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Roles for fluid and/or melt advection in forming high-*P* mafic migmatites, Fiordland, New Zealand

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ABSTRACT A series of striking migmatitic structures occur in rectilinear networks through western Fiordland, New Zealand, involving, for the most part, narrow anorthositic dykes that cut hornblende-bearing orthogneiss. Adjacent to the dykes, host rocks show patchy, spatially restricted recrystallization and dehydration on a decimetre-scale to garnet granulite. Although there is general agreement that the migration of silicate melt has formed at least parts of the structures, there is disagreement on the role of silicate melt in dehydrating the host rock. A variety of causal processes have been inferred, including metasomatism due to the ingress of a carbonic, mantle-derived fluid; hornblende-breakdown leading to water release and limited partial melting of host rocks; and dehydration induced by volatile scavenging by a migrating silicate melt. Variability in dyke assemblage, together with the correlation between dehydration structures and host rock silica content, are inconsistent with macroscopic metasomatism, and best match open system behaviour involving volatile scavenging by a migrating trondhjemitic liquid.

Key words: garnet granulite; granulite formation; metasomatism; migmatite; partial melting.

INTRODUCTION

Striking migmatitic structures occur in western Fiordland, New Zealand (Fig. 1) involving, for the most part, narrow anorthositic dykes that cut hornblende-bearing orthogneiss (e.g. Turner, 1939). Adjacent to the dykes, the gneiss shows patchy, spatially restricted recrystallization, on a decimetre-scale, to garnet granulite in domains referred to as 'garnet reaction zones' (Blattner, 1976; Oliver, 1977; Fig. 2a). Physical relationships in these migmatites have similarities to, and major differences from, sites of arrested granulite formation through structurally controlled dehydration of amphibolite facies white gneiss across southern India and Sri Lanka (Janardhan *et al.*, 1979; Raith & Srikantappa, 1993). Clear field relationships and petrologically informative assemblages in the two areas have provided fertile ground for the study of fluid–rock-melt interaction at granulite facies conditions. Although there is agreement on the migration of silicate melt in both locations, there is disagreement on any role of carbonic fluids ascending from deep-seated (mantle) sources (Friend, 1981; Newton, 1992).

In Fiordland, the garnet reaction zone structures occur between Milford and Breaksea Sounds (Fig. 1), over an area of 160 × 40 km. One of the best-exposed examples occurs in the Pembroke Valley, NW of Milford Sound (Fig. 1), where vertical and planar garnet reaction zones cut granulite facies gabbroic to dioritic gneisses in spectacular rectilinear patterns. Blattner (1976) inferred that garnet reaction zones in the Pembroke Valley possibly formed in response to the ingress of mantle-derived carbonic fluids along a pre-existing joint network localized along otherwise unrelated anorthositic dykes. Oliver (1977) examined similar garnet reaction zones in Doubtful Sound (Fig. 1) and proposed an alternative model involving the partial melting of host gabbroic gneiss; mobilisate sourced from a localized area migrated into a vein leaving the garnet reaction zone as a melt-depleted domain. Blattner & Black (1980) then re-evaluated the Pembroke example, to propose a model involving volatiles released by hornblende breakdown in gabbroic gneiss facilitating small proportions of partial melting, the mobilisate having segregated into veins at structural levels above those currently exposed. Bradshaw (1989) examined garnet reaction zone samples collected across northern Fiordland, and inferred a two-stage model – early, unrelated anorthositic dykes developed a network of fractures that were later utilized as pathways by CO_2-rich fluids to dehydrate gabbroic gneiss in the vicinity of the fractures. Daczko *et al.* (2001a) proposed that a trondhjemitic liquid, sourced from the partial melting of adjacent bodies of dioritic gneiss and migrating through the gabbroic gneiss, scavenged H_2O mostly from hornblende to induce the garnet reaction zones hosted by gabbroic gneiss in the Pembroke Valley. Blattner (2005) presents an alternative metasomatic model involving the local migration of a sodic-rich dehydrating fluid to form the structures.

The various models conceptually build from an open- or closed-system approach to the study of these

