**Geological Society, London, Special Publications**
February 2018, Volume 463 Issue 1 Pages 199-226
http://dx.doi.org/10.1144/SP463.9
http://archimer.ifremer.fr/doc/00439/55100/




# Regional volcanism of northern Zealandia: post-Gondwana break-up magmatism on an extended, submerged continent

Mortimer N. [1,*], Gans P. B. [2], Meffre S. [3], Martin C. E. [4], Seton M. [5], Williams S. [5], Turnbull R. E. [1], Quilty P. G. [3], Micklethwaite S. [6], Timm C. [7], Sutherland R. [8], Bache Francois [9], Collot Julien [10], Maurizot P. [10], Rouillard P. [10], Rollet N. [11]

[1] GNS Science, Dunedin, New Zealand
[2] Department of Earth Science, University of California, Santa Barbara, USA
[3] Department of Earth Sciences, University of Tasmania, Hobart, Australia
[4] Department of Geology, University of Otago, Dunedin, New Zealand
[5] School of Geosciences, University of Sydney, Australia
[6] School of Earth, Atmosphere and Environment, Monash University, Melbourne, Australia
[7] GNS Science, Lower Hutt, New Zealand
[8] School of Geography, Environment and Earth Sciences, Victoria University of Wellington, New Zealand
[9] Santos Ltd., Adelaide, Australia
[10] Service Geologique de Nouvelle Calédonie, Nouméa, New Caledonia
[11] Geoscience Australia, Canberra, Australia

* Corresponding author : N. Mortimer, email address : n.mortimer@gns.cri.nz

**Abstract :**

Volcanism of Late Cretaceous–Miocene age is more widespread across the Zealandia continent than previously recognized. New age and geochemical information from widely spaced northern Zealandia seafloor samples can be related to three volcanotectonic regimes: (1) age-progressive, hotspot-style, low-K, alkali-basalt-dominated volcanism in the Lord Howe Seamount Chain. The northern end of the chain (c. 28 Ma) is spatially and temporally linked to the 40–28 Ma South Rennell Trough spreading centre. (2) Subalkaline, intermediate to silicic, medium-K to shoshonitic lavas of >78–42 Ma age within and near to the New Caledonia Basin. These lavas indicate that the basin and the adjacent Fairway Ridge are underlain by continental rather than oceanic crust, and are a record of Late Cretaceous–Eocene intracontinental rifting or, in some cases, speculatively subduction. (3) Spatially scattered, non-hotspot, alkali basalts of 30–18 Ma age from Loyalty Ridge, Lord Howe Rise, Aotea Basin and Reinga Basin. These lavas are part of a more extensive suite of Zealandia-wide, 97–0 Ma intraplate volcanics. Ages of northern Zealandia alkali basalts confirm that a late Cenozoic pulse of intraplate volcanism erupted across both northern and southern Zealandia. Collectively, the three groups of volcanic rocks emphasize the important role of magmatism in the geology of northern Zealandia, both during and after Gondwana break-up. There is no compelling evidence in our dataset for Late Cretaceous–Paleocene subduction beneath northern Zealandia.

## Introduction

Zealandia is a 4.9 $Mkm^2$ continent that was formerly a part of Gondwana and now lies 94% submerged in the SW Pacific Ocean (Luyendyk 1995; Mortimer *et al.* 2017) (Fig. 1). It consists of a basement of Cambrian to Early Cretaceous terranes and batholiths (Austral Superprovince) and a cover of Late Cretaceous to Holocene sedimentary basins (Zealandia Megasequence; Mortimer *et al.* 2014a). A major tectonic feature of Zealandia is the modern day Pacific-Australia plate boundary (Alpine Fault-Hikurangi Trench in Fig. 1). This divides Zealandia into northern and southern parts and is responsible for Miocene to Holocene subduction-related volcanic rocks on the North Island of New Zealand. In addition to Neogene subduction-related volcanism, Zealandia has a record of different styles and compositions of protracted, scattered, low-volume volcanism that is not related to subduction (Cole 1986; Weaver & Smith 1989; Panter *et al*. 2006; Tulloch *et al*. 2009; Timm *et al*. 2010). This intraplate volcanism erupted in New Zealand sedimentary basins from the Late Cretaceous to the Holocene (Mortimer *et al.* 2014a). Zealandia intraplate volcanic rocks share a broadly similar age range and composition with those in formerly adjacent West Antarctica and Australia (Johnson *et al.* 1989). These now-dispersed lavas have previously been described as a Diffuse Alkaline Magmatic Province (DAMP; Finn *et al*. 2005).

The datasets used to characterise and explain Zealandia intraplate magmatism have, to date, mostly come either from onland New Zealand or from islands and dredges in southern Zealandia which lies on the present day Pacific Plate (e.g. Cole 1986; Gamble *et al*. 1986; Herzer *et al*. 1989; Weaver & Smith 1989; Baker *et al.* 1994; Tappenden 2003; Nicholson & Black 2004; Cook *et al.* 2004; Hoernle *et al*. 2006; Panter *et al.* 2006; Sprung *et al*. 2007; Coombs *et al*. 2008; Tulloch *et al.* 2009; Timm *et al*. 2009, 2010; McCoy-West *et al*. 2010; van der Meer *et al*. 2013; Scott *et al.* 2015). In contrast, examples of intraplate magmatism from offshore northern Zealandia, on the present day Australian Plate are far fewer (e.g. Green 1973; Baubron *et al*. 1976; McDougall *et al*. 1981; Mortimer *et al*. 1998; Timm *et al*. 2010; Dadd et al. 2011; Higgins *et al*. 2011; Nicholson *et al*. 2011). In large part this is because New Zealand and its subantarctic islands have the most accessible igneous rock occurrences. Most published accounts of intraplate volcanism in both northern and southern Zealandia preceded the use of the name Zealandia as a continent, and were equivocal as to the geological setting of the Lord Howe Rise and Norfolk Ridge. As such the older literature on the intraplate magmatism of the Zealandia continent lacks context and is not comprehensive.

In this paper we present 18 Ar-Ar ages, two U-Pb ages, six micropaleontological ages, 22 whole rock geochemical analyses and 19 Nd isotope analyses from Late Cretaceous to Miocene volcanic rock samples on the Loyalty, Fairway and Norfolk ridges, Lord Howe Rise, and in the New Caledonia, Aotea and Reinga basins (Fig. 1). These samples were collected in rock dredges on the GEORSTOM, AUSFAIR, IPOD, DRASP and ECOSAT cruises (Table 1; Monzier & Vallot 1983; Colwell *et al*. 2006; Collot *et al*. 2013; Bache *et al*. 2014a; Seton *et al.* 2016a, respectively).

Our new dataset adds considerably to the existing meagre collection of igneous rocks from northern Zealandia. In turn this enables a more complete picture of the magmatism across all of Zealandia to be presented and explained. This paper builds on and extends syntheses of intraplate volcanism by Finn *et al*. (2005), Hoernle *et al*. (2006), Timm *et al.* (2010) and Bryan *et al*. (2012), and the Zealandia stratigraphic-magmatic framework of Mortimer *et al.* (2014a). It is a companion paper to the dating of Lord Howe Rise lavas by Higgins *et al.* (2011), Reinga Basin sedimentary rock interpretations of Browne *et al.* (2016) and investigations of the South Rennell Trough spreading centre by Seton *et al*. (2016b).

## Northern Zealandia Framework

The three main emergent areas of northern Zealandia are New Zealand's North Island, the west coast of New Zealand's South Island and New Caledonia (Fig. 1). Continental basement of Paleozoic-Mesozoic accreted terranes is exposed in all three places. Several small islands, island groups, reefs and atolls pockmark northern Zealandia. The largest of these are the Three Kings, Norfolk, Lord Howe, Chesterfield and Loyalty islands. The submerged part of northern Zealandia is dominated by the 2000 x 300 km Lord Howe Rise. East and west of this lie the Dampier and Norfolk ridges and to the southeast are the Challenger Plateau and onland New

Zealand. The New Caledonia Trough, a composite Cretaceous and Eocene rift basin (Sutherland *et al*. 2010), is the deepest part of the Zealandia continent and comprises two separate sedimentary basins, New Caledonia and Aotea basins (these, rather than the single trough, are shown in Fig. 1). There has been debate as to whether the basins are floored by continental or oceanic crust (Klingelhoefer *et al*. 2007) and some of the new data reported in this paper bear on this.

The exposed bedrock geology of the Three Kings, Norfolk, Lord Howe, Chesterfield and Loyalty islands consists solely of intraplate volcanic rocks. Some islands and seamounts form linear chains and have been proposed as hotspot tracks. The 2600 km long, N-S trending Tasmantids are entirely constructed on oceanic crust except for Cato seamount which impinges on the Zealandia continent (Exon *et al*. 2006). In contrast the 1900 km long, N-S trending Lord Howe Seamount Chain is entirely constructed on Zealandia continental crust except possibly for Horsehead seamount at its northernmost end (Fig. 1). The Tasmantids in the northern Tasman Sea have been shown by McDougall & Duncan (1988) and Quilty (1993) to get younger to the south and these authors presumed a similar younging for the Lord Howe chain. Three other postulated north-south trending hotspot tracks are the 500 km long Capel-Faust-ZONECO5 seamounts (van de Beuque *et al*. 1998; Exon *et al*. 2004; Dadd *et al.* 2011), a 900 km linear N-S alignment of seamounts on the eastern Norfolk Ridge (Rigolot 1988) and an 1100 km alignment of seamounts along the western Norfolk Ridge (Fig. 1).

## Methods

Methods and analytical laboratories used for whole-rock geochemistry varied depending on sample size. Large (c. >20 g) samples were crushed in a tungsten carbide ring mill and analysed by X-ray fluorescence (XRF) methods at Spectrachem Analytical, Lower Hutt, New Zealand and by fused glass bead ICPMS methods at Washington State University, Pullman, USA (see Mortimer *et al.* 2010 for methods). Small (c. 5-10 g) samples were crushed in agate mortars and analysed by XRF and fused bead ICPMS methods at Washington State University. Two very small (c. <5 g) samples were analysed by laser ICPMS scanning of polished mounts at the University of Tasmania. Except for the latter two samples we report Ba, Cr, Cu, Ni, V, Sc and Zn as analysed by XRF instead of ICPMS.

Argon geochronology at the University of California Santa Barbara followed methods described in Mortimer *et al.* (2014b). U-Pb laser ICPMS (inductively coupled plasma mass spectrometry) geochronology at the University of Tasmania followed methods described in Sack *et al*. (2011). Laser ICPMS pyroxene geochemistry methods at the University of Otago, and Nd isotope methods at the University of Otago followed methods described in Mortimer *et al*. (2014b) and Weis *et al*. (2006) respectively.

Samples prefixed "P" are archived in GNS Science's National Petrology Reference Collection, as are thin sections, rock powders and mineral separates. Location information, sample descriptions and images, and analytical data are stored in the online Petlab database (http://pet.gns.cri.nz; Strong *et al*. 2016).

## Data and results

In this section we describe sample petrography, age and composition under three main geological-geographic headings. Sample locations are given in Table 1, a dating summary in Table 2, and full geochemical and Nd isotope data in Tables 3 and 4. Full geochronological, mineral composition and micropaleontological data are given in Supplementary Data Files 1-4. A recurring theme in our dataset is the difficulty in extracting reliable primary geochemical and geochronological signals. The samples still yield useful provisional data, despite small sample size, secondary alteration of mafic minerals and glass to clays, and presence of zeolites, phosphates and carbonate in amygdules, veins and matrix patches. Concentrations of incompatible large-ion-lithophile elements such as Rb, Sr, Th and K are very vulnerable to such secondary alteration and we have avoided using these elements in our interpretations. We have been conservative in our evaluations of the primary composition of the rocks, placing more emphasis on relatively immobile high field strength elements such as Nb, Zr and Ti. We have also increased many statistically geochronological age uncertainties where mineralogy and degassing behaviour indicates poor sample quality.

A number of samples display petrographic evidence for low temperature alteration or weathering but we are confident, except where otherwise noted, that most of the ages reported here are primary eruption and crystallization ages, not alteration ages. This is justified by petrographic characteristics of most samples (e.g., pristine igneous zoning and twinning in both phenocrystic and groundmass plagioclase), relatively high radiogenic yields of most samples, and apparent K/Ca ratios from both groundmass and plagioclase separates that are typical of igneous compositions, not hydrothermal phases. Thus we attribute most of the complexities in the argon spectra to the fact that we are dating very low K/Ca materials, and to issues with argon loss and reactor induced recoil from very fine-grained groundmass samples.

*Lord Howe Seamount Chain*

The Lord Howe seamount chain consists of at least 19 definable volcanic centres (Fig. 1; Missegue & Collot 1987; McDougall & Duncan 1988; Quilty 1993). Prior to this study, lavas had been sampled at Lord Howe Island, Middleton Reef and Gifford Guyot, all in the southern part of the chain (McDougall *et al.* 1981; Mortimer *et al.* 2010; Dadd *et al*. 2011). We present analytical results of samples from the two northernmost seamounts in the chain, the informally named Horsehead seamount (ECOSAT DR15) and from a dredge site c. 50 km north of the Chesterfield Islands (ECOSAT DR16). Both sites yielded only small, altered samples and we acknowledge the data are poor quality and interpretations provisional.

*Horsehead.* From ECOSAT dredge 15, c. 5 kg of hard cream-coloured shallow water, Mn-crusted limestone was recovered. Several small (0.5-3 cm diameter) pebbles of lava were present between the Mn crust and limestone, with some fully enclosed by the limestone. P82218A and Bi are c. 1.5x1x1cm red-brown plagioclase-pyroxene porphyritic lava pebbles and P82218C a grey lava pebble. No pebbles were fresh, all showed extensive clay alteration.

The argon spectrum of groundmass from P82218C was fairly flat (slightly hump-shaped) for the first 75% of gas released with good K/Ca ratios (0.03-0.06) and high radiogenic yields (90-95%) for most of the spectrum (Fig. 2a). Ages and K/Ca ratios both dropped at the highest temperatures due to recoil. We used the broad flat, central step at 27.2 ± 0.5 Ma as a preferred (igneous) age for the sample, expanding the statistical uncertainty to reflect the broad hump shape and likely minor influence of both argon loss and recoil. The argon spectrum of plagioclase from Horsehead P82218Bi started with ages c. 45 Ma and then climbed to c. 75 Ma (see Supplementary Data File 1). K/Ca ratios were 0.013-0.050, reasonable for igneous plagioclases. Radiogenic yields for the low T steps were high. However, there were no good isochrons and we suspect there is excess argon in the higher T steps of this plagioclase. At face value, a preferred age might be c. 48 ± 3 Ma (arbitrary error assigned to bound the ages of the four low T steps) but our confidence in this is low, with an older interpretation possible. We do not use P82218Bi to date Lord Howe Seamount chain volcanism.

