The Origin of HIMU in the SW Pacific: Evidence from Intraplate Volcanism in Southern New Zealand and Subantarctic Islands

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ABSTRACT

This paper presents field, geochemical and isotopic (Sr, Nd, Pb) results on basalts from the Antipodes, Campbell and Chatham Islands, New Zealand. New $^{40}Ar/^{39}Ar$ age determinations along with previous K-Ar dates reveal three major episodes of volcanic activity on Chatham Island (85-82, 41-35, ~5 Ma). Chatham and Antipodes samples comprise basanite, alkali and transitional basalts that have HIMU-like isotopic ($^{206}Pb/^{204}Pb$ >20.3-20.8, $^{87}Sr/^{86}Sr$ <0.7033, $^{143}Nd/^{144}Nd$ >0.5128) and trace element affinities (Ce/Pb 28-36, Nb/U 34-66, Ba/Nb 4-7). The geochemistry of transitional to Q-normative samples from Campbell Island is explained by interaction with continental crust. The volcanism is part of a long-lived (~100 Myr), low-volume, diffuse alkaline magmatic province that includes deposits on the North and South Islands as well as portions of West Antarctica and SE Australia. All of the continental areas were juxtaposed on the eastern margin of Gondwanaland at >83 Ma. A ubiquitous feature of mafic alkaline rocks from this region is their depletion in K and Pb relative to other highly incompatible elements when normalized to primitive mantle values. The inversion of trace element data indicates enriched mantle sources that contain variable proportions of hydrous minerals. We propose that the mantle sources represent continental lithosphere that host amphibole/phlogopite-rich veins formed by plume and/or subduction related metasomatism between 500 and 100 Ma. The strong HIMU signature ($^{206}Pb/^{204}Pb$ >20.5) is considered to be an in-grown feature generated by partial-dehydration and loss of hydrophile elements (Pb, Rb, K) relative to more magmaphile elements (Th, U, Sr) during short-term storage at the base of the lithosphere.

KEY WORDS: continental alkaline basalts; mantle metasomatism; OIB, HIMU; Sr, Nd and Pb isotopes; West Antarctica; New Zealand; lithospheric mantle

INTRODUCTION

It is widely accepted that most mafic alkaline magmas erupted in continental areas that have HIMU (high time-integrated $^{238}U/^{204}Pb$ or high μ) isotopic signatures similar to oceanic island basalts (OIB: $^{206}Pb/^{204}Pb$ >20.5 and low $^{87}Sr/^{86}Sr$ <0.7030 and $^{3}He/^{4}He$ 5-7 R/Ra) are products of small degree melts from sub-lithospheric mantle sources (Wilson et al., 1995; Ballentine et al., 1997; Franz et al., 1999; Janney et al., 2002). The origin of the HIMU source component is often attributed to chemically modified oceanic lithosphere that was subducted and stored in the deep mantle, aged and eventually transported back to the surface via mantle plumes (Hofmann, 1997; Moreira & Kurz, 1999; Stracke et al., 2003; 2005). But it is becoming increasingly recognized that sources of HIMU may also exist within sub-continental lithosphere generated by the evolution of metasomatic fluids and melts (Stein et al., 1997; Blusztajn & Hegner, 2002; Pilet et al., 2005). A lithospheric versus sub-lithospheric origin of the HIMU component in continental basalts in the SW Pacific (New Zealand, West Antarctica and SE Australia) has been a matter of debate for several decades.

The intraplate igneous rocks of southern New Zealand are low in volume (<10,000 km^3), widely scattered within a 1000 × 800 km area and include several large shield volcanoes, mafic lava fields and small intrusive complexes (Weaver and Smith, 1989). The mafic rocks are predominately alkaline and have OIB-like major and trace element compositions and isotopic signatures that resemble a HIMU mantle source (Gamble et al., 1986; Barreiro & Cooper, 1987; Weaver & Smith, 1989; Baker et al., 1994; Hoke et al., 2000). Coombs et al. (1986) and Sun et al. (1989) recognized the regional OIB-HIMU like character of continental volcanism in New Zealand, Tasmania and West Antarctica. Lanyon et al. (1993), Weaver et al. (1994) and Storey et al. (1999) relate the

HIMU volcanism to plume sources that entered the upper mantle beneath Gondwanaland in the mid- to late Cretaceous and suggest that plume activity played a role in Antarctic-New Zealand breakup and the opening of the Tasman Sea. A younger and smaller plume has been invoked to explain Cenozoic uplift and volcanism in Marie Byrd Land (LeMasurier & Rex, 1989; Behrendt et al., 1992; 1996; Hole & LeMasurier, 1994; LeMasurier & Landis, 1996; Storey et al., 1999). An alternative plume model is one in which the source for all of the HIMU volcanism in the SW Pacific can be related to an ancient plume head that was fossilized in the uppermost mantle prior to Gondwanaland breakup (Rocholl et al., 1995; Hart et al., 1997; Panter et al., 2000a). Others have proposed magmatism without plume origins. Rocchi et al. (2002; 2004) suggest that the upper mantle source for alkaline magmas was metasomatically enriched during late Cretaceous extension and subsequently melted in response to reactivation of trans-lithospheric fractures during Cenozoic times. Finn et al. (2005) proposed that Cenozoic volcanism leading to this Diffuse Alkaline Magmatic Province (DAMP) is a response to the sudden detachment and sinking of subducted slabs into the lower mantle causing vertical and lateral flow that triggered melting of a previously metasomatised mantle lithosphere.

Past studies are weighted heavily on data gathered from Cenozoic basalts but most of their models call upon sources that are at least Mesozoic in age. Prior to this investigation, Mesozoic igneous rocks that approach OIB-HIMU end-member compositions in terms of Pb isotopes (^{206}Pb/^{204}Pb >20) have been identified only within the mid-Cretaceous (c. 90-100 Ma) Tapuaenuku Igneous Complex (Baker et al., 1994) on the South Island of New Zealand (Fig. 1). Other late Cretaceous continental basalts in New Zealand and Australia have similar geochemical characteristics but complete data sets, in particular Pb isotopes, are not yet published. We present here a detailed study of continental basalts from three islands off the east and southeastern coast of New Zealand (Fig. 1). The oldest basalts on Chatham Island are of late Cretaceous age (~85 Ma)

with initial $^{206}Pb/^{204}Pb$ values $\geq$ 20 and trace element contents similar to OIB. The Cenozoic basalts from the same region, as well as basalts from Marie Byrd Land, West Antarctica (Hart et al., 1997; Panter et al., 2000a) have very similar isotopic and trace element characteristics. The purpose of this study is to : (1) to constrain processes involved in the genesis of mafic magmas in southern New Zealand; (2) to determine mantle source compositions; (3) to evaluate the origin of the HIMU-like signature; and (4) to use the new data to help constrain regional models proposed for magmatism.

REGIONAL GEOLOGICAL HISTORY

The Campbell and Antipodes Islands are situated along the southeastern margin of the Campbell Plateau, and the Chatham Islands lie at the eastern end of the Chatham Rise (Fig. 1). The basement geology of the Chatham Rise and Campbell Plateau consists of Paleozoic−Mesozoic metasedimentary and plutonic rocks (Beggs et al., 1990; Wood & Herzer, 1993) that correlate with major tectonostratigraphic terranes recognized on the mainland of New Zealand (Bishop et al., 1985; Bradshaw, 1989; Adams et al., 1998) and in Marie Byrd Land, Antarctica (Bradshaw et al., 1997; Pankhurst et al., 1998; Sutherland, 1999).

   The late Cretaceous breakup of the proto-Pacific margin of Gondwanaland was foreshadowed by mid-Cretaceous extension and crustal thinning over a broad area (Bradshaw, 1989; Laird, 1993; Beggs, 1993; Davy, 1993, Luyendyk et al., 2001; Luyendyk et al., 2003), rapid regional uplift (Tulloch & Kimbrough, 1989; Richard et al., 1994; Adams et al., 1995; Spell et al., 2000) and a sudden change from subduction-related to rift-related magmatism (Weaver et al., 1994; Tulloch & Kimbrough, 1995; Waight et al., 1998a). The switch in tectonic regime corresponded with the oblique arrival of the Pacific-Phoenix spreading center along the Gondwanaland margin at ~100 Ma (Bradshaw, 1989; Luyendyk, 1995; Mukasa & Dalziel, 2000). Ultimately, the interaction between

the Pacific-Phoenix spreading center and the subduction zone led to the breakup of the supercontinent and inception of the Pacific-Antarctic Ridge shortly before 83 Ma (Molnar et al., 1975; Larter et al., 2002).

Cretaceous rift-related magmatism along the New Zealand sector of the Gondwanaland margin includes the Mandamus (Weaver & Pankhurst, 1991), Tapuaenuku (Baker et al., 1994) and Blue Mountain (Grapes, 1975) layered igneous complexes, numerous other intrusions (Waight et al., 1998b) and dispersed volcanic fields, including a large basaltic shield volcano on the Chatham Islands (Grindley et al., 1977). These igneous rocks range in age from 100 to 60 Ma with a peak in activity between 100 and 90 Ma (Baker et al., 1994, Table 1). Following the breakup, New Zealand experienced pronounced thermal relaxation as it moved northward on the Pacific Plate. Consequently, the Paleocene-Eocene epochs were a period of relative magmatic quiescence (Weaver & Smith, 1989) and volcanic rocks of late Eocene to early Oligocene age are minor in volume and widely dispersed.

Over the past 45 Myr tectonic activity in New Zealand has been the result of the progressive development of the Australian-Pacific plate boundary (Sutherland, 1995). Transtension and inception of the paleo-Alpine Fault system, whose age is contrained by dikes of the Westland swarm (Fig. 1) emplaced between 32 and 25 Ma (Adams & Cooper, 1996), and followed by transpression and rapid uplift of the Southern Alps beginning at ~6 Ma (Walcott, 1998). Adams & Cooper (1996) proposed that the termination of a major volcanic episode, which produced several large centers on the Banks and Dunedin Peninsulas in the middle to late Miocene, was in response to the change to a compressive tectonic regime.

Pliocene-Pleistocene volcanism in southern New Zealand was restricted to small areas on the South Island (Duggan & Reay, 1986) and on the Antipodes and Chatham Islands (Cullen, 1969; Grindley et al., 1977). Although at present there is no active volcanism in southern New Zealand,

geophysical evidence and helium emission studies indicate the existence of hot regions of decompressing upper mantle (Godfrey et al., 2001; Hoke et al., 2000).

VOLCANIC GEOLOGY

Campbell Island is New Zealand's southernmost subantarctic island (Fig. 1). Miocene volcanic rocks cover most of the island and consist of lava flows, pyroclastic rocks and volcanoclastic breccias (Morris, 1984, Morris & Gamble, 1990). Apart from a shallow intrusion of gabbro that predates volcanism by ~ 9 Myr, most of the deposits are late Miocene in age (~7.0 Ma, Adams et al., 1979).

The Antipodes Islands are a small isolated island group that lies at the eastern edge of the Campbell Plateau (Fig. 1). The islands are composed of alkaline lavas and pyroclastic rocks, including tuff cone and ring deposits (Cullen, 1969; Gamble et al., 1986; Gamble & Adams, 1990). A Quaternary age for the islands is inferred based on the well-preserved volcanic morphology and two K-Ar dates (Cullen, 1969).

The Chatham Islands are a populated group of islands that lie over 700 km east of the mainland of New Zealand (Fig. 1). The group consists of two main islands, Chatham and Pitt, which are surrounded by several smaller islands and a number of islet clusters. Campbell et al. (1993) provide a comprehensive review of the geology, geochronology and biostratigraphy of the Chatham Islands. The petrology and geochemistry of the Eocene and Cretaceous volcanics are reported by Morris (1985a,b).

The mid- to late-Cretaceous volcanic and sedimentary rocks of the Chatham Islands rest unconformably on a pre-Cretaceous basement of metasediments. The Cenozoic sequence consists of thin biogenic and clastic sedimentary units interspersed with localized volcanic deposits. Based on mapping and twenty six K-Ar dates, Grindley et al. (1977) recognized that volcanism on the Chatham Islands occurred in three distinct episodes; late Cretaceous (81-70 Ma) Southern

Volcanics*,* late Eocene (41-36 Ma) Northern Volcanics and Miocene-Pliocene (~5.0 Ma) Rangitihi Volcanics.

The late Cretaceous Southern Volcanics are volumetrically the most significant and widely distributed group. The Southern Volcanics consist of lava flows 2-5 m thick that often show reddened brecciated bases and scoriaceous tops indicative of subaerial emplacement. Exposed lava sequences are found up to 300 m thick occur on the southern coast of Chatham Island and thin progressively to the north consistent with a southern source located in the Pitt Strait (Morris, 1985a; Campbell et al., 1993).

The late Eocene Northern Volcanics form small (<150 m in height) but prominent hills on the northern half of Chatham Island (Fig. 2). The hills represent variably eroded cones composed predominately of interbedded basaltic lavas and pyroclastics. At Mairangi cone, reddened scoriaceous deposits containing bomb and block ejecta were produced by Strombolian/Vulcanian activity. At Matakitaki cone, dark-green palagonitized tuff containing vesiculated lapilli-sized sideromelane fragments were produced by phreatomagmatic activity.

The Miocene-Pliocene Rangitihi Volcanics are concentrated in two areas on the northern coast of Chatham Island (Fig. 2). The deposits exposed at Cape Young and Maunganui consist of interbedded tuffs and tuff-breccias, lavas and fossiliferous marine sediments. The Rangitihi Volcanics are characterized by megacrysts of amphibole (up to 4 cm in length) and also contain abundant crustal and mantle xenoliths. The presence of tuffaceous foramineferan packstone surrounding and interclated with lobes of pillow basalts at the base of the volcanic sequence at Maunganui suggests that volcanic activity began with shallow submarine eruptions (Campbell et al., 1993).

