Kyanite-paragonite-bearing assemblages, northern Fiordland, New Zealand: rapid cooling of the lower crustal root to a Cretaceous magmatic arc

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ABSTRACT

Fiordland, New Zealand exposes the lower crustal root of an Early Cretaceous magmatic arc that now forms one of Earth’s most extensive high-P granulite facies belts. The Arthur River Complex, a dioritic to gabbroic suite in northern Fiordland, is part of the root of the arc, and records an Early Cretaceous history of emplacement, tectonic burial, and high-P granulite facies metamorphism that accompanied partial melting of the crust. Late random intergrowths of kyanite, quartz and plagioclase partially pseudomorph minerals in the earlier high-T assemblages of the Arthur River Complex, indicating high-P cooling of an over thickened crustal root by c. 200 °C. The kyanite intergrowths are themselves partially pseudomorphed by paragonite, commonly in the presence of phengitic white mica. Biotite–plagioclase intergrowths that partially pseudomorph phengitic white mica and diopside–plagioclase intergrowths that partially pseudomorph jadeitic diopside, combined with published thermochronology results, are consistent with later rapid decompression. A short duration anticlockwise P–T path may be explained by the high-P juxtaposition of comparatively cool upper crustal rocks following their tectonic burial and under thrusting during the waning stages of Early Cretaceous orogenesis. This was then followed by the decompression giving the rapid exhumation within 20 Myr of peak metamorphism, as suggested by the isotopic data.

Key words: cooling; high-P granulites; magmatic arc; P–T path; thermobarometry.

INTRODUCTION

Studies of the deepest levels of young magmatic arcs are important for interpreting the evolution of orogenic belts and environments in which new continental crust is generated. These studies are somewhat hindered by the limited exposure of truly lower crustal rocks (e.g. Miller et al., 1993). Plate tectonic models emphasise the importance of large lateral and vertical motions of such arc crust (Whitney et al., 1999), drawing on evidence from changes in metamorphic assemblages (Whitney et al., 1999; Clarke et al., 2000). Rapid increases in metamorphic pressure are mostly ascribed to tectonic thickening and burial during plate convergence (Bradshaw, 1989a; Umhoefer & Miller, 1996). Rapid increases in metamorphic temperature are commonly ascribed to magmatic activity, pronounced cooling to tectonic stabilisation, and the termination of metamorphism is most commonly associated with rapid exhumation (e.g. Monie et al., 1994; Treloar, 1997). We have discovered a range of Cretaceous assemblages in northern Fiordland, New Zealand, that superficially contrast with some of the common tectonic interpretations.

Perhaps the most striking metamorphic feature that has been described in gabbroic rocks from Fiordland involves garnet–clinopyroxene-bearing corona reaction textures that mantle enstatite and hornblende in garnet reaction zones. These reflect c. 25 km of burial of an Early Cretaceous granulite facies terrane (Clarke et al., 2000). Large garnet poikiloblasts that are surrounded by leucosome in dioritic components of the Arthur River Complex reflect high-P crustal anatexis that postdates burial (Daczko et al., 2001b). In this paper, we describe high-P amphibolite facies assemblages involving kyanite, paragonite and phengitic white mica (hereafter referred to as phengite) that partially pseudomorph the granulite facies minerals and reflect rapid high-P cooling of the rocks by c. 200 °C. Biotite–plagioclase-bearing intergrowths that partially pseudomorph phengite, and textures involving the breakdown of jadeitic diopside to diopside-plagioclase intergrowths, developed during decompression (e.g. Franz et al., 1986; Elveold & Gilotti, 2000) that followed the rapid cooling. The high-P amphibolite facies assemblages indicate that the northern Fiordland rocks cooled substantially prior to the onset of extension that led to the unroofing of the root of the arc during the mid-Cretaceous (cf. Gibson et al., 1988; Tulloch & Kimbrough, 1989).
The geology of the south island of New Zealand can be divided into three domains. The Eastern and Western Provinces (Landis & Coombs, 1967; Bishop et al., 1985) are separated by a belt of rocks referred to as the Median Tectonic Zone (Kimbrough et al., 1993, 1994) or Median Batholith (Mortimer et al., 1999). The Western Province contains mostly Lower Palaeozoic paragneiss, cut by Devonian, Carboniferous and Cretaceous granitoids (Muir et al., 1996; Wandres et al., 1998). It includes the Arthur River Complex (Bradshaw, 1990; Figs 1 & 2), 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-type and structure (Clarke et al., 2000). Recent geochronological studies indicate Mesozoic and Palaeozoic ages for orthogneiss units from this belt (Mattinson et al., 1986; Bradshaw, 1990; Tulloch et al., 2000), suggesting it contains both Median Batholith and Western Province components (Tulloch et al., 2000). In Milford Sound, the Arthur River Complex includes dioritic and gabbroic gneisses of the Harrison Gneiss, Pembroke Granulite and Milford Gneiss (Fig. 2; Wood, 1972; Blattner, 1978, 1991; Clarke et al., 2000). The Anita Shear Zone forms the northwestern boundary of the Arthur River Complex; Palaeozoic paragneiss of the Western Province lie north-west of the shear zone (Fig. 2; Hill, 1995a,b; Klepeis et al., 1999). The Late Jurassic to Early Cretaceous (c. 147–137 Ma) Darran Complex, named after the Darran Diorite (Wood, 1972; Bradshaw, 1990; Kimbrough et al., 1994), lies to the east of the Arthur River Complex and forms part of the Median Batholith (Fig. 2). The boundary between these two units has been proposed as a faulted contact (Koons, 1978; Bradshaw, 1990) or as a strain gradient (Blattner, 1991; Clarke et al., 2000). The 126–119 Ma Western Fiordland Orthogneiss intrudes the Arthur River Complex, 19 km southwest of Milford Sound at Mt Daniel (Bradshaw, 1990).

Structural and Metamorphic overview

The Arthur River Complex, exposed in northern Fiordland, contains high-P granulite facies dioritic to gabbroic rocks that experienced at least five deformation events in the Early Cretaceous (Blattner, 1991; Clarke et al., 2000; Daczko et al., 2001a). The following overview of the structural and metamorphic history of the Arthur River Complex is a summary of data presented by Clarke et al. (2000), Daczko et al. (2001a,b). A summary of structural abbreviations is provided in Table 1. The earliest foliation (S1), preserved in the Pembroke Granulite, is defined by two-pyroxene–hornblende-bearing granulite...
Table 1. Summary of structural and metamorphic events referred to in text.