The hard limestone from Horsehead (DR15A) enclosing some volcanic clasts gave a tentative late Early Miocene age, in agreement with the dated clasts from Horsehead being older. Soft white limestone from Horsehead (DR15C) gave a Pleistocene age (Supplementary Data File 2).

Because of small sample size, only ICPMS trace elements were able to be obtained from two Horsehead clasts P82218A and 82218C (Table 3). The lack of major element data means they cannot be plotted on Fig. 3a and 3b but petrography and Sc contents indicate a likely basaltic composition (Winchester & Floyd 1977). Zr content and convex-up multi-element normalised patterns with peaks at Ta and Nb match those of typical intraplate basalts (Figs 3c, 3d, 4a). Horsehead is arguably the only Lord Howe Seamount Chain volcano to have erupted on oceanic, rather than continental, crust. Yet it has the second lowest initial εNd of all four Lord Howe Seamount Chain volcanoes for which we have data (Fig. 5). The initial εNd falls within the range of the E-MORBs of the South Rennell Trough immediately to the north and is not dissimilar to a Lord Howe Island lava (Table 4, Fig. 5).

*Chesterfield Islands.* From ECOSAT dredge 16 c. 0.2 kg of separate, pebble-sized pieces of lava and limestone were obtained. P82221 is a 4x2x1 cm angular piece of subtrachytic, sparsely olivine-phyric basalt. There is fresh plagioclase in the groundmass, but otherwise, groundmass and olivine are completely replaced by clays. P82224 consists of three c. 1 cm pieces of olivine-plagioclase porphyritic altered basalt with a subtrachytic groundmass; clay fills amygdules.

The Ar-Ar degassing spectrum of Chesterfield sample P82221 groundmass was similar to Horsehead P82218C. However, P82221 gave not quite as flat a spectrum, and also slightly lower K/Ca ratios and radiogenic yields (see Supplementary Data File 1). We used the flat step in the middle of spectrum to give an interpreted preferred age of 28.1 ± 1.0 Ma (uncertainty boosted to greater than just statistical uncertainty because of the sharper hump). The argon release spectrum of Chesterfield P82224 groundmass was the most difficult to interpret of the three Lord Howe seamount chain groundmass samples. The spectrum was more hump-shaped, with no real flat top, thus there was more evidence for both argon loss and recoil (Supplementary Data File 1). We regard the age of the top of the hump, c. 23 Ma, as a minimum age (Table 2).

As with Horsehead, because of the small clast size, only ICPMS trace element data were obtained. Although the multi-element normalised patterns are also convex-up, both analysed Chesterfield samples (P82221 and 82224) have about half the concentration of large ion lithophile elements and high field strength elements than the Horsehead lavas (Fig. 4a), and their

Nb/Yb ratio is lower (Fig. 3d). Although the lack of major elements again hinders assignment of a rock name, they have the features of transitional rather than alkaline basalts. Chesterfield lava P82221 has a higher initial εNd when compared to that of the analysed Horsehead lava (Fig. 5). The reasons for these chemical and isotopic differences are explored in the Discussion section below.

*New Caledonia Basin margins*

A group of lavas of distinct chemistry and age occur around the margins of the New Caledonia and Fairway Basins in the northern part of northern Zealandia (Figs. 1, 3, 4b, 5). These samples have not been dredged from well-preserved, upstanding volcanic seamounts. Instead they are samples of seismic acoustic basement exposed as relatively subdued, current-swept areas (e.g. Le Noroit, IPOD sites), or on fault scarps that expose rocks older than seismic sedimentary cover (e.g. Nereus Reef, Lansdowne Bank, AUSFAIR sites).

*Le Noroit Seamounts.* Although described as seamounts, a seismic line (Daniel *et al.* 1977, fig. 4) shows that they consist of a broad (c. 100 x 100 km), partly faulted basement high that has not been completely covered by the sediments of the New Caledonia and d'Entrecasteaux basins. ECOSAT dredge 11 was taken from the highest seamount. It yielded no substantial solid basement rock but only manganese crusts (one up to 11 cm thick) and a few dozen c. 2-5 cm diameter manganese nodules. The nodules contained <1 cm angular kernels of pale grey, green and red lava in their cores as well as various calcareous and phosphatic rocks.

Automated scanning electron microscopy of 18 polished manganese nodules identified small (7-30 micron), rare (n=15) zircons in two of the lava kernels which were then dated by *in situ* LAICPMS methods. For DR11Ei, 10 of the 11 zircons were Paleocene in age and one was Middle Jurassic (Fig. 6). The Paleocene zircons gave an intercept age of 63.8 ± 3.1 Ma that we interpret as the crystallisation age of the lava. The single 168 Ma zircon is probably a xenocryst incorporated in the lava from underlying (continental) crust. The four zircons found in DR11Ev collectively give an intercept age of 65.5±4.2 Ma, within error of DR11Ei.

The chemistry of the two Le Noroit lavas reveals them to be trachytes, slightly more siliceous than trachyandesite and showing an iron enrichment trend (Figs. 3a, 3b). Their overall high incompatible element content (Figs 3c, 4b) indicates they are part of an alkaline suite. We explain their relatively low Eu, Nb, Ta and Ti content in part due to fractionation of plagioclase, amphibole, biotite, ilmenite and titanite. The initial εNd of Le Noroit lava DR11Fi (Table 4) is slightly more radiogenic than the Lord Howe Seamount Chain lavas (Fig. 5).

*Lansdowne Bank and Nereus Reef*. Launay *et al*. (1977, fig. 2) and Collot *et al*. (2008, figs 11, 13) presented seismic profiles across the northern Fairway Ridge. Two dredges were taken from the northern Fairway Ridge on the ECOSAT cruise, one on the steep, northeast side of the Lansdowne Bank (DR17) and another on the steep, northeast side of Nereus Reef (DR18) (Fig. 1). Although 65 km apart, similar lithologies occur in  the two dredges and we describe them together.

Lansdowne Bank yielded 18 small pieces of hard, dark green-grey, fine to medium grained aphyric lava and volcaniclastic sandstone. About half of these were >10 mm in size (the largest being 15x10x5 mm), and the other half <5 mm. All pieces were angular in shape. The fact that some samples have clean broken faces and very thin (<0.5 mm) crusts on non-broken faces suggested they probably were broken off *in situ* rock outcrops. In thin section the lavas contain many secondary minerals including chlorite and zeolite. From Nereus Reef, a dozen angular pieces of red coloured, hydrothermally altered, veined and brecciated plagioclase-augite porphyritic lava were dredged, the largest was DR18Bi (10x8x6 cm) and the smallest 3-4 cm in size. Despite the obvious alteration of the Lansdowne and Nereus samples, three samples were chosen for Ar-Ar geochronology of groundmass separates and four samples for whole rock geochemistry. Because of the small sample sizes, different samples had to be selected for the different kinds of analysis.

All three Ar-Ar dated samples from the northern Fairway Ridge had complex gas release spectra in the form of two humps (e.g. Fig. 2b, see Supplementary Data File 1 for all three spectra). The low temperature humps represent degassing of high K/Ca material, probably clays, and show the combined effects of argon loss and reactor induced recoil. The higher temperature humps had higher K/Ca (0.4-0.8) probably corresponding to degassing of groundmass adularia of hydrothermal origin. The ages in the high-temperature domains climbed to c. 78 Ma in Lansdowne P82230, c. 81 Ma in Lansdowne P82231 and c. 58 Ma in Nereus P82240. Based on the abundance of secondary minerals in thin sections, even the oldest ages in the high-temperature humps are likely to be partly or wholly alteration ages. As such, we interpret these as minimum ages for the stratigraphic ages of the lavas (Table 2) which could actually be as old as Permian or Early Cretaceous.

Supporting age information was obtained from Lansdowne Bank limestone DR17Gi. This is a separate sample of hard foraminiferal limestone (not enclosing, or in contact with, any of the lavas); *Miogypsinoides* suggests an earliest Miocene, or possibly latest Oligocene, age and a shallow-water, tropical paleoenvironment. From Nereus Reef, foraminiferal limestone DR18Ci contains c. 30% red clasts similar to the altered volcanics described above. The limestone contains a juvenile *Lepidocyclina* which indicates an Early-Middle Miocene age and a paleo-water depth shallower than c. 100 m.

The small sample size and extreme secondary alteration of the northern Fairway Ridge lavas present considerable difficulty in the interpretation of their primary geochemistry. Based on petrography and Sc content, all five samples appear to be altered basaltic andesites and andesites. Zr varies from 39-122 ppm and Ba, Th, Nb, La and Ce show even more inter-sample variation (Table 3, Figs 3c, 4b), but to what extent this variation is primary or secondary is hard to assess. The five northern Fairway ridge lavas overlap in trace element composition with the two Le Noroit lavas, but show more extreme negative depletion in Nb and Ta and, as expected, lower Nb/Yb ratios (Fig. 3d). The initial εNd of the Nereus and Lansdowne lavas (Table 4, Fig. 5) overlap those of the South Rennell Trough spreading centre, the Lord Howe Seamount Chain and Le Noroit seamounts.

*AUSFAIR5, Southern Fairway Ridge.* Despite its subdued bathymetric expression south of 26°S, Collot *et al.* (2009) showed that the Fairway Ridge continues as a well-defined magnetic and structural feature that is co-linear with the West Norfolk Ridge and divides the New Caledonia Basin from the Aotea Basin (Fig. 1). Dredge site 5 on the AUSFAIR cruise (Colwell *et al*. 2006) was made on the steep, eastern side of this part of the Fairway Ridge and is labelled as 'Northern West Norfolk Ridge' on the seismic profile of fig. 5 in Exon *et al*. (2007). The dredged rocks included palagonitic volcanic breccias, some carbonate cemented. The largest and freshest volcanic clast was chosen for study, a c. 5x4x2 cm angular plagioclase-augite-hornblende-olivine porphyritic andesite (AUSFAIR-DR5B, P81400). Hornblende is primary and there is no biotite.

Hornblende from AUSFAIR5 sample P81400 was Ar-Ar dated. The gas release spectrum yielded a “pseudo-plateau” for c. 90% of gas released (Fig. 2c). We used the step at the top of the central hump, with the highest precision and radiogenic yield, to give an age of 74.1 ± 0.3 Ma which we interpret as the age of crystallisation of the lava.

Compositionally, the P81400 is a medium-K andesite and has moderate Fe and Zr for its $SiO_2$ content (Fig. 3a, b, c). On a multi-element normalised diagram (Fig. 4c) the pattern has a prominent negative Nb-Ta anomaly and is similar in shape to the two central Lord Howe Rise trachytes (see below) but is somewhat less fractionated. Analysis of fresh clinopyroxenes from P81400 overlap those of reference basalts from orogenic and non-orogenic settings (Fig. 3e).

*AUSFAIR3, Central Lord Howe Rise.* Although not spatially on the margins of the New Caledonia Basin, the AUSFAIR3 dredge site is on a fault scarp near the edge of the Fairway Basin (Fig. 1; Colwell *et al*. 2006). Higgins *et al*. (2010) reported U-Pb zircon ages from two lava samples from AUSFAIR-DR3: DR3D1 was described as a trachyte and gave an age of 96.9±0.7 Ma and DR3G1 was described as a latite (potassic trachyandesite) and gave an age of 74.1±0.7 Ma. In this paper we present the first whole rock geochemical data of these lavas (Table 3). At face value, Fig. 3a indicates they are rhyolites. However, as previously noted by Higgins *et al*. (2010), they lavas contain secondary quartz but no quartz phenocrysts. Because hydrothermal alteration may have increased the silica content of the lavas, we conservatively and loosely refer to both lavas as trachytes. Their high to extreme $K_2O$ content (4.3 and 5.3 wt%) classifies them as shoshonitic and they have the highest large ion lithophile element (Ba, Th) concentrations of our dataset (Fig. 4b). The two AUSFAIR3 lavas are grouped with the New Caledonia Basin margin lavas because they are of Late Cretaceous age, show pronounced negative Nb and Ta anomalies on normalised multielement diagrams (Fig. 4c) and they are not basalts. The AUSFAIR3 lavas show strong compositional similarities with the 97 Ma high-K to shoshonitic rhyolite described from DSDP 207 on the Lord Howe Rise (Fig. 1, Fig. 4e, Tulloch *et al*. 2009).

*IPOD4, Offshore New Caledonia.* Southwest of New Caledonia, the seafloor descends to the floor of the New Caledonia Basin and is one of the steepest large submarine slopes within Zealandia (with 30° slopes in some places). Just outside the fringing reef near Koumac, near the top of the slope, dredge 4 of the IPOD cruise (IPOD4 in Fig. 1) recovered several dm-sized pieces of glassy, autobrecciated and agglomerated vesicular lava. No volcanic edifice was visible in multibeam bathymetry. Some fractures in the lavas were lined with thin Mn crusts and then further infilled with limestone. Some samples in the dredge consisted of angular lava clasts in a micritic limestone. A thin section of IPOD DR4-VRAC2 (P84022) revealed variably devitrified glass with sparse plagioclase phenocrysts and a thin Mn rind.

Two glass and one plagioclase separate from IPOD P84022 were dated by Ar-Ar methods. Degassing spectra from both glass separates were similar, both climbing gradually (one from c. 40 up to 45 Ma, the other from c. 45 up to 48 Ma) then plummeting with dropping K/Ca. These spectra (Supplementary Data File 1) showed classic combined recoil and low temperature Ar loss features. In the degassing of plagioclase from the same sample the spectrum was satisfactorily flattish, with most steps within error. The weighted mean plateau age from the first three steps (73% of gas) was 40.0 ± 1.1 Ma. The glass ages had higher apparent precision, but glass in submarine settings has a tendency to trap a non-atmospheric (excess argon) component and thus give spuriously old ages. The plagioclase had very low K/Ca, and tiny signals, but seemed reliable. All things considered, we very provisionally conclude that the ages of all the separates are in rough agreement and that an age of 42 ± 5 Ma should be reported as the age of crystallisation of the lava. Morgans (2014) reported a Late Pliocene age for limestone in cracks in the IPOD4 lava, not inconsistent with an Eocene age of eruption.