SAMPLE DESCRIPTION AND ANALYTICAL TECHNIQUE

This study is based on 36 mafic igneous rocks from the Campbell, Antipodes and Chatham island groups. The majority of the samples were collected from lava flows and small shallow intrusions. Most of the samples are dense, holocrystalline and porphyritic with phenocrysts of olivine and clinopyroxene (Table 1). Plagioclase feldspar is abundant (10-20%) as phenocrysts in Campbell Island lavas and is also the dominant interstitial phase in gabbro. Magnetite along with plagioclase occurs in the groundmass of most samples (Table 1) and kaersutite is found in Pliocene basalts from Chatham Island and in Pleistocene lavas from Antipodes Island (Gamble et al., 1986). Dense holocrystalline samples are fresh and unaltered but some glassy and more vesicular samples show secondary alteration. Devitrification of hypohyaline groundmasses is observed in some lavas and blocks of the Northern Volcanics and includes a palagonitized sideromelane tuff from Matakitaki cone on Chatham Island.

Thirty-two samples were analyzed for major and trace-elements (V, Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba and Pb) on a Philips PW2400 XRF spectrometer at New Mexico Tech. Analytical precisions on major elements with concentrations > 1 wt.% are < 0.1% (1σ) and for trace elements typically less than 4% (1σ). Lead concentrations for 12 samples were determined by ICP-MS with precisions of 1 to 2%, others by XRF with precisions of ~10% (Table 2). Other trace elements were measured at New Mexico Tech by INAA using 26% and 18% efficient high-purity Ge detectors (Hallett & Kyle, 1993). Based on repeat analyses of standards, we estimate analytical precision to be < 1% for Sc, La, and Sm; < 3% for Ce, Eu, Hf, Ta, Th and Lu; < 5% for Tb and Yb; and < 10% for Nd, Cs, and U.

Many of the Chatham Island samples have loss-on-ignition (LOI) values that exceed 1.0 wt.% (Table 2). There is a broad correlation between higher LOI values and samples that contain glass and amygdules. But only when considering the Northern Volcanics are correlations found between

LOI and some major and trace elements. The geochemistry of the most highly altered samples (LOI > 5 wt.%), will not be considered in the petrogenetic discussions. For the remaining samples, major and trace elements are recalculated to 100% volatile-free (Table 2).

Sr, Nd and Pb isotopic analysis of 18 samples (Table 4) were performed at the Woods Hole Oceanographic Institution using conventional thermal ionization mass spectrometry (Hauri & Hart, 1993). All sample chips were first leached in warm 6 *N* HCl for 1 hour before dissolution. Precisions of the Sr and Nd data are ±0.003-0.005% (2σ). Reproducibility of Pb data is 0.05% per amu based on repeat runs of NBS981.

A total of 12 Chatham Island samples were dated by the ^{40}Ar/^{39}Ar method (Table 3). The whole rocks samples were crushed, sieved, leached with dilute HCl, washed in distilled water and hand-picked to remove phenocrysts and altered material to produce a groundmass concentrate. Amphibole separates were handpicking with the aid of a binocular microscope. The samples and Fish Canyon Tuff sanidine monitor (age = 27.84 Ma) were irradiated for 14-hours at the Nuclear Science Center reactor, College Station, Texas. Argon isotopic compositions of samples and monitors were determined at the New Mexico Geochronological Laboratory.

RESULTS

^{40}Ar/^{39}Ar geochronology – Chatham Island

Twelve ^{40}Ar/^{39}Ar dates from basalts have been determined to better constrain the volcanic history of Chatham Island. Apparent ages were determined from age spectra and isotope correlation (^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar) diagrams (Table 3). The latter provide a quantitative measure of the initial argon composition and allow the identification of excess argon which has ^{40}Ar/^{36}Ar ratios greater than the present-day atmospheric value of 295.5. The ^{40}Ar/^{36}Ar intercept values in Table 3 indicate that excess argon is not significant in Chatham Island samples. The anomalous ^{40}Ar/^{36}Ar

ratios for amphibole are a consequence of high uncertainties in the fit of the regression line. In all cases, the plateau age spectrum is interpreted to represent the eruption age of the basalts (Table 3 "preferred age" and Fig. 3). Degassing of the three amphibole samples occurred over a very narrow range of temperatures which resulted in a small number of steps comprising >90% of the total $^{39}Ar_K$ released. Sample CHT-5 degassed primarily in one temperature step (1200°C, $^{39}Ar_K$ = 91.7%) and therefore does not meet plateau criteria (Fig. 3b). Its age however is indistinguishable from the plateau age for sample CHT-8 which was collected from a stratigraphically and lithologically equivalent unit. Alteration is the likely reason for the discordant age spectrum of groundmass samples CHT-11 and CHT-20. The low radiogenic ^{40}Ar yields caused by alteration translate into high uncertainties on the age of individual temperature steps. Radiogenic yields are significantly higher for amphibole separated from CHT-20 providing an apparent age with a higher precision (Table 3).

The $^{40}Ar/^{39}Ar$ ages provide several important modifications to the volcanic history of Chatham Island based on the K-Ar dates of Grindley et al. (1977). Our results indicate that the late Cretaceous volcanism, which produced the Southern Volcanics, is significantly older than previously thought. The $^{40}Ar/^{39}Ar$ age determinations from this study range from 82.26 ± 0.79 Ma to 85.45 ± 0.59 Ma while prior K-Ar dates range from 70.4 ± 1.2 Ma to 81.4 ± 2.0 Ma (revised using the decay constants and isotopic abundances recommended by Steiger & Jager, 1977). Our samples were collected from units that encompass most of the volcanic stratgraphy of Chatham Island and from some of the same sites sampled for K-Ar dating. Two basalts collected ~1 km apart on the same lava flow at Ohira Bay yield indistinguishable $^{40}Ar/^{39}Ar$ ages of 84.16 ± 0.73 Ma and 84.2 ± 1.2 Ma (samples CHT-1 and CHT-3, respectively; Table 3). These ages are significantly older than the revised K-Ar age of 79 ± 2.0 Ma (sample R3198 of Grindley et al., 1977) from the same flow. Other locations where our results yield significantly older ages relative to previous K-Ar ages include samples collected from Waitaha Creek (CHT-12) and Cape Fournier, (CHT-27).

We therefore conclude that the age of the Southern Volcanics from the Chatham Islands are more tightly clustered around 84-85 Ma rather than the younger and longer (~10 Myr) time-span proposed by Gindley et al. (1977). A relatively short period of eruption for the bulk of the Southern Volcanics is supported by the age of samples collected from the base and top of thick (80-100 m) lava sequences that are indistinguishable within the resolution of argon dating.

The Cenozoic volcanism on the Chatham Islands consists of at least 10 separate volcanic lithostratigraphic units but only half have been dated by radiometric methods (Campbell et al., 1993). Previous K-Ar ages for the Northern Volcanics are late Eocene (41-36 Ma). In this study, one sample of the Northern Volcanics collected from Mt. Chudleigh (Fig. 2) has a slightly younger age of 32.1 ± 4.8 Ma (CHT-11). Four samples of the Pliocene-Miocene Rangitihi Volcanics were dated by the $^{40}Ar/^{39}Ar$ method and generally agree with previous K-Ar ages. Two amphibole separates from basaltic lavas at Cape Young yield indistinguishable ages of 4.96 ± 0.25 Ma and 4.97 ± 0.10 Ma (CHT-5 and CHT-8, respectively; Table 3). Approximately 12 km to the west at Maunganui (Fig. 2), a lava flow on the coast is dated at 4.34 ± 0.45 Ma (CHT-17, Fig. 3d). Our $^{40}Ar/^{39}Ar$ age determinations indicate that Rangitihi Volcanics also exist at the Tawreikoko volcanic cone (Fig. 2). Tawreikoko cone is composed of breccias and lavas mapped as Northern Volcanics but is cut by a kaersutite-bearing basaltic dike of *Rangitihi* age (4.95 ± 0.27 Ma, CHT-20 amp, Table 3).

Major and Trace Elements

Mafic igneous rocks from the Chatham, Antipodes and Campbell islands range in composition from ultrabasic to basic (42-51 wt.% SiO_2), have magnesium numbers (Mg#) between 44 and 65, and are classified as basanite (*ne*-normative, >10% *ol*-normative), tephrite (*ne*-normative, <10% *ol*-normative), alkali- and transitional basalts (<10% *hy*-normative), subalkali basalt, and *Q*-gabbro

(>10% *hy*-normative, *Q*-normative) according to the recommendations of Le Maitre et al. (2002). One sample from Chatham Island (CHT-14) is intermediate in composition and classified as a basaltic trachyandesite (Table 2).

The broad correlation of MgO with major and trace elements displayed in Fig. 4 suggests that most of the samples have been modified by crystal fractionation. The fractionation of olivine is indicated by increasing Al_2O_3 and decreasing Ni (not shown in Fig. 4) ($K_D^{ol/melt}$ Ni 10-23, Hart & Davis, 1978) while fractionation of clinopyroxene is indicated by decreasing MgO with CaO/Na_2O and Cr ($K_D^{Cpx/melt}$ Cr 3.8, Hart & Dunn, 1993). A negative correlation between Zr/Hf ratios and Sc content, particularly well defined in the Southern Volcanics, is also indicative of clinopyroxene control during crystallization (David et al., 2000).

With decreasing MgO the Rangitihi Volcanics show a systematic increase in the concentration of most incompatible elements (e.g., Ba, Nb, La, Th) and depletion in elements compatible with olivine and clinopyroxene (Fig. 4). The trend of increasing FeO^t with decreasing MgO (not shown) argues against significant fractionation of Fe-Ti oxides. The slight decrease in SiO_2 with MgO (Fig. 4) and corresponding increase in Si-undersaturation (from ~4% to >10% normative nepheline, Table 2) is in response to the removal of kaersutite; a Ti-rich, silica-poor amphibole that is found in high modal proportions in Rangitihi Volcanics (Table 1). The fractionation of kaersutite has also buffered TiO_2 concentrations. TiO_2 will increase with crystallization of olivine and clinopyroxene with little or no fractionation of Fe-Ti oxides but the high TiO_2 content of kaersutite (~5 wt.%) relative to the magma (~< 3 wt.%) counteracts this affect. Removing kaersutite from the magma also depletes Ti relative to middle rare earth elements (MREE) Eu and Tb (Ti/Ti*, Fig. 4) and other large ion lithophile elements (LILE). The coherent fractionation trends of Rangitihi Volcanics can be modeled by the fractionation of 25% clinopyroxene, 19% kaersutite, 15% olivine, 10% plagioclase and 4% titanomagnetite from the least fractionated basanite (CHT-20, MgO >12 wt.%)

to produce a 27% residual that closely approximates the major element ($\Sigma r^2 = 0.04$) and trace element concentrations (errors for U and Th < 20%, Zr, Hf, Ba < 15% and Sr, La, Ce, Ta, Nb < 10%) of tephrite (CHT-17, MgO < 6 wt.%). This least-squares mass balance and Rayleigh distillation model uses mineral analyses from Rangitihi Volcanics and the mafic mineral/melt partition coefficients of Caroff et al. (1993). Mass balance models for other suites suggest that clinopyroxene and olivine (± plagioclase) controlled the evolution of alkali basalt to hawaiite for late Cretaceous and Eocene sequences on Chatham Island (Morris, 1985a; 1985b). Morris (1984) also modeled the differentiation of transitional basalt to hawaiite on Campbell Island by the removal of plagioclase and lesser amounts of clinopyroxene, consistent with the observed petrography.

   To help evaluate the source of the basalts and melting processes we have selected the most primitive samples from each island. Seven of the basalts are relatively unfractionated (Mg# 62-66, Cr >300 ppm and Ni >250 ppm) and include one sample from Campbell Island (OU39796) and one from each of the three main age-delimited volcanic groups on Chatham Island. The least fractionated Antipodes Island sample (ANT-3) is comparable in concentration with respect to Al_2O_3, CaO, Cr and V but has a lower Mg# (56) and Ni (148 ppm) contents indicating greater amounts of olivine have been fractionated. To compensate for olivine fractionation the samples were normalized to Mg# 73. This was accomplished by adding olivine, incrementally, to each composition while maintaining a constant Fe^{2+}/Mg K_D value equal to 0.30 until the Mg# reached 73 and olivine reached Fo_{90}. Trace element concentrations were reduced by the percentage of olivine added back to each composition (Table 2).

   The olivine-normalized basanite, alkali- and transitional-basalts from the Antipodes, Campbell and Chatham Islands are compared on multi-element plots in Figs. 5 and 6. The samples display similar enriched patterns with peaks at Na-Ta and prominent negative K- and Pb-anomalies (Fig. 5). The basalts also show parallel and moderately steep patterns on REE plots with La_N/Yb_N

values between 12 and 28 and La_N/Sm_N values between 2.4 and 3.2 (Fig. 6), which implies that all

of the basalts are products of small melt fractions of a garnet-bearing source. A notable difference,

however, is evident in their relative Ti concentrations. The Ti/Ti* values for the basalts are variable

(0.8-1.7) and span this range of values in samples from all localities (Fig. 4). There is also a

difference in Zr/Nb and Hf/Nb values between the Late Cretaceous (Zr/Nb = 5.2-5.8, Hf/Nb = 0.12-

0.13) and Cenozoic (Zr/Nb = 3.7-3.8, Hf/Nb = 0.09-0.10) basalts from Chatham Island. Setting

aside these subtle variations it is apparent that the overall trace element distribution (Fig. 5) and low

LILE/Nb values (e.g. Fig. 7) of the New Zealand samples are comparable to other continental

alkaline basalts from the SW Pacific (Johnson, 1989; Finn et al., 2005) and ocean islands, in

particular, basalts that have the HIMU type isotopic signature (St. Helena and the Austral-Cook

island chain).

