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Sm–Nd and Rb–Sr isotopic and geochemical systematics in Phanerozoic granulites from Fiordland, Southwest New Zealand

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Abstract. Sm–Nd and Rb–Sr isotopic analyses are reported for granulite facies orthogneisses from Fiordland southwest New Zealand. Whole-rock samples define a Rb–Sr isochron age of 120 ± 15 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70391 ± 4. ε_{Nd} values (at 120 Ma) show a relatively wide range of from -0.4 to 2.7 indicating decoupling of Sr-Nd isotope systems. Associated ultramafic rocks have initial $^{87}Sr/^{86}Sr$ ratios of from 0.70380 to 0.70430 and ε_{Nd} values of from 0.1 to 3.0. The different initial ratios suggest that the various intrusions, although contemporaneous, were not derived through fractionation of a single parent magma. A metasedimentary enclave incorporated during emplacement of the granulitic rocks preserves a Proterozoic isotopic signature with a measured $\varepsilon_{Nd}(0)$ value of -10.2, $^{87}Sr/^{86}Sr$ ratio of 0.73679 and a T^{Nd} provenance age of 1490 Ma. The Rb–Sr whole rock age of the granulites is the same as obtained from recent U-Pb zircon dating (Mattinson et al. 1986) and is interpreted as the time of magmatic emplacement and essentially contemporaneous granulite facies metamorphism. Rb–Sr and Sm–Nd analyses of mineral systems indicate that the terrain had cooled below $\sim 300°$ C by ~ 100 Ma providing further evidence that high grade metamorphism was of exceptionally short duration.

Unmetamorphosed leucogabbros from the Early Cretaceous Darran Complex of eastern Fiordland have significantly higher ε_{Nd} values (3.9 to 4.6) and slightly lower $^{87}Sr/^{86}Sr$ (0.70373 to 0.70386) than the western Fiordland granulites. This indicates that the western and eastern Fiordland complexes are not correlative although both have geochemical similarities to Phanerozoic calc-alkaline island-arc suites. The Fiordland granulites are LREE enriched ($La_N/Yb_N = 12$ to 40) and have trace element characteristics (e.g. high K/Rb and low Rb/Sr ratios) typical of many Rb-depleted Precambrian granulite terrains. The Fiordland trace element trends, however are attributed to magmatic, not metamorphic processes, reflecting the character of the Early Cretaceous magma sources. The range of ε_{Nd} values, but uniform initial $^{87}Sr/^{86}Sr$ of the western Fiordland granulites is consistent with derivation of the parent Early Cretaceous magmas at least in part from a LREE enriched, low Rb/Sr protoliths of mid-to late-Paleozoic age. Partial melting of this protolith occurred during or immediately preceding a period of great crustal thickening culminating in rapid thickening of existing crust by ~ 20 km following emplacement of the granulitic rocks. The rapid crustal thickening was probably a consequence of a collisional event in which an Early Cretaceous magmatic arc was over-ridden by one or more thrust sheets.

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Introduction

Although granulite facies rocks are common in Proterozoic and Archean shield terrains, they are almost completely absent from Phanerozoic orogenic belts. Granulite facies metamorphism has sometimes been viewed as a phenomenon resulting primarily from tectonothermal conditions unique to the Precambrian. The limited development of granulites in the Phanerozoic (e.g. Windley 1981) poses several important questions. Does it reflect a fundamental change in tectonic and/or thermal regimes operating within deep crustal environments or are the tectonic processes responsible for exhuming deep crustal sections generally less efficient in Phanerozoic than in the Precambrian, requiring longer time scales (>500 Ma) to be effective? Although Phanerozoic granulites are of only limited extent, they may provide insights into these and other important questions inasmuch as their tectonic setting, protoliths, and metamorphic history are generally better constrained in the Phanerozoic than in the more ubiquitious Precambrian examples.

In this study we present Sm–Nd and Rb–Sr isotopic data together with major and trace element geochemical data for regionally extensive Phanerozoic feldspathic granulitic orthogeneisses and associated rocks from Fiordland, New Zealand (Fig. 1). Additional isotopic data are presented for unmetamorphosed gabbronorites of similar chemical composition from the Darran Complex in eastern Fiordland, interpreted by some investigators (e.g., Blattner 1978) to be the granulite protolith. The Fiordland granulites are of particular interest in that they record a history of unusually high pressure crystallization (9–13 kb) (e.g., Newton and Perkins 1982), postdating an earlier period of lower pressure (5–6 kb) crystallization (Bradshaw 1983, 1985). The high pressure event corresponds to depths of burial of ~ 45 km, equivalent to lowermost regions of continental crust of "normal" thickness. The Fiordland granulites were initially inferred to be of Precambrian age (Oliver 1976, 1980; Oliver and Coggon 1979). In a recent study, however, Mattinson et al. (1986) have found concordant to slightly discordant Early Cretaceous U–Pb zircon ages interpreted as the time of synmetamorphic magmatic emplacement of

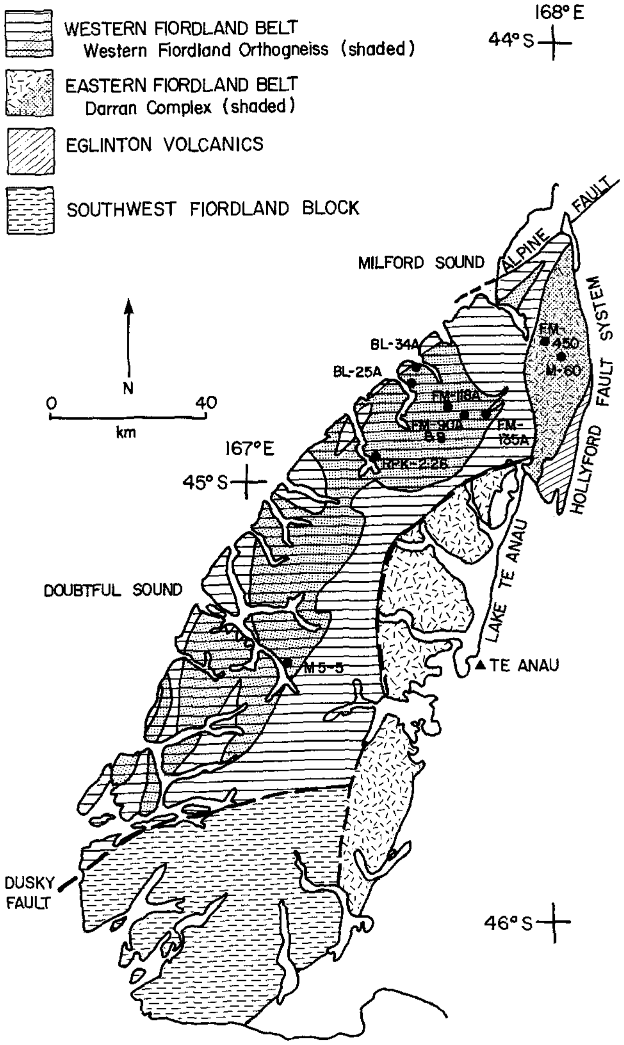

Fig. 1. Geologic map adapted from Bradshaw (1985) and Mattinson et al. (1985) showing location of analysed samples from Fiordland. Granulitic orthogneisses (WFO) are from the Franklin Mts. area of western Fiordland Leucogabbros are from the unmetamorphosed Darran complex in eastern Fiordland

the granulite protolith. The present investigation, undertaken concomitant with the U–Pb dating study of Mattinson et al. (1986), has a threefold aim. First to assess the timing of Fiordland granulite facies metamorphism and subsequent cooling history using the Sm–Nd and Rb–Sr isotope systems. Secondly to provide additional isotopic, trace and major element constraints on the age and petrogenesis of the premetamorphic protoliths, and thirdly to investigate major and trace element systematics in a Phanerozoic granulite terrain.

Geologic setting

New Zealand is the main subaerial exposure of a complex of crustal fragments including New Caledonia, Lord Howe Rise, Chatham Rise and the Campbell Plateau. These fragments originally made up a portion of the former margin of Gondwana that was rifted away from the Australian-Antarctic craton in late Cretaceous and early Tertiary time (e.g., Molnar et al. 1975; Weissel et al. 1977; Gleadow and Duddy 1980).

Fiordland is situated in the rugged southwest corner of New Zealand's South Island and is composed mostly of plutonic and high grade metamorphic rocks. It lies along a complex transform boundary of the Indian and Pacific plates, southeast of the offshore extension of the Alpine Fault, the main onland expression of the plate boundary. Metasedimentary rocks in Fiordland are generally thought to represent deeper level equivalents of the lower grade Paleozoic rocks exposed in the West Nelson area, which has been offset ~450 km by Cenozoic right lateral movement on the Alpine Fault (for a review of the NZ Paleozoic, see Cooper 1979). More detailed field-based studies have only been undertaken recently in Fiordland (e.g., Oliver 1976, 1980; Oliver and Coggon 1979; Blattner 1978; Gibson 1982a, b). Most of the published work was hampered by the lack of a reliable geochronologic framework, with little consensus emerging among the different investigators. The most recent field-work is contained in unpublished theses (King 1984; Ward 1984; Bradshaw 1985), on which the following brief summary is based.