<table>
<thead>
<tr>
<th>Event</th>
<th>Structure</th>
<th>Metamorphism</th>
<th>Reference</th>
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<tbody>
<tr>
<td>D1 – S1</td>
<td>Pervasive S1-L1 two-pyroxene-hornblende fabric in Pembroke Granulite</td>
<td>&lt; 8 kbar, &gt; 750 °C</td>
<td>Clarke et al. (2000)</td>
</tr>
<tr>
<td>D2 – Grt reaction zones</td>
<td>Partial melting, fracturing, trondhjemite veining and garnet reaction zone development</td>
<td>~ 14 kbar, ~ 750–850 °C</td>
<td>Daczko et al. (2001a)</td>
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<tr>
<td>D3 – S3</td>
<td>Pervasive S3-L3 fabric in narrow steeply dipping mylonites</td>
<td>~ 14 kbar, ~ 700 °C</td>
<td>Daczko et al. (2001a)</td>
</tr>
<tr>
<td>D4 – S4</td>
<td>Thrust faults in Pembroke Granulite, Pervasive S4-L4 steeply dipping fabric in Milford Gneiss</td>
<td>&gt; 12 kbar, ~ 600–700 °C</td>
<td>Daczko et al. (2002a)</td>
</tr>
<tr>
<td>Ky-Pg-Phg assemblages</td>
<td>Random in Pembroke Granulite</td>
<td>~ 11–13 kbar, ~ 600–700 °C</td>
<td>This study</td>
</tr>
<tr>
<td>Phg Breakdown</td>
<td>Pervasive shallowly dipping fabric (dextral transpression) in Anita Shear Zone</td>
<td>&lt; 12 kbar?, &lt; 600 °C</td>
<td>This study</td>
</tr>
<tr>
<td>Post-D4 Pegmatites</td>
<td>Pegmatites with garnet-biotite-plagioclase-bearing selvage</td>
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<td>This study</td>
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<td>ASZ2</td>
<td>Pervasive steeply dipping fabric (dextral transpression) in Anita Shear Zone</td>
<td>&gt; 7 kbar, ~ 600 °C</td>
<td>Klepeis et al. (1999)</td>
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facies assemblages. S1 generally strikes east to east-north and displays steep to near-vertical dips to the south and SSE. A weakly developed mineral lineation plunges variably to the east and west. S1 mineral assemblages reflect conditions of < 8 kbar and > 750 °C. S1 is cut by steeply dipping planar fractures (D2) that are commonly filled by trondhjemitic veins. In dioritic gneiss, the veins are linked to large garnet poikiloblasts, commonly surrounded by leucosome. These textures reflect high-P partial melting of dioritic gneiss at T > 750 °C. Gabbroic gneiss, in contact with the diorite gneiss, shows no evidence of partial melting. However, adjacent and parallel to the D2 fractures and veins in gabbroic gneiss, S1 minerals are pseudomorphed by garnet-clinoxyroxene-bearing assemblages in what are referred to as garnet reaction zones (Blattner, 1976; Oliver, 1977; Bradshaw, 1989b). Assemblages in the garnet reaction zones record metamorphic conditions of 12–14 kbar and 750–850 °C. S1 and the garnet reaction zones were deformed by two phases of collisional-style granulite facies deformation at lower crustal conditions. A series of approximately 1 m wide shear zones (D3) formed within a pure-shear-dominated sinistral regime that led to bulk horizontal shortening and NE–SW stretching. D4 thrust faults in the Pembroke Granulite and a north-striking, steeply dipping foliation (S4) in the Milford and Harrison Gneisses cut the D3 shear zones. The development of S4 was accompanied by partial rehydration and appreciable cooling, as temperature conditions evolved from being close to or close to the fluid-undersaturated diorite solidus (D2) to those that enabled retrograde white mica growth (Daczko et al., 2001b). Hydrous fluid ingress at peak conditions would have initiated appreciable partial melting in all rocks (e.g. Johannes & Holtz, 1991). Throughout Milford Sound, S4 shows variable mineral assemblages in rocks of similar composition, reflecting D4 deformation over a wide range of conditions, or rehydration over some period of time during cooling and hydration; or (ii) S4 experienced reactivation following cooling and hydration. Fabrics of the Anita Shear Zone that are related to exhumation of the high-P rocks cut S4 further west (Klepeis et al., 1999).

Table 2. Geochronological data.

<table>
<thead>
<tr>
<th>Site</th>
<th>Easting</th>
<th>Northing</th>
<th>Dated material</th>
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<th>Dating Method</th>
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<td>2.0</td>
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<td>K-Ar</td>
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<td>2.0</td>
<td>Gaur (2000)</td>
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<td>K-Ar</td>
<td>120</td>
<td>2.0</td>
<td>Gaur (2000)</td>
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</table>
Geochronological overview

U–Pb zircon ion probe analyses distinguish three age populations for a single sample of the Arthur River Complex: (1) large Palaeozoic oscillatory zoned cores yield an age of 355 ± 10 Ma; (2) large Early Cretaceous cores with sector zoning yield an age of 134 ± 2 Ma; and (3) low-U zircon rims (on both Palaeozoic and Cretaceous cores) with an average age of 120 Ma (Tulloch et al., 2000). The data allow for a Palaeozoic or Early Cretaceous protolith for the Arthur River Complex orthogneisses. The metamorphic rims on zircon grains suggest that peak metamorphism occurred at c. 120 Ma. These data compare well with timing constraints made on the basis of fabric development that suggest that all fabrics in the Arthur River Complex post-date emplacement of the Western Fiordland Orthogneiss at 126–119 Ma (Clarke et al., 2000). The peak metamorphism in the Arthur River Complex coincides with the final stages of Western Fiordland Orthogneiss emplacement.

K–Ar isotopic dating of hornblende grains from the Pembroke Granulite yield ages of c. 138 Ma (Table 2; Nathan et al., 2000). K–Ar ages for hornblende grains from the Milford and Harrison Gneisses give ages of c. 111–90 Ma (Table 2, Nathan et al., 2000), consistent with rapid cooling of the Arthur River Complex by c. 90 Ma. Therefore, the Arthur River Complex shows a similar geochronological history to the Western Fiordland Orthogneiss, which was emplaced between 126 and 119 Ma, buried and metamorphosed at high-P granulite facies conditions, and, on the basis of U–Pb apatite dates, had cooled to < 300–400 °C by c. 90 Ma (Table 2, Mattinson et al., 1986).

PETROLOGY

In this section, we describe the petrology of the textures inferred to represent former sites of partial melting, textures involving kyanite-paragonite-phengite-bearing assemblages, and textures involving the breakdown of jadeitic diopside that are useful for estimating the postpeak metamorphic P–T path for the Arthur River Complex. Petrographic observations were supplemented with maps of oxide weight percent obtained by applying matrix corrections to raw intensity X-ray maps. All microprobe data were collected on a Cameca SX50 microprobe at the University of New South Wales. Eight X-ray intensity maps were collected in two sessions using four wavelength dispersive spectrometers, with an accelerating voltage of 15 kV, a beam current of 20 nA and a beam width of 1–3 µm. The element maps were collected with a 300-ms count time at each point and a 4-µm step size between points. The raw intensity maps were converted to maps of oxide weight percent by using the x-factor approach of Bence & Albee (1968) for matrix correction (Clarke et al., 2001).