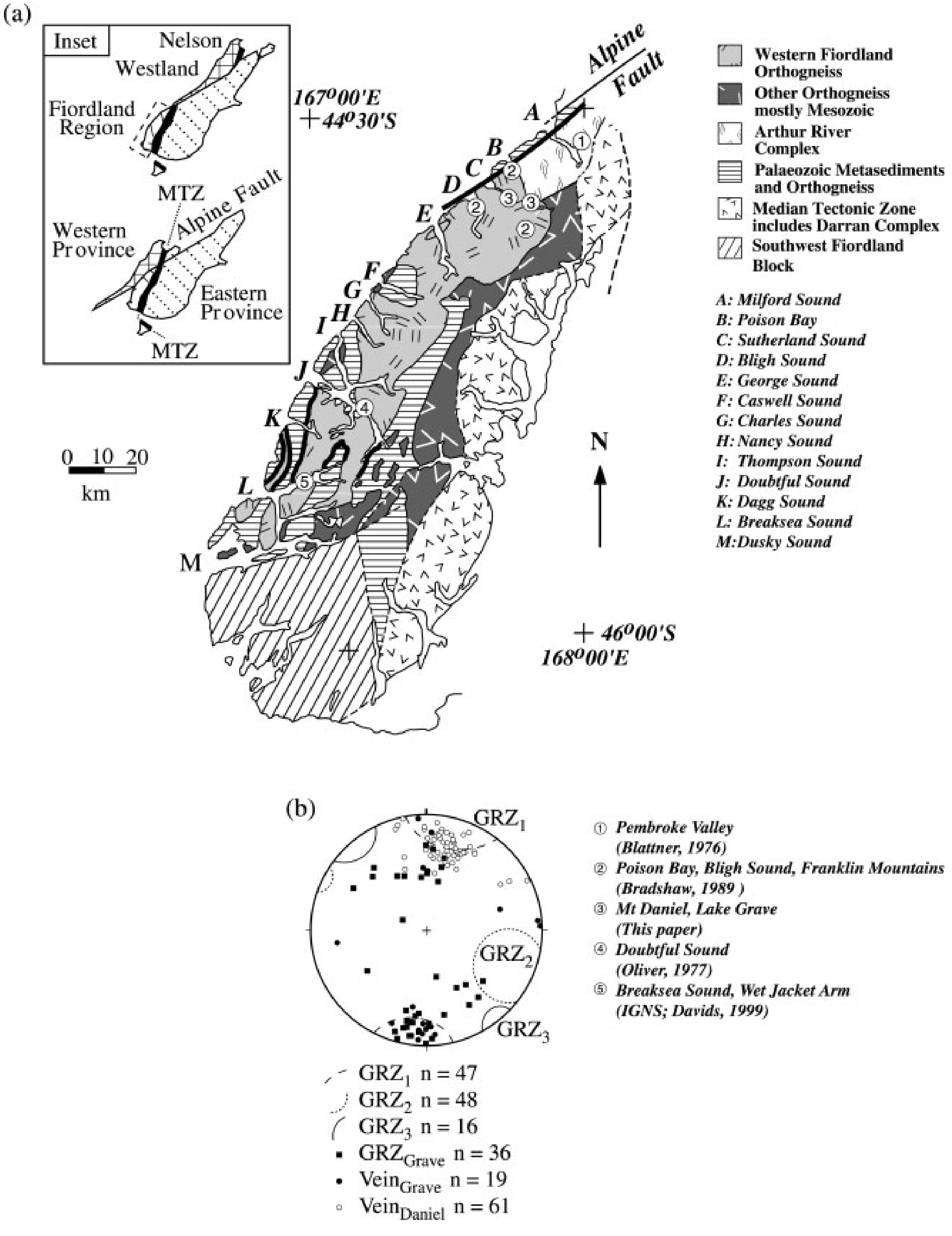

Fig. 1. Geology of western Fiordland, indicating locations discussed in the text. Inset shows pre-Cenozoic configuration of the South Island, which places the Westland-Nelson region adjacent to Fiordland.

migmatites, and related garnet reaction zones, which may or may not have involved the presence of a silicate melt. Quantitative assessments of migmatite petrogenesis, constrained by geochemical and isotopic analysis, converge on four main mechanisms: (i) injection of a silicate liquid (Sederholm, 1907, 1934; Buddington, 1948; Olsen, 1983); (ii) sub-solidus metamorphic differentiation (Eskola, 1932; Sawyer & Robin, 1986); (iii) metasomatism (Gresens, 1967; Olsen, 1985); and (iv) partial melting (Holmquist, 1921; Mehnert, 1968, 1973; Brown, 1973; Sawyer, 1987). Each process may operate solely, or in combination with one or more other processes. In this paper, we initially review field, geochemical and structural observations that might discriminate between open- and closed-system behaviour in migmatites, and

Fig. 2. (a) Anorthositic veins mantled by garnet reaction zones in gabbroic gneiss, Pembroke Valley (fig. 2c from Schröter *et al.*, 2004). (b) Rectilinear network defined by garnet-bearing leucosomes, dioritic gneiss, Pembroke Valley. Large isolated peritectic garnet grains, enclosed by small amounts of leucosome, also occur in the middle of the view. (c) Peritectic garnet forming trains and in leucosome, dioritic gneiss, Pembroke Valley. (d) Lithological control on width of garnet reaction zone. A anorthositic vein and garnet reaction zone cut gabbroic gneiss and a thin felsic layer that is comparatively amphibole-poor. The garnet reaction zone is far less extensive in the felsic layer because of the lower proportion of hydrous minerals.

re-evaluate the strengths and weaknesses of models proposed for the Pembroke example. The significance of the structures also needs to be evaluated, in terms of whether they represent the products of an uncommon process, or the uncommonly well-preserved product of a common process.

MIGMATITE FORMATION AND METAMORPHISM

The term migmatite refers to a mixed rock (Sederholm, 1907; Mehnert, 1968; Brown, 1973) involving apparently igneous and metamorphic components. These reflect the principal rock components involving a ‘leucosome’ – a felsic segregation, and a ‘mesosome’ – a darker material that hosts the leucosome, the two sometimes being separated by a ‘melanosome’ – a dark, commonly hydrous-mineral-rich selvedge. Migmatites are the end products of amphibolite and granulite facies metamorphism, commonly best developed in metapelite but also present in metapsammite and felsic to mafic orthogneiss. The distinction between open and closed systems depends on the scale of the feature being studied. In migmatites, the distinction focuses on relationships between the leucosome and mesosome.