P84022 is the only glass in our geochemical dataset and, as such, gives reasonably reliable primary compositions (even so, we note it has 4.3 wt% loss on ignition). It is a medium-K dacite that has low Zr, Nb and Ta and the flattest normalised trace element composition (Fig. 4c) of our dataset but only has a small negative Eu anomaly. In this regard it is curiously basalt-like and very different from the other siliceous igneous rocks shown in Fig. 4c and d which, as expected, have higher trace element concentrations. Based on its Nb/Yb ratio (Fig. 3d), P84022 is derived from very depleted mantle.

*Scattered northern Zealandia seamounts*

The third group of lavas are not part of either the Lord Howe Seamount Chain or acoustic basement. Instead they were sampled from isolated, sometimes partly eroded, volcanic edifices, recognisable as such in multibeam bathymetry or crossing seismic lines. Our new samples are from the Loyalty Ridge, southern Lord Howe Rise, Aotea Basin and Norfolk Ridge area. Similar isolated volcanic centres and cones in northern Zealandia have been described and sampled by van de Beuque *et al*. (1998), Exon *et al.* (2004), Mortimer *et al*. (2010) and Dadd *et al.* (2011), and in southern Zealandia by Timm *et al.* (2010).

*ECOSAT8, Loyalty Ridge.* ECOSAT dredge 8 was made on an unnamed seamount towards the northwest end of the Loyalty Ridge (Fig. 1). Sample DR08Ai (P82194) was an altered plagioclase porphyritic basalt with c. 30% zeolite and calcite amygdules. The degassing of plagioclase from P82194 gave an excellent flat argon spectrum with a well-defined plateau and isochron (Supplementary Data File 1). K/Ca ratios were reasonably high (0.013), and radiogenic yields were good for most of the spectrum (60-95%). We interpret the 24.6 ± 0.3 Ma weighted mean plateau age of the sample (700-1150°C steps, 98% of gas) as the age of crystallisation of the basalt.

The whole rock chemistry of this low-K, high Ti alkali basalt shows the effects of secondary alteration and sediment infiltration. This is particularly noticeable in terms of the high CaO, $P_2O_5$, LOI and As, and low $K_2O$. We also note the strong and unusual decoupling/depletion of the rare earth elements (REEs) relative to high field strength elements Nb, Ta, Zr and Hf (Fig. 4c) and speculate that this is due to a low REE content in amygdaloidal minerals. Despite this, it is clear from the multi-element normalised pattern in Fig. 4c, that P82194 is of ocean island basalt type affinity and is derived from very enriched mantle (rightmost point in Fig. 3d).

*GO357, Southern Lord Howe Rise.* A prominent volcanic edifice on the southern Lord Howe Rise was dredged on the GEORSTOM III SUD cruise (GO357 on Fig. 1). A seismic line across the seamount is shown in Bentz (1974, fig. 10) and Launay *et al*. (1977, fig. 2). Geochemical analyses of the dredged calcite amygdaloidal alkali basalt from GO357 (P57144) and of (petrologically unrelated) gabbro basement xenoliths in the basalt (P57145) were presented by Mortimer (2004).

For the current study we performed Ar-Ar dating of a plagioclase separate from the xenolith (P57145). This gave a reasonably flat spectrum, though most of the gas came out over a fairly narrow temperature range (Fig. 2d, Supplementary Data File 1). We interpret the weighted mean plateau age of 27.0±0.3 Ma, as the age of rapid cooling of the heated xenolith after eruption and therefore to date, within error, the eruptive age of the enclosing lava.

Like the Loyalty Ridge lava, P57144 has high LOI and CaO (Table 3). Except for a small negative Ti anomaly, P57145 has the smooth, convex-up normalised multi-element pattern typical of intraplate ocean island low-K alkali basalts (Fig. 4c). It has the second highest Nb/Yb ratio of our dataset (Fig. 3d) so is derived from very enriched mantle.

*GO346, Eastern Norfolk Ridge.* A small seamount on the eastern flank of the southern Norfolk Ridge lies approximately 150 km south of Norfolk Island (Fig. 1). It was dredged on the GEORSTOM III SUD cruise (site GO346 on Fig. 1). Subsequently, the Sonne-7 cruise shot a reflection seismic line across the seamount (Hinz 1979). Sample GO346D1 (P78644) is a plagioclase-olivine microporphyritic basalt.

Step heating of a groundmass separate from P78644 gave a simple argon release spectrum with an excellent flat plateau for first 58% of gas. The ages decreased at higher temperatures, probably due to recoil effects. Our preferred age for the crystallisation of the basalt is the weighted mean plateau age of 18.1±0.2 Ma (Supplementary Data File 1). P78644 has the lowest Ti and Nb/Y content of the basalts in this seamount group and is a transitional (tholeiitic to mildly alkaline) low-K basalt. This is reflected in its flattish multi-element normalised pattern (Fig. 4c).

*DRASP19, Reinga Basin.* The Reinga Basin lies c. 70 km east of, and parallel to, the West Norfolk Ridge (Fig. 1). DRASP dredge d19C (DRASP19 on Fig. 1) was made on the northeastern edge of a subdued high on the west side of the basin. The area around the dredge site was not fully surveyed by multibeam bathymetry but, seemingly, the feature is part of a low, shield-like, volcano (Bache *et al*. 2014a, figure on p. 21). Sample d19C (P83198) is a plagioclase-augite-olivine basalt showing extensive clay alteration of olivine and groundmass.

Ar-Ar dating of Reinga Basin P83198 groundmass gave results that were difficult to interpret (Supplementary Data File 1). Most gas was released at very low temperatures, probably from clays. K/Ca ratios are adequate (0.13-0.21), but the signals were small. Ages monotonically decreased from 26 Ma indicating a major recoil issue. There was no good plateau or isochron. For a loosely constrained age, we used the first two steps but increased the uncertainty: 25.5±2.5 Ma. Foraminifera in two separate limestone samples from the same dredge were dated by Browne *et al*. (2016) as Early Oligocene and Early to Middle Miocene, i.e. close to the lava age. Thin sections show that neither limestone contains volcaniclastic detritus.

No ICPMS trace element data are available for P83198 but the high $TiO_2$ and Nb/Y ratio and the partial but convex-up multi-element normalised diagram (Fig. 4c) show that the lava is a classic sodic alkali basalt.

*DRASP27, West side of Aotea Basin.* At the foot of slope of the southeastern Lord Howe Rise, a meandering submarine canyon impinges on an ovoid shaped 10 x 5 km low plateau before debouching on the floor of the western Aotea Basin (Bache *et al*. 2014a, figure on p. 23). The plateau has an irregular top but, based on the volcanic rocks recovered, a volcanic-volcaniclastic unit may have been sampled. Sample d27B (P83225; DRASP27 on Fig. 1) is a holocrystalline, coarse-grained basalt comprising interlocking grains of titanaugite, plagioclase and olivine (the latter altered to clay minerals). In contrast, sample d27C (P83226) is a highly vesicular olivine porphyritic basalt.

The overall Ar-Ar gas release spectrum of P83225 groundmass was fairly flat at c. 27 Ma for first 80% of gas released, then dropped to 23 Ma. K/Ca ratios were good (0.3 to 0.6). As a reasonable interpretation, we take the weighted mean pseudoplateau age for the first 80% of gas and increase the uncertainty, giving an age of 27.0±0.5 Ma. For plagioclase from the same sample, the spectrum was fairly flat, but descended slightly from 28.5 to 25.0 Ma. K/Ca ratios are c. 0.025, and radiogenic yield is good at c. 55%. The statistical weighted mean plateau age was 27.7±1.2 Ma. It is reassuring to see agreement in age between the two different materials from the same sample. As a preferred crystallisation age for P83225, we select the plagioclase age of 27.7±1.2 Ma.

Groundmass from P83226 degassed in a typical hump-shaped fashion, indicating both low temperature argon loss and recoil. Ages climbed from 26 to 30 Ma, flattened, and then descended to 13 Ma at high temperatures. The central pseudo-plateau part of the spectrum gave an age of 29.4±0.5 Ma. Given that it is not strictly a plateau and we are unsure as to which part of the spectrum is most reliable, we report the age as 29.5±1.5 Ma i.e. overlapping or possibly a little older than P83225. Palynomorphs from mudstone d27H from the same dredge gave an early Teurian (66-60 Ma) age (Browne *et al*. 2016) suggesting a stratigraphic relationship of Paleocene mudstone overlain by Oligocene lava.

No ICPMS trace element data are available for Aotea Basin sample P83226 but the Nb/Y ratio and the partial multi-element normalised diagram (Fig. 4c) show that the lava is a mildly alkaline basalt, slightly more enriched than the subalkaline P78644.

*DRASP2, Aotea Seamount.* This prominent seamount at the southern end of the Aotea Basin has long been speculated to be of volcanic origin (Brodie 1965). It is c. 50x15x0.8 km in size, elongated in an east-northeast direction. DRASP cruise dredge d02 from the western end of the seamount obtained plagioclase-titanaugite-olivine basalts (Bache *et al*. 2014a, figure on p. 14), thus confirming the volcanic origin. In thin section, olivine is completely altered to clay but the groundmass appears fresh and unaltered.

The argon dating of groundmass from sample d02C (P83160) gave reliable results. As expected given the very fine-grained matrix, most gas came out at fairly low temperatures. Ages decreased from 22.7 to 22.4 Ma in the first 85% of gas released, then plummeted to ages as low as 7 Ma in the highest T steps (associated with degassing of Ca-rich phases). Such a spectrum is typical of recoil. For most of the spectrum, K/Ca is high (1-3) as is radiogenic signal (85-92%). Given the evidence for recoil, and monotonically descending ages, we interpret the crystallisation age of the lava as 22.5±0.2 Ma.

No ICPMS trace element data are available for Aotea Seamount sample P83160 but the Nb/Y ratio >2, $TiO_2$ >3wt% and the partial multi-element normalised diagram (Fig. 4c) show that the lava is probably a strongly alkaline to nephelenitic basalt.

## Discussion

*Lord Howe Seamount Chain*

Volcanic rocks have now been sampled and dated from five of the 19 Lord Howe Seamount Chain centres. Limestones dated using foraminifera have been sampled from another two (Figs. 1, 7). Our samples from Horsehead and Chesterfield seamounts, although small and poor in quality, are important as they provide data from the northernmost end of the chain. A linear regression through all Lord Howe Seamount chain lava ages gives an average southward rate of younging of c. 60 mm/yr, similar to the subparallel Tasmantids seamount chain (Duncan & McDougall 1988; Quilty 1993) and to alignments of 35-2 Ma volcanic centres in mainland Australia (west of Fig. 1; Knesel *et al.* 2008; Sutherland *et al.* 2012; Davies *et al.* 2015). All chains show a deflection from linearity at c. 26-23 Ma (Figs. 1, 7; Kalnins *et al.* 2015). This indicates, to a first approximation, that the sources of the volcanism of both the Tasmantid and Lord Howe chains were (a) approximately fixed relative to each other, and (b) to some degree coeval. The sparse dating, sometimes only of post-volcanic guyot limestones, does not allow precise bracketing of the age range of volcanism at any one seamount.

The volcanism along the Tasmantid and Lord Howe chains marks the northward passage of the Australian Plate over sources of magmatism that are approximately fixed in the mantle. Recent absolute and relative plate motion models (Steinberger *et al*. 2004; Wessel & Kroenke 2008; Müller *et al*. 2016) indicate good agreement between predictions from Indo-Atlantic and Pacific hotspots (Fig. 7b). These updated predictions are affirmatively tested with the measured age progression along the Lord Howe chain (Fig. 7b).

All Lord Howe Seamount Chain samples lie along the mantle array on a Nb/Yb vs Th/Yb diagram (Fig. 3c). Pearce & Norry (1979) used the Zr/Y ratio of basalts to explore the petrogenesis of alkali and tholeiitic basalts. The Zr/Y ratio of most lavas along the Lord Howe Seamount Chain is between 8 and 14 (Fig. 7a), typical of alkali basalts and their differentiates and of the Tasmantids. The notable exception is Chesterfield which has Zr/Y = 3. The Chesterfield Islands and Bellona platforms represent the largest volume of Lord Howe chain eruptions: they have very shallow water depths (45-80 m), an area of 16,000 $km^2$ and resulted from the coalescence of five volcanic centres (Missegue & Collot 1987). The high emplacement rate for the Early Miocene Chesterfield-Bellona eruptive pulse fits with the low Zr/Y which can indicate a high degree of mantle melting. Published geochemical data from the intraoceanic Tasmantid seamount chain (Figs. 4d, 7a) indicate a range of alkaline to subalkaline (including picritic) compositions and therefore also a range of melting regimes with time (Eggins *et al.* 1991).

Despite all the Lord Howe Seamount Chain volcanoes erupting through continental crust, all lavas have high initial εNd and points to a minimal degree of crustal contamination (to low εNd) by older basement (Fig. 5). The overall high initial εNd and multi-element normalised patterns for the Lord Howe Seamount Chain (with pronounced humps at Nb and Ta) resemble typical low-silica basalts described from the Chatham Islands by Panter *et al.* (2006) and Timm *et al*. (2010). The low silica Chatham Island, and other southern Zealandia locations, lavas also generally have HIMU-type (high $\mu$ = U/Pb) isotopic compositions as opposed to Timm *et al.*'s EM-type (Enriched Mantle) high silica basalts, which have negative slopes descending from Ba (Figs 3d, 4f). Tasmantids isotope data have been interpreted as relating to an EM-I type mantle plume (Eggins *et al.* 1991), seemingly quite different from the Lord Howe Seamount Chain (Fig. 5).

The space-time relationship of the Lord Howe Seamount Chain to the South Rennell Trough is interesting in the spatial coincidence of hotspot volcanism and backarc spreading. The approximate pole of rotation of c. 45-28 Ma South Rennell Trough spreading is located at the south end of the South Rennell Trough i.e. at Horsehead Seamount (Seton *et al.* 2016b). This age range is bracketed by the 48±3 and 27 Ma lava ages from Horsehead (Fig. 9), and the E-MORBs of the South Rennell spreading centre overlap in geochemical and Nd isotopic composition with Horsehead and Chesterfield lavas (Fig. 5). This match in space, time and composition suggests a genetic relationship between backarc basin spreading and a mantle plume. A plume control on ridge location has been suggested for the western Galapagos by Sinton *et al.* (2003), and Jellinek *et al*. (2003) showed that theoretically, lithospheric separation can capture some or all of a nearby ascending deep mantle plume. The South Rennell Trough and Lord Howe Seamount Chain may be another example of plume-related spreading in a backarc setting (the Eocene-Miocene arc and trench being located to the north and east, possibly under Vanuatu).

