The significance of kyanite and paragonite-bearing assemblages, northern Fiordland, New Zealand: rapid cooling at the lower crustal root of a Cretaceous magmatic arc

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ABSTRACT Western Fiordland, New Zealand exposes the lower crustal root (depths > 45 km) of an Early Cretaceous magmatic arc that now forms one of Earth’s most extensive high-P granulite facies belts. The Arthur River Complex, at Milford Sound, is part of the root of the arc and records an Early Cretaceous history of tectonic burial, high-P granulite facies metamorphism, partial melting of the crust and penetrative deformation. We describe newly discovered kyanite-bearing symplectites that replace early assemblages and leucosomes that were produced during the partial melting. The kyanite symplectites were themselves replaced by paragonite, commonly in the presence of phengitic white mica. The kyanite and paragonite-bearing assemblages indicate unusual Early Cretaceous high-P cooling of the root of the arc by $T \approx 200 \, ^{\circ}C$ at lower crustal depths. Biotite + plagioclase symplectites that partially pseudomorph phengitic white mica are consistent with later rapid decompression. These results combine to form an anticlockwise $P$-$T$ path, which, on the basis of available isotopic geochronologic data, was completed in less than 20 Ma. We present a new mechanism for cooling an overthickened root of an arc, that involves juxtaposition of the root with relatively cool rocks, such as those of the adjacent Darran Complex following the tectonic burial and underthrusting of the Darran Complex at the waning stages of Early Cretaceous orogenesis.

Key words: high-P granulites, $P$-$T$ path, thermobarometry, cooling, magmatic arc

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. However, such studies are hindered by the limited exposure of the lower crustal root of arc systems (eg. Miller et al., 1993). Many plate tectonic models emphasise the importance of large lateral and vertical motions of arc crust (eg. Whitney et al., 1999) and the evidence for these motions is commonly interpreted from changes in metamorphic assemblages (eg. Whitney et al., 1999; Clarke et al., 2000). Rapid increases in metamorphic pressure have commonly been ascribed to tectonic thickening and burial during contraction within an arc setting (eg. Bradshaw, 1989a, 1989b; Umhoefer & Miller, 1996). Rapid increases in metamorphic temperature are commonly ascribed to magmatic activity, and cooling is most commonly associated with rapid exhumation (eg. Monie et al., 1994, Treloar, 1997). We have discovered a range of Cretaceous assemblages in northern Fiordland, New Zealand, that contrast with some of these common interpretations.

Perhaps the most striking metamorphic feature that has been described in rocks from Fiordland involves garnet-clinopyroxene-bearing corona reaction textures that mantle enstatite in garnet reaction zones; these reflect approximately 25 km of Early Cretaceous burial (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 followed burial (Daczko et al., in press). We report on symplectic intergrowths of kyanite, quartz and plagioclase, and assemblages involving paragonite with or without phengitic white mica (hereafter referred to in the text as phengite) that replace the high-P assemblages. The kyanite and paragonite-bearing (± phengite) bearing assemblages reflect high-P cooling of the rocks by $T \approx 200 \, ^{\circ}C$. Subsequent biotite + plagioclase that partially pseudomorph phengite reflect later decompression (eg. Franz et al., 1986). This latter texture is consistent with our interpretation 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 (c.f. Gibson et al., 1988; Tulloch & Kimbrough, 1989).

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). The Western Province contains mostly Lower Palaeozoic paragneisses, cut by Devonian, Carboniferous and Cretaceous granitoids (Muir et al., 1996; Wandres et al., 1998). It includes the Arthur River Complex (Bradshaw, 1990; Fig. 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), and Mesozoic and Palaeozoic ages have been inferred for orthogneiss units from this belt (Mattinson et al., 1986; Bradshaw, 1990; Tulloch et al., 2000). In Milford Sound, the Arthur River Complex includes dioritic and trondhjemitic gneisses of the Harrison Gneiss and gabbroic gneisses of the Pembroke Granulite and Milford Gneiss (Fig. 2; Wood, 1972; Blattner, 1978, 1991, Clarke et al., 2000). 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 (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 (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 116-126 Ma Western Fiordland Orthogneiss intrudes the Arthur River Complex, 19 km southwest of Milford Sound (Bradshaw, 1990).