The formation of migmatites by the 'injection' of exotic leucosome, commonly along pre-existing structures such as bedding or foliation planes, occurs close to granite intrusions in the upper crust. The margins of injected leucosome are commonly sharp and marked by a hydrous mineral-rich selvedge. Such situations may be distinguishable from *in situ* migmatites on the basis of geochemical criteria (Barr, 1985; Greenfield *et al.*, 1996), field relationships (Masberg, 1996), mass balance constraints (Olsen, 1983; Grant, 1986) or stable isotope data (Linklater *et al.*, 1994). Leucosome formation in nebulitic or patch structures may reflect 'sub-solidus metamorphic differentiation', where there has been no forceful disruption of the migmatite. Chemical potential gradients, developed around large aluminosilicate porphyroblasts because of evolving P–T conditions, have been inferred to account for such features (Fisher, 1973).

'Metasomatism' involves the introduction and removal of material with corresponding changes in the mineralogy and/or composition of the affected rocks (Bhaska Rao, 1986). Hydrous fluids are usually the mechanism facilitating the change, generated by crystallizing magmas or metamorphic dehydration reactions. Crustal-scale migration of carbonic fluids has also been inferred to control metamorphic changes in high-grade rocks (see below). Fluid transport in permeable media may take place by element diffusion or physical movement involving a fluid flux and/or diffusion driven by chemical potential gradients in a static rock framework. Diffusion is a slower process and commonly forms millimetre- to centimetre-scale features, whereas fluid advection can result in larger-scale changes. A related example is the occurence, during diagenesis, of many types of sandstone-carbonate sourced from the distal breakdown of organic matter, which forms most of the sandstone cement. Phenomena involving arrested *in situ* granulite formation across southern India and Sri Lanka (Friend, 1981; Janardhan *et al.*, 1979) have been explained as the products of structurally controlled metasomatism and dehydration induced by carbonic fluids ascending from an unknown source (Newton, 1992). This interpretation has been questioned on the basis of field, petrological, geochemical and isotopic data (Burton & O'Nions, 1990; Harris *et al.*, 1993; Raith & Srikantappa, 1993; Harley & Santosh, 1995), as relationships may also be explained by partial melting (Sandiford *et al.*, 1988; Burton & O'Nions, 1990).

'Partial melting' is the most commonly invoked mechanism for migmatite formation (Ashworth, 1985). The availability of H_2O is the single most critical aspect to melt production (Johannes & Holtz, 1990); it may be sourced from a hydrous fluid, or the breakdown of a hydrous mineral such as muscovite, biotite or hornblende. The result of the addition of water to an anhydrous system is the lowering of the melting point at a given pressure. More water may be accommodated in solution at higher pressure; hence the melting point depression becomes progressively greater as pressure increases. New material formed during partial melting may be called 'neosome'. However, the common separation of liquid and solid components of the neosome related to migration can develop complex leucosomes (see below). The common textural relationship of a leucosome hosting ferromagnesian porphyroblasts, such as garnet (e.g. Waters & Whales, 1984; Powell & Downes, 1990) is inferred to reflect the preferential development of neosome around solid (peritectic) products of a melting step controlled by the incongruent breakdown of a hydrous mineral, such as biotite (Powell & Downes, 1990). The ability to successfully model the partial melting processes in common metapelitic rocks (White *et al.*, 2001) has led to the development of a more systematic approach to the problem in such rocks. The inability to currently model calcic silicate liquids implies that we rely on the more traditional geochemical approaches to such problems.

In the context of partial melting, leucosomes represent combinations of: (i) solid products of the melting reaction such as plagioclase or quartz; and (ii) crystallized melt or melt products (e.g. accumulations of early formed crystals or the fractionated, residual melt), trapped in a drainage network (Brown & Solar, 1999; Sawyer, 2001; Solar & Brown, 2001). Only in rare circumstances will leucosome correspond to neosome. In extreme examples, it is possible that because of its lower viscosity, all neosome gets removed from the drainage network leaving no leucosome. Alternatively, as a channel network closes, any remaining melt is dispersed back into the matrix as overgrowths on matrix minerals (Sawyer, 2001). In the Pembroke example, it is common to observe thin films of plagioclase and less commonly quartz along grain boundaries or as overgrowths on residual grains in dioritic gneiss (see below), representing crystallized melt. Similar textures are observed in the anorthositic dykes, the compositions of which do not represent any sensible minimum melt. The following two important observations led Daczko *et al.* (2001a) to interpret the anorthositic dykes as mostly cumulate material sourced from migrating trondhjemitic neosome: (i) simple CIPW norm calculations indicate that the bulk chemistry of the dykes comprises an 89–95% anorthitic plagioclase feldspar component. (ii) There was no evidence of melting or hydration of the garnet reaction zone in contact with the dyke as would be expected if a silicate liquid solidified into a dyke and released excess H_2O into the surrounding rock, consistent with most of the melt having moved farther away leaving behind cumulate material to form the dyke. Leucosomes that enclose garnet poikiloblasts in the dioritic gneiss, and those forming the anorthositic dykes, are not complete neosome; they represent cumulate material stranded by melt production and migration.