Sr, Nd and Pb Isotopes

Results of isotope analysis for Chatham, Antipodes and Campbell island samples are presented in

Table 4 and are plotted with reference to basalts from the south-central Pacific and south Atlantic

oceans in Fig. 8. Also included in Fig. 8 are samples from three alkaline suites on the South Island

of New Zealand; the early-Miocene Westland dike swarm (Barreiro & Cooper, 1987), mafic clasts

within the Port Chalmers Breccia (PCB) of the Dunedin Volcanic Group (Price et al., 2003) and the

mid-Cretaceous Tapuaenuku igneous complex (Baker et al., 1994; Baker unpublished data). All

data plotted in Fig. 8 are measured values. Although it is customary to correct for the radiogenic in-

growth of daughter nuclides in order to discuss source signatures we suggest that a better

comparison between Mesozoic and Cenozoic samples can be made if the values are left

uncorrected. We consider the measured values to be close approximations of their present-day

source values. To evaluate this assertion, initial isotopic ratios for the Cretaceous Chatham Island

basalts were projected to the present day using parent/daughter ratios calculated by means of a two-

stage mantle evolution model. In Table 4, the model source ratios differ from measured ratios by $\leq$ 0.00008 for $^{87}Sr/^{86}Sr$, $\leq$ 0.00004 for $^{143}Nd/^{144}Nd$ and $\leq$ 0.19 for $^{206}Pb/^{204}Pb$.

Together, the basalts from the Chatham and subantarctic islands show a restricted range in measured $^{143}Nd/^{144}Nd$ (0.5128–0.5129) and $^{207}Pb/^{204}Pb$ (15.6–15.7) values, a moderate range in measured $^{87}Sr/^{86}Sr$ (0.7029–0.7040) and $^{208}Pb/^{204}Pb$ (39.1–40.5) values, and a wide range in measured $^{206}Pb/^{204}Pb$ values (19.2–20.8). With the exception of one sample (CHT-11) all Chatham Island and Antipodes Island basalts have high $^{206}Pb/^{204}Pb$ (20.3–20.8) and low $^{87}Sr/^{86}Sr$ (~ 0.703) values and define moderately tight clusters on isotope correlation plots (Fig. 8). In Fig. 8, the Chatham and Antipodes basalts mostly lie between the FOZO and HIMU mantle domains redefined by Stracke et al. (2005) based on oceanic basalts from the Austral-Cook island chain and St. Helena. The samples from Tapuaenuku and the Westland dike swarm show wider variations in $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values, and along with the Dunedin samples (PCB), are intermediate between rocks from Campbell Island and those from the Chatham and Antipodes Islands. The gabbros from Tapuaenuku have the lowest $^{143}Nd/^{144}Nd$ values while the Q-gabbro and transitional to subalkaline basalts from Campbell Island have, on average, the highest $^{87}Sr/^{86}Sr$ values.

DISCUSSION

Crustal Contamination

Continental alkaline basalts with high Sr isotope ratios and OIB-like trace element signatures are often attributed to small degree melts of a metasomatically enriched mantle lithosphere (e.g., Baker et al., 1997; Zhang & O'Reilly, 1997; Späth et al., 2001; Barry et al., 2003). High Sr ratios in basalts may, however, reflect contamination from radiogenic crust. Chemical contributions from continental crust have previously been proposed for some of the mafic rocks from the Tapuaenuku igneous complex (Baker et al., 1994) and for the Westland dike swarm (Barreiro & Cooper, 1987).

In each case, the samples that have slightly elevated Sr isotope ratios (>0.7035, Fig. 8c) also have low Sr concentrations and therefore are more susceptible to contamination from highly radiogenic crust.

The transitional to slightly silica-oversaturated basalts from Campbell Island have elevated $^{87}Sr/^{86}Sr$ values and low Sr contents (~350-700 ppm) relative to Chatham and Antipodes samples (~700-1300 ppm, Table 2). They also have lower average Nb/U values (ca. 34) relative to OIB (ca. 47, Hofmann et al., 1986) and Antipodes and Chatham island basalts (ca. 46), which may indicate fractionation and addition of low Nb/U crust [10-20 for total continental crust (Sims & DePaolo, 1997) and ~5 for bulk metasediments from southern New Zealand (Mortimer & Roser, 1992)]. To evaluate the possibility that Campbell Island samples have been contaminated by crust we have modeled several evolutionary paths for combined assimilation and fractional crystallization (AFC) on isotope and trace element ratio plots (Fig. 9). A mildly fractionated basalt from Chatham Island (CHT-17) was selected for the starting composition and several possible assimilants, representing the pre-Cenozoic basement of New Zealand (Graham & Mortimer, 1992; Graham et al., 1992) and modern near-trench bulk sediments collected from the Kermadec-Hikurangi margin to the north of New Zealand (Gamble et al., 1996), were used. The AFC paths in Fig. 9 show that samples with higher $^{87}Sr/^{86}Sr$ and lower $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, Nb/U and Nb/Rb values may be explained by assimilation of arc sediments with concurrent fractional crystallization of $\le 30\%$ (1-*F*).

Mantle Metasomatism

It has long been proposed that metasomatic enrichment of the upper mantle by hydrous- or carbonate-rich fluids or low volume partial melts may be a necessary precursor to alkaline magmatism (Sun & Hanson, 1975; Lloyd & Bailey, 1975; Wass & Rodgers, 1980) and studies of alkaline rocks from New Zealand support this assertion (Gamble et al., 1986; Barreiro & Cooper, 1987; Weaver & Smith, 1989; Baker et al., 1994; Cook et al., 2005). Alkalis (e.g., K, Rb, Ba) and

water are stored within metasomatised upper mantle in amphibole and phlogopite and are retained in these minerals relative to anhydrous minerals during melting (Adam et al., 1993; Dalpé & Baker, 1994; LaTourrette et al., 1995). This effect is displayed prominently by negative K-anomalies on primitive mantle-normalized multi-element plots (Fig. 5). Spidergrams of other New Zealand mafic alkaline rocks also show negative K-anomalies (Gamble et al., 1986; Weaver & Smith, 1989) suggesting that this is a widespread characteristic of the mantle source (Gamble et al., 1986).

In an effort to constrain mantle source compositions and the role of hydrous phases during melt generation we use the inversion technique described by Hart et al. (1997) for modal batch partial melting. Source models are based on the regression of two dominant data arrays observed on reciprocal plots (Fig. 10). The first model consists of the inversion of the entire filtered data set that includes basalts from each age delimited suite on Chatham Island and basalts from Antipodes Island (Figs. 10a & 10b). The second model is based solely on the regression of the Cretaceous Southern Volcanics from Chatham Island (Figs. 10c & 10d). The results of these calculations are listed in Table 5 and are shown in Fig. 11. The patterns for the two modeled sources are roughly parallel and are both enriched in highly incompatible elements and depleted in HREE relative to primitive upper mantle (McDonough and Sun, 1995). Also, both patterns show pronounced negative Pb and positive Ti anomalies. The models differ most significantly with respect to absolute concentration of LIL elements – Rb, Ba, Th, U, and K, and HFS elements – Zr and Hf. The composition derived for the Southern Volcanics is considered to represent a single homogeneous source, which is consistent with their relatively restricted collective age (~84–85 Ma; Table 3), limited geographic extent (Fig. 2) and similar petrological characteristics (Figs. 4−6). The model composition derived from the entire data set must therefore represent a combined signature that includes a less enriched component.

We believe that some of the compositional disparity between the two models reflects differences in source mineralogy. As discussed previously, amphibole is an important host for K

($K_D^{amp/melt}$ 1.36; Dalpé & Baker, 1994) and Rb and Ba are compatible in phlogopite ($K_D^{phl/melt}$ 5.8 and 2.9, respectively; Adam et al., 1993). Modal variations in the melt source of ± 3% or less of amphibole and phlogopite with their proportions set at ~ 4:1 can adequately account for the differences in K and Ba concentrations between the two models with the Southern Volcanics source containing a higher percentage of both minerals. The difference in Rb content between the two models is not well matched and would require a higher bulk proportion of phlogopite. The estimates are based on the simple addition using the compositions of vein minerals in peridotites reported by Ionov and Hofmann (1995) and Zanetti et al. (1996). If addition of amphibole and phlogopite to the melt source occurs at the expense of clinopyroxene, either by vein-wallrock interaction or reactive porous flow, then the source may become depleted in Th and U (Schmidt et al., 1999; Tiepolo et al., 2000) relative to neighboring elements (Ba, Nb, Ta and K) on multi-element plots (Fig. 11). The addition of amphibole and phlogopite may also contribute to Ti enrichment, although other Ti-rich phases (e.g., ilmenite and rutile) are known to occur in significant modal abundance in some metasomatised peridotites (Haggerty, 1987; Ionov et al., 1999).

The difference in Zr and Hf concentrations between the models cannot be explained by the simple addition of hydrous phases. However, van Achterbergh et al. (2001) document progressive modal metasomatism in natural peridotites by the reactive replacement of garnet and orthopyroxene by clinopyroxene and phlogopite (± Cr-spinel) accompanied by enrichment in Sr, Na, K, LREE and HFSE (Ti, Zr and Nb) and depletion in Y and HREE. The presence of garnet in the melt sources for New Zealand basalts can be inferred from high Zr/Hf (38-47) and Zr/Yb (120-220) values (*cf.* van Westrenen, et al., 2001) and moderately steep mantle-normalized patterns (La_N/Yb_N 12-28) (Fig. 6). The subtle Zr-Hf negative anomalies on mantle-normalized plots (Fig. 5) also imply garnet control during melting ($D^{garnet/melt}$ Zr > Hf ≈ Sm >> Sr; Hauri et al., 1994).

The origin of the negative Pb anomalies in Fig. 11 is less clear. Negative Pb anomalies are present for basalts as well (Fig. 5) along with most oceanic basalts that are normalized to a primitive mantle Ce/Pb value of 11. This may indicate upper mantle sources that are deficient in Pb relative to primitive mantle. However, Pb may be retained in the mantle by sulfide during melting (Salters et al., 2002; Hart et al., 2005). Alternatively, experimental results indicate that Pb, along with K and Rb, are partitioned into aqueous fluids relative to silicate melts and therefore may be fractionated from elements with lower $D^{\text{fluid/melt}}$ (e.g., Sr, Nb, Th, U) during metasomatism (Brenan et al., 1995; Keppler, 1996). Based on mineral/fluid partition coefficients it has also been suggested that dehydration of amphibole-rich peridotite could produce a residual source that is depleted in Pb and Rb relative to U, Th, Nb and Sr (Brenan et al., 1995; Stein et al., 1997). The characteristic negative Pb anomalies of the basalts (Fig. 5) may therefore reflect Pb loss during partial dehydration of metasomatised mantle.

Timing of Metasomatism

The metasomatism recorded by alkaline rocks and mantle xenoliths extends to continental areas outside of New Zealand. Recall that during the Paleozoic and Mesozoic the continental blocks of New Zealand were part of the eastern margin of Gondwanaland, juxtaposed to southeastern Australia, Tasmania, and the Victoria Land and Marie Byrd Land provinces of present-day west Antarctica (Sutherland, 1999; Lawver et al., 1992; DiVenere et al., 1994). In each of these areas metasomatised mantle sources for Cenozoic alkaline magmas have been proposed (Hart et al., 1997; Panter et al., 2000a; Rocchi et al., 2002; Orlando et al., 2000; Zhang & O'Reilly, 1997; Handler et al., 2003). Estimates for the timing of metasomatism are broad but most suggest that enrichment took place 100 to 400 Myr before the mid-Cretaceous breakup of New Zealand from Antarctica.

Depth and Location of Melting

19

An estimate of pressures of melting for Chatham and Antipodes basalts is calculated using the algorithms derived by Herzberg & Zhang (1996). Our calculations using filtered data corrected for olivine fractionation yield average pressures of ~4.1 GPa (FeO), ~4.4 GPa (MgO), >3.4 GPa (CaO), ~3.9 GPa (Al_2O_3) and >5.2 GPa (Na_2O) for basalts from Chatham Island and average pressures of ~5.3, ~5.5, >5.1, ~4.3 and >3.1 GPa for basalts from Antipodes Island. The results suggest that melt-equilibration occurred at a greater depth beneath Antipodes Island than Chatham Island; ~160 km versus ~120-130 km based on the MgO and FeO parameters. In contrast, the pressures calculated for each of the three major episodes of volcanism on Chatham Island indicate that the depth of melting has not varied significantly (± 0.15 GPa) over the period of ~80 Ma. These results are broadly comparable to depths of melting estimated by Hart et al. (1997) for alkaline basalts from the Hobbs Coast, Marie Byrd Land (~110-140 km) using the same Herzberg-Zhang equations, and those of Huang et al. (1997) for alkaline basalts from the North Island of New Zealand (~80-140 km) using the experimental data of Hirose & Kushiro (1993).