Structural and Metamorphic overview

The Arthur River Complex, exposed in northern Fiordland, contains high- P granulite facies rocks that experienced at least five deformation events in the Early Cretaceous (Blattner, 1991; Clarke et al., 2000; Daczko et al., 2001). The following overview of the structural and metamorphic history of the Arthur River Complex is a composite summary of data presented by Clarke et al. (2000), Daczko et al. (2001) and Daczko et al. (in press). A summary of structural abbreviations is provided in Appendix 1. The earliest foliation (S1) is preserved in the Pembroke Granulite, where it is defined by two-pyroxene-hornblende-bearing granulite facies assemblages. S1 generally strikes east to east-northeast 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 \( P < 8 \text{ kbar} \) and \( T > 750 \text{ °C} \). S1 is cut by steeply dipping planar fractures (D2) that are commonly filled with trondhjemitic veins. The veins are linked to large garnet poikiloblasts, which may be surrounded by leucosome in dioritic gneiss. These textures reflect high- \( P \) partial melting of the dioritic gneiss at \( T > 750 \text{ °C} \). Gabbroic gneiss, in contact with the dioritic 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 \( P = 14 \text{ kbar} \) and \( T = 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 Gneiss cut the D3 shear zones. Throughout Milford Sound, S4 shows variable mineral assemblages that reflect deformation over a wide range of temperatures. For example, sample 9608c contains the assemblage garnet, clinopyroxene, hornblende, plagioclase and quartz that give garnet-clinopyroxene thermometry estimates of $T \approx 800$ °C (Table 2 in Clarke et al., 2000). The paragonite with or without phengite-bearing assemblages presented here reflect conditions of $T = 600-700$ °C and indicate that either (i) S4 developed over some period of time during cooling or (ii) S4 experienced reactivation involving renewed shearing leading to recrystallisation following some cooling. Fabrics of the Anita Shear Zone cut S4 to the west (Klepeis et al., 1999).

Geochronologic overview

U-Pb zircon ion probe analyses distinguish three age populations for 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). More work is required to resolve the meaning of U-Pb zircon ion probe ages of c. 155 Ma and c. 105 Ma, which may reflect a more complex geochronologic history for the Arthur River Complex (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 the peak of metamorphism occurred at c. 120 Ma. K-Ar isotopic dating of hornblende grains from the Pembroke Granulite yield ages of c. 138 Ma (Table 1; Nathan et al., 2000). K-Ar ages for hornblende grains from the Milford and Harrison Gneisses give ages of c. 90-111 Ma (Table 1, 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 geochronologic history to the Western Fiordland Orthogneiss, which was emplaced between 116-126 Ma, buried and metamorphosed at high-P granulite facies conditions, and, on the basis of U-Pb apatite dates, had cooled to $T < 300-400 \, ^\circ C$ by c. 90 Ma (Table 1, Mattinson et al., 1986).

**PETROLOGY**

In this section, we describe the petrology of the textures inferred to represent sites of partial melting and the kyanite and paragonite (± phengite) bearing assemblages that are useful for estimating the post-peak metamorphic P-T path for the Arthur River Complex. We used a standard petrological microscope to analyse the textures and supplemented this data with maps of oxide weight percent obtained by completing matrix corrections on raw intensity X-ray maps. All microprobe data was 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 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 $\alpha$-factor approach of Bence & Albee (1968) for matrix correction (Clarke et al., in press).

**Melting textures**

Samples of dioritic gneiss from the Pembroke Granite (eg. 9802, 9805 and 9831X) show 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. (in press) to represent sites of partial melting in the dioritic gneiss at $T > 750 \, ^\circ C$. Saywer (1999) presents microstructural criteria for identifying rocks that have partially melted and the following text describes textures within leucosome from sample 9805 (Fig. 3) that are consistent with the interpretation that the dioritic gneiss partially melted. 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 contain inclusions of mostly quartz with...
or without minor hornblende, clinzoisite, rutile and apatite. The leucosome consists of plagioclase and quartz and contains rounded grains of clinzoisite and hornblende. Quartz commonly shows quadrangular shapes with concave sides (arrow 1, Fig. 3). Thin films of quartz and plagioclase occur along some grain boundaries in the leucosome (eg. arrow 2, Fig. 3).

