Transformation of two-pyroxene hornblende granulite to
garnet granulite involving simultaneous melting and
fracturing of the lower crust, Fiordland, New Zealand

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ABSTRACT
Granulite facies gabbroic and dioritic gneisses in the Pembroke Valley, Milford Sound, New Zealand, are cut by vertical and planar garnet reaction zones in rectilinear patterns. In gabbroic gneiss, narrow dykes of anorthositic leucosome are surrounded by fine-grained garnet granulite that replaced the host two-pyroxene hornblende granulite at conditions of \( T > 750 \) °C and \( P \approx 14 \) kbar. Major and trace element whole-rock geochemical data indicate that recrystallization was mostly isochemical. The anorthositic veins cut contacts between gabbroic gneiss and dioritic gneiss, but change in morphology at the contacts, from the anorthositic vein surrounded by a garnet granulite reaction zone in the gabbroic gneiss, to zones with a septum of coarse-grained garnet surrounded by anorthositic leucosome in the dioritic gneiss. The dioritic gneiss also contains isolated garnet grains enclosed by leucosome, and short planar trains of garnet grains linked by leucosome. Partial melting of the dioritic gneiss, mostly controlled by hornblende breakdown at water-undersaturated conditions, is inferred to have generated the leucosomes. The form of the leucosomes is consistent with melt segregation and transport aided by fracture propagation; limited retrogression suggests considerable melt escape. Dyking and melt escape from the dioritic gneiss are inferred to have propagated fractures into the gabbroic gneiss. The migrating melt scavenged water from the surrounding gabbroic gneiss and induced the limited replacement by garnet granulite.

Key words: two-pyroxene granulite; garnet granulite; lower crust; partial melting; fracturing.

INTRODUCTION
In this paper, we present structural, metamorphic and geochemical data to establish a mechanism responsible for the simultaneous melting and fracturing of the lower continental crust. Extensive rectilinear, leucosome-filled fracture networks cut gabbroic and dioritic gneiss along a well exposed glacial slab in the Pembroke Granulite near Milford Sound, New Zealand (Blattner, 1976). Adjacent to fractures in the gabbroic gneiss, the host two-pyroxene hornblende granulite assemblage has been replaced by garnet granulite assemblages that reflect conditions involving \( T > 750 \) °C and \( P = 14 \) kbar (Clarke et al., 2000). Pods of more fertile dioritic gneiss preserve evidence of partial melting that we infer to have been controlled by hornblende breakdown at water-undersaturated conditions. Leucosome generated by melting of the dioritic gneiss invaded adjacent, sub-solidus gabbroic gneiss. Peritectic garnet porphyroblasts and leucosome in the dioritic gneiss often form elongate trains that parallel leucosome filled fracture networks in both the gabbroic and dioritic gneiss. Fracture networks are continuous across the dioritic-gabbroic gneiss contacts. These spatial relationships indicate that microfracturing assisted melt segregation in the dioritic gneiss, and we infer that millimetre- to centimetre-scale fracturing induced by melt accumulation allowed melt to escape and invade the gabbroic gneiss. We present whole-rock geochemical data to show that the partial replacement of two-pyroxene hornblende granulite by garnet granulite was isochemical; we also infer that the water-undersaturated melt in the fractures dehydrated the wall rocks to produce the garnet granulite reaction zones. The Pembroke Granulite preserves a well-exposed example of arrested high-\( P \) granulite facies metamorphism, and evidence for melt-induced fracturing of the lower continental crust.

REGIONAL GEOLOGY
The geology of the south island of New Zealand can be divided into three domains. Eastern and Western Provinces (Landis & Coombs, 1967; Bishop et al., 1985; inset Fig. 1) are separated by a belt of rocks referred to as the Median Tectonic Zone (Kimbrough et al., 1993, 1994; inset Fig. 1) or Median Batholith (Mortimer et al., 1999). Most of the Eastern Province formed by convergent margin processes and contains arc-volcanic
rocks, arc-derived sedimentary sequences, and accretionary complexes of Permian-Cretaceous age (MacKinnon, 1983; Bradshaw, 1989a; Mortimer, 1995). The Western Province contains extensive Lower Paleozoic metasediments that are cut by Devonian, Carboniferous and Cretaceous granitoids (Muir et al., 1996; Wandres et al., 1998). Rocks within this province preserve a polyphase mid-Paleozoic history that occurred when ancestral New Zealand lay within or outboard of the Pacific margin of Gondwana (Wood, 1972; Carter et al., 1974; Gibson & Ireland, 1996; Mortimer et al., 1999).

The Median Tectonic Zone is a comparatively narrow belt of tectonically disrupted arc-related rocks that includes the Darran Complex in northern Fiordland (Bradshaw, 1993; Kimbrough et al., 1993, 1994, Fig. 1). U-Pb zircon ages for rocks of the Median Tectonic Zone mostly fall into two age groups: 247 – 195 Ma and 157 – 131 Ma (Kimbrough et al., 1994). Late Triassic Median Tectonic Zone plutons that intrude the Eastern Province indicate that these two provinces were together at this time (Williams & Harper, 1978; Mortimer et al., 1999). Rocks of the Median Tectonic Zone and the Western Province were intruded by plutons of the 126-105 Ma Western Fiordland Orthogneiss / Separation Point Suite (Bradshaw, 1990; Kimbrough et al., 1994; Fig. 1).