Partial melting textures

Samples of dioritic gneiss from the Pembroke Granulite (e.g. 9802, 9805 and 9831X) have large garnet poikiloblasts (up to 25 mm across) surrounded by leucosome that cuts S1. The garnet poikiloblasts and leucosomes are interpreted by Daczko et al. (2001b) to represent sites of partial melting in the dioritic gneiss at T > 750 °C. Textures within the leucosomes (sample 9805; Fig. 3) are consistent with the interpretation that the dioritic gneiss partially melted, using the microstructural criteria of Sawyer, 1999). Figure 3 shows maps of silica and calcium oxide weight percent for sample 9805. The figure shows part of a large garnet poikiloblast on the left, surrounded by leucosome in the centre of the figure, with partially melted dioritic gneiss on the right. The large garnet poikiloblasts mostly contain inclusions of quartz, with or without minor hornblende, clinozoisite, rutile and apatite. The leucosome consists of plagioclase and quartz and contains rounded grains of clinozoisite and hornblende. Quartz commonly shows quadrangular shapes with concave sides (arrow 1, Fig. 3). 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 (arrow 2, Fig. 3). The films of plagioclase (arrow 2 in the CaO map in Fig. 3) are commonly zoned, up to 50 µm across, and are more calcic than the rest of the plagioclase in the leucosome (see later).

Kyanite and paragonite (± phengite) bearing textures

Dioritic gneiss samples 9802, 9805 (outside the area shown in Fig. 3) and 9831X have intergrowths of kyanite, quartz and plagioclase that cut S1 and postdate formation of the leucosomes. The kyanite-bearing intergrowths (up to 3 mm across) are random in orientation and display irregular grain shape with cuspatc boundaries. Figure 4 shows maps of Si, Al, Ca and Na oxide weight percent for a kyanite-bearing intergrowth in sample 9831X. Kyanite is generally found armoured by plagioclase and separated from the rest of the rock by areas of quartz (Fig. 4). The kyanite-bearing intergrowths may contain inclusions of hornblende (arrow 1, Fig. 4), clinozoisite, rutile and apatite. In thin section, the intergrowths of kyanite, quartz and plagioclase display curved and irregular grain boundaries with S1 plagioclase and hornblende (Fig. 5a). Many kyanite-bearing intergrowths contain hornblende inclusions suggesting that coarsely-grained S1 plagioclase was replaced by the intergrowths before S1 hornblende (Fig. 5b), suggesting:

\[ \text{plagioclase}_1 = \text{kyanite} + \text{quartz} (+ \text{minor plagioclase}_2) \]  

A second interpretation of the kyanite-bearing textures is that they represent relics of kyanite crystals partially replaced by plagioclase.
concurrent with partial replacement of hornblende at the contact with former kyanite. We prefer the interpretation that kyanite is intergrown with the plagioclase and quartz and that the intergrowths are late and cut S1 and the leucosomes for the following reasons. The kyanite-bearing intergrowths occur in intensely foliated rock, but are random in orientation, consistent with post-S1 formation. The intergrowths have very irregular boundaries, inconsistent with any shape that could be expected for a relict kyanite grain. The intergrowths entrain rounded grains of plagioclase and hornblende, consistent with the interpretation that they are partially pseudo-

**Fig. 4.** Matrix corrected maps of oxide weight percent for SiO2, Al2O3, CaO and Na2O of a kyanite, quartz and plagioclase intergrowth in sample 9831X. The maps cover an area approximately 1000 × 1500 µm. Grey scale is black for minimum elemental concentration and white for maximum elemental concentration. Minimum and maximum ranges: SiO2 is 0–100 wt.%, Al2O3 is 0–63 wt.%, CaO is 0–28 wt.%, Na2O is 0–13 wt.%. The white mineral is kyanite. The brightest mineral on the Na2O map is plagioclase. Arrow labelled with ‘l’ points to a hornblende inclusion within the intergrowth.

**Fig. 5.** (a) Photomicrograph of intergrowths of kyanite, quartz and plagioclase after S1 plagioclase and hornblende in sample PV1. Field of view 2.8 mm. (b) Photomicrograph of paragonite (+ phengite) grains that replace the kyanite-bearing intergrowths in sample 9802. Field of view 2.8 mm. (c) Photomicrograph of paragonite and phengite replacing the rim of a garnet grain in sample PK12B. Field of view 2.8 mm. (d) Photomicrograph of garnet and phengite in the selvage adjacent to a post-D4 pegmatite (sample PK7B). Field of view 2.8 mm. (e) Photomicrograph of biotite partially pseudomorphing phengite adjacent to garnet in sample 9831X. Field of view 1.4 mm. (f) Photomicrograph of biotite and plagioclase after phengite adjacent to hornblende in sample 9831X. Field of view 1.4 mm.
phengite replacement of a phengite grain is almost complete, biotite is garnet or hornblende (Fig. 5e,f). In textures where the pseudomorph is in contact with a ferro-magnesian mineral such as with or without plagioclase, in samples of both the Pembroke accompanined the emplacement of the pegmatite to be estimated. that it allows the metamorphic conditions that followed D4 and with plagioclase and quartz (Fig. 5d). This assemblage is useful in pegmatite. The selvages mostly contain garnet, biotite and phengite that penetrate the host rock for approximately 5 mm around the S4 is cut by muscovite-bearing pegmatites with metasomatic selvages that penetrate the host rock for approximately 5 mm around the pegmatite. The selvages mostly contain garnet, biotite and phengite with plagioclase and quartz (Fig. 5d). This assemblage is useful in that it allows the metamorphic conditions that followed D4 and accompanied the emplacement of the pegmatite to be estimated.

The rims of some S4 phengite grains are pseudomorphed by biotite with or without plagioclase, in samples of both the Pembroke Granulate and Milford Gneiss. This texture is most common where the phengite is in contact with a ferro-magnesian mineral such as garnet or hornblende (Fig. 5e,f). In textures where the pseudomorphic replacement of a phengite grain is almost complete, biotite is observed with plagioclase and minor quartz and potassium feldspar (Fig. 5). Biotite in the texture is best developed along grain boundaries where phengite is inferred to have been in contact with hornblende. Biotite is least developed where phengite is inferred to have been in contact with coarse-grained plagioclase and clinozoisite. Post-S4 plagioclase in these textures is commonly observed to separate phengite and biotite (Fig. 5e,f). Figure 6 shows maps of silica, magnesium, calcium and sodium oxide weight percent for the texture shown in Fig. 5(f). The figure shows that quartz is a minor product (arrow 1, Fig. 6) and that the anorthite content of the post-S4 plagioclase is higher than that of S4 plagioclase (see later). This suggests that the breakdown of phengite in the presence of hornblende or garnet produced excess Ca that was taken up in the post-S4 plagioclase intergrown with the biotite, suggesting the reaction:

\[ \text{phengite} + \text{hornblende (or garnet)} = \text{biotite} + \text{plagioclase} \]

(+ minor quartz, K-feldspar)

