New Zealand Journal of Geology & Geophysics, 2006, Vol. 49: 291–303 291
0028–8306/06/4903–0291

SHRIMP ion probe zircon geochronology and Sr and Nd isotope geochemistry for southern Longwood Range and Bluff Peninsula intrusive rocks of Southland, New Zealand

RICHARD C. PRICE
School of Science and Engineering
University of Waikato
Private Bag 3105
Hamilton, New Zealand

TREVOR R. IRELAND
Research School of Earth Sciences
Australian National University
Canberra, ACT 0200, Australia

ROLAND MAAS
School of Earth Sciences
University of Melbourne
Parkville, Vic. 3010, Australia

RICHARD J. ARCULUS
Department of Earth & Marine Sciences
Australian National University
Canberra, ACT 0200, Australia

Abstract Permian–Jurassic ultramafic to felsic intrusive complexes at Bluff Peninsula and in the southern Longwood Range along the Southland coast represent a series of intra-oceanic magmatic arcs with ages spanning a time interval of 110 m.y. New SHRIMP U-Pb zircon data for a quartz diorite from the Flat Hill complex, Bluff Peninsula, yield an age of 259 ± 4 Ma, consistent with other geochronological and paleontological evidence confirming a Late Permian age. The new data are consistent with an age of c. 260 Ma for the intrusive rocks of the Brook Street Terrane. SHRIMP U-Pb zircon ages for the southern Longwood Range confirm that intrusions become progressively younger from east to west across the complex. A gabbro at Oraka Point (eastern end of coastal section) has an age of 245 ± 4 Ma and shows virtually no evidence of zircon inheritance. The age is significantly different from that of the Brook Street Terrane intrusives. Zircon ages from the western parts of the section are younger and more varied (203–227 Ma), indicating more complex magmatic histories. A leucogabbro dike from Pahia Point gives the youngest emplacement age of 142 Ma, which is similar to published U-Pb zircon ages for the Anglem Complex and Paterson Group on Stewart Island.

Keywords U-Pb geochronology; zircon; SHRIMP; granites; Brook Street Terrane

G05057; Online publication date 24 July 2006
Received 8 December 2005; accepted 19 May 2006

INTRODUCTION

The geology of the south coast of New Zealand's South Island represents the juxtaposition of a continental foreland (Western Province) with arc-related rocks to the east (Eastern Province). The boundary between these rocks was originally part of the Median Tectonic Line (Landis & Coombs 1967), a feature which has conceptually been progressively redefined as a "Zone" (Williams & Harper 1978; Frost & Coombs 1989; Bradshaw 1993; Kimbrough et al. 1993, 1994; Muir et al. 1998) and most recently as a "Batholith" (Mortimer et al. 1999a). The nature of the Median Batholith is important to our understanding of the assembly of New Zealand in the context of the Pacific margin of Gondwana. Precise delineation of the boundaries of the various Median interpretations with the Western and Eastern Provinces is problematic because in a number of key areas, intrusive rocks of broadly similar character are major components of all three terranes; most of these intrusives have petrological characteristics expected of rocks formed in subduction-related magmatic settings (e.g., Coombs et al. 1976; Houghton & Landis 1989; Muir et al. 1998; Spandler et al. 2003). The combination of geochemistry and geochronology offers one of the best ways of distinguishing and grouping these intrusives and thereby more precisely defining the boundaries between the various terranes. In this paper we assess the nature of magmatic intrusives that have been subdivided to mark a boundary between the Eastern Province and the Median batholith/tectonic zone.

GEOLOGICAL BACKGROUND

The Longwood Complex (Mutch 1957, 1959) in Southland (Fig. 1, 2) is composed of a wide variety of coarse-grained igneous rocks including olivine-, pyroxene-, and amphibole-bearing ultramafic rocks, gabbros, troctolites, diorites, and granites and trondhjemites (Challis & Lauder 1977; Price & Sinton 1978; Bignall 1987; Rombouts 1994; Mortimer et al. 1999b; Wadsworth 2000). Inland, within the Longwood Range, the complex is poorly exposed, but coastal outcrops between Colac and Te Waewae Bays (Fig. 2A) provide an excellent east–west section. Mortimer et al. (1999b) compiled geochronological data covering the Longwood Range and used this information to separate eastern, Permian-aged rocks of the Brook Street Terrane from a western, Middle Triassic to Early Jurassic, intrusive suite. The Brook Street rocks to the east are dominantly volcanics and volcaniclastic sediments, but Mortimer et al. (1999b) argued that within the Longwood Complex, the terrane is represented by gabbro, diorite, granite, and trondhjemite intrusives (Mortimer et al. 1999b). The younger, western Longwood Complex, consisting of ultramafic rocks, gabbros, diorites, tonalites, and granites, was considered by Mortimer et al. (1999b) to be part of the Median Batholith.

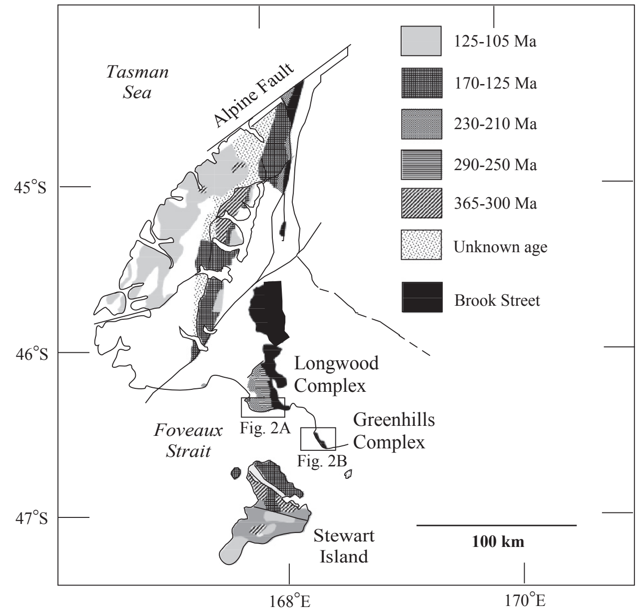


Fig. 1 Age distribution of intrusives of the Median Tectonic Zone (Median Batholith) in southwestern South Island and Stewart Island (Mortimer et al. 1999a,b). Location of detailed maps of southern Longwood Range and Bluff Peninsula (Fig. 2A,B) are also shown.

The most southerly exposures of the Brook Street Terrane on the South Island occur on Bluff Peninsula, southeast of the Longwood Range (Fig. 1). Here a series of gabbroic and ultramafic complexes has intruded and metamorphosed volcaniclastic and calcareous sediments containing fossils of late Early Permian age (Mossman & Force 1969). The most northerly (Green Hills) intrusion (Fig. 2B) is layered from an ultramafic base to a gabbroic top (Mossman 1973) so that cumulate dunites and wehrlites give way vertically to rhythmically layered, noritic gabbros. Outcrops to the southeast of the Green Hills intrusion, at Flat Hill and Bluff Hill (Fig. 2B), are dominated by noritic gabbros showing layering and micro-textures that are also consistent with a cumulate origin. Spandler et al. (2003) argued that the Green Hills intrusion is largely cumulate and formed as a magmatic feeder and storage system below an intra-oceanic, subduction-related volcanic arc, and although the other intrusions (Bluff and Flat Hill) lack significant ultramafic cumulates, they are likely to have formed in the same way as part of a sub-arc, volcanic plumbing system.

Previously published geochronological information for the Longwood Range and Bluff Peninsula igneous rocks includes K-Ar, Ar-Ar, and Rb-Sr mineral ages (Aronson 1968; Devereux et al. 1968; Mortimer et al. 1999b) and isotope dilution, thermal ionisation mass spectrometric (ID-TIMS), U-Pb zircon analysis (Kimbrough et al. 1992, 1994; Mortimer et al. 1999b; Tulloch et al. 1999). For Bluff Peninsula, K-Ar ages of 246 ± 10 Ma (hornblende) and 247 ± 10 Ma (whole rock) and a Rb-Sr biotite age of 245 ± 7 Ma (Aronson 1968) are broadly consistent with the paleontological evidence for a Permian age (Mossman 1973; Frost & Coombs 1989), although they are younger than ID-TIMS U-Pb zircon ages of 264 ± 4 and 267 ± 4 Ma obtained by Kimbrough et al. (1992).

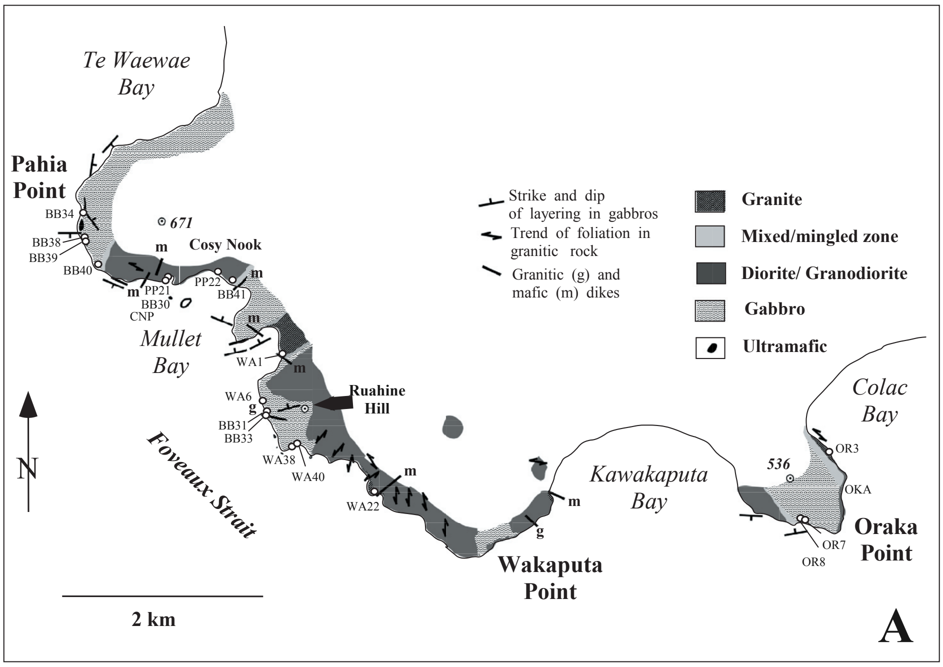
Mortimer et al. (1999b) presented new Ar-Ar and ID-TIMS U-Pb zircon data and integrated these with previously published geochronological information to show that intrusive rocks of at least two distinct age groups are exposed in the Longwood Range. Intrusives to the east, assigned by Mortimer et al. (1999b) to the Brook Street Terrane, give Ar-Ar ages ranging from 251.7 ± 0.8 to 249.1 ± 0.6 Ma. U-Pb zircon data are more equivocal and were interpreted to indicate two separate intrusive events dated at 261 ± 2 and 292 ± 8 Ma, respectively. The western Longwood Range was shown to be made up of younger intrusives that were assigned to the Median Batholith. Ar-Ar ages obtained by Mortimer et al. (1999b) for these western intrusives range from 240.4 ± 3.8 to 219.4 ± 0.8 Ma, with U-Pb zircon ages of Kimbrough et al. (1994) showing a range from 207 to 230 Ma. K-Ar mineral dates (Devereux et al. 1968) overlap with these ages but are generally younger (138–222 Ma, using decay constants of Steiger & Jäger 1977).