Three distinct geologic regions are recognized in Fiordland, viz. western and eastern belts (Bradshaw 1985) and southwest Fiordland block (Oliver and Coggon 1979; Ward 1984). These regions are separated by major faults and have different tectonometamorphic histories. The southwest Fiordland block is characterised by abundant syn- and post-tectonic granites and locally poorly reconstituted metasediments preserving relict sedimentary structures. Ordovician graptolites (Benson and Keble 1936) and lithostratigraphy (Ward 1984) can be directly correlated with Ordovician and Cambrian sequences in West Nelson. Metamorphism is of andalusite-sillimanite facies series with metamorphic grade increasing from the southwest from biotite to sillimanite + K-feldspar zone. The main fabric-forming deformation predates early Mesozoic emplacement of the cross-cutting Lake Mike Granite (Ward 1984). By analogy with the West Nelson sequence the dominant metamorphism is inferred to be of mid Paleozoic age. This contrasts with the Early Cretaceous age of prevasive metamorphism and deformation north of Dusky Fault (Mattinson et al. 1986 and this study).

The structure of Fiordland north of Dusky Fault is characterized by the juxtaposition of two contrasting northeast trending rock belts (Fig. 1). The western belt incorporates the western and central Fiordland geological regions of Oliver and Coggon (1979), and comprises a variety of amphibolite facies metasedimentary and metaplutonic rocks plus the granulitic Western Fiordland Orthogneiss described below. The rocks of the western belt are faulted (King 1984; Bradshaw 1985) against an eastern belt including acid to intermediate volcanics and high level, virtually unmetamorphosed intrusions ranging from granite through to olivine gabbro and troctolite (e.g., Williams and Harper 1978; Oliver and Coggon 1979; King 1984). The easternmost rocks of this belt are unconformably overlain by Tertiary sediments.

Near Milford Sound, rocks of the western belt become highly deformed and attenuated in a zone of regional compression in which both the western and eastern Fiordland belts pinch out between the Alpine and Hollyford Fault systems. In the vicinity of Milford, metagabbros and metadiorities of the western belt are in contact with rocks in the eastern belt described by Bradshaw (1985) as the Darran Complex, a composite batholithic body of Early Cretaceous age consisting largely of gabbronorite, but also including varieties of dioritic, gabbroic, and ultramafic rocks, flanked to the east by minor granitic rocks. Although locally deformed, these rocks are essentially unmetamorphosed in the sense of not having been overprinted by a separate thermal event.

Fiordland granulitic rocks

The WFO concordantly underlies and intrudes a suite of amphibolite facies ortho- and paragneisses which includes Mid-Paleozoic granitic gneisses (Aronson 1968; Oliver 1980). Although in the Doubtful Sound region these rocks appear to be in fault contact (Oliver 1976, 1980; Oliver and Coggon 1979), clear-cut intrusive relationships are locally preserved in northern Fiordland, with the WFO enclosing rafted enclaves of granitoid gneiss and amphibolite facies ortho- and paragneiss derived from the country rock (Bradshaw 1985, and in preparation). Amphibolitization of the granulitic rock within ~ 1 km of the external contacts, and locally adjacent to some enclaves and shear zones, is attributed to infiltration of H_2O-rick fluids derived from the country rock (cf., Oliver 1980).

Regionally extensive granulite facies rocks in Fiordland are restricted to a distinctive suite of two-pyroxene dioritic rocks termed Western Fiordland Orthogeneiss (WFO) (Bradshaw 1985; Mattinson et al. 1986). The unit includes both granulites and their retrogressed equivalents, plus associated ultramafic intrusions such as hornblendite and pyroxenite. By far the most common granulite subassemblage is orthopyroxene + clinopyroxene + plagioclase ($<$An40) $\pm$ pargasitic hornblende; garnet granulite subassemblages (e.g., garnet + clinopyroxene $\pm$ quartz) are locally developed in mesoscopic reaction zones overprinting the feldspathic rocks (Blattner 1976; Oliver 1977; Bradshaw 1985). Essentially bimineralic garnet + clinopyroxene -rich eclogitic rocks are locally developed as products of similar garnet-forming reactions in hornblende-rich ultramafic rocks (Oliver 1976; Bradshaw 1985).

The WFO is a composite body consisting of virtually hundreds of separate intrusions. Two-pyroxene feldspathic rocks predominate, ranging from gabbroic diorite through monzodiorite to minor mesoperthitic monzonite. Concordant intersheeting is locally developed at intrusion margins and on an outcrop scale defines a crude mesoscopic layering. In other cases earlier intrusive material is represented by swarms or isolated concordant tabular bodies of centimetre to metre scale. Cumulate layering is in all cases rare. The presence of granulites in what is otherwise essentially an amphibolite facies terrain is attributed to autometamorphism resulting from synkinematic magmatic emplacement of WFO magmas (Bradshaw 1985).

The WFO is criss-crossed by hornblende-bearing plagioclase-rich veins and locally pegmatitic dikes, interpreted as late stage crystallization products of WFO feldspathic magmas (Bradshaw 1985). Some of the veins (and dikes) have been overprinted by garnet assemblages (e.g., S-21B of the present study) and have served as loci for development of mesocopic reaction zones which locally overprint enclosing 2-pyroxene granulitic rocks. The garnet-bearing assemblages have formed chiefly via reactions involving hornblende dehydration (e.g., Blattner 1976; Oliver 1977). The common occurrence of scapolite and CO_2-rich fluid inclusions in the garnet-bearing veins (Bradshaw 1985) is compatible with dehydration occurring in response to localized infiltration of carbonic fluids along earlier-formed fractures developed at vein margins. This restricted development of garnet occurs throughout the WFO and provides an important marker in the metamorphic and structural evolution of the rocks as these assemblages record only the latest, high pressure, event (Bradshaw 1985).

Both WFO and country rock record a similar metamorphic history characterized be early "low" pressure and later high pressure crystallization. Physical conditions of crystallization of mineral rims are estimated from mineral thermometry (Ellis and Green 1979) and barometry to have been 650–700° C at 10–13 kb (Bradshaw 1985, and Newton and Perkins 1982). Strongly zoned garnets coexisting with plagioclase, quartz, and Al_2SiO_5 minerals (kyanite at rims, sillimanite inclusions in garnet cores) in metapelitic rafts, country rock gneisses and contamination zones overprinting WFO, show a continuous core to rim increase in grossular content. Zoned clinopyroxenes co-existing with plagioclase and quartz in granulitic WFO show a core to rim increase in jadeite content. Phase equilibria in both systems are compatible with a pressure increase of >6 kb occurring during mineral crystallization. Thus the WFO is thought to have been emplaced initially at mid-crustal depths of ≤ 20 km, with later high pressure reflecting metamorphism at lower crustal depths of ~ 45 km.

Samples and methods

Descriptions of the samples analyzed are presented in the appendix; sample localities are illustrated in Fig. 1. The analyzed granulites come from widely separated localities and were selected to bracket the range of WFO whole rock compositions reported by Bradshaw (1985) from a study of >30 samples.

Sm–Nd isotopic analyses were undertaken using procedures described by McCulloch and Chappell (1980). Samples were decomposed with HF in teflon bombs for several days at a temperature of $\sim 205°$ C. After removal from the oven, $HClO_4$ was added to the samples and the $HClO_4$-HF mixture evaporated to dryness. Any remaining insoluble fluorides were eliminated by treating the samples with 6N HCl in teflon bombs. After removal from the oven, the HCl solution was partially evaporated and then diluted to ~ 1.5 N HCl, the concentration required for the ion exchange chemistry. The bomb procedures were adopted to ensure the total dissolution of resistant REE-bearing phases such as zircon and monazite. Duplicate analyses using bomb dissolutions agree within analytical uncertainty (McCulloch and Black 1982). The $^{143}Nd/^{144}Nd$ ratios are normalised using $^{146}Nd/^{142}Nd = 0.636151$ and the value obtained for the BCR-1 standard is 0.511833 ± 20. The $^{87}Sr/^{86}Sr$ ratio obtained for the NBS-987 standard is 0.71022 ± 4.

Major and trace elements were determined by XRF analysis using a Phillips PW-1400 instrument housed in the Geology Dept, Univ. of Canterbury, Christchurch, N.Z. Major and trace elements were analyzed following procedures of Norrish and Chappell (1967). REE analyses were obtained using the spark source mass spectrometer at ANU (Taylor and Gorton 1977). Chondrite normalizing values are from Taylor and McLennan (1985).

Results

1 Major and trace-element geochemistry

Major and trace-element compositions of representative samples analysed for Sr and Nd isotopes are presented in Table 1. The WFO granulitic rocks are characterized by moderate SiO_2 contents ($\sim 55\%$ to $\sim 60\%$), high Al_2O_3 ($\sim 17\%$ to 23%), high alkalis ($Na_2O + K_2O = \sim 6\%$ to 9%), and unusually high Sr (typically >1000 ppm). Additional samples analyzed in Bradshaw (1985) extend the range to lower SiO_2 (to ~ 50 wt%). All samples cluster on or near the silica saturation boundary, in agreement with the observed paucity of modal quartz. The rock suite is of mildly alkaline character (Bradshaw 1985) with an alkali-lime index of 54–57 overlapping the boundary between the alkali-calcic and calc-alkali fields. The alkaline character primarily reflects high Na_2O contents (5% to 6%), a feature previously noted by Oliver (1976) for equivalent rocks in the Doubtful Sound region of Fiordland.