*No other age-progressive seamount chains*

In addition to the Tasmantid and the Lord Howe seamount chain, three other putative north-south trending age-progressive seamount chains have been identified on the eastern Australian Plate (thin, white, dashed lines in Fig. 1). If they showed similar age progressions to the Lord Howe and Tasmantids chains then they would all be expected to become younger to the south at a rate of c. 1.8 Ma per degree of latitude. The existence of the easternmost chain, proposed by Rigolot (1988) linking 3 Ma Norfolk Island with 10 Ma seamounts on the Loyalty Ridge, is not supported by the intervening 23-25 Ma potassic volcanics (Fig. 8c). The 900 km linear chain along the west side of the Norfolk Ridge may yet show a north-south age progression and has been sampled to test this hypothesis (Mortimer *et al*. 2015). The 500 km long Capel-Faust seamount chain may be a relatively short track on the Australian Plate (Dadd *et al.* 2011) but precise age data are still lacking to establish this.

With available age data, age-progressive hotspot-style volcanism can only be demonstrated for the Lord Howe and Tasmantid seamount chains (Fig. 8c), restricted to the western part of northern Zealandia. We regard all other widely scattered, Late Cretaceous to Holocene intraplate volcanism in Zealandia (Fig. 8) as derived from asthenospheric and/or lithospheric sources unrelated to postulated deep mantle plumes (Hoernle *et al*. 2006; Timm *et al.* 2010).

*Continental crust of Fairway Ridge and New Caledonia Basin*

The New Caledonia Basin is the longest and most submerged sedimentary basin in Zealandia (Fig. 1). Whereas New Caledonia is underlain by continental crust, no drillhole has yet penetrated basement in the basin or the Fairway Ridge that bounds the basin to the west. Based on geophysical data, a variety of hypotheses of oceanic crust or rifted continental crust have been proposed for the New Caledonia Basin and the Fairway Ridge (see summaries by Lafoy *et al*. 2005 and Klingelhoefer *et al.* 2007).

Our new dredge data provide the first direct samples of New Caledonia Basin and Fairway Ridge acoustic basement. We regard it as significant that the lavas dredged from Le Noroit seamounts, Lansdowne Bank, Nereus Reef and the AUSFAIR5 site are andesites, basaltic trachyandesites and trachytes. As such, these features cannot be basaltic oceanic crust. The high εNd values for the northern Fairway Ridge and Le Noroit lavas (Fig. 4) do not necessarily argue against continental crust basement. Eastern Zealandia Mesozoic greywacke terranes can have high initial εNd (Price *et al*. 2015), and lavas that pass through continental crust don't inevitably assimilate it (e.g. Timm *et al*. 2010). The Jurassic zircon in one of Le Noroit lavas does, however, indicate that part of the New Caledonia Basin probably is underlain by continental crust. Middle to Late Jurassic detrital zircons have been found in the Boghen and Central basement terranes of New Caledonia (Adams *et al*. 2009). Our data support a thinned continental crust origin for the New Caledonia Basin and Fairway Ridge (Lafoy *et al.* 2005). In a wider context (Fig. 8a) we regard the c. 88 Ma siliceous volcanics of the Nouméa Basin in New Caledonia (Nicholson *et al*. 2011) as a related syn-rift continental igneous suite, along with the 101 Ma Houhora Complex of New Zealand's Three Kings Islands, West Coast South Island granitoids and the Mount Somers Volcanic Group in southern Zealandia (Fig. 1; Tulloch *et al.* 2009).

*Late Cretaceous to Eocene subduction?*

It is important for global plate circuits to establish whether a Late Cretaceous-Paleogene subduction zone existed off or along the eastern edge of northern Zealandia. So far this remains controversial (see review by Matthews *et al*. 2015). The lack of preservation of clear bathymetric volcanic chains and basins means that tectonic models have to be based on geochemical interpretations of dredged lavas. This is fraught with difficulty because mantle melting processes rarely have a direct connection to surficial tectonic regimes, and even compositionally distinctive lavas such as shoshonites, boninites and adakites can form in a variety of melting regimes. Subalkaline basalts and andesites commonly erupt in orogenic (subduction-related) settings. However, non-orogenic basalts and andesites, with broadly similar whole rock compositions to orogenic lavas, are well known, especially from continental rift settings (e.g. Hebrides, Columbia River, Sonora; Morrison 1978, Morris *et al.* 2000, Till *et al*. 2009).

Amid the plethora of geochemical discrimination diagrams, negative Nb and Ta anomalies on multi-element normalised plots are considered an indicator of subduction-related process (Baier *et al.* 2008 and references therein). The known partitioning of Ti, Nb and Ta into titanite, FeTi oxides and amphibole could, in principle, lead to depletion of these elements in andesites, dacites and rhyolites through crystal fractionation as magmas move and change between mantle and the surface. However an example of 97 Ma lavas from Mount Somers Volcanic Group in the

South Island (Fig. 1) shows that double-normalising to yttrium partially corrects for fractional crystallisation in the basalt, andesite, dacite, rhyolite spectrum. As such, the double-normalised element concentrations of the Mt Somers rhyolite in Fig. 4e are graphically "lowered" to be close to those of the basalt and it is seen that and Nb and Ta anomalies do not substantially deepen with increasing $SiO_2$. There are further complications, however, in that: (a) long-lived earlier subduction (e.g. Cambrian to Early Cretaceous subduction under Gondwana; Mortimer *et al*. 2014) may pre-condition the lithospheric mantle such that, when it later melts in an intracontinental setting, the resulting basalts may have negative Nb and Ta anomalies, (b) melts of earlier subduction related basement terranes, plutons or lavas in an intraplate setting may yield siliceous lavas with negative Nb and Ta anomalies, and (c) assimilation of very large amounts of continental crust may, in some cases, impose negative Nb and Ta anomalies on lavas. Thus, relying on negative Nb and Ta anomalies from a few samples to infer paleosubduction may give erroneous and misleading results. This longstanding and important issue cannot be resolved in this paper.

So, with all the above caveats, what can be made of the small samples of very altered Late Cretaceous to Eocene intermediate to siliceous volcanic rocks dredged from around the New Caledonia Basin? Taken at face value, the negative Nb and Ta anomalies of the lavas from around the edge of the New Caledonia Basin could be interpreted as having been acquired as a result of Late Cretaceous to Eocene subduction under northern Zealandia (e.g. Schellart *et al.* 2006; Nicholson & Black 2004, Nicholson *et al*. 2010). This is supported by the high initial εNd of the Lansdowne, Nereus and Le Noroit lavas indicating melting of depleted mantle (arguably mantle wedge), and by relatively high Th/Yb at a given Nb/Yb, Pb and large ion lithophile element concentrations (Figs. 3d, 5). Comparing the iron enrichment and $SiO_2$ vs Zr trends of subduction and intraplate suites from the SW Pacific and selected parts of the world (Fig. 3b, c), we find that, on balance, all continental intraplate igneous suites (even subalkaline ones) tend to have higher FeOT/MgO and Zr than subduction related suites at the same $SiO_2$ content, even though the best fit lines conceal a huge amount of intra-suite and intra-region variation. The Lansdowne, Nereus, AUSFAIR3, AUSFAIR5 and IPOD lavas mainly plot along low FeOT/MgO and Zr trends (Fig 3b). They also plot well off the mantle array and in the field of continental and oceanic arcs on a Nb/Yb vs Th/Yb diagram (Fig. 3d). However a subduction interpretation for each individual seafloor site is made less certain by various factors: samples from every site are few (1-3 per dredge) and thus show limited compositional range; the lack of primitive basalts adds complications to geochemical interpretation, the two Le Noroit samples are extremely small, the Lansdowne and Nereus lava samples are extremely small and altered. There is also a general absence of independent supporting evidence such as identifiable volcanic chains, accretionary wedges or paleotrenches. The samples lie 250-500 km from the eastern edge of Zealandia so, if they do represent a continental arc, the arc-trench gap is quite wide.

An alternative view (and our preferred view) is that the lavas are not subduction-related but are of continental rift (i.e. intraplate) origin. In this scenario they would have acquired their Nb and Ta anomalies via melting of, or interaction with, existing continental crust or from a relict Gondwana slab. The high Zr of the AUSFAIR3 and Le Noroit lavas and high FeOT/MgO of the AUSFAIR5 lava (Figs. 3b, c) suggests they likely to be intracontinental, non-orogenic lavas. The AUSFAIR3 lavas also overlap the field of intraplate A-type granites from Antarctica (Fig. 3d). Taken at face value, the chemistry of the Nereus and Lansdowne would seem to be the most consistent with a subduction-related setting. But these rocks are hydrothermally altered, and yield only minimum Ar-Ar ages. They could be samples of pre-Late Cretaceous (e.g. Darran Suite, Mortimer et al. 2014a) magmatism along the Gondwana margin.

The c. 42 Ma dacite dredged by the IPOD cruise from offshore Koumac is especially challenging to interpret. The glass age is speculative and may be affected by either excess argon or argon loss. The trace element (including rare-earth element) concentrations are puzzlingly basalt-like, not dacite-like. The lack of a prominent Eu anomaly suggests little fractionation so possibly the dacite is an anatectic melt of mafic crust (if so, the low Sr/Y indicates a garnet-free source). Taken at face value the low Nb/Yb, Nb, Y+Nb and Zr contents (Figs 3c, 3d, 4c) do indicate a subduction-related origin although some continental rift granites can have the relatively low Y+Nb content of P84022 (Förster *et al*. 1997). The fresh glassy dacite does not have any known onshore correlatives (basalts in the Late Eocene Pandope flysch of the Poya Terrane nappe are metamorphosed). Cluzel *et al*. (2005) reported dates of 27 and 24 Ma from two rare granitoid stocks in onland New Caledonia that also showed multi-element normalised patterns with negative Nb and Ta anomalies.

*Distribution and causes of Zealandia intraplate magmatism*

*Diffuse Alkaline Magmatic Province*. Finn *et al*. (2005) outlined the extent of a Cenozoic Diffuse Alkaline Magmatic Province (DAMP) in the eastern Australian plate and in Antarctica, now dispersed over an area of c. 40 $Mkm^2$. Our new data in the context of a Zealandia continent

(Mortimer *et al*. 2017) support the overall concept but, at the same time, require some modification to the DAMP as defined and explained by Finn *et al.* (2005).

First, it should be emphasised that widespread intraplate magmatism commenced across Zealandia in the Late Cretaceous (at c. 101 Ma; Tulloch *et al.* 2009) and is not just a Cenozoic phenomenon (Fig. 9). Second, the better definition of continent-ocean boundaries in the SW Pacific region (Mortimer *et al.* 2017), gives a whole new perspective and clarity to the magmatism. DAMP activity is mainly restricted to areas of continental crust, not the intervening oceanic crust. As such, the DAMP is better described as low-volume magmatism mainly scattered across a c. 12 $Mkm^2$ area of formerly contiguous Australia, Zealandia and Antarctica continental crust.

Both age-progressive and non-age progressive magmatism were lumped into the SW Pacific DAMP by Finn *et al*. (2005). From our analysis we agree that the age, geochemical and isotopic ranges of the Lord Howe and Tasmantid seamount chains fall within those of other Zealandia intraplate magmatism, yet only the seamount chains show an age progression. Finally, although alkaline suites do indeed dominate sampled rocks (the “A” in DAMP), rocks of subalkaline and ultra-alkaline composition are also widespread across Zealandia (Fig. 8; Timm *et al*. 2010).

The challenge for petrogenetic models is to explain the close juxtaposition in space and time between lavas of very different major element, trace element and isotopic composition. Tulloch *et al*. (2009) observed a general pattern of early Late Cretaceous Zealandia rhyolites and granites being of I-type character, and late Late Cretaceous rhyolites and granites being of more A-type character. They attributed this change to progressively thinning crust allowing mantle-derived magmas to reach the surface. Although it is a generalisation, we see a similar change in Fig. 8 with subalkaline lavas tending to be more abundant in the Cretaceous, and alkaline and ultra-alkaline lavas in the Cenozoic.

Finn *et al.* (2005) suggested that long-lived Paleozoic-Mesozoic subduction would likely lead to enrichment of Nb and Ta in the sub-continental lithospheric mantle whereas conventional wisdom indicates that the opposite happens, with these elements being retained in rutile or aluminous clinopyroxene, subducted to greater depths and lost from the sub-continental lithospheric mantle (e.g. Baier *et al*. 2008). Models of Zealandia intraplate magmatism petrogenesis (e.g. Weaver & Smith 1989; Finn *et al*. 2005; Panter *et al*. 2006; Hoernle *et al*. 2006; Sprung *et al.* 2007 and Timm *et al*. 2010) are all variations of the edge-driven convection model of King & Anderson (1998). An important observation we can add to this debate is that the features (spatial distribution, age, compositional range) of the non-age progressive igneous rocks are broadly similar in northern and southern Zealandia (Fig. 9). This is despite the two halves of the continent having had very different histories. Since the Late Cretaceous, southern Zealandia has been locked in a passive margin relationship to the Hikurangi Plateau and Pacific Plate. In contrast, the greater bathymetric relief of northern Zealandia suggests more variation in lithospheric thickness. As the crustal and lithospheric structure of Zealandia becomes better known (Mortimer *et al.* 2017), and more volcanoes are sampled and dated, it may be possible more accurately to identify steps in lithospheric thickness and find some spatial control to the intraplate magmatism (cf. Davies *et al*. 2015).

*Siliceous Large Igneous Province.* As well as the DAMP, another concept that has been introduced to Australasian Mesozoic geology is that of a SLIP (Silicic Large Igneous Province), arising largely from studies of the Cretaceous Whitsunday volcanics in Australia (Bryan 2007; Bryan *et al.* 2012). Bryan (2007, fig. 1) included the Lord Howe Rise in the Whitsunday SLIP, mainly on the basis of rhyolite in DSDP 207 but also on the inferred extent of Cretaceous volcaniclastic rift basins on the Lord Howe Rise. Subsequent seismic and petrological work (Collot *et al.* 2009; Bache *et al.* 2014b; this study) has identified more basins and more silicic igneous rocks in northern Zealandia. While these might seem to support the expansion of a SLIP from mainland Australia onto the Lord Howe Rise, there are a few things to consider: (1) many of the northern Zealandia silicic volcanics ages are younger than the 95 Ma Whitsunday cut-off proposed by Bryan (2007); (2) some of the rocks may possibly be subduction-related, not intraplate (e.g. Nereus, Lansdowne, see above), (3) the rocks may not occur in sufficient volume to define a large igneous province, and (4) Late Cretaceous silicic igneous rocks are not restricted to northern Zealandia but occur in southern Zealandia as well, so is all of Zealandia part of a Late Cretaceous SLIP?