Pressure estimates and evidence for residual hydrous potassic minerals place important limits on the thermal regime of the melt sources. Experimental studies show that the temperature and pressure stability limits of amphiboles vary with composition. Pargasitic amphibole is stable at temperatures <1100˚C at pressures of ~3 GPa (Mengel & Green, 1986; Niida & Green, 1999) while K-richterite is stable to higher temperatures (~1200˚-1250˚C) at higher pressures (3-5 GPa, Trønnes, 2002; Foley, 1991). At these pressures the delimited temperature requires a lithospheric source (*cf*. Class & Goldstein, 1997; LeRoex et al., 2001). Only synthetic F-rich amphiboles (Foley, 1991) are stable at temperatures that exist at the top of the asthenosphere (~1300˚C, McKenzie & Bickle, 1988) but they have not been identified in natural samples (Class & Goldstein, 1997).

Shear wave velocity models consistently show that the regions of alkaline magmatism from eastern Australia to New Zealand and West Antarctica are characterized by slow velocity anomalies restricted to a zone between ~60 and 200 km depth (see Finn et al., 2005, Fig. 4). Lithospheric

thickness estimates of 100-150 km based on elastic models and seismic anisotropy from Australia (Debayle & Kennett, 2000; Simons et al., 2003) and New Zealand (Scherwath et al., 2002) and scattered broad-band seismometer data from West Antarctica (Winberry & Anandakrishnan, 2003), suggest that part of the observed low velocity zones (<~100-150 km depth) beneath the continental areas of the SW Pacific (see Finn et al., 2005, Fig 4) reflect melt/volatile sources within the lithosphere and not in the asthenosphere (Finn et al., 2005). A dominantly lithospheric source for volcanism is also consistent with the fact that over the last ~85 Myr, the Chatham Islands have drifted nearly 3000 km north (~65˚S to ~44˚S) on the Chatham Rise–Campbell Plateau block of Zealandia (Fig. 12) without major changes in source composition or depth of melting (~120-130 km).

Origin of Metasomatism and Implications for HIMU Signatures

The strong HIMU isotopic signature (defined here as $^{206}Pb/^{204}Pb > 20.5$, $^{87}Sr/^{86}Sr \sim 0.703$) of basalts from the Antipodes and Chatham Islands, along with other mafic igneous rocks from the South Island (Figs. 1 and 8), indicate the wide-spread occurrence of a pre-Cenozoic HIMU mantle component within the New Zealand lithosphere. Basalts with equally strong HIMU character are found in Marie Byrd Land (Hart et al., 1997; Panter et al., 2000a) and their melt sources, along with sources for other alkaline rocks with elevated $^{206}Pb/^{204}Pb$ ratios (≥ 19.5) found throughout the SW Pacific (Fig. 12), have been related to a common origin that pre-dates the Late Cretaceous breakup of the eastern margin of Gondwanaland. Previous studies call upon sources produced by mantle plume activity originating in Mesozoic time (Lanyon et al., 1993; Weaver et al., 1994; Rocholl et al., 1995; Hart et al., 1997) or pre-Cenozoic sources developed from metasomatised continental lithosphere (Rocchi et al., 2002; Cook et al., 2004; Finn et al., 2005) or a combination of both (Panter et al., 2000a). A strong case against active plumes in the Cenozoic is based on geological

and geophysical evidence that has been thoroughly reviewed and discussed by Finn et al. (2005).

We will not reiterate these arguments and will limit our discussion to pre-Cenozoic scenarios for

metasomatism and the origin of the HIMU component in the SW Pacific.

Considering the geochemical and geophysical evidence presented above, we propose that the

HIMU source 1) resides within the subcontinental lithosphere and 2) was produced by the evolution

of metasomatic fluids and melts. The case for a lithospheric source for HIMU magmatism is

underscored by the fact that the highest $^{206}Pb/^{204}Pb$ ratios (>20-20.5) are measured only in

continental basalts, whereas basalts from nearby ocean islands (Balleny, Scott, Peter I) and crust

(Macquarie Island) all have consistently lower ratios (19.0-19.8; Fig. 12a). Indeed, a lithospheric

source for the HIMU magmatism has already been proposed, but as plume-derived proto-

lithosphere that was introduced and "stagnated" beneath Gondwanaland (Rocholl et al., 1995; Hart

et al., 1997; Panter et al., 2000a). With regards to our second assertion that the HIMU signature

was generated by the evolution of metasomatic agents – we consider our findings, along with those

of others (e.g., Gamble et al., 1986; Baker et al., 1994), to have firmly established the occurrence of

residual K-rich hydrous minerals in the melt sources for HIMU-like alkaline magmas in southern

New Zealand. Yet the temporal relationship between the HIMU component and the metasomatism

has not been discussed. It has been recognized in Marie Byrd Land that the strong HIMU

component is preferentially sampled by low degree ($\leq 2\%$) partial melts (Hart et al., 1997; Panter et

al., 2000a). This is indicated by the negative correlation between K/K* and Pb/Pb* and $^{206}Pb/^{204}Pb$

values; i.e. lower K/K* and Pb/Pb* values [values < 1 appear as negative K- and Pb-anomalies on

primitive mantle normalized multi-element plots (Fig. 5)] represent smaller degrees of melting

when K- and Pb-compatible minerals are retained in the residuum. Similar correlations for the New

Zealand data strengthen this interpretation (Figs. 13b and 13c), although as discussed earlier, low

relative Pb contents may be a relic of the source composition (Fig. 11) and not solely a product of

partial melting. Nevertheless, it follows that melting localized around veins containing minerals

with lower solidus temperatures (amphibole, mica, apatite, clinopyroxene) will consume a greater proportion of these minerals relative to more refractory assemblages (olivine and orthopyroxene) in the surrounding peridotites. This establishes a link between metasomatism and the strong HIMU signature. In-situ storage of modified lithosphere over a sufficient time span before reactivation and further fractionation by vein-plus-wall-rock melting mechanisms (*cf.*, Foley, 1992) may explain some of the range in isotope compositions for SW Pacific basalts (see Finn et al., 2005, Fig. 7) and the variable enrichment of their melt sources (Fig. 11; also see Hart et al., 1997, Fig. 8, and Rocchi et al., 2002, Fig. 10).

Ancient Plumes and Metasomatism

Amphibole and phlogopite may have been introduced to the Gondwanaland lithosphere by infiltrating melts/fluids derived from rising mantle plume material. A possible pre-Cenozoic plume has been associated with the fragmentation of eastern margin of Gondwanaland in the mid-late Cretaceous (Lanyon et al., 1993; Weaver et al., 1994; Storey et al., 1999). Weaver et al. (1994) place the axis of their proposed 2000 km diameter plume-head at the reconstructed boundary between New Zealand and the Marie Byrd Land, which intersects the region delimited by the highest $^{206}Pb/^{204}Pb$ values (>20.5) in Fig. 12c. But the arguments against a late Cretaceous plume point to the lack of large scale regional uplift (LeMasurier & Landis, 1996), the unrealistically short time interval (5-10 Myr) for the switch from subduction-driven magmatism to plume-driven magmatism (Dalziel et al., 2000; Mukasa & Dalziel, 2000) and the much lower than expected magma production rates relative to plume-associated large flood basalt provinces (Finn et al., 2005). An earlier plume event may have been responsible for magmatism that produced the Jurassic Karoo-Ferrar large igneous province (Storey, 1995; Storey & Kyle, 1997; Dalziel et al., 2000; Storey et al., 2001). But the geochemical character of the mantle source for Ferrar magmatism is unresolved (Kyle et al., 1983; Demarchi et al., 2001; Hergt et al., 1991; Molzahn et al., 1996; Hergt

& Brauns, 2001). Hart et al. (1997) suggest that a large two-component (HIMU + FOZO) mantle plume metasomatised and enriched the Gondwanaland lithosphere prior to breakup. In this model, the rising plume head – weakened by thermal entrainment of ambient mantle, was flattened and flowed over a vast region beneath the Gondwanaland lithosphere with little if any associated volcanism. The plume and metasomatically enriched material was then preserved to form a young and geochemically stratified component of the sub-Gondwanaland crust (*cf.* "fossil plume" of Stein & Hofmann, 1992).

Geochemical studies that favor ancient mantle plumes as sources for continental alkaline magmatism in the SW Pacific however do not adequately account for the seemingly unavoidable physical and chemical interaction between a rising plume head and subduction that was active along the proto-Pacific margin of Gondwanaland between ~500 and 100 Ma (Bradshaw, 1989; Borg & DePaolo, 1991; Elliot, 1991; Lawver et al., 1992). Dalziel et al. (2000) present a model in which the impingement of a plume-head beneath subducted oceanic lithosphere in the late Paleozoic flattened the angle of slab decent and contributed to the early Mesozoic Gondwanide orogeny. The thermal and mechanical break-through of the slab by the plume is considered to have taken place some 30 to 60 Myr later and was followed by Karoo-Ferrar magmatism. Subduction was re-established along the proto-Pacific margin soon after the slab was penetrated. Although Dalziel et al. (2000) do not discuss the geochemical implications of their model; they do offer a plausible scenario for plume-lithosphere interaction beneath a region that would later become the source of alkaline magmatism.

Subduction and Metasomatism

The most important mechanism responsible for the introduction of hydrous and CO_2-rich melts and fluids back into the mantle is the subduction of oceanic lithosphere, including hydrothermally altered upper crust (± sediments). There are several lines of evidence to suggest that the

metasomatised mantle sources for continental alkaline magmatism in the SW Pacific may be linked

to subduction with or without plume influence. First, the calculated chronology of metasomatic

enrichment estimated from basalts and mantle xenoliths coincides with subduction along the eastern

margin of Gondwanaland (~500-100 Ma). Second, if it is accepted that the metasomatism resides

within the subcontinental lithosphere and was in place before Gondwanaland breakup, then the melt

sources for alkaline magmas would be inboard and roughly parallel to subduction at ≥ 100 Ma (Fig.

12c). Additionally, it is important to note that the regions with the longest history of subduction —

correspond with sources having the strongest HIMU signatures (highest $^{206}Pb/^{204}Pb$ values, Fig. 12).

But if the metasomatism is subduction-related, then why does the magma lack the *classic*

subduction component (high LILE/HFSE ratios, e.g., Ba/Nb, Rb/Nb, etc.) measured in island and

continental arc magmas? We suggests that the alkaline melts were generated, in part, within a

region of the lithosphere that has been metasomatised (veined) by subduction but does not contain

what would be regarded as a typical arc signature. On the basis of the concept of chromatographic

separation of trace elements in mantle environments (e.g., Navon & Stolper, 1987; Hawkesworth et

al., 1993), Ionov & Hofmann (1995) and Stein et al. (1997) have developed subduction-related

metasomatic models to explain the retention of Nb and Ta in hydrous minerals within the lower-

most portion of the mantle wedge above a devolatilizing slab [Fig. 14a (1)]. In their model, slab

fluids enriched in incompatible elements migrate upward into the mantle wedge. Some of the fluids

reach the melt-generation zone above the wet solidus for peridotite (the source for arc magmas, [Fig

14a (2)] while others react, metasomatically, with the surrounding peridotite near the cool base of

the wedge to form Nb-rich amphiboles and micas in veins. This enriched region of the mantle is

transported by buoyancy-induced convective flow (Davies & Stevenson, 1992) to areas above the

P-T stability limit of amphibole where it becomes partially dehydrated [Fig. 14a (3 & 4)]. The post-

metasomatic partial dehydration of the mantle causes it to become depleted in hydrophile elements

Rb and Pb relative to more magmaphile elements Th, U, Nb and Sr (Brenan et al., 1995; Keppler, 1996), producing high Th-U/Pb, low Rb/Sr and Rb/Nb, and relatively unmodified Sm/Nd ratios. If this mantle region is then isolated near the base of the lithosphere [Fig. 14a (5)] for a sufficient period of time it may develop isotopic signatures that are similar to mantle sources of HIMU-type ocean island basalts.

Cause of Cretaceous-Cenozoic Magmatism

The most likely trigger for the Cretaceous alkaline magmatism in New Zealand was extension and lithospheric thinning associated with the breakup of New Zealand from Antarctica, which was in turn a response to the collision (Bradshaw, 1989) or near collision (Luyendyk, 1995) of the Pacific-Phoenix ridge with the eastern margin of Gondwanaland. According to Finn et al. (2005), most of the Cenozoic magmatism in the SW Pacific was in response to the sudden detachment and sinking of subducted slabs into the lower mantle during the late Cretaceous. This may have caused vertical and lateral flow of warm asthenosphere into 'thin-spots' at the base of the lithosphere (*cf.* King & Anderson, 1995), catalyzing melting of amphibole/phlogopite-rich veins (Fig. 14b). Also, mid-Cenozoic to active extension in the southern Ross Sea (Cape Roberts Science Team, 1998, 1999, 2000; Willis et al., 2004) and dextral transtension along faults in northern Victoria Land (Rocchi et al., 2002; Di Vincenzo et al., 2004) may have caused local decompression melting for volcanism in these areas.

CONCLUSIONS

Continental intraplate mafic magmatism in southern New Zealand consists of relatively small volume melts erupted from widely distributed centers located on the South Island and offshore on the submerged continental crust of the Chatham Rise and Campbell Plateau. We have presented geochemical data on mafic rocks from three islands; Campbell, Antipodes and Chatham, in order to

elucidate the magma history, mantle sources and fundamental cause of alkaline volcanism in this region as well as in adjacent continental areas of the SW Pacific. Our main conclusions are:

(1) Volcanism on Chatham Island produced subaerially emplaced lavas and associated pyroclastic rocks in 3 distinct eruptive episodes: late Cretaceous (85-82 Ma), late Eocene (41-35 Ma) and Miocene-Pliocene (~5 Ma). Dating by the $^{40}Ar/^{39}Ar$ method modifies earlier interpretations based on K-Ar dates (Grindley et al., 1977); most notably, that the Cretaceous basalts are significantly older than previously thought.