(2)

Sample ARCSC is a garnet-clinoptyroxene mafic hornfels from the Arthur River Complex at Mt Daniel (Fig. 1). The Arthur River Complex is intruded by the Western Fiordland Orthogneiss batholith at Mt Daniel and sample ARCSC is located in the contact aureole of the batholith (Daczko et al., in press). The sample contains textures important to the postpeak, P–T path, rare amongst the garnet-clinoptyroxene hornfels in that area as it contains coarse-grained plagioclase with the peak assemblage of garnet, jadeitic diopside, hornblende, quartz and rutile. This assemblage is used below to infer peak metamorphic conditions for this area of the Arthur River Complex. Figure 7 shows maps of silica, aluminium, calcium and sodium oxide weight percent for sample ARCSC. The maps show coarse-grained garnet, jadeitic diopside, plagioclase and quartz. The rims of the jadeitic diopside have been replaced by fine-grained intergrowths of diopside and plagioclase (arrow 1, Fig. 7), suggesting the reaction:

\[ \text{jadeitic diopside} = \text{diopside} + \text{plagioclase} \]

(3)
MINERAL CHEMISTRY

Mineral chemistries of the textures described above are used to estimate metamorphic conditions that accompanied the development of the textures. Representative electron microprobe analyses of minerals used in P–T calculations are presented in Table 3. Data were collected on a Cameca SX50 electron microprobe at the University of New South Wales with an accelerating voltage of 15 kV, a beam current of 20 nA and a beam width of 1–3 μm.

There are four textural varieties of garnet in samples of the Arthur River Complex discussed in this paper: (i) large garnet poikiloblasts from former sites of partial melting (Fig. 3); (ii) garnet within S4 (Fig. 5c,e); (iii) garnet in metasomatic selvages associated with post-D4 pegmatites (Fig. 5d); and (iv) in the garnet-clinopyroxene hornfels from the Western Fiordland Orthogneiss contact aureole at Mt Daniel (Fig. 7). No two textural varieties are found in the same sample. Large garnet poikiloblasts from sites of former partial melting in dioritic gneiss of the Pembroke Granulite (samples 9802, 9805 & 9831X) are unzoned pyrope-and grossular-rich almandine with Alm$_{56}$Sps$_{2}$Py$_{25}$Gr$_{17}$ where Alm = 100Fe/(Fe + Mg + Mn + Ca), Sps = 100Mn/(Fe + Mg + Mn + Ca), Py = 100Mg/(Fe + Mg + Mn + Ca) and Gr = 100Ca/(Fe + Mg + Mn + Ca). S4 garnet has a variable composition in the range Alm$_{53}$–70Sps$_{50}$–Py$_{14}$–27Gr$_{15}$–26$. This variability most probably reflects minor variability in whole rock compositions across the dioritic to gabbroic suite of the Arthur River Complex. Individual garnet grains within S4 are most commonly unzoned. However, garnet in sample PK5 is unusual and shows bell-shaped zoning profiles with a core composition of Alm$_{53}$Sps$_{5}$Py$_{13}$Gr$_{25}$ and a rim composition of Alm$_{58}$Sps$_{7}$Py$_{19}$Gr$_{19}$. Garnet in the metasomatic selvage adjacent to the post-D4 pegmatite has a variable composition in the range Alm$_{59}$–61Sps$_{8}$–11Py$_{14}$–27Gr$_{15}$–24$. Garnet in the garnet-clinopyroxene hornfels at Mt Daniel is unzoned pyrope- and grossular-rich almandine with Alm$_{43}$Sps$_{1}$Py$_{25}$Gr$_{30}$. Garnet microprobe analyses from all dioritic and gabbroic samples plot in a similar region on a ternary diagram (Fig. 8a). The overall trend on Fig. 8(a) implies exchange vectors involving Ca ↔ Mg or (Fe, Ca) ↔ 2 Mg in garnet.

There are seven textural varieties of plagioclase in samples of the Arthur River Complex discussed in this paper: (i) plagioclase within leucosome from sites of former partial melting (Fig. 3 middle); (ii) plagioclase in dioritic gneiss that hosts sites of former partial melting (outside leucosome, Fig. 3 far right); (iii) plagioclase associated with kyanite intergrowths (Figs 4, 5a,b); (iv) plagioclase within S4 (Figs 5c,f & 6); (v) plagioclase intergrown with biotite at sites of former phengite breakdown (Figs 4, 5a,b); (vi) coarse-grained plagioclase from the garnet-clinopyroxene hornfels at Mt Daniel (Fig. 7); and (vii) fine-grained plagioclase intergrown with diopside at former sites of jadeitic diopside breakdown at Mt Daniel (Fig. 7). Plagioclase within leucosome from sites of former partial melting is oligoclase to andesine with...
Table 3. Representative microprobe analyses (wt% oxide and cation data).

<table>
<thead>
<tr>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Cr₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>MgO</th>
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<th>FeO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>Total</th>
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<tr>
<td>38.5</td>
<td>42.3</td>
<td>26.6</td>
<td>0.0</td>
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<td>1.1</td>
<td>1.1</td>
<td>6.3</td>
<td>3.0</td>
<td>1.7</td>
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</tr>
<tr>
<td>38.4</td>
<td>41.6</td>
<td>27.2</td>
<td>0.0</td>
<td>0.0</td>
<td>1.3</td>
<td>1.3</td>
<td>1.0</td>
<td>5.3</td>
<td>6.7</td>
<td>1.7</td>
<td>2.0</td>
<td>3.0</td>
<td>0.0</td>
<td>0.1</td>
<td>100.4</td>
</tr>
<tr>
<td>38.3</td>
<td>42.2</td>
<td>27.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>5.3</td>
<td>6.7</td>
<td>1.7</td>
<td>2.0</td>
<td>3.0</td>
<td>0.0</td>
<td>0.1</td>
<td>100.2</td>
</tr>
<tr>
<td>38.3</td>
<td>42.5</td>
<td>27.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
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<td>1.7</td>
<td>2.0</td>
<td>3.0</td>
<td>0.0</td>
<td>0.1</td>
<td>100.3</td>
</tr>
</tbody>
</table>

Fig. 8. Representative compositions from the assemblages discussed in the text for (a) garnet (b) white mica and (c) hornblende.
shown in Fig. 5a, b). The garnet shows no embayments and is assumed to be in equilibrium with the kyanite intergrowths. Compositions of adjacent grains (Table 4) give pressure estimates of \( P = 12.2 \) kbar for an estimated \( T = 650 \) °C (after Newton & Haselton, 1981). In sample 9802, garnet is also in grain contact with hornblende, plagioclase and quartz. The assemblage garnet, hornblende, plagioclase and quartz yield pressure estimates of 11.7 kbar for an estimated \( T = 650 \) °C (after Kohn & Spear, 1990). \( P-T \) conditions may also be estimated using the average pressure-temperature approach of THERMOCALC (Powell & Holland, 1988), with the internally consistent thermodynamic data set of Holland & Powell (1990; data file created April 1996). All mineral end-member activities were calculated using the computer program AX (Holland, 1993) and the defaults suggested in Powell & Holland (1988). All results quoted from THERMOCALC below show 2σ errors. Using the average \( P \) approach of THERMOCALC, the assemblage garnet, hornblende, clinozoisite, plagioclase, kyanite and quartz in samples 9802 and 9831X (which contains identical textures to those described for 9802) give 13.3 ± 2.2 kbar and 12.9 ± 1.6 kbar, respectively, which are within error of the directly calibrated barometric results (Table 4).