With increasing SiO_2 the bulk of the WFO granulitic samples define a general trend of increasing Na_2O and K_2O, and decreasing FeO_{tot}, MgO and CaO, with Al_2O_3 remaining roughly constant (Bradshaw 1985). The trend of continuously decreasing FeO and MgO with increasing

Table 1. Major and trace element data for Fiordland granulitic rocks and Darran Complex leucogabbros

	BL-25A	FM-90A	FM-90B	FM-118	FM118 Plag	M-45C	M-60	RPK-2.26
	Granulites					Leuco-gabbros	Leuco-gabbros	Meta-sediment
SiO_2	56.62	56.37	60.22	54.60		51.03	53.59	72.89
Al_2O_3	16.98	16.93	21.18	17.08		17.94	17.74	13.63
TiO_2	1.44	1.43	0.60	1.26		2.26	1.11	0.73
FeO*	6.34	6.11	2.13	7.29		9.79	9.07	4.93
MnO	0.10	0.13	0.03	0.11		0.15	0.15	0.05
MgO	2.91	3.66	0.74	5.20		4.48	4.19	2.05
CaO	5.02	5.69	4.86	7.31		8.89	7.89	1.06
Na_2O	4.81	4.76	6.43	4.58		4.65	4.01	2.08
K_2O	3.14	2.31	2.52	1.20		0.90	1.17	2.87
P_2O_5	0.47	0.50	0.17	0.45		0.58	0.42	0.11
Sr	795	1178	1487	1484	2029	725	694	92
Rb	112	43	32	8	2.05	16	39	105
Y	26	17	6	11	0.4	27	25	
Zr	831	71	116	55		62	148	
Hf	19.7	1.7	2.6	1.4	–	1.5	4.7	7.5
Nb	19	15	4	6	0.3	8	4	
Ba	810	815	1050	580	290	385	360	705
U	1.50	1.02	0.38	0.12	–	0.29	1.44	2.14
Th	3.3	3.2	1.0	0.75	–	1.2	3.7	15.8
La	39.4	35.7	17.5	17.3	10.7	18.9	15.2	45.2
Ce	94.0	80.9	37.8	42.0	16.0	43.5	40.5	95.7
Pr	10.9	10.0	4.1	5.0	1.2	6.1	5.1	10.6
Nd	43.2	34.6	14.2	23.9	3.5	27.3	20.4	40.6
Sm	8.0	6.4	2.3	4.4	0.4	6.1	4.7	8.0
Eu	1.7	1.8	1.8	1.3	0.9	1.4	1.3	1.5
Gd	6.0	4.6	2.2	3.4	0.3	5.6	4.4	6.6
Tb	0.9	0.7	0.3	0.5	0.1	0.9	0.7	1.1
Dy	4.8	3.5	1.3	2.7	0.2	4.76	4.2	6.5
Ho	0.8	0.6	0.2	0.4	0.02	0.9	0.9	1.3
Er	2.4	1.5	0.4	0.9	–	2.4	2.4	3.6
Yb	2.2	1.3	0.3	0.7	–	2.1	2.2	3.1
K/Rb	280	448	666	1445		467	249	230
Eu/Eu*	0.7	0.9	2.2	1.1	8.7	0.7	0.8	0.6

alkali content is a common feature of broadly calc-alkaline differentiation sequences. However, it should be noted that the most "evolved" rocks here (e.g., FM-90B) are plagioclase-rich leucocratic monzodiorites, not granites. They occur as minor late stage intrusions invading less evolved rocks, indicating a strong late stage trend towards plagioclase enrichment. As these rocks are volumentrically insignificant on a regional scale, specific processes governing their development may not be representative of processes controlling the evolution of the feldspathic rock group as a whole.

The trace element chemistry of WFO granulitic rocks is characterized by high to very high Sr contents (800–1850 ppm), and widely variable Rb (1–116 ppm), Zr (30–960 ppm), and Nb (3–20 ppm) (quoted compositional ranges are from Bradshaw 1985). Rb content shows a crude antipathetic variation with Sr, yielding a wide range of Rb/Sr ratios (0.147 to 0.003). The antipathetic variation of Rb with Sr and sympathetic variation of Rb with K (see below) suggest that much of the variation is of primary origin and reflects magmatic processes. Overall, Rb content shows a strong positive correlation with K. Both elements show a high degree of mineralogical control, varying as a positive function of modal abundance of K-feldspar and/or biotite. K/Rb ratios reported for these rocks in Bradshaw (1985) range from ~2800 to 265, with the bulk of the samples having K/Rb ratios <1200 (Fig. 2). Low Rb/Sr (<0.02) and high K/Rb ratios (>500) are common features of many Precambrian granulite terranes (e.g., Tarney and Windley 1977; Rudnick et al. 1985). These features are often attributed to Rb-depletion accompanying granulite grade metamorphism, with Rb-loss attributed to processes such as generation of mobile anatectic melts (Heier 1973), or migrating fluids generated from dehydration reactions or mantle degassing (Collerson and Fryer 1978). Although Rb-loss is commonly involked to explain the high K/Rb ratios typical of many granulite terranes, primary magmas having K/Rb ratios as high as 1800 have been reported in island-arc basalts (e.g., Gill 1981) indicating that Rb-depletion is also a characteristic of some island-arc magmas. In the present case there is no compelling evidence to suggest that selective Rb-depletion has occurred during metamorphism. Many of the low-Rb rocks show dominant relict igneous textures indicating that no significant mineralogical changes have occurred following magmatic crystallization. A trend of increasing K/Rb ratio with decreasing K content, is also shown by unmetamorphosed rocks of the Darran complex (Fig. 2).

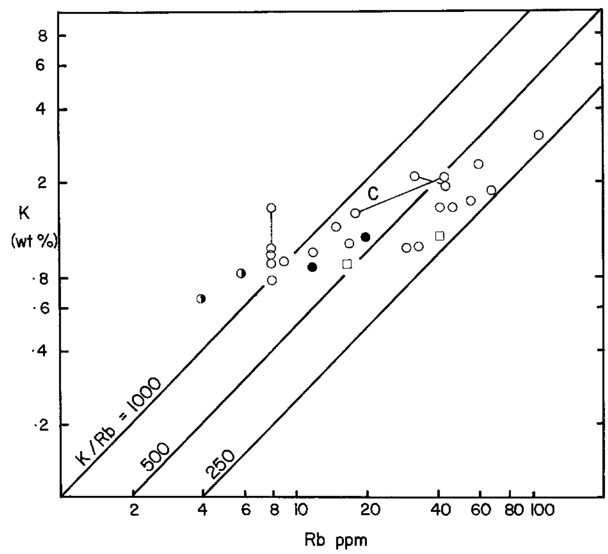

Fig. 2. K versus Rb contents for the western Fiordland orthogneisses (*solid circles* are garnet bearing samples). *Tie lines* connect samples from the same locality. *Tie-line "C"* connects FM90A and FM90B. Darran Complex leucogabbros shown by *squares*. Data from Bradshaw (1985) and this study; *half filled circles* from Oliver (1976)

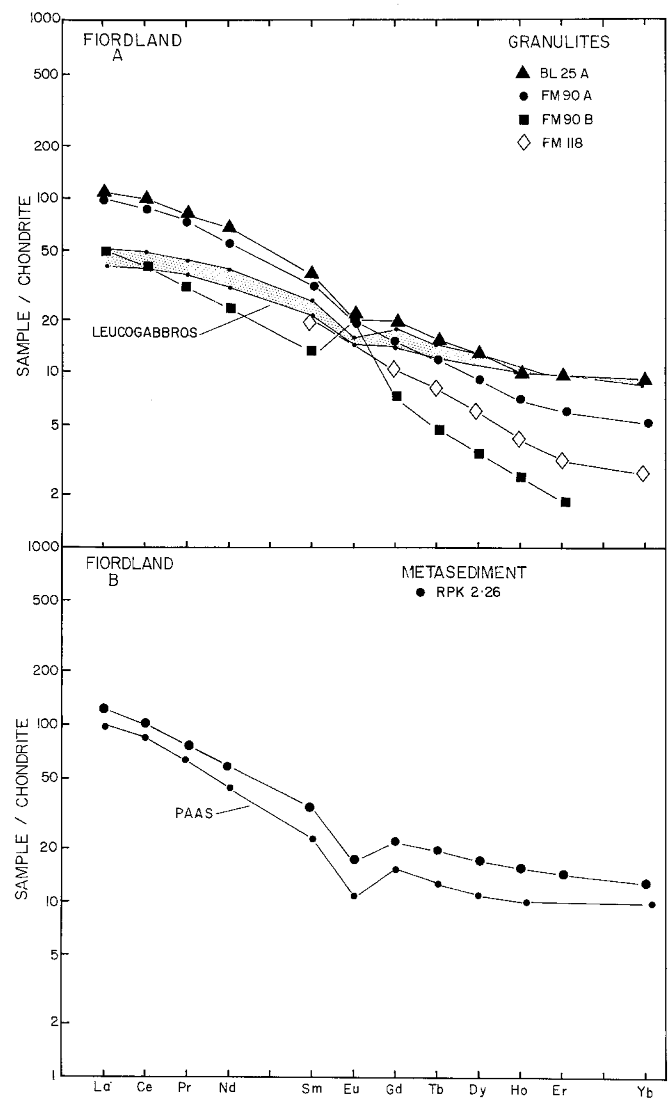

Fig. 3 A, B. Rare earth element abundances of the feldspathic granulites, leucogabbros and sediment. **A** Comparison of granulitic orthogneisses from Fiordland leucogabbros from the Darran Complex. The granulites have both positive and slight negative Eu anomalies. Leucogabbros from the Darran Complex have distinctive patterns with smaller depletions of HREE relative to LREE. **B** Comparison of the Fiordland metasediment with PAAS (Nance and Taylor 1976). The metasediment has a pattern which is very similar to PAAS but at higher abundance levels. Chondrite values are from Taylor and Gorton (1977)

