early high-pressure–low-temperature stage of metamorphism (10–12 kbar minimum, 450–500° C) which produced eclogite in mafic dykes and phengite–garnet assemblages in pelites. This was overprinted by higher temperature–lower pressure amphibolite facies metamorphism (700–750° C, 7–9 kbar minimum) which produced complex symplectic textures in rocks of all compositions. Rocks of the Fleur de Lys Supergroup, which were deposited in the stratigraphically higher levels of the rifted margin, reached pressures of 7–8.5 kbar at about 450°C during the early stages of metamorphism, overprinted by assemblages which indicate maximum temperatures of 550–600° C at about 6.5 kbar. The metamorphic history of both units is interpreted to be the result of thermal relaxation following initial burial of a continental margin by overriding thrust sheets. Since there is no evidence that maximum pressures or temperatures within the Fleur de Lys Supergroup were ever as high as those reached in the East Pond Metamorphic Suite, these rocks may have followed parallel, 'nested' $P-T-t$ paths, with the more deeply buried East Pond Metamorphic Suite subjected to greater thermal relaxation effects. Quantitative modelling of $P-T-t$ paths is not possible with the present data, owing to both large uncertainties in $P-T$ estimates, and in the time of metamorphism.

Key words: geothermobarometry; metamorphic history; 'nested' $P-T-t$ paths; Newfoundland, Canada; $P-T-t$ paths.

INTRODUCTION

Quantitative tectonic models of overthrusting at continental margins require data from metamorphic rocks to constrain the thermal, burial and uplift histories of rifted margin sequences involved in continental collision (e.g. Jamieson & Beaumont, 1988; Dahlen & Suppe, 1988). Some metamorphic studies have documented significant differences in $P-T-t$ paths from rocks at different structural and stratigraphic levels of the original rifted margin which can be related to the tectonics of collision (e.g. Selverstone, 1985). Although the Early Palaeozoic geology of western Newfoundland has long been interpreted in terms of the development of a rifted margin and its subsequent destruction by overthrusting (e.g. Rodgers & Neale, 1963; Williams & Stevens, 1974), no recent systematic study has been done on metamorphism of the continental margin sequences.

The western part of the Baie Verte Peninsula, Newfoundland, is underlain by gneissic, metasedimentary, and meta-igneous rocks generally interpreted to represent a Late Proterozoic–early Ordovician continental margin, buried during overthrusting associated with the Ordovician Taconian orogeny (e.g. Williams, 1979; Hibbard, 1983). Previous work on the metamorphic rocks of the Baie Verte area focused mainly on eclogite occurrences (e.g. de Wit & Strong, 1975) and spectacular metamorphic textures (de Wit, 1976a,b; de Wit, 1980; Jamieson & Vernon, 1987; Piasecki, 1988). This paper is an attempt to quantify the metamorphic history and $P-T$ conditions for the major lithologies in the area and to provide a metamorphic framework against which tectonic models for the region may be compared.

GEOLOGICAL SETTING

Metamorphic rocks east of the Baie Verte lineament have been divided into two main units (Fig. 1; Hibbard, 1983). The East Pond Metamorphic Suite comprises migmatitic gneisses, interpreted to represent relics of the Grenvillian crystalline basement upon which the margin was constructed, and a sequence of pelitic to psammitic schists, metaconglomerates and metabasites, interpreted to represent the Late Proterozoic–Early Cambrian sedimentary rocks deposited on the attenuated basement during the early development of the rifted margin, and mafic dykes related to rifting (e.g. Church, 1969; de Wit & Strong, 1975; Hibbard, 1983). These rocks are structurally overlain by pelitic, semi-pelitic and psammitic schists and amphibolites of the Fleur de Lys Supergroup (Church, 1969; Kennedy, 1971; Hibbard, 1983), which are generally thought to have originated as sedimentary and volcanic

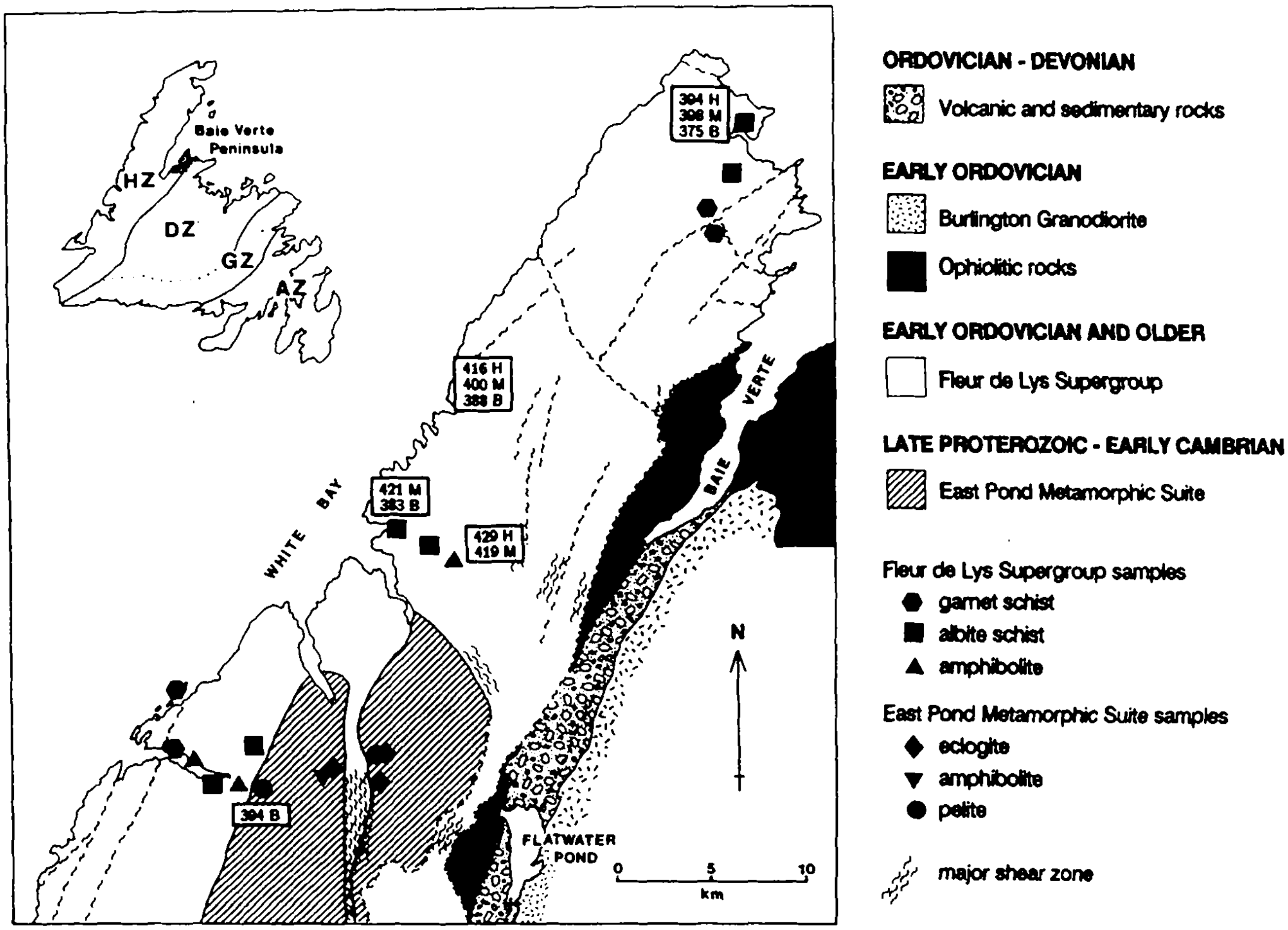

Fig. 1. General geological map of the western Baie Verte Peninsula (after Hibbard, 1983; Jamieson & Vernon, 1987; Piasecki, 1988) showing the distribution of the East Pond Metamorphic Suite and Fleur de Lys Supergroup. Sample localities shown on the map include only samples analysed for this study or illustrated in the text. Numbers refer to $^{40}Ar/^{39}Ar$ cooling ages for hornblende (H), muscovite (M) and biotite (B) (Dallmeyer, 1977; Hibbard, 1983).

rocks deposited on the continental slope and rise during the later stages of rifted margin development. In many places Fleur de Lys Supergroup rocks are separated from the East Pond Metamorphic Suite by ductile shear zones (Hibbard, 1983; Piasecki, 1988).

The structural geology of the area is complex and although the general features are understood on a regional scale, the detailed geometry within and between units is not clear at present, except locally (e.g. Bursnall, 1975; Piasecki, 1988). Although up to seven phases of deformation have been described, most workers have grouped the structures into four main deformation phases (Hibbard, 1983). The earliest of these affected only basement relics, while the other three affected the entire region, with local variations in intensity (Bursnall, 1975; Bursnall & de Wit, 1975; Hibbard, 1983). Jamieson & Vernon (1987) demonstrated that the peak of metamorphism in the Fleur de Lys Supergroup coincided with the development of the pervasive S_2 foliation (D_M of Hibbard, 1983). Numerous synmetamorphic shear zones ('tectonic slides' of Kennedy, 1975; Bursnall, 1975) have been identified (Fig. 1; Hibbard, 1983; Piasecki, 1988), some of which were re-activated several times (e.g. Bursnall, 1975; Hibbard, 1983). Thus original stratigraphic relationships are difficult to reconstruct except through broad correlation with less deformed regions elsewhere in western Newfoundland, and a detailed structural and kinematic history for the region has yet to be worked out.

EAST POND METAMORPHIC SUITE

Eclogite and associated amphibolite

The eclogites contain the mineral assemblage garnet + omphacite + quartz + rutile + hornblende + phengite + zoisite ± Mg-calcite (Table 1; Fig. 2). Although garnet and omphacite occur together without intervening symplectite in a few patches (Fig. 2a), extremely fine-grained symplectite forms a grain boundary network through most samples (Fig. 2b, upper left). Symplectite surrounding

Table 1. Summary of mineral assemblages in the Baie Verte area. The relative timing is based on textural relations within units (e.g. Jamieson & Vernon, 1987) and does not imply synchroneity between units.

	Early	Main	Late
East Pond Metamorphic Suite			
Eclogite	gt + om + hb$_1$ + ph + rut + zo + qz ± Mg-cal	di + pl + hb$_2$ + bt + sph + gt + zo + qz	
Amphibolite	gt + hb + rut + pl + qz	hb + ab + sph + ep + qz	
Pelite	ph + gt + qz + all	bt + mus + pl + Kfd + ep + qz	gt$_2$ + ab + mus + bt + qz
Fleur de Lys Supergroup			
Amphibolite	ep + par + mus + ilm + hb + pl + gt + qz	hb + ab + ep + bt + sph + qz	act + chl + pl + ep + qz
Garnet schist	mar + ph + par + qz + ctd + chl + rut + hem + all	gt + ab + str + ilm + par + chl + bt + mus + qz	chl + ab + mus + ilm + tour + qz
Albite schist	par + bt + mus + Kfd + gt + sph + ep ± hb + qz	gt + bt + mus + pl + ab ± sph ± ilm + qz	pl + bt + mus + chl + tour + qz

Abbreviations: ab = albite; act = actinolite; all = allanite; bt = biotite; chl = chlorite; ep = epidote; gt = garnet; hb = hornblende; hem = hematite; ilm = ilmenite; Kfd = K-feldspar; mar = margarite; Mg-cal = Mg-calcite; om = omphacite; par = paragonite; ph = phengite; pl = plagioclase; qz = quartz; rut = rutile; sph = titanite; str = staurolite; tour = tourmaline; zo = zoisite

pyroxene, garnet, amphibole and zoisite consists of diopside and plagioclase (An_{39}–An_7); symplectite surrounding phengite consists of biotite and intermediate plagioclase (An_{44}–An_{14}). Except in chloritized zones adjacent to late veins, garnet–quartz, garnet–hornblende and garnet–phengite contacts are sharp, although hornblende is strongly zoned adjacent to garnet (Fig. 2b).

The eclogite assemblage is best developed near the centres of boudinaged mafic dykes. On boudin margins and adjacent to veins, the epidote amphibolite facies assemblage hornblende + albite + titanite + epidote + quartz is prevalent. Residual garnet is preserved as inclusions in hornblende or surrounded by coarse hornblende–plagioclase symplectite in some epidote amphibolites (Fig. 2c). Titanite, ilmenite and rutile are common, with titanite mantling both rutile and ilmenite. Although there is no unambiguous evidence that these amphibolites ever contained an eclogite assemblage, they bear a remarkable similarity to amphibolites developed from eclogite in the Weissenstein area of Germany (Franz, Thomas & Smith, 1986).