Using the average \( P \) approach of THERMOCALC, the same assemblage in samples 9802 and 9831X give 677 ± 64 °C and 653 ± 46 °C, respectively (Table 4).

Gabbroic gneiss (sample 9828) from the Pembroke Granulite also contains paragonite-bearing assemblages. The compositions of adjacent grains of garnet, hornblende, plagioclase and quartz in sample 9828 give pressure estimates of 11.1 kbar for an estimated \( T = 650 \) °C (after Kohn & Spear, 1990). The same sample and assemblage give temperature estimates of 703 °C for an estimated \( P = 12 \) kbar (after Graham & Powell, 1984). Using the average \( P \) and average \( T \) approach of THERMOCALC, the assemblage garnet, hornblende, clinozoisite, plagioclase, paragonite and quartz in sample 9828 gives 13.1 ± 1.4 kbar and 687 ± 34 °C, which are within error of the directly calibrated thermobarometric results (Table 4).

Milford Gneiss samples PK4 and PK5 contain well-developed phengite and paragonite-bearing S4 mineral assemblages. All minerals used in thermobarometric calculations were in grain contact and show no reaction between grains. The compositions of adjacent grains of S4 garnet, hornblende, plagioclase and quartz in sample PK5 give pressure estimates of 11.4 kbar for an estimated 650 °C (after Kohn & Spear, 1990). The same sample and assemblage gives temperature estimates of 736 °C for an estimated \( P = 12 \) kbar (after Graham & Powell, 1984). Using the average \( P \) and average \( T \) approach of THERMOCALC, the assemblage garnet, hornblende, clinozoisite, plagioclase, paragonite and quartz in sample PK5 gives 13.2 ± 1.7 kbar and 694 ± 42 °C, which are within error of the directly calibrated thermobarometric results (Table 4).

For Milford Gneiss sample PK4, the compositions of adjacent grains of garnet, hornblende, plagioclase and quartz give pressure estimates of 10.9 kbar for an estimated 650 °C (after Kohn & Spear, 1990). The same sample and assemblage gives temperature estimates of 704 °C for an estimated 12 kbar (after Graham & Powell, 1984). Using the average \( P \) and average \( T \) approach of THERMOCALC, the assemblage garnet, hornblende, clinozoisite, plagioclase, phengite and quartz in sample PK4 gives 11.9 ± 1.8 kbar and 629 ± 56 °C, which is a slightly lower temperature estimate than that obtained from the directly calibrated thermometry (Table 4).

For the selvage around the post-D4 pegmatite (sample PK7B, Fig. 5d), the compositions of adjacent grains of garnet and biotite give temperature estimates of 605 °C for an estimated \( P = 9 \) kbar (after Perchuk & Lavrent’eva, 1983). Using the average \( P \) and average

### Table 4. \( P-T \) estimates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location Milford 1 : 50 000 metric grid</th>
<th>Assemblage</th>
<th>Timing</th>
<th>Assumed ( P ) (kbar)</th>
<th>( T ) (°C)</th>
<th>Calculated result</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>9802</td>
<td>Pembroke Ck 21044 56120</td>
<td>Grt-Hbl-Czo-Pl-Qtz-Ky</td>
<td>Cooling</td>
<td>12</td>
<td>650</td>
<td>11.7, 12.2</td>
<td>3</td>
</tr>
<tr>
<td>9831X</td>
<td>Pembroke Ck 21044 56121</td>
<td>Grt-Hbl-Czo-Pl-Qtz-Ky</td>
<td>Cooling</td>
<td>12.9</td>
<td>653</td>
<td>653 ± 46</td>
<td>12.9 ± 1.6</td>
</tr>
<tr>
<td>PK5</td>
<td>Lake Pukutahi 21086 56164</td>
<td>Grt-Hbl-Pg-Pl-Czo-Qtz</td>
<td>Post S4</td>
<td>12</td>
<td>650</td>
<td>704</td>
<td>12.9 ± 1.6</td>
</tr>
<tr>
<td>PK4</td>
<td>Lake Pukutahi 21082 56167</td>
<td>Grt-Hbl-Phengite-Pl-Czo-Qtz</td>
<td>S4</td>
<td>12</td>
<td>650</td>
<td>704</td>
<td>12.9 ± 1.6</td>
</tr>
<tr>
<td>PK7B</td>
<td>Lake Pukutahi 21071 56163</td>
<td>Grt-Bt-Phengite-Pl-Qtz</td>
<td>Post S4</td>
<td>12</td>
<td>650</td>
<td>704</td>
<td>12.9 ± 1.6</td>
</tr>
<tr>
<td>ARC5C</td>
<td>Mt Daniel 20083 56130</td>
<td>Grt-Cpx-Hbl-Pl-Qtz</td>
<td>Post S4?</td>
<td>12</td>
<td>650</td>
<td>704</td>
<td>12.9 ± 1.6</td>
</tr>
</tbody>
</table>

**Methods:**
Using the average approach of THERMOCALC, the assemblage garnet, biotite, plagioclase, amphibole and quartz in sample PK7B gives $P = 8.8 \pm 1.5$ kbar and $T = 677 \pm 52$ °C, which is slightly higher temperature than the directly calibrated thermometry results (Table 4).

Sample ARC5C from the contact aureole of the Western Fiordland Orthogneiss at Mt Daniel contains the peak assemblage garnet, jadeitic diopside, hornblende, plagioclase and quartz (Fig. 7). Core analyses of coarse-grained unzoned minerals were used in the thermobarometric calculations. The compositions of adjacent grains of garnet, jadeitic diopside, plagioclase and quartz give pressure estimates of 14.9 kbar for an estimated $T = 800$ °C (after Newton & Perkins, 1982). The same sample and assemblage gives temperature estimates of 855 °C for an estimated $P = 14$ kbar (after Ellis & Green, 1979). If a correction is made for Fe$^{3+}$ in clinopyroxene, then the temperature estimates drop to 667 °C (Table 4). The compositions of adjacent grains of garnet, hornblende, plagioclase and quartz give pressure estimates of 14.7 kbar for an estimated $T = 800$ °C (after Kohn & Spear, 1990). The same sample and assemblage gives temperature estimates of 869 °C for an estimated $P = 14$ kbar (after Graham & Powell, 1984). Using the average $P$ and average $T$ approach of THERMOCALC, the assemblage garnet, jadeitic diopside, hornblende, plagioclase and quartz in sample ARC5C gives 14.4 ± 1.9 kbar and 688 ± 48 °C, which is a slightly lower temperature estimate than that obtained from the directly calibrated thermometry (Table 4).