In terms of exploring a causal relationship between SLIP magmatism and continental breakup, it should also be noted that, at the latitude of the Whitsunday Islands (currently 26-20°S in coastal Australia), seafloor spreading (Zealandia-Gondwana separation) did not actually start until c. 62 Ma, rather than the oft-quoted c. 85 Ma for Zealandia-Gondwana separation to the south (Gaina *et al.* 1999). Thus the hiatus between the end of SLIP magmatism and spreading is c. 23 m.y. rather than c. 10 m.y.

*Space-time-composition patterns.* Numerous studies such as those of Cole (1986), Weaver & Smith (1989), Finn *et al.* (2005) and Timm *et al*. (2010), have searched without success for space-time-composition patterns in subsets of Zealandia intraplate lavas - the Horomaka

Supersuite of Mortimer *et al*. (2014a). We have compiled all known occurrences of lavas in Fig. 8 and show them on schematic palinspastic reconstructions appropriate for their age. Once again, no obvious age trends emerge but some subtle patterns are present e.g. the aforementioned slightly greater abundance of subalkaline lavas in the early Late Cretaceous and ultra-alkaline lavas in the Cenozoic.

Although we have not attempted to calculate volumes or fluxes, it is apparent from Figs. 8 and 9 that lavas of Late Cretaceous and Oligocene-Neogene age are more common than those of Eocene age. The Late Cretaceous pulse can be understood as magmatism associated with syn-rift deformation prior to, during and immediately after Zealandia breakup from Gondwana. The Oligocene to Neogene pulse of intraplate magmatism is more difficult to explain as it does not coincide with any major plate motion change. To the south of Zealandia, the Emerald Basin opened from c. 45 Ma and this is also when a subduction phase initiated off northern Zealandia (Sutherland *et al*. 2010), propagating south to form a volcanic arc in New Zealand by c. 23 Ma (Cole 1986; Figs. 8b,c). However, the timing as presented is in conflict with the concept of plate motion changes that have been direct driving forces for increased mantle lithosphere melting within Zealandia. It is simply possible that the younger rocks are more easily sampled, by virtue of their higher stratigraphic positions. By the same token, the Late Cretaceous syn-rift magmatism in Zealandia may be far more common, and is therefore underrepresented in Figs. 8a and 9. Magnetic anomalies on the Campbell Plateau and either side of the Aotea Basin (Sutherland 1999, fig. 3) may represent such Late Cretaceous magmatism.

## Conclusions

New sampling, dating, and geochemical and isotopic analysis of small and altered volcanic rock samples from the submerged northern Zealandia continent, combined with earlier work, reveal three volcanotectonic regimes (Figs. 8, 9):

(1) *age-progressive, Oligocene-Pliocene, alkaline volcanism of the Lord Howe Seamount Chain*. Inception of the Lord Howe Seamount Chain as a linear feature began at c. 28 Ma. Prior to that the position of the Lord Howe plume was coincident with the South Rennell Trough, a backarc spreading centre which was active from c. 45-28 Ma. The Lord Howe Seamount Chain is partly coeval with the nearby Tasmantids seamount chain. Although basalts from each chain are derived from melting of different sorts of geochemical and isotopic mantle, positions of both plumes are approximately fixed in the mantle and are well-predicted from plate kinematic

modelling. Age-progressive, hotspot-type volcanism is not known from anywhere else in Zealandia.

(2) *Late Cretaceous-Paleogene, generally subalkaline intermediate to silicic volcanism on and near ridges and rises around the New Caledonia Basin*. Our new samples are of >78 Ma to c. 42 Ma age but similar silicic suites elsewhere in northern Zealandia are as old as 101 Ma. The samples support a continental crust basement for the New Caledonia Basin and Fairway Ridge. The tectonic setting of eruption of most of these lavas, based on geochemistry, is intraplate continental. The very highly-altered Nereus and Lansdowne lavas may have a subduction-related chemistry, but their stratigraphic age is older than their Late Cretaceous hydrothermal overprint. There is no unambiguous volcanic evidence in our dataset for Late Cretaceous to Paleocene subduction beneath northern Zealandia. The c. 42 Ma IPOD4 dacite seems to have the clearest subduction related geochemistry but the correct interpretation of negative Nb and Ta anomalies in ancient lavas is a longstanding problem that we cannot resolve.

(3) *alkaline, ultra-alkaline and subalkaline volcanism, scattered across both northern and southern Zealandia with no clear spatial or compositional pattern*. Our new northern Zealandia samples are of 30-18 Ma age and reinforce a late Cenozoic pulse in what is otherwise low-volume and long-lived (c. 97 - 0 Ma) intraplate volcanism. Unlike the Lord Howe Seamount Chain lavas, this volcanism is unrelated to any mantle plume. The dispersed magmatism mostly coincides with areas of continental crust within Zealandia, not the surrounding oceanic crust.

To date, most of our knowledge of intraplate volcanism on Zealandia has come from the southern part of the continent. The sampling and analysis of offshore northern Zealandia volcanic rocks described in this paper provides a more complete picture of syn-and post-Gondwana breakup magmatism on the entire Zealandia continent.

## Acknowledgements

We thank the captains and crews of N/O *Le Noroit*, N/O *Marion Dufresne*, R/V *Southern Surveyor*, N/O *l'Alis* and R/V *Tangaroa* without whom the samples described in this paper would not have been obtained. Neville Orr, Ben Durrant, John Simes, Belinda Smith Lyttle, Craig Fraser, Charles Knaack and Diane Johnson provided technical assistance. Information, discussions and/or encouragement from Rick Herzer, Greg Browne, Mark Lawrence, Robert Crookbain, Andy Tulloch and Volkmar Damm are acknowledged. Comments by Ron Hackney, Takehiko Hashimoto and three anonymous reviewers helped improve earlier versions of the manuscript. The analytical work was supported by core funding to GNS Science from the New Zealand Ministry for Business, Employment and Innovation.

## REFERENCES


ADAMS, C. J, CLUZEL, D. & GRIFFIN, W. L. 2009. Detrital-zircon ages and geochemistry of sedimentary rocks in basement Mesozoic terranes and their cover rocks in New Caledonia, and provenances at the Eastern Gondwanaland margin. *Australian Journal of Earth Sciences*, **56**, 1023–1047.

BACHE, F., SUTHERLAND, R., MORTIMER, N., BROWNE, G. H., LAWRENCE, M. J. F., BLACK, J., FLOWERS, M., ROUILLARD, P., PALLENTIN, A., WOELZ, S., WILCOX, S., HINES, B., JURY, S. & ROOP, H. 2014a. Tangaroa TAN1312 voyage report: Dredging Reinga and Aotea basins to constrain seismic Stratigraphy and Petroleum systems (DRASP), NW New Zealand. GNS Science Report 2014/05, 136pp.

BACHE, F., MORTIMER, N., SUTHERLAND, R., COLLOT, J., ROUILLARD, P., STAGPOOLE, V. & NICOL, A. 2014b. Seismic stratigraphic record of transition from Mesozoic subduction to continental breakup in the Zealandia sector of eastern Gondwana. *Gondwana Research*, **26**, 1060–1078.

BAKER, J., GAMBLE, J. A. & GRAHAM, I.J. 1994. The age, geology, and geochemistry of the Tapuaenuku Igneous Complex, Marlborough, New Zealand. *New Zealand Journal of Geology and Geophysics*, **37**, 249–268.

BAIER, J., AUDETAT, A. & KEPPLER, H. 2008. The origin of the negative niobium tantalum anomaly in subduction zone magmas. *Earth & Planetary Science Letters*, **267**, 290-300.

BAUBRON, J. C., GUILLON, J. H. & RÉCY, J. 1976. Géochronologie par la méthode K/Ar du substrat volcanique de l'île de Maré, archipel des Loyauté (Sud-Ouest Pacifique). *Bulletin BRGM*, **3 série 2**, 165–176.

BEIER, C., VANDERKLUYSEN, L., REGELOUS, M., MAHONEY, J. J. & GARBE-SCHÖNBERG, D. 2011. Lithospheric control on geochemical composition along the Louisville Seamount Chain. *Geochemistry, Geophysics, Geosystems*, **12**, Q0AM01, doi:10.1029/2011GC003690.

BENTZ, F. P. 1974. Marine geology of the southern Lord Howe Rise, southwest Pacific. In: Burk, C. A.; Drake, C. L. ed. The geology of continental margins. New York, Springer-Verlag. Pp. 537–547.

Brodie, J. W. 1965. Aotea Seamount, Eastern Tasman Sea. *New Zealand Journal of Geology and Geophysics*, **8**, 510–517.

Browne, G. H., Lawrence, M. J. F., Mortimer, N., Clowes, C. D., Morgans, H. E. G., Hollis, C. J., Beu, A. G., Black, J. A., Sutherland, R. & Bache, F. 2016. Stratigraphy of Reinga and Aotea basins, NW New Zealand: constraints on regional correlations and reservoir character from dredge samples. *New Zealand Journal of Geology & Geophysics*, **59**, accepted.

Bryan, S. E. 2007. Silicic Large Igneous Provinces. *Episodes*, **30**, 20–31.

Bryan, S. E., Cook, A., Allen, C. M., Siegel, C., Purdy, D., Greentree, J. & Uysal, T. 2012. Early-mid Cretaceous tectonic evolution of eastern Gondwana: from silicic LIP magmatism to continental rupture. *Episodes*, **35**, 142–152.

Cluzel, D., Bosch, D., Paquette, J.-L., Lemennicier, Y., Montjoie, P. & Menot, R.-P. 2005. Late Oligocene post-obduction granitoids of New Caledonia: a case for reactivated subduction and slab break-off. *Island Arc*, **14**, 254–271.

Cole, J. W. 1986. Distribution and tectonic setting of late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand Bulletin*, **23**, 7–20.

Collot, J., Geli, L., Lafoy, Y., Vially, R., Cluzel, D., Klingelhoefer, F. & Nouzé, H. 2008. Tectonic history of northern New Caledonia Basin from deep offshore seismic reflection: relation to late Eocene obduction in New Caledonia, southwest Pacific. *Tectonics*, **27**, TC6006, doi:10.1029/2008TC002263.

Collot, J., Herzer, R. H., Lafoy, Y. & Geli, L. 2009. Mesozoic history of the Fairway-Aotea Basin: implications for the early stages of Gondwana fragmentation, *Geochemistry, Geophysics, Geosystems*, **10**, Q12019, doi:10.1029/2009GC002612

Collot, J., Rouillard, P., Juan, C., Patriat, M., Lenault, Y., Privat, A. & Maurizot, P. 2013. Rapport de mission de la campagne océanographique IPOD (Investigating Post Obduction Deposits) a bord du N/O Alis du 1er au 18 Aout 2012. Rapport Service Géologique de Nouvelle Calédonie 2013(01), 140p. http://dx.doi.org/10.17600/12100080

Colwell, J., Foucher, J.-P., Logan, G. & Balut, Y. 2006. Partie 2, Programme AUSFAIR (Australia–Fairway basin bathymetry and sampling survey) Cruise Report. Les rapports de campagnes a la mer, MD 153/AUSFAIR–ZoNéCo 12 and VT 82/GAB on board R/V Marion Dufresne. Institut Polaire Français Paul Emile Victor, Plouzané, France, OCE/2006/05.

Cook, C., 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*, **46**, 473–503.

Coombs, D. S., Adams, C. J., Roser, B. P. & Reay, A. 2008. Geochronology and geochemistry of the Dunedin Volcanic Group, eastern Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*, **51**, 195–218.

Dadd, K. A., Locmelis, M., Higgins, K. & Hashimoto, T. 2011. Cenozoic volcanism of the Capel-Faust Basins, Lord Howe Rise, SW Pacific Ocean. *Deep-Sea Research II*, **58**, 922–932.

Daniel, J., Jouannic, C., Larue, B. & Recy, J. 1977. Interpretation of D'Entrecasteaux Zone (north of New Caledonia). International Symposium on Geodynamics in the Southwest Pacific, Nouméa 1976. Editions Technip, Paris, pp. 117–124.

Davies, D. R., Rawlinson, N., Iaffaldano, G. & Campbell, I. H. 2015. Lithospheric controls on magma composition along Earth's longest continental hotspot track. *Nature*, **525**, 511–514.

Eggins, S. M., Green, D. H. & Falloon, T. H. 1991. The Tasmantid Seamounts: shallow melting and contamination on an EM1 mantle plume. *Earth and Planetary Science Letters*, **107**, 448–462.

Exon, N. F., Quilty, P. J., Lafoy, Y. and Auzende, J.-M. 2004. Miocene volcanic seamounts on northern Lord Howe Rise: lithology, age, ferromanganese crusts, and origin. *Australian Journal of Earth Sciences*, **51**, 291–300.

Exon, N. F., Hill, P. J., Lafoy, Y., Heine, C. & Bernardel, G. 2006. Kenn Plateau off northeast Australia: a continental fragment in the southwest Pacific jigsaw. *Australian Journal of Earth Sciences*, **53**, 541–564.

Exon, N. F., Lafoy, Y., Hill, P. J., Dickens, G. R. & Pecher, I. 2007. Geology and petroleum potential of the Fairway Basin in the Tasman Sea. *Australian Journal of Earth Sciences*, **54**, 629–645.

Finn, C. A., Muller, R. D. & Panter, K. S. 2005. A Cenozoic diffuse alkaline magmatic province (DAMP) in the southwest Pacific without rift or plume origin. *Geochemistry, Geophysics, Geosystems*, **6**, Q02005, doi:10.1029/2004GC000723.

Förster, H.-J., Tischendorf, G. & Trumbull, R. B. 1997. An evaluation of the Rb vs. (Y+Nb) discrimination diagram to infer tectonic setting of siliceous igneous rocks. *Lithos*, **40**, 261–293.

Gaina, C., Muller, R. D., Royer, J.-Y. & Symonds, P. 1999. Evolution of the Louisiade triple junction. *Journal of Geophysical Research*, **104**, 12927–12939.

Gamble, J. A., Morris, P. A. & Adams, C. J. 1986. The geology, petrology and geochemistry of Cenozoic volcanic rocks from the Campbell Plateau and Chatham Rise. Royal Society of New Zealand Bulletin, **23**, 344–365.

Green, T. H. 1973. Petrology and geochemistry of basalts from Norfolk Island. *Journal of the Geological Society of Australia*, **20**, 259–272.

Heap, A. D., Hughes, M., Anderson, T., Nichol, S., Hashimoto, T., Daniell, J., Przeslawski, R., Payne, D., Radke, L., and Shipboard Party 2009. Seabed environments and subsurface geology of the Capel and Faust basins and Gifford Guyot, Eastern Australia – post survey report. Geoscience Australia Record, **2009/22**.