Some of the ID-TIMS U-Pb zircon data of Kimbrough et al. (1994) for the southern Longwood Range show dispersion and suggest the possibility of recycling of continental crust; for example, Kimbrough et al. (1994) allude to the presence of inherited or xenocrystic zircons in the Wakaputa Granite, and concordia plots for Oraka Point data suggest multiple components. On the other hand, the Brook Street Terrane has been shown to represent a primitive oceanic arc (e.g., Spandler et al. 2003, 2005). In this paper we present new Sensitive High Resolution Ion Micro-probe (SHRIMP) U-Pb zircon age data and Nd and Sr isotopic information for intrusive rocks of the southern Longwood Range and SHRIMP U-Pb zircon data for a rock from Bluff Peninsula in Southland. SHRIMP provides a very precise means of understanding dispersion and inheritance in zircon populations, and in combination with Sr-Nd data can resolve whether crustal recycling, and particularly recycling of continental crust, occurred in the magmatic systems now represented by the intrusive rocks of the southern Longwood Range and Bluff Peninsula.

METHODS

For SHRIMP zircon analyses, whole rock samples were crushed and sieved and zircons separated using standard heavy-liquid separation techniques. For each zircon separate, grain mounts were prepared in epoxy resin so that zircons could be sectioned and polished for *in situ* analysis using the SHRIMP-RG instrument at the Australian National University in Canberra, Australia. Polished grain mounts were photographed and cathodoluminescence (CL) images (Fig. 3) prepared to examine crystal morphology and zoning (Hoskin 2000; Corfu et al. 2003).

Zircons were analysed with a conventional analytical cycle incorporating concentrations (UO^+, ThO^+) relative to Zr_2O^+, Pb isotopic compositions, and a U-UO calibration for instrumental fractionation of Pb^+/U^+ (Muir et al. 1996). Reference standards used were SL13 for U concentration normalisation, and the 417 Ma Temora standard (Black et al. 2003) for U-Pb age calibration. Ages were calculated using the 207-correction method described in detail by Muir et al. (1996). A given data point is extrapolated to concordia from a common Pb composition that is assumed to be coeval with the zircon. This avoids propagating substantial uncertainty from the $^{204}Pb/^{206}Pb$ measurement in the course of a conventional (204-based)



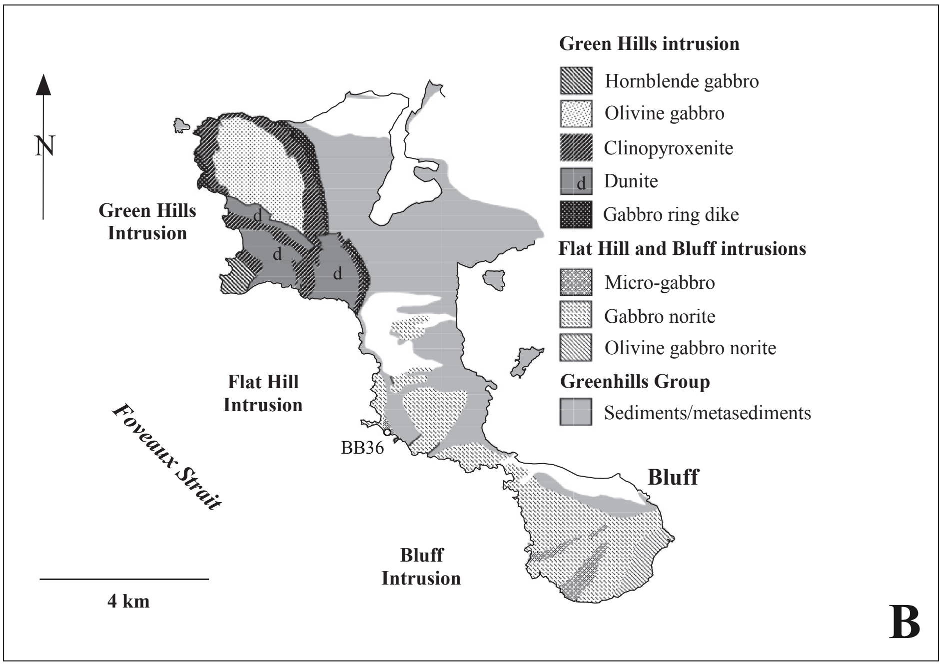


Fig. 2 **A**, Exposures of southern Longwood Complex along the coast between Te Waewae Bay and Colac (Price & Sinton 1978). Sample localities are indicated. **B**, Geological map of Bluff Peninsula incorporating data from Mossman (1973), Graham (1977), and Spandler et al. (2003). SHRIMP sample locality BB36 is also shown.

correction. While this method precludes the use of $^{207}Pb/^{206}Pb$ to assess concordance, the amount of material consumed in an analysis makes the determination of radiogenic ^{207}Pb (via ^{204}Pb correction) too imprecise in Phanerozoic rocks to be of any general utility. Beyond the grouping of data according to textural characteristics (CL), data are assessed for commonality of U-Pb systematics through assessment of the data distribution around the mean. The dispersion of the data points (through mean square of weighted deviates—MSWD) is assessed relative to statistical expectation (*F*-test). Outliers are examined on the basis of offset from the mean in terms of the individual errors; an error offset of 2.5 σ or greater is regarded as significant. If significant dispersion was found in the dataset beyond a few outliers, the data were further assessed for potential group populations. Only in one case in this study were complex U-Pb groupings found (sample BB31).

The final reported ages include the weighted mean of the group of analyses added in quadrature with the error of the mean of the Temora standards. For these data, three normalisations were used for the 3 days of analysis. The uncertainties in the Temora standards were as follows: day 1, 0.54% (10/11 analyses, MSWD = 1.06) used for sample CNP; day 2, 0.58% (13/13 analyses, MSWD = 1.20) used for samples OKA, BB33, BB30A; and day 3, 0.60% (9/10 analyses, MSWD = 0.53) for samples BB36B, BB34B, and BB31.

Fig. 3 Representative cathodoluminescence images of zircons used in the SHRIMP study of southern Longwood Range and Bluff Peninsula intrusive rocks.

Sm-Nd and Sr isotope analyses were obtained at La Trobe University, Melbourne. Sample powders spiked with mixed $^{149}Sm/^{150}Nd$ tracer were dissolved in Krogh-type high-pressure vessels for 3 days (HF/HNO_3, 6*M* HCl), followed by extraction of Sr and LREE on 0.1 ml columns of EICHROM™ Sr resin and TRU resin, respectively (Pin et al. 1994). Sm and Nd were purified on 3 ml HDEHP columns (Richard et al. 1976). Total blanks were <0.1 ng Nd and Sr. Isotopic analyses were carried out on a Finnigan-MAT262 TIMS. Unspiked Sr fractions were loaded onto single Ta filaments as phosphates and data were collected in multi-dynamic collection mode at ion beams near 2×10^{-11} A of ^{88}Sr. Mass bias was corrected by normalising to $^{86}Sr/^{88}Sr = 0.1194$. $^{87}Rb/^{86}Sr$ is based on Rb/Sr as determined by XRF (error ± 2%). Sm and Nd were loaded as nitrates on the Ta side of a Re-Ta double filament; Nd isotope data were collected in static multi-collection mode at ^{144}Nd ion currents of $1–2 \times 10^{-11}$A. Mass bias was corrected by normalising to $^{146}Nd/^{144}Nd = 0.7219$. Spike subtraction and isotope dilution calculations were done offline. $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios for USGS standards are: BCR-1 0.1381 ± 3, 0.512634 ± 14; BHVO-1 0.1496 ± 2, 0.512986 ± 21 (external 2 SD precisions, $n = 5$). Present-day CHUR is 0.1967, 0.512638; $\lambda^{87}Rb = 1.42\ 10^{-11}\ a^{-1}$, $\lambda^{147}Sm = 6.54\ 10^{-12}\ a^{-1}$.

SHRIMP ZIRCON GEOCHRONOLOGY

U-Th-Pb isotopic compositions were determined in zircon populations of six samples from coastal exposures of the southern Longwood Range and one sample from the Flat Hill intrusion on Bluff Peninsula. Results are presented in Table 1 and shown graphically (Fig. 4, 5) in the form of Tera Wasserburg concordia diagrams (Tera & Wasserberg 1972).