(2) Fractionation-corrected compositions from all three islands display similar trace element contents that have typical OIB-type characteristics (e.g., Ce/Pb 28-36, Nb/U 34-36, Ba/Nb 4-7, La_N/Yb_N 12-28) and prominent negative K- and Pb-anomalies on primitive mantle-normalized multi-element plots. The basalts show a restricted range in measured isotope ratios and the majority have high $^{206}Pb/^{204}Pb$ (20.3–20.8) and low $^{87}Sr/^{86}Sr$ (~ 0.7030) values similar to HIMU sources for OIB. The more radiogenic $^{87}Sr/^{86}Sr$ (>0.7036) rocks from Campbell Island can be explained by the assimilation of crust.

(3) Inversion models for the Antipodes and Chatham islands indicate sources that are enriched in highly incompatible elements relative to primitive mantle. Chemical heterogeneity, inferred from the models, is associated with modal variations in anhydrous and hydrous (amphibole and mica) minerals within a veined mantle.

(4) Calculated melt equilibration depths of ~160 km (Antipodes) and ~130 km (Chatham) together with estimates from geophysical data and the *P-T* stability limits of hydrous minerals suggest that melting occurred primarily within the subcontinental lithospheric mantle. This is also supported by the fact that Chatham Island drifted ~3000 km over 85 Myr without a significant change in source composition or depth of melting.

(5) Metasomatised lithosphere is considered the source for alkaline magmatism in other areas of New Zealand as well as adjacent continental fragments of Gondwanaland (SE Australia,

Tasmania, Victoria Land and Marie Byrd Land). The timing of metasomatism is constrained between 500 and 100 Ma, coincident with subduction and distribution of HIMU volcanism.

(6) Metasomatism and enrichment of the uppermost mantle by a plume and subsequent preservation of this material at the base of the Gondwanaland lithosphere prior to breakup may be the source for late Cretaceous-Cenozoic alkaline magmatism in the SW Pacific. However, models that ascribe to an ancient plume source must also account for the likely physical and chemical interaction between a rising plume head and subducted oceanic lithosphere.

(7) Metasomatism, enrichment and the source of the strong HIMU signature may be the result of a complex multi-stage chromatographic separation process (*cf*. Stein et al., 1997) consisting of: (a) devolatilization of subducted oceanic crust, which enriched the overlying peridotite in incompatible elements (e.g., Th, U, K, Pb, Nb, Sr, Rb, LREE) and deposited K-Nb (Ta)-rich hydrous minerals in veins; (b) buoyant convection and partial dehydration of the veined peridotite, depleting hydrophile elements (e.g., Pb, Rb, $\pm$ K) relative to more magmaphile elements (e.g., Th, U, Sr); (c) preservation and storage of what has become a high Th-U/Pb and low Rb/Sr source at the base of the Gondwanaland lithosphere.

(8) The metasomatised lithospheric source was later sampled by low degrees of partial melting triggered by extension-related decompression and/or warm upwelling asthenosphere over the past 100 Myr.

List of Tables

Figure Captions

1) Regional location map of New Zealand showing location of Campbell, Antipodes and Chatham
islands. The Challenger Plateau, Campbell Plateau and Chatham Rise are areas of submerged
continental crust. The Hikurangi Plateau is a large oceanic plateau. Also shown are locations for
the Westland dike swarm (WDS), Tapuaenuku Igneous Complex (TIC) and Port Chalmers Breccia
(PCB).

2) Simplified geologic map of Chatham Island showing exposures of the three major volcanic
groups; late Cretaceous Southern Volcanics (*ps*), Eocene-Oligocene Northern Volcanics (*kn*) and
Miocene-Pliocene Rangitihi Volcanics (*mr*) (Campbell et al., 1993). The numbers in parenthesis
that follow geographic names refer to samples collected (e.g., Matakitaki (15) is the location site of
sample CHT-15).

3) Representative $^{40}Ar/^{39}Ar$ ages for Chatham Island basalts. a-f: age release, K/Ca and radiogenic
argon release ($^{40}Ar^*$) spectra of groundmass and amphibole fractions. Thicknesses of boxes
represent 2σ error.

4) Variations in major and trace elements with MgO (wt.%). Ti/Ti* is the ratio between Ti
concentration and the values interpolated between neighbor elements, Eu and Tb, on primitive

mantle normalized multi-element diagrams as shown in Fig. 5. Trends in Rangitihi basalts are considered evidence for progressive magmatic differentiation by mineral fractionation (see text).

5) Trace element distribution of primitive basalts from Antipodes, Campbell and Chatham Islands. The major and trace element concentrations of samples have been corrected for olivine fractionation and are normalized to primitive upper mantle values of McDonough & Sun (1995). The shaded field encompasses young basalts with MgO >6.0 wt.% from the Austral-Cook Islands and includes the islands of Mangaia and Tubuai (compiled from the GEOROC database; http://georoc.mpch-mainz.gwdg.de). The Austral-Cook samples were not corrected for olivine fractionation.

6) Primitive mantle normalized rare earth element abundances for the same samples as shown in Fig. 5. Normalization values of McDonough & Sun (1995).

7) Plot of Ba/Nb versus La/Nb ratios. Field for Austral-Cook Island basalts delimits the same data and sources in Figs. 5 and 6. Chatham Island sample CHT-14 is evolved and classified as a basaltic trachyandesite. PUM = Primitive Upper Mantle (McDonough & Sun, 1995). Mid-ocean ridge basalts (MORB) from the East Pacific Rise (EPR) compiled from the PETDB data base (http://www.petdb.org/index.jsp).

8) $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ isotope correlation plots of southern New Zealand basalts in comparison with oceanic basalts. Tapuaenuku gabbros are from Baker et al. (1994; J. Baker unpublished data - Pb isotopes measured on leached feldspars and Sr and Nd are from whole rocks). All of the data are plotted as measured values. The Westland dikes are lamprophyres, phonolites and carbonatites from Barreiro & Cooper (1987). Mafic clasts from the Port Chalmers Breccia (PCB), part of the Dunedin Volcanic Group, New Zealand, consist of *ne*-normative ultramafic cumulate, amphibole gabbro and basanite from Price et al. (2003). Basalts from subantarctic islands Peter I (Hart et al., 1995), Balleny and Scott (Hart et al., 1992, 1995; Hart & Kyle, 1994) are also included. Data from St. Helena and the Austral-Cook Islands (A-C), including their classification as FOZO (FOcus ZOne; originally described by Hart et al., 1992) and HIMU types, are from Stracke et al. (2005). MORB samples from the Pacific-Antarctic Ridge (PAR) 56-66ºS are from Vlastélic et al. (1999). Macquarie Island mafic glasses (Mg#s 58-69) are from Kamenetsky et al. (2000).

9) Plots of $^{207}Pb/^{206}Pb$ and $^{87}Sr/^{86}Sr$ ratios plotted against 1/Sr (a & c) and Nb/U and Nb/Rb plotted against $^{206}Pb/^{204}Pb$ (b & d) for mafic rocks from southern New Zealand. The calculated assimilation-fractional crystallization (AFC) curves use a starting composition of tephrite (CHT-17) – a derivative of 54% closed system fractional crystallization of basanite sample CHT-20 (refer to text for the specific minerals fractionated). In (a), (b) and (d) all AFC models (DePaolo, 1981) assume a rate of assimilation to fractional crystallization (*r*) of 0.8, bulk distribution coefficients (*D*) used are: $D_{Sr} = 1.0$, $D_{Nb} = 0.2$, and D_{Rb}, D_{Pb} and $D_U = 0.1$. Potential assimilants are Torlesse (T) and Waipapa (W) Terrane metasediments (Graham and Mortimer, 1992; Graham et al., 1992) and modern near-trench bulk sediments (BS) collected from the Kermadec-Hikurangi margin (Gamble et al., 1996; BS refers to sediment sample N17/30 unless otherwise indicated). Also shown is average upper continental crust (UCC) from Rudnick & Fountain (1995). (c) D_{Sr} and *r* values for the assimilation of bulk sediments (BS) by tephrite are indicated. Samples and symbols are the same as in Fig. 8. Numbers along AFC curves denote the % fraction of liquid remaining.

10) Representative reciprocal plots (a) Ce–La and (b) Ba–Ce of Antipodes and Chatham Island basalts. Regression lines show slope and intercepts with corresponding 2σ errors. Several samples that are not included in the inversions were those that have been significantly fractionated (MgO ≤ 6 wt.%, Table 2) or possibly contaminated by crust (Campbell Island samples OU39737 and OU39796). Of the remaining samples; CHT-5, -8 and -16 were eliminated because they are considered to represent derivatives of parental magma CHT-20 by fractional crystallization (the Rangitihi Volcanics lineage shown in Fig. 4 and discussed in the text), and CHT-9 and -18 were excluded because, along with some of the other samples from the Northern Volcanic suite, they show strong linear correlations between LOI and elements such as Sr, Rb and Ba, indicating secondary alteration. The remaining seventeen samples were corrected for olivine fractionation before they were linearly regressed. In (a) the entire filtered data set is regressed. In (b) the Southern Volcanic suite is regressed.

11) Model source concentrations for the Southern Volcanic suite and the combined Chatham Island-Antipodes Island data set normalized to the primitive mantle (PM) values of McDonough & Sun (1995). The source compositions were calculated using the inversion method described by Hart et al. (1997) for modal batch melting. Both inversions are based on $Yb_o = 0.147$ (⅓ PM) and the error bars, calculated from errors on regression line slopes and intercepts (e.g., Fig. 10), are plotted at ±2σ. For Ce, the error is within the size of the symbol.

12) Plate reconstructions of the SW Pacific and the proto-Pacific margin of Gondwanaland (modified from Finn et al., 2005). Colors indicate age of ocean floor (Müller et al., 1993). (a) A 15 Ma construction overlain by locations of late Cretaceous and Cenozoic alkaline mafic rocks with measured $^{206}Pb/^{204}Pb$ ratios greater than 19.0. Abbreviations include NZ – New Zealand, CR – Chatham Rise, CP – Campbell Plateau, MI – Macquarie Island, LHR – Lord Howe Rise, BI – Balleny Islands, SI – Scott Island, MBL – Marie Byrd Land, PI – Peter I. (b) A 50 Ma construction. (c) A 100 Ma construction with $^{206}Pb/^{204}Pb$ ratios contoured at 0.5 intervals. Sources for Pb isotopes listed in Fig. 8 with additional sources for Auckland basalts (NZ) from Cook et al. (2004) and Huang et al. (1997); Tasmania basalts from Lanyon et al. (1993); SE Australian basalts from Ewart et al. (1988) and Zhang et al. (1999); Marie Byrd Land (Antarctica) basalts from Hart et al. (1997), Panter et al. (2000a) and Panter et al. (1997); Victoria Land (Antarctica) basalts from Sun & Hanson (1975), Rocholl et al. (1995) and Panter et al. (2003); Antarctic Peninsula basalts from Hole et al. (1993).

13) Plots of a) MgO+FeO*, b) K/K* and c) Pb/Pb* versus $^{206}Pb/^{204}Pb$ for basalts from New Zealand (this study) and Marie Byrd Land (Hobbs Coast, Hart et al., 1997; Crary Mountains, Panter et al., 2000a). K/K* and Pb/Pb* values determined by $K_{PM}/\sqrt{(Ta_{PM} \times La_{PM})}$ and $Pb_{PM}/\sqrt{(Ce_{PM} \times Nd_{PM})}$, respectively. In (a) labeled values are average melt equilibration pressures (in GPa) determined using the algorithims of Herzberg & Zhang (1996) for MgO and FeO* (total iron as FeO). In (b) labeled values represent percent partial melt determined by Hart et al. (1997) for the Hobbs Coast and Panter et al. (2000a) for the Crary Mountains. All of the data has been corrected for olivine fractionation.

14) Schematic cartoon showing the development of HIMU-like mantle reservoirs by subduction-related metasomatism (a) that may become sources for continental alkaline magmatism in the SW Pacific (b). (a) Model of the active Gondwanaland margin prior to 100 Ma. **1** – hydrated peridotite; incompatible element enriched fluids liberated from progressive dehydration of subducted oceanic crust + sediments migrate into the overlying mantle wedge, react and precipitate Nb-rich amphibole

and mica in veins (Ionov & Hofmann, 1995). **2** – melt zone; residual fluids depleted in Nb (and Ta) migrate upward and induce melting above the wet solidus to form arc magmas. **3** – reverse flow; diapirs of hydrated peridotite are decoupled from the descending slab and rise buoyantly (Davies & Stevenson, 1992). **4** – partial dehydration; buoyant diapirs rise through the warmer central portion of the wedge where amphibole becomes unstable. Fluids liberated by this process are enriched in Pb and Rb relative to U, Th and Sr, producing a high U-Th/Pb and low Rb/Sr residuum. **5** – isolation & storage; partially dehydrated, amphibole-rich peridotite stabilizes at the base of the continental lithosphere where it becomes isolated from convective flow. Relatively short-term (≤0.5-0.1 Ga) of this mantle may generate HIMU-like sources. (b) Schematic cross section after Gondwanaland breakup (<83 Ma). The Pacific-Antarctic Ridge (PAR) separates southeast New Zealand from the Marie Byrd Land coast. Localized extension and/or upwelling asthenosphere induce melting of metasomatised lithosphere in thin spots to produce alkaline magmas with HIMU-like isotopic signatures. The metasomatism may have been produced by subduction-related processes illustrated in panel (a) or by plume-lithosphere interaction prior to continental breakup.