The Arthur River Complex (Bradshaw, 1990; Fig. 1) is a belt of granulite facies orthogneiss that lies at the boundary between the Median Tectonic Zone and Western Province rocks in northern Fiordland (Fig. 1). It is heterogeneous in rock-types and structure (Clarke et al., 2000), and Mesozoic and Paleozoic ages have been inferred for orthogneiss units from this belt (Mattinson et al., 1986; Bradshaw, 1990). In Milford Sound, the Arthur River Complex includes dioritic gneisses of the Harrison Gneiss and gabbroic gneisses of the Pembroke Granulite and Milford Gneiss (Wood, 1972; Blattner, 1991). The Anita Shear Zone forms the north-western boundary of the Arthur River Complex; rocks of the Western Province lie north-west of the shear zone (Hill, 1995a,b; Klepeis et al., 1999; Fig. 1). The structural relationship between the Arthur River Complex and the Darran Complex (to the east) is less clear, due to most contacts being obscured by vegetation. On the basis of transects made along remote ridges, Blattner (1978, 1991) inferred a gradational transition from hornblende-diorites of the Darran Complex into amphibolites of the Harrison Gneiss, and showed that there is no significant chemical difference between the two units. However, other authors have postulated that, in places, regional faults separate the two complexes (e.g. Bradshaw, 1990). We prefer an interpretation that at least parts of the Arthur River Complex are rocks of the Median Tectonic Zone that experienced granulite facies metamorphism in the Cretaceous (Blattner, 1991), but this interpretation requires confirmation by isotopic dating. The Arthur River Complex is intruded by the Western Fiordland Orthogneiss at its southern-most extent (Bradshaw, 1990, Fig. 1).

Interpretations of the Cretaceous tectonic history of western Fiordland are controversial. Using conventional U-Pb zircon dating (Mattinson et al., 1986) and estimates of metamorphic pressure-temperature paths, Bradshaw (1989b, 1990) and Bradshaw & Kimbrough (1989) inferred a Cretaceous metamorphic
history that involved the mid-crustal emplacement of the Western Fiordland Orthogneiss batholith coeval with low- to medium-pressure granite facies metamorphism. A substantial increase in pressure (\(P \sim 6\) kbar) and the subsequent formation of garnet granite throughout Fiordland was attributed by these authors to tectonic burial consequent to the convergence of arc (Median Tectonic Zone) and continent (Western Province) rocks. Using petrographic and field data presented by Bradshaw (1989b, 1989c, 1990), Oliver (1990) and Brown (1996) inferred that the high-pressure granite facies conditions were produced by magma loading following emplacement of the Western Fiordland Orthogneiss at mid-crustal conditions. Muir et al. (1995, 1998) used geochemical and geochronologic data to argue that an early Cretaceous magmatic arc, chemically equivalent to the Darran Complex, was thrust beneath western Fiordland to depths in excess of 40 km and melted to produce the Western Fiordland Orthogneiss. In comparison, Gibson & Ireland (1995), and Ireland & Gibson (1998) inferred that the Western Fiordland Orthogneiss intruded Western Province rocks that were already at lower crustal conditions, and that the Cretaceous history of western Fiordland involved only decompression.

Field and petrographic data for the garnet granite facies assemblages that occur in planar reaction zones throughout western Fiordland are central to many of these arguments. Garnet granite is most commonly found in a thin zone either side of anorthositic veins that cut two-pyroxene hornblende-bearing assemblages in the Arthur River Complex and Western Fiordland Orthogneiss (Blattner, 1976; Oliver, 1977; Blattner & Black, 1980; Bradshaw, 1989c). Previous work has focussed only on textures in the garnet reaction zones that cut gabbroic gneiss. Blattner (1976) provided a field and petrologic description of the gabbroic gneiss and garnet reaction zones. He used the presence of scapolite in some anorthositic veins to infer that the garnet reaction zones formed in response to an influx of mantle-derived \(\text{CO}_2\)-rich fluids along a pre-existing joint network. In this model, anorthositic veins, common to the centre of most garnet reaction zones, are unrelated to the garnet reaction zones. Oliver (1977) studied similar garnet reaction zones in the Doubtful Sound region, but proposed an alternative model that involved the partial melting of gabbroic gneiss; melt was inferred to have segregated from the site of production (i.e. a garnet reaction zone) to an adjacent anorthositic vein. Blattner & Black (1980) suggested that volatiles released by hornblende breakdown in gabbroic gneiss of the Pembroke Granulite may have led to melting of plagioclase, to form small proportions of melt as intergranular films. The segregation of these melts may have then contributed to scapolite-bearing anorthositic veins at a structural level above that currently exposed. The interpretations of Blattner & Black (1980) are similar to those of Oliver (1977) in that the garnet reaction zones represent ‘restite’ or ‘melanosome’ produced during partial melting. However, Blattner & Black (1980) do suggest that the \(\text{CO}_2\) and \(\text{SO}_3\) in scapolite must have come from an external source. Bradshaw (1989c) examined garnet reaction zone textures over a wide area of Fiordland, and inferred a two-stage model. He inferred that hornblende-plagioclase veins invaded a network of pre-existing fractures that were subsequently utilised by \(\text{CO}_2\)-rich fluids that moved along these weaknesses to dehydrate gabbroic gneiss adjacent to the fractures and/or veins.

Excellent exposures in recently deglaciated rocks that experienced only partial replacement of the two-pyroxene hornblende-granulite by garnet granulite have led to a good understanding of metamorphic reactions involved in the change from two-pyroxene hornblende-bearing orthogneiss to garnet-clinopyroxene-plagioclase-quartz granulite assemblages (Blattner, 1976; Oliver, 1977; Bradshaw, 1989c). However, the tectonic and metamorphic processes that led to the localized development of garnet granulite have yet to be resolved.