**Kyanite and paragonite (± phengite) bearing textures**

Samples 9802 and 9831X have symplectic intergrowths of kyanite, quartz and plagioclase that cut S1 and postdate formation of the leucosomes. The kyanite-bearing symplectites are up to 3 mm across and display irregular grain shape with cuspate boundaries. Figure 4 shows maps of silica, aluminium, calcium and sodium oxide weight percent for a kyanite-bearing symplectite in sample 9831X. Kyanite is generally found armoured by plagioclase and separated from the rest of the rock by films of quartz (Fig. 4). The kyanite-bearing symplectites may contain inclusions of hornblende (arrow 1, Fig. 4), clinzoisite, 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 symplectites contain hornblende inclusions suggesting that coarse-grained plagioclase was replaced by the symplectites before hornblende (Fig. 5b).

Paragonite with or without phengite cut the kyanite symplectites in the Pembroke Granulite (Fig. 6). Rapid cooling at the lower crustal root of a magmatic arc, Fiordland New Zealand - N. R. DACZKO et al.
5b) and may define S4 in the Milford Gneiss (Fig. 5c). Grains of paragonite and phengite in the Pembroke Granulite are randomly oriented and may be up to 4 mm long. They are most commonly observed in plagioclase. Paragonite and phengite in the Milford Gneiss are most commonly aligned with S4 hornblende, plagioclase, clinozoisite, garnet and quartz. Figure 5c covers an area with S4 paragonite and phengite that partly replace garnet in sample PK12B from the northern side of Lake Pukutahi (Fig. 2).

**Post-D4 textures**

S4 is cut by muscovite-bearing pegmatites that have a metasomatic selvage that penetrates the host rock for approximately 5mm around the pegmatite. The selvage mostly contains garnet, biotite and phengite with plagioclase and quartz (Fig. 5d). This assemblage is useful in that it allows us to estimate the metamorphic conditions that followed D4 and accompanied the emplacement of the pegmatite.
The rims of some S4 phengite grains are replaced by biotite with or without plagioclase in samples of both the Pembroke Granulite 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 pseudomorphous replacement of a phengite grain is almost complete, biotite is observed with plagioclase and minor quartz and potassium feldspar (Fig. 5f). 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 is commonly observed to separate phengite and biotite. Figure 6 shows maps of silica, magnesium, calcium and sodium oxide weight percent for the texture shown in Fig. 5f. 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.

MINERAL CHEMISTRY AND THERMOBAROMETRY

In this section we outline the mineral chemistry of the textures described above. We then use this data 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 2.

Large garnet poikiloblasts from the dioritic gneiss of the Pembroke Granulite (samples 9802 and 9831X) are unzoned pyrope- and grossular-rich almandine with $\text{Alm} = 100 \Fe/(\Fe+\Mg+\Mn+\Ca)$, $\text{Spss} = 100 \Mn/(\Fe+\Mg+\Mn+\Ca)$, $\text{Py} = 100 \Mg/(\Fe+\Mg+\Mn+\Ca)$ and $\text{Gr} = 100 \Ca/(\Fe+\Mg+\Mn+\Ca)$. S4 garnet has a variable composition in the range $\text{Alm}_{53-35}\text{Spss}_{5-25}\text{Py}_{4-25}\text{Gr}_{15-25}$. 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...
Table 2. Representative electron microprobe analyses (wt.% oxide and cation data) for samples 9831X, 9828 and PK5. Data were collected on 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.

<table>
<thead>
<tr>
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<th>9831X (cooling)</th>
<th>9828 (hydration)</th>
<th>PK5 (s4)</th>
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<tr>
<td>K₂O</td>
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<tr>
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<tr>
<td>Cr</td>
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</tr>
<tr>
<td>Fe</td>
<td>1.7</td>
<td>1.8</td>
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<tr>
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<tr>
<td>K</td>
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Al₉₆₄Sp₃₄Py₂₁Gr₂₅ and a rim composition of Al₉₅₈Sp₂₁Py₁₈Gr₁₇. Garnet in the metasomatic selvage adjacent to the post-D4 pegmatite has a variable composition in the range Al₉₅₈₆₄₃₄Sp₂₁Py₁₈₅₃₄Gr₁₇₂₅. Garnet microprobe analyses from all samples plot in a similar region on a ternary diagram (Fig. 7a). The overall trend on Fig. 7a implies exchange vectors involving Ca ↔ Mg or (Fe, Ca) ↔ 2Mg in garnet.