Metasediments

The mafic dykes cut layered, locally porphyroblastic, pelitic to psammitic schists whose protoliths were probably sediments deposited in late Precambrian rift basins (Hibbard, 1983). Pelitic schist adjacent to an eclogitized dyke contains the assemblage phengite + quartz + garnet$_1$ + allanite + ilmenite which is partially converted to the assemblage biotite + muscovite + albite + quartz + epidote + garnet$_2$. The reaction proceeds through breakdown of phengitic muscovite to symplectic intergrowths of biotite + intermediate plagioclase (Fig. 2d). Garnet occurs in two forms. Relatively large, corroded, matrix garnet, always separated from phengite by a narrow rim of intermediate plagioclase (An_{30}), is interpreted as a relic of the earlier high-pressure assemblage. A later generation of small, idioblastic garnet, locally with biotite, occurs within albite porphyroblasts.

Other metasedimentary rocks in the East Pond Metamorphic Suite have similar mineral assemblages, locally also including K-feldspar. Coarse symplectic intergrowths of white mica, biotite, epidote and albite were interpreted by de Wit (1980) to result from Taconian retrogression of Grenvillian basement gneiss assemblages. However, symplectite has been observed in most East Pond Metamorphic Suite metasediments, and is absent from the only outcrop of reworked basement noted in the course of this investigation. Thus most, if not all, of the textures described by de Wit (1980) probably resulted from polyphase Taconian metamorphism.

P–T conditions

Systematic changes in mineral texture and composition in the eclogites and associated rocks suggest that an early high-pressure assemblage, involving omphacite (Fig. 3; Table A1), garnet of the type found in 'Group C' eclogites (Fig. 4; Table A2), edenitic hornblende with high Na_B content (Fig. 5; Table A3), and Si-rich phengite (Fig. 6; Table A4), was overprinted by a later higher temperature and/or lower pressure assemblage. The later stage of metamorphism formed diopside (Fig. 3; Table A1) and intermediate plagioclase (Fig. 7; Table A5) in symplectite, and resulted in zoning of garnet towards more Mg-rich rims adjacent to hornblende (Fig. 4) and of hornblende towards more pargasitic compositions adjacent to garnet (Fig. 5).

The results of garnet–clinopyroxene, garnet–phengite and garnet–hornblende thermometry on eclogites least affected by retrogression are summarized in Table 2 and Fig. 8. The wide range of calculated temperatures (*c.* 300–750° C) reflects the following factors: (1) non-ideal Fe–Mg exchange in the garnet–clinopyroxene system has not been calibrated at low temperature and is likely to be affected by the high jadeite content of the pyroxene (Fig. 3; Koons, 1984; Pattison & Newton, 1989); (2) the results of the Ellis & Green (1979) and the Pattison & Newton (1989) garnet–clinopyroxene thermometers differ by as much as 150° C for the same data; (3) the garnet–hornblende thermometer of Graham & Powell (1984) was calibrated against the Ellis & Green (1979) garnet–clinopyroxene thermometer, and is therefore subject to its limitations; (4) diffusion during subsequent heating may

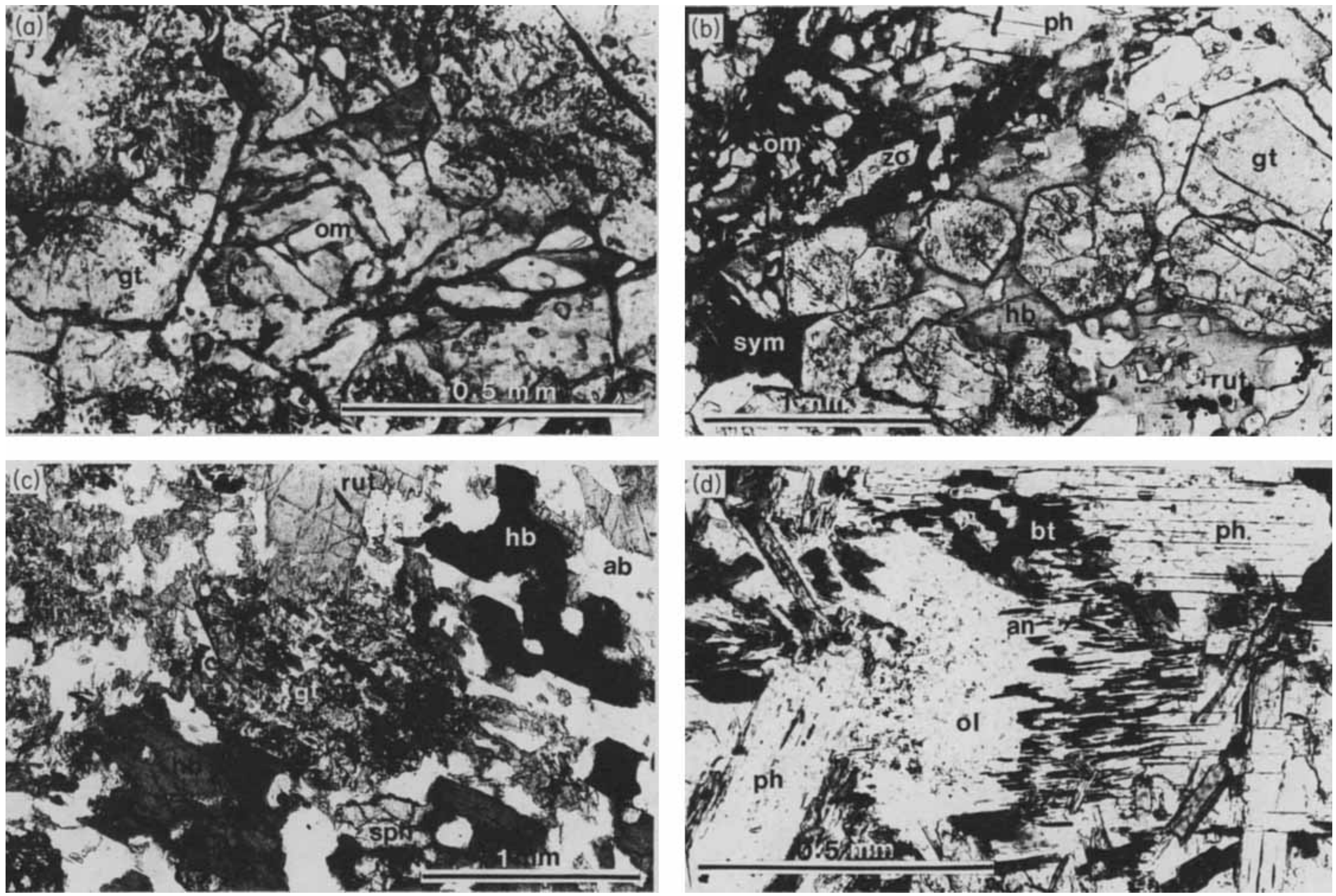

Fig. 2. East Pond Metamorphic Suite textures. (a) Garnet (gt) and omphacite (om) in symplectite-free area, BV86-20. Inclusions in garnet include rutile, quartz and Mg-calcite. See Figs 3 and 4 for mineral compositions. (b) Garnet (gt)–hornblende (hb) patch in eclogite, BV86-20. Note zoning in hornblende adjacent to garnet, fine-grained symplectite (sym) developed around omphacite (om), zoisite (zo) and phengite (ph) in upper left, and rutile (rut) in lower right. (c) Amphibolite on eclogite margins (BV86-24) showing hornblende–plagioclase symplectite developed around residual garnet (gt). Matrix consists of coarse hornblende (hb)–albite (ab) intergrowth, with finer grained hornblende–plagioclase intergrowths probably replacing earlier garnet. Both titanite (sph) and rutile (rut) are present, but rutile is preserved only within hornblende. See Figs 5 and 7 for mineral compositions. (d) Biotite (bt)–plagioclase symplectite developed at the margin of phengite (ph) in schist, BV86-21, adjacent to eclogite BV86-20. Plagioclase in this example is myrmekitic with compositions ranging from andesine (an) near biotite to oligoclase (ol) in the central part of the clear area. See Figs 6 and 7 for mineral compositions.

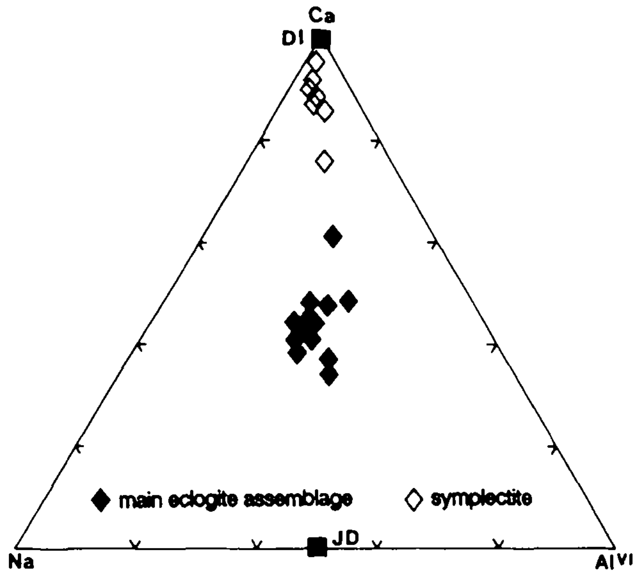

Fig. 3. Clinopyroxene compositions, East Pond Metamorphic Suite eclogites, showing trend from omphacite in main eclogite assemblage towards diopside in symplectites. JD = jadeite; DI = diopside.

have affected eclogite Fe-Mg distributions, even where early textures are well preserved; (5) all the results, particularly the garnet–clinopyroxene temperatures, are strongly dependent on the calculated Fe^{2+} and Fe^{3+} values. Garnet–clinopyroxene temperature estimates using $Fe^{2+} = Fe_{tot}$ are up to 200°C higher than those using calculated Fe^{2+} and Fe^{3+} values (Table 2; Fig. 8); these presumably represent maximum and minimum temperatures, respectively. Since the compositions of the Baie Verte omphacites suggest an important Fe^{3+} component (Table A1), the lower temperature estimates are preferred. However, this still leaves a range of *c.* 350–630°C, depending on the choice of calibration (Table 2).

Temperatures of 436–470°C were estimated using a garnet inclusion in coarse phengite from pelites adjacent to an eclogite dyke (Table 2; Green & Hellman, 1982), which is a maximum temperature, since Fe^{3+} was not estimated. This overlaps with the garnet–hornblende temperatures and with the minimum temperatures estimated from the garnet–clinopyroxene thermometer of Pattison & Newton (1989) using Fe^{3+} (Fig. 8), and falls slightly below the minimum range based on the Ellis & Green (1979) thermometer. A temperature of 450–500°C is therefore considered a reasonable, although imprecise, approximation to the actual temperature of eclogite formation.