**Petrography and Field Relations**

The Pembroke Granulite (Fig. 1) may be subdivided into gabbroic, dioritic and ultramafic gneiss. Gabbroic gneiss forms the majority of the Pembroke Granulite (>70% of 0.75 km\(^2\) area studied) and is generally found in the lower reaches of the Pembroke Valley. Dioritic gneiss is generally found in the upper reaches of the Pembroke Valley, but may also outcrop as pods within the gabbroic gneiss. Ultramafic gneiss is subordinate to the other two components of the Pembroke Granulite and is generally found as small pods, up to 50 m across, most commonly within the dioritic gneiss. Areas with igneous textures are enveloped by high-strain domains containing \(S_1\) minerals that preserve flaser textures and include deformed grains up to 10 mm in length. Rocks pervasively recrystallized during \(D_1\), mostly contain pargasitic hornblende and plagioclase that are elongate in \(S_1\). \(S_1\) is variable in orientation and intensity, but generally strikes east to east-north-east and dips steeply toward the south and south-south-east. Minerals defining \(S_2\) are inferred to reflect conditions of \(P < 8\) kbar and \(T > 750\) °C (Clarke et al., 2000). \(S_3\) is cut by steeply dipping planar fractures (\(D_2\)) that are commonly filled by anorthositic veins (Fig. 2a). In domains a few centi-
metres either side of the fractures and veins, S₁ minerals in gabbroic gneiss have been pseudomorphed by garnet, clinopyroxene, quartz and rutile, with or without kyanite. These areas of replacement outcrop as distinctive pink alteration bands or what is referred to as a “garnet reaction zone” (bleached area adjacent to leucosome-filled fractures in Fig. 2a). Garnet-clinopyroxene granulite facies assemblages in the garnet reaction zones record metamorphic conditions of $P \approx 14$ kbar and $T > 750 \, ^{\circ}\text{C}$ (Clarke et al., 2000). Similar reaction zones are not observed adjacent to garnet-bearing leucosome in dioritic gneiss.

Small pods within the gabbroic gneiss that show slight variations in grain size and/or composition may also be cut by anorthositic veins, and host garnet reaction zones similar to that in the adjacent coarser grained gabbroic gneiss (Fig. 2b). These observations indicate that the process forming the garnet-clinopyroxene granulite is strongly related to rock interaction with the D₂ fractures and anorthositic veins, and is independent of minor variations in whole-rock composition or grain size. S₁ and the garnet reaction zones are variably deformed by east-striking, steeply dipping, narrow (< 1 m wide) mylonite zones (D₃) that preserve evidence for sinistral displacement and a well-developed, west-plunging mineral and stretching lineation (L₃). Two sets of D₄ shear zones cut the D₃ mylonites: (1) shallowly southeast-dipping thrusts that have a southeast-plunging mineral lineation and top to the northwest displacement, and branch into (2) steeply-
dipping narrow shear zones developed between thrust zones. Metamorphic conditions that accompanied D_3 and D_4 are inferred to have been $P \approx 14$ kbar and $T \approx 700$ °C (Clarke et al., 2000; Daczko et al., 2000). Detailed discussions of the structural and metamorphic evolution of the Pembroke Granulite are described in Daczko et al. (2000) and Clarke et al. (2000).

**Gabbroic Gneiss**

The gabbroic gneiss contains elongate and aligned clusters of pargasitic hornblende, orthopyroxene, clinopyroxene, plagioclase, quartz and ilmenite that define a well-developed gneissic S_1 foliation (Fig. 2a). Orthopyroxene with exsolution blebs of clinopyroxene or opaque minerals, and clinopyroxene with exsolution blebs of orthopyroxene and opaque minerals, are inferred by us to be relics from an igneous protolith. Clusters of pyroxene are commonly incompletely mantled by S_1 pargasitic hornblende.

The gneissic S_1 foliation is cut by a system of anorthositic veins and garnet reaction zones that generally contain two components: (1) a central fracture commonly filled by a garnet-bearing anorthositic vein; and (2) a diffuse garnet-bearing reaction zone that grades into the host gabbroic gneiss (Fig. 2a). Mineral proportions obtained by point counting the different domains are presented in Table 1 (grid references of sample localities are presented in appendix 1). The anorthositic veins are mostly oligoclase (An_{0.2}-An_{0.7}). The abundance of other minerals in the anorthositic veins is highly variable, but generally much less than 10% total. Minerals present in small proportions include garnet, kyanite, quartz, hornblende, clinopyroxene, and scapolite, though scapolite is generally restricted to larger veins up to 10 cm wide. Scapolite was not found in garnet reaction zone domains, being restricted to the anorthositic veins. Scapolite has crystal form and preserves concentric chemical zoning possibly indicating an igneous origin.

D_3 fractures and the garnet reaction zones form a lattice pattern that consists of three sets: east-striking, north-striking, and north-east-striking (Fig. 2c). On the basis of measurements of more than 200 anorthositic veins and associated garnet reaction zones in gabbroic gneiss (~0.75 km² area), the average width of the anorthositic veins is approximately 4 mm and the average width of the anorthositic vein plus garnet reaction zones is approximately 40 mm (Fig. 3). Most anorthositic veins are less than 5 mm in width, though some veins are up to 30 mm in width. Most garnet reaction zones are 10-50 mm in width, though some reaction zones are up to 100 mm in width. The surface traces of many individual anorthositic veins and garnet reaction zones are continuous and planar for distances in excess of 50 m. Garnet reaction zones in gabbroic gneiss are commonly symmetrically disposed about the anorthositic veins (Fig. 2a). The distance between two reaction zones is commonly less than 100 mm and the boundaries of some closely spaced garnet reaction zones overlap. Fractures, anorthositic veins and garnet reaction zones cut and slightly offset older fractures, anorthositic veins and garnet reaction zones. This indicates that fracturing, veining and garnet-clinopyroxene granulite formation were synchronous.

