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Direct observation of adakite melts generated in the lower continental crust, Fiordland, New Zealand

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ABSTRACT

Adakites have a distinct chemistry that links them to melting of a mafic source at high pressure. They have been attributed to melting of subducted oceanic crust or melting of the mafic crustal roots of thick continental arcs, and are an important contrast to mantle wedge melting as a means of generating continental crust. We report the first direct evidence for the generation of adakitic melts in mafic lower continental crust, in an exhumed Cretaceous arc in the South Island of New Zealand. The lower crustal Pembroke Granulite has the bulk chemistry and partial melting textures involving peritectic garnet appropriate for a source region for an adakitic melt. The melt migrated from the area through a fracture network now filled with trondhjemitic veins. Emplacement of the melt was in the upper crust of the Cretaceous section, illustrated by the presence of coeval adakites in the upper crustal Nelson-Westland region.

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Introduction

Adakites are silicic to intermediate igneous rocks diagnostic of high-T, high-*P* melting of a mafic crustal source in the presence of garnet. They were first attributed to melting of young, hot oceanic crust at subduction zones (Kay, 1978; Defant and Drummond, 1990). An alternative view is that such melts can also form in continental arcs where the crust is thick enough for garnet to be stable ($P > 1.2$–1.5 GPa, Peacock *et al.*, 1994), and the lower crust has the appropriate mafic composition (Atherton and Petford, 1993). We refer to these end-members as slab-derived and continental arc root-derived adakites, respectively.

When adakites were initially observed in the Aleutian arc (Kay, 1978), geologists were faced with the enigma of an arc magmatic rock type with geochemical characteristics (high La/Yb and Sr/Y, low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$) typical of derivation from young oceanic crust, rather than from the mantle wedge from which melts are derived in traditional models of arc magma genesis (e.g. Gill,

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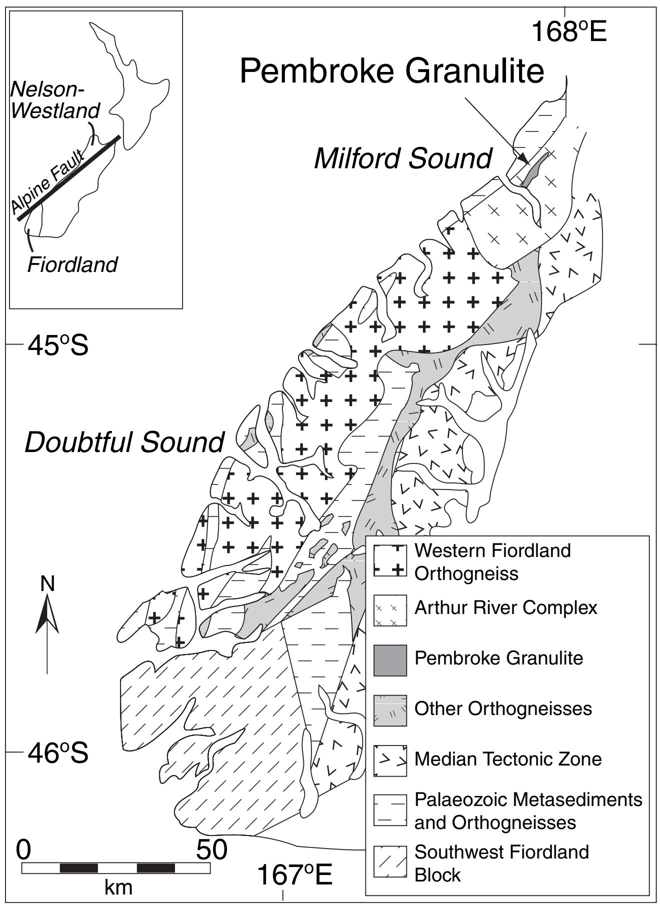

Fig. 1 Geological map of Fiordland showing the location of the Pembroke Granulite. Shown in the inset are the locations of the Nelson-Westland region, host to the Separation Point adakites, and the location of the Alpine Fault (after Clarke *et al.*, 2000).