MAJOR PHYSICAL AND CHEMICAL RELATIONSHIPS

Outcrops in the Pembroke Valley comprise two main rock types: (i) dioritic gneiss, which is inferred to have partially melted at peak conditions (Fig. 2b, c); and (ii) gabbroic gneiss, which is inferred to have remained at sub-solidus conditions. This difference between the two rock types controls many of the textures discussed below. Garnet reaction zones occur almost exclusively in gabbroic gneiss, as planar areas where the two-pyroxene-hornblende host is recrystallized to garnet granulite adjacent to centimetre- to decimetre-wide anorthositic dykes (Fig. 2a, d). Partial melting in the dioritic gneiss and garnet granulite recrystallization (dehydration) in the gabbroic gneiss accompanied peak conditions of > 750 °C and *c*. 14 kbar; these features cut S1 two-pyroxene hornblende granulite assemblages in both rock types that reflect conditions of *c*. 750 °C and < 8 kbar (Clarke *et al*., 2000). On the basis of U-Pb SHRIMP data, protoliths to the rocks are calc-alkaline plutons dominated by 136–129 Ma magmatic zircon, which experienced high-grade metamorphism between *c*. 120 and 100 Ma (Hollis *et al*., 2003). The terrane experienced rapid cooling to < 400 °C by 90 Ma (Nathan *et al*., 2000). The anorthositic dykes cut contacts between gabbroic, dioritic and ultramafic gneiss without host-rock displacement (Fig. 2d), and have Sr and Nd isotopic ratios indistinguishable from those of their hosts. Depending on the discrimination diagram employed, the so-called dioritic gneiss may or may not plot in the gabbroic field, and the main rock types show a restricted spectrum of compositions. However, the 'dioritic' and gabbroic gneisses are always separated on a SiO_2 discrimination diagram and the 'dioritic' gneiss contains appreciable clinozoisite and biotite found lacking in the gabbroic gneiss. Garnet reaction zones flanking the dykes terminate at gabbroic-dioritic gneiss contacts (Fig. 3). At such locations, the anorthositic dyke is continuous with a planar felsic segregation commonly involving a septum of coarse-grained garnet surrounded by anorthositic leucosome. Klepeis & Clarke (2004) have summarized regional tectonic relationships of the evolving Cretaceous orogen, involving migmatite formation in the root of a mafic arc undergoing convergence with a continental margin.

Bodies of dioritic gneiss mostly lack garnet reaction zones. Instead, they contain isolated garnet grains enclosed by leucosome, and short planar trains of

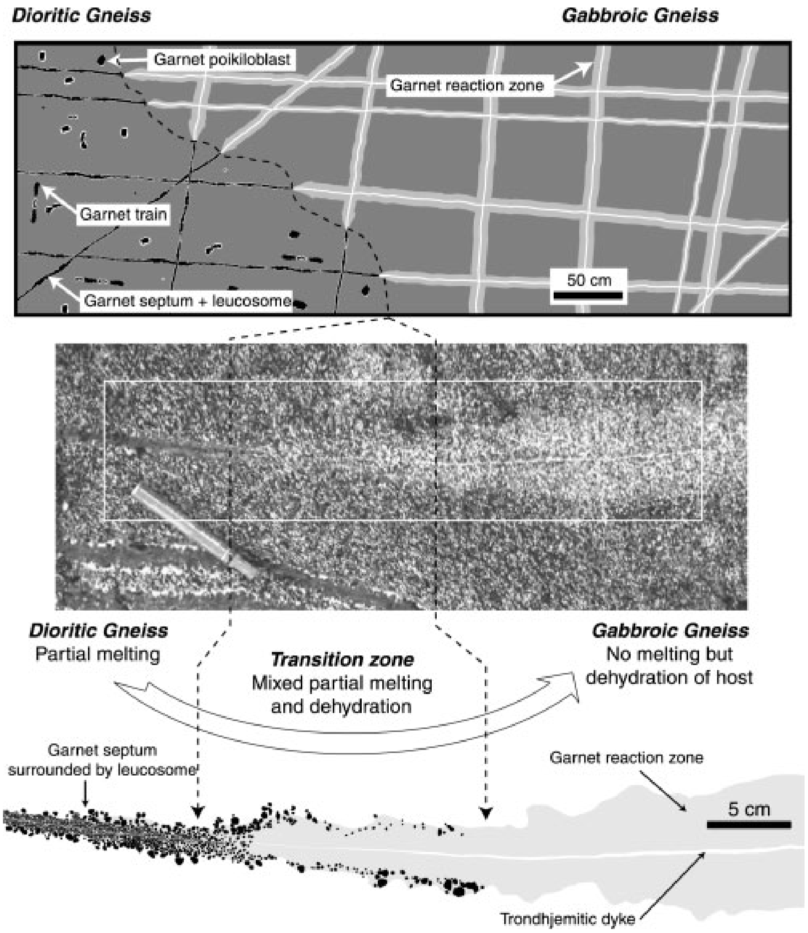

Fig. 3. Field relationships and inferred processes. Trondhjemitic mobilisate, sourced from migmatitic structures in the dioritic gneiss accumulate in planar leucosomes and migrates from this source rock through sub-solidus gabbroic gneiss where it induces dehydration and leaves behind an anorthositic cumulate.