Contacts between the anorthositic veins and the garnet reaction zones commonly show interlocking grain boundaries, though some samples preserve a clear microscopic line that defines the original fracture/host gabbroic gneiss contact. Strings of idioblastic garnet grains, up to 5 mm wide, commonly line the margins of the anorthositic veins at contacts with the gabbroic gneiss (Fig. 2a). These garnet grains may define asymmetrical patterns, such that one side of the anorthositic vein may cross-like chemical zoning.
have much more garnet or one side may lack garnet (e.g. upper side of centre vein in Fig. 2a). Two of the sets of garnet reaction zones intersect at approximately 90°; garnet reaction zones from the third set intersect the first two at approximately 45°. All D2 fractures and associated veins and garnet reaction zones have steep to near-vertical dips.

**Dioritic Gneiss**

S1 in the dioritic gneiss is defined by pargasitic hornblende, orthopyroxene, clinopyroxene, biotite, clinozoisite, plagioclase (grains 1-2 mm in diameter), quartz and opaque minerals. This assemblage is similar to that of the gabbroic gneiss, but has more quartz and biotite and less pyroxene. Plagioclase is again the dominant mineral. The unit contains garnet-bearing leucosomes, some of which are continuous with anorthositic veins that cut gabbroic gneiss (Fig. 2d). However, garnet-bearing leucosomes in the dioritic gneiss do not have garnet reaction zones. Large garnet poikiloblasts up to 10 cm across (Fig. 4), surrounded by plagioclase and quartz, occur through the dioritic gneiss. In places, several garnet poikiloblasts line up to form trains (Fig. 4) enclosed by planar anorthositic veins, which may be aligned with or cut S1. The garnet and the anorthositic veins are inferred by us to have formed by the incongruent melting of the host rock, as discussed below. Where most extensively developed, these garnet-bearing leucosomes contain two components: (1) a septum of linked garnet poikiloblasts, enclosed by (2) a zone of plagioclase and quartz-bearing leucosome, which is in turn surrounded by the host dioritic gneiss. The large garnet-bearing leucosomes form lattice-like networks similar in size and distribution to those of the anorthositic veins and garnet reaction zones in the gabbroic gneiss. At some localities where dioritic gneiss is in contact with gabbroic gneiss, garnet-bearing leucosomes in the dioritic gneiss change along their length over a distance of a few centimetres into narrow anorthositic veins surrounded by garnet reaction zones in the gabbroic gneiss (Fig. 2d). Figure 5 shows a cartoon representation of the pattern of garnet reaction zones at the boundary between gabbroic and dioritic gneiss. Limited retrogression of the peak assemblage suggests that partial melt has escaped from the dioritic gneiss.

**GEOCHEMISTRY**

In this section we aim to classify the main rock types in the Pembroke Granulite and to examine the interplay between host rock, garnet reaction zone and anorthositic vein in the gabbroic gneiss. Samples were crushed in a hydraulic press, and rock fragments, generally < 2 cm³, were separated into vein material (that included garnet porphyroblasts common along vein margins), garnet reaction zone material and host gabbroic gneiss. The diffuse nature of the contact between garnet reaction zone and host gabbroic gneiss generally resulted in the exclusion of small areas of overlap (< 2 mm wide). Therefore the analyses are a guide to bulk trends in changes in whole-rock composition and may not be strictly representative. Representative samples of dioritic gneiss were crushed without attempting to separate peritectic garnet or leucosome material. The separates were then...
Individually crushed to a fine powder in a tungsten-carbide mill with careful cleaning between samples. Concentrations of the major elements Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P and selected trace elements were determined by Philips PW2400 X-ray fluorescence (XRF) spectrometer at the University of New South Wales, Sydney, Australia, following the procedures of Norrish & Hutton (1969). Whole-rock geochemical analyses of major and trace element concentrations of eight representative samples are presented in Table 2. Additional rare earth elements were determined by instrumental neutron activation analysis (INAA) at the Becquerel Laboratories, Lucas Heights Science and Technology Centre, Sydney, Australia (see Table 2 for list). Sr and Nd isotopic data were obtained at the Centre for Isotope Studies, CSIRO Laboratories, Sydney, Australia, using a VG354 sector thermal ionisation mass spectrometer, and are presented in Table 3.

**Rock classification**

Two samples of gabbroic gneiss that contain sufficiently large areas of host gneiss, garnet reaction zone and anorthositic vein were collected for whole-rock and isotope analysis. Two additional samples of dioritic gneiss were collected for classification and comparison. The SiO$_2$ contents of the gabbroic and dioritic gneiss are approximately 49%, and 52-54%, respectively. Both rock types have moderate TiO$_2$ (0.8-1.1%) and Al$_2$O$_3$ (19-19.5%) contents, and comparatively high Na$_2$O (4.1-4.8%) contents. Samples of the anorthositic veins have higher SiO$_2$ (54-57%) and Al$_2$O$_3$ (24-26%) contents. The anorthositic veins are poor in Fe$_2$O$_3$ (1-4%), MgO (0.6-2.3%), TiO$_2$ (0.10-0.35%), and MnO (0.02-0.07%), and have CaO and K$_2$O contents that are similar to most rocks in the Pembroke Granulite. The P$_2$O$_5$ content of the samples of anorthositic vein is very low at ~0.07%, and their Na$_2$O content is very high at 5-6%.