Sample BB34B—Leuco-gabbro, Pahia Point

This leuco-gabbro is the westernmost sample from Pahia Point (New Zealand grid ref. D46/011189). It contains a mixed population of small (<150 µm), subhedral and prismatic, oscillatory-zoned zircons (Fig. 3A). Ten analyses of nine grains show a range in U concentration of 310–1800 ppm, Th 150–1100 ppm, and Th/U 0.33–1.12. Common ^{206}Pb is low (<1% measured ^{206}Pb) in all grains. The mean $^{238}U/^{206}Pb$ age shows excess scatter (MSWD = 3.3) and this is apparently due to the presence of an older population. These older grains have an age of c. 150 Ma, but all have U concentrations over 1000 ppm, and the old ages may reflect a matrix effect perturbing the U calibration. The youngest seven of the analyses yield a mean age of 142.4 ± 2.3 Ma (2 σ_m; MSWD = 0.78) and this is taken as representing the age of this rock. The SHRIMP age is similar to ID-TIMS U-Pb zircon ages obtained by Kimbrough et al. (1994) for rocks from the Anglem Complex (138–141 Ma) and Paterson Group (146 +3/–1 Ma) across Foveaux Strait on Stewart Island. Similar Late Jurassic/Early Cretaceous U-Pb zircon ages have also been obtained on intrusive and eruptive rocks at several localities throughout eastern Fiordland and Nelson (Kimbrough et al. 1994; Muir et al. 1997, 1998; Mortimer et al. 1999a,b) but have not previously been reported in the Longwood Range. K-Ar hornblende and biotite ages on nearby gabbroic rocks range from 138 to 166 Ma (Devereux et al. 1968).

Sample BB30A—Diorite, Pahia Point

Sample BB30A is a diorite from Cosy Nook (D46/026175) on the eastern side of Pahia Point (Fig. 2A). The zircons from this sample are euhedral and prismatic, up to 500 µm in length, and show coarse oscillatory zoning (Fig. 3B). Twelve analyses of 12 grains show U concentrations of 110–530 ppm, Th 90 380 ppm, and Th/U 0.48–1.14. Common ^{206}Pb is close to or below 1% total ^{206}Pb. The mean U-Pb age shows excess scatter (MSWD = 3.8) due to two young outliers. After excluding these analyses, the mean age is 211.0 ± 3.4 Ma (2 σ_m; MSWD = 1.06), which is consistent with a well-constrained, concordant U-Pb zircon age of 207 +7/–1 Ma obtained by Kimbrough et al. (1994) for a gabbro dike at Ruahine Bay on the eastern side of Pahia Point.

Sample CNP—Diorite from Pahia Point

This sample, from Cosy Nook (Fig. 2A), is from the same diorite unit sampled at locality BB30A on the eastern side of Pahia Point (D46/026175). It contains relatively coarse (>500 µm) prismatic crystals of zircon with homogeneous central and thick (up to 50 µm) outer banding (Fig. 3C). Seventeen analyses of 12 grains have U concentrations of 100–420 ppm, Th 80–210 ppm, and Th/U 0.3–1.03 with the majority close to the upper end of the range. Common ^{206}Pb is generally close to or below 1% relative to total ^{206}Pb. Despite the textural complexity of these grains, all 17 analyses combine to form a satisfactory U-Pb mean age of 203.2 ± 2.8 Ma (2 σ_m; MSWD = 0.83), which is similar to the age obtained for sample BB30A, and therefore consistent with the range of ages obtained by other methods for western Longwood Range intrusives.

Sample BB31—Granodiorite, Wakaputa/Ruahine

Sample BB31 is a granodiorite from below Ruahine Hill (D46/050141). It contains a complex population of small (up to 200 µm) zircons that range from subhedral to prismatic in shape. Many crystals show complex oscillatory zoning (Fig. 3D) and some have complex cores that appear to have been corroded before later overgrowth. Eighteen zircon analyses have been divided into three populations on the basis of their U-Pb and textural characteristics. Five bright (CL) outer bands have U concentrations of 120–230 ppm; Th 90–190 ppm, and Th/U 0.70–0.94. Four grains that yield apparently older ages have U of 200–550 ppm, Th 110–300 ppm, and Th/U 0.54–0.64. The main population shows a range in U of 190–750 ppm, Th 130–500 ppm, and Th/U 0.48–1.48. Common ^{206}Pb is close to or below 1% of total measured ^{206}Pb. The MSWD of all analyses exceeds 7, indicating that the population includes samples of different ages. After removing the analyses of the petrographically distinct outer bands, the MSWD remains excessive at 4.4. The remaining grains can be split into two populations with data in the ranges 208–222 Ma ($n = 9$; MSWD = 0.78) and 227–234 Ma ($n = 4$; MSWD = 0.19). The population of young outer zones overlaps the main population, and has a mean age of 203.5 ± 5.4 Ma (2 σ_m; MSWD = 2.2), the main population has an age of 215.0 ± 4.0 Ma (2 σ_m), with the older population at 230.1 ± 4.0 Ma. These ages are significantly older that those obtained for gabbroic rocks of Pahia Point, farther to the west. The data do, however, show some consistency with other geochronological information for intrusive rocks along the coast between Ruahine Hill and the eastern side of Wakaputa Point. Data reported by Kimbrough et al. (1994) for a "hybrid" rock from Wakaputa Point are significantly dispersed along concordia with three near-concordant fractions at 220 (leached fraction), 227, and 230 Ma. These ages are consistent with a mixture of the two older components we have identified. Leaching

Table 1 SHRIMP U-Pb zircon data for Southland intrusive rocks.

	U (ppm)	Th (ppm)	Th/U	$^{204}Pb/^{206}Pb$	±	$f^{206}Pb$ (%)	$^{207}Pb/^{206}Pb$	±	$^{238}U/^{206}Pb$	±	Age (Ma)	±
BB34B												
1.1	308	152	0.49	0.00118	0.00068	0.62	0.0545	0.0024	44.91	1.32	141.1	4.1
2.1o	1815	625	0.34	0.00005	0.00013	0.09	0.0499	0.0007	42.69	0.44	149.1	1.5
3.1	432	299	0.69	0.00065	0.00033	0.45	0.0530	0.0017	44.77	0.56	141.8	1.8
5.1	841	703	0.84	0.00013	0.00012	0.13	0.0501	0.0009	44.86	0.60	141.9	1.9
6.1o	1142	440	0.39	0.00025	0.00014	0.11	0.0501	0.0011	41.91	0.97	151.8	3.5
7.1	1047	350	0.33	0.00005	0.00010	0.10	0.0498	0.0008	45.19	0.47	141.0	1.5
8.1	1289	1441	1.12	0.00005	0.00012	0.00	0.0490	0.0010	43.80	1.21	145.5	4.0
9.1	347	164	0.47	0.00000	0.00032	0.31	0.0518	0.0014	43.36	0.84	146.6	2.8
9.2	398	188	0.47	0.00008	0.00040	0.51	0.0536	0.0013	44.06	0.61	143.9	2.0
10.1o	1416	553	0.39	0.00015	0.00008	–0.13	0.0480	0.0011	41.36	1.22	154.2	4.5
BB30A												
1.1	151	139	0.92	0.00083	0.00101	1.02	0.0596	0.0024	30.49	0.69	205.9	4.6
2.1	147	92	0.63	0.00096	0.00052	0.29	0.0530	0.0034	29.73	0.67	212.7	4.8
3.1	118	110	0.94	0.00131	0.00076	0.70	0.0566	0.0022	30.67	0.81	205.4	5.3
4.1y	330	377	1.14	0.00023	0.00075	0.50	0.0545	0.0022	33.34	0.69	189.6	3.9
5.1	112	103	0.93	0.00247	0.00097	1.17	0.0610	0.0022	30.07	0.61	208.5	4.2
6.1	162	150	0.92	0.00199	0.00071	1.01	0.0595	0.0019	30.82	0.76	203.8	5.0
7.1y	319	175	0.55	0.00061	0.00050	0.34	0.0533	0.0017	31.53	0.54	200.6	3.4
8.1	342	177	0.52	0.00024	0.00016	0.12	0.0515	0.0014	29.58	0.39	214.1	2.8
9.1	232	152	0.65	0.00004	0.00025	0.42	0.0542	0.0016	29.52	0.72	213.9	5.2
10.1	532	257	0.48	0.00006	0.00010	0.08	0.0512	0.0013	29.58	0.35	214.1	2.5
11.1	148	132	0.89	0.00001	0.00046	0.33	0.0535	0.0025	29.57	0.79	213.7	5.6
12.1	126	114	0.91	0.00001	0.00035	0.47	0.0545	0.0031	30.61	0.60	206.3	4.1
Cosy Nook CNP												
1.1	166	151	0.91	0.00128	0.00053	0.02	0.0504	0.0025	31.10	0.73	204.0	4.8
2.1	145	135	0.93	0.00260	0.00082	0.58	0.0555	0.0037	30.82	0.73	204.7	4.9
3.1	150	139	0.93	0.00117	0.00087	0.56	0.0553	0.0018	31.01	0.47	203.5	3.1
4.1	236	208	0.88	0.00083	0.00040	0.21	0.0522	0.0023	30.68	0.37	206.3	2.5
5.1	348	181	0.52	0.00061	0.00038	0.20	0.0520	0.0011	31.18	0.36	203.1	2.3
6.1	138	128	0.92	0.00171	0.00117	0.22	0.0522	0.0024	31.33	0.50	202.1	3.2
7.1	159	151	0.95	0.00088	0.00041	0.47	0.0544	0.0025	31.16	0.59	202.7	3.8
8.1	141	143	1.01	0.00083	0.00057	0.41	0.0539	0.0017	31.34	0.52	201.7	3.3
10.1	99	80	0.80	0.00126	0.00089	0.66	0.0562	0.0023	31.20	0.82	202.0	5.2
10.2	107	94	0.87	0.00168	0.00218	1.54	0.0644	0.0040	29.77	0.91	209.7	6.4
11.1	416	126	0.30	0.00072	0.00035	0.16	0.0516	0.0010	31.72	0.44	199.8	2.7
11.2	148	153	1.03	0.00115	0.00102	1.33	0.0622	0.0034	32.10	0.82	195.2	5.0
12.1	183	181	0.99	0.00089	0.00062	0.41	0.0541	0.0017	29.85	0.61	211.6	4.3
12.2	171	169	0.99	0.00193	0.00094	0.54	0.0550	0.0014	31.83	0.62	198.4	3.8
13.1	134	124	0.93	0.00179	0.00062	0.82	0.0577	0.0017	30.63	0.69	205.4	4.6
13.2	150	138	0.92	0.00168	0.00073	0.58	0.0555	0.0019	30.63	0.74	205.9	4.9
13.3	153	144	0.94	0.00001	0.00126	0.66	0.0562	0.0026	30.97	0.53	203.6	3.5
BB31												
1.1	501	374	0.75	0.00050	0.00017	0.12	0.0517	0.0016	28.80	0.98	219.8	7.3
2.1o	553	297	0.54	0.00044	0.00015	0.12	0.0519	0.0016	27.42	0.21	230.6	1.8
3.1	347	245	0.71	0.00023	0.00046	0.37	0.0540	0.0017	28.48	1.01	221.7	7.8
3.2	749	377	0.50	0.00008	0.00013	0.07	0.0512	0.0017	28.61	0.79	221.3	6.0
4.1o	198	106	0.54	0.00041	0.00067	0.41	0.0544	0.0023	27.76	0.54	227.3	4.4
5.1	261	386	1.48	0.00035	0.00029	0.36	0.0536	0.0017	29.90	1.22	211.3	8.5
6.1	367	234	0.64	0.00107	0.00044	1.47	0.0639	0.0012	28.83	0.43	216.6	3.2
7.1r	223	186	0.83	0.00034	0.00033	0.60	0.0558	0.0019	30.04	0.64	209.8	4.4
7.2	264	128	0.48	0.00020	0.00021	0.41	0.0540	0.0020	30.39	0.96	207.9	6.5
8.1r	121	90	0.75	0.00141	0.00081	0.95	0.0588	0.0023	31.89	0.53	197.2	3.3
8.2	342	502	1.47	0.00037	0.00022	0.05	0.0508	0.0014	30.00	0.40	211.3	2.8
9.1o	275	166	0.60	0.00071	0.00030	0.64	0.0567	0.0025	26.93	2.43	233.6	20.8
10.1o	412	263	0.64	0.00050	0.00025	0.20	0.0526	0.0012	27.57	0.75	229.2	6.2
11.1	269	136	0.51	0.00076	0.00062	0.56	0.0557	0.0023	28.95	0.58	217.7	4.3
12.1r	234	165	0.71	0.00011	0.00035	0.54	0.0553	0.0027	29.55	2.42	213.4	17.2
13.1r	153	107	0.70	0.00108	0.00061	0.91	0.0585	0.0027	30.91	0.89	203.4	5.8
14.1r	116	109	0.94	0.00198	0.00109	0.71	0.0569	0.0033	29.21	0.99	215.5	7.2
14.2	192	181	0.95	0.00091	0.00077	0.45	0.0544	0.0030	30.16	1.83	209.3	12.5