**P–T and T–M$_{H_2O}$ pseudosections**

The thermobarometric results indicate that the kyanite, paragonite and phengite-bearing assemblages evolved in the deep crust ($P = 11–13$ kbar) at temperatures of c. 600–700 °C. The petrological analysis of the paragonite and phengite-bearing assemblages presented above suggests that water played a vital role in the development of the white mica-bearing assemblages. However, the available thermobarometric techniques give no information with respect to the proportion of the component, H$_2$O, in the bulk composition. We define a bulk rock with 0 wt % H$_2$O and 100 wt % (CaO + Na$_2$O + FeO + MgO + Al$_2$O$_3$) as $M_{H_2O} = 0$ and a bulk rock with 50 wt % H$_2$O and 50 wt % (CaO + Na$_2$O + FeO + MgO + Al$_2$O$_3$) as $M_{H_2O} = 1$. Therefore, for example, a bulk rock with 20 wt % H$_2$O has $M_{H_2O} = 0.4$ by definition.

Figure 9 represents $P$–$T$ and $T$–$M_{H_2O}$ pseudosections appropriate to the bulk composition of the dioritic gneiss of the Pembroke Granulite. On two-dimensional diagrams such as these, one variable ($P$, $T$ or $M_{H_2O}$) must be held constant. As a starting point, $P$ and $T$ were modelled by holding $M_{H_2O}$ constant at water saturated conditions (Fig. 9a). Although it is unlikely that these rocks were ever water saturated, Fig. 9(a) indicates that kyanite is not stable at the water saturated $P$–$T$ conditions modelled and paragonite is only stable at $P > 8$ kbar and $T < c. 650$ °C. Figure 9(a) also shows: (i) the $P$–$T$ conditions inferred to have accompanied partial melting (pre-D4, dark grey box; Clarke et al., 2000; Daczko et al., 2001b); (ii) thermobarometric results for S4 and paragonite–kyanite-bearing assemblages calculated using THERMOCALC and presented above (error ellipses shaded light grey); and (iii) thermobarometric results for assemblages in the Anita Shear Zone (Klepeis et al., 1999) that cut S4 (error ellipse shaded medium grey). The effect of cooling at H$_2$O-undersaturated conditions can be illustrated on a 2D diagram by fixing pressure. On the basis of the thermobarometric constraints presented in Fig. 9(a) and those outlined above for the kyanite and paragonite textures, the $T$–$M_{H_2O}$ diagram (Fig. 9b)
is drawn for $P = 12$ kbar and $T = 550–750$ °C (dashed line on Fig. 9a). The modelled rock composition, on a molar basis, varies with water content (Fig. 9b) from CaO = 17.70, Na₂O = 9.10, FeO = 28.90, MgO = 14.55, Al₂O₃ = 29.74, H₂O = 0.00 ($M_{H₂O} = 0$) to CaO = 14.16, Na₂O = 7.28, FeO = 23.12, MgO = 11.64, Al₂O₃ = 23.79, H₂O = 20 ($M_{H₂O} = 0.4$). The pseudosection was also calculated with quartz in excess, and illustrates the mineral evolution with respect to changing temperature and $M_{H₂O}$ as well as the preservation of various mineral assemblages in terms of recrystallization and fluid availability. A horizontal line on the diagram represents the addition or subtraction of H₂O at any given temperature. The indicated H₂O-saturation line is the limiting boundary beyond which any further increase of $M_{H₂O}$ mainly increases the mode of fluid. Figure 9(b) illustrates the dependence of the modelled assemblages on $T$ and $M_{H₂O}$. Garnet (Grt) and hornblende (Hbl) are stable in every field on the diagram and are therefore not labelled in each field but at the top of the figure along with the excess phase quartz (Qtz). Clinopyroxene is stable at $T > 685$ °C and $M_{H₂O} < 0.04$, however, the mode of clinopyroxene is mostly much $< 5\%$, suggesting that it does not play a vital role in the assemblage changes predicted by the model.

Fig. 9. (a) $P–T$ pseudosection for $P = 6–18$ kbar and $T = 550–850$ °C, constructed in the model system CNFMASH (CaO-Na₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O), using THERMOCALC (version 2.75) and the 20 April 1996 internally consistent thermodynamic data set (Powell et al., 1998). The bulk rock composition used to construct the diagram is CaO = 17.70, Na₂O = 9.10, FeO = 28.90, MgO = 14.55, Al₂O₃ = 29.74, quartz and water in excess. Minerals included in the construction of the grid are garnet (Grt), hornblende (Hbl), paragonite (Pg), clinzoisite (Czo), kyanite (Ky), orthopyroxene (Opx), clinopyroxene (Cpx), and plagioclase (Pl). Divariant fields are labelled with three phases; trivariant fields are labelled with two phases and quadrivariant fields are labelled with one phase. Garnet and hornblende are stable across the entire diagram. The dashed line at $P = 12$ kbar is where Fig. 9 (b) projects into the page away from water saturated conditions, along the $M_{H₂O}$ (molar proportion of water) axis. The dark grey box represents metamorphic conditions that accompanied partial melting of these rocks (Clarke et al., 2000; Daczko et al., 2001b); it indicates peak $P–T$ conditions for northern Fiordland. The black dots are thermobarometry results for the S4 and paragonite-kyanite-bearing assemblages presented in Table 4 (THERMOCALC, error ellipses shaded grey). The medium grey error ellipse surrounds data for $P–T$ conditions that accompanied Anita Shear Zone 1 (Klepeis et al., 1999); ASZ1 cuts S4 and provides a lower limit to the $P–T$ conditions and textures modelled in this paper. (b) $T–M_{H₂O}$ pseudosection for $P = 12$ kbar and $T = 550–750$ °C. The bulk rock composition ranges from CaO = 17.70, Na₂O = 9.10, FeO = 28.90, MgO = 14.55, Al₂O₃ = 29.74, H₂O = 0.00 ($M_{H₂O} = 0$) to CaO = 14.16, Na₂O = 7.28, FeO = 23.12, MgO = 11.64, Al₂O₃ = 23.79, H₂O = 20 ($M_{H₂O} = 0.4$). The fluid phase is assumed to be pure H₂O. $M_{H₂O}$ is defined as the molar proportion of the component, H₂O, in the bulk composition (Guiraud et al., 2001). A horizontal line on the diagram represents the addition or subtraction of H₂O at a given temperature. Garnet and hornblende are stable across the entire diagram. (c) Fig. 9(b) contoured for mineral modes.
Changes in mineralogy of the northern Fiordland rocks involved, in summary: (1) the consumption of hornblende, with or without clin zoisite, plagioclase and quartz, during melting; (2) the consumption of plagioclase, with or without hornblende and quartz, to form intergrowths of kyanite, quartz and plagioclase; (3) the consumption of kyanite, plagioclase and garnet to form paragonite and phengite. As the model does not account for the presence of any melt phase, the diagram does not help in understanding the partial melting textures or conditions at which partial melting occurred. However, the position of the melting textures must lie below the water saturation line and at temperatures greater than 750 °C (Daczko et al., 2001b). These partial melting conditions lie above the top of Fig. 9(b), but provide a probable starting position for the inferred $T$–$M_{H_2O}$ path. The modelling suggests that kyanite (Ky) would become stable if the rock cooled below 635 °C at $P = 12$ kbar. The thermobarometry outlined above suggests that the kyanite-bearing textures in samples 9802 and 9831X developed at pressures of approximately 12 kbar and temperatures of 605–740 °C, taking into account the $2 \sigma$ errors on the temperature estimates. The high temperatures indicated by the thermobarometry may reflect a mixed population of grains, involving some that grew during the high-$T$ metamorphic conditions. On the basis of conditions indicated for kyanite-bearing assemblages in the pseudosection, we prefer the lower temperature end of the range of thermometry results.