**Fig. 5.** Cartoon showing how the geometry and style of garnet reaction zones vary across the gabbroic / dioritic gneiss contact. A contrast in the rheology of the partially molten dioritic gneiss and solid gabbroic gneiss appears to have produced little deflection or refraction, as veins traversed the dioritic/gabbroic gneiss boundary. The scale of melt movement is most probably larger than the scale of the diagram.
Table 2. Representative major-oxide and selected trace element data for host gabbroic gneiss, garnet reaction zone and anorthositic vein in samples 9834 and 9835, and diorite gneiss in samples 9808 and 9829B. Loss of ignition at 1050°C. All concentrations for As, Cd, Mo, Sb, Sn, Th and U are less than the lower limit of detection (generally <3ppm). Rare earth elements by INAA at Becquerel Laboratories, Lucas Heights, Sydney, Australia.
normalised to 146Nd/144Nd = 0.7219; O’Nions Nd standard yielded 143Nd/144Nd = 0.511109

composition was measured on a VG354 sector thermal ionisation mass spectrometer at CSIRO, Sydney, Australia. 87Sr/86Sr normalised to Table 3.

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Comparisons between host gabbroic gneiss, garnet reaction zone and anorthositic vein

The oxide concentration and trace element concentration in garnet reaction zones, from two samples of gabbroic gneiss, were divided by the concentrations in the host gabbroic gneiss, and the ratio of associated enrichment/depletion is shown in Fig. 6. As shown in the figure, there is little difference in SiO₂, MgO, MnO, CaO and K₂O content between the host two-pyroxene hornblende and adjacent garnet-clinoxyroxene granulite assemblages. There is a subtle enrichment in TiO₂, Fe₂O₃, Al₂O₃ and TiO₂, and distinct depletion in Na₂O content of the garnet reaction zone, relative to the composition of the host gabbroic gneiss. The loss of Na₂O in the alkali content indicates that metasomatic alteration accompanied the formation of the garnet reaction zones, but it was a minor effect. We do not consider the apparent changes in P₂O₅ to be reliable, due to the small content of P₂O₅ in the gabbroic gneiss and garnet reaction zones (less than 0.3 wt.%). All trace element contents of the host gabbroic gneiss and garnet reaction zones are similar, except for Cu (Fig. 6). The trace amount of Cu in the host gabbroic gneiss is approximately 11-12 ppm and approximately 19-20 ppm for the garnet reaction zones. Higher trace amounts of Cu (25-50 ppm) are found in the anorthositic veins and diorite gneiss (~85-95 ppm). The apparent enrichment of Nb and Rb, and depletion of Hf, in sample 9834 is not considered by us to be reliable, due to the small content of these trace elements.

The gabbroic gneiss, diorite gneiss and anorthositic veins of the Arthur River Complex cannot be discriminated on the basis of measured Sr and Nd isotopic ratios (Table 3). The anorthositic vein material are enriched in Rb and Sr and depleted in Sm and Nd.

Table 3. Rb-Sr and Sm-Nd isotope data. Rb and Sr concentrations were determined by X-ray fluorescence spectrometer. The 87Sr/86Sr composition was measured on a VG354 sector thermal ionisation mass spectrometer at CSIRO, Sydney, Australia. 26Sr/28Sr normalised to 87Sr/86Sr = 0.1194; NBS 987 Sr standard yielded 87Sr/86Sr = 0.710241. 87Rb/86Sr ratios calculated from the measured Rb and Sr concentration and 87Sr/86Sr ratio. Decay constant used for 87Rb = 1.42x10⁻¹¹ a⁻¹. 87Sr/86Sr ratios calculated from the measured Rb and Sr concentration and 87Sr/86Sr ratio. Decay constant used for 87Sr/86Sr = 0.0021%, n=27. 87Rb/86Sr ratios calculated from the measured Rb and Sr concentration and 87Sr/86Sr ratio. Decay constant used for 87Sr/86Sr = 0.0028%, n=8.
compared to the gabbroic and dioritic gneisses. Initial Sr isotope ratios and $\varepsilon_{Nd}$ values have been calculated for arbitrary initial ages of 120 Ma and 330 Ma, to account for the limited constraint of protolith age and timing of partial melting (Bradshaw, 1990). The low $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio points to a mantle or lower crustal origin for the gabbroic and dioritic protoliths. The low radiogenic Sr isotopic composition of all samples suggests no contamination by a more evolved crustal component. The range of $\varepsilon_{Nd}$ values suggest that the anorthositic vein material is much younger than the host gneisses and a Cretaceous age for the partial melting that is inferred to have produced the anorthositic veins. However, these interpretations need confirmation by well-constrained isotopic dating.

Garnet and rutile are absent from gabbroic gneiss that encloses the garnet reaction zones. Orthopyroxene and hornblende are mostly absent from the inner garnet reaction zones, whereas they are common in the host gabbroic gneiss and in outer parts of the garnet reaction zone (near the diffuse garnet reaction zone/ host gabbroic gneiss boundary). Clinopyroxene, plagioclase, quartz and opaque minerals are present in both areas. Plagioclase is less abundant in the garnet reaction zones than in the host gabbroic gneiss. As discussed below, the gabbroic gneiss shows small grains of kyanite in plagioclase. Modal clinopyroxene and quartz increase with the transformation of host gabbroic gneiss to garnet reaction zone. Thus, the two-pyroxene hornblende granulite to garnet-clinopyroxene granulite transformation involves the breakdown of orthopyroxene and hornblende, in the presence of plagioclase, to form garnet, clinopyroxene and quartz, and the breakdown of ilmenite to form rutile. The following reaction approximates the transformation (see also Blattner, 1976; Oliver, 1977; Bradshaw, 1989c):

$$\text{Prg-Hb + Opx + Plag } \rightarrow \text{Grt + Cpx + Qtz + H}_2\text{O} (1)$$

As reaction 1 is principally pressure-dependent, the change is consistent with burial of the Pembroke Granulite. The change has been modelled in CNFMASH (CaO-Na$_2$O-FeO-MgO-Al$_2$O$_3$-SiO$_2$-H$_2$O), using THERMOCALC (v2.6) and the “20 April 1996” internally-consistent thermodynamic data set (Powell et al., 1998), and indicates a change in conditions from $P < 8$ to $P = 14$ kbar (Clarke et al., 2000).