Herzer, R. H., Challis, G. A., Christie, R. H. K., Scott, G. H. & Watters, W.A. 1989. The Urry Knolls, late Neogene alkaline basalt extrusives, southwestern Chatham Rise. *Journal of the Royal Society of New Zealand*, **19**, 181–193.

Higgins, K., Hashimoto, T., Fraser, G., Rollet, N. & Colwell, J. 2011. Ion microprobe (SHRIMP) U-Pb dating of Upper Cretaceous volcanics from the northern Lord Howe Rise, Tasman Sea. *Australian Journal of Earth Sciences*, **58**, 195–207.

Hinz, K. 1979. Report of the *Sonne* southeast Asia cruise 1978: cruise SO-7 – 16.10.1978 – 22.12.1978. *BGR Report*, 6300/79.

Hoernle, K., White, J. D. L., van den Bogaard P., Hauff, F., Coombs, D. S., Werner, R., Timm, C., Garbe-Schönberg, D., Reay, A. & Cooper, A. F. 2006. Cenozoic intraplate volcanism on New Zealand: upwelling induced by lithospheric removal. *Earth and Planetary Science Letters*, **248**, 350–367.

Jellinek, A. M., Gonnermann, H. M. & Richards, M. A. 2003. Plume capture by divergent plate motions: implications for the distribution of hotspots, geochemistry of mid-ocean ridge basalts, and estimates of the heat flux at the core–mantle boundary. *Earth & Planetary Science Letters*, **205**, 361–378.

Johnson, R. W., Knutson, J. & Taylor, S. R. 1989. Intraplate volcanism in eastern Australia and New Zealand. Melbourne, Australian Academy of Sciences.

Kalnins, L. M., Cohen, B. E., Fitton, J. G., Mark, D. F., Richards, F. D. & Barfod, D. N. 2015. The East Australian, Tasmantid, and Lord Howe Volcanic Chains: possible mechanisms behind a trio of hotspot trails. American Geophysical Union, Fall Meeting 2015, abstract #DI41A-2591.

KING, S. D. & ANDERSON, D. L. 1998. Edge-driven convection. *Earth & Planetary Science Letters*, **160**, 289–296.

KLINGELHOEFER, F., LAFOY, Y., COLLOT, J., COSQUER, E., GÉLI, L., NOUZÉ, H. & VIALLY, R. 2007. Crustal structure of the basin and ridge system west of New Caledonia (southwest Pacific) from wide-angle and reflection seismic data. *Journal of Geophysical Research*, **112,** B11102, doi:10.1029/2007JB005093.

KNESEL, K. M., COHEN, B. E., VASCONCELOS, P. M. & THIEDE, D. S. 2008. Rapid change in drift of the Australian plate records collision with Ontong Java plateau. Nature, 454, 754–757.

LAFOY, Y., BRODIEN, I., VIALLY, R & EXON, N. F. 2005. Structure of the basin and ridge system west of New Caledonia (Southwest Pacific): a synthesis. *Marine Geophysical Researches*, **26**, 37–50.

LAUNAY, J., DUPONT, J., LAPOUILLE, A., RAVENNE, C. & DE BROIN, C. E. 1977. Seismic traverses across the northern Lord Howe Rise and comparison with the southern part (south-west Pacific). In: International Symposium on Geodynamics in South-West Pacific, Noumea, 27 August–2 September 1976. Paris, Editions Technip. Pp. 155–164.

LE MAITRE, R.W. 1989. A classification of igneous rocks and glossary of terms. Oxford, Blackwell Scientific Publications.

LETERRIER, J., MAURY, R. C., THONON, P., GIRARD, D. & MARCHAL, M. 1982. Clinopyroxene composition as a method of identification of the magmatic affinities of paleo-volcanic series. *Earth & Planetary Science Letters*, **59**, 139–2154.

LUYENDYK, B. P. 1995. Hypothesis for Cretaceous rifting of east Gondwana caused by subducted slab capture. *Geology*, **23**, 373–376.

MATTHEWS, K. J., WILLIAMS, S. E., WHITTAKER, J. M., MÜLLER, R. D., SETON, M., CLARKE, G. L. 2015. Geologic and kinematic constraints on Late Cretaceous to mid Eocene plate boundaries in the southwest Pacific. *Earth-Science Reviews*, **140**, 72–107.

MCCOY-WEST, A. J., BAKER, J. A., FAURE, K. & WYSOCZANSKI, R. 2010. Petrogenesis and origins of mid-Cretaceous continental intraplate volcanism in Marlborough, New Zealand: implications for the long-lived HIMU magmatic mega-province of the SW Pacific. *Journal of Petrology*, **51**, 2003–22045.

MCDOUGALL, I., EMBLETON, B. J. J. & STONE, D. B. 1981. Origin and evolution of Lord Howe Island. *Journal of the Geological Society of Australia*, **28**, 155–176.

MCDOUGALL, I. & DUNCAN, R. A. 1988. Age progressive volcanism in the Tasmantid Seamounts. *Earth & Planetary Science Letters* **89**, 207–220.

McMillan, N. J., Dickin, A. P. & Haag, D. 2000. Evolution of magma source regions in the Rio Grande rift, southern New Mexico. *Geological Society of America Bulletin*, **112**, 1582–1593.

Missegue, F. & Collot, J.-Y. 1987. Etude geophysique du Plateau des Chesterfields (Pacifique sud-ouest). Resultats preliminaires de la campagne Zoneco de N/O Coriolis. *Comptes Rendu Academie Sciences Paris*, **304 (7), Serie II**, 279–283.

Miyashiro, A. 1974. Volcanic rock series in island arcs an active continental margins. *American Journal of Science*, **274**, 321–355.

Monzier, M. & Vallot, J. 1983. Rapport preliminaire concernent les dragages realises lors de la campagne GEORSTOM III SUD (1975). Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), *Centre de Noumea Geologie- Geophysique Rapport*, **2-83**. 77 p.

Morgans, H. E. G. 2014. Foraminiferal biostratigraphy from New Caledonia IPOD dredge samples. *GNS Science Consultancy Report*, **2014/223**.

Morris, G. A., Lartson, P. B. & Hooper, P. R. 2000. 'Subduction style' magmatism in a non-subduction setting: the Colville Igneous Complex, NE Washington state, USA. *Journal of Petrology*, **41**, 43–67.

Morrison, M. A. 1978. The use of "immobile" trace elements to distinguish the palaeotectonic affinities of metabasalts: applications to the Paleocene basalts of Null and Skye, northwest Scotland. *Earth & Planetary Science Letters*, **39**, 407–416.

Mortimer, N. 2004. Basement gabbro from the Lord Howe Rise. *New Zealand Journal of Geology and Geophysics*, **47**, 501–507.

Mortimer, N., Herzer, R. H., Gans, P. B., Parkinson, D.L. & Seward, D. 1998. Basement geology from Three Kings Ridge to West Norfolk Ridge, southwest Pacific Ocean: evidence from petrology, geochemistry and isotopic dating of dredge samples. *Marine Geology*, **148**, 135–162.

Mortimer, N., Herzer, R. H., Gans, P. B., Laporte-Magoni, C., Calvert, A. & Bosch, D. 2007. Oligocene–Miocene tectonic evolution of the South Fiji Basin and Northland Plateau, SW Pacific Ocean: Evidence from petrology and dating of dredged rocks. *Marine Geology*, **237**, 1–24.

Mortimer, N., Hauff, F. & Calvert, A. C. 2008a. Continuation of the New England Orogen, Australia, beneath the Queensland Plateau and Lord Howe Rise. *Australian Journal of Earth Sciences*, **55**, 195–209.

Mortimer, N., Dunlap, W. J., Palin, J. M., Herzer, R. H., Hauff, F. & Clark, M. 2008b. Ultra-fast early Miocene exhumation of Cavalli Seamount, Northland Plateau, Southwest Pacific Ocean. *New Zealand Journal of Geology and Geophysics*, **51**, 29–42.

Mortimer, N., Gans, P. B., Palin, J. M., Meffre, S., Herzer, R. H. & Skinner, D. N. B. 2010. Location and migration of Miocene–Quaternary volcanic arcs in the SW Pacific region. *Journal of Volcanology and Geothermal Research*, **190**, 1–10.

Mortimer, N., Gans, P. B., Hauff, F. & Barker, D. H. N. 2012. Paleocene MORB and OIB from the Resolution Ridge, Tasman Sea. *Australian Journal of Earth Sciences,* **59**, 953–964.

Mortimer, N., Rattenbury, M. S., King, P. R., Bland, K. J., Barrell, D. J. A., Bache, F., Begg, J. G., Campbell, H. J., Cox, S. C., Crampton, J. S., Edbrooke, S. W., Forsyth, P. J., Johnston, M. R., Jongens, R., Lee, J., Leonard, G. S., Raine, J. I., Skinner, D. N. B., Timm, C., Townsend, D. B., Tulloch, A. J., Turnbull, I. M. & Turnbull, R.E. 2014a. High-level stratigraphic scheme for New Zealand rocks. *New Zealand Journal of Geology and Geophysics*, **57**, 402–419.

Mortimer, N., Gans, P. B., Palin, J. M., Herzer, R. H., Pelletier, B. & Monzier, M. 2014b. Eocene and Oligocene basins and ridges of the Coral Sea-New Caledonia region: Tectonic link between Melanesia, Fiji, and Zealandia. *Tectonics*, **33**, doi:10.1002/2014TC003598.

Mortimer, N., Patriat, M., Agranier, A., Bassoullet, C., Campbell, H., Durance, P., Amann, M., Etienne, S., Guérin, C., Jordan, N., Juan, C., Mengin, M., Pitel, M., Roussel, C. & Soetaert, F. 2015. The VESPA research cruise (Volcanic Evolution of South Pacific Arcs): a voyage of discovery to the Norfolk, Loyalty and Three Kings Ridges, northeast Zealandia. *Geoscience Society of New Zealand Miscellaneous Publication*, **143A**, 98–99.

Mortimer, N., Campbell, H. J., Tulloch, A. J., King, P. R., Stagpoole, V. M., Wood, R. A., Rattenbury, M. S., Sutherland, R., Adams, C. J., Collot, J. & Seton, M. 2017. Zealandia: Earth's hidden continent. *GSA Today,* **27**, doi: 10.1130/GSAT321A.1.

Nelson, C. S., Briggs, R. M. & Kamp, P. J. J. 1986. Nature and significance of volcanogenic deposits at the Eocene/Oligocene boundary, Hole 593, Challenger Plateau, Tasman Sea. *Initial Reports Deep Sea Drilling Project*, **90**, 1175–1187.

Nicholson, K. N. & Black, P. M. 2004. Cretaceous to early Tertiary basaltic volcanism in the Far North of New Zealand: geochemical associations and their tectonic significance. *New Zealand Journal of Geology and Geophysics*, **47**, 437–446.

Nicholson, K. N., Maurizot, P., Black, P. M., Picard, C., Simonetti, A., Stewart, A. & Alexander, A. 2011. Geochemistry and age of the Nouméa Basin lavas, New Caledonia: evidence for Cretaceous subduction beneath the eastern Gondwana margin. *Lithos*, **125**, 659–674.

Panter, K. S., Blusztajn, J., Hart, S.R., Kyle, P.R., Esser, R. & McIntosh, W. C. 2006. The origin of HIMU in the SW Pacific: evidence from intraplate volcanism in southern New Zealand and Subantarctic Islands. *Journal of Petrology*, **47**, 1673–1704.

Pearce, J. A. & Norry, M. J. 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contributions to Mineralogy and Petrology*, **69**, 33–47.

Pearce, J. A. & Peate, D. W. 1995. Tectonic implications of the composition of volcanic arc magmas. *Annual Review of Earth and Planetary Sciences*, **23**, 251–285.

Price, R. C., Mortimer, N., Smith, I. E. M. & Maas, R. 2015. Whole-rock geochemical reference data for Torlesse and Waipapa terranes, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, **58**, 213–228.

Quilty, P. G. 1993. Tasmantid and Lord Howe seamounts: biostratigraphy and palaeoceanographic significance. *Alcheringa*, **17**, 27–53.

Rigolot, P. 1988. Prolongement meridional des grandes structures geologiques de Nouvelle-Caledonie et decouverte de monts sous-marins interpretes comme un jalon dans un nouvel alignement de hot-spot. *Comptes Rendu Academie Sciences Paris*, **307, Serie II**, 965–972.

Sack, P. J., Berry, R. F., Meffre, S., Falloon, T. J., Gemmell, J. B. & Friedman, R. M. 2011. In situ location and U-Pb dating of small zircon grains in igneous rocks using laser ablation–inductively coupled plasma–quadrupole mass spectrometry. *Geochemistry, Geophysics, Geosystems*, **12**, doi 10.1029/2010GC003405

Schellart, W. P., Lister, G. S. & Toy, V. G. 2006. A Late Cretaceous and Cenozoic reconstruction of the Southwest Pacific region: tectonics controlled by subduction and slab rollback processes. *Earth-Science Reviews*, **76**, 191–233.

Scott, J. M., Turnbull, I. M., Sagar, M. W., Tulloch, A. J., Waight, T. E. & Palin, J. M. 2015. Geology and geochronology of the Sub-Antarctic Snares Islands/Tini Heke, New Zealand. *New Zealand Journal of Geology and Geophysics*, **58**, 202–212.

Seton, M., Williams, S., Mortimer, N., Meffre, S. & Micklethwaite, S. 2016a. Voyage report for SS2012V06 Eastern Coral Sea Tectonics (ECOSAT), R/V Southern Surveyor, October-November 2012. *GNS Science Report*, **2016-49**. Lower Hutt, New Zealand: GNS Science.

SETON, M., MORTIMER, N., WILLIAMS, S., QUILTY, P. G., GANS, P. B., MEFFRE, S., MICKLETHWAITE, S., ZAHIROVIC, S., MOORE, J. & MATTHEWS, K. J. 2016b. Melanesian back-arc basin and arc development: constraints from the eastern Coral Sea. *Gondwana Research*, **39,** 77–95.

SINTON, J., DETRICK, R., CANALES, J. P., ITO, G. & M. BEHN, M. 2003. Morphology and segmentation of the western Galápagos Spreading Center, 90.5°–98°W: plume-ridge interaction at an intermediate spreading ridge. *Geochemistry, Geophysics, Geosystems*, **4,** 8515, doi:10.1029/2003GC000609, 12.