1981). It was initially suggested that adakitic melt is produced through melting of eclogite in young hot subducting slabs, where melting can occur before devolatilization reactions raise the solidus temperature, followed by equilibration of the melt with olivine and orthopyroxene in the mantle wedge such that the melt could attain the high Mg composition observed in adakites (Defant and Drummond, 1990; Drummond and Defant, 1990; Defant and Kepezhinskas, 2001). This hypothesis was supported by experimental studies (Wolf and Wyllie, 1989; Rapp *et al.*, 1991, 1999, 2003; Foley *et al.*, 2002; Klemme *et al.*, 2002) that showed that partitioning between melt and garnet, hornblende and/or clinopyroxene during melting of the subducting slab tholeiite will produce melt with high Sr/Y and high La/Yb. The observation that adakites occur in subduction zone settings where the slab is too old and cool for melting to be expected led to the idea that slab melting can also be caused by high heat flow near the slab, such as asthenospheric flow around slab edges and through slab tears (Pe-Piper and Piper, 1994; Abratis and Wörner, 2001; Yogodzinski *et al.*, 2001). Slab-derived adakite chemistry is also influenced by incorporation of metasomatic mantle wedge (Yogodzinski *et al.*, 1995, 2001) and/or crustal (Sen and Dunn, 1994; Stern and Kilian, 1996; Sajona and Maury, 1998) material.

Critical to the slab melt model of adakite production is that the geochemical characteristics of adakites were primarily derived from those of oceanic crust. Adakites exist, however, whose chemical characteristics do not appear to be derived from the melting of MORB-like oceanic crust, which lack mantle interaction chemical signatures, which are not associated with hot, young subduction zones, and/or which lie at significant distances from subduction zones (Atherton and Petford, 1993; Muir *et al.*, 1995; Harris *et al.*, 1996; Petford and Atherton, 1996; Wolde *et al.*, 1996; Wareham *et al.*, 1997). These observations led to the suggestion that adakites can also be derived from melting of deep continental crust of mafic composition, where the crust is thick enough for garnet stability at its root (Atherton and Petford, 1993; Muir *et al.*, 1995).

Melting in subducting slabs and in the lower continental crust has important implications for continental crustal formation. While only a very small portion of magma genesis in the Phanerozoic is attributed to melting in such regimes, higher mantle temperatures, smaller plate sizes, and younger crustal ages in the Archaean meant that melting in both oceanic crust and in continental arc roots was much more prevalent (e.g. Rapp *et al.*, 2003). Traditionally, slab-derived adakites have been seen as an analogue for Archaean tonalite–trondhjemite–granodiorite (TTG) suites (e.g. Martin, 1999), although recent studies, recognizing the lack of a mantle interaction signature in many Archaean TTG, have suggested that continental arc root-derived adakites may be a better parallel (e.g. Smithies, 2000; Rapp *et al.*, 2003).