REFERENCES

Adam, J., Green, T.H. & Sie, S.H. (1993). Proton microprobe determined partitioning of Rb, Sr, Ba, Y, Zr, Nb and Ta between experimentally produced amphiboles and silicate melts with variable F content. *Chemical Geology* **109**, 29-49.

Adams, C.J., Morris, P.A. & Beggs, J.M. (1979). Age and correlation of volcanic rocks of Campbell Island and metamorphic basement of the Campbell Plateau, south-west Pacific. *New Zealand Journal of Geology and Geophysics* **22**, 679-691.

Adams, C.J., Seward, D. & Weaver, S.D. (1995). Geochronology of Cretaceous granites and metasedimentary basement on Edward VII Peninsula, Marie Byrd Land, West Antarctica. *Antarctic Science* **7**, 265-276.

Adams, C.J., Campbell, H.J., Graham, I.J. & Mortimer, N. (1998). Torlesse, Waipapa and Caples suspect terranes of New Zealand: integrated studies of their geological history in relation to neighboring terranes. *Episodes* **21**, 135-240.

Adams, C.J. & Cooper, A.F. (1996). K-Ar age of a lamprophyre dike swarm near Lake Wanaka, west Otago, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics* **39**, 17-23.

Baker, J.A., Gamble, J.A. & Graham, I.J. (1994). The age, geology, and geochemistry of the Tapuaenuku Igneous Complex, Marlborough, New Zealand. *N.Z. Jour. Geol. Geophys*. **37**, 249-268.

Baker, J.A., Menzies, M.A., Thirlwall, M.F. & Macpherson, C.G. (1997). Petrogenesis of Quaternary intraplate volcanism, Sana'a, Yemen: plume-lithosphere interaction and polybaric melt hybridization. *Journal Petrology* **38**, 1359-1390.

Ballentine, C.J., Lee, D.-C. & Halliday, A.N. (1997). Hafnium isotopic studies of the Cameroon line and new HIMU paradoxes. *Chemical Geology* **139**, 111-124.

Barreiro, B.A. & Cooper, A.F. (1987). A Sr, Nd and Pb isotope study of alkaline lamprophyres and related rocks from Westland and Otago, South Island, New Zealand. *Geol. Soc. Amer. Spec. Pub*. **215**, 115-125.

Barry, T.L., Saunders, A.D., Kempton, P.D., Windley, B.F., Pringle, M.S., Dorjnamjaa, D. & Saandar, S. (2003). Petrogenesis of Cenozoic basalts from Mongolia: evidence for the role of asthenospheric versus metasomatized lithosphere mantle sources. *Journal Petrology* **44**, 55-91.

Beggs, J.M. (1993). Depositional and tectonic history of the Great South Basin. In: P.F. Balance (editor) South Pacific Sedimentary Basins. Sedimentary Basins of the World, 2. Elsevier, Amsterdam, 93-107.

Beggs, J.M., Challis, G.A. & Cook, R.A. (1990). Basement geology of the Campbell Plateau: implications for correlation of the Campbell magnetic anomaly system. *N.Z. Jour. Geol. Geophys.* **33**, 401-404.

Behrendt, J.C., LeMasurier, W.E. & Cooper, A.K. (1992). The West Antarctic rift system- a propogating rift "captured" by a mantle plume. In: Y. Yoshida, K. Kaminuma, K. Shirashi (Editors) Recent Progress in Antarctic Earth Science. Terra Scientific Publishing Company, Tokyo, 315-322.

Behrendt, J.C., Saltus, R., Damaske, D., McCafferty, Flinn, C.A., Blankenship, D. & Bell, R.E. (1996). Patterns of Late Cenozoic and tectonic activity in the West Antarctic rift system revealed by aeromagnetic surveys. *Tectonics* **15**, 660-676.

Bishop, D.G., Bradshaw, J.D. & Landis, C.A. (1985). Provisional terrane map of South Island, New Zealand. In: D.G. Howell (Editor) Tectonostratigraphic Terranes: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series No.1, Huston, Texas, 515-521.

Blusztajn, J. & Hegner, E. (2002). Osmium isotopic systematics of melilitites from the Tertiary Central European Volcanic Province in SW Germany. *Chemical Geology* **189**, 91-103.

Borg, S.G. & DePaolo, D.J. (1991). A tectonic model of the Antarctic Gondwana margin with implications for southeast Australia isotopic and geochemical evidence. *Tectonophysics* **196**, 339-358.

Bradshaw, J.D. (1989). Cretaceous geotectonic patterns in the New Zealand region. *Tectonics* **8**, 803-820.

Bradshaw, J.D., Pankhurst, R.J., Weaver, S.D., Storey, B.C., Muir, R.J., Ireland, T.R. (1997). New Zealand superterranes recognized in Marie Byrd Land and Thruston Island. In: Ricchi, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes. Terra Antarctica Publication, Siena, pp. 429-436.

Brenan, J.M., Shaw, H.F., Ryerson, F.J. & Phinney, D.L. (1995). Mineral-aqueous fluid partitioning of trace elements at 900°C and 2.0 GPa: Constraints on the trace element chemistry of mantle and deep crustal fluids. *Geochimica et Cosmochimica Acta* **59**, 331-3350.

Campbell, H.J., Andrews, P.B., Beu, A.G., Maxwell, P.A., Edwards, A.R., Laird, M.G., Hornibrok, N.dB., Mildenhall, D.C., Watters, W.A., Buckeridge, J.S., Lee, D.E., Strong, C.P., Wilson, G.J. & Hayward, B.W. (1993). Cretaceous-Cenozoic geology and biostratigraphy of the Chatham Islands, New Zealand. Institute of Geological & Nuclear Sciences Monograph 2, Institute of Geological & Nuclear Sciences Ltd., Lower Hutt, New Zealand, 269 pp.

Cape Roberts Science Team (1998). Studies from the Cape Roberts Project, Ross Sea, Antarctica - Initial Report on CRP-1. In: C.A. Ricci (Editor), *Terra Antarctica*, Museo Nazionale dell'Antartide, Siena, pp. 1-187.

Cape Roberts Science Team (1999). Studies from the Cape Roberts Project, Ross Sea, Antarctica - Initial Report on CRP-2/2A. In: C.A. Ricci (Editor), *Terra Antarctica*, Museo Nazionale dell'Antartide, Siena, pp. 1-173.

Cape Roberts Science Team (2000). Studies from the Cape Roberts Project, Ross Sea, Antarctica - Initial Report on CRP-3. In: C.A. Ricci (Editor), *Terra Antarctica*, Museo Nazionale dell'Antartide, Siena, pp. 1-209.

Caroff, M., Maury, R.C., Leterrier, J., Joron, J.L., Cotten, J. & Guille, G. (1993). Trace element behavior in the alkali basalt-comenditic trachyte series from Mururoa Atoll, French Polynesia. *Lithos* **30**, 1-22.

Class, C. & Goldstein, S.L. (1997). Plume-lithosphere interactions in the ocean basins; constraints from the source mineralogy, *Earth and Planetary Science Letters*, **150** (3-4), 245-260.

Cook, G., Briggs, R.M., Smith, I.E.M. & Maas, R. (2004). Petrology and geochemistry of intraplate basalts in the south Auckland volcanic field, New Zealand: evidence for two coeval magma suites from distinct sources. *Journal of Petrology*, doi:10.1093/petrology/egh084

Coombs, D.S., Cas, R., Kawachi, Y., Landis, C.A., McDonough, W.F. & Reay, A. (1986). Cenozoic volcanism in north, east and central Otago. In: I.E.M Smith (ed.) Late Cenozoic volcanism in New Zealand. Royal Society of New Zealand, 278-312.

Cullen, D.J. (1969). Quaternary volcanism at the Antipodes Islands: its bearing on structural interpretation of the southwest Pacific. *Jour. Geophys. Res*. **74**, 4213-4220.

Dalpé, C. & Baker, D.R. (1994). Partition coefficients for rare-earth elements between calcic amphibole and Ti-rich basanitic glass at 1.5 GPa, 1100°C. *Mineralogical Magazine* **58A**, 207-208.

Dalziel, I.W.D., Lawver, L.A. & Murphy, J.B. (2000). Plumes, orogenesis, and supercontinental fragmentation. *Earth Planet. Sci. Lett.* **178**, 1-11.

David, K., Schiano, P. & Allègre, C.J. (2000). Assessment of the Zr/Hf fractionation in oceanic basalts and continental materials during petrogenetic processes. *Earth Planet. Sci. Lett*. **178**, 285-301.

Davies, J.H. & Stevenson, D.J. (1992). Physical model of source region of subduction zone volcanics. *Journal of Geophysical Research* **97**, 2037-2070.

Davy, B. (1993). The Bounty Trought- basement structure influences on sedimentary basin evolution. In: P.F. Balance (editor) South Pacific Sedimentary Basins. Sedimentary Basins of the World, 2. Elsevier, Amsterdam, 69-90.

Debayle, E. & Kennett, B.L.N. (2000). Anisotropy in the Australasian upper mantle from Love and Rayleigh waveform inversion. *Earth and Planetary Science Letters* **184** (1), 339-351.

Demarchi, G., Antonini, P., Piccirillo, E.M., Orsi, G., Civetta, L. & D'Antonio, M. (2001). Significance of orthopyroxene and major element constraints on the petrogenesis of Ferrar tholeiites from southern Prince Albert Mountains, Victoria Land, Antarctica. *Contrib. Mineral. Petrol.* **142**, 127-146.

DePaolo, D.J. (1981). Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth Planet. Sci. Letters*. **53**, 189-202.

Di Vincenzo, G., Rocchi, S., Rossetti, F. & Storti, F. (2004). $^{40}Ar/^{39}Ar$ dating of pseudotachylytes: the effect of clast-hosted extraneous argon in Cenozoic fault-generated friction melts from the West Antarctic Rift System. *Earth and Planetary Science Letters* **223**, 349-364.

DiVenere, V., Kent, D.V. & Dalziel, I.W.D. (1994). Mid-Cretaceous paleomagnetic results from Marie Byrd Land, west Antarctica: A test of post-100 ma relative motion between east and west Antarctica. *Journal of Geophysical Research* **99**, 15,115-15,139.

Duggan M.B. & Reay, A. (1986). The Timaru Basalt. *Royal Soc. New Zealand Bull*. **23**, 246-277.

Elliot, D.H. (1991). Triassic-Early Cretaceous evolution of Antarctica. In: Thomson M.R.A. (editor) Geological Evolution of Antarctica, Cambridge University Press, New York, 541-548.

Esawi, E.K. (2004). AMPH-CLASS: an Excel spreadsheet for the classification and nomenclature of amphiboles based on the 1997 recommendations of the International Mineralogical Association. *Computers & Geosciences* **30**, 753-760.

Ewart, A., Chappell, B.W. & Menzies, M.A. (1988). An overview of the geochemical and isotopic characteristics of the eastern Australian Cainozoic volcanic provinces, *Journal of Petrology,* Special Lithosphere Issue, 225-273.

Finn, C.A., Müller, R.D. & Panter, K.S. (2005). A Cenozoic diffuse alkaline magmatic province in the SW Pacific without rift or plume origin. *Geochemistry, Geophysics, Geosystems* (G[3]), doi:10.1029/2004GC000723

Foley, S. (1991). High-pressure stability of the fluor- and hydroxyl-endmembers of paragasite and K-richterite. *Geochimica et Cosmochimica Acta* **55**, 2689-2694.

Foley, S. (1992). Vein-plus-wall-rock melting mechanisms in the lithosphere and the origin of potassic alkaline magmas. *Lithos* **28**, 435-453.

Franz, G., Steiner, G., Volker, F., Pudlo, D. & Hammerschmidt, K. (1999). Plume related alkaline magmatism in central Africa – the Meidob Hills (W Sudan). *Chemical Geology* **157**, 27-47.

Gamble, J.A. & Adams, C.J. (1990). Antipodes Islands. In: W.E. LeMasurier and J.W. Thomson (eds) Volcanoes of the Antarctic Plate and Southern Oceans. *Antarctica Research Series* **48**, American Geophysical Union, 468-469.

Gamble, J.A., Morris, P.A. & Adams, C.J. (1986). The geology, petrology and geochemistry of Cenozoic volcanic rocks from the Cambell Plateau and Chatham Rise. In: I.E.M. Smith (Ed.), Late Cenozoic Volcanism in New Zealand. *Royal Soc. of N.Z. Bull.* **23**, 344-365.

Gamble, J.A., Woodhead, J., Wright, I. & Smith, I. (1996). Basalt and sediment geochemistry and magma petrogenesis in a transect from oceanic island arct to rifted continental margin arc: the Kermadic-Hikurangi margin, SW Pacific. *Journal of Petrology* **37**, 1523-1546.

Godfrey, N.J., Davey, F., Stern, T.A. & Okaya, D. (2001). Crustal structure and thermal anomalies of the Dunedin region, South Island, New Zealand. *Jour. Geophys. Res*. **106**, 30,835-30,848.

Graham, I.J. & Mortimer, N. (1992). Terrane characterization and timing of metamorphism in the Otago Schist, New Zealand, using Rb-Sr and K-Ar geochronology. *New Zealand Jour. Geol. Geophys*. **35**, 391-401.

Graham, I.J., Gulson, B.L., Hedenquist, J.W. & Mizon, K. (1992). Petrogenesis of Late Cenozoic volcanic rocks from the Taupo Volcanic Zone, New Zealand, in the light of new lead isotope data. *Geochimica et Cosmochimica Acta* **56**, 2797-2819.

Grapes, R.H. (1975). Petrology of the Blue Mountain complex, Marlborough, New Zealand. *Journal of Petrology* **16**, 371-428.