**Comparisons with previous work**

With the exception of decreased Na$_2$O content, the garnet reaction zones in the Pembroke Granulite have the
same bulk geochemistry as the host gabbroic gneiss. In this section, we combine our representative geochemical data with data published by Blattner (1976), Oliver (1977) and Bradshaw (1989c), for the purpose of comparing the garnet reaction zones in the Pembroke Granulite (Blattner, 1976; this study) with those studied in the Western Fiordland Orthogneiss (Oliver, 1977; Bradshaw, 1989c). Garnet reaction zones described from the Western Fiordland Orthogneiss are similar to those described above for the gabbroic gneiss in the Pembroke Valley. Figure 7 shows compiled data plotted on Peacock and aluminium saturation index (ASI) diagrams, after Brown (1982) and Zen (1986) respectively. A consistent calc-alkalic trend can be observed for the combined data set. Tie lines drawn between all paired host rock and garnet reaction zone points indicate that the garnet reaction zones are slightly less metaluminous (ASI 0.90-0.95) compared to the adjacent host rocks (ASI 0.75-0.80). The anorthositic veins straddle the boundary between the peraluminous and metaluminous classification (ASI 1). The systematic trend is consistent with all the Fiordland garnet reaction zones having formed by a similar process.

QUANTITATIVE CATION MAPPING

In this section we aim to examine in detail the interplay between host rock and garnet reaction zone in the gabbroic gneiss using quantitative cation maps. The determination of the number of cations of Si, Al, Fe, Mn, Mg, Ca, Na and K for 24 oxygens was completed by first collecting raw intensity X-ray maps using a Cameca SX50 microprobe at the University of New South Wales with an accelerating voltage of 15 kV and a beam width of 1-3 µm. We collected a 3.5 cm by 2.5 mm map that traversed the anorthositic vein / garnet reaction zone boundary and the garnet reaction zone / host gabbroic gneiss boundary in gabbroic gneiss sample 9814. This map was collected with a 70 ms count time at each point and a 10 µm step size between points. The raw intensity maps were converted to maps of oxide weight percent by using the α-factor approach of Bence & Albee (1968) for matrix correction (G.L. Clarke & N.R. Daczko, unpublished data). The matrix-corrected data were then recalculated for 24 oxygens to give cation proportions. Appropriate threshold values of cation proportions were then be used to calculate mineral modes.

The cation map was analysed to determine modes across the transition from two-pyroxene hornblende granulite to garnet-clinopyroxene granulite. The map was initially divided into garnet reaction zone and host gabbroic gneiss. Table 4 presents the modes determined for this analysis. Minor minerals, such as kyanite (less than 1 vol.%) and apatite (less than 2 vol.%), occur in approximately the same proportions in the garnet reaction zone as in the host gabbroic gneiss. Other minerals present in small proportions, such as quartz and clinozoisite are rare in the host gabbroic gneiss and increase to greater than 1 vol.% in the garnet reaction zone. The plagioclase mode decreases from 56 vol.% in the host gabbroic gneiss to 51 vol.% in the garnet reaction zone. Related to this is an increase in the total mode of the main mafic minerals (garnet, clinopyroxene and hornblende) from 42 vol.% in the host gabbroic gneiss to 51 vol.% in the garnet reaction zone. The plagioclase mode decreases from 56 vol.% in the host gabbroic gneiss to 51 vol.% in the garnet reaction zone. The plagioclase mode decreases from 56 vol.% in the host gabbroic gneiss to 51 vol.% in the garnet reaction zone. Related to this is an increase in the total mode of the main mafic minerals (garnet, clinopyroxene and hornblende) from 42 vol.% in the host gabbroic gneiss to 45 vol.% in the garnet reaction zone. The 12 vol.% hornblende mode in the garnet reaction zone represents the incomplete replacement of S̃ hornblende at the margins of the garnet reaction zone.

In order to examine the garnet reaction zone / host gabbroic gneiss boundary, the cation map was divided into many smaller equally sized areas and analysed to determine if there was any systematic change in modes across the garnet reaction zone / host gabbroic gneiss boundary. The change in plagioclase mode be-

<table>
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<th>Kyanite</th>
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<th>Vein</th>
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<tr>
<td>0.9</td>
<td>0.7</td>
<td>0.2</td>
<td></td>
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<tr>
<td>Quartz</td>
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<tr>
<td>Clinozoisite</td>
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<td>2.8</td>
</tr>
<tr>
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<td>26.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Clinopyroxene</td>
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</tr>
<tr>
<td>Amphibole</td>
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<td>100</td>
</tr>
<tr>
<td>% clinopyroxene in mafic component</td>
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<td>14.4</td>
<td>0</td>
</tr>
<tr>
<td>% amphibole in mafic component</td>
<td>95.5</td>
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</table>

Table 4. Modes of gabbroic gneiss sample 9814, determined by image analysis of cation maps.
tween the two areas is approximately 4 vol.%. This change was too small to examine graphically across the two zones, and so we could not determine whether the mode of plagioclase was depleted most near the garnet reaction zone / host gabbroic gneiss boundary or near the garnet reaction zone / anorthositic vein boundary. However, the modes of minerals such as quartz, garnet, clinopyroxene and hornblende show systematic trends across the transition.