In the WFO the essentially linear K vs Rb trend, with K/Rb increasing markedly at lower K content could suggest fractionation of a potassic phase (e.g., K-bearing plagioclase) concentrating K relative to Rb. The late stage plagioclase-rich intrusions (e.g., FM-90B) however show the reverse trend of increasing K/Rb with increasing K_2O. As there is only limited evidence for fractionation, the observed four-fold variation in K/Rb ratios is attributed to varying K/Rb in the source region from which the magmas were derived.

The two Darran Complex gabbronorites have major element compositions broadly similar to granulitic rocks of the WFO but in contrast are unmetamorphosed in the sense of not having experienced a separate postmagmatic thermal event. Blattner (1978) also noted their similarity, leading him to suggest that the rocks were cogenetic and formed as part of the same intrusive complex. The samples studied here are from the western and central parts of the Darran Complex (M-45C and M-60, respectively) and are of more evolved composition (higher SiO_2 and total alkalis) compared to gabbroic rocks from the eastern Darran Complex described by Williams and Harper (1978) and Williams and Smith (1983). Gabbroic and associated granitoid rocks of the Darran Complex have an alkali-lime index of ~ 58, corresponding to the middle of the calc-alkali series. These rocks however lack the mildly alkaline character apparent in the WFO rock suite and also differ in terms of trace element chemistry, having consistently lower Sr for a given Rb content than rocks of the WFO.

Chondrite normalized REE abundances for WFO granulites, Darran Complex gabbronorites and a metasedimentary raft enclosed by WFO are shown in Fig. 3a and b. The WFO granulites have pronounced LREE enrichments ($La_N/Yb_N = 12$ to 40) which is consistent with melting of a garnet bearing source (Arth and Hanson 1975 and Rudnick and Taylor 1986). The plagioclase-rich granulite FM-90B has the lowest total REE abundances and a distinct positive Eu anomaly, which together with its very high Al_2O_3 and Sr content is compatible with an origin involving plagioclase accumulation. The occurrence of this sample as a late intrusion would seem to require mobilization of earlier fractionated material from depth. The other granulite samples have small negative (BL-25A) or non-detectable (FM-90A and FM118) Eu anomalies. In the latter case this point is significant in that both FM-90A and FM118 have high Sr contents which cannot therefore be easily related to plagioclase accumulation; the high Sr content of the suite appears to be a characteristic of the magma source (see below). Further support for the lack of extensive plagioclase accumulation as an explanation for these high Sr contents is provided by the REE analysis of a plagioclase seperate from FM118. As may be anticipated the plagio-

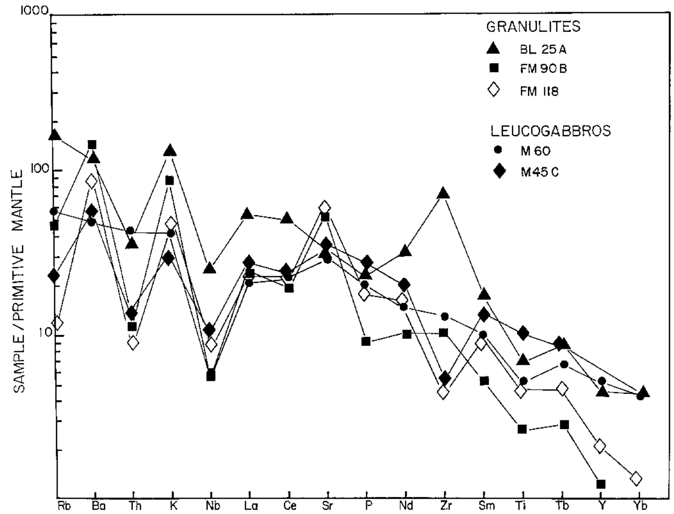

Fig. 4. Primitive mantle normalised plot of WFO granulites and Darran Complex leucogabbros. (Normalizing values from McDonough et al. 1985). All samples show Nb depletions with the three granulites also having Ti depletions. These features are analogous to those found in island-arc calc-alkaline basalts

clase separate has both high Sr contents as well as a large positive Eu anomaly (Eu/Eu* = 8.7) and thus indicates that little or no plagoclase accumulation has occurred in this sample.

The Darran Complex gabbronorites analyzed in this study have slightly lower total REE abundances and lesser degrees of LREE enrichments than WFO granulitic rocks ($La_N/Yb_N = 5$ to 6 vs 12 to 40, respectively). Both gabbronorites show slight negative Eu anomalies (Fig. 3). In contrast, gabbronorites analyzed by Williams and Smith (1983) from the eastern part of the Darran Complex show markedly lower total REE abundances and distinct positive Eu anomalies. The low total REE abundances were interpreted by Williams and Smith (1983) as reflecting high crystal/liquid ratios in a calc-alkaline cumulate sequence. The occurrence of rocks showing positive Eu anomalies in the east, and negative anomalies in the west of the complex is compatible with the interpretation of Williams and Smith (1983) of the gabbroic rocks as part of a differentiated basic intrusion in which progressive fractionation, indicated by increasing pyroxene Fe/Mg ratios, proceeded from east to west.

Chondrite normalized REE abundances for migmatitic metasediment RPK-2.26 are shown in Fig. 3b along with the post-Archean average Australian shale (PAAS of Nance and Taylor 1976). In contrast to the variable patterns of WFO granulitic rocks the metasediment has REE abundances which are subparallel to PAAS. This suggests a relatively homogeneous sediment source and together with the isotopic data presented below is compatible with a Proterozoic provenance age.

Selected elemental abundances are shown on a primitive mantle normalised diagram in Fig. 4. Relative to La and K, all the samples show marked Nb depletion with the feldspathic granulites and leucogabbros possessing relatively high La_N/Nb_N ratios of >2. High La_N/Nb_N ratios are a feature of island-arc type volcanism in contrast to intraplate alkali volcanics which generally have $La_N/Nb_N < 1$ (e.g., Thompson et al. 1984; Nakamura et al. 1985). In addition the two granulite samples shown in Fig. 4 have Ti depletions which is also a common feature of island-arc volcanics. One of the samples (BL 25A) has unusually high abundances of Zr and Hf. This may reflect heterogeneous distribution of zircon or may possibly be due to mobility of Zr and Hf during granulite facies metamorphism and could have implications for the growth of zircons during granulite facies metamorphism.

In summary, the WFO granulitic rocks and gabbronorites from the Darran Complex share many common geochemical features that are consistent with both suites being products of calcalkaline island-arc magmatism. Differences in REE abundance patterns and minor element ratios, however, suggest that the Western Fiordland granulites and Darran Complex gabbronorites are not comagmatic, in agreement with the isotopic data presented below.

2 Rb–Sr and Sm–Nd isotopic systematics

Isotopic compositions are listed in Table 2 and shown in Figs. 5–9. Rb–Sr isotopic data for six whole-rock samples of granulitic WFO (solid symbols in Fig. 5) have low $^{87}Rb/^{86}Sr$ ratios (0.014 to 0.397) but yield a reasonably precise isochron age of 120 ± 15 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70391 ± 4 (uncertainties in age and initial represent 95% confidence limits). In an attempt to provide more definitive age constraints, the minerals biotite, clinopyroxene and plagioclase were analysed from one of the granulites (FM-118). The minerals and whole-rock yield an internal Rb–Sr isochron age of 101 ± 3 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70393 ± 7 essentially identical to the above. This age is controlled by biotite and indicates that cooling had occurred below the Rb–Sr closure temperature of biotite ($\sim$300–350° C) by $\sim$100 Ma. A noteable feature of the mineral-whole rock isochron is the aberrant behaviour of orthopyroxene. It has an anomalously high initial $^{87}Sr/^{86}Sr$ ratio of 0.70423 ± 6 compared to the whole-rock value of 0.70393 ± 4. A repeat analysis yielded the same result; at present we can see no obvious explanation for this observation, which implies highly selective internal isotopic disequilibrium.