Grindley, G.W., Adams, C.J.D., Lumb, J.T. & Watters, W.A. (1977). Paleomagnetism, K-Ar dating and tectonic interpretation of Upper Cretaceous and Cenozoic volcanic rocks of the Chatham Islands, New Zealand. *New Zealand J. Geol. Geophys*. **20**, 425-467.

Haggerty, S.E. (1987). Metasomatic mineral titanites in upper mantle xenoliths, in *Mantle Xenoliths* edited by P.H. Nixon, pp. 671-690, Wiley, Chichester.

Hallett, R.B. & Kyle, P.R. (1993) XRF and INAA determinations of major and trace elements in Geological Survey of Japan igneous and sedimentary rock standards. Geostandards Newsletter 17, 127-133.

Handler, M.R., Wysoczanski, R.J. & Gamble, J.A. (2003). Proterozoic lithosphere in Marie Byrd Land, West Antarctica: Re-Os systematics of spinel peridotite xenoliths. *Chemical Geology* **196**, 131-145.

Hart, S.R. & Davis, K.E. (1978). Nickel partitioning between olivine and silicate melt. *Earth Planet. Sci. Lett*. **40**, 203-219.

Hart, S.R., Blusztajn, J. & Craddock, C. (1995). Cenozoic volcanism in Antarctica; Jones Mountains and Peter I Island. *Geochimica et Cosmochimica Acta* **59**, 3379-3388.

Hart, S.R., Hauri, E.H., Oschmann, L.A. & Whitehead, J.A. (1992). Mantle plumes and entrainment: isotopic evidence: *Science* **256**, 517-520.

Hart, S.R. & Dunn, T. (1993). Experimental Cpx/melt partitioning of 24 trace-elements. *Contrib. Mineral. Petrol*. **113**, 1-8.

Hart, S.R., Blusztajn, J., LeMasurier, W.E. & Rex, D.C. (1997). Hobbs Coast Cenozoic volcanism: implications for the West Antarctic rift system. *Chemical Geology* **139**, 223-248.

Hart, S.R., Gaetani, G.A. & Kelemen, P.B. (2005). Mantle Pb paradoxes: the sulfide solution. Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract V23D-06.

Hauri, E.H. & Hart, S.R. (1993). Re-Os isotope systematics of HIMU and EMII oceanic island basalts from the south Pacific Ocean. *Earth Planet. Sci. Lett.* **114**, 353-371.

Hauri, E.H., Wagner, T.P. & Grove, T.L. (1994). Experimental and natural partitioning of Th, U, Pb and other trace elements between garnet, clinopyroxene and basaltic melts. *Chemical Geology* **117**, 149-166.

Hawkesworth, C.J., Gallagher, K., Hergt, J.M. & McDermott, F. (1993). Trace element fractionation processes in the generation of island arc basalts. *Phil. Trans. R. Soc. Lond.* **342**, 179-191.

Hergt, J.M. & Brauns, C.M. (2001). On the origin of Tasmanian dolerites. *Australian Jour. Earth Sciences* **48**, 543-549.

Hergt, J.M., Peate, D.W. & Hawkesworth, C.J. (1991). The petrogenesis of Mesozoic Gondwana low-Ti flood basalts. *Earth and Planetary Science Letters* **105**, 134-148.

Herzberg, C. & Zhang, J. (1996). Melting experiments on anhydrous peridotite KLB-1: compositions of magmas in the upper mantle and transition zone. *Journal of Geophysical Research* **101**, 8271-8295.

Hirose, K. & Kushiro, I. (1993). Partial melting of dry peridotites at high pressures; determination of compositions of melts segregated from peridotite using aggregates of diamond. *Earth and Planetary Science Letters* **114**, 477-489.

Hofmann, A.W. (1997). Mantle geochemistry: a message from oceanic volcanism. *Nature* **385**, 219-229.

Hofmann, A.W., Jochum, K.P., Seufert, M. & White, W.M. (1986). Nb and Pb in oceanic basalts: new constraints on mantle evolution. *Earth Planet. Sci. Lett.* **79**, 33-45.

Hoke, L., Poreda, R., Reay, A. & Weaver, S.D. (2000). The subcontinental mantle beneath southern New Zealand, characterized by helium isotopes in intraplate basalts and gas-rich springs. *Geochem. Cosmoch. Acta* **64**, 2489-2507.

Hole, M.J. & LeMasurier, W.E. (1994). Tectonic controls on the geochemical composition of Cenozoic, mafic alkaline volcanic rocks from West Antarctica. *Contributions to Mineralogy and Petrology* **117**, 187-202.

Hole, M.J., Kempton, P.D. & Miller I.L. (1993). Trace-element and isotopic characteristics of small-degree melts of the asthenosphere: evidence from the alkalic basalts of the Antarctic Peninusula, *Chemical Geology* **109**, 51-68.

Huang, Y., Hawkesworth, C., van Calsteren, P., Smith, I. & Black, P. (1997). Melt generation models for the Auckland volcanic field, New Zealand: constraints from U-Th isotopes. *Earth and Planetary Science Letters* **149**, 67-84.

Ionov, D.A., Grégoire, M. & Prikhod'ko, V.S. (1999). Feldspar–Ti-oxide metasomatism in off-cratonic continental and oceanic upper mantle, *Earth and Planetary Science Letters* 165, 37-44.

Ionov, D.A. & A.W. Hofmann (1995). Nb-Ta-rich mantle amphiboles and micas: implications for subduction-related metasomatic trace element fractionations, *Earth and Planetary Science Letters* **131**, 341-356.

Janney, P.E., Le Roex, A.P., Carlson, R.W. & Viljoen, K.S. (2002). A chemical and multi-isotope study of the Western Cape olivine melilitite province, South Africa: implications for the sources of kimberlites and the origin of the HIMU signature in Africa. *Journal of Petrology* **43**, 2339-2370.

Johnson, R.W. (1989). *Intraplate volcanism in eastern Australia and New Zealand*, Cambridge Univ. Press, Cambridge.

Kamenetsky, V.S., Everard, J.L., Crawford, A.J., Varne, R., Eggins, S.M. & Lanyon, R. (2000). Enriched end-member of primitive MORB melts: petrology and geochemistry of glasses from Macquarie Island (SW Pacific). *Journal of Petrology* **41**, 411-430.

Keppler, H. (1996). Constraints from partitioning experiments on the composition of subduction-zone fluids. *Nature* **380**, 237-240.

King, S.D. & Anderson, D.L. (1995). An alternative mechanism of flood basalt formation. *Earth and Planetary Science Letters* **136**, 269-279.

Kyle, P.R., Pankhurst, R.J., & Bowman, J.R. (1983) Isotopic and chemical variations in Kirkpatrick Basalt Group rocks from South Victoria Land. In: Antarctica Earth Sciences (ed. R.L. Oliver, P.R. James, J.B. Jago). Australian Academy of Science, Canberra, p. 234-237.

Laird, M.G. (1993). Cretaceous continental rifts: New Zealand region. In: P.F. Ballance (editor) South Pacific Sedimentary Basins. Sedimentary Basins of the World, 2. Elsevier, Amsterdam, 37-49.

Laird, M.G. & Bradshaw, J.D. (2004). The break-up of a long-term relationship: the Cretaceous separation of New Zealand from Gondwana. *Gondwana Research* **7**, 273-286.

Lanyon, R., Varne, R. & Crawford, A.J. (1993). Tasmanian Tertiary basalts, the Balleny plume, and opening of the Tasman Sea (southwest Pacific Ocean). *Geology* **21**, 555-558.

Larter, R.D., Cunningham, A.P., Barker, P.F., Gohl, K. & Nitsche, F.O. (2002). Tectonic evolution of the Pacific margin of Antarctica: 1. Late Cretaceous tectonic reconstructions. *Jour. Geophys. Res*. **107**(B12), 2345, doi:10.1029/2000JB000052.

LaTourrette, T., Hervig, R.L. & Holloway, J.R. (1995). Trace element partitioning between amphibole, phlogopite, and basanite melt. *Earth and Planetary Science Letters* **135**, 13-30.

Lawver, L.A., Gahagan, L.M. & Coffin, M.F. (1992). The development of paleoseaways around Antarctica: The Antarctic paleoenviornment: A perspective on global change. *Antarctic Research Series* **56**, p. 7-30.

Le Maitre, R. W. (2002). Igneous Rocks: A Classification and Glossary of Terms. Cambridge University Press, 236 pp.

LeMasurier, W.E. & Rex, D.C. (1989). Evolution of linear volcanic ranges in Marie Byrd Land, West Antarctica. *Jour. Geophys. Res*. **94**, 7223-7236.

LeMasurier, W.E. & Landis, C.A. (1996). Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand. *Geol. Soc. Amer. Bull*. **108**, 1450-1466.

Lloyd, F.E. & Bailey, D.K. (1975). Light element metasomatism of the continental mantle: the evidence and the consequences. *Physics and Chemistry of the Earth* **9**, 389-416.

Luyendyk, B.P. (1995). Hypothesis for Cretaceous rifting of east Gondwana caused by subduction slab capture. *Geology* **23**, 373-376.

Luyendyk, B.P., Wilson, D & Siddoway, C. (2003). Eastern margin of the Ross Sea Rift in western Marie Byrd Land, Antarctica: Crustal structure and tectonic development, *Geochemistry, Geophysics, Geosystems (G3)*, **4** (10), 1090, doi:10.1029/2002GC000462.

Luyendyk, B.P., Sorlien, C.C., Wilson, D.S., Bartek, L.R. & Siddoway, C.S. (2001). Structural and tectonic evolution of the Ross Sea rift in the Cape Colbeck region, Eastern Ross Sea, Antarctica. *Tectonics* **20**, 933-958.

McKenzie, D. & Bickle, M.J. (1988). The volume and composition of melt generated by extension of the lithosphere. *Journal of Petrology* **29** (3), 625-679.

McDonough, W.F. & Sun, S.S. (1995). The composition of the Earth, in *Chemical Geology*, edited by W.F. McDonough, N.T. Arndt, and S. Shirey, p. 223-253, Elsevier, Amsterdam.

Mengel, K. & Green, D.H. (1986). Stability of amphibole and phlogopite in metasomatized peridotite under water-saturated and water-undersaturated conditions, in *Kimberlites and Related Rocks*, edited by J. Ross, A.L. Jaques, J. Ferguson, D.H. Green, S.Y. O'Reilly, R.V. Danchin, and A.J.A. Janse, pp. 571-581, Blackwell Science, Oxford.

Molnar, P., Atwater, T., Mammerickx, J. & Smith, S.M. (1975). Magnetic anomalies, bathymetry and the tectonic evolution of the South Pacific since the Late Cretaceous. *Royal Astronomical Society Geophysical Journal* **40**, 383-420.

Molzahn, M., Reisberg, L. & Wörner, G. (1996). Os, Sr, Nd, Pb, O isotope and trace element data from the Ferrar flood basalts, Antarctica: evidence for an enriched subcontinental lithosphere source. *Earth Planet. Sci. Lett*. **144**, 529-546.

Moreira, M. & Kurz, M.D. (1999). Subducted oceanic lithosphere and the origin of the 'high μ' basalt helium isotopic signature. *Earth Planet. Sci. Lett*. **189**, 49-57.

Morris, P.A. (1984). Petrology of the Campbell Island volcanics, southwest Pacific Ocean. *J. Volcan. Geotherm. Res.* **21**, 119-148.

Morris, P.A. (1985a). Petrology of Late Cretaceous alkaline volcanic rocks from the Chatham Islands, New Zealand. *New Zealand J. Geol. Geophys*. **28**, 253-266.

Morris, P.A. (1985b). The geochemistry of Eocene-Oligocene volcanics on the Chatham Islands, New Zealand. *New Zealand J. Geol. Geophys*. **28**, 459-469.

Morris, P.A. & Gamble, J.A. (1990). Campbell Island. In: W.E. LeMasurier and J.W. Thomson (editors) Volcanoes of the Antarctic Plate and Southern Oceans. *Antarctica Research Series* **48**, American Geophysical Union, 474-475.

Mortimer, N. & Roser, B.P. (1992). Geochemical evidence for the position of the Caples-Torlesse boundary in the Otago Schist, New Zealand. *Jour. Geol. Soc. Lond*. **149**, 967-977.

Mukasa, S.B. & Dalziel, I.W.D. (2000). Marie Byrd Land, west Antarctica: evolution of Gondwana's Pacific margin constrained by zircon U-Pb geochronology and feldspar common-Pb isotopic compositions. *Geol. Soc. Amer. Bull*. **112**, 611-627.

Müller, R.D., Royer, J.-Y. & Lawver, L.A. (1993). Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks, *Geology* **21**, 275-278.

Navon, O. & Stolper, E. (1987). Geochemical consequences of melt percolation: the upper mantle as a chromatographic column. *The Journal of Geology* **95**, 285-307.

Niida, K. & Green, D.H. (1999). Stability and chemical composition of pargasitic amphibole in MORB pyrolite under upper mantle conditions. *Contributions to Mineralogy and Petrology* **135**, 18-40.

Orlando, A., Conticelli, S., Armienti, P. & Borrini, D. (2000). Experimental study on a basanite from the McMurdo Volcanic Group, Antarctica; inference on its mantle source, *Antarctic Science*, **12** (1), 105-116.

Pankhurst, R.J., Weaver, S.D., Bradshaw, J.D., Storey, B.C. & Ireland, T.R. (1998). Geochronology and geochemistry of pre-Jurassic superterranes in Marie Byrd Land, Antarctica. *Jour. Geophys. Res.* **103**, 2529-2547.