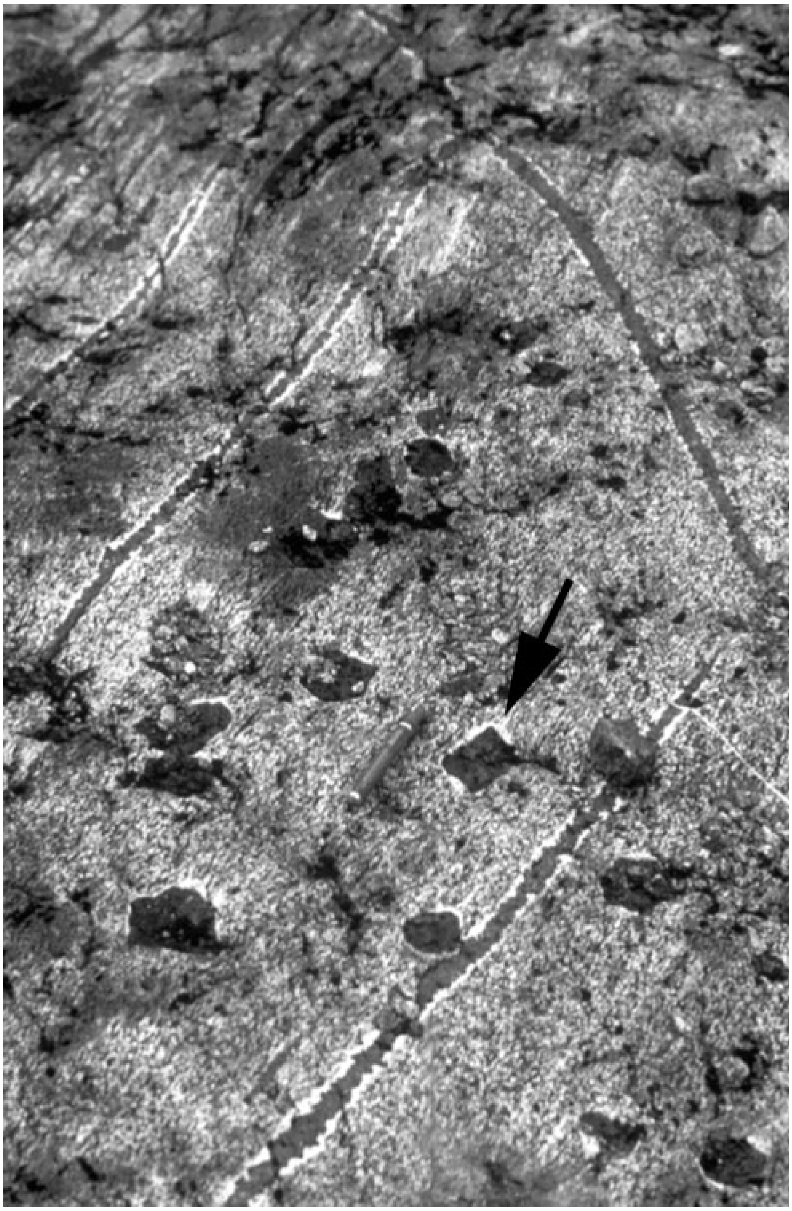

Fig. 2 Dioritic gneiss in the Pembroke Granulite showing poikiloblastic garnet (arrowed) surrounded by leucosome, and large planar trondhjemitic veins. Two of the three vein orientations are visible. Trains of garnet poikiloblasts aligned in trondhjemitic veins are also shown. Pen shown for scale.

Direct evidence supporting formation of adakite melts in the lower continental crust has been lacking. Most of our evidence is indirect, coming from high-level adakitic volcanic and plutonic rocks, such as at Mt St Helens (Defant and Drummond, 1993), the Andean Arc (Atherton and Petford, 1993), and the Cretaceous arc of New Zealand (Muir *et al.*, 1995), and from experimental studies, which are further complicated because our understanding of the abundance and distribution of many trace elements during high-pressure partial melting remains poor (Bea *et al.*, 1994). Deeply exposed arc sections provide an opportunity to look for direct evidence of adakitic melts, but such settings are rare, and textural relationships tend to be complicated by deformation after melting. However, remarkably undeformed mafic units in the deeply exposed crustal section in Fiordland, New Zealand provide direct evidence for melting of lower arc crust to produce adakite melts.

Geological setting

We provide direct evidence of melting of arc crust as exposed in a deeply exhumed section of a Cretaceous arc in Fiordland, New Zealand (Fig. 1), which formed along the eastern margin of Gondwana. Rifting in the Late Cretaceous resulted in extensional exhumation of the Fiordland section. The mafic lower crustal part of the section, encompassing the Pembroke Granulite ($P = 1.2–1.4$ GPa; $T =$ 750–800 °C, Daczko *et al.*, 2001a,b), preserves well-exposed migmatitic textures (Fig. 2) that are here and elsewhere (Clarke *et al.*, 2000; Antignano *et al.*, 2001; Daczko *et al.*, 2001b; Klepeis *et al.*, 2003; Schröter *et al.*, 2004) interpreted to have been the result of partial melting. It has been determined experimentally that melting was controlled by the breakdown of hornblende, clinozoisite and biotite (Antignano *et al.*, 2001). These partial melting textures are connected to leucosome-filled fractures (Fig. 2). Melting was synchronous with and most likely in response to nearby emplacement of the 126–116 Ma Western Fiordland Orthogneiss (Mattinson *et al.*, 1986; Hollis *et al.*, 2003), supporting the modelling of Petford and Gallagher (2001) that suggests that melting in the lower continental crust may often be in response to nearby intrusive magmatism. We estimate that melt fraction was around 5%, but the Pembroke Granulite is only exposed in and around one valley of relatively small area (*c.* 10–15 km^2, Fig. 1), with its true lateral and vertical extent indeterminate. Therefore, it is not possible to give an accurate estimate of the volume of rock that was partially melting and the volumetric melt production. The migmatitic textures consist of large (up to 25 mm across) poikiloblastic garnet that cut the predominant dioritic gneiss assemblage of pargasitic hornblende, plagioclase, biotite, quartz and clinozoisite, and are surrounded by trondhjemitic leucosome in migmatitic textures (Fig. 2). Where well developed, the garnet poikiloblasts may be aligned into trains that are enclosed by planar trondhjemitic veins (Fig. 2) that cut all assemblages in the Pembroke Granulite. These garnet are chemically identical to peritectic garnet in migmatitic textures (Schröter *et al.*, 2004), and it is envisaged that these are peritectic garnet that were carried by the melt as it migrated into the fractures. The Pembroke Granulite has remained remarkably undeformed since formation of the migmatitic textures, despite rapid exhumation (Daczko *et al.*, 2001b).