(continued)

Table 1 *(continued)*

	U (ppm)	Th (ppm)	Th/U	$^{204}Pb/^{206}Pb$	±	$f^{206}Pb$ (%)	$^{207}Pb/^{206}Pb$	±	$^{238}U/^{206}Pb$	±	Age (Ma)	±
BB33												
1.1	963	833	0.87	0.00035	0.00013	0.28	0.0533	0.0016	27.87	0.17	226.6	1.4
1.2	279	166	0.60	0.00005	0.00037	0.48	0.0552	0.0021	27.45	0.48	229.6	4.0
2.1y	276	167	0.60	0.00046	0.00036	0.55	0.0555	0.0017	29.34	0.65	214.9	4.7
3.1	579	405	0.70	0.00047	0.00023	0.13	0.0518	0.0012	27.92	0.38	226.6	3.1
4.1y	269	306	1.14	0.00069	0.00069	0.61	0.0560	0.0014	28.86	0.40	218.3	3.0
5.1	300	252	0.84	0.00001	0.00029	0.51	0.0552	0.0016	28.44	0.38	221.6	2.9
6.1	434	529	1.22	0.00065	0.00025	0.47	0.0550	0.0011	27.70	0.40	227.6	3.3
7.1	426	216	0.51	0.00012	0.00050	0.32	0.0536	0.0015	27.90	0.49	226.3	3.9
8.1y	356	403	1.13	0.00041	0.00032	0.49	0.0550	0.0015	29.20	0.56	216.0	4.1
9.1	238	271	1.14	0.00000	0.00023	0.41	0.0545	0.0016	27.47	0.51	229.6	4.2
10.1	347	287	0.83	0.00001	0.00044	0.32	0.0537	0.0015	27.31	0.51	231.1	4.2
11.1y	203	168	0.83	0.00039	0.00031	0.40	0.0541	0.0017	29.40	0.84	214.8	6.1
12.1	479	254	0.53	0.00006	0.00011	0.31	0.0535	0.0012	28.23	0.48	223.7	3.7
13.1	249	200	0.80	0.00093	0.00056	0.33	0.0537	0.0016	27.66	0.54	228.2	4.4
Oraka Point OKA												
1.1	170	144	0.85	0.00305	0.00099	1.40	0.0637	0.0034	26.52	0.59	235.3	5.3
2.1	336	385	1.15	0.00011	0.00031	0.24	0.0534	0.0020	25.29	0.51	249.4	5.0
3.1	234	214	0.91	0.00115	0.00116	0.64	0.0570	0.0020	25.46	0.77	246.8	7.3
4.1	314	334	1.06	0.00093	0.00042	0.47	0.0555	0.0014	25.44	0.42	247.4	4.0
5.1y	351	365	1.04	0.00145	0.00054	0.67	0.0569	0.0018	27.67	0.53	227.3	4.3
6.1	408	308	0.76	0.00042	0.00039	–0.04	0.0510	0.0022	24.48	1.67	258.3	17.3
7.1	333	392	1.18	0.00043	0.00045	0.36	0.0544	0.0016	25.30	0.44	249.0	4.3
8.1	218	170	0.78	0.00211	0.00087	0.54	0.0560	0.0022	25.87	0.63	243.2	5.9
9.1	419	517	1.23	0.00081	0.00031	0.22	0.0532	0.0014	25.51	0.46	247.3	4.4
10.1y	391	472	1.21	0.00063	0.00058	0.40	0.0545	0.0034	27.24	0.57	231.5	4.9
11.1	286	305	1.07	0.00183	0.00102	0.84	0.0586	0.0018	26.52	0.57	236.6	5.0
12.1	435	539	1.24	0.00057	0.00021	0.19	0.0528	0.0012	25.85	0.46	244.3	4.3
BB36B												
1.1	86	49	0.57	0.00191	0.00079	0.97	0.0603	0.0035	24.08	0.62	259.8	6.7
2.1	138	73	0.53	0.00166	0.00058	0.59	0.0566	0.0017	24.93	0.54	252.1	5.4
3.1	103	41	0.40	0.00108	0.00106	0.77	0.0587	0.0022	23.56	0.56	265.9	6.2
4.1	120	69	0.57	0.00155	0.00073	0.58	0.0568	0.0020	24.10	0.43	260.6	4.6
5.1	59	34	0.57	0.00366	0.00130	1.33	0.0635	0.0031	24.17	0.56	257.9	6.0
6.1	114	71	0.62	0.00092	0.00122	0.33	0.0546	0.0017	23.64	0.34	266.3	3.8
7.1	104	63	0.60	0.00185	0.00074	0.67	0.0576	0.0023	24.09	0.58	260.5	6.2
8.1	87	32	0.37	0.00264	0.00093	1.04	0.0609	0.0021	24.62	0.61	254.0	6.2
9.1y	62	34	0.54	0.00311	0.00225	2.31	0.0722	0.0030	25.52	0.75	242.1	7.1
10.1	113	59	0.53	0.00141	0.00088	0.34	0.0545	0.0019	24.16	0.56	260.6	6.0
11.1	112	71	0.63	0.00001	0.00054	0.83	0.0588	0.0019	25.03	0.52	250.5	5.1
12.1	105	60	0.57	0.00129	0.00075	1.03	0.0608	0.0020	24.33	0.48	257.1	5.0

Labels: Grain.spot; o = older population; y = younger population; r = rims.
f206Pb: Fraction of common ^{206}Pb to total ^{206}Pb as determined from the deviation of $^{207}Pb/^{206}Pb$ from concordance $^{207}Pb/^{206}Pb$, $^{238}U/^{206}Pb$ uncorrected for common Pb.
Age: $^{238}U/^{206}Pb$ age at concordia following extrapolation from data point, assuming coeval common Pb.
All errors are ±2 σ.

removes damaged, highest U zircon, and the leached fraction should be a more robust indicator of emplacement age. Interestingly, Kimbrough et al. (1994) interpreted the older 230 Ma age as the emplacement age, whereas the younger age from the leached fraction (c. 220 Ma) is close to the age of our main zircon population (215.0 ± 4.0 Ma, see above). We conclude that the ID-TIMS and SHRIMP ages are consistent and reflect the complexity of the geological history preserved in the zircons of this rock. For a sample from a nearby locality, Devereux et al. (1968) record K-Ar hornblende and biotite ages of 222 and 213 Ma, respectively.