The Rb-Sr whole-rock isochron age is in excellent agreement with concordant U-Pb zircon ages (118–120 Ma) reported by Mattinson et al. (1986) for rocks from the same area. Inasmuch as the samples analyzed here come from discrete intrusions from widely separated localities, the isochron is interpreted as a close approximation to the magmatic age, dating the time of separation of the different magma pulses from a source of uniform $^{87}Sr/^{86}Sr$. Large scale post-magmatic homogenization of Sr isotopes is precluded by the preservation of different initial ratios in closely associated ultramafic intrusions and metasediment rafts (see below); both of the latter occur on scales smaller than individual WFO feldspathic intrusions. $^{87}Rb/Sr^{86}$ and $^{87}Sr/^{86}Sr$ ratios for the websterite intrusion BL-4A and garnet + clinopyroxene separates from eclogitized ultramafic intrusion S-21A yield initial ratios (at 120 Ma) of 0.70405 and 0.70429, respectively. Garnet separated from cross-cutting pegmatoid dike S-21B has an initial $^{87}Sr/^{86}Sr$ ratio of 0.70380. The different initial ratios suggest that the ultramafic and feldspathic rocks were derived from different sources, indicating that these rocks could not have been strictly cogenetic. The different initial ratios for the two ultramafic rocks further suggest that either two different

Table 2. Sm-Nd and Rb-Sr isotopic data for Fiordland, New Zealand

Samples	Rb	Sr	Sm	Nd	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(0)$	ε_{Nd}	$^{87}Sr/^{86}Sr(I)$
	ppm									(120 m.y.)	
Granulites											
FM118 WR	6.98	1397	5.26	27.31	0.0144	0.70396±4	0.1164	0.511822±20	−0.3	1.0	0.70393
cpx	0.33	63.47	12.90	46.84	0.0151	0.70398±6	0.1666	0.511911±22	1.5	1.9	0.70395
opx	0.23	13.36	1.75	9.62	0.505	0.70432±6	0.1103	0.511892±18	1.1	2.4	0.70423
plag	2.05	2029	0.36	3.66	0.0029	0.70392±4	0.0593	0.511813±26	−0.4	1.7	0.70391
biotite	148.10	56.99			7.5086	0.71466±6					0.70185
FM90A	39.99	1137	6.38	34.64	0.1015	0.70406±4	0.1114	0.511879±32	0.8	2.1	0.70389
FM90B	30.12	1432	2.33	14.17	0.0607	0.70404±6	0.0997	0.511896±26	1.2	2.7	0.70394
FM135	15.60	1331	4.28	22.69	0.0338	0.70395±3	0.1141	0.511750±26	−1.7	−0.4	0.70389
BL25A	109.00	791.9	7.97	43.17	0.3972	0.70358±4	0.1116	0.511828±26	−0.1	1.1	0.70390
BL34A	77.95	1107	6.74	34.27	0.2034	0.70427±4	0.1189	0.511876±26	0.8	2.0	0.70392
Leucogabbros											
M45C WR	14.88	700.8	6.11	27.31	0.0612	0.70384±4	0.1354	0.512024±22	3.7	4.6	0.70374
cpx	1.55	29.05	10.78	29.93	0.1541	0.70399±6	0.2177	0.512052±30	4.2	3.9	0.70373
plag	2.86	1083	1.40	8.05	0.0076	0.70388±5	0.1055	0.511977±20	2.7	4.2	0.70387
M60	37.35	673.3	4.68	20.45	0.1601	0.70407±4	0.1385	0.512008±26	3.3	4.2	0.70380
Ultramafics											
S21A cpx	0.06	151.5	8.29	31.23	0.0011	0.70429±9	0.1606	0.511943±28	2.1	2.6	0.70429
S21A gnt	0.15	6.78	3.14	3.79	0.0638	0.70441±9	0.5008	0.512082±28	4.8	0.1	0.70430
S21B WR			6.35	29.29			0.1311	0.511936±22	1.9	3.0	
S21B cpx			7.86	27.87			0.1707	0.511911±34	1.5	1.9	
S21B gnt	1.26	66.0	4.00	6.48	0.0550	0.70390±7	0.3732	0.512110±22	5.4	2.6	0.70380
BL 4A	17.62	74.13	9.09	37.82	0.6861	0.70522±8	0.1454	0.511825±18	−0.2	0.6	0.70405
Metasediment											
RPK 2.26	105.4	92.3	8.00	40.63	3.3050	0.73679±9	0.1192	0.511313±10	−10.2	−9.0	0.73115

$\varepsilon_{Nd} = [(^{143}Nd/^{144}Nd)^T_{INIT}/(^{143}Nd/^{144}Nd)^T_{CHUR} - 1]10^4$ where $(^{143}Nd/^{144}Nd)^T_{INIT}$ are initial ratios at $T = 120$ m.y. and $(^{143}Nd/^{144}Nd)^T_{CHUR} = 0.511836 - 0.1967\ (e^{\lambda T} - 1)$ where $\lambda = 6.54 \times 10^{-12}\ yr^{-1}$

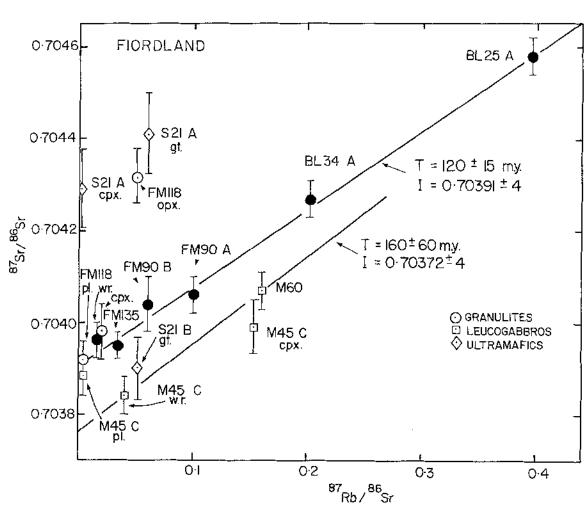

Fig. 5. Rb–Sr isochron diagram for feldspathic granulites, associated ultramafics from western Fiordland and leucogabbros from the Darran complex of eastern Fiordland. Whole-rock samples of the granulites (*solid circles*) define an age of 120±15 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70391±4. The ultramafic samples have insufficient variation in Rb/Sr to define an age but have a relatively wide range of initial $^{87}Sr/^{86}Sr$ of from 0.70380 to 0.70430 (calculated at 120 m.y.). Leucogabbros from the Darran Complex give a relatively imprecise age of 160±60 m.y. but have the lowest initial $^{87}Sr/^{86}Sr$ ratio of 0.70372±4

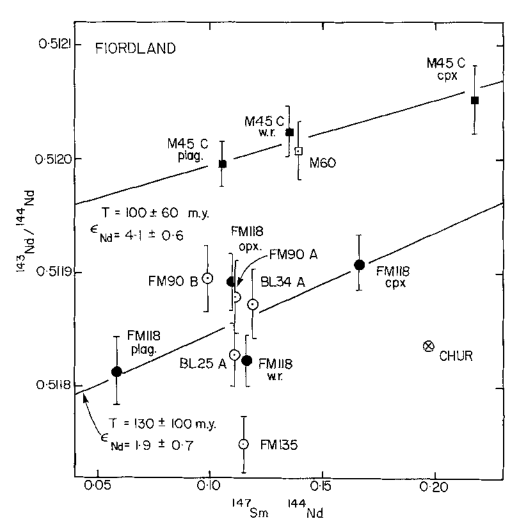

Fig. 6. Sm–Nd isochron diagram for whole-rocks and minerals from the feldspathic granulites of western Fiordland (*circles*) and Darran Complex leucogabbros from eastern Fiordland (*squares*). *Solid symbols* show coexisting minerals and whole-rocks. There is insufficient variation in Sm/Nd to define precise ages but at 120 m.y. the granulites have significantly lower initial $^{143}Nd/^{144}Nd$ (ε_{Nd} = 0.4 to 2.7) compared to the Darran leucogabbros (ε_{Nd} = 3.9 to 4.6)

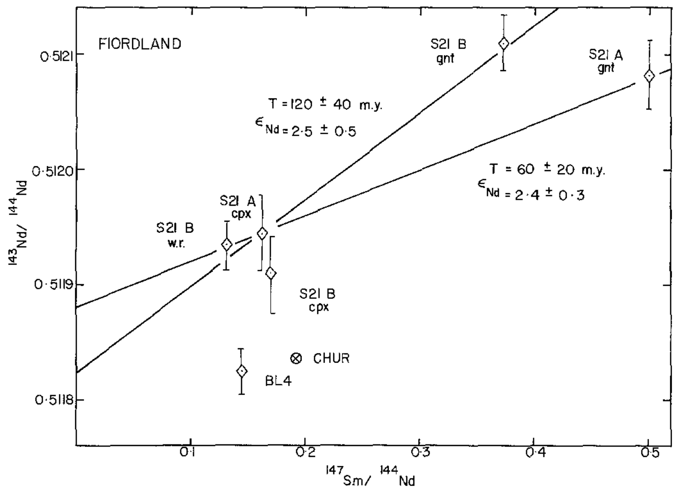

Fig. 7. Sm–Nd mineral isochrons for ultramafics (WFO eclogite S21A and garnet granulite pegmatite S21B). The age of 120±40 m.y. for S21B is identical to the Rb–Sr whole-rock age of the felsic granulites, consistent with this being the time of granulites facies metamorphism. The age of 60±20 m.y. for S21A may indicate a younger thermal event but this cannot be resolved with the present uncertainty limits. Websterite whole-rock (BL4) shown for comparison