garnet grains linked by spatially restricted leucosome (Fig. 2b, c). Peak conditions (> 750 °C, *c.* 14 kbar) inferred for rocks of the Pembroke Valley are at temperatures well above their water-saturated solidi (e.g. Rushmer, 1991; Lopez & Castro, 2001; Klepeis *et al.*, 2003) and the limited development of migmatitic structures require that there be no free water at peak conditions. Pervasive garnet and spatially related leucosome throughout the dioritic gneiss have been used to infer that closed-system partial melting produced the migmatite (Daczko *et al.*, 2001a). In this interpretation, garnet is a peritectic product of the melting step, balancing Fe and Mg components supplied by reactant hornblende and clinozoisite. Textures within the leucosomes are consistent with the interpretation that the dioritic gneiss partially melted, using the microstructural criteria of Sawyer (1999). The large garnet poikiloblasts mostly contain inclusions of quartz, with or without minor hornblende, clinozoisite, rutile and apatite. Leucosome mostly consists of plagioclase and quartz, and contains rounded and embayed grains of clinozoisite and hornblende (fig. 3 in Daczko *et al.*, 2002). Quartz commonly shows rectangular shapes with concave sides. Quartz and plagioclase grains show no evidence of strain, such as recrystallized grain margins or undulose extinction, consistent with these samples experiencing little ductile deformation associated with or following the partial melting. Thin films of quartz and plagioclase occur along some larger plagioclase grain boundaries in the leucosome. The films of plagioclase are commonly zoned, up to 50 μm across, and are more calcic than the rest of the plagioclase in the leucosome (fig. 3 in Daczko *et al.*, 2002). Limited retrogression of the peak assemblage suggests that partial melt must have escaped the dioritic gneiss (e.g. Waters & Whales, 1984; White & Powell, 2002). Sites of inferred melt escape are represented by the planar leucosome structures that continue in the surrounding gabbroic gneiss. Studies prior to that of Daczko *et al.* (2001a) did not consider these dioritic migmatites, which provide evidence of open-system behaviour in the gabbroic gneiss.

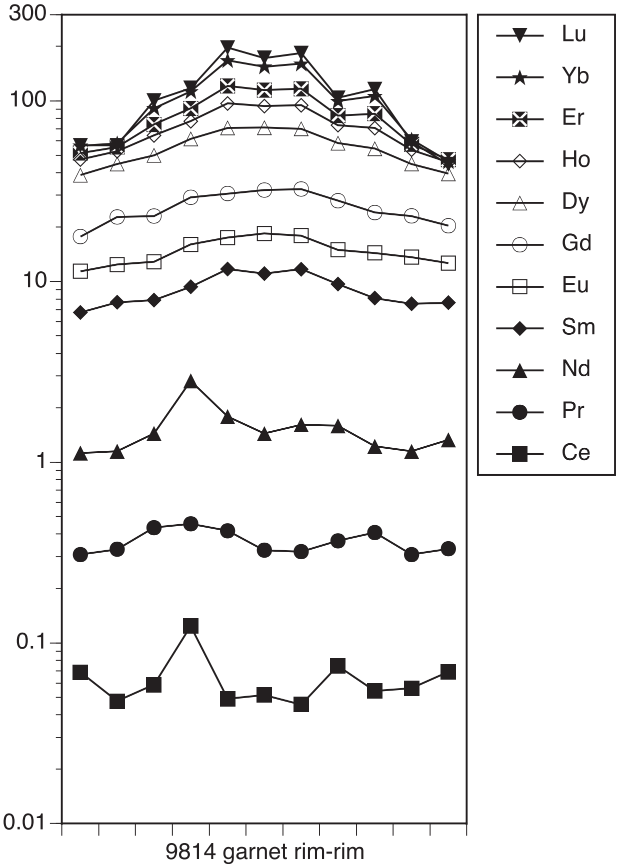

Fig. 4. Chondrite-normalized REE composition of a garnet grain in the anorthositic dyke portion of sample 9814, a gabbroic gneiss with a garnet reaction zone. The plot shows REE values for a series of analyses collected as a profile across one grain. The garnet is enriched in heavy REEs (relative to chondrite), and most enriched in the heaviest REEs. The degree of enrichment decreases from the core to both rims. This garnet grain was 8 mm in diameter in the thick section.