Plagioclase in the leucosome surrounding the garnet poikiloblasts in the dioritic gneiss of the Pembroke Granulite is oligoclase with Xₐₙ = 0.20-0.36. Plagioclase in the dioritic host rock of the Pembroke Granulite is oligoclase with Xₐₙ = 0.17-0.26. S4 plagioclase in dioritic gneiss straddles the oligoclase/andesine boundary with Xₐₙ = 0.28-0.32. Paragonite from the Pembroke Granulite and Milford Gneiss has Xₐₙ = [Na/(Na+K)] = 0.79-0.88 and 2.87-2.98 silica cations per formula unit (p.f.u., 11 oxygens; Fig. 7b). However, most phengite grains have ~3.1 silica cations p.f.u. The
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Fig. 7. Representative compositions from the assemblages discussed in the text for (a) garnet, (b) white mica and (c) hornblende.

paragonite substitution in the phengite is approximately 20%. The small spread in data plotted in Fig. 7b is observed both within and between samples. Hornblende in the Pembroke Granulite and Milford Gneiss is mostly pargasite with less ferro-pargasite (after Leake et al., 1997); \( X_M = \frac{[\text{Mg}]}{[\text{Mg}+\text{Fe}]} \) is mostly between 0.52-0.63. Kyanite generally contains less than 1 wt% Fe\(^3+\).

P-T estimates obtained from applying a variety of thermobarometric techniques to the mineral assemblages described above are summarised in Table 3. For dioritic gneiss of the Pembroke Granulite (sample 9802), the compositions of adjacent grains of garnet, kyanite, plagioclase and quartz give pressure estimates of \( P = 12.2 \text{ kbar} \) for an estimated \( T = 650 \text{ °C} \) (after Newton & Haselton, 1981). The assemblage garnet, hornblende, plagioclase and quartz yield pressure estimates of \( P = 11.7 \text{ kbar} \) for an estimated \( T = 650 \text{ °C} \) (after Kohn & Spear, 1990). P-T conditions may also be estimated using the average pressure-temperature approach of THERMOCALC (v.2.6; 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 2\( \sigma \) errors. Using the average P approach of THERMOCALC, the assemblage garnet, hornblende, clinzoisite, plagioclase, kyanite and quartz in samples 9802 and 9831X give \( P = 13.3 \pm 2.2 \text{ kbar} \) and \( P = 12.9 \pm 1.6 \text{ kbar} \) respectively, which are within error of the directly calibrated barometric results (Table 3). Using the average T approach of THERMOCALC, the same assemblage in samples 9802 and 9831X give \( T = 677 \pm 64 \text{ °C} \) and \( T = 653 \pm 46 \text{ °C} \) respectively (Table 3).

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 \( P = 11.1 \text{ kbar} \) for an estimated \( T = 650 \text{ °C} \) (after Kohn & Spear, 1990). The

<table>
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<th>Sample</th>
<th>Location</th>
<th>Assemblage</th>
<th>Timing</th>
<th>Assumed</th>
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<th>Method</th>
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Table 3. P-T estimates obtained from applying a variety of thermobarometric techniques to the mineral assemblages for samples discussed in text. Methods: (1) Kohn & Spear (1990); (2) Newton & Haselton (1981); (3) Graham & Powell (1984); (4) Perchuk & Larent’eva (1983); (5) Powell & Holland (1988).
same sample and assemblage give temperature estimates of $T = 703 \, ^\circ C$ for an estimated $P = 12 \, \text{kbar}$ (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 $P = 13.1 \pm 1.4 \, \text{kbar}$ and $T = 687 \pm 34 \, ^\circ C$, which are within error of the directly calibrated thermobarometric results (Table 3).