Table 1 Characteristic LA-ICPMS and XRF analyses of selected textures in the Pembroke Granulite, and a dioritic gneiss melt modelled using MELTS (Ghiorso and Sack, 1995).

	Pembroke Granulite										
	Dioritic Gneiss					Migmatitic textures		Trondhjemitic veins		Separation Point	MELTS
	Plag.	Hbl	Cz	Bi	W.R.	Gt.	Plag.	W.R.	Plag.		
Sr	1140	41.45	3900	227	120–50	4.09	2426	1201	2120	1176	
Y	0.0631	3.63	42	2.2	22–7	13.2	0.356	<2.8	1.08	10	
Sr/Y	18072	11	93	103	2–17	0.3	6816	>493	1963	118	
La/Lu	>30	0.001–0.5	143.3	4	7.7–2.3	<0.0025	>300	66.3	>300	199	
SiO_2	63.19	41.33	38.51	35.61	52.74	38.59	63.77	54.14	64.03	67.66	67.9
TiO_2	0.01	1.04	0.09	1.41	1.06	0.07	0.00	0.35	0.00	0.24	0.16
Al_2O_3	23.63	14.78	27.34	18.79	19.33	21.49	22.32	24.29	23.03	17.70	18.7
FeO/Fe_2O_3	0.04	14.68	7.32	14.71	8.28	25.34	0.01	4.07	0.01	1.87	0.8
MnO	0.04	0.07	0.04	0.12	0.12	1.84	0.02	0.07	0.03	0.04	2.3
MgO	0.00	10.85	0.10	13.21	3.98	5.32	0.00	2.31	0.00	0.35	0.1
CaO	4.39	10.64	23.01	0.01	7.85	7.79	3.68	9.1	3.98	2.53	2.1
Na_2O	8.67	2.19	0.01	0.23	4.83	0.02	9.66	5.22	9.18	5.78	4.7
K_2O	0.08	1.09	0.01	8.30	0.67	0.00	0.12	0.33	0.13	2.48	2.1
P_2O_5					0.31			0.08		0.11	1.1
LOI					0.81			0.68		0.47	
Total	100.06	96.73	96.43	92.41		100.46	99.59		100.40		

Plag., plagioclase; Hbl, hornblende; Cz, clinozoisite; Bi, biotite; W.R., whole rock; Gt., Garnet. A Separation Point adakite whole rock is included for comparison (Muir *et al.*, 1995). Trondhjemitic vein whole-rock data is from Daczko *et al.* (2001b)). Trace element data are in ppm. Major element data are weight per cent oxides. La and Lu are chondrite normalized values. Greater and less than signs indicate that the given range continues beyond LA-ICPMS detection limits.

The Nelson-Westland region of New Zealand contains adakitic rocks of the 125–105 Ma Separation Point Batholith (Fig. 1; Tulloch and Challis, 2000). This region lay contiguous with Fiordland before dextral movement along the tertiary sub-vertical Alpine Fault produced 460 km horizontal offset. While neighbouring, the Nelson-Westland region did not precisely overlie Fiordland in the Cretaceous, but does represent the upper continental crustal equivalent of the lower crustal section present in Fiordland. We argue that the Separation Point Batholith shows the presence of adakites in the upper crust of the section, and that melting in the lower crustal Pembroke Granulite produced an adakitic melt with a very similar composition, whether or not there is a direct genetic link between the two. The key point is that we show *in-situ* production of adakite melts in the lower continental crust.

Results

We present geochemical data from point analyses acquired using a Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICPMS), at Macquarie University, Sydney, Australia, following the method of Norman *et al.* (1996). Bulk rock data were determined using a Philips PW2400 X-ray fluorescence (XRF) spectrometer at the University of New South Wales, and through instrumental neutron activation analysis (INAA) at the Becquerel Laboratory, Lucas Heights Science and Technology Centre, Sydney, Australia. Results are presented in Table 1 for analyses of minerals and whole-rock compositions from three textures: (1) dioritic gneiss in the Pembroke Granulite; (2) migmatitic textures within the dioritic gneiss; and (3) trondhjemitic veins that extend from the migmatitic textures to beyond the Pembroke Granulite. Comparative results from the Separation Point Batholith (Muir *et al.*, 1995), and from melt modelling using the MELTS software (Ghiorso and Sack, 1995) are also presented in Table 1.