Gabbroic gneiss, the common rock type in the Pembroke Valley, has three main components (Fig. 2a): (i) anorthositic dykes that have sharp boundaries and large euhedral grains of garnet and, less commonly, diopside, orthopyroxene, hornblende or scapolite; which cut (ii) the host two-pyroxene-hornblende gneiss. Small proportions of phengitic white mica, kyanite and clinozoisite may also be present in rare anorthositic dykes. The two components are mostly separated by (iii) garnet reaction zones. The width of the zones mostly reflects the hornblende mode of the host (Fig. 2d), and locally the garnet reaction zones may lack an anorthositic dyke at their core. Daczko *et al.* (2001a) observed that garnet in the anorthositic dykes is texturally distinct from garnet in the garnet reaction zones, but similar to garnet in migmatitic structures in the dioritic gneiss. This observation led to the prediction that the anorthositic dyke was sourced from the partial melting of the dioritic gneiss. In a detailed study of the trace-element content of the main silicates, Schröter *et al.* (2004) confirmed this prediction – garnet in anorthositic dykes hosted by gabbroic gneiss has REE contents that distinguish it from garnet in adjacent garnet reaction zones, but identical to peritectic garnet in the dioritic gneiss. Garnet in anorthositic dykes (hosted by gabbroic gneiss) is also subtly zoned in pyrope and grossular components, and systematically zoned in REEs (Fig. 4). The zoning profile is most pronounced in the heavy REEs, and is similar to spessartine growth zoning profiles in low-grade garnet from elsewhere (e.g. Tracy, 1982; Marmo *et al.*, 2002).

With the exception of the rectilinear networks, gabbroic gneiss lacks pervasive leucosome development, and peak conditions are inferred to have been at lower temperature than the solidus for these less-fertile compositions (Daczko *et al.*, 2001a). The chemical and textural distinctions between garnet in the dykes and the garnet reaction zone, the sharp boundaries of the dykes, and the lack of relics of the host rock in the dyke have been used to support the interpretation that the anorthositic dyke was injected into the gabbroic gneiss (Daczko *et al.*, 2001a; Schröter *et al.*, 2004). The chemical and spatial links are consistent with a trondhjemitic mobilisate, sourced from partial melting of the adjacent dioritic gneiss (Fig. 3), passing through the gabbroic gneiss as a trondhjemitic dyke, leaving behind a plagioclase-rich cumulate as the majority of trondhjemitic liquid moved to structurally higher levels. The anorthositic dykes in the gabbroic gneiss thus form an injection migmatite, albeit an unusual rectilinear network.

The strong spatial relationship between the anorthositic dykes and garnet reaction zones has been noted by all researchers, although Daczko *et al.* (2001a) noted that garnet reaction zones lacking a clear dyke could reflect either dyke terminations or sites of prior melt flux (i.e. a closed and healed dyke). For the samples from the Pembroke Valley, there is little chemical difference between the garnet reaction zone and host gabbroic gneiss (Daczko *et al.*, 2001a), differences being restricted to variations in alkali and Cu content. The garnet reaction zone mineral assemblages involve diopside, plagioclase, garnet, rutile and quartz with or without kyanite. Garnet occupies the same textural position as hornblende in the host outside the garnet reaction zone; it forms a necklace around relic phenocrysts and S1 minerals. There are progressive changes in mode and mineral composition from the patchy outside edge of the garnet reaction zone to the sharp internal anorthositic dyke wall (fig. 8 of Daczko *et al.*, 2001a) – the hornblende mode is opposite to that of garnet and diopside. The main difference between the host gabbroic gneiss and the garnet reaction zone is thus the proportion of hornblende, the assemblage becoming progressively less hydrous as the anorthositic dyke is approached. Although there is general agreement that the garnet reaction zones in the Pembroke Valley reflect the metasomatic alteration of the host, there is disagreement on the causal process. In the next few paragraphs, structural observations are outlined that are consistent with our interpretation of dyking by a trondhjemitic liquid and provide an overview of how the Pembroke example relates to other well-exposed sites throughout Fiordland.

The curvature of some anorthositic dyke tips in the bridge between parallel but offset dykes (fig. 6d in Klepeis & Clarke, 2004) provides additional information on their possible origin. The relationships are characteristic of a stress field modified by the internal fluid pressure of opening veins (Ramsay & Lisle, 2000, p. 766–767). Such features are typical of en echelon tension gashes that form in the upper crust involving regions of brittle deformation and high strain rates. In such situations, microscopic cracks can dramatically weaken a rock by concentrating stress at the tips of favourably oriented microcracks. Joints are cracks oriented approximately perpendicular to the least principal stress. Observations of jointing patterns reveal the ways in which joints intersect and terminate (Cruikshank *et al.*, 1991). Where the exposed portion of the joint plane intercepts the main part of a joint, it appears as a straight line on the outcrop, whereas if the level of exposure intercepts the fringe elements of the joint plane, the trace of the joint is commonly a series of en echelon lines at an angle to the main joint plane. Pollard & Aydin (1988) outlined three main joint intersection geometries: those that meet at 'Y'-, 'X'- or 'T'-intersections. In the Pembroke example, the rectilinear dykes meet at high angles, making X-intersections, and where an offset of one dyke across another occurs, there is no consistent step direction – a common feature of joint sets. Joint planes commonly end as hooked terminations or in an en echelon pattern (Fig. 6d of Klepeis & Clarke, 2004). Fluid pressure is commonly invoked to explain how tension joints can form at depths where overburden confining pressures are large. In such cases, fluid pressure reduces the acting principal stresses, shifting the stress circle on a Mohr diagram left towards the field of tensional stress (Secor, 1965). With high fluid pressures and low differential stresses, the stress circle intersects the tensile failure envelope and the rock fails. However, peak conditions that accompanied garnet reaction zone formation invalidate the presence of a hydrous fluid, and the lack of carbonate, graphite or any evidence of carbonic metasomatism make the presence of a casual carbonic fluid unlikely. As most anorthositic dykes and related garnet reaction zones show no displacement of host rock, Daczko *et al.* (2001a) proposed a model involving dyke-controlled fracturing. Bons *et al.* (2001) have modelled the step-wise movement of silicate melt through such structures.