The development of the phengite-bearing assemblages is not modelled; we have not included K in the model system as phengite would be the only potassic mineral. As phengite occurs with paragonite, it is inferred that it will broadly follow the same trends as paragonite in the model. The introduction of paragonite and phengite as stable phases in the rocks must have involved the addition of $H_2O$ to the rocks and can be represented by a horizontal line on the pseudosection. The small modes of paragonite and phengite in samples 9828, PK4 and PK5 (generally < 10%) are consistent with $T = 575–625$ °C and $M_{H_2O} \approx 0.12$ (Fig. 9). Such conditions involve slightly lower temperatures than the thermobarometry presented above (by < 50 °C).

Critical textural evidence in the rocks involves: (1) plagioclase in leucosomes and S1 plagioclase, with or without hornblende, being partially pseudomorphed by intergrowths of kyanite, quartz and plagioclase; (2) kyanite being cut by paragonite; and (3) paragonite, with or without phengite and hornblende, partially pseudomorphing garnet during hydration related to the development of S4. A $T$–$M_{H_2O}$ path that can account for these features is indicated by an arrow on Fig. 9(b); the terrane would need to cool by at least 100 °C and by up to 200 °C from peak conditions to reach kyanite-bearing fields. The progressive addition of small proportions of water would have taken the rocks through the kyanite-bearing field, into the kyanite-paragonite-bearing field and finally out of the kyanite-bearing fields into a garnet-hornblende-paragonite-plagioclase quadrivariant field. Along such a path, kyanite would have been introduced and then consumed, garnet and plagioclase modes would have decreased by c. 10% each, and hornblende and paragonite modes increased by c. 10% each. The modelling does not take into account Fe$^{3+}$ or Ti contents in any mineral. Fe$^{3+}$ is likely to have had stabilised clin zoisite – it occurs in all samples – but is not stable anywhere in the model system.

DISCUSSION

Paragonite-hornblende-bearing assemblages in mafic rocks are indicators of high- $P$ regional metamorphism (Konzett & Hoinkes, 1996). Hornblende-bearing mafic rocks of the Arthur River Complex in northern Fiordland, New Zealand were buried to depths in excess of 45 km during the Early Cretaceous and experienced temperatures sufficiently elevated to promote incongruent partial melting in dioritic lithologies (Clarke et al., 2000; Daczko et al., 2001b). The simultaneous development of garnet-clinopyroxene....

Fig. 10. (a) Anticlockwise $P$–$T$ path for the Arthur River Complex. Points on the path are compiled from Clarke et al. (2000) for S1 and D2 (grey box), Daczko et al. (2001a) for S3, thermobarometric results in this paper for S4, Klepeis et al. (1999) for Anita Shear Zone 1 and 2 (ASZ1, ASZ2). Shaded ellipses are THERMOCALC error ellipses. The geochronologic constraints are from data presented in Table 2. (b) Tectonic cartoon constructed for c. 110 Ma showing an obliquely convergent arc-continental collisional setting (modified from Daczko et al., 2001a). Eastern and Western Provinces are shown. MB = Median Batholith; ARC = Arthur River Complex; WFO = Western Fiordland Orthogneiss. Note the tectonic burial and under thrusting of the leading edge of the Median Batholith beneath the Arthur River Complex.
reaction zones in gabbroic rocks of the Pembroke Granulite, with the partial melting of dioritic rocks (Daczko et al., 2001b), suggests that temperatures accompanying partial melting were between 750–850 °C (table 2 in Clarke et al., 2000). S1 assemblages and leucosome that encloses peritectic garnet were overgrown by random intergrowths of kyanite, quartz and plagioclase. The mineral chemistry of these assemblages indicate that metamorphic conditions of $P = 11–13$ kbar and $T = 600–700$ °C accompanied the development of the intergrowths. The results of thermobarometry and consideration of $P$—$T$ and $T$—$M_{H_2O}$ modelling at fixed $P = 12$ kbar suggest that the kyanite intergrowths developed in response to cooling of the rocks, at depth, by 100–200 °C with minor change in pressure (Fig. 10a). Paragonite and phengite-bearing assemblages that partially to completely pseudomorph kyanite and garnet, also formed at metamorphic conditions of $P = 11–13$ kbar and $T = 600–700$ °C. The micaceous assemblages represent appreciable hydration of the rocks at some point on their cooling path (e.g. Barnicoat & Fry, 1986). Our $P$—$T$ estimates for the Fiordland rocks are similar to those inferred for paragonite-hornblende-bearing assemblages from the Austroalpine Schneeberg Complex in southern Tyrol, Italy (Konzett & Hoinkes, 1996). They corroborate conclusions reached by Evans (1990) and Konzett & Hoinkes (1996), that paragonite and calcic hornblende assemblages reflect restricted $P$—$T$ conditions within the epidote-amphibolite facies for mafic rocks. The thermobarometric results indicate that the high-$P$ conditions prevailed during cooling of the Fiordland block; rapid exhumation cannot be invoked as the cause of the changes in mineral assemblage, in contrast with models commonly inferred for the cooling of arc rocks. As these large changes in $P$—$T$ occurred in $< 20$ Myr, it is unlikely that thermal relaxation of the deep crust led to the rapid cooling.

As part of the final stage of metamorphism in the rocks described in this study, phengite was partially replaced by biotite and plagioclase, with or without quartz and K-feldspar. The breakdown of phengite and a mafic phase (clinoptyroxene, garnet or hornblende) to form biotite and plagioclase is a reaction commonly ascribed to decompression in many lithologies (Lappin & Smith, 1978; Heinrich, 1982; Franz & Spear, 1983; Gomez-Pugnaire et al., 1985; Franz et al., 1986; Konzett & Hoinkes, 1996; Konopásek, 1998). We infer that rapid decompression followed the high-$P$ amphibolite facies conditions, postdating D4 cooling (Fig. 10a). The breakdown of jadeitic diopside to form diopside and plagioclase in samples from Mt Daniel is also a reaction commonly ascribed to decompression (e.g. Elveold & Gilotti, 2000), matching the phengite breakdown textures. The emplacement of the post-D4 pegmatite at $P \approx 9$ kbar also supports an interpretation of decomposition following D4 cooling.