SPRUNG, P., SCHUTH, S., MÜNKER, C. & HOKE, L. 2007. Intraplate volcanism in New Zealand: the role of fossil plume material and variable lithospheric properties. *Contributions to Mineralogy Petrology*, **153**, 669–687.

STEINBERGER, B., SUTHERLAND, R. & O'CONNELL, R. J. 2004. Prediction of Emperor-Hawaii seamount locations from a revised model of global plate motion and mantle flow. *Nature*, **430**, 167-173.

STEINER, A. & STRECK, M. J. 2014. The Strawberry Volcanics: generation of 'orogenic' andesites from tholeiite within an intra-continental volcanic suite centered on the Columbia River flood basalt province, USA. *Geological Society, London, Special Publication*, **385**, 281–302.

STOREY, B. C., HOLE, M.J., PANKHURST, R. J., MILLAR, I. L. & VENNUM, W. 1988. Middle Jurassic within-plate granites in West Antarctica and their bearing on the break-up of Gondwanaland. *Journal of the Geological Society, London*, **145**, 999–1007.

STRONG, D. T., TURNBULL, R. E., HAUBROCK, S. E. & MORTIMER, N. 2016. Petlab: New Zealand's national rock catalogue and geoanalytical database. *New Zealand Journal of Geology & Geophysics*, **59**, 475–481.

SUN, S.-S. & MCDONOUGH, W. F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, London, Special Publication*, **42**, 313–345.

SUTHERLAND, F. L., GRAHAM, I. T., MEFFRE, S., ZWINGMANN, H. & POGSON, R. E. 2012. Passive-margin prolonged volcanism, east Australian plate: outbursts, progressions, plate controls and suggested causes. *Australian Journal of Earth Sciences*, **59**, 983–1005.

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

SUTHERLAND, R., COLLOT, J., LAFOY, Y., LOGAN, G. A., HACKNEY, R., STAGPOOLE, V., URUSKI, C., HASHIMOTO, T., HIGGINS, K., HERZER, R. H., WOOD, R., MORTIMER, N. & ROLLET, N.

2010. Lithosphere delamination with foundering of lower crust and mantle caused permanent subsidence of New Caledonia Trough and transient uplift of Lord Howe Rise during Eocene and Oligocene initiation of Tonga–Kermadec subduction, western Pacific. *Tectonics*, **29**, TC2004, doi:10.1029/2009TC002476.

Tappenden, V. 2003. Magmatic response to the evolving New Zealand Margin of Gondwana during the Mid-Late Cretaceous. Unpublished Ph.D. thesis, University of Canterbury.

Till, C. B., Gans, P. B., Spera, F. J., MacMillan, I. & Blair, K. D. 2009. Perils of petrotectonic modeling: a view from southern Sonora, Mexico. *Journal of Volcanology and Geothermal Research*, **186,** 160–168.

Timm, C., Hoernle, K., Werner, R., Hauff, F., van den Bogaard, P., White, J. D L., Mortimer, N. & Garbe-Schönberg, D. 2010. Temporal and geochemical evolution of the Cenozoic intraplate volcanism of Zealandia. *Earth-Science Reviews*, **98**, 38–64.

Tulloch, A. J., Ramezani, J., Mortimer, N., Mortensen, J., van den Bogaard, P. & Maas, R. 2009, Cretaceous felsic volcanism in New Zealand and Lord Howe Rise (Zealandia) as a precursor to final Gondwana break-up. *Geological Society, London, Special Publication*, **321**, 89–118.

van der Meer Q. H. A., Scott, J. M., Waight, T. E., Sudo, M., Schersten, A., Cooper, A. F. & Spell, T. L. 2013. Magmatism during Gondwana break-up: new geochronological data from Westland, New Zealand. *New Zealand Journal of Geology and Geophysics*, **56**, 229-242.

van de Beuque, S., Auzende, J.-M., Lafoy, Y. & Missegue, F. 1998. Tectonique et volcanisme tertiaire sur la ride de Lord Howe (Sud-Ouest Pacifique). *Comptes Rendus de l'Académie des Sciences*, **Series IIA, 326**, 663–669.

Weaver, S. D. & Smith, I. E. M. 1989. New Zealand intraplate volcanism. p. 157–188 in Intraplate volcanism in eastern Australia and New Zealand. Edited by R. W. Johnson, J. Knutson & S. R. Taylor. Cambridge University Press.

Weaver, S. D., Adams, C. J., Pankhurst, R. J. & Gibson, I. L. 1992. Granites of Edward VII Peninsula, Marie Byrd Land: anorogenic magmatism related to Antarctic-New Zealand rifting. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **83**, 281–290.

Weis, D., Kieffer, B., Maerschalk, C., Barling, J., de Jong, J., Williams, G. A., Hanano, D., Pretorius, W., Mattielli, N., Scoates, J. S., Goolaerts, A., Friedman, R. M., and Mahoney, J. B. 2006. High-precision isotopic characterization of USGS reference materials by TIMS and MC-ICP-MS. *Geochemistry, Geophysics, Geosystems*, **7**, Q08006.

Wessel, P. & Kroenke, L. W. 2008. Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis. Journal of Geophysical Research, Solid Earth, 113, B06101, doi:10.1029/2007JB005499

Winchester, J. A. & Floyd, P. A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, **20**, 325–343.

## FIGURE & TABLE CAPTIONS

**Fig. 1.** Volcanic rock samples of northern Zealandia and the surrounding oceanic crust. Existing analysed samples from Cole (1986), Nelson *et al*. (1986), McDougall & Duncan (1988), Weaver & Smith (1989), Quilty (1993), Auzende *et al*. (2000), Stagg *et al*. (2002), Exon *et al*. (2004), Hoernle *et al.* (2006), Panter *et al.* (2006), Hoffman *et al.* (2008), Collot *et al*. (2009), Heap *et al.* (2009), Tulloch *et al.* (2009), Timm *et al*. (2010), Mortimer *et al*. (1998, 2007, 2008ab, 2014) and Scott *et al*. (2015). VMFZ=Vening Meinesz Fracture Zone, CFZ=Cook Fracture Zone.

**Fig. 2.** Ar-Ar degassing spectra of selected samples. Height of rectangles in this figure are $\pm 1\sigma$ but reported ages are $\pm 2\sigma$. Black rectangles are those used to interpret the age. For degassing spectra, isochron plots, K/Ca plots and raw data for all samples, see Supplementary Data File 1.

**Fig. 3.** Binary geochemistry plots of new analyses. **(a)** Whole rock anhydrous $SiO_2$ vs. anhydrous $Na_2O$+$K_2O$ from Le Maitre (1989). **(b)** Whole rock anhydrous $SiO_2$ vs FeOT/MgO, tholeiitic and calcalkaline dividing line from Miyashiro (1974). Lines are second order polynomial curve fits to various subduction-related and intraplate datasets from McMillan *et al.* (2000), Nicholson et al. (2010), Steiner & Streck (2014) and Petlab (http://pet.gns.cri.nz) and Georoc (http://georoc.mpch-mainz.gwdg.de/georoc/) databases. **(c)** Whole rock anhydrous $SiO_2$ vs Zr. Note that, on the basis of petrography and Sc content, four Lord Howe Seamount Chain basalts for which there are no $SiO_2$ analyses are plotted at $SiO_2$=50 wt% and four northern Fairway Ridge basaltic andesites are plotted at $SiO_2$=55 wt%. Lines are second order polynomial curve fits to various subduction-related and intraplate datasets from same sources as b. **(d)** Whole rock Nb/Yb vs Th/Yb after Pearce & Peate (1995). Reference Edward VII Peninsula and

Ferrar Antarctic intraplate granites from Storey *et al*. (1988) and Weaver *et al.* (1992). **(e)** Clinopyroxenes from andesite P81400, reference fields from Leterrier *et al*. (1982).

**Fig. 4.** Multi-element diagrams normalised to primitive mantle of Sun & McDonough (1989). All analyses have been double normalised to $Y_n$=10 for better comparison between variably differentiated samples. Cs, Rb, U, K, Pb, Sr and P have been omitted because substantial secondary alteration effects to their concentrations. **(a)** Lord Howe Seamount Chain lavas (this study, Mortimer *et al.* 2010, Dadd *et al*. 2011). **(b)** lavas from periphery of New Caledonia Basin (this study). **(c)** northern Zealandia scattered seamounts (this study). **(d)** seamount chain reference data from Eggins *et al.* (1991) and Beier *et al*. (2011). **(e)** continental tholeiite reference data from McMillan *et al.* (2000), Tappenden (2003), Steiner & Streck (2014). **(f)** Cenozoic southern Zealandia data from Timm *et. al*. (2010).

**Fig. 5.** Whole rock Nb/Y vs initial εNd of northern Zealandia lavas. Lord Howe Seamount Chain and New Caledonia Basin margins described in this paper. Back-arc basin basalts (BABBs) described in Mortimer *et al.* (2014b) and Seton *et al*. (2016b). Degree of alkalinity on x-axis after Winchester & Floyd (1977), Tasmantid Seamount field from Eggins *et al.* (1991), basement fields (that span range of initial εNd from 100-0 Ma) from Mortimer *et al.* (2008a) and Price *et al*. (2015).

**Fig. 6.** U-Pb Tera-Wasserburg plot of Le Noroit zircons.

**Fig. 7. (a)** Co-variation of latitude, age and mean Zr/Y of dated Lord Howe Seamount Chain and Tasmantid lavas (this study, McDougall *et al*. 1981, Eggins et al. 1991, Quilty 1993, Mortimer *et al*. 2010, Dadd *et al*. 2011). **(b)** Predicted Tasmantid and Lord Howe seamount trails based on the absolute motion of the Australian Plate, anchored at the oldest Lord Howe Island age. Modelled tracks were computed using two alternative absolute reference frames, one based on global moving hotspot predictions (Global MHS; Steinberger *et al*. 2004) and the other computed using a fixed hotspot assumption for the Pacific plate only (Pacific FHS; Wessel & Kroenke 2008). The plotted Lord Howe Seamount Chain trails neglect any relative motion across the South Rennell Trough. Because of the way they are derived, the computed lines do not resolve changes in absolute motion on time scales less than 10 m.y. Triangles show the locations of actual dated samples.

**Fig. 8.** Age and composition of volcanic rocks of Zealandia summarised on schematic paleogeographic reconstructions at **(a)** 60 Ma, **(b)** 30 Ma and **(c)** 0 Ma. Lavas erupted in the preceding 30-40 m.y. are shown in each panel. Data from sources listed in Fig. 1 caption plus Beier *et al*. (2011), Nicholson *et al.* (2011) and Mortimer *et al*. (2012). Ages rounded to nearest 1 m.y. Some closely-spaced onland occurrences have been combined and/or simplified for plotting at this generalised map scale. Northern Zealandia is fixed. SFB=South Fiji Basin, LB=Lau Basin.

**Fig. 9.** Summary of Late Cretaceous-Holocene magmatic chronology of northern and southern Zealandia. Northern Zealandia has three compositional groups of magmatic rocks, southern Zealandia just one. Rock compositions are generalised to represent the main types. Data from sources listed in Fig. 1 caption. TVZ=Taupo Volcanic Zone.

**Table 1**. Location data for samples described in this paper. Marine expedition acronyms, ships and cruise numbers are as follows: DRASP (Dredging Reinga and Aotea basins to constrain seismic Stratigraphy and Petroleum systems) R/V *Tangaroa* TAN1312 November 2013; AUSFAIR (AUStralia-FAIRway basin bathymetry and sampling survey) N/O *Marion Dufresne* MD153 February 2006; ECOSAT (Eastern COral SeA Tectonics) R/V *Southern Surveyor* SS2012v06 November 2012; IPOD (Investigation of Post-Obduction Deposits) R/V *l'Alis* August 2012; GEORSTOM III SUD N/O *Le Noroit* November 1975.

**Table 2.** Reported ages of rocks dated in this study. All quoted numerical age uncertainties in this table and in the text are $\pm 2\sigma$. High, medium and low quality of Ar-Ar samples is explained in Mortimer *et al.* (2014b).

**Table 3.** Whole rock geochemical data for this study. Major elements as wt% oxides, trace elements are ppm. WSU=Washington State University, SCA=Spectrachem Analytical, UTAS=University of Tasmania, OU=University of Otago. oliv=olivine, cpx=clinopyroxene, plag=plagioclase, hbl=hornblende, bi-biotite, pptic=porphyritic, zeol=zeolite, cc=calcite.

**Table 4.** Nd isotope data for samples selected from this study (first ten rows), and from Mortimer *et al.* (2010, 2014b) and Seton *et al.* (2016b) (last nine rows). Chondritic Uniform

Reservoir values used are $^{143}Nd/^{144}Nd = 0.512638$ (present day), $^{147}Sm/^{144}Nd = 0.1967$, $\lambda^{147}Sm = 6.54 \times 10^{-12}$/yr.