Eclogite barometry is hampered by the absence of plagioclase (Newton, 1986). However, minimum pressures for the Baie Verte eclogites can be estimated using symplectite plagioclase compositions. Although plagioclase in these extremely fine-grained aggregates is difficult to analyse, reliable results ranged from An_{39} to An_7, with textural evidence suggesting an overall trend from more calcic to more sodic plagioclase with increasing degree of re-equilibration (Fig. 7). The pressure estimates in Table 2 and Fig. 8 are based on the most calcic plagioclase in each symplectite (Table A5). Simultaneous solution of the garnet–clinopyroxene thermometer and the garnet–clinopyroxene–plagioclase–quartz geobarometer yielded a minimum *P* of 7.0 kbar at 350°C and 11.0 kbar at 750°C (Table 2), the wide range reflecting the uncertainties in garnet–clinopyroxene temperatures as discussed above. An additional constraint on minimum pressure can be derived from Si contents of coarse phengite – values of

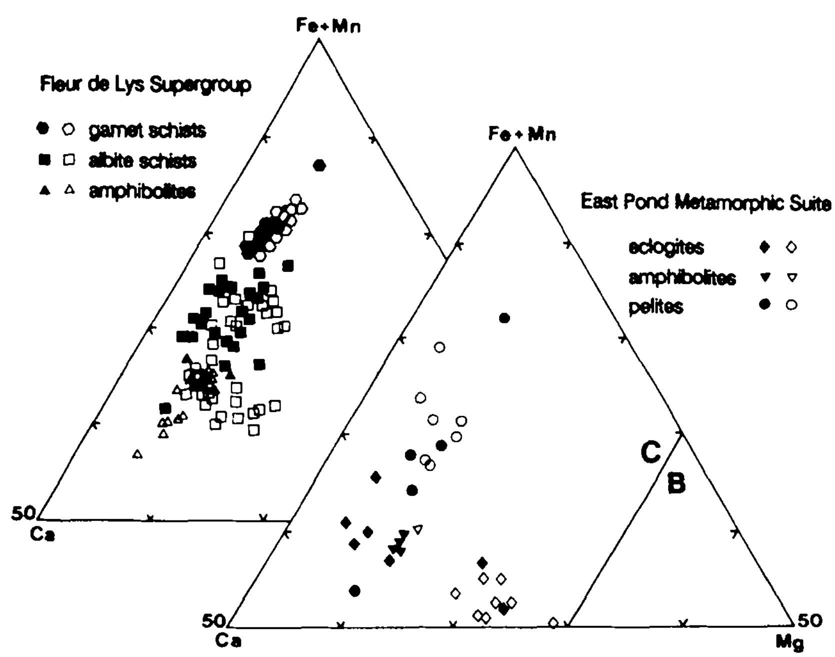

Fig. 4. Garnet compositions from Fleur de Lys Supergroup and East Pond Metamorphic Suite. Closed symbols represent core compositions or garnet inclusions in albite. Open symbols represent rim and matrix garnet compositions. Note relative lack of zoning in Fleur de Lys garnet schist porphyroblasts – the cluster of points represents 62 analyses (see Jamieson & Vernon, 1987, for maps of these garnets). C = field of Group C eclogite garnets and B = field of Group B eclogite garnets, after Coleman *et al.* 1965.

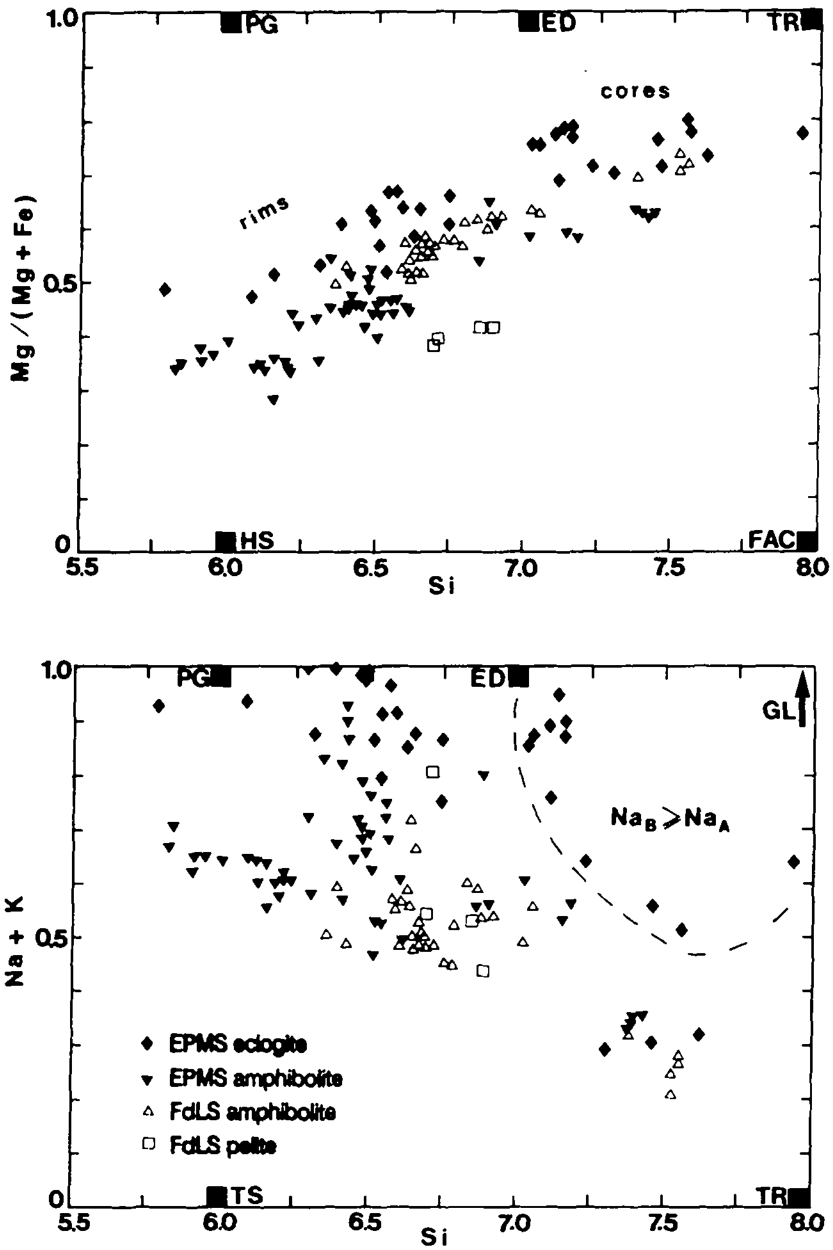

Fig. 5. Amphibole compositions from eclogites and amphibolites (nomenclature after Leake, 1978). Despite the relatively high Na_B contents of early eclogite amphiboles, no true barroisite or sodic amphibole has been recognized in these samples. Strong zoning towards lower Mg/(Fe + Mg) and lower Si (and thus higher Al^{IV}) from core to rims in eclogite amphiboles reflects re-equilibration with adjacent garnet during thermal relaxation. PG = pargasite; ED = edenite; TR = tremolite; HS = hastingsite; FAC = ferro-actinolite; GL = glaucophane; TS = tschermakite; EPMS = East Pond Metamorphic Suite; FdLS = Fleur de Lys Supergroup.

3.4–3.5 Si per $O_{10}(OH)_2$ (Fig. 6; Table A4) suggest minimum pressures of 10–12 kbar at 450° C (Massonne & Schreyer, 1987).

An additional approach to minimum *P–T* conditions in these rocks involves calculation of two reactions inferred to be responsible for the development of plagioclase and diopside in the symplectites:

pyrope + grossular + quartz = anorthite + diopside (1)

jadeite + quartz = albite. (2)

These reactions were calculated using the program and thermodynamic database Ge0-CALC (Perkins, Brown & Berman, 1986; Berman, 1988; Brown, Berman & Perkins, 1988), with activities calculated from the observed mineral compositions (reactions 1′, 1″, 2′, 2″, Fig. 8; Tables A1, A2, A5, A7). The symplectite-forming reactions involved crossing these reaction lines towards lower pressures and/or higher temperatures. Comparison of the calculated reaction boundary with the temperature range for the pre-symplectite assemblage (450–500° C) yields minimum pressures of 10–12 kbar, similar to the range estimated by other methods (Table 2; Fig. 8).

Titanite commonly mantles early rutile in partially retrograded eclogites and associated amphibolites; its appearance is associated with the disappearance of calcite as an accessory phase, and in one sample it is spatially related to the margins of a calcite-bearing vein. This is

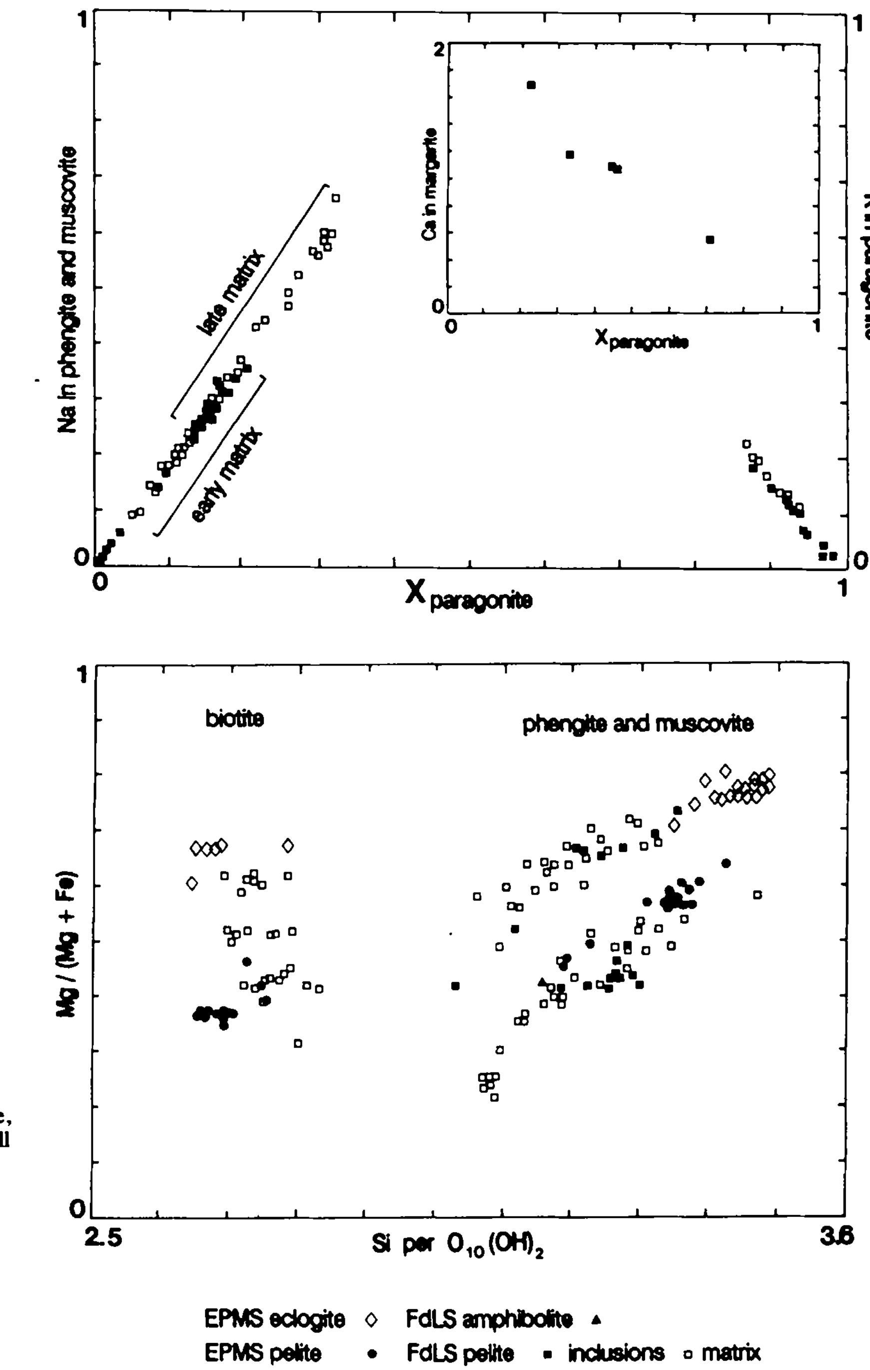

Fig. 6. Mica compositions from Fleur de Lys Supergroup and East Pond Metamorphic Suite rocks. Upper diagram shows solid solution ranges in Fleur de Lys Supergroup white micas, plotted on the basis of $O_{20}(OH)_4$. Increased Na in late matrix muscovites, which do not coexist with paragonite, is consistent with a temperature increase during metamorphism. Inset shows margarite compositions – owing to the very fine grain-size, most of these analyses probably include some overlap with adjacent paragonite. Lower diagram shows phengite, muscovite and biotite compositions from all rocks. The range in biotite Mg/(Mg + Fe) primarily reflects bulk composition – the ratio is approximately constant for any single sample. This is also reflected in the parallel trends for muscovite and phengite Mg/(Mg + Fe); however, in white micas total Mg + Fe and Si generally decrease from inclusions to early matrix to late matrix grains.

consistent with formation of titanite from rutile and calcite during the eclogite–amphibolite transition, at temperatures of 500–600° C (reaction 3, Fig. 8). The position of the epidote amphibolite to amphibolite facies boundary (Apted & Liou, 1983) suggests that temperatures in the epidote amphibolites adjacent to the eclogite did not exceed 700–750° C (reaction 4b, Fig. 8) at pressures of 7–9 kbar, which is consistent with temperature estimates for the syn- to post-symplectite assemblages from garnet–hornblende and garnet–phengite thermometry (Table 2). Attempts to apply the recently proposed garnet–hornblende–plagioclase–quartz barometer of Kohn & Spear (1989) to garnet amphibolites proved unsuccessful, owing to disequilibrium, calibration problems, or both.