Sample BB33—Felsic dike, Wakaputa/Ruahine

Sample BB33 (D46/056140) is from a felsic dike intruding the granodiorite near locality BB31. The zircon population from this dike is morphologically similar to that of the host granodiorite. Zircons are generally small (<180 µm), equant, and prismatic to subhedral. All show complex oscillatory zoning and some have corroded and complexly zoned cores (Fig. 3E). Fourteen analyses of 13 grains show U concentrations of 200–960 ppm, Th 170–830 ppm, and Th/U 0.51–1.22. Common ^{206}Pb is close to or below 1% of total ^{206}Pb measured. The mean age of the data (225 Ma) shows a marginally high MSWD (2.02) for 14 analyses. Four analyses as a group appear to give a lower age estimate and excluding these data gives a mean age of 226.6 ± 3.2 Ma (MSWD = 0.66); although more precise, this age is only marginally higher than the mean of all the data. The younger population has an age of 217 ± 5 Ma (MSWD = 0.19). These ages are consistent with the SHRIMP data for BB31 and the ID-TIMS U-Pb zircon data for the "Oraka hybrid" of Kimbrough et al. (1994).

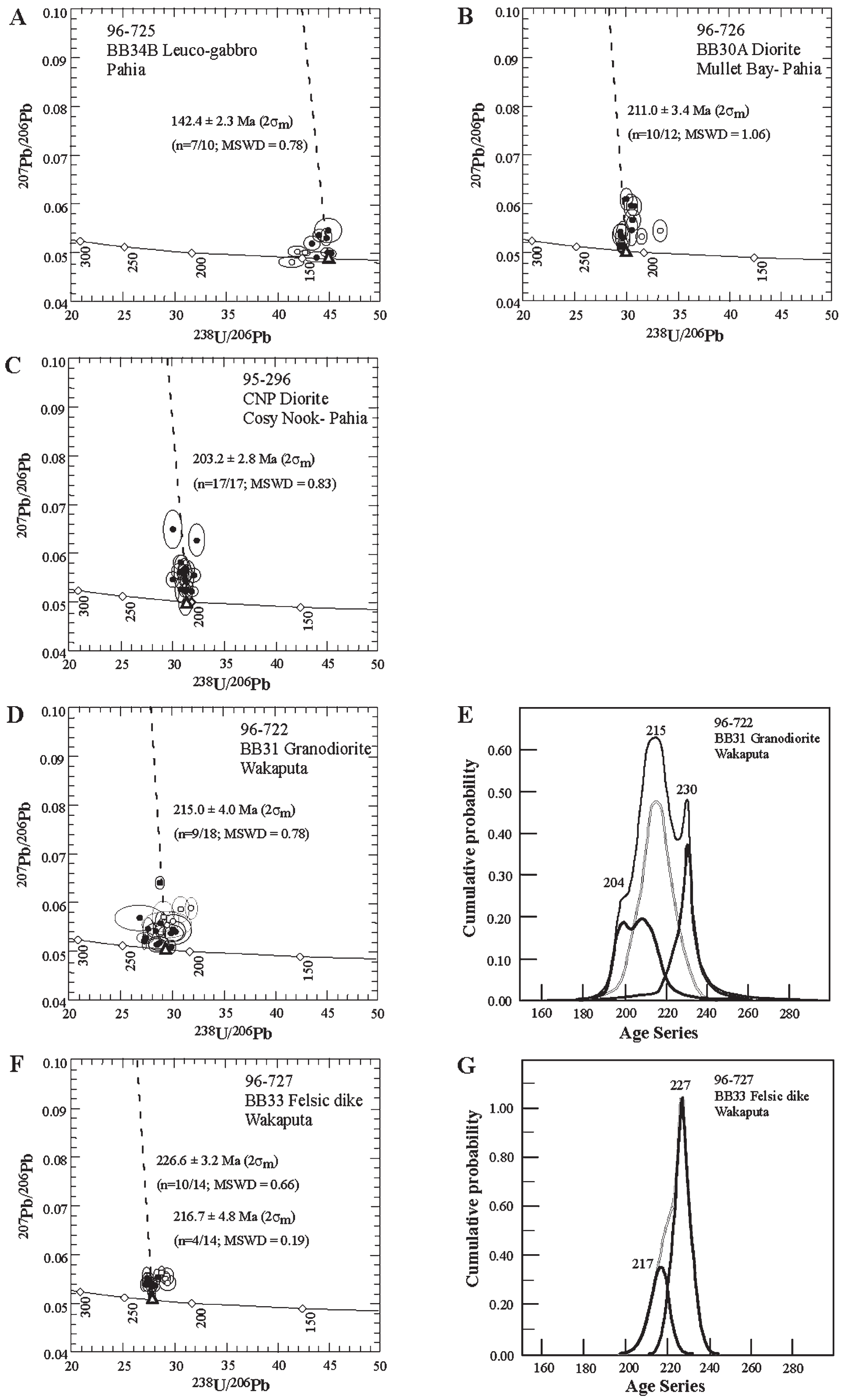


Fig. 4 Tera-Wasserburg U-Pb zirconconcordia diagrams (A–D, and F) for southern Longwood Range intrusive rocks. Error ellipses are at 1 σ. Also shown are cumulative probability diagrams for two of the analysed samples; BB31 (E) and BB33 (G).

Sample OKA—Gabbro, Oraka Point

This sample is a gabbro from Oraka Point on the southeastern corner of the Longwoods Complex (D46/167129). It contains prismatic, weakly zoned zircon crystals with well-defined homogeneous centres. Individual crystals are prismatic and range in size up to 400 μm (Fig. 3F). Twelve analyses of 12 grains show a range in U concentrations of 170–430 ppm, Th 140–540 ppm, and Th/U 0.76–1.24. Common ^{206}Pb is close to or below 1% of total ^{206}Pb measured. The mean U-Pb age of all data shows excess scatter with an MSWD of 2.6. Two outliers are 2.5 σ removed below the mean and are rejected. This leaves the mean age as 245.0 ± 4.3 Ma (2 σ_m; MSWD

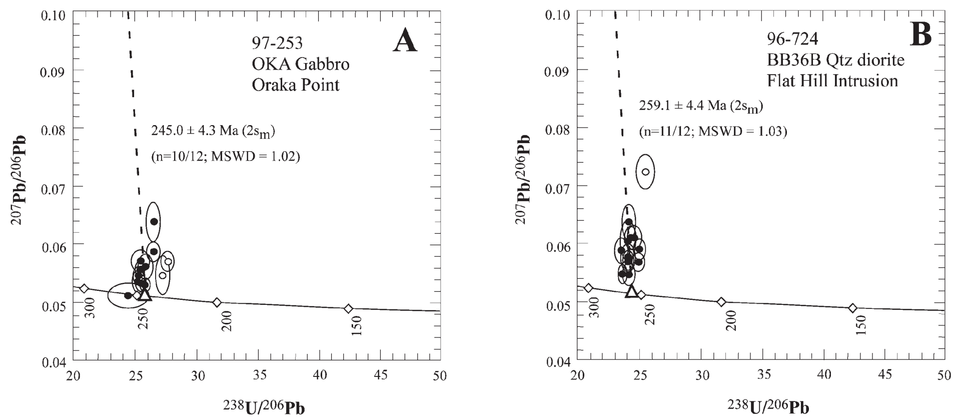


Fig. 5A,B Tera-Wasserburg U-Pb zircon concordia diagrams for samples from the southern Longwood Range (97-253) and Bluff Peninsula (96-724). Error ellipses are at 1 σ.

Table 2 Rb-Sr and Sm-Nd isotopic data for gabbros and granitoids, southern Longwood Range, Southland.

	Age (Ma)	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}	T_{DM}, Ga	$^{87}Sr/^{86}Sri$	$\varepsilon_{Nd}i$
Oraka													
OR3	245	72	310	0.671	0.705370	6.79	28.43	0.1444	0.512921	+5.5	0.51	0.70303	+7.2
OR7A	245	1.1	693	0.0046	0.703263	2.89	10.79	0.1616	0.512858	+4.3		0.70325	+5.4
OR7B	230	161	109	4.269	0.717060	2.43	13.28	0.1105	0.512793	+3.0	0.53	0.70310	+5.6
OR8	245	2.8	715	0.0113	0.703304	6.06	21.58	0.1699	0.512888	+4.9		0.70326	+5.7
Ruahine-Wakaputa													
WA22X1	215	21	560	0.108	0.703985	8.38	37.02	0.1369	0.512734	+1.9	0.83	0.70365	+3.5
WA1A	215	97	451	0.622	0.705612	4.65	22.86	0.1228	0.512727	+1.7	0.71	0.70371	+3.8
WA1Xe	215	85	454	0.541	0.705327							0.70367	
WA6A	215	25	643	0.155	0.704092	5.54	23.71	0.1413	0.512746	+2.1	0.85	0.70362	+3.6
WA38X	215	34	497	0.198	0.704210	10.70	49.10	0.1312	0.512762	+2.4	0.72	0.70361	+4.2
WA40	215	77	506	0.439	0.705085							0.70374	
Pahia													
BB38	203	3	1044	0.0083	0.703962	0.38	1.49	0.1553	0.512717	+1.6		0.70394	+2.6
BB39	203	3	1106	0.0078	0.703903	0.54	1.93	0.1679	0.512749	+2.2		0.70388	+2.9
BB40	203	15	680	0.0638	0.704096	2.47	10.74	0.1388	0.512756	+2.3	0.80	0.70391	+3.8
BB41A	203	61	837	0.211	0.704334	1.50	9.01	0.1007	0.512709	+1.4	0.60	0.70373	+3.9
BB41B	203	61	833	0.212	0.704358							0.70375	
BB41C	203	149	732	0.588	0.705018							0.70332	
BB41E	203	57	649	0.254	0.704521	4.15	20.04	0.1253	0.512715	+1.5	0.75	0.70379	+3.4
PP21	203	74	508	0.421	0.704961	4.33	20.11	0.1301	0.512755	+2.3	0.72	0.70375	+4.0
PP22	203	94	466	0.583	0.705450	5.21	23.74	0.1328	0.512750	+2.2	0.76	0.70377	+3.8

Internal (in-run, 2 σ mean) precisions for measured Sr and Nd isotope ratios are ≈ ±0.000020 (Sr) and ≤ ±0.000015 (Nd). External (2 σ) precision, or reproducibility, is estimated at ±0.000030 (Sr) and ±0.000020 (Nd). Rb and Sr by XRF, $^{87}Rb/^{86}Sr$ ± 2%. Sm and Nd by isotope dilution, $^{147}Sm/^{144}Nd$ ± 0.2% (2 σ).