Panter, K.S., Kyle, P.R. & Smellie, J.L. (1997). Petrogenesis of a phonolite-trachyte succession at Mount Sidley, Marie Byrd Land, Antarctica. *Journal of Petrology* **38**, 1225-1253.

Panter, K.S., Hart, S.R., Kyle, P., Blusztanjn, J. & Wilch, T. (2000a). Geochemistry of Late Cenozoic basalts form the Crary Mountains: characterization of mantle sources in Marie Byrd Land, Antarctica. *Chemical Geology* **165**, 215-241.

Panter, K.S., Hart, S.R., & Kyle, P. (2000b). Evidence for a Cretaceous Antarctic Plume ("Erebus Plume") in New Zealand. *EOS, Transactions, American Geophysical Union* **81**, F1357.

Panter, K.S., Blusztajn, J., Wingrove, D., Hart, S. & Mattey, D. (2003). Sr, Nd, Pb, Os, O isotope, Major and trace element data from basalts, South Victoria Land, Antarctica: Evidence for open-system processes in the evolution of mafic alkaline magmas: *European Geophysical Society, Geophysical Research Abstracts* **5**, 07583.

Pilet, S., Hernandez, J., Sylvester, P.J. & Poujol (2005). The metasomatic alternative for ocean island basalt chemical heterogeneity. *Earth and Planetary Science Letters* **236**, 148-166.

Price, R.C., Cooper, A.F., Woodhead, J.D. & Cartwright, I. (2003). Phonolite diatremes within the Dunedin Volcano, South Island, New Zealand. *Journal of Petrology* **44** (11), 2053-2080.

Richard, S.M., Smith, C.H., Kimbrough, D.L., Fitzgerald, P.G., Luyendyk, B.P. & McWilliams, M.O. (1994). Cooling history of the northern Ford Ranges, Marie Byrd Land, West Antarctica. *Tectonics* **13**, 837-857.

Rocchi, S., Armienti, P., & Di Vincenzo, G. (2004). No plume, no rift magmatism in the west Antarctic rift. In: Foulger, G.R., Anderson, D.L., Natland, J.H. and Presnall, D.C. (eds.) Plates, Plumes & Paradigms: *Geological Society of America Special Paper ##*, pp. 000-000.

Rocchi, S., Armienti, P., D'Orazio, M., Tonarini, S., Wijbrans, J.R. & Di Vincenzo, G. (2002). Cenozoic magmatism in the western Ross Embayment: Role of mantle plume versus plate dynamics in the development of the West Antarctic Rift System. *J. Geophys Res*. **107** (B9), 2195.

Rocholl, A., Stein, M., Molzahn, M., Hart, S.R. & Wörner, G. (1995). Geochemical evolution of rift magmas by progressive tapping of a stratified mantle source beneath the Ross Sea rift, northern Victoria Land, Antarctica. *Earth Planet. Sci. Lett*. **131**, 207-224.

Rudnick, R.L & Fountain, D.M. (1995). Nature and composition of the continental crust; a lower crustal perspective. *Reviews of Geophysics* **33**, 267-309.

Salters, V.J.M., Longhi, J.E. & Bizimis, M. (2002). Near mantle solidus trace element partitioning at pressures up to 3.4 GPa. *Geochemistry, Geophysics and Geosystems* **3** (7), 10.1029/2001GC000148.

Scherwath, M. Stern, T. & Molnar, P. (2002). Pn anisotropy and distributed upper mantle deformation associated with a continental transform fault. *Geophysical Research letters* **29**, 1175, 10.1029/2001GL014179.

Schmidt, K.H., Bottazzi, P., Vannucci, R. & Mengel, K. (1999). Trace element partitioning between phlogopite, clinopyroxene and leucite lamproite melt, *Earth and Planetary Science Letters,* **168**, 287-299.

Simons, F.J., Zielhuis, A. & van der Hilst, R.D. (1999). The deep structure of the Australian continent from surface wave tomography, *Lithos*. **48**, 17-43.

Simons, F.J., van der Hilst, R.D. & Zuber, M.T. (2003). Spatiospectral localization of isostatic coherence anisotropy in Australia and its relation to seismic anisotropy: Implications for lithospheric deformation, *Journal of Geophysical Research* **108**, 2250, doi:10.1029/2001JB000704.

Sims, K.W.W. & DePaolo, D.J. (1997). Inferences about mantle magma sources fro incompatible element concentration ratios in oceanic basalts. *Geochem. Cosmochim. Acta* **61**, 765-784.

Späth, A., Le Roex, A.P. & Opiyo-Akech, N. (2001). Plume-lithosphere interaction and the origin of continental rift-related alklaline volcanism – the Chyulu Hills volcanic province, southern Kenya. *Journal of Petrology* **42**, 765-787.

Spell, T.L., McDougall, I. & Tulloch, A.J. (2000). Thermochronologic constraints on the breakup of the Pacific Gondwana margin: the Paparoa metamorphic core complex, South Island, New Zealand. *Tectonics* **19**, 433-451.

Steiger, R.H. & Jäger, E. (1977). Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett*. **36**, 359-362.

Stein, M & Hofmann, A.W. (1992). Fossil plume head beneath the Arabian lithosphere? *Earth and Planetary Science Letters* **114**, 193-209.

Stein, M., Navon, O. & Kessel, R. (1997). Chromatographic metasomatism of the Arabian-Nubian lithosphere. *Earth and Planetary Science Letters* **152**, 75-91.

Storey B.C. (1995). The role of mantle plumes in continental breakup: case histories from Gondwanaland. *Nature* **377**, 301-308.

Storey, B.C. & Kyle, P.R. (1997) An active mantle mechanism for Gondwana breakup. South African Journal Geology, 100 (4), 283-290.

Storey B.C., Leat, P.T., Weaver, S.D., Pankhurst, R.J., Bradshaw, J.D. & Kelly, S. (1999). Mantle plumes and Antarctica-New Zealand rifting: evidence from mid-Cretaceous mafic dykes. *Jour. Geol. Soc. Lond*. **156**, 659-671.

Storey B.C., Leat, P.T. & Ferris, J.K. (2001). The location of mantle-plume centers during the initial stages of Gondwana breakup. In: Ernst, R.E. & Buchan, K.L. (editors) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Paper 352, 71-80.

Stracke, A., Bizimis, M. & Salters, V.J.M. (2003). Recycling oceanic crust: quantitative constraints. *Geochem. Geophys. Geosys*., **4**(3), 8003, doi:10.1029/2001GC000223

Stracke, A., Hofmann, A.W. & Hart, S.R. (2005). FOZO, HIMU, and the rest of the mantle zoo. *Geochem. Geophys. Geosys*., **6**(5), 5007, doi:10.1029/2004GC000824

Sun, S.-S. & Hanson, G.N. (1975). Rare earth element evidence for differentiation of McMurdo Volcanics, Ross Island, Antarctica. *Contributions in Mineralogy and Petrology* **54**, 139-155.

Sun, S.-S., McDonough, W.F. & Ewart, A. (1989). Four component model for East Australian Basalts. In: R.W. Johnson (editor), Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press, 333-347.

Sutherland, R. (1995). The Australia-Pacific boundary and Cenozoic plate motions in the SW Pacific: some constraints from Geosat data. *Tectonics* **14**, 819-831.

Sutherland, R. (1999). Basement geology and tectonic development of the greater New Zealand region: an interpretation from regional magnetic data. *Tectonophysics* **308**, 341-362.

Tiepolo, M., Vannucci, R., Oberti, R., Foley, S., Bottazzi, P. & Zanetti, A. (2000). Nb and Ta incorporation and fractionation in titanian pargasite and kaersutite: crystal-chemical constraints and implications for natural systems, *Earth and Planetary Science Letters* **176**, 185-201.

Todt, W., Cliff, R.A., Hanser, A. & Hofmann, A.W. (1996). Evaluation of a ^{202}Pb-^{205}Pb double spike for high-precision lead isotope analysis. In: A. Basu and S.R. Hart (editors), Earth Processes: Reading the Isotopic Code. Geophys. Monogr. 95, 429-437.

Trønnes, R.G. (2002). Stability range and decomposition of potassic richterite and phlogopite end members at 5-15 GPa. *Mineralogy and Petrology* **74**, 129-148.

Tulloch, A.J. & Kimbrough, D.L. (1989). The Paparoa metamorphic core complex, New Zealand: Cretaceous extension associated with fragmentation of the Pacific margin of Gondwana. *Tectonics* **8**, 1217-1234.

Tulloch, A.J. & Kimbrough, D.L. (1995). Mesozoic plutonism in western New Zealand – a 50 Ma transition from subduction to continental rifting on the Gondwana margin. In**:** M. Brown and P. Piccoli (editors), The origin of granites and related rocks. Third Hutton Symposium, abstracts. *U.S. Geological Survey Circular* **1129**, 153-156.

van Achterbergh, E., Griffin, W.L. & Stiefenhofer, J. (2001). Metasomatism in mantle xenoliths from the Letlhakane kimberlites: estimation of element fluxes, *Contrib. Mineral. Petrol.* **141**, 397-414.

van Westrenen, W., Blundy, J.B. & Wood, B.J. (2001). High field strength element/rare earth element fractionation during partial melting in the presence of garnet: implications for identification of mantle heterogeneities, *Geochem. Geophys. Geosyst*. **2**, Paper number 2000GC000133.

Vlastélic, I., Aslanian, D., Dosso, L., Bougault, H., Olivet, J.L. & Géli, L. (1999). Large-scale chemical and thermal division of the Pacific mantle. *Nature* **399**, 345-350.

Waight, T.E., Weaver, S.D. & Muir, R.J. (1998a). Mid-Cretaceous granitic magmatism during the transition from subduction to extension in southern New Zealand: a chemical and tectonic synthesis. *Lithos* **45**, 469-482.

Waight, T.E., Eby, G.N., Maas, R. & Weaver, S.D. (1998b). French Creek Granite and Hohonu dyke swarm, South Island, New Zealand; Late Cretaceous alkaline magmatism and the opening of the Tasman Sea. *Australian Journal of Earth Sciences* **45** (6), 823-835.

Walcott, R.I. (1998). Modes of oblique compression: late Cenozoic tectonics of the South Island of New Zealand. *Reviews of Geophysics* **36**, 1-26.

Wass, S.Y. & Rogers, N.W. (1980). Mantle metasomatism: precursor to continental alkaline volcanism. *Geochim. Cosmochim. Acta.* **44**, 1811-1823.

Watters, W.A., Campbell, H.J. & Adams, C.J.D. (1987). Notes on the geology of Southeast Island and Star Keys, Chatham Islands. *New Zealand Geological Survey record* **20**, 139-145.

Weaver, S.D. & Pankhurst, R.J. (1991). A precise Rb-Sr age for the Mandamus igneous complex, North Canterbury, and regional tectonic implications. *New Zealand Journal of Geology and Geophysics* **34**, 341-345.

Weaver, S.D. & Smith, I.E.M. (1989). New Zealand intraplate volcanism. In: R.W. Johnson, J. Knutson, S.R. Taylor (Editors), Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press and Australian Academy of Science, 157-187.

Weaver, S.D., Storey, B.C., Pankhurst, R.J., Mukasa, S.B., DiVenere, V.J. & Bradshaw, J.D. (1994). Antarctica-New Zealand rifting and Marie Byrd Land lithospheric magmatism linked to ridge subduction and mantle plume activity. *Geology* **22**, 811-814.

Willis, M.J., Wilson, T.J. & James, T.S. (2004). Neotectonic Crustal Motions in the Antarctic Interior Measured by the TAMDEF GPS Network, *Eos Transactions of the American Geophysical Union*, *85* (17), JA123.

Wilson, M., Rosenbaum, J.M. & Dunworth, E.A. (1995). Melilitites: partial melts of the thermal boundary layer? *Contributions to Mineralogy and Petrology* **119**, 181-196.

Winberry, J.P. & Anandakrishnan, S. (2003). Seismicity and neotectonics of West Antarctica, *Geophysical Research Letters* **30,** SDE 1-4.

Workman, R.K., Hart, S.R., Jackson, M., Regelous, M., Farley, K.A., Blusztajn, J., Kurz, M. & Staudigel, H. (2004). Recycled metasomatized lithosphere as the origin of the Enriched Mantle II (EM2) end-member: evidence from the Samoan volcanic chain, *Geochemistry, Geophysics, Geosystems (G3)* **5** (4), Q04008, doi:10.1029/2003GC000623, 2004.

Wood, R.A. & Herzer, R.H. (1993). The Chatham Rise, New Zealand. In: P.F. Balance (editor) South Pacific Sedimentary Basins. Sedimentary Basins of the World, 2. Elsevier, Amsterdam, 329-348.

Zanetti, A., Vannucci, R., Bottazzi, P., Oberti, R. & Ottolini, L. (1996). Infiltration metasomatism at Lherz as monitored by systematic ion-microprobe investigations close to a hornblendite vein. *Chemical Geology* **134**, 113-133.

Zhang, M. & O'Reilly, S.Y. (1997). Multiple sources for basaltic rocks from Dubbo, eastern Australia: geochemical evidence for plume-lithosphere mantle interaction. *Chemical Geology* **136**, 33-54.

Zhang, M., O'Reilly, S.Y. & Chen, D. (1999). Location of Pacific and Indian mid-ocean ridge-type mantle in two time slices: Evidence from Pb, Sr, and Nd isotopes for Cenozoic Australian basalts, *Geology* **27**, 39-42.

Zindler, A. & Hart, S.R. (1986). Chemical geodynamics. *Annual Review of Earth and Planetary Sciences* **14**, 493-571.