Both eclogites and their metasedimentary host rocks contain biotite + intermediate plagioclase (An_{40}) symplectite replacing early coarse phengite (Fig. 2d). In the schists, where symplectite is coarser grained and therefore easier to study, the reaction apparently takes the form:

$$\text{phengite}_1 + Na^+ + Ca^{2+} = \text{phengite}_2 + \text{biotite} + \text{plagioclase} + K^+ + H_2O \quad (3)$$

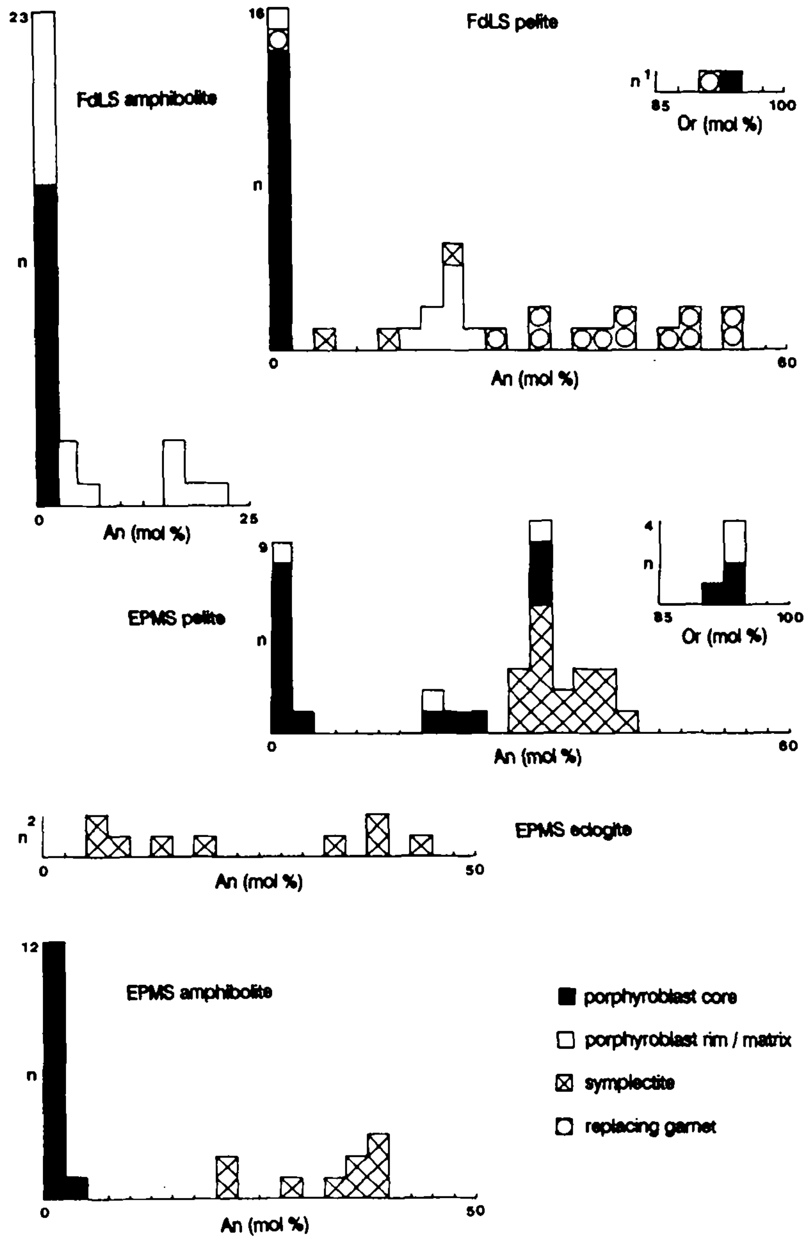

Fig. 7. Feldspar compositions from all rocks. Note the strong concentration of porphyroblast core compositions towards pure albite ($<An_{2.5}$). The range of plagioclase compositions in symplectites and in retrograde intergrowths with biotite and muscovite after garnet (see Figs 2d and 4) indicates disequilibrium and precludes precise thermobarometry based on these reactions.

as inferred by Franz *et al.* (1986). This reaction was not modelled owing to uncertain phengite Fe^{3+} and fluid composition. Phengite Si contents of 3.1–3.2 adjacent to symplectite suggest minimum pressures of 7–9 kbar during symplectite formation (e.g. Massonne & Schreyer, 1987). In the pelitic schists, a further stage of reaction produced oligoclase (An_{26}) + quartz myrmekite; locally K-feldspar is intergrown with oligoclase. In the same rocks, albite porphyroblasts containing a second generation of garnet post-date the symplectites; garnet$_2$ also occurs with biotite in some quartz-rich segregations.

Garnet–phengite and garnet–biotite thermometry on adjacent schists support results from the eclogite. Temperature estimates from garnet$_1$ enclosed in phengite suggest maximum temperatures of 438–470° C for the pre-symplectite stage of metamorphism; adjacent rim-matrix data indicate a range of 545–616° C. Temperature estimates of 713–740° C based on garnet$_2$–biotite pairs in quartz presumably reflect the second stage of garnet growth, near the peak metamorphic temperature. These results overlap with those based on re-equilibrated garnet–hornblende pairs in the adjacent eclogites (Table 2; Fig. 8), and are considered the most reliable estimate of peak temperatures in the East Pond Metamorphic Suite.

In summary, eclogites, amphibolites and pelites in the East Pond Metamorphic Suite reflect early high-pressure, low-temperature metamorphism at 10–12 kbar at least and at 450–500° C, followed by re-equilibration at 600–750° C

Table 2. *P–T* estimates from East Pond Metamorphic Suite eclogites and associated amphibolites and pelites. Fe^{2+} = all Fe calculated as Fe^{2+}; Fe^{3+} = Fe^{2+} and Fe^{3+} calculated on stoichiometric basis (e.g. Koons, 1984; Mottana, 1986).

(A) PRE-SYMPLECTITE ASSEMBLAGES

(i) Garnet–clinopyroxene thermometry (±50° C; EG = Ellis & Green, 1979; PN = Pattison & Newton, 1989)

Rim (Fe^{2+}) 708–746 EG; 594–638 PN
Rim (Fe^{3+}) 511–628 EG; 344–492 PN

(ii) Garnet–phengite thermometry (±50° C; Green & Hellman, 1982). Since Fe^{3+} was not estimated, these represent maximum *T*.

Core–inclusion (Fe^{2+}) 436–470 Rim–matrix (Fe^{2+}) 545–616

(iii) Garnet–hornblende thermometry (±50° C, Graham & Powell, 1984). Fe^{3+} calculated assuming [cations – (Na + Ca + K)] = 13 (e.g. Holland & Richardson, 1979).

Core–inclusion (Fe^{2+}) 372–680
Core–inclusion (Fe^{3+}) 305–622

(iv) Minimum *P* based on simultaneous solution of garnet–clinopyroxene thermometer [(i) above] and garnet–clinopyroxene–plagioclase–quartz barometer (Newton, 1986), using composition of most calcic plagioclase in garnet–omphacite symplectite (Fig. 7; Table A5)

Rim (350° C) 7.0 kbar Rim (750° C) 11.0 kbar

(v) Minimum *P* based on $Si^{4+}/O_{10}(OH)_2$ in coarse phengite (Massonne & Schreyer, 1987)

Core–inclusion (450° C) 10–12 kbar

(B) SYN- AND POST-SYMPLECTITE ASSEMBLAGES

(vi) Garnet–hornblende thermometry

Rim (Fe^{2+}) 652–869
Rim (Fe^{3+}) 619–758

(vii) Garnet–biotite thermometry (±50° C, Ferry & Spear, 1978). Post-symplectite garnet$_2$–albite–biotite–muscovite–quartz assemblage

Rim (Fe^{2+}, 7–9 kbar) 713–740

(viii) Minimum *P* based on $Si^{4+}/O_{10}(OH)_2$ in phengite adjacent symplectite (Fig. 6)

Rim (Fe^{2+}, 600° C) 7–9 kbar

and 7–9 kbar. However, more precise temperature estimates are limited by difficulties in estimating Fe^{3+} and by problems in applying high-temperature calibrations to these low-temperature rocks; only minimum pressure estimates are possible for both stages of metamorphism.

FLEUR DE LYS SUPERGROUP

Well preserved porphyroblast–inclusion–matrix relationships in pelitic schists and amphibolites of the Fleur de Lys Supergroup (Jamieson & Vernon, 1987) allow the evolution of metamorphic texture and mineralogy to be documented. Garnet schists, albite schists and amphibolite are interlayered in many places, suggesting that observations compiled from the three different lithologies can be used to reconstruct the metamorphic history. In all cases, mineral assemblages fall into essentially three categories – early, prograde assemblages preserved as inclusions in porphyroblasts; the peak metamorphic assemblage including the porphyroblasts and their coexisting matrix phases; and retrograde assemblages that overprint the other two (Table 1).

Amphibolite

Amphibolites contain epidote, ilmenite, titanite, white mica, and locally garnet as inclusions within albite porphyroblasts, and matrix hornblende and biotite; matrix amphibole is typically pargasitic to actinolitic hornblende (Fig. 5; Table A3). Retrograde assemblages include alkali feldspar and chlorite replacing biotite, with coarse chlorite, actinolite, titanite and epidote in the low strain zones between porphyroblasts. The mineralogy suggests peak metamorphic conditions in the epidote amphibolite facies, with a greenschist facies retrograde overprint. Some amphibolites contain idioblastic garnet inclusions in albite or quartz bands (Fig. 9a), but matrix garnet is generally strongly corroded and replaced by chlorite, plagioclase and actinolite.

Garnet schists

Garnet porphyroblasts contain the included assemblage chlorite + white mica (phengite + paragonite + margarite) + chloritoid + rutile + allanite + hematite ± ilmenite (Table 1; Fig. 9b). Textural relationships suggest that chloritoid