= 1.02). Kimbrough et al. (1994) obtained a ID-TIMS U-Pb zircon age of 247 +5/–1 Ma for a granite sample taken from the eastern side of Oraka Point, although Kimbrough et al. (1992) used the Pb-Pb age of 260 ± 2 Ma for this particular sample to infer Brook Street affinity. The data for three fractions lie on a discordia with the leached fraction being the most concordant and giving the oldest Pb-U age.

Sample BB36B—Quartz diorite, Bluff Peninsula

This sample, from a quartz diorite dike exposed along the coast at the western edge of the Flat Hill intrusion (Fig. 2B) on Bluff Peninsula (E47/482919), contains small (<120 µm) subhedral zircons with weakly zoned central bands and thin overgrowths (Fig. 3G). Twelve analyses of 12 grains show a range in U concentrations of 60–140 ppm, Th 32–73 ppm, and Th/U 0.37–0.63. Common Pb is generally below 1% ^{206}Pb total; one point with >2% also has a distinctly young U-Pb age. The mean $^{206}Pb/^{238}U$ age for the remaining 11 analyses is 259.1 ± 4.4 Ma (2 σ_m; MSWD = 1.03). This age compares with hornblende K-Ar age determinations of 247 and 258 Ma (Devereux et al. 1968) and a Rb/Sr biotite age of 246 ± 7 Ma (Aronson 1965) for samples from the nearby Green Hills intrusion. Kimbrough et al. (1992) obtained near-concordant U-Pb zircon ages of 257 and 255 Ma on coarse and fine zircon separates from the Greenhills Complex.

SR-ND ISOTOPES

Isotopic data for 19 samples from coastal sections of the southern Longwood Range are listed in Table 2. Initial isotopic ratios ($^{87}Sr/^{86}Sr_i$, ε_{Ndi}) were calculated using age constraints available from the literature and from the U-Pb zircon dating reported here. While not every analysed intrusive complex has

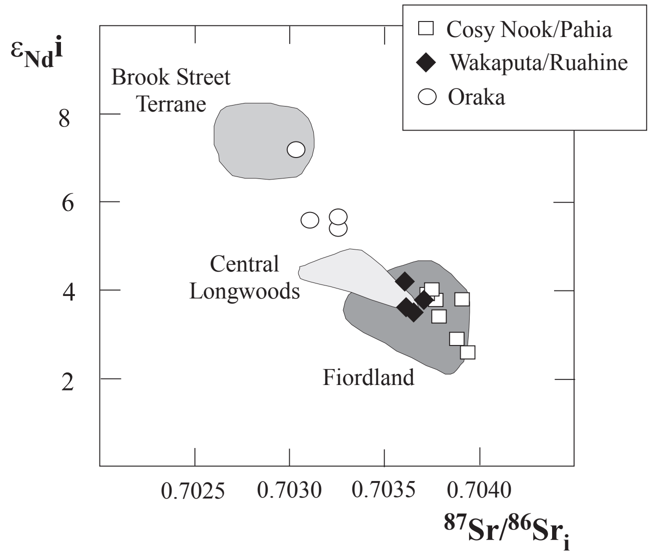


Fig. 6 Initial Sr-Nd isotopic ratios ($^{87}Sr/^{86}Sr_i$ versus ε_{Ndi}) for gabbroic and granitoid intrusives from coastal exposures in the southern Longwood Range (see Table 2). Also shown are data for other 260–220 Ma intrusives from the central Longwood Range (Mortimer et al. 1999b; Tulloch et al. 1999), and for Mesozoic (160–120 Ma) granitoids from the Median Batholith (Fiordland; Muir et al. 1998). The central Longwoods intrusives have previously been assigned to the Brook Street Terrane (Pourakino Trondhjemite, Hekeia Gabbro, high ε_{Ndi}) and Median Batholith (Holly Burn Intrusives, lower ε_{Ndi}), respectively. Initial Sr-Nd isotope data for sample OU49154 ("Pahia" Dike, 207 Ma gabbronorite; Mortimer et al. 1999b) are almost identical to those for our sample WA1, collected c. 200 m south of OU49154 in Mullet Bay. Samples from the Pahia and Ruahine/Wakaputa areas plot entirely within the fields for Median Batholith granitoids. The older intrusives from Oraka Point have higher ε_{Ndi} and resemble compositions found in the Brook Street Terrane. The more primitive isotopic character of Brook Street Terrane arc rocks (with ε_{Ndi} >+6) is supported by data for volcanogenic sandstones and Colac Granite (ε_{Ndi} ≈+5.5 to +8.5; see Mortimer et al. 1999b).

been dated, the available data provide reasonably tight (probably to within ±10 Ma) constraints on the intrusive age(s) at each locality. Inaccuracies of 10 Ma in age assignments would typically generate errors of ≤0.0003 in age-corrected $^{87}Sr/^{86}Sr_i$, due to the low Rb/Sr and relatively young absolute ages of the southern Longwood Range granitoids. Age correction errors in ε_{Ndi} are negligible.

In an earlier study of the Longwood Range intrusives, Mortimer et al. (1999b) noted a change from lower $^{87}Sr/^{86}Sr_i$ and higher ε_{Ndi} in intrusions with Permian ages (Pourakino Tronhjemite, Hekeia Gabbro, "Colac" Granite) in the east, to slightly higher $^{87}Sr/^{86}Sr_i$ and markedly lower ε_{Ndi} in intrusions with Triassic ages (Holly Burn Intrusives, diorites and granites) in the western Longwood Range. Our data for intrusives from the southern Longwood Range confirm this observation although the Sr isotopic differences are subtle. $^{87}Sr/^{86}Sr_i$ increases from Oraka Point (0.70303–0.70325) westwards through the Wakaputa Point/Ruahine Hill section (0.70361–0.70374) to Pahia Point (0.70332–0.70394). Nd isotopic ratios vary more strongly along the same traverse: ε_{Ndi} at Oraka Point is in the range +7.2 to +5.4, decreasing to +3.5 to +4.2 in the Wakaputa Point/Ruahine Hill section, and reaching the lowest values (+4.0 to +2.6) in the Cosy Nook/Pahia Point area. Initial Sr-Nd isotopic compositions across the section are clearly anti-correlated (Fig. 6).

At Oraka Point, a sample from a granitic vein (OR7B) appears to be anomalous, having much higher Rb, lower Sr, higher Rb/Sr, and lower Sm/Nd than the other samples analysed from this locality. Age correction to 245 Ma (the SHRIMP zircon age for an Oraka Point gabbro) produces an unrealistically low $^{87}Sr/^{86}Sr_i$ (0.70218) for this sample. By comparison, $^{87}Sr/^{86}Sr_{245}$ for the other three analysed Oraka Point samples (two gabbros, one diorite) is in the range 0.70303–0.70326. We therefore suspect that OR7B represents a separate, younger, magmatic or thermal resetting event. The Rb-Sr isotope data can be used to derive a model age of 230 ± 3 Ma (assuming $^{87}Sr/^{86}Sr_i$ of 0.7030–0.7033), which is used as the "age" of this sample in Table 2. Ages near 230 Ma are known from the Longwood Range intrusives: 230 Ma zircons are present in sample BB31 from below Ruahine Hill (see above), and 230 Ma granitoids have been reported from the western Longwood Range (e.g., Kimbrough et al. 1994); these were assigned to the Median Batholith (Mortimer et al. 1999b).

DISCUSSION

Bluff (c. 260 Ma)

The SHRIMP zircon U-Pb data for the sample from the Flat Hill intrusion on Bluff Peninsula give an age of 259 ± 4 Ma, providing a precise estimate of the timing of emplacement. Kimbrough et al. (1992) obtained Pb-Pb zircon ages of 264 ± 4 and 267 ± 4 Ma for a Bluff Peninsula gabbro norite.

Despite its importance in New Zealand geology, the geochronology of the Brook Street Terrane is still poorly defined. The best radiometric age constraints come from Bluff Peninsula and the Pourakino Trondhjemite in the Longwood Range. Our estimate of the age of the Bluff intrusives is 259 ± 4 Ma, which is consistent with all other geochronological data for these and surrounding rocks. Tulloch et al. (1999) have obtained a similar concordant U-Pb age of 261 ± 2 Ma for the Pourakino Trondhjemite. Mortimer et al. (1999b) also dated the Pourakino Trondhjemite by U-Pb and inferred a much older age of c. 292 Ma from a discordia upper intercept. This age is highly anomalous in terms of other geochronology for this intrusive unit (e.g., U-Pb data in Tulloch et al. (1999) and Ar-Ar data reported by Mortimer et al. (1999b)). The available data are most consistent with the interpretation that the intrusive rocks of the Brook Street Terrane were emplaced over a short time period (few million years?) around 260 Ma.

The primitive nature of the Brook Street Terrane igneous rocks, as inferred from the Sr-Nd isotopic systematics and the geochemistry reported by Spandler et al. (2003) supports our contention that the magmas they represent were emplaced over a short period of time. A prolonged magmatic history extending over tens of millions of years would be very likely to involve some crustal recycling and there should be evidence for this in the geochemistry and the Sr-Nd isotope systematics.