Daczko *et al.* (2001b) described the network of vertical, planar fractures that form a distinctive lattice pattern on horizontal surfaces in the Pembroke Valley. The grid of fractures and associated garnet reaction zones show spacings of < 1 m. The grid consists of three sets of fractures, for which the labels GRZ_1, GRZ_2 and GRZ_3 were proposed. GRZ_1 fractures are east-striking and display vertical to steep dips to the south. GRZ_2 fractures intersect GRZ_1 fractures at high angles, strike north to NNE and dip very steeply to the west. GRZ_3 fractures bisect the angle between the first two sets, strike NE and dip steeply to the SE (Fig. 1). Similar numbers of individual garnet reaction zones occur in sets GRZ_1 and GRZ_2. However, these exceed by far the number of garnet reaction zones in the GRZ_3 set. At Lake Grave and Mt Daniel (Fig. 1), we have also made detailed measurements of the orientation of dykes with or without garnet reaction zones, and most parallel GRZ_1 fractures in the Pembroke example (Fig. 1). A subordinate number are oriented similarly to GRZ_2 fractures and very few are oriented similarly to GRZ_3 fractures. The regional persistence of orientation is consistent with far-field stresses having been critical in determining the orientations of the anorthositic dykes and garnet reaction zones.

These relationships are not preserved everywhere. For example, vague outlines of the anorthositic dykes and garnet reaction zones can be recognized in the Milford Gneiss, which is the intensely recrystallized equivalent of host rocks in the Pembroke Valley (Blattner, 1991). These relationships mostly reflect the low intensity of high-grade strain that affected the Pembroke Granulite subsequent to the development of the garnet reaction zones.

DISCUSSION

Granulite facies assemblages that record > 750 °C are common in high-grade Precambrian terranes, and require that water activity at peak conditions be < 1, to avoid pervasive partial melting (e.g. Lopez & Castro, 2001). Dehydration is commonly inferred to have occurred in response to a prograde reaction sequence or progressive melt removal (e.g. White & Powell, 2002). Small proportions of scapolite in mafic rocks can reflect the consequent enrichment of CO_2 in any remaining fluid. In such circumstances, the degree of partial melting is mostly controlled by the availability of hydrous minerals to react with quartz and plagioclase. Migmatitic structures in dioritic gneiss from the Pembroke Valley are consistent with this lithology having been previously richer in quartz and hydrous minerals, but the lack of a low-grade equivalent prevents any quantitative constraint on the proportion of melt removed. The lower alkali and silica content of the gabbroic gneiss would have made it less fertile, thereby remaining sub-solidus at peak conditions.

In this context, it is worthwhile evaluating the fluids that might have induced the formation of garnet reaction zones in the gabbroic gneiss. A decision needs to be made as to whether the anorthositic dykes and garnet reaction zones were contemporaneous. Protoliths to the host rock were emplaced only a few million years before the partial melting, most probably into a mid- or lower crustal setting (Clarke *et al.*, 2000; Hollis *et al.*, 2003), but there is sufficient time for the processes to have been separate. Models proposed by Blattner (1976) and Bradshaw (1989) involving the ingress of carbonic fluids along a pre-existing vein network leading to dehydration of rocks adjacent to the fluid pathways have the following two main problems: (i) there is no confirmed source or sink for such fluids; (ii) the termination of the garnet reaction zones at lithological boundaries of rocks that are mineralogically close to the gabbroic gneiss begs special cases of fluid flow. Continuity of the dykes across the gabbroic-dioritic gneiss boundaries, at which point the garnet reaction zones terminate, qualitatively indicates a genetic link. Locations where garnet reaction zones lack a central anorthositic dyke may be terminations of a dyke in the third dimension, or sites of prior melt flux (Daczko *et al.*, 2001a).

Assuming a genetic link between dyke and garnet reaction zone, the causal fluid needs to have: (i) been capable of generating the sharp boundaries of the anorthositic dykes; (ii) had a radiogenic signature close to that of calcalkaline hosts; (iii) been capable of inducing dehydration in the gabbroic gneiss, but not in the dioritic gneiss; and (iv) been capable of forming mineral assemblages that vary on a metre-scale and include texturally equilibrated garnet, diopside, orthopyroxene and hornblende. Furthermore, the garnet-forming process in the anorthositic dykes needs to account for growth zoning preserved by REEs (Fig. 4). The injection of a hydrous fluid along specific fractures would lead to the focussed partial melting of the gabbroic gneiss, as such fluid would immediately bring the rock to solidus conditions. Were large volumes of hydrous fluids to have travelled through the fractures, they would have induced ‘extensive’ partial melting at the elevated temperatures recorded by the garnet granulite assemblages. A rapid, limited influx on a fracture network might form structures similar to those observed in the Pembroke Valley. However, geochemical data indicate that the anorthositic dykes are exotic to the gabbroic gneiss and little material other than water was removed from the garnet reaction zones.