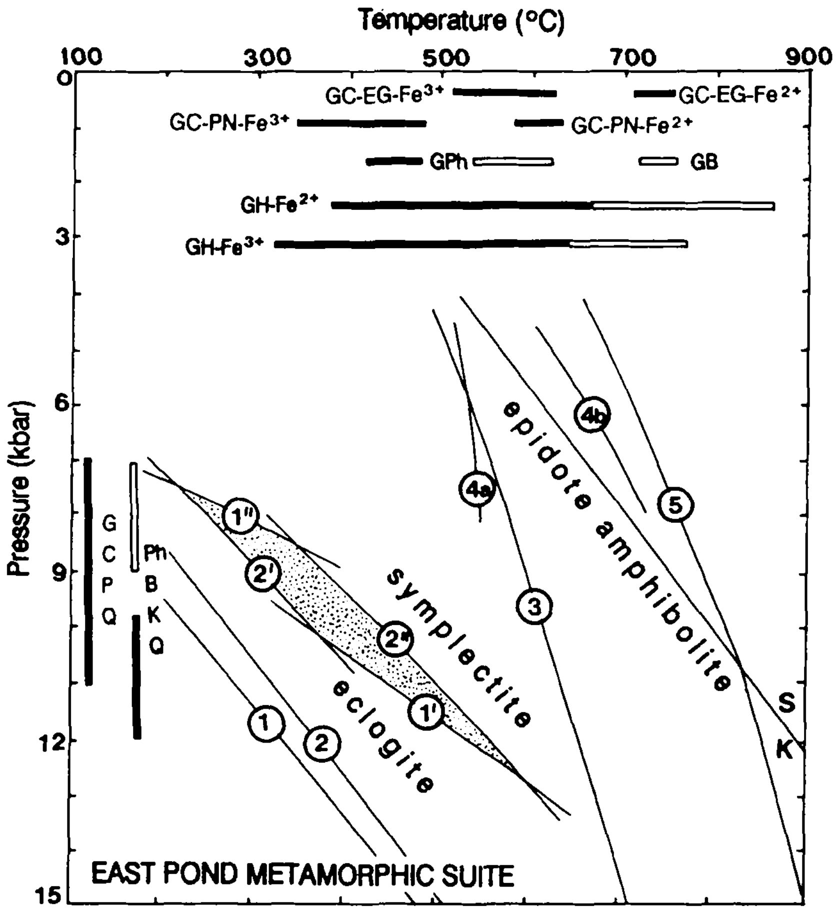

Fig. 8. *P–T* diagram, East Pond Metamorphic Suite, showing relevant reactions and thermobarometric *P–T* estimates. All reactions were computed using GeO-CALC (Perkins *et al.*, 1986; Brown *et al.*, 1988; Berman, 1988; Table A7) unless otherwise indicated. (1) pyrope + grossular + quartz = diopside + anorthite, all $a = 1.0$; (2) jadeite + quartz = albite, all $a = 1.0$; (3) rutile + calcite + quartz = titanite + CO_2; (4a) greenschist = epidote amphibolite (Apted & Liou, 1983); (4b) epidote amphibolite = amphibolite (Apted & Liou, 1983); (5) muscovite + quartz = *K*-feldspar + Al_2SiO_5 + H_2O. Kyanite–sillimanite boundary (K–S) plotted for reference. (1′), (1″), (2′), (2″) correspond to reactions 1 and 2 plotted for the range of mineral compositions observed in the EPMS eclogites. The stippled area bounded by these reactions corresponds to the minimum *P–T* conditions for the EPMS eclogites. Calculated temperature ranges are plotted as horizontal bars and calculated pressure ranges are plotted as vertical bars. Solid bar = pre-symplectite or core-inclusion assemblage; open bar = syn-post-symplectite or matrix assemblage; Fe^{2+} = total Fe as Fe^{2+}; Fe^{3+} = calculated Fe^{2+} and Fe^{3+}; otherwise, Fe = Fe^{2+}. GC–EG = garnet–clinopyroxene thermometer (Ellis & Green, 1979); GC–PN = garnet–clinopyroxene thermometer (Pattison & Newton, 1989); GPh = garnet–phengite thermometer (Green & Hellman, 1982); GB = garnet–biotite thermometer (Ferry & Spear, 1978); GH = garnet–hornblende thermometer (Graham & Powell, 1984); GCPQ = garnet–clinopyroxene–plagioclase–quartz barometer (Newton & Perkins, 1982) calculated for the temperature range 250–535° C; PhBKQ = phengite–biotite–K-feldspar–quartz barometer (Massonne & Schreyer, 1987). See text and Table 2 for further details.

formed by reaction between chlorite and phengite, and that garnet formed by reaction between chloritoid and quartz. The matrix assemblage includes staurolite and albite porphyroblasts, three textural generations of white mica (Jamieson & Vernon, 1987), ilmenite, epidote and biotite as well as the garnet porphyroblasts. Biotite is rare in garnet schists, where it is generally replaced by late chlorite and white mica; in some cases it is not clear whether biotite was ever part of the matrix assemblage.

Albite schists

Large albite porphyroblasts normally contain small inclusions of garnet, white mica (paragonite + phengite), biotite, graphite, ilmenite or titanite, local epidote and rare hornblende (Fig. 9c). The matrix contains biotite, muscovite, garnet, plagioclase, titanite, and/or ilmenite, and quartz. Matrix garnet is commonly corroded and partly replaced by biotite, muscovite and intermediate plagioclase (An_{20-55}) (Fig. 9d). In strongly retrograded samples, post-tectonic chlorite almost completely replaces garnet and post-tectonic tourmaline overgrows the foliation, suggesting late influx of a B-rich fluid.

P–T conditions

The mineral assemblages in metapelites, particularly the garnet schists, are very similar to those described by Thompson, Tracy, Lyttle & Thompson (1977) from the Gassetts Schist in Vermont. As discussed by these authors, the high variance of the mineral assemblage means that quantitative thermobarometry and reaction modelling are difficult. Obvious textural and compositional disequilibrium among plagioclase, garnet and mica further hampers *P–T* estimates. However, some idea of the *P–T* evolution of the metapelites can be gained by garnet–biotite and garnet–hornblende thermometry from a few samples, and by constraints from generalized reactions.

Garnet–biotite thermometry (Ferry & Spear, 1978) and garnet–hornblende thermometry (Graham & Powell,

Table 3. *P–T* estimates from Fleur de Lys Supergroup pelitic schists and amphibolites.

(A) *P–T* ESTIMATES FROM PORPHYROBLAST CORES AND S_1–S_2 ASSEMBLAGES		
(i) Garnet–biotite thermometry (±50° C, Ferry & Spear, 1978; estimates based on other calibrations generally differ by <20° C)		
Albite schists:	416–488	
(ii) Garnet–hornblende thermometry (±50° C; Graham & Powell, 1984)		
Albite schists:	(Fe^{2+}) 481–494	(Fe^{3+}) 395–400
Amphibolites:	(Fe^{2+}) 476	(Fe^{3+}) 397
(iii) *P* based on phengite–biotite–K-feldspar–quartz included in titanite within albite (Massonne & Schreyer, 1987)		
Albite schists:	7–8.5 kbar	
(B) *P–T* ESTIMATES FROM PORPHYROBLAST RIMS AND MATRIX ASSEMBLAGES		
(iv) Garnet–biotite thermometry		
Albite schists:	506–575	
(v) Garnet–hornblende thermometry		
Amphibolites:	(Fe^{2+}) 553–588	(Fe^{3+}) 450–479
(vi) Spear & Cheney (1989) petrogenetic grid for garnet-forming reaction in garnet schists		
$T = 550°$ C	$P = 6.5$ kbar	

1984) were applied to the few samples not strongly affected by retrograde reactions. Estimated temperatures range from *c.* 410–500° C for porphyroblast cores and inclusions, to *c.* 500–590° C for porphyroblast rims and matrix assemblages (Table 2; Fig. 10). This is significantly lower than the peak temperatures (700–750° C) inferred for the East Pond Metamorphic Suite (Fig. 8). Barometers involving plagioclase, mica and garnet (e.g. Ghent & Stout, 1981) could not be applied to these rocks owing to widespread disequilibrium among matrix phases (Fig. 9d), and the extremely low An-content of albite porphyroblasts containing idioblastic garnet inclusions (Fig. 7).

In one sample (Fig. 9c), large titanite crystals included in albite contain phengite, biotite, K-feldspar and quartz inclusions. This assemblage permits the Si content of the phengite (3.3–3.4) to be used as a barometer (Massonne & Schreyer, 1987), which yields an estimate of 7–8.5 kbar at 450° C for the pre-porphyroblast stage of metamorphism. Garnet schists contain three white micas within garnet porphyroblasts (Fig. 6; Table A4). Margarite forms fine lamellae intergrown with paragonite, and paragonite forms single crystals as well as lamellae intergrown with phengitic muscovite (Si content = 3.2–3.3). Both phengite and paragonite are intergrown with included chloritoid and/or chlorite (Fig. 9b). Finely intergrown phengitic muscovite and paragonite define the matrix S_2 and S_3 (Jamieson & Vernon, 1987); coarse muscovite overgrows the matrix fabrics. The compositions of the coexisting muscovite and paragonite cannot be used for thermometry because the phengite content of the muscovite is too high (e.g. Chatterjee & Flux, 1986). However, there is a general shift from more phengitic and less sodic compositions in muscovite inclusions and early matrix micas to less phengitic and more sodic late matrix muscovites (Fig. 6). This corresponds qualitatively to the pattern expected for increasing temperature (increasing solid solution of muscovite towards paragonite) and decreasing pressure (decreasing Si in muscovite) during garnet growth and subsequent matrix recrystallization (e.g. Guidotti & Sassi, 1976; Chatterjee & Flux, 1986).

The remarkable compositional homogeneity (Fig. 4; compare compositions from garnet and albite schists) and internal textures of the large garnet porphyroblasts in the Fleur de Lys garnet schists (Jamieson & Vernon, 1987) suggest a single, probably short-lived, episode of garnet growth near peak *P–T* conditions. Chloritoid occurs only as inclusions in garnet, whereas staurolite never occurs as inclusions. Chloritoid and quartz inclusions are never in contact within the porphyroblasts. These observations are consistent with the reaction:

$$\text{chloritoid} + \text{quartz} = \text{almandine} + \text{staurolite} + H_2O, \quad (4)$$

which occurs at about 550° C over a wide pressure range (reaction 2, Fig. 10). Rutile coexists with hematite within garnet porphyroblasts (Fig. 9b), but only ilmenite is present in the matrix, requiring $T > 400°$ C for porphyroblast formation (reaction 1, Fig. 10). The presence of margarite and quartz as inclusions in garnet, and the absence of margarite from the matrix, suggests temperatures above the maximum stability limit of margarite, i.e. $T > 550°$ C (reaction 3, Fig. 10), for the peak metamorphic assemblage. However, the stability of paragonite + quartz at all stages in the garnet schists indicates $T < 600$–$700°$ C (reaction 4, Fig. 10). The temperature range of garnet porphyroblast formation is thus limited to a fairly narrow range, 550–650° C. The absence of carbonate, the

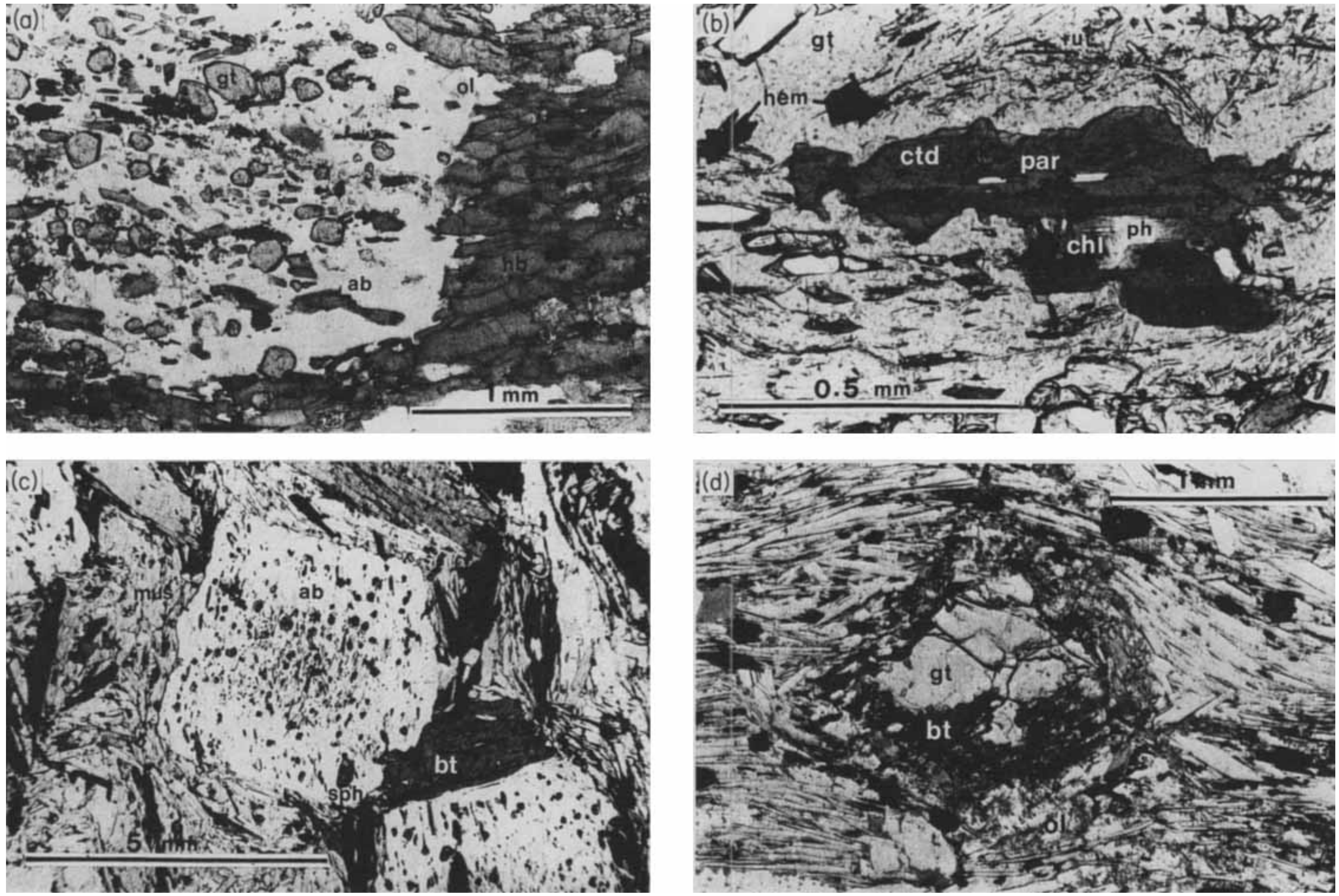

Fig. 9. Fleur de Lys Supergroup textures. (a) Garnet amphibolite (BVA-2) showing albite (ab) porphyroblast choked with garnet (gt), hornblende, epidote, ilmenite and titanite inclusions. The porphyroblast is zoned with narrow oligoclase (ol) rims adjacent to matrix hornblende (hb). The matrix garnet is generally replaced by chlorite. (b) Chloritoid (ctd) inclusion in garnet (gt) containing tiny paragonite (par) crystals and phengite (ph)–chlorite (chl) intergrowth (BVS-1); margarite is intergrown with paragonite elsewhere in the same sample. Other inclusions are rutile (rut), hematite (hem) and quartz. (c) Coarse albite (ab) porphyroblasts in mildly deformed albite schist (BV83-17). Inclusions in albite are titanite (sph), hornblende, white mica (paragonite + phengite), biotite, garnet and ilmenite. Titanite also contains inclusions of K-feldspar, biotite, muscovite, and quartz. The matrix consists of coarse to moderately recrystallized biotite (bt) and muscovite (mus). Note the slightly curved inclusion trail in albite continuous into the matrix, with slight tightening of the matrix fabric around the porphyroblast. (d) Matrix garnet (gt) in albite schist replaced by fine-grained biotite (bt), muscovite and oligoclase (ol) (BV83-3).