Milford Gneiss samples PK4 and PK5 contain well developed phengite and paragonite-bearing S4 mineral assemblages. The compositions of adjacent grains of S4 garnet, hornblende, plagioclase and quartz in sample PK5 give pressure estimates of $P = 11.4 \, \text{kbar}$ for an estimated $T = 705 \, ^\circ C$ (after Kohn & Spear, 1990). The same sample and assemblage gives temperature estimates of $T = 736 \, ^\circ C$ for an estimated $P = 12 \, \text{kbar}$ (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 $P = 13.2 \pm 1.7 \, \text{kbar}$ and $T = 694 \pm 42 \, ^\circ C$, which are within error of the directly calibrated thermobarometric results (Table 3).

For Milford Gneiss sample PK4, the compositions of adjacent grains of garnet, hornblende, plagioclase and quartz give pressure estimates of $P = 10.9 \, \text{kbar}$ for an estimated $T = 650 \, ^\circ C$ (after Kohn & Spear, 1990). The same sample and assemblage gives temperature estimates of $T = 704 \, ^\circ C$ for an estimated $P = 12 \, \text{kbar}$ (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 $P = 11.9 \pm 1.8 \, \text{kbar}$ and $T = 629 \pm 56 \, ^\circ C$, which is a slightly lower temperature estimate than that obtained from the directly calibrated thermometry (Table 3).

For the selvage around the post-D4 pegmatite (sample PK7B), the compositions of adjacent grains of garnet and biotite give temperature estimates of $T = 605 \, ^\circ C$ for an estimated $P = 9 \, \text{kbar}$ (after Perchuk and Lavrent’eva, 1983). Using the average $P$ and average $T$ approach of THERMOCALC, the assemblage garnet, biotite, phengite, plagioclase and quartz in sample PK7B gives $P = 8.8 \pm 1.5 \, \text{kbar}$ and $T = 677 \pm 52 \, ^\circ C$, which is slightly higher temperature than the directly calibrated thermometry results (Table 3).

$T-XH_2O$ pseudosection

The thermobarometric results indicate that the paragonite and phengite-bearing assemblages evolved in the deep crust ($P = 11-13 \, \text{kbar}$) at approximately $T = 600-700 \, ^\circ C$. 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 fluid that accompanied the development of the kyanite and paragonite ($\pm$phengite) bearing assemblages. $P-T$ pseudosections, calculated with H$_2$O in excess, are suitable where H$_2$O-saturated conditions can be inferred, but inappropriate for examining mineralogical changes that involved H$_2$O-undersaturated conditions, as inferred for the development of the kyanite-bearing symplectite textures.

To examine these changes in conditions, a quantitative $T-XH_2O$ pseudosection has been constructed in the model system CNFMASH (CaO-Na$_2$O-FeO-MgO-Al$_2$O$_3$-SiO$_2$-H$_2$O), using THERMOCALC (version 2.75) and the '20 April 1996' internally consistent thermodynamic data set (Powell et al., 1998). Details of the use of THERMOCALC for grid and pseudosection construction are outlined in Powell et al. (1998). Minerals included in the construction of the grid are garnet (g), hornblende (hb), paragonite (pa), clinozoisite (cz), kyanite (ky), orthopyroxene (opx), clinopyroxene (cpx), plagioclase (plag) and quartz (q). Most of the activity models used in the calculations assume ideal mixing on all sites and are identical to those used by Powell et al. (1998). Where present, the fluid phase is assumed to be pure H$_2$O. In the $T-XH_2O$ diagram H$_2$O is considered explicitly (Guiraud et al., 1996; Carson et al., 1999; Clarke et al., 2000): $XH_2O$ is defined as the molar proportion of the component, H$_2$O, in the bulk composition.