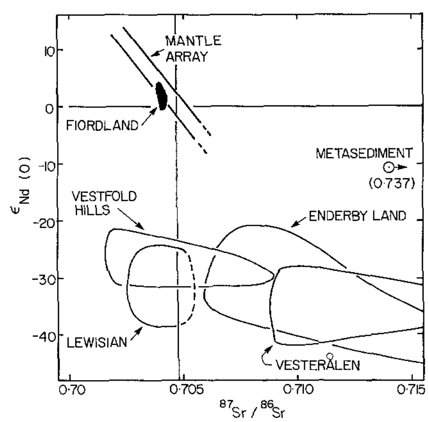

Fig. 8. Comparison of measured $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios of Fiordland with those from Proterozoic and Archean granulite terrains. (Collerson et al. 1982; Hamilton et al. 1979; Jacobsen and Wasserburg 1979; McCulloch and Black 1984). Fiordland has primitive measured ratios which fall within the lower portion of the present-day mantle array, clearly indicating a Phanerozoic protolith. The oldest component identified in New Zealand is the metasediment which has a mid-Proterozoic provenance age

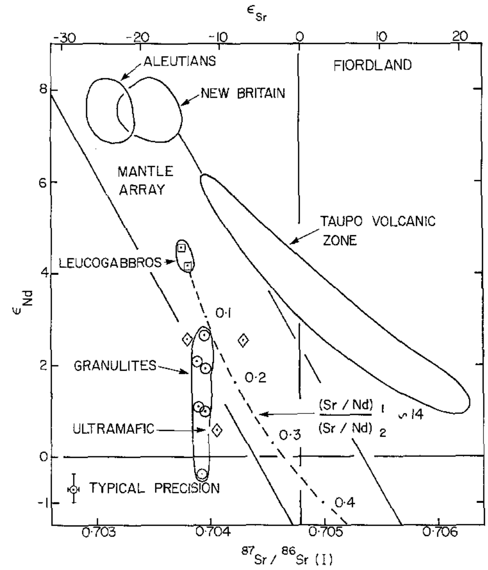

Fig. 9. Initial Nd and Sr isotopic compositions (at 120 m.y.) of the granulites and ultramafics from western Fiordland and the leucogabbros from the Darran Complex of eastern Fiordland. The leucogabbros have isotopic compositions consistent with a Mesozoic island-arc origin. The granulites (and ultramafics) have similar initial $^{87}Sr/^{86}Sr$ as the Darran leucogabbros but significantly lower ε_{Nd} values. Contamination of a magma of the same composition as the leucogabbros with the metasediment (RPK-2.26), would produce an array as shown by the *dashed line*. To produce the range in ε_{Nd} values in the granulites would require assimilation of 10% to 35% sediment. This would also produce a relatively large range in $^{87}Sr/^{86}Sr$ (0.7040 to 0.7048) which is not observed. The lower ε_{Nd} values of the granulites and ultramafics from western Fiordland are attributed to an older mid-Paleozoic protolith

sources are involved, or, in the case of eclogitic rock S-21A, that subsequent localized isotopic re-equilibration may have occurred with an infiltrating fluid of higher $^{87}Sr/^{86}Sr$ ratio. Eclogitization of hornblende-rich ultramafic rocks in the WFO is attributed by Bradshaw (1985) to dehydration accompanying infiltration of CO_2-rich fluids.

Sm–Nd isotopic data for plagioclase, clinopyroxene and orthopyroxene separates from granulite FM-118 yield an internal mineral-whole rock isochron of 130±100 Ma and an initial $^{143}Nd/^{144}Nd$ ratio corresponding to $\varepsilon_{Nd}=1.9\pm0.7$ (Fig. 6). This age is similar to, but much less precise, than the Rb–Sr ages described above. Garnet and clinopyroxene separates from eclogitic rock S-21A and garnet granulite pegmatite S-21B have a relatively large dispersion in $^{147}Sm/^{144}Nd$ (0.16 to 0.50), yielding internal isochron ages of 60±20 Ma and 120±40 Ma and ε_{Nd} values of 2.4±0.3 and 2.5±0.5 respectively (Fig. 7). The older age for S-21B is in agreement with the more precise Rb-Sr mineral age of 101±3 Ma for FM-118. The younger age of 60±20 Ma for S-21A, although at the limit of analytical uncertainties, may suggest a more recent metamorphic disturbance of the Sm–Nd system. Mattinson et al. (1986) report a U-Pb apatite cooling age of 57 Ma for a granulite from the same area, close to the offshore extension of the Alpine Fault. K/Ar biotite ages of <10 Ma have been reported near the Alpine Fault elsewhere in New Zealand (e.g. Adams et al. 1979); the young ages have been attributed to high heat flow related to recent rapid uplift.

Sm–Nd analyses of the same granulite whole-rock samples analyzed for Rb-Sr have an insufficient dispersion in $^{147}Sm/^{144}Nd$ (0.0997 to 0.1189) to define an isochron. A plot of $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$ shows that all these rocks could not have had the same initial ratio. Initial $^{143}Nd/^{144}Nd$ ratios calculated at 120 Ma correspond to a range in ε_{Nd} values from 2.7 to -0.4. These are among the most primitve ε_{Nd} values yet reported for felsic LREE enriched granulites and clearly indicate a young (Phanerozoic) protolith age for the terrain (Fig. 8). These differences also imply that the various feldspathic intrusions were not strictly cogenetic in the sense of being derived through differentiation of a single parent magma. The essentially constant initial $^{87}Sr/^{86}Sr$ is in contrast to the significant range in ε_{Nd} values of the WFO and is anomalous in respect to the commonly observed correlation of Nd-Sr isotopes. The WFO samples plot as a vertical array extending below the mantle array (Fig. 9). The origin and possible petrogenetic implications of the decoupled Sr and Nd isotopic systematics is discussed in more detail below.

Migmatitic metasediment RPK-2.26 from a raft enclosed within the WFO has substantially more evolved isotopic compositions than the above rocks, with a measured $^{87}Sr/^{86}Sr$ ratio of 0.73679 and an ε_{Nd} (0) value of -10.2 – T^{Nd} and T^{Sr} model ages calculated using depleted mantle parameters (eg. Liew and McCulloch 1985) are 1490 Ma and 700 Ma respectively. The model ages approximate the time at which the material making up the sediment initially differentiated from the mantle and became incorporated into the continental crust (e.g. DePaolo and Wasserburg 1976; McCulloch and Wasserburg 1978). Owing to the apparent resistance of Sm–Nd to disturbance during sedimentation, diagenesis, and high grade metamorphism (e.g. McCulloch and Wasserburg 1978), the Sm–Nd model age provides an estimate of the provenance age. The significantly younger age given by the Rb–Sr systematics probably reflects disturbance due to enrichment of Rb and/or reequilibration of $^{87}Sr/^{86}Sr$ during sedimentation and/or later metamorphism. Although details of the pre-Cretaceous history of this rock are unknown, in the early Cretaceous it experienced sillimanite + K-feldspar grade metamorphism and partial melting associated with emplacement of the now enclosing WFO. The Sm–Nd model age is in general agreement with Proterozoic U-Pb ages obtained from detrital zircon in mid-Paleozoic Greenland Group sediments in west Nelson (Aronson 1968).

Rb–Sr isotopic analyses of two unmetamorphosed gabbronorites from the Darran Complex samples yield a poorly defined Rb–Sr whole-rock age of 160 ± 60 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70372 ± 4 (Fig. 5). This is in general agreement with the concordant U-Pb zircon age of 137 ± 1 Ma reported by Mattinson et al. (1986) for similar rocks. Although the Darran Complex Rb–Sr age is not distinguishable from the Rb–Sr whole-rock age of the WFO granulites, the initial $^{87}Sr/^{86}Sr$ ratio of the Darran Complex is slightly but significantly lower (0.70372 ± 4 compared to 0.70391 ± 4). The ε_{Nd} values of the Darran Complex gabbronorites are also substantially different, with more positive values of 4.6 and 4.2 compared to values of -0.4 to 2.7 for the WFO. The minerals plagioclase and clinopyroxene were analyzed from M-45C and together with the whole rock give a Sm–Nd age of 100 ± 60 Ma and an ε_{Nd} value of 4.1 ± 0.6.

Metamorphic history

Isotopic data presented in this study provide further evidence indicating a Cretaceous age for the main phase of magmatism, intense tectonism and granulite facies metamorphism in Fiordland north of Dusky Fault. Constraints on the timing of these events is provided by the Rb–Sr whole-rock isochron dating the time of magmatic crystallization of the WFO granulite protolith at 120 ± 15 Ma, and Rb–Sr mineral ages dating the time of final uplift and cooling of this body to ~ 300–350° C by about 100 Ma. Rb–Sr biotite and U-Pb apatite cooling ages of ~ 90 Ma have also been reported by Aronson (1968) and Mattinson et al. (1986), respectively, from the western-central Fiordland region. The combined geochronologic constraints reported in the present study and in Mattinson et al. (1986) indicate that mid-crustal emplacement of the WFO magmas, onset of collision and subsequent high pressure metamorphism, together with final uplift and cooling to 300–350° C, all occurred in an interval of ~ 20 Ma. The Fiordland granulites are thus products of a metamorphic event of exceptionally short duration, with rapid uplift and cooling of the high pressure metamorphic terrane required by the short interval between the time of magmatic emplacement and uplift-controlled final cooling.