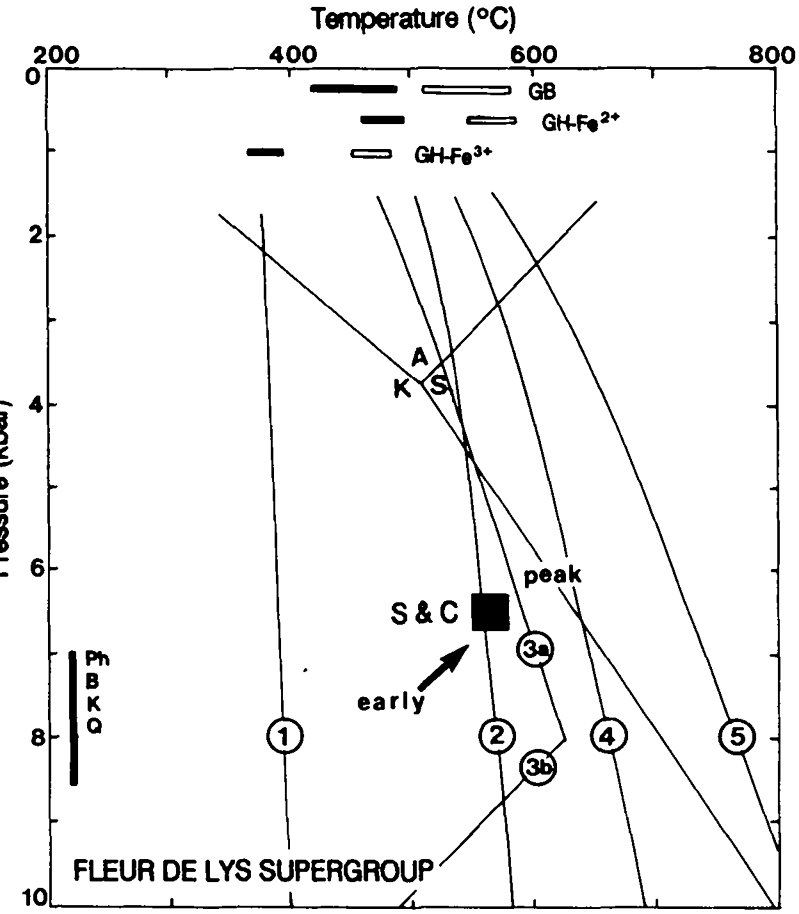

Fig. 10. P–T diagram, Fleur de Lys Supergroup, showing reactions and calculated P–T ranges. All reaction boundaries calculated using GeO-CALC, assuming $a_{H_2O} = 1.0$, using observed mineral compositions (Tables A2, A4, A6, A7; Perkins *et al.*, 1986; Brown *et al.*, 1988; Berman, 1988). (1) rutile + hematite = ilmenite + O_2; (2) chloritoid + quartz = staurolite + almandine + H_2O; (3a) margarite + quartz = anorthite + kyanite + H_2O; (3b) margarite + quartz = zoisite + kyanite + H_2O; (4) paragonite + quartz = albite + kyanite + H_2O; (5) muscovite + quartz = K-feldspar + Al_2SiO_5 + H_2O; Al_2SiO_5 boundaries (A–K–S) plotted for reference. S & C = P–T of garnet formation from chloritoid in garnet schists, based on the petrogenetic grid of Spear & Cheney (1989). Solid bars = porphyroblast core and inclusion assemblages; open bars = porphyroblast rim and matrix assemblages. Other abbreviations as for Fig. 8. Arrow indicates change in P–T conditions from 'early' to 'peak' assemblages. See text and Table 3 for further details.

predominance of H_2O-rich assemblages, and the lack of any detectable F or Cl in mica (R. A. Jamieson, unpublished data) in the Fleur de Lys garnet schists suggests that the assumption $a_{H_2O} \simeq 1$ is reasonable for these rocks.

Comparison of garnet schist data with a recently published petrogenetic grid for pelites (Spear & Cheney, 1989) indicates a pressure of 6.5 kbar at 550° C for the chloritoid-out reaction, consistent with other evidence discussed above. The presence of minute rims of biotite on chloritoid within at least one garnet porphyroblast suggests that the P–T path may have barely intersected the chloritoid + biotite stability field discussed by Spear & Cheney (1989). However, the general absence of biotite coexisting with chloritoid suggests a relatively high Ca–Mn content for the garnet schists.

The plagioclase data shown in Fig. 7 suggest the presence of a 'peristerite gap' in the range An_7–An_{15} for Fleur de Lys amphibolites, with a somewhat wider gap for Fleur de Lys and East Pond Metamorphic Suite pelites. However, as noted above, complex textural relationships involving albite and oligoclase in all the investigated samples make any interpretation based on feldspar compositions of dubious value. In the Fleur de Lys amphibolites, where textures are least complex and feldspars most likely to be in equilibrium, the compositional range of porphyroblast rim and matrix plagioclase (An_{3-7} and An_{15-22}) is consistent with the fairly low pressures (<5 kbar) and temperatures (<450° C) likely to have been present during retrogression (e.g. Maruyama, Liou, & Suzuki, 1982).

To summarize, data from included mineral assemblages and porphyroblast cores indicate that early P–T conditions reached 7–8.5 kbar at about 450° C. Peak metamorphic conditions in the garnet schists were approximately 550° C and 6.5 kbar. Matrix assemblages are either similar to the peak assemblages, or indicate substantial retrogression; no quantitative P–T estimates were obtained owing to disequilibrium. Although precise data are lacking, there is no evidence that Fleur de Lys Supergroup rocks ever experienced either the pressures (minimum of 10–12 kbar) or temperatures (700–750° C) achieved in the East Pond Metamorphic Suite.

DISCUSSION

Comparison with previous work

De Wit & Strong (1975) inferred temperatures of 350–450° C and pressures of 8–12 kbar for garnet–

omphacite assemblages in the East Pond Metamorphic Suite eclogites, very similar to the estimates presented above. They also suggested that symplectite formation was related to increasing temperature, probably accompanying decreasing pressure, consistent with the observations presented here. However, de Wit & Strong (1975) linked eclogite stability to low water pressure, based on the interpretation of their host rocks as 'dry' late Precambrian gneisses. Since the majority of the dykes cut pelitic and psammitic schists rather than anhydrous basement gneisses (e.g. Hibbard, 1983) the role of fluid in these rocks needs to be re-assessed. Clearly the eclogites contained some water – hornblende, phengite and zoisite are stable, although accessory Mg-calcite in many samples suggests that a_{H_2O} was at least locally <1. The advanced to complete replacement of eclogite by epidote amphibolite on boudin margins and adjacent to veins, the local preservation of symplectite-free eclogite assemblages, and the grain-boundary network character of the symplectites suggest that the availability of fluid was a determining factor in the extent to which symplectite developed. However, it is now recognized that anomalously low a_{H_2O} is not required to explain the formation of low-temperature eclogite (Newton, 1986) and it is concluded here that fluid played a kinetic, rather than a thermodynamic, role in the eclogite to epidote amphibolite transformation in these rocks.

Cordierite and kyanite previously reported from the Fleur de Lys Supergroup (Bursnall, 1975; Kennedy, 1975) were not observed in this study. The cordierite reported by Bursnall (1975) was restricted to the eastern side of the Baie Verte peninsula in an area not sampled in this study. Although kyanite was not observed in the schists (*cf.* Kennedy, 1975), it is present and apparently stable in an outcrop of reworked basement gneisses in the East Pond Metamorphic Suite, where it may represent a relic of a pre-Fleur de Lys, probably Grenvillian, metamorphic assemblage.

Age of metamorphism

The recent recognition of important Acadian (late Silurian–Devonian) tectonism in western Newfoundland (e.g. Cawood & Williams, 1988) raises the question of the precise timing of the various stages of metamorphism recognized in these rocks. Is all the metamorphism Taconian, or could some of it be Acadian, as originally suggested by Bursnall & de Wit (1975)? Jamieson & Vernon (1987) argued for peak metamorphism being mainly Taconian, based on textural evidence for the relative timing of garnet and albite porphyroblast growth and on regional cooling ages (Fig. 1; Dallmeyer, 1977). The preservation of low-temperature eclogite suggests that the early phase of metamorphism involved relatively cold continental crust and thus pre-dated tectonic reworking in subsequent orogenic events. Widespread early Silurian silicic magmatism south and east of the Baie Verte area (e.g. Coyle & Strong, 1988) further supports the idea that the Silurian hornblende cooling ages (Fig. 1) represent the minimum age of metamorphism. However, Devonian mica cooling ages (Fig. 1; Dallmeyer, 1977; Hibbard, 1983) may reflect either slow cooling or subsequent overprinting by an Acadian event of insufficient intensity to re-set the hornblende ages. This could account for the late muscovite, chlorite and tourmaline widespread in the Fleur de Lys Supergroup. Although this question will only be resolved through more extensive geochronology, the bulk of the evidence to date still suggests that the main phase of metamorphism in the western Baie Verte peninsula pre-dated 420 Ma.

Tectonic implications

This is the first report of margarite in a regional metamorphic assemblage in this part of the Appalachians. The similarity of this occurrence to the Gassetts Schist assemblage (Thompson *et al.*, 1977), which occupies a very similar tectono-stratigraphic setting, suggests that complex low-grade assemblages may be more common in the metamorphosed continental margin rocks along the north-western side of the Appalachians than previously recognized.

The metamorphic conditions inferred for these rocks, albeit imprecise, imply burial of East Pond Metamorphic Suite rocks to at least 30 km (>10 kbar), and of the Fleur de Lys Supergroup to at least 20 km (>7 kbar). Rocks of the Fleur de Lys Supergroup apparently did not reach either the maximum pressures or the maximum temperatures achieved within the East Pond Metamorphic Suite. It appears likely that the metamorphic conditions estimated here correspond to parts of two 'nested' $P-T-t$ loops, with the Fleur de Lys Supergroup path within the East Pond Metamorphic Suite path (Fig. 11). This is consistent with the inferred pre-metamorphic distribution of these rocks, with the East Pond Metamorphic Suite originally deeper and thus subject both to higher pressures and greater thermal relaxation effects (e.g. England & Thompson, 1984).

If the $P-T$ estimates are realistic, then the East Pond Metamorphic Suite and Fleur de Lys Supergroup must have been juxtaposed along post-peak-metamorphic tectonic boundaries. Shear zones have been documented along the contacts in several areas (Fig. 1; Hibbard, 1983; Piasecki, 1988). Textures indicate a complex kinematic history with early layer-parallel overthrusting to the north overprinted by later fabrics with variable vergence (Piasecki, 1988). These shear zones are generally also zones of intense retrogression, with chlorite overprinting early biotite and garnet. Although albite porphyroblasts are prominent in many shear zones partly because of matrix deformation around them, they are by no means restricted to them, and it can be unequivocally demonstrated that they pre-date shearing in many areas (e.g. Fig. 9c; Jamieson & Vernon, 1987). The interpretation of Piasecki (1988) that albite formation and shearing are genetically linked is therefore over-simplified.