An alternative interpretation involves a specific fluid having formed both the anorthositic dykes and garnet reaction zone by metasomatism. This would require extensive metasomatism of the host rock to form the dyke, and less-intense metasomatism to form the garnet reaction zones. Such a fluid would need to be undersaturated in water, to avoid partially melting the host, and have had the unusual composition of being alkali-rich, yet silica-poor, as the anorthositic dykes lack quartz. No petrographic relics of host rock occur in the dykes, and no outgoing pathways of material demanded by the metasomatic origin can be seen. A source for the fluid needs to have been at least 160 × 40 km in area, probably much larger, with a radiogenic signature identical to both the gabbroic and dioritic gneisses. We cannot conceive the generation of such a fluid. Dehydration of continental crust undergoing prograde metamorphism seems the only viable source, yet it would yield a distinct radiogenic signature. In addition, ingress of the fluid on such a scale must lead to identical assemblages in similar rocks. This does not match the patchy occurrence of chemically zoned garnet, scapolite, diopside and orthopyroxene, which occur with plagioclase in the anorthositic dykes. Blattner (2005) has suggested that there could have been a combination of processes: dykes formed by silicate melt and the garnet reaction zones formed by sodic metasomatism. It is not clear what would have induced a chemical potential gradient in Na, or the fluid that would have enabled metre-scale migration of Na.

The observations best match the behaviour of one fluid – a trondhjemitic liquid formed by partially melting the dioritic gneiss (Daczko *et al*., 2001a). However, the extensive development of the garnet reaction zones and the limited width of many anorthositic dykes focus attention on the genetic link and partial melt characteristics. The common separation of silicate melts and hydrous fluids, appropriate to upper crustal conditions, may be inappropriate at deeper levels (Shen & Keppler, 1997; Newton & Manning, 2003); with increasing pressure, the solubility of water in silicate melts, and that of silicate melt in hydrous fluids, increases. Ongoing studies in this field will establish whether a silicate melt that behaved more like a hydrous fluid could have formed at conditions recorded in the Pembroke Granulite.

Remaining questions in the model presented by Daczko *et al*. (2001a) and reaffirmed here include a plausible mechanism to account for the rectilinear anorthositic dyke network, the simplification of lithologies in the Pembroke Valley to two rock types, and the observation of anorthositic dykes that cut garnet reaction zones. Given their depth of formation, and overwhelming evidence for contraction during and after dyking (Daczko *et al*., 2001b), it seems unlikely that the anorthositic dyke network reflects crustal extension. The orientation of the fracture network is inferred to have been controlled by far-field deviatoric stresses, with the development of high pore-fluid pressures in melt pockets having led to local reaction-induced fracturing (Connolly *et al*., 1997; Rushmer, 2001). There seems insufficient leucosome production at the currently exposed structural level in the Pembroke Valley, but observed sites of melt pooling could reflect more fertile processes only subtly deeper. Reclassification of the dioritic and gabbroic gneiss samples into a restricted chemical spectrum does not affect the interpretation – for a given set of P–T–X conditions, a rock closer to diorite in composition would be more fertile for partial melting than a true gabbroic gneiss.

Complexity in dyke-garnet reaction zone structures and cross-cutting relationships can be accounted for by evolving P–T or fluid conditions. Cretaceous metamorphism in the Pembroke Valley occurred over a short period, in which P–T and fluid activity evolved. Rocks previously at sub-solidus conditions may hit their solidus because of increasing temperature or, possibly, the ingress of a supercritical fluid, although this is doubtful at crustal conditions for a complex fluid (Shen & Keppler, 1997). A rock intermediate between end-member gabbroic and dioritic gneisses could be expected to change from hosting garnet reaction zone structures (sub-solidus) to becoming a (less fertile) migmatite as temperature increased. Although the relative change in pressure conditions from S1 assemblages to those that accompanied garnet reaction zone formation are reasonably well understood, the relative change in temperature conditions is less well understood because of aspects of superposed recrystallization and diffusional re-equilibration. However, it seems difficult to avoid temperatures that accompanied partial melting of the diorite having been higher than those that accompanied the development of S1.

Garnet reaction zones in the Pembroke Valley are locally intensely deformed (Daczko *et al*., 2001b). Only vague outlines of the anorthositic dykes can be recognized in the Milford Gneiss, which is the intensely recrystallized equivalent of host rocks in the Pembroke Valley (Blattner, 1991). However, such low-strain windows persist throughout the high-grade rocks of western Fiordland, and identical garnet reaction zones occur in Cretaceous rocks of the Kohistan arc, northern Pakistan (Yamamoto & Yoshino, 1998). Although distinguished by host-rock composition and hence critical hydrous-mineral breakdown reactions, the dehydration structures in India and Sri Lanka are also steeply dipping and regionally persistent (Raith & Srikantappa, 1993). The persistence of the vertical network through western Fiordland is consistent with comparatively rapid uplift of that terrane having not involved significant rotation of the preserved sites about a horizontal pole. Migration of silicate melt is a common feature of granulite facies conditions, although such rocks are commonly extensively deformed. On the basis of related links to structures in Pakistan, India and Sri Lanka, we prefer the interpretation that the Pembroke example is a well-exposed example of volatile scavenging by a migrating silicate liquid, a common process, the evidence for which is usually destroyed by deformation and recrystallization.

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