The Anita Shear Zone cuts S4 at the western boundary of the Arthur River Complex (Klepeis et al., 1999). Structural and metamorphic data presented by Klepeis et al. (1999) suggest that the fabrics of the Anita Shear Zone preserve a record of Cretaceous-Tertiary decompression from $P \approx 12$ kbar and $T \approx 600$ °C (ASZ1 on Fig. 10a) to $P \approx 8.5$ kbar and $T \approx 600$ °C (ASZ2 on Fig. 10a). This decompression is consistent with the phengite breakdown textures presented here, though their timing is uncertain. On the basis of metamorphic conditions estimated for the post-D4 pegmatite, the initial phases of deformation in the Anita Shear Zone (ASZ1) most probably predate the emplacement of the pegmatite. Furthermore, the development of the decomposition textures most likely postdates ASZ1, as ASZ1 evolved at high-$P$ (12 kbar). Finally, reactivation of the Anita Shear Zone (ASZ2) during dextral transpression occurred at mid-crustal levels, suggesting that the post-D4 pegmatites were most probably synchronous with or post dated this phase of deformation. The metamorphic data combine in the simplest way to form an anticlockwise $P$—$T$ path (Fig. 10a). However, we cannot exclude the possibility of heating of the over thickened crust (as would be expected) to produce a small clockwise $P$—$T$ loop at high-$P$ that would then be followed by near isobaric cooling during D4.

U-Pb zircon ion probe analyses distinguish a Cretaceous metamorphic peak with an average age of $c. 120$ Ma in the Arthur River Complex (Tulloch et al., 2000). K-Ar isotopic dating of hornblende gives ages of $c. 111–90$ Ma (Table 2, Nathan et al., 2000). The apatite cooling ages for the Western Fiordland Orthogneiss, in northern Fiordland, also suggest cooling of the terrane to $< 300–400$ °C by $c. 90$ Ma (Table 2, Mattinson et al., 1986). The available geochronological data and metamorphic data presented here suggest that the Arthur River Complex cooled rapidly between $c. 120$ and $c. 90$ Ma. Cooling during rapid exhumation is ruled out, on the basis of the persistence of high-$P$ conditions, at least during the early stages of cooling. We propose the following tectonic scenario that involves juxtaposition of the high-$T$ arc rocks with cold crust of the Median Batholith to account for the rapid cooling:

1. On the basis of U-Pb zircon and apatite ages, and K-Ar hornblende ages, the Darran Complex (major component of Median Batholith in northern Fiordland) was emplaced in the Late Jurassic, at upper crustal conditions ($P < 3$ kbar) and cooled rapidly (Mattinson et al., 1986; Wandres et al., 1998). The Western Fiordland Orthogneiss was emplaced between 126 and 119 Ma, into rocks including the Arthur River Complex, that were at middle to lower crustal conditions ($P < 8$ kbar; Clarke et al., 2000).

2. Early Cretaceous convergence during arc accretion or collision of the Median Batholith with the palaeo-Pacific margin of Gondwana led to the rapid burial of the Arthur River Complex and Western
Fiordland Orthogneiss to \( P \approx 14 \) kbar (Bradshaw, 1989b; Clarke et al., 2000; Daczko et al., 2001a).

(3) Continued convergence resulted in sinistral pure-shear-dominated shear zones (D3) and deep crustal ductile thrust faults (\( P = 14 \) kbar) in the Pembroke Granulite (Daczko et al., 2001a). Strain resulting from convergence was partitioned mostly into the Milford Gneiss, producing a well-developed foliation (S4) that evolved during cooling at the root of the magmatic arc.

(4) Cold upper crustal components of the Median Batholith were tectonically buried and juxtaposed against the Arthur River Complex during the waning stages of Early Cretaceous orogenesis. The juxtaposition of the cold crust with the hot rocks led to rapid cooling of the Arthur River Complex and concurrent heating of the leading edge of the Median Batholith.

Metamorphic textures in the Median Batholith at the margin with the Arthur River Complex at Selwyn Creek involve igneous muscovite rimmed by phengite and paragonite, and garnet poikiloblasts enveloped by leucosome (Dockrill, 2000). These textures are consistent with rapid burial and heating of the leading edge of the Median Batholith during convergence (Dockrill, 2000). Dockrill (2000) presents thermobarometric data that suggests the peak metamorphic conditions attained by parts of the Median Batholith adjacent to the Arthur River Complex (at Selwyn Creek) involved \( T = 560–615 \) °C and \( P = 11–12 \) kbar. The metamorphic textures and thermobarometry presented by Dockrill (2000) are consistent with our model of rapid cooling in the Arthur River Complex in that they represent an equal and opposite temperature path to that presented here for rocks of the Arthur River Complex. Also, phengite in the Median Batholith displays similar textures to that in the Arthur River Complex suggesting that the Selwyn Creek gneisses of the Median Batholith and Arthur River Complex experienced the same decompression history. Our interpretations are consistent with those of Muir et al. (1998), who used geochemical and geochronological data to argue that a Mesozoic magmatic arc, chemically equivalent to the Darran Suite of the Median Batholith, was thrust beneath western Fiordland to depths in excess of 40 km in the Early Cretaceous. This model is also consistent with studies of rocks from elsewhere that conclude that significant parts of the lower crust may be formed from metastably persisting low-\( P \) assemblages such as those observed throughout most of the Median Batholith (Austrheim & Griffin, 1985; Jamveit et al., 1990; Ellis & Maboko, 1992; White & Clarke, 1997).

CONCLUSIONS

The Arthur River Complex in northern Fiordland, New Zealand was exhumed from the root of a Cretaceous magmatic arc. High-\( P \) granulite facies conditions, at the root of the arc, formed in a convergent margin setting, and led to the partial melting of dioritic gneiss in the Pembroke Granulite and elsewhere in the Arthur River Complex. Intergrowths of kyanite, quartz and plagioclase and assemblages involving paragonite, with or without phengitic white mica, partially pseudomorph peak metamorphic assemblages. The kyanite-paragonite-phengite-bearing assemblages reflect unusual, short-lived high-\( P \) cooling of the rocks by up to 200 °C. The rapid cooling of the root of the arc must have occurred in < 20 Myr, and is inferred to have been in response to juxtaposition of the Arthur River Complex with cold upper crustal components of the Median Batholith during convergence (Fig. 10b). Subsequent biotite-plagioclase intergrowths that partially pseudomorph phengite, and diopside-plagioclase intergrowth that partially pseudomorph jadeitic diopside, reflect the postcooling exhumation of the high-\( P \) terrane.

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