The geological and petrological evidence are consistent with accumulation of Taconian overthrust loads at a rifted

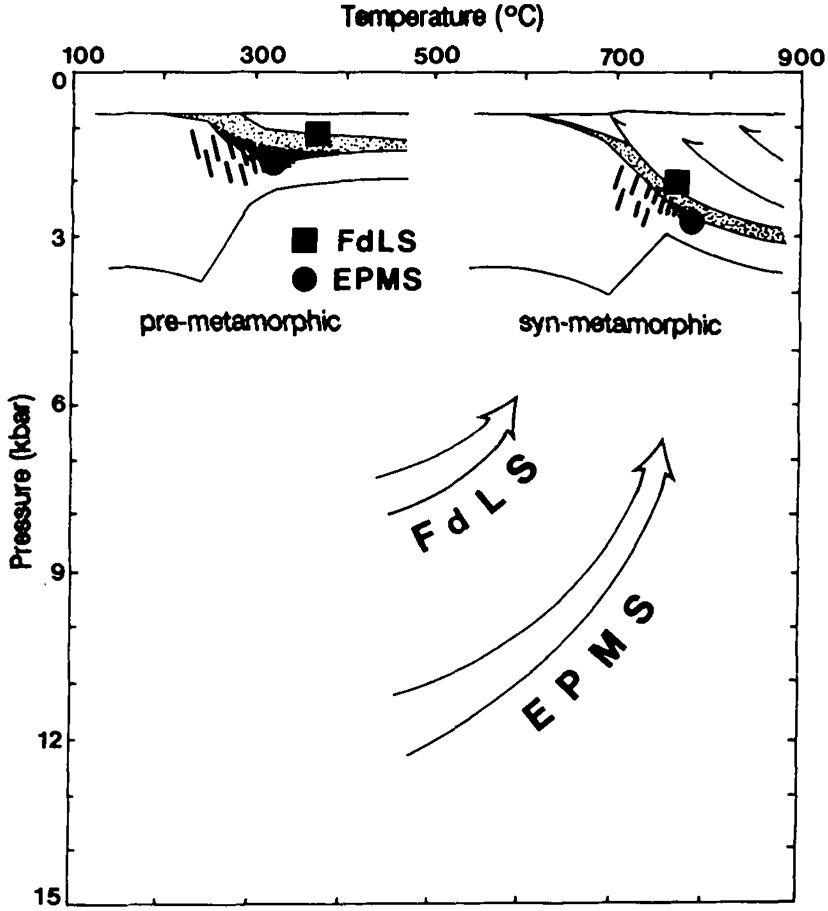

Fig. 11. Partial $P-T-t$ paths for the Fleur de Lys Supergroup (FdLS) and East Pond Metamorphic Suite (EPMS), showing nested pattern interpreted to result from burial of different levels of rifted margin. Insets show schematic pre- and syn-metamorphic configurations (modified after Stockmal *et al.*, 1986; Jamieson & Beamont, 1988). Stippled area indicates continental margin sediments; short bars represent rift-related dykes.

margin. Since there is no evidence that Early Palaeozoic continental shelf rocks in western Newfoundland were buried by 30 km of overthrusts, this extended margin probably accommodated the excess material needed to account for the inferred burial depths (Fig. 11; Stockmal, Beaumont & Boutilier, 1986; Jamieson & Beaumont, 1988). Emplacement of these rocks to their present position, underlain by continental crust of normal thickness (Keen *et al.*, 1986), may have resulted from the post-Taconian regional tectonic adjustment suggested by seismic and structural evidence (e.g. Stockmal, Colman-Sadd, Keen, O'Brien & Quinlan, 1987; Cawood & Williams, 1988; Lithoprobe East, 1989, unpublished data). Unfortunately existing geochronological data do not allow this part of the tectonic history to be clarified. Given the large uncertainties in $P-T$ estimates, and lack of precise data on the age of peak metamorphism and of exhumation, calculation of a complete $P-T-t$ model must await the results of geochronological studies in progress.

CONCLUSIONS

1. East Pond Metamorphic Suite eclogites and adjacent pelites share a common metamorphic history, characterized by low-temperature–high-pressure metamorphism with subsequent re-equilibration at higher temperatures and lower pressures. $P-T$ estimates suggest that eclogites formed at 450–500° C and at least 10–12 kbar, with re-equilibration within the epidote amphibolite facies at 700–750° C and 7–9 kbar.

2. The Fleur de Lys Supergroup experienced a similar pattern of metamorphism, with pre-porphyroblast assemblages developed at 7–8.5 kbar and about 450° C, and porphyroblast formation at about 550° C and 6.5 kbar. However, there is no evidence that these rocks reached the higher pressures and temperatures seen in the structurally and stratigraphically underlying East Pond Metamorphic Suite.

3. The discrepancy in $P-T$ conditions is consistent with burial and subsequent thermal relaxation affecting different structural levels of a rifted margin sequence, resulting in 'nested' $P-T-t$ paths.

4. The age of peak metamorphism was probably Taconian, but the possibility of a greenschist facies Acadian overprint cannot be ruled out. Quantitative $P-T-t$ modelling is not possible with the present data because of the imprecise $P-T$ estimates and the need for more geochronological data on both the age of metamorphism and the cooling history.

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APPENDIX: Mineral compositions (Tables A1–A6) and solution models (Table A7) used in thermobarometry and reaction calculations

Table A1. Clinopyroxene compositions from the East Pond Metamorphic Suite eclogites. Fe^{3+} calculated after Koons (1984) and Mottana (1986). *n* = number of analyses.

Sample	CPX 1	CPX 2	CPX 3	CPX 4
n	11	3	2	4
SiO_2	55.01	54.43	54.95	53.18
TiO_2	0.06	0.08	0.05	0.07
Al_2O_3	9.35	9.03	9.46	2.19
FeO	4.76	4.47	4.40	6.04
MgO	9.22	9.66	9.40	13.51
CaO	15.24	15.63	14.70	24.42
Na_2O	6.38	5.67	6.11	1.05
Total	100.04	98.96	99.05	100.46
Si	1.956	1.961	1.973	1.948
Al^{IV}	0.044	0.039	0.027	0.052
Al^{VI}	0.348	0.345	0.373	0.043
Ti	0.002	0.002	0.001	0.002
Fe^{3+}	0.133	0.085	0.077	0.080
Fe^{2+}	0.009	0.049	0.055	0.105
Mg	0.489	0.519	0.503	0.738
Ca	0.580	0.603	0.565	0.958
Na	0.440	0.396	0.425	0.075
Sum	4.000	4.000	4.000	4.000
Oxygens	6	6	6	6

CPX 1 – Average omphacite in contact with garnet in symplectite-free zone, BV86-20; CPX 2 – Average omphacite surrounded by symplectite, BV83-9-2; CPX 3 – Average omphacite surrounded by symplectite, BV83-9-4; CPX 4 – Average diopside in fine-grained symplectite, BV86-20.

Table A2. Garnet compositions from the Baie Verte area. Fe^{3+} calculated after Mottana (1986). C = core; R = rim; *n* = number of analyses.

Sample	GNT1R	GNT1C	GNT2R	GNT2C	GNT3R	GNT4	GNT5R	GNT5C	GNT6R	GNT6C	GNT7	GNT8R	GNT8C	GNT9R	GNT9C
n	4	1	10	1	6	3	7	2	39	20	5	5	6	3	5
SiO_2	38.19	37.40	37.94	37.73	38.42	37.47	36.94	36.92	36.68	36.64	37.42	36.95	37.00	36.58	36.48
TiO_2	0.03	0.00	0.05	0.03	0.16	0.20	0.09	0.21	0.14	0.21	0.05	0.09	0.03	0.12	0.16
Al_2O_3	21.63	20.96	21.37	20.81	21.87	20.65	21.05	20.84	20.15	20.12	21.29	21.90	22.03	20.97	20.66
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.12	0.00	0.00	0.00	0.11	0.09
FeO	24.39	25.34	24.91	24.87	23.89	26.81	27.82	27.36	34.85	31.06	29.61	30.15	30.42	27.59	27.43
MnO	0.26	1.93	0.25	3.13	0.44	0.83	0.56	0.57	1.78	4.98	1.27	0.56	1.64	0.44	2.53
MgO	6.27	1.78	4.84	1.27	5.75	2.87	3.02	2.80	1.61	1.27	2.17	1.64	2.41	1.69	1.85
CaO	8.65	12.42	10.29	12.20	10.07	11.56	10.32	11.16	4.38	5.21	8.29	8.82	6.66	12.24	10.63
Total	99.42	99.83	99.65	100.04	100.62	100.39	99.81	99.84	99.70	99.61	100.10	100.11	100.19	99.74	99.83
Si	2.972	2.966	2.963	2.998	2.955	2.946	2.923	2.921	2.984	2.983	2.979	2.944	2.944	2.910	2.911
Al^{IV}	0.028	0.034	0.037	0.002	0.045	0.054	0.077	0.079	0.016	0.017	0.021	0.056	0.056	0.090	0.089
Al^{VI}	1.948	1.925	1.930	1.947	1.937	1.859	1.885	1.863	1.913	1.913	1.975	2.000	2.009	1.876	1.854
Ti	0.002	0.000	0.003	0.002	0.009	0.012	0.005	0.013	0.009	0.013	0.003	0.005	0.002	0.007	0.005
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.007	0.000	0.000	0.000	0.007	0.005
Fe^{3+}	0.077	0.109	0.101	0.052	0.089	0.171	0.182	0.190	0.077	0.071	0.040	0.045	0.042	0.192	0.210
Fe^{2+}	1.509	1.571	1.525	1.601	1.447	1.592	1.660	1.620	2.293	2.045	1.931	1.964	1.982	1.644	1.621
Mn	0.018	0.130	0.017	0.211	0.029	0.056	0.038	0.038	0.123	0.343	0.086	0.038	0.110	0.030	0.171
Mg	0.685	0.210	0.563	0.150	0.659	0.337	0.356	0.330	0.195	0.155	0.258	0.195	0.286	0.200	0.220
Ca	0.762	1.055	0.861	1.038	0.830	0.974	0.875	0.946	0.382	0.454	0.707	0.753	0.568	1.044	0.909
Sum	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Oxygens	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
X_{alm}	0.514	0.538	0.524	0.534	0.500	0.538	0.565	0.550	0.766	0.682	0.647	0.665	0.672	0.561	0.553
X_{gro}	0.237	0.322	0.264	0.321	0.265	0.329	0.300	0.324	0.128	0.152	0.237	0.256	0.193	0.359	0.313
X_{pyr}	0.227	0.070	0.186	0.050	0.217	0.114	0.122	0.113	0.065	0.052	0.086	0.066	0.097	0.069	0.076
X_{spe}	0.006	0.043	0.005	0.070	0.009	0.019	0.013	0.013	0.041	0.115	0.029	0.013	0.037	0.010	0.059

GNT 1—Garnet in contact with omphacite, symplectite-free area, EPMS eclogite, BV86-20; GNT 2—Garnet in contact with zoned hornblende, symplectite-free area, EPMS eclogite, BV86-20; GNT 3—Garnet associated with omphacite and symplectite, EPMS eclogite, BV83-9; GNT 4—Relict garnet in coarse plagioclase-hornblende symplectite, EPMS amphibolite, BV86-24; GNT 5—Garnet included in coarse hornblende, EPMS amphibolite, BV86-24; GNT 6—Large porphyroblast, FdLS garnet schist, BVS-4 (Jamieson & Vernon, fig. 14b); GNT 7—Garnet inclusions in albite, FdLS albite schist, BV83-3; GNT 8—Matrix garnet, partly replaced by mica and plagioclase, FdLS albite schist, BV83-3; GNT 9—Garnet in FdLS amphibolite, BVA-2.

Table A3. Amphibole compositions, Baie Verte area. Fe^{3+} calculated assuming [cations − (Ca + Na + K)] = 13.000 (e.g. Holland & Richardson, 1979). Nomenclature and site notation after Leake (1978). C = core; R = rim; *n* = number of analyses.