The apparent lack of inherited zircons in the Flat Hill intrusion could also be taken as an indication of limited crustal recycling, but the retention of inherited zircons is highly dependent on the composition and temperature of the magma now represented by the host rock. Magma composition determines zircon saturation (Watson 1979; Watson & Harrison 1983; Hanchar & Watson 2003) and inherited zircons are unlikely to survive in high temperature, mafic magmas.

Oraka (245 Ma)

The new SHRIMP data for the southern Longwood Range support the observations of Kimbrough et al. (1994) and Mortimer et al. (1999b) that within the Longwood Range north–south-trending intrusive suites with significantly divergent emplacement ages are juxtaposed over a lateral cross-section of <20 km. Most of the intrusives exposed at Oraka Point were emplaced in the Late Permian/Early Triassic, but in our view the age of 245 Ma is not consistent with the interpretation that these rocks are part of the significantly older (260 Ma) Brook Street Terrane intrusive suite. It appears that the original assignment of the Oraka rocks to Brook Street was based on the 260 Ma Pb-Pb age reported by Kimbrough et al. (1992). This estimate was subsequently revised by Kimbrough et al. (1994) to 247 Ma (the U-Pb age on the same sample). The interpretation of these data is central to the identification of intrusive rocks of the Brook Street Terrane. It is our view that Brook Street intrusives have distinctive geochemical attributes (primitive isotopic and trace element compositions—Spandler et al. 2003, 2005) and ages of emplacement close to 260 Ma. If this conclusion is valid, then the 245 Ma age at Oraka Point represents a distinct and separate magmatic episode. This is entirely consistent with the age and geochemical progression farther to the west in the southern Longwood Range.

Mortimer et al. (1999b) obtained a Late Permian/Early Triassic hornblende Ar-Ar plateau age of 246 Ma on an intrusive suite in the eastern Longwood Range that they termed the Hekeia Gabbro. This age is within error of the SHRIMP intrusion age and confirms the proposal by Mortimer et al. (1999b) for an extensive Hekeia Gabbro suite along the eastern side of the Longwood Range and extending to the coast.

There is also evidence from the Sr isotopic data that a Triassic thermal event has affected the Oraka rocks. This could be the emplacement age of some of the granitic dikes on the peninsula or it might be an indication of a broader scale thermal overprint. Intrusives outcropping immediately to the west, between Wakaputa Point and Pahia Point, have Late Triassic to Late Jurassic/Early Cretaceous ages.

As with the Flat Hill intrusion, the Oraka intrusives have primitive isotopic compositions and there is no evidence for any inheritance in the zircon populations. Like their counterparts in the Brook Street Terrane, they represent magmas generated in a primitive intra-ocean arc. The isotopic compositions are markedly more primitive than those of intrusives farther to the west in the southern Longwood Range.

Wakaputa-Ruahine-Pahia (230–204 Ma)

The intrusives to the west of the Oraka Point suite are not only younger but they are isotopically more evolved. Although the differences are relatively subtle, the higher $^{87}Sr/^{86}Sr_i$ ratios and lower ε_{Ndi} in the Wakaputa/Pahia section imply some involvement of older (though still relatively primitive) crust in the petrogenesis of these rocks. Coupled with the geochronological information, the isotopic data indicate that different magmatic systems were progressively developed during a time interval of 25–30 m.y.

Intrusive rocks of the Wakaputa/Ruahine section show more complex magmatic histories. They contain inherited zircon (230 Ma, granodiorite BB31, Ruahine Hill), which may be derived from assimilation of earlier intrusives; Kimbrough et al. (1994) reported a 230 Ma U-Pb zircon age from at least one diorite from the same area.

$^{87}Sr/^{86}Sr_i$ and ε_{Ndi}, while generally juvenile and indicative of an oceanic magmatic setting, change from 0.70361–0.70374 and +3.52 to +4.22, respectively, for the Wakaputa/Ruahine intrusives, to 0.70373–0.70394 and +2.6 to +4.0 in the intrusives of Pahia Point. The isotopic trend towards lower ε_{Ndi} is associated with a general decrease in emplacement age.

The complexity of the zircon populations in Wakaputa/Ruahine rocks contrasts with the relatively simple systematics observed in the Brook Street and 245 Ma Oraka intrusives. There are at least three apparent age groupings. The oldest group of ages, 227–230 Ma (BB33, BB31), indicates inheritance; 211–217 Ma (BB30A, BB31, BB33) ages probably record an emplacement event; and the youngest ages of 203–204 Ma could represent an emplacement age (CNP) or a thermal overprint (BB31). The cross-correlation of ages within these rocks indicates common history.

Pahia (142 Ma)

Sample BB34B contains the youngest zircon population, and magmatic activity of this age has been identified throughout southern New Zealand, for example in the Anglem Complex on Stewart Island. This magmatic event on the South Island would cause localised (partial) resetting of Ar-Ar and provides an explanation for some of the Cretaceous/Late Jurassic ages obtained by this method in the southern Longwood Range.

Intra-oceanic arcs in southern New Zealand

Despite subtle temporal differences, all the intrusive suites that we have examined show relatively primitive Sr and Nd isotopic characteristics, precluding the possibility of significant involvement of old continental crust in their magmatic evolution. This is consistent with the zircon geochronology, which shows some evidence for limited crustal recycling but no older zircon ages that might have been derived from continental crust. The conclusion must be that all of the intrusive suites of the Brook Street Terrane and the southern Longwood Range were generated and evolved in intra-oceanic settings.

The data for the southern Longwood Range intrusives indicate that intrusive complexes with subtly different compositions and different ages have been juxtaposed over relatively short lateral distances (20 km). The pattern is one of successive emplacement of subduction-related, intra-oceanic arcs along or adjacent to the Gondwanan margin over a long period from late Paleozoic to Cretaceous times. What is not resolved is whether these arcs were emplaced successively in essentially the same spatial context or progressively accreted at the Gondwanan margin. Comparisons with the present-day Tonga-Kermadec intra-oceanic subduction system may provide some constraints on scale and timing of magmatic evolution.

The Tongan volcanic arc consists of two chains of volcanic islands. The active arc lies 50–60 km to the west of an older (40–50 Ma) chain of extinct volcanic islands and seamounts (Bryan et al. 1972; Ewart et al. 1977). The age separation between these two arc systems is broadly analogous to that observed between the different magmatic systems identified across the southern Longwood Range, but the distance between the arcs is not. South of the Tonga Arc, subduction-related magmatism is manifested in the single chain of volcanic islands and seamounts that make up the Kermadec Arc, with the older arc system lying to the west and separated from the active volcanic chain by the Lau-Havre back-arc system (Ewart et al. 1977; Ewart & Hawkesworth 1987). The Tonga-Kermadec subduction system has been active on a time-scale (40–50 m.y., e.g., Kroenke 1984) comparable to that spanned by the Brook Street/southern Longwood Range magmatic systems, but it is doubtful whether the spatial distributions observed today in southern New Zealand prevailed throughout this interval. Given the dynamic nature of modern intra-oceanic arcs, the possibility that the 50 m.y. history of the southern New Zealand intra-oceanic arcs has been spatially compressed by thrusting or tectonic juxtaposition of arcs of different age cannot be precluded.

In the southern Longwood Range, there is evidence that at least four differently aged magmatic systems occur over a lateral cross-section of <20 km. The zircon populations from rocks emplaced at 204–207 Ma contain evidence for recycling of material that must have been intruded at c. 230 Ma, and it is therefore reasonable to suppose that these younger magmas were emplaced into an older sub-arc intrusive system. There is, however, no evidence in the younger intrusives for recycling of material with ages comparable to those of the Oraka Point intrusives, and it is likely that the arc system represented by these rocks was generated farther to the east and tectonically juxtaposed at a later time with the younger magmatic arc systems to the west. Similarly, the absence of any evidence in the 245 Ma Oraka rocks for recycled Brook Street Terrane suggests that the latter was tectonically juxtaposed with the Oraka arc system. These interpretations are consistent with the spatial and temporal relationships observed in modern intra-oceanic arcs such as the Tonga-Kermadec system.

CONCLUSIONS

New SHRIMP U-Pb zircon data for Longwood Range and Bluff Peninsula intrusive rocks are broadly consistent with previously published geochronological information. They confirm previous estimates of an age around 260 Ma for the Brook Street Terrane. The Sr and Nd isotopic data are consistent with the view that the Brook Street Terrane represents a primitive, intra-oceanic magmatic arc. SHRIMP zircon geochronology for these intrusives shows little evidence for crustal recycling.

For rocks in coastal exposures of the southern Longwood Range, new SHRIMP geochronological and Sr-Nd isotopic information indicates the presence of intrusives showing a significant range of ages and subtle isotopic variability. Zircons from Oraka Point give an emplacement age of 245 ± 4 Ma, which is significantly different from ages available for intrusive rocks of the Brook Street Terrane and from the age of southern Longwood Range rocks farther to the west. These rocks appear to be representative of a separate magmatic event, but their primitive Sr and Nd isotopic compositions suggest that, like their counterparts in the Brook Street Terrane, they formed in an intra-oceanic subduction setting.

Granitic rocks exposed near Ruahine Hill to the west of Wakaputa Point have an intrusion age of c. 215 Ma, with inherited zircons preserving evidence for recycling of older (230 Ma) crust. SHRIMP ages are progressively younger to the west, towards Pahia Point, with ages of 211 ± 3 and 203 ± 3 Ma being obtained for two diorites. Zircons in these two samples show no obvious evidence for inheritance. One sample from Pahia Point gives a significantly younger SHRIMP age of 142 ± 2 Ma. The initial $^{87}Sr/^{86}Sr$ ratios shift progressively from east to west, with samples from the Wakaputa Point–Cosy Nook section giving initial ratios in the range 0.70361–0.70371 and those from the Cosy Nook–Pahia Point coastal section giving initial ratios of 0.70332–0.70394.