Figures 8a-d shows plots of modes for quartz, garnet, clinopyroxene, and hornblende. Quartz and garnet are only found in the garnet reaction zone and the mode of each increases toward the garnet reaction zone / anorthositic vein boundary (Fig. 8a,b). Clinopyroxene is found as part of the S1 assemblage in the host gabbroic gneiss and as part of the garnet-clinopyroxene granulite assemblage in the garnet reaction zone. For the areas analysed, S1 clinopyroxene is less than 1 vol.% in the host gabbroic gneiss, whereas clinopyroxene becomes more than 6 vol.% in the garnet reaction zone. Figure 8c shows that this change is proportional to distance from the garnet reaction zone / host gabbroic gneiss boundary and increases away from it. The hornblende mode shows an antithetic trend to those of quartz, garnet and clinopyroxene (Fig. 8d). Figure 8e-g shows plots of the percentages of garnet, clinopyroxene and hornblende in the mafic component of the rock, which consists of approximately 65-70 vol.% garnet, 10-25 vol.% clinopyroxene and less than 20 vol.% hornblende. In the host gabbroic gneiss the mafic component is over 95 vol.% hornblende for sample 9814.

DISCUSSION

Garnet-clinopyroxene-rutile-bearing assemblages adjacent to D2 fractures and anorthositic veins cut S1 two-pyroxene hornblende assemblages in gabbroic gneiss of the Pembroke Granulite (Fig. 1). The formation of garnet granulite in gabbroic gneiss was related to an increase in pressure from conditions of $P < 8$ kbar for $T = 750 \, ^\circ\, C$ at the time of S1 development to $P \approx 14$ kbar for $T = 750 \, ^\circ\, C$ when the garnet reaction zones formed (Clarke et al., 2000). In the gabbroic gneiss, there is no consistent relationship between anorthositic vein thickness and the width of the associated garnet reaction zone, and the transformation to garnet reaction zone was largely isochemical. These observations are consistent with the anorthositic vein material having not been derived from garnet reaction zones in the gabbroic gneiss (c.f. Oliver, 1977; Blattner & Black, 1980). Some D2 fractures, anorthositic veins and garnet reaction zones cut older D2 fractures, anorthositic veins and garnet reaction zones. This observation precludes interpretations involving the localisation of the garnet reaction zones and melt migration along a pre-existing fracture network (cf. Blattner, 1976; Oliver, 1977; Bradshaw, 1989c). The processes of rock fracturing, veining and garnet granulite formation were synchronous and repetitive in the gabbroic gneiss. The lattice pattern of D2 fracturing and veining indicates that brittle deformation accompanied the formation of the garnet reaction zones, when this belt of patchily recrystallized granulite was at crustal depths of approximately 45 km.

In the dioritic gneiss, post-S1 leucosomes that enclose idioblastic garnet and garnet trains indicate that this rock was partially molten. We infer that garnet was
a peritectic product of a melt-producing reaction controlled by hornblende breakdown. Similar textures involving isolated patches of garnet-bearing leucosomes have been described from metapelitic granulites at Round Hill near Broken Hill (Powell & Downes, 1990), where limited nucleation of peritectic garnet is inferred to have localised the formation of melt segregations (Powell & Downes, 1990). Garnet-bearing leucosomes in the dioritic gneiss are continuous with garnet reaction zones and anorthositic veins in gabbroic gneiss (Fig. 2d), which is consistent with a causal relationship between the partial melting of the dioritic gneiss and formation of the garnet reaction zones in the gabbroic gneiss. Partial melting reactions commonly have a positive volume change and thus are a potential cause of embrittlement (e.g. Clemens & Mawer, 1992; Petford, 1995). If partial melting is to induce fracturing, the rate of the melt-producing reaction must be greater than the rate at which creep might accommodate the associated volume change (Connolly et al., 1997). Connolly et al. (1997) demonstrated experimentally that reaction-induced microfracturing is a feasible mechanism of permeability enhancement during partial melting on regional metamorphic time scales. Therefore we infer that partial melting of the dioritic gneiss induced fracturing, in the presence of melt, which in turn greatly assisted melt segregation and the transition from distributed anorthositic leucosome to veins or dykes that cut gabbroic gneiss.

We suggest that partial melting in the dioritic gneiss is broadly similar to that determined experimentally for intermediate bulk compositions by Rutter & Wyllie (1988). These compositions undergo dehydration melting at lower temperature conditions than in mafic rocks, such as the gabbroic gneiss, at a given pressure (Rapp, 1995). Therefore we suggest that for a set temperature and pressure, partial melting in one rock may be concurrent with dehydration (involving no melting) in another. Therefore our model involves veining of gabbroic granulite by an orthositic melt at low $a_{\text{H}_2\text{O}}$ and high-$P$. This led to vein-parallel desiccation, which manifests as loss of hornblende and gain of garnet-clinopyroxene, transforming a metastable medium-$P$ ($P < 8$ kbar) granulite into a high-$P$ ($P = 14$ kbar) garnet granulite in gabbroic gneiss.