Sample	HB 1C	HB 1R	HB 2C	HB 2R	HB 3	HB 4	HB 5
n	3	5	5	9	2	7	8
SiO_2	52.21	42.58	49.60	44.94	52.13	43.24	45.87
TiO_2	0.08	0.23	0.21	0.28	0.13	0.62	0.32
Al_2O_3	6.72	16.74	9.98	14.07	5.55	13.01	9.75
FeO	8.87	14.85	8.35	12.11	10.46	18.80	14.57
MnO	0.01	0.11	0.00	0.07	0.03	0.40	0.51
MgO	16.43	9.34	15.41	11.63	15.01	8.34	12.60
CaO	10.15	9.96	9.52	10.14	13.19	10.45	10.20
Na_2O	1.95	2.79	2.91	2.75	0.99	1.84	1.84
K_2O	0.08	0.39	0.43	0.68	0.14	0.54	0.28
Total	96.50	96.99	96.41	96.67	97.63	97.24	95.94
Si	7.359	6.224	7.049	6.545	7.537	6.421	6.700
Al^T	0.631	1.776	0.951	1.455	0.463	1.579	1.300
Al^c	0.487	1.111	0.721	0.962	0.483	0.700	0.379
Ti	0.008	0.025	0.022	0.031	0.014	0.069	0.035
Fe^{3+}	0.509	0.631	0.406	0.365	0.000	0.783	1.085
Fe^{2+}	0.538	1.185	0.586	1.110	1.265	1.552	0.695
Mn	0.001	0.014	0.000	0.009	0.004	0.050	0.063
Mg	3.456	2.035	3.264	1.110	3.234	1.846	2.743
Ca	1.535	1.560	1.450	1.582	2.043	1.663	1.596
Na^B	0.465	0.440	0.550	0.418	0.000	0.337	0.404
Na^A	0.069	0.351	0.251	0.359	0.278	0.193	0.117
K	0.014	0.073	0.078	0.126	0.026	0.102	0.052
Sum	15.072	15.425	15.329	15.485	15.347	15.295	15.170
Oxygens	23	23	23	23	23	23	23

HB 1—Zoned hornblende in contact with garnet, EPMS eclogite, BV86-20; HB 2—Zoned hornblende in contact with garnet, EPMS eclogite, BV83-9; HB 3—Actinolite in symplectite, EPMS eclogite, BV86-20; HB 4—Matrix hornblende in EPMS amphibolite derived from eclogite, BV86-24; HB 5—Matrix amphibole in FdLS amphibolite, BV83-9A.

Table A4. Mica compositions from East Pond Metamorphic Suite eclogites and pelites and Fleur de Lys Supergroup schists. n = number of analyses.

Sample	MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6	MIC 7	MIC 8	MIC 9	MIC 10	MIC 11	MIC 12	MIC 13	MIC 14
n	16	4	8	18	4	6	1	8	9	11	6	2	6	4
SiO_2	53.05	35.53	50.40	34.66	48.41	45.99	31.50	48.67	47.45	46.73	47.70	47.53	47.19	36.04
TiO_2	0.31	1.27	0.88	2.05	0.17	0.04	0.05	0.26	0.04	0.22	0.44	0.08	0.60	1.76
Al_2O_3	27.88	20.03	27.27	17.86	30.61	38.41	50.55	31.00	39.45	34.07	32.42	39.38	32.53	17.96
FeO	1.98	12.61	3.60	23.92	3.57	1.17	1.12	2.91	0.69	2.28	1.70	0.31	1.88	21.47
MnO	0.03	0.10	0.03	0.30	0.00	0.04	0.13	0.00	0.00	0.00	0.01	0.05	0.00	0.15
MgO	3.57	13.91	2.96	7.69	1.55	0.05	0.19	1.54	0.02	0.71	1.71	0.05	1.58	9.09
CaO	0.00	0.00	0.00	0.00	0.02	0.31	12.08	0.00	0.21	0.00	0.01	0.18	0.10	0.03
Na_2O	0.35	0.13	0.28	0.06	1.18	7.23	1.93	1.33	6.81	1.89	0.98	7.15	0.90	0.09
K_2O	9.28	10.32	9.88	9.64	8.34	0.37	0.02	8.51	0.81	8.15	9.27	0.73	9.12	8.41
Total	96.43	93.90	95.31	96.23	93.85	93.61	97.57	94.22	95.48	94.05	94.24	95.46	93.90	95.00
Si	6.902	5.335	6.745	5.370	6.534	6.000	4.110	6.529	6.045	6.267	6.389	6.052	6.348	5.520
Al^{IV}	1.098	2.664	1.255	2.630	1.466	2.000	3.890	1.471	1.955	1.733	1.611	1.948	1.652	2.480
Al^{VI}	3.177	0.882	3.043	0.629	3.400	3.902	3.877	3.426	3.965	3.649	3.503	3.957	3.502	0.760
Ti	0.030	0.144	0.089	0.241	0.017	0.004	0.005	0.026	0.004	0.022	0.045	0.008	0.061	0.205
Fe	0.215	1.584	0.403	3.099	0.403	0.128	0.122	0.326	0.074	0.256	0.190	0.033	0.212	2.750
Mn	0.003	0.012	0.003	0.039	0.000	0.004	0.014	0.000	0.000	0.000	0.001	0.005	0.000	0.019
Mg	0.691	3.113	0.590	1.776	0.312	0.010	0.037	0.308	0.004	0.142	0.341	0.009	0.317	2.075
Ca	0.000	0.000	0.000	0.000	0.003	0.043	1.689	0.000	0.029	0.000	0.001	0.025	0.014	0.005
Na	0.088	0.037	0.073	0.018	0.309	1.829	0.488	0.346	1.682	0.491	0.255	1.765	0.235	0.027
K	1.542	1.979	1.687	1.905	1.436	0.062	0.003	1.456	0.132	1.394	1.584	0.119	1.565	1.643
Sum	13.746	15.750	13.888	15.707	13.880	13.982	14.235	13.562	13.890	13.954	13.920	13.921	13.906	15.484
Oxygens	22	22	22	22	22	22	22	22	22	22	22	22	22	22
X_{par}	0.05		0.04		0.18	0.95	0.00	0.19	0.91	0.26	0.14	0.93	0.13	
X_{mus}	0.95		0.96		0.82	0.03	0.23	0.81	0.07	0.74	0.86	0.06	0.86	
X_{mar}					0.00	0.02	0.77	0.00	0.02	0.00	0.00	0.01	0.01	
X_{ann}		0.34		0.64										0.57
X_{phl}		0.66		0.36										0.43

MIC 1—Coarse phengite in EPMS eclogite, BV86-20; MIC 2—Phlogopite in symplectite replacing MIC 1, BV86-20; MIC 3—Coarse phengite in EPMS pelitic schist, BV86-21; MIC 4—Biotite replacing MIC 3, BV86-21; MIC 5—Phengite included in garnet, FdLS garnet schist, BVS-1; MIC 6—Paragonite included in garnet, BVS-1; MIC 7—Margarite included in garnet (most calcic), BVS-4; MIC 8—Matrix muscovite, defining S_3 foliation, BVS-1; MIC 9—Matrix paragonite, defining S_3 foliation, BVS-1; MIC 10—Matrix muscovite, overgrowing S_3 foliation, BVS-1; MIC 11—Muscovite included in albite, FdLS albite schist, BV83-1; MIC 12—Paragonite included in albite, BV83-1; MIC 13—Matrix muscovite, BV83-1; MIC 14—Matrix biotite, BV83-1.

Table A5. Plagioclase compositions from the Baie Verte area. C = core; R = rim; n = number of analyses.

Sample	PL 1A	PL 1B	PL 2A	PL 2B	PL 3A	PL 3B	PL 4	PL 5C	PL 5R	PL 6	PL 7
n	1	1	1	1	1	1	9	14	13	12	19
SiO_2	60.10	64.19	59.97	67.68	57.15	65.95	68.77	68.45	61.92	57.14	67.44
Al_2O_3	24.31	21.34	24.88	19.62	27.42	22.34	19.46	19.67	23.65	26.44	20.10
FeO	0.45	0.61	0.73	0.55	0.24	0.22	0.16	0.06	0.07	0.20	0.03
MgO	0.04	0.39	0.40	0.37	0.00	0.00	0.02	0.00	0.00	0.00	0.00
CaO	7.17	4.09	7.40	1.40	9.19	2.81	0.41	0.13	4.66	8.81	0.13
Na_2O	7.59	9.16	6.40	10.05	6.34	9.70	11.47	11.62	8.97	6.97	11.24
K_2O	0.10	0.06	0.19	0.06	0.00	0.04	0.04	0.07	0.15	0.03	0.07
Total	99.76	99.84	99.97	99.73	100.38	101.02	100.33	100.00	99.42	99.59	99.01
Si	2.690	2.845	2.675	2.969	2.554	2.867	2.995	2.989	2.760	2.576	2.972
Al	1.283	1.115	1.308	1.015	1.444	1.145	0.998	1.012	1.241	1.404	1.043
Fe	0.017	0.023	0.027	0.020	0.009	0.008	0.006	0.002	0.003	0.008	0.001
Mg	0.003	0.026	0.026	0.024	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Ca	0.344	0.194	0.353	0.066	0.440	0.131	0.019	0.006	0.223	0.426	0.006
Na	0.659	0.787	0.553	0.855	0.549	0.817	0.969	0.984	0.775	0.609	0.960
K	0.007	0.004	0.011	0.003	0.002	0.000	0.002	0.004	0.009	0.002	0.004
Sum	5.002	4.994	4.953	4.952	4.998	4.967	4.990	4.997	5.011	5.025	4.986
Oxygens	8	8	8	8	8	8	8	8	8	8	8
X_{Ab}	0.653	0.799	0.603	0.925	0.554	0.862	0.972	0.988	0.768	0.583	0.989
X_{An}	0.341	0.197	0.385	0.071	0.444	0.138	0.026	0.008	0.223	0.415	0.007
X_{Or}	0.006	0.004	0.011	0.004	0.002	0.000	0.002	0.004	0.009	0.002	0.004

PL 1—Plagioclase in symplectite surrounding omphacite, EPMS eclogite, BV86-20. A = most calcic, B = least calcic; PL 2—Plagioclase in symplectite surrounding omphacite, EPMS eclogite, BV83-9. A = most calcic, B = least calcic; PL 3—Plagioclase in symplectite surrounding phengite, EPMS pelite, BV86-20. A = most calcic, B = least calcic; PL 4—Matrix plagioclase in EPMS amphibolite derived from eclogite, BV86-24; PL 5—Average porphyroblast composition, FdLS albite schists; PL 6—Average plagioclase replacing garnet, FdLS albite schist, BV86-10; PL 7—Average albite porphyroblast in FdLS amphibolite, BV83-9A.

Table A6. Chloritoid, chlorite and staurolite compositions from the Fleur de Lys Supergroup garnet schists. n = number of analyses.

Sample	CTD 1	CHL 1	CHL 2	STR 1
n	7	3	6	5
SiO_2	24.54	24.67	24.29	28.22
TiO_2	0.06	0.07	0.08	0.33
Al_2O_3	41.04	22.38	22.45	54.84
FeO	24.51	27.33	29.50	8.48
MnO	0.17	0.13	0.01	0.15
MgO	2.45	11.97	12.01	0.77
ZnO	0.00	0.00	0.00	4.06
Na_2O	0.01	0.04	0.01	0.26
Total	92.78	86.59	88.35	97.11
Si	1.344	5.317	5.192	3.580
Al^{IV}	2.647	2.683	2.808	8.194
Al^{VI}	0.000	2.997	2.843	0.000
Ti	0.002	0.011	0.013	0.032
Fe	1.123	4.926	5.273	0.900
Mn	0.008	0.024	0.002	0.016
Mg	0.200	3.845	3.826	0.146
Zn	0.000	0.000	0.000	0.380
Na	0.001	0.017	0.003	0.064
Sum	5.325	19.820	19.960	13.311
Oxygens	12	28	28	23

CTD 1—Chloritoid included in garnet, FdLS garnet schist, BVS-1; CHL 1—Chlorite included in garnet, BVS-1; CHL 2—Coarse matrix chlorite, FdLS garnet schist, BV83-11; STR 1—Matrix staurolite, FdLS garnet schist, BVS-1.

Table A7. Sources of activity models used in thermobarometry and reaction calculations (Tables 2 and 3, Figs 8 and 10). In the absence of a generally accepted solution model and/or microprobe data, ideality was assumed for other phases.

Mineral	Reference
Garnet	Ganguly & Saxena (1984)
Clinopyroxene	Newton (1986)
Muscovite	Chatterjee & Flux (1986)
Paragonite	Chatterjee & Flux (1986)
Biotite	Indares & Martignole (1985)
Plagioclase	Fuhrman & Lindsley (1988)