Discussion

The chemistry of the trondhjemitic veins (Table 1) is unlikely to be a direct dioritic gneiss melt, so we argue that the entire melt was not quenched to form the veins. It is necessary to use other means to constrain what the melt composition was. The most useful constraints on whether an adakitic melt was produced are given by looking at the Sr, Y and rare earth element compositions of the various Pembroke Granulite textures. A constraint on the actual melt composition is provided using the MELTS program (Ghiorso and Sack, 1995).

The chondrite-normalized rare earth element compositions of the unmelted dioritic gneiss, along with those of the hornblende, clinozoisite and biotite that controlled the melt forming reaction (Antignano *et al.*, 2001) are shown in Fig. 3. Garnet in the partial melting textures of the dioritic gneiss (Fig. 3) shows a high level of enrichment in heavy rare earth elements (HREE) and depletion of light rare earth elements (LREE; La/Yb = 0.003; Table 1) relative to the

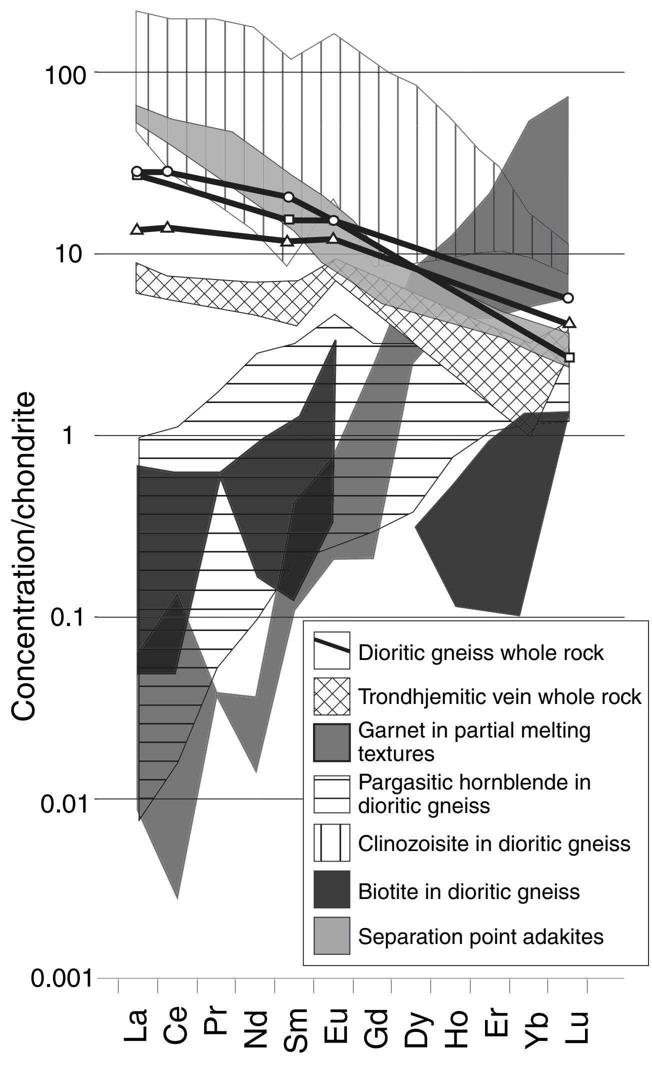

Fig. 3 Chondrite normalized whole-rock rare earth element patterns for the Pembroke Granulite dioritic gneiss and trondhjemitic veins, as well as rare earth element patterns from point analyses of garnet in partial melting textures in the Pembroke Granulite, and pargasitic hornblende, clinozoisite, and biotite in the Pembroke Granulite dioritic gneiss. For clarity, fields encompassing all analyses for a given mineral or rock are shown rather than individual lines for each analysis. The field containing whole-rock rare earth element patterns for the Separation Point Batholith adakites (Muir *et al.*, 1995) is also shown.

unmelted dioritic gneiss and to the minerals that control the melt forming reaction. The melt that was produced must therefore have had adakite-like LREE enrichment and HREE depletion. While this melt was not apparently quenched, the trondhjemitic veins which crystallized from the melt, along with their constituent plagioclase, show LREE enrichment relative to HREE. Mass imbalance for LREE between the reactants and products of the melt forming reaction is interpreted as reflecting the removal of melt from the region. Additionally, REE-rich apatite which is present in the dioritic gneiss may not be involved in the melt forming reaction. It is noted that the melt produced must have had a similar REE slope to that of the Separation Point Batholith in the upper crustal Nelson-Westland region (Muir *et al.*, 1995), consistent with the interpretation that such adakitic compositions can be produced by melting the dioritic gneiss and leaving garnet as a peritectic phase.