Figure 8 represents a $T-XH_2O$ pseudosection appropriate to the bulk composition of the dioritic gneiss of the Pembroke Granulite. On the basis of thermobarometry outlined above, it is drawn at fixed $P = 12 \, \text{kbar}$ for $T = 550-750 \, ^\circ C$. The rock composition used was obtained from bulk rock analysis of element maps of oxide weight percent for sample 9805 (see Marmo et al., in press). The rock composition modelled varies (Fig. 8) from CaO = 17.70, Na$_2$O = 9.10, FeO = 28.90, MgO = 14.55, Al$_2$O$_3$ = 29.74, H$_2$O = 0.00 ($XH_2O=0$) to CaO = 14.16, Na$_2$O = 7.28, FeO = 23.12, MgO = 11.64, Al$_2$O$_3$ = 23.79, H$_2$O = 20 ($XH_2O=0.4$). The pseudosection is drawn for quartz in excess, and illustrates the mineral evolution with respect to changing temperature and $XH_2O$, as well as the preservation of various mineral assemblages in terms of recrystallisation and fluid availability. A horizontal line on the diagram represents the addition or subtraction of H$_2$O at a given temperature. The indicated H$_2$O-saturation line is the limiting boundary beyond which any further increase
of $X\text{H}_2\text{O}$ mainly increases the mode of fluid. Figure 8 illustrates the change in assemblages modelled for $T$-$X\text{H}_2\text{O}$ space. Garnet (g) and hornblende (hb) 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 quartz (q). Clinopyroxene is stable at $T > 686^\circ$C and $X\text{H}_2\text{O} < -0.04$, however the mode of clinopyroxene is mostly much less than 5%, suggesting that it does not play a vital role in the assemblage changes predicted by the model.

The changes in mineralogy of the northern Fiordland rocks involve: (1) the consumption of hornblende ($\pm$ clinozoisite, plagioclase and quartz) during melting; (2) the consumption of plagioclase ($\pm$ hornblende and quartz) to form symplectic intergrowths of kyanite, quartz and plagioclase; (3) the consumption of kyanite, plagioclase and garnet to form paragonite and phengite. The model does not account for a melt phase. However, the position of the melting textures must lie below the water saturation line and at temperatures greater than 750°C (Daczko et al., in press). This places the melting textures off the top of the diagram but within the garnet-hornblende-plagioclase-clinopyroxene quadrivariant field. The modelling suggests that kyanite (ky) will become stable if the rock cools below $T = 635^\circ$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 $P = 12$ kbar and temperatures of $T = 607-741^\circ$C, taking into account the $2\sigma$ errors on the temperature estimates. The high temperature results may reflect a mixed population of grains involving some that grew during the high-$T$ metamorphic conditions. We therefore prefer the lower temperature end of the range of thermometry results.

The development of the phengite-bearing assemblages is not modelled, as we do not have potassium in the model system. However, phengite generally occurs with paragonite in the samples and we infer that phengite will broadly follow the same trends as paragonite in the model. The introduction of paragonite and phengite must have involved the addition of $\text{H}_2\text{O}$ to the rock and can be represented by a horizontal line on the pseudosection. The observed small modes of paragonite and phengite in samples 9828, PK4 and PK5 (generally less than 10%) are consistent with $T = 575-625^\circ$C and $X\text{H}_2\text{O}$ equal to approximately 0.12 in the model system. Such conditions involve slightly lower temperatures than the thermobarometry presented above (by less than 50°C), which is within error of the modelling.

Following the proposed arrow on Fig. 8, the rock cools by at least $T = 100^\circ$C and by up to $T = 200^\circ$C
and the leucosomes that enclose peritectic garnet were overgrown by symplectic intergrowths of kyanite, quartz and plagioclase. Thermobarometry on these assemblages indicates that metamorphic conditions of \( P = 11-13 \) kbar and \( T = 600-700 \) °C accompanied the development of the symplectites. The thermobarometry and our models in \( T-X_h2o \) metamorphic space at fixed \( P = 12 \) kbar suggest that the kyanite symplectites developed in response to cooling of the rocks at depth by \( T = 100-200 \) °C, consistent with the thermobarometric results (Fig. 9a). In addition, the paragonite and phengite-bearing assemblages that partially to completely consume kyanite and garnet, also formed at metamorphic conditions of \( P = 11-13 \) kbar and \( T = 600-700 \) °C. This latter result suggests that these assemblages represent hydration of the rocks at some point on a cooling path (e.g. Barnicoat & Fry, 1984). The \( P-T \) estimates presented here are similar to those presented by Konzett & Hoinkes (1996) for paragonite-hornblende-bearing assemblages from the Austroalpine Schneeberg Complex in southern Tyrol, Italy. Our results corroborate those of Evans (1990) and Konzett & Hoinkes (1996) which suggest that paragonite and calcic hornblende assemblages reflect restricted \( P-T \) conditions within the epidote-amphibolite facies for mafic rocks. The thermobarometry indicates that the high-\( P \) conditions prevailed during cooling, so rapid exhumation can not be invoked as the cause, contrasting with common models for cooling of arc rocks. As these large changes in \( P-T \) occurred in less than 20 Ma, it is unlikely due to time constraints 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 (± quartz and potassium feldspar). The breakdown of phengite and a mafic phase (clinoxyroxene, 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-\( P \) conditions, post dating D4 cooling (Fig. 9a). The emplacement of the post-D4 pegmatite at \( P = 9 \) kbar also supports this interpretation.