The above considerations suggest an average cooling rate as high as 30° C/Ma could have occurred over this interval (emplacement temperature of WFO magmas assumed to be ~ 1000° C). Using this estimate, additional constraints can be placed on the timing of peak pressure and subsequent onset of uplift. For a constant cooling rate, the 650–700° C conditions accompanying high pressure metamorphism could have been attained within ~ 10 Ma of magmatic emplacement, at about ~ 110 Ma. Although subject to considerable uncertainty, this estimate provides a likely minimum age for the beginning of uplift, allowing as much time for uplift as for collision, crustal thickening via overthrusting, and high pressure metamorphism combined. The maximum age for beginning of uplift is provided by the concordant 118 Ma U-Pb zircon age of WFO gneiss reported by Mattinson et al. (1986).

Assuming the geothermal gradient immediately above the Western Fiordland Orthogneiss at the time of uplift was ~ 35° C/km, blocking of the Rb/Sr mineral isotope system at 300–350° C would have occurred at a depth of ~ 10 km. An indicated peak metamorphic pressure of ~ 12–13 kb, is equivalent to ~ 45 km depth assuming an average crustal density of 2.8 g/cm^3. This indicates uplift on the order of 35 km over an internal as short as 10–18 Ma; this requires uplift rates on the order of 2 to 3.5 mm/year. Although this is faster than maximum uplift rates proposed for the Himalayas (0.8 mm/year; Sharma et al. 1980; Zeitler 1980) and the Alps (~ 1 mm/yr; Clark and Jager 1969), it is well within the range estimated for recent uplift in the New Zealand Southern Alps (up to 17 mm/yr; Wellman 1979).

The driving force behind the rapid uplift following collision in the Early Creataceous is not clear. Although uplift is likely to have resulted in part from isostatic over-compensation aided by surface erosion acting to restore the overthrust-thickened crust to more normal thickness, long-term uplift rates as high as these might conceivably require involvement of external tectonic forces. A collisional regime, resulting from opening of the Tasman Sea may have produced circumstances similar to that of the present day Alpine Fault (a compressional transform boundary). However, insufficient data are available at present to warrant further speculation on this point.

Protolith history: WFO magma source constraints

The extremely primitive isotopic character of Fiordland rocks is evident in Fig. 8 which shows the present day measured $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of felsic granulites from a variety of terrains. The Western Fiordland granulites have measured ε_{Nd}(o) values and $^{87}Sr/^{86}Sr$ ratios that overlap in part with present-day mantle compositions. In contrast the ε_{Nd}(o) values of Proterozoic and Archean granulites typically range from $\varepsilon_{Nd}\sim$-20 to -40 while $^{87}Sr/^{86}Sr$ ratios have a wide variation of from $\sim$0.702 to 0.715 (see also Ben Othman et al. 1984, for a recent summary). This contrast in present-day isotopic compositions for granulites with broadly similar major and trace-element compositions (Table 1) provides first-order evidence for the very recent (Phanerozoic) formation of the Western Fiordland granulites.

In considering the origin of the Fiordland magma sources it is instructive to examine the detailed covariation of initial $^{87}Sr/^{86}Sr$ and ε_{Nd} values. These are shown in Fig. 9 calculated at 120 Ma, the Rb–Sr whole rock isochron age. The gabbronorites from the Darran Complex have the most primitive initial ratios and plot within the mantle array, consistent with only a limited interval between the time of extraction from the mantle and crystallization. The WFO granulitic rocks have a slightly higher initial $^{87}Sr/^{86}Sr$ ratio than the Darran Complex rocks, but have significantly lower ε_{Nd} values, and form a vertical array lying partially below the present-day mantle array.

The decoupling of Sr and Nd isotopes necessary to form the vertical array could result from a variety of mechanisms including: 1) direct derivation from a mantle source possessing the observed variations in initial $^{143}Nd/^{144}Nd$ composition; 2) variable contamination of primary mantle derived magmas with country rocks (e.g. RPK-2.26) into which the WFO was emplaced; and 3) derivation from a low Rb/Sr, LREE enriched protolith having an $\sim$100 to 300 Ma prehistory.

Firstly derivation from a mantle source of an appropriate composition is implausible, for although a limited number of alkaline volcanics (e.g. McDonough et al. 1985) have Nd and Sr isotopic compositions of inferred mantle origin, that partially overlap with the granulites they have distinctive geochemical characteristics (e.g. pronounced LREE enrichments, $La_N/Nb_N<1$) that are not present in the granulites. In addition the granulites have calcalkaline affinities, not those of intraplate basalts.

The second alternative is contamination with country rock. At the presently exposed structural level in Fiordland, pelitic rocks are the most obvious source of contamination. In the Western Fiordland granulites they commonly occur as extensively migmatized rafts; near raft margins the metasediments at least locally appears intergradational with the feldspathic granulites. One possible interpretation of monzonitic rocks such as BL-25A is that they are hybridised feldspathic rocks resulting from either assimilation of raft material or from mixing with K-rich fluids or anatectic melts derived from the rafts. This interpretation is not however consistent with the isotopic data. Simple two component mixing between a primitive mantle-derived magma such as the Darran leucogabbros (Fig. 9) and the metasedimentary xenolith RPK 2.26 would result in sympathetic variations in both ε_{Nd} and $^{87}Sr/^{86}Sr$ ratios which is not observed. This is illustrated in Fig. 9 where $\sim$10% to 35% assimilation is required to produce the range in ε_{Nd} values of from $+3$ to -0.4. This should result in a range in initial $^{87}Sr/^{86}Sr$ of from 0.7040 to 0.7048 whereas the granulites have essentially constant initial $^{87}Sr/^{86}Sr$ ratios of 0.70391 ± 4. A more immature sediment with lower Rb/Sr and $^{87}Sr/^{86}Sr$ ratios is also unsatisfactory as it would have higher Sr concentrations (RPK-2.26 has only 92 ppm Sr) and hence produce similar or larger shifts in $^{87}Sr/^{86}Sr$. Thus contamination with the presently exposed country rock is not consistent with the Nd–Sr data. Very specific contaminants (eg. old lower crust having low ε_{Nd} and low Rb/Sr and initial $^{87}Sr/^{86}Sr$ ratios), although unobserved cannot of course be discounted.

The final and most plausible explanation for the Nd–Sr isotopic covariation exhibited by the granulites is that their magma sources have had a limited but significant crustal prehistory. For example, a protolith with similar Sm/Nd and Rb/Sr ratios as the Darran leucogabbros would decrease its ε_{Nd} value by $\sim$1 unit per 100 Ma, but due to the very low Rb/Sr ratio would have essentially constant $^{87}Sr/^{86}Sr$. Thus an $\sim$100 to 300 Ma crustal prehistory (i.e. Carboniferous-Devonian mantle differentiation age for the protolith) would result in a protolith with similar initial Nd and Sr isotopic composition as the Darran Complex evolving to form the WFO granulite Nd–Sr array. Implicit in this model is that the low Rb/Sr ratios of the granulites is primarily a protolith feature as is observed in the Darran leucogabbros and not a feature of granulite facies metamorphism. The range in ε_{Nd} values of the granulites may be due to a combination of factors including variable Sm/Nd ratios, a range in protolith ages (i.e. 300 ± 100 Ma) or alternatively mixing between early Cretaceous mantle derived magmas and a crustal protolith. In the latter case the Nd isotopic data would provide only minimum constraints on the age of the crustal protolith.

No mid-Paleozoic components have been found in the Western Fiordland granulites by conventional U-Pb analyses (Mattinson et al. 1986). However only a small proportion of old inheritered zircons may survive both partial melting associated with the formation of the WFO magmas and subsequent high grade granulite facies metamorphism assuming that they were ever present in the original source. Evidence for older crust is present in the Doubtful Sound area of southwest Fiordland where Aronson (1968) reported U-Pb zircon age of $\sim$360 Ma and Oliver (1980) a Rb-Sr whole-rock age of 376 Ma. Recent Sm–Nd studies (McCulloch 1986) also indicate the presence of possible Proterozoic basement in the Doubtful Sound area.

The range in initial Nd identified in the WFO granulites also has important implications for Sm–Nd whole rock dating of Precambrian high grade terrains. For example, if the Precambrian analogues do not have uniform initial Nd as observed in the WFO and if for example the mafic granulites (with high Sm/Nd) also have higher initial Nd then a whole rock isochron based on combining felsic and mafic rocks would give both an erroneous old age and high ε_{Nd} values.