The transition from two-pyroxene hornblende granulite to garnet-clinopyroxene granulite

The transition from two-pyroxene hornblende granulite to garnet granulite is restricted to garnet reaction zones in the gabbroic gneiss. The development of garnet granulite assemblages involved the dehydration of $S_1$ assemblages adjacent to the $D_1$ fractures and anorthositic veins in the gabbroic gneiss. The replacement of $S_1$ hornblende by garnet and clinopyroxene is most complete adjacent to the garnet reaction zone / anorthositic vein boundary, and gradually decreases away from this boundary. There is a clear physical and chemical link between the anorthositic veins in the gabbroic gneiss and the transition from two-pyroxene hornblende granulite to garnet granulite. Oliver (1977) and Blattner & Black (1980) inferred that the anorthositic veins were sourced from partial melting in the garnet reaction zones. However, the near-isochronal nature of the reaction zones preclude this possibility and partial melting in the dioritic gneiss is a more plausible source for the anorthositic veins. The observation of scapolite in some anorthositic veins led Blattner (1976) and Bradshaw (1989c) to propose that the introduction of $\text{CO}_2$-rich fluids along the $D_1$ fractures and veins promoted the transition to garnet granulite in reaction zones adjacent to fluid pathways. However, garnet reaction zones are absent from the dioritic gneiss, despite anorthosite-filled fractures that localise the garnet reaction zones being continuous across boundaries of gabbroic and dioritic gneiss. As the garnet-bearing leucosomes are continuous across the boundaries and the garnet reaction zones are not, we prefer an interpretation involving the interaction of a low-$H_2O$ melt with the gabbroic gneiss to form the garnet granulite. This interpretation is supported by an exception to the general isochemical pattern for the transition to garnet granulite established above, namely a doubling of Cu content in the garnet reaction zones ($Cu = 19-20$ ppm), compared to the Cu content of the adjacent host gabbroic gneiss ($Cu = 11-12$ ppm). As high trace amounts of Cu occur in the anorthositic veins ($Cu = 25-50$ ppm) and dioritic gneiss ($Cu = 85-95$ ppm), we infer that the additional Cu was introduced into the garnet reaction zones during interaction with anorthositic veins sourced from the comparatively Cu-rich dioritic gneiss. Further work on these textures could involve a study of trace elements in individual minerals to reveal which minerals controlled the sites of trace Cu. Finally, scapolite grains are restricted to the anorthositic vein material and possibly show igneous features. Elements (Cl, $\text{CO}_3$, $\text{SO}_4$, OH) needed for scapolite growth may have come from the breakdown of amphibole in the dehydration melting stage in the dioritic gneiss and in the garnet reaction zone stage in the gabbroic gneiss. This interpretation requires testing by in situ chemical analysis of hornblende and scapolite grains.

The transition from two-pyroxene hornblende granulite to garnet granulite has been studied in the mafic granulites of the Jijal complex of the Kohistan arc...
In this region, elongate patches and bands of garnet granulite transect a two-pyroxene host. Garnet-bearing veins are generally located in the middle of the reaction zones, similar to the Pembroke example. Geochemical studies of the Kohistan rocks indicate that this transformation was also essentially isochemical, but with Na$_2$O contents of the replacement rocks slightly lower than that of the host granulite. Yamamoto & Yoshino (1998) also inferred the loss of K$_2$O in some samples as a consequence of the transition, and concluded that increasing pressure, along with infiltration of H$_2$O-poor and probably CO$_2$-rich fluid, was responsible for the replacement textures. The Kohistan arc example indicates that the vein-related transformation of two-pyroxene hornblende granulite to garnet granulite may be a common process related to the partial melting of lower crustal rocks.

**Fracturing in the lower continental crust**

The granulites that host the garnet reaction zones in the Pembroke Valley experienced elevated temperature conditions at comparatively deep crustal levels. The example described here indicates that partially molten, lower continental crust was able to fracture in a pattern similar to that of dyking in mantle peridotites underlying spreading ridges (e.g. Sleep, 1988). In both the Pembroke example and mantle peridotites, vertical dyking was followed or accompanied by ductile flow. However, the similarity of $P$-$T$ conditions inferred from the garnet reaction zones and $D_3$ mylonites (Clarke et al., 2000; Daczko et al., 2000) indicates that decompression did not induce melting and fracturing, unlike the mechanism controlling melting underneath spreading ridges. The products of incipient, incongruent melting in the dioritic gneiss of the Pembroke granulite are centred on peritectic garnet grains, suggesting that garnet nucleation may have initially been a rate controlling step (Powell & Downes, 1990). Melt in low proportions was able to segregate, possibly into microfractures that have since been annealed. However, progressive melt accumulation around several garnet grains (Fig. 4) possibly involved a positive volume change and this initiated fracturing. The volume change associated with dehydration melting of amphibole ± biotite and clinozoisite is not well understood and requires further investigation. If the partial melting we describe involved a positive volume change, this indicates that density-driven porous flow and filter pressing were not mechanisms controlling melt segregation for the Pembroke example. Instead we infer that dyke tapping (Sleep, 1988) or microfracturing (Connolly et al., 1997) were the principal segregation mechanisms. Once in veins, melt would have migrated laterally into the gabbroic gneiss and almost certainly vertically.

As the water-poor anorthositic melt moved through the fracture system, we infer that it dehydrated the hornblende-rich wall rock of the gabbroic gneiss, activating the patchy and mostly isochemical change from two-pyroxene hornblende granulite to garnet-granulite. Fractures induced by dyke injection are oriented normal to the minimum compressive stress ($\sigma_3$) and parallel to the maximum and intermediate compressive stresses ($\sigma_1$ and $\sigma_2$, respectively), as explained by Moores & Twiss (1995). The steeply-dipping nature and planar angular relationships of the fractures and garnet reaction zones most probably reflect the late Cretaceous deviatoric stress field and indicate the terrain has undergone minimal body rotation (Fig. 9). We have no data to constrain how much melt was produced or how far melt moved vertically. Nonetheless, from the geometry of the veins, the scale of melt migration was probably larger than the observable rock area. The Pembroke example presents strong geological reasons for fracturing of the lower continental crust being a viable mechanism for the generation and initial ascent of felsic melt (Turcotte, 1982; Clemens & Mawer, 1992).

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REFERENCES


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**Appendix 1.** New Zealand grid references for samples discussed in text.

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<th>Sample</th>
<th>Rock Type</th>
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