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 \( P = 12 \) kbar and \( T = 600 \) °C (ASZ1 on Fig. 9a) to \( P = 8.5 \) kbar and \( T = 600 \) °C (ASZ2 on Fig. 9a). This decompression is consistent with the phengite breakdown textures presented here, although the exact 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 most probably predated the emplacement of the pegmatite. However, reactivation of the Anita Shear Zone 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 to form an anticlockwise \( P-T \) path (Fig. 9a).

U-Pb zircon ion probe analyses distinguish Palaeozoic and Cretaceous cores that are rimmed by low-U metamorphic zircon with an average age of c. 120 Ma in the Arthur River Complex (Tulloch et al., 2000). This age most probably reflects the high \( P-T \) metamorphism of the Arthur River Complex. K-Ar isotopic dating of hornblende give ages of c. 90-111 Ma (Table 1, Nathan et al., 2000). The apatite cooling ages for the Western Fiordland Orthogneiss, in northern Fiordland, also suggest cooling of the terrain to \( T < 300^{\circ} \)
400 °C by c. 90 Ma (Table 1, Mattinson et al., 1986). The available geochronologic data and metamorphic data presented here suggest that the Arthur River Complex cooled rapidly between c. 120 Ma 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 Darran Complex 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 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 126-116 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 median of the Late Jurassic, at the root of the Arthur River Complex and Western Fiordland Orthogneiss to P = 14 kbar (Bradshaw, 1989b; Clarke et al., 2000; Daczko et al., 2001).

3. Continued convergence produced sinistral pure-shear-dominated shear zones (D3) and deep crustal ductile thrust faults (P = 14 kbar) in the Pembroke Granulite (Daczko et al., 2001). 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. The cold crust of the Darran Complex was 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.

Metamorphic textures in the Darran Complex at the margin with the Arthur River Complex involve igneous muscovite rimmed by phengite and paragonite and garnet poikiloblasts enveloped by leucosome (Dockrill, 2000) that are consistent with rapid burial and heating of the Darran Complex (Dockrill, 2000). Dockrill (2000) presents thermobarometric data that suggests the peak metamorphic conditions attained by the Darran Complex adjacent to the Arthur River Complex involved T = 560-615 °C and P = 10.9-12.1 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. Our interpretation also supports that of Muir et al. (1998), who used geochronal and geochronologic data to argue that a Mesozoic magmatic arc, chemically equivalent to the Darran Complex, was thrust beneath western Fiordland to depths > 40 km in the Early Cretaceous. This model is consistent with other studies 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 Darran Complex (Austrheim & Griffin, 1985; Jamveit et al., 1990; Ellis & Maboko, 1992; White & Clarke, 1997).

CONCLUSION

The Arthur River Complex in northern Fiordland, New Zealand represents a part of the exposed root of a Cretaceous magmatic arc. High-P granulite facies metamorphic conditions, at the root of the arc, were produced in a convergent margin setting and led to the partial melting of dioritic gneiss in the Pembroke Granulite. Symplectic intergrowths of kyanite, quartz and plagioclase and assemblages involving paragonite with or without phengitic white mica replaced the high-T assemblages. The kyanite and paragonite (± phengite) bearing assemblages reflect unusual high-P cooling of the rocks by T = 200 °C. Rapid cooling of the root of the arc occurred in less than 20 Ma in response to juxtaposition of the Arthur River Complex with cold upper crust of the Darran Complex during convergence (Fig. 9b). Elevated temperature and pressure conditions estimated from assemblages in the Darran Complex are consistent with this interpretation. Subsequent biotite + plagioclase that partially pseudomorph phengite reflect later decompression of the high-P rocks.

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