Additional constraints on the nature of the WFO magma source are provided by the trace element chemistry. The high Sr content, strongly fractionated REE patterns, and small negative to absent Eu anomalie, are compatible with derivation of WFO feldspathic rocks from a plagioclase-free, garnet hornblende -bearing source. In the absence of plagioclase, Sr and Eu behave as incompatible elements and are preferentially enriched in the melt fraction relative to the residuum. In the presence of garnet, HREE behave as compatible elements and are preferentially concentrated in the residuum relative to the coexisting melt. Unless the percentage of melting was extremely small (e.g. $<10\%$), the high alkali content (chiefly Na_2O) indicates alkali concentrations in the original source requiring the presence of alkalic phases. In the absence of plagioclase, likely candidates are jadeitic pyroxene and possibly Napargasite; nepheline could not coexist with quartz-normative magmas. Potassium could have resided in phlogopite, sanidine, or amphibole. The metaluminous character of the feldspathic rocks could suggest that alkalis entered the melt coordinated with Al, as for example in jadeite component in clinopyroxene; additional Al may have been provided by an alkali-poor phase such as garnet. Possible source lithologies frequently invoked to explain the origin of calcalkaline or high K andesites having total REE abundances and LREE/HREE ratios similar to the Western Fiordland Orthogneiss include LREE- and alkali-enriched eclogite, garnet peridotite, or garnet pyroxenite. The generally low mg number of the feldspathic rocks (100 Mg/(Mg+Fe) <38) indicates that they are too evolved to be primary melts derived from mantle peridotite (e.g., Ringwood 1978). Thus an origin involving partial melting of a secondary source (i.e., a crustal protolith) is suggested.

The late-stage magmas showing evidence of plagioclase enrichment require either plagioclase accumulation (and subsequent mobilization) or extensive fractionation of orthopyroxene, clinopyroxene, and oxides. The overall extent to which magma evolution may have been influenced by fractionation of feldspar is unclear. Although REE data suggest no significant involvement of feldspar in the magma evolution process, minor element ratios are consistent with a high degree of fractionation of K-bearing plagioclase (or some other K-bearing phase).

Conclusions

The Western Fiordland granulites have surprisingly primitive Nd and Sr isotopic compositions. The low initial $^{87}Sr/^{86}Sr$ (0.70391±4) and relatively high ε_{Nd} values (−0.4 to 2.7) are consistent with derivation of WFO magmas from a low Rb/Sr, LREE enriched, Mid-Paleozoic protolith of probable island-arc origin undergoing partial melting and high grade granulite facies metamorphism in the Early Cretaceous. The data presented here and in Mattinson et al. (1986) indicate that high grade metamorphism and tectonism following mid-crustal emplacement of the WFO was of exceptionally short duration. Partial melting, magma emplacement, crustal thickening via overthrusting, high pressure metamorphism and final uplift and cooling all occurred within an interval as short as ~20 Ma. This is compatible with Fiordland granulite formation being essentially an autometamorphic process resulting from synkinematic emplacement of largely anhydrous magmas, with high pressure metamorphism occurring during cooling from magmatic temperatures. These findings are in contrast to earlier studies which suggested Tuhuan (mid-Paleozoic) retrogressive metamorphism of Precambrian granulite facies basement (Oliver 1980).

To account for these new results the following scenario is proposed. During the Mid-Paleozoic (Devonian-Carboniferous) island-arc magmatism occurred along what was probably at that time the southeastern margin of Gondwanaland. The magmatism was of calcalkaline affinity and may have involved either a continent-arc subduction or accretion of an essentially intra -oceanic arc. A comparable situation may be present in the New England fold belt of eastern Australia where Carboniferous-Devonian plutonic rocks of predominantly island-arc origin occur (Hensel et al. 1985). In contrast to the New England fold belt, in western Fiordland, enclaves of metasediment with old (mid-Proterozoic) provenance ages occur. These represent rafts from country rock into which the Early Cretaceous rocks intruded. In the Early Cretaceous emplacement of the regionally extensive Western Fiordland Orthogneiss at mid-crustal depths is suggested by the comparatively low pressures recorded during metamorphism in both country rock and Western Fiordland Orthogneiss. This regional high T-P metamorphism (andalusite-sillimanite facies series) is attributed primarily to heat input into the middle crust by emplacement of voluminous magmas; this mechanism is consistent with thermal models of Wells (1980) for regions experiencing major crustal growth by magmatic accretion.

In view of the early low-P crystallization history, the subsequent high-T high-P metamorphism has tectonic significance. The ~6 kb increase in load pressure indicates major crustal thickening, equivalent to onloading of material of about 20 km thickness over rocks already buried at depths of 15–20 km. Thus, rocks initially metamorphosed at pressures equivalent to mid-crustal depths were subsequently subjected to pressures equivalent to those at the base of a 45 km thick crustal section. Modern plate tectonic settings in which major crustal thickening of the magnitude proposed here is known to occur are arc-arc, arc-continent or continent-continent collision zones. Perhaps the best known example of the latter is the Himalayas (e.g. Dewey and Bird 1970). It is suggested that crustal thickening in Fiordland occurred during a collisional event in which an Early Cretaceous magmatic arc in was over-ridden by one or more thrust sheets.

Exposure of the deep crustal section represented by the Fiordland granulites in a consequence of two unusual periods of great uplift. The first occurred immediately following collision and may have been as rapid as 3.5 mm/yr. The second, still ongoing period began with the Cenozoic inception of the transpressive Alpine Fault regime. This indicates that unusual tectonic conditions appear to be necessary during both mid-crustal emplacement of these rocks and finally during their rapid exhumation. An important implication of this work is that granulites of magmatic derivation are not restricted to the lower crust but can occur as in Fiordland at mid-crustal depths within thickened crust.

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Appendix. Locations and descriptions of analyzed specimens

Sample number	Field location		Rock description and mineral assemblange
	Name	Grid Ref.	
Western Fiordland orthogneiss			
FM-90A (51252)	Franklin Mtns	121/716859	Weakly foliated 2-pyroxene diorite gneiss with relict igneous textures. Plagioclase, biotite, hornblende, clinopyroxene, orthopyroxene, K-feldspar, oxides, apatite, quartz
FM-90B (51253)	(as above)	–	Semi-concordant dike cutting FM-90A. Weakly foliated 2-pyroxene meta-leuco monzodiorite with relict igneous textures. Plagioclase, K-feldspar, hornblende, biotite, clinopyroxene, oxides, apatite, orthopyroxene, quartz
FM-118B (51288)	Franklin Mtns	121/664869	Lineated, weakly foliated 2-pyroxene meta-diorite; contains some relict igneous textures. Antiperthitic plagioclase, clinopyroxene, orthopyroxene, K-feldspar, oxides, biotite, apatite, quartz. Boulder from head of Robb Creek
FM-135A (51110)	Clinton Cirque	121/772928	Massive, 2-pyroxene meta- diorite containing dominant relict igneous textures. Plagioclase, orthopyroxene, clinopyroxene, biotite, hornblende, oxides, K-feldspar, apatite, quartz
BL-34A (51337)	Sutherland Sd	121/579018	Well foliated granoblastic 2-pyroxenen monzo-diorite gneiss. Plagioclase, K-feldspar, clinopyroxene, orthopyroxene, hornblende, oxides, biotite, apatite, quartz. Outcrop from cliff at beach face
BL-25A (51357)	Bligh Sound	121/558959	Lineated, weakly foliated 2-proxene monzonite (mangerite) gneiss. Plagioclase-orthoclase mesoperthite, clinopyroxene, orthopyroxene, hornblende, oxides, biotite, apatite, quartz
Other WFO and related rocks			
BL-4A (51372)	Bligh Sound	121/548883	Phlogopite-bearing websterite semi-concordantly intruding 2-pyroxene gneiss. Clinopyroxene, orthopyroxene, phlogopite, oxides, apatite. Shoreline outcrop
S-21A (51306)	Sutherland Sd	121/604302	Concordant orthopyroxene eclogite horizon in feldspathic pyroxene gneiss. Coarse garnets up to ~ 1 cm diameter. Clinopyroxene, garnet, orthopyroxene, late amphibole, apatite, oxides, rutile. Float boulder on beach
S-21B (51307)	Sutherland Sd	121/604302	Plagioclase-rich pegmatoid dike in which coarse tabular hornblende has been psuedomorphed by symplectites of garnet + clinopyroxene. Dike crosscuts 2-pyroxene gneiss which is locally overprinted by garnet-forming reaction zone at dike margin
RPK-2.26 (51435)	George Sound	130/485736	Migmatitic metasediment enclosed as <50 m wide raft within WFO; gradational into anatectic granitic gneiss at raft margins. Quartz, K-feldspar, plagioclase, biotite, garnet, sillimanite, kyanite, rutile, ilmenite. Shoreline outcrop
Darran Complex gabbronorite			
M-45C (51694)	Milford Road	122/941088	Leucogabbronorite: igneous lamination defined by alignment of coarse euhedral plagioclase laths. Minor recrystallization in response to deformation. Plagioclase, clinopyroxene, orthopyroxene, biotite, hornblende, oxides, apatite, K-feldspar, quartz, myremkite. Outcrop near 1980 slip near Donne River
M-60	Darran Mtns	122/995027	Leucogabbronorite similar to above. Outcrop on ridge of NW of Barrier Pk

1. Grid reference from NZMS 1 maps; number preceding slash is sheet number
2. Mineral assemblage listed in order of decreasing modal abundance. Rock names after Streckeisen (1976)
3. *Numbers in parathesis* are Otago University numbers