Sr and Y composition is a useful way of distinguishing adakites from MORB and island-arc derived igneous rocks. Figure 4 is a plot of Sr/Y vs. Y for Pembroke Granulite dioritic gneiss and trondhjemitic vein whole-rock samples, and individual minerals associated with the partial melting textures and trondhjemitic veins within the dioritic gneiss. The curves shown are the array of Sr and Y compositions for products of partial melting of garnet amphibolite and garnet granulite (after Defant and Drummond, 1990). The starting bulk rock and amphibole compositions plot near the reflex point of the curves. Crystallization of peritectic garnet (Sr/Y ~ 0; Y $= 8$–194 ppm) will involve incorporation of Y but not Sr, driving the melt composition to higher Sr/Y than the starting material, consistent with it being an adakitic melt. The trondhjemitic veins, which are partial crystallites from the melt, have high Sr/Y. Adakitic Separation Point Batholith whole-rock samples are also shown to illustrate the presence of similar adakitic compositions higher up in the Cretaceous crustal section.

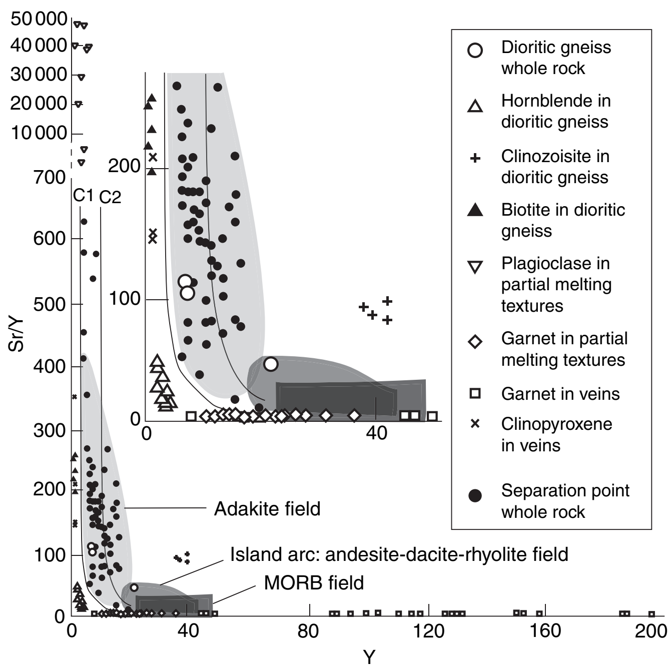

Fig. 4 Plot of Sr/Y vs. Y for whole-rock samples of the dioritic gneiss and trondhjemitic veins of the Pembroke Granulite, minerals associated with migmatitic textures in dioritic gneiss of the Pembroke Granulite, and whole-rock samples of the Separation Point Batholith (Muir *et al.*, 1995). Partial melting curves for basalt leaving residues of garnet granulite (C1) and 10% garnet amphibolite (C2) are from Defant and Drummond (1990).

To further assess whether melting of the Pembroke Granulite dioritic gneiss would produce an adakitic melt, we modelled the phase equilibria of melting using the MELTS software (Ghiorso and Sack, 1995). Various dioritic gneiss bulk-rock compositions were 'melted' in the pressure range $P =$ 1.4–2.0 GPa, and temperature range 700–900 °C, producing garnet, clinopyroxene (both present in the partial melting textures) and melt. Degrees of melting range from 4 to 16%. One example melt composition, for a 5% melt fraction, is presented in Table 1. The melt composition produced by MELTS for the *P–T* ranges above provide a good match with the composition of the Separation Point Suite listed by Muir *et al.* (1995), consistent with the argument that the adakitic compositions in the upper crust of the New Zealand crustal section can be produced by melting in the Pembroke Granulite.

These geochemical relationships are consistent with peritectic garnet in the dioritic gneiss representing a melt-depleted fraction from a mobilized melt that could have evolved to produce an adakitic melt similar to those preserved as the Separation Point Batholith. The geochemical criteria for the melt being adakitic are satisfied, and the data are consistent with the interpretation that the dioritic Pembroke Granulite represents the source of an adakitic melt, and as such is the first direct evidence for adakite formation through melting of mafic lower continental crust.

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