As might be expected, initial ε_{Nd} values show a broad negative correlation with initial $^{87}Sr/^{86}Sr$ ratios, and all the intrusive rocks analysed have primitive Sr isotopic compositions, indicating that the magmas they represent were generated in intra-oceanic tectonic settings.

ACKNOWLEDGMENTS

The research has benefited considerably from discussions with Nick Mortimer and his generosity in making field information and data readily available. Tony Reay's contribution to the field programme is gratefully acknowledged. Nick Mortimer and Paul Hoskin are thanked for constructive reviews. The work has been supported and funded by the Australian Research Council, the University of Waikato, La Trobe University, and the Australian National University.

REFERENCES

Aronson JL 1965. Reconnaissance rubidium-strontium geochronology of New Zealand plutonic and metamorphic rocks. New Zealand Journal of Geology and Geophysics 8: 401–423.

Aronson JL 1968. Regional geochronology of New Zealand. Geochimica et Comsochimica Acta 32: 669–697.

Bignall G 1987. Geology of the southern part of the Longwoods Complex, Southland coast and Centre Island, New Zealand. Unpublished MSc thesis, University of Otago, Dunedin, New Zealand.

Black LP, Kamo SL, Allen CM, Aleinikoff JN, Davis DW, Korsch RJ, Foudoulis C 2003. TEMORA 1: a new zircon standard for Phanerozoic U-Pb geochronology. Chemical Geology 200: 155–170.

Bradshaw JD 1993. A review of the Median Tectonic Zone: terrane boundaries and terrane amalgamation near the Median Tectonic Line. New Zealand Journal of Geology and Geophysics 36: 117–125.

Bryan WB, Stice GD, Ewart A 1972. Geology and geochemistry of the volcanic islands of Tonga. Journal of Geophysical Research 77: 566–585.

Challis GA, Lauder WR 1977. The pre-Tertiary geology of the Longwood Range 1:50 000. New Zealand Geological Survey Miscellaneous Series Map 11. Wellington, New Zealand, Department of Scientific and Industrial Research.

Coombs DS, Landis CA, Norris RJ, Sinton JM, Borns DJ, Craw DJ 1976. The Dun Mountain ophiolite belt, New Zealand, its tectonic setting, constitution and origin, with special reference to the southern portion. American Journal of Science 276: 561–603.

Corfu F, Hanchar JM, Hoskin PWO, Kinny P 2003. Atlas of zircon textures. In: Hanchar JM, Hoskin PWO ed. Zircon. Reviews in Mineralogy and Petrology 53: 470–500.

Devereux I, McDougall I, Watters WA 1968. Potassium-argon mineral dates on intrusive rocks from the Foveaux Strait area. New Zealand Journal of Geology and Geophysics 11: 1230–1235.

Ewart A, Hawkesworth CJ 1987. The Pleistocene-Recent Tonga-Kermadec arc lavas: interpretation of new isotopic and rare earth data in terms of a depleted mantle source model. Journal of Petrology 28: 495–530.

Ewart A, Brothers RN, Mateen A 1977. An outline of the geology and geochemistry, and the volcanic rocks of the Tonga-Kermadec-New Zealand island arc. Journal of Volcanology and Geothermal Research 2: 205–250.

Frost CD, Coombs DS 1989. Nd isotope character of New Zealand sediments: implications for terrane concepts and crustal evolution. American Journal of Science 289: 744–770.

Graham IJ 1977. The geology of Ocean Beach, Southland, New Zealand. Unpublished BSc Honours thesis, University of Otago, Dunedin, New Zealand.

Hanchar JM, Watson EB 2003. Zircon saturation thermometry. In: Hanchar JM, Hoskin PWO ed. Zircon. Reviews in Mineralogy and Petrology 53: 89–112.

Hoskin PWO 2000. Patterns of chaos: fractal statistics and the oscillatory chemistry of zircon. Geochimica et Cosmochimica Acta 64: 1905–1923.

Houghton BF, Landis CA 1989. Sedimentation and volcanism in a Permian arc-related basin, southern New Zealand. Bulletin of Volcanology 51: 433–450.

Kimbrough DL, Mattinson JM, Coombs DS, Landis CA, Johnston MR 1992. Uranium-lead ages from the Dun Mountain ophiolite belt and Brook Street terrane, South Island, New Zealand. Geological Society of America Bulletin 104: 429–443.

Kimbrough DL, Tulloch AJ, Geary E, Coombs DS, Landis CA 1993. Isotopic ages from the Nelson region of South Island, New Zealand: crustal structure and definition of the Median Tectonic Zone. Tectonophysics 225: 433–448.

Kimbrough DL, Tulloch AJ, Coombs DS, Landis CA, Johnston MR, Matheson JM 1994. Uranium-lead zircon ages from the Median Tectonic Zone, New Zealand. New Zealand Journal of Geology and Geophysics 37: 393–419.

Kroenke LW 1984. Cenozoic tectonic development of the southwest Pacific. U.N. ESCAP, CCOP/SOP Technical Bulletin 6.

Landis CA, Coombs DS 1967. Metamorphic belts and orogenesis in southern New Zealand. Tectonophysics 4: 501–518.

Mortimer N, Tulloch AJ, Spark RN, Walker NW, Ladley E, Allibone A, Kimbrough DL 1999a. Overview of the Median Batholith, New Zealand: a new interpretation of the geology of the Median Tectonic Zone and adjacent rocks. Journal of African Earth Sciences 29: 257–268.

Mortimer N, Gans P, Calvert A, Walker A 1999b. Geology and thermochronometry of the east edge of the Median Batholith (Median Tectonic Zone): a new perspective on Permian to Cretaceous crustal growth of New Zealand. The Island Arc 8: 404–425.

Mossman DJ 1973. Geology of the Green Hills ultramafic complex, Bluff Peninsula, Southland, New Zealand. Geological Society of America Bulletin 84: 39–62.

Mossman DJ, Force LM 1969. Permian fossils from the Green Hills Group, Bluff, Southland, New Zealand. New Zealand Journal of Geology and Geophysics 12: 659–672.

Muir RJ, Ireland TR, Weaver SD, Bradshaw JD 1996. Ion microprobe dating of Palaeozoic granitoids: Devonian magmatism in New Zealand and correlations with Australia and Antarctica. Chemical Geology 127: 191–210.

Muir RJ, Ireland TR, Weaver SD, Bradshaw JD, Waight TE, Jongens R, Eby GN 1997. SHRIMP U-Pb geochronology of Cretaceous magmatism in northwest Nelson-Westland, Southland, New Zealand. New Zealand Journal of Geology and Geophysics 40: 453–463.

Muir RJ, Ireland TR, Weaver SD, Bradshaw JD, Evans JA, Eby GN, Shelley D 1998. Geochronology and geochemistry of a Mesozoic magmatic arc system, Fiordland, New Zealand. Journal of the Geological Society London 155: 1037–1052.

Mutch AR 1957. Facies and thickness of the Upper Paleozoic and Triassic sediments of Southland. Transactions of the Royal Society of New Zealand 84: 499–511.

Mutch AR 1959. Longwoods Complex. In: Fleming CA ed. Lexique Stratigraphique International 6 (Océanie). Paris, Centre National de la Recherche Scientifique. 194.

Pin C, Briot D, Bassin C, Poitrasson F 1994. Concomitant separation of strontium and samarium-neodymium for isotopic analysis in silicate samples, based on specific chromatography. Analytica Chimica Acta 298: 209–217.

Price RC, Sinton JM 1978. Geochemical variations in a suite of granitoids and gabbros from Southland, New Zealand. Contributions to Mineralogy and Petrology 67: 267–278.

Richard P, Shimizu N, Allegre CJ 1976. $^{143}Nd/^{144}Nd$, a natural tracer: an application to oceanic basalts. Earth and Planetary Science Letters 31: 269–278.

Rombouts M 1994. Geology of the southern Longwoods tops, western Southland. Unpublished MSc thesis, University of Otago, Dunedin, New Zealand.

Spandler CJ, Arculus RJ, Eggins SM, Mavrogenes JA, Price RC, Reay A 2003. Petrogenesis of the Green Hills Complex, Southland, New Zealand: magmatic differentiation and cumulate formation at the roots of a Permian island arc volcano. Contributions to Mineralogy and Petrology 144: 703–721.

Spandler CJ, Worden K, Arculus RJ, Eggins SM 2005. Igneous rocks of the Brook Street Terrane, New Zealand: implications for Permian tectonics of eastern Gondwanaland and magma genesis in modern intra-oceanic arcs. New Zealand Journal of Geology and Geophysics 48: 167–183.

Steiger RH, Jäger E 1977. Subcommission on geochronology: convention in the use of decay constants in geo- and cosmo-chronology. Earth and Planetary Science Letters 36: 359–362.

Tera F, Wasserburg GJ 1972. U-Th-Pb systematics in three Apollo 14 basalts and the problem of initial Pb in lunar rocks. Earth and Planetary Science Letters 14: 313–345.

Tulloch AJ, Kimbrough DL, Landis CA, Mortimer N, Johnston MR 1999. Relationships between the Brook Street Terrane and Median Tectonic Zone (Median Batholith): evidence from Jurassic conglomerates. New Zealand Journal of Geology and Geophysics 42: 279–293.

Wadsworth CA 2000. Petrochemistry of a gabbro-norite contact zone, Pahia Point, Southland. Unpublished MSc thesis, University of Otago, Dunedin, New Zealand.

Watson EB 1979. Zircon saturation in felsic liquids: experimental results and applications to trace element geochemistry. Contributions to Mineralogy and Petrology 70: 407–419.

Watson EB, Harrison TM 1983: Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. Earth and Planetary Science Letters 64: 295–304.

Williams JG, Harper CT 1978. Age and status of the Mackay Intrusives in the Eglinton-upper Hollyford area. New Zealand Journal of Geology and Geophysics 21: 733–742.