**Supplementary File 1.** Ar-Ar geochronology data

**Supplementary File 2.** Micropaleontology data

**Supplementary File 3.** LA-ICP-MS U-Pb zircon geochronology data

**Supplementary File 4.** LA-ICP-MS pyroxene compositional data

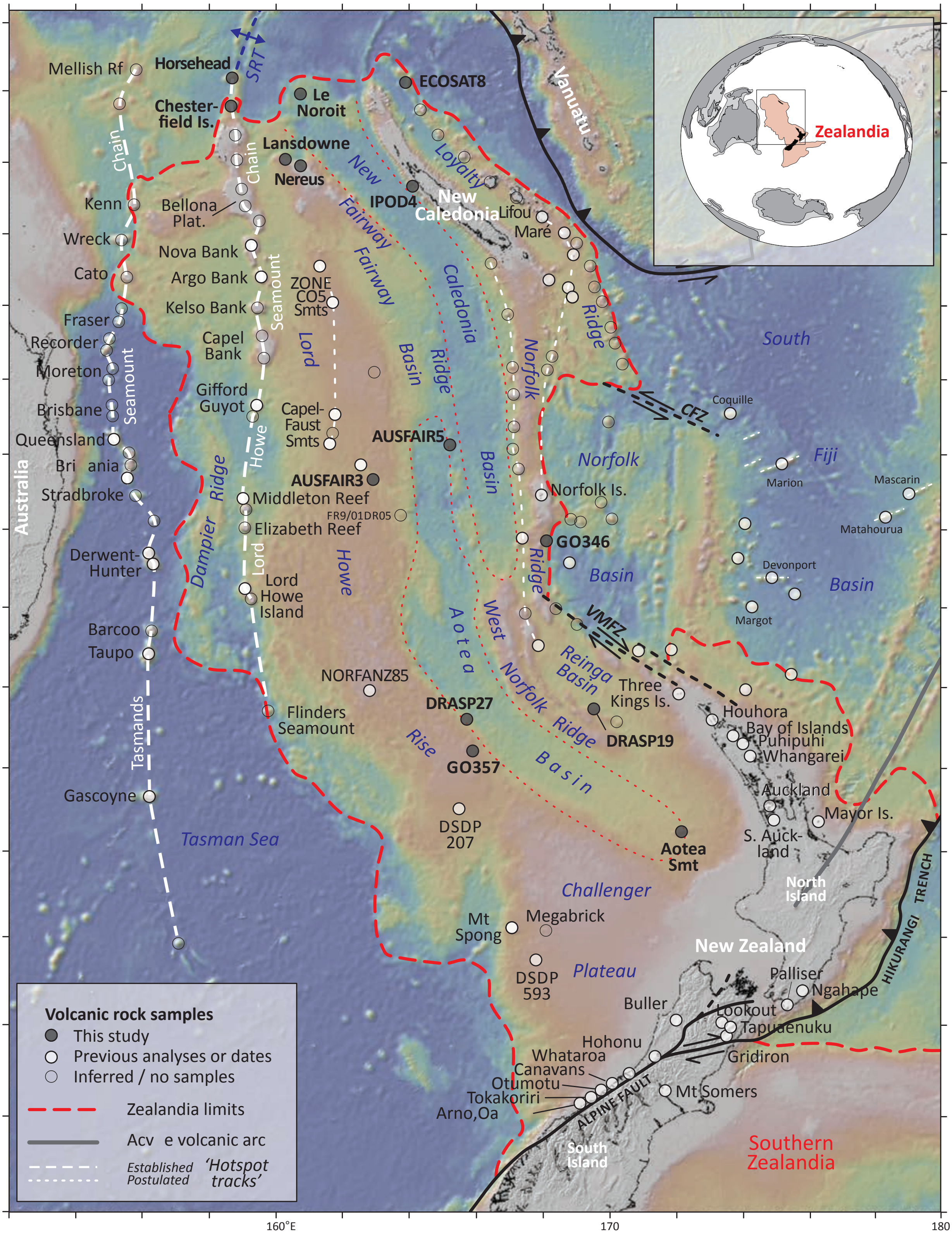
| Cruise and dredge | Lat (°S) | Long (°E) | Depth (m) | Site Description | Rocks recovered |
|---|---|---|---|---|---|
| ***Lord Howe Seamount Chain*** | | | | | |
| ECOSAT DR15 | 17.6918 | 158.4713 | 1850-2600 | Horse Head Seamount | Basalts, limestone |
| ECOSAT DR16 | 18.7083 | 158.3688 | 2500-2800 | Chesterfield Plateau, NW side | Basalts, limestone |
| ***New Caledonia Basin margins*** | | | | | |
| ECOSAT DR17 | 20.1399 | 160.7699 | 650-1200 | Lansdowne Bank, Fairway Ridge | Altered andesites |
| ECOSAT DR18 | 19.9178 | 160.1923 | 800-1500 | Nereus Reef, Fairway Ridge | Altered andesites |
| ECOSAT DR11 | 17.9856 | 160.7284 | 2250-2500 | Le Noroit Seamounts | Trachyte cores in Mn nodules |
| AUSFAIR DR03 | 28.4219 | 162.7899 | 1450-1700 | Fault scarp, Lord Howe Rise | Rhyolites |
| AUSFAIR DR05 | 27.7127 | 165.2894 | c. 2900 | Southern Fairway Ridge, east flank | Andesite breccia |
| IPOD DR4 | 20.6418 | 164.1222 | c. 710 | Offshore from Koumac, New Caledonia | Autobrecciated dacite, limestone |
| ***North Zealandia scattered seamounts*** | | | | | |
| GEORSTOM 357 D1 | 35.6585 | 165.9749 | 770-1250 | Seamount, SE Lord Howe Rise | Gabbro xenolith in alkali basalt |
| GEORSTOM 346 D1 | 30.4769 | 168.0898 | 1840-2300 | Seamount, E Norfolk Ridge | Vesicular ol-plag basalt |
| DRASP d02 | 37.5588 | 171.9598 | 1389-1570 | Aotea Seamount | Basanite |
| DRASP d19 | 34.5218 | 169.6479 | 1715-1777 | Seamount, Reinga Basin | Amygdaloidal basalt |
| DRASP d27B | 34.7359 | 165.6869 | 1981-2221 | Seamount, W side Aotea Basin | Basalts, mudstones |
| ECOSAT DR08 | 17.583 | 164.0078 | 1300-1500 | Seamount, Loyalty Ridge | Amygdaloidal basalt breccia |

| Cruise and dredge # | GNS # | Lab # | Dated material | Quality | Age ± 2σ (Ma) |
|---|---|---|---|---|---|
| ***Lord Howe Seamount Chain*** | | | | | |
| ECOSAT DR15A Horsehead | na | na | Forams | na | late E Miocene? |
| ECOSAT DR15B Horsehead | P82218Bi | SB66-25 | Ar-Ar plagioclase | Low | 48 ± 3? |
| ECOSAT DR15B Horsehead | P82218C | SB66-26 | Ar-Ar groundmass | Medium | 27.2 ± 0.5 |
| ECOSAT DR15C Horsehead | na | Q1135 | Forams | na | Pleistocene |
| ECOSAT DR16Ai Chesterfield | P82221 | SB66-28 | Ar-Ar groundmass | Medium | 28.1 ± 1.0 |
| ECOSAT DR16Aiv Chesterfield | P82224 | SB66-32 | Ar-Ar groundmass | Low | >23 |
| ***New Caledonia basin margins*** | | | | | |
| ECOSAT DR11Ei Le Noroit | na | na | U-Pb zircon | na | 63.8 ± 3.1 |
| ECOSAT DR11Ev Le Noroit | na | na | U-Pb zircon | na | 65.5 ± 4.2 |
| ECOSAT DR17A Lansdowne | na | na | Forams | na | E Miocene |
| ECOSAT DR17Aii Lansdowne | P82230 | SB66-3 | Ar-Ar groundmass | Low | >78 |
| ECOSAT DR17Aiii Lansdowne | P82231 | SB66-4 | Ar-Ar groundmass | Low | >81 |
| ECOSAT DR17Gi Lansdowne | na | na | Forams | na | L Olig- E Mio |
| ECOSAT DR18Bii Nereus | P82240 | SB66-5 | Ar-Ar groundmass | Low | >58 |
| ECOSAT DR18Ci Nereus | na | na | Forams | na | Early Miocene |
| AUSFAIR DR05-B1 Fairway Ridge | P81400 | SB65-7 | Ar-Ar hornblende | High | 74.1 ± 0.3 |
| IPOD DR4-VRAC2 New Caledonia | P84022 | SB67-65,66,67 | Ar-Ar gmass, plag | Low | 42 ± 5? |
| ***North Zealandia scattered seamounts*** | | | | | |
| ECOSAT DR08Ai Loyalty Ridge | P82194 | SB66-44 | Ar-Ar plagioclase | High | 24.6 ± 0.3 |
| GEORSTOM 357 D1 Lord Howe Rise | P57145 | SB63-5 | Ar-Ar plagioclase | High | 27.0 ± 0.3 |
| GEORSTOM 346 D1 Norfolk Ridge | P78644 | SB61-108 | Ar-Ar groundmass | High | 18.1 ± 0.2 |
| DRASP d19C Reinga Basin | P83198 | SB67-62 | Ar-Ar groundmass | Low | 25.5 ± 2.5 |
| DRASP d27C Aotea Basin | P83225 | SB67-29,60 | Ar-Ar gmass, plag | Medium | 27.7 ± 1.2 |
| DRASP d27C Aotea Basin | P83226 | SB67-31 | Ar-Ar groundmass | Medium | 29.5 ± 1.5 |

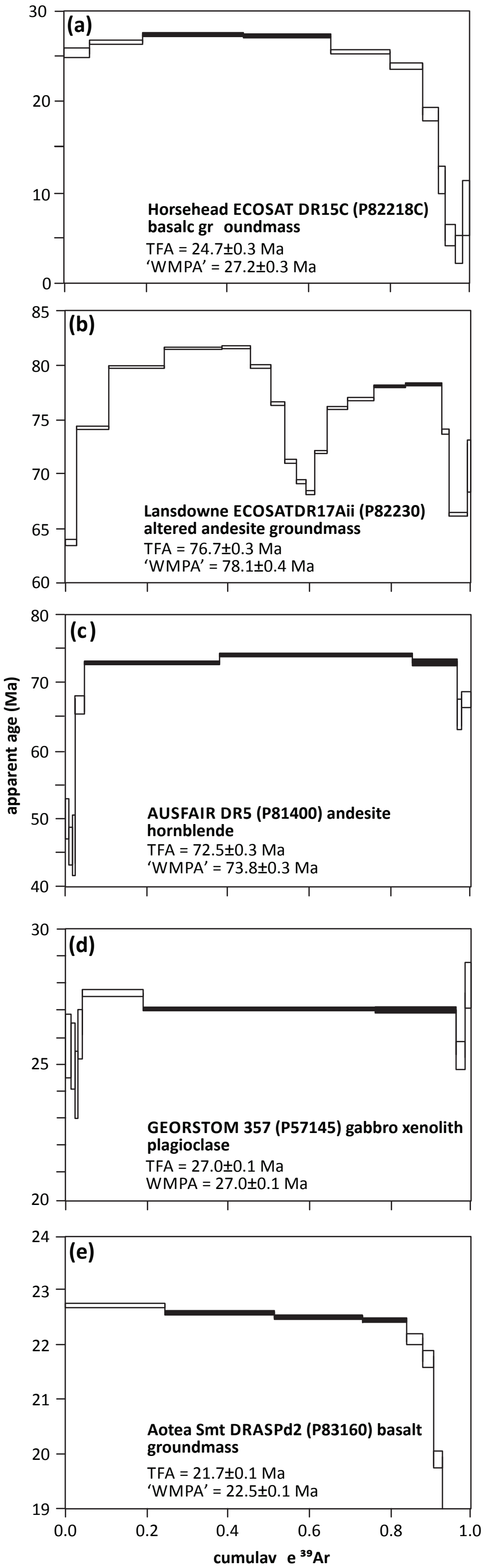
| Dredge | GNS # | Approx wt. | Rock Description | Laboratory | SiO2 | TiO2 | Al2O3 | Fe2O3T | MnO | MgO | CaO | Na2O | K2O | P2O5 | LOI | Total | As | Ba |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Lord Howe Seamount Chain*** | | | | | | | | | | | | | | | | | | |
| ECOSAT DR15Bi Horsehead | P82218A | 10 g | Cpx plag basalt clast in limestone | WSU | | | | | | | | | | | | | | 122 |
| ECOSAT DR15Bii Horsehead | P82218B | 10 g | Cpx plag basalt clast in limestone, dark reddish brown | WSU | | | | | | | | | | | | | | 149 |
| ECOSAT DR16Ai Chesterfield | P82221 | <5 g | Aphyric subtrachytic textured lava. Clay alteration | WSU | | | | | | | | | | | | | | 52 |
| ECOSAT DR16Aiv Chesterfield | P82224 | <5 g | Sparsely plag pptic lava. Dk brown clay alteration | WSU | | | | | | | | | | | | | | 60 |
| Lord Howe Island LH2 | GD6060 | 250 g | Doleritic plag-cpx basalt, zeol amygdaloidal | SCA, WSU | 48.39 | 2.78 | 15.23 | 11.25 | 0.14 | 5.67 | 8.55 | 3.63 | 1.47 | 0.51 | 2.16 | 99.78 | <1 | 343 |
| ***New Caledonia Basin margins*** | | | | | | | | | | | | | | | | | | |
| ECOSAT DR17Aiv Lansdowne | P82232 | <5 g | V strongly altered reddish volc sandstone, basaltic devitrified? | WSU | | | | | | | | | | | | | | 157 |
| ECOSAT DR17Av Lansdowne | P82233 | <5 g | Reddish plag-porphyritic andesite, strongly altered | WSU | | | | | | | | | | | | | | 183 |
| ECOSAT DR18Bi Nereus | P82239 | 800 g | Strong hydroth altered (zeol) red aphyric devitrified andesite | WSU | 50.35 | 0.56 | 17.9 | 6.83 | 0.14 | 5.24 | 4.01 | 5.46 | 1.76 | 0.46 | 7.11 | 99.81 | 13 | 15 |
| ECOSAT DR18Bii Nereus | P82240 | 50 g | Strong hydroth altered red plag-pptic devitrified andesite | WSU | | | | | | | | | | | | | | 1771 |
| ECOSAT DR18Di Nereus | P82246 | 20 g | Strong hydroth altered orange red plag-ol basalt | WSU | | | | | | | | | | | | | | 136 |
| ECOSAT DR11Ei Le Noroit | na | <5 g | Grey aphyric trachyte corestone to Mn nodule | UTAS | 58.78 | 0.77 | 16.38 | 6.66 | 0.03 | 0.59 | 4.48 | 4.7 | 5.97 | 1.64 | | 100 | 36 | 308 |
| ECOSAT DR11Ev Le Noroit | na | <5 g | Grey aphyric trachyte corestone to Mn nodule | UTAS | 58.66 | 0.96 | 17.57 | 6.83 | 0.03 | 0.46 | 3.17 | 4.58 | 6.92 | 0.82 | | 100 | 8 | 455 |
| AUSFAIR DR03-D1 Lord Howe Rise | P81396 | 300 g | Plag-hbl-bi lava, mafics altered | WSU | 72.17 | 0.28 | 14.13 | 2.2 | 0.07 | 0.58 | 0.68 | 2.9 | 5.29 | 0.1 | 1.56 | 99.96 | | 846 |
| AUSFAIR DR03-G1 Lord Howe Rise | P81397 | 250 g | Plag-altd mafic lava w qtz or zeol amygdules | WSU | 67.29 | 0.78 | 14.55 | 5.15 | 0.07 | 1.17 | 0.61 | 3.29 | 4.31 | 0.25 | 2.46 | 99.93 | | 913 |
| AUSFAIR DR05-B1 Fairway Ridge | P81400 | 100 g | Plag cpx hbl oliv andesite clast in volcanic breccia | WSU | 50.44 | 1.2 | 19.38 | 7.02 | 0.05 | 2.43 | 6.75 | 3.81 | 1.19 | 1.19 | 6.1 | 99.56 | | 244 |
| ***North Zealandia scattered seamounts*** | | | | | | | | | | | | | | | | | | |
| GEORSTOM 357 D1 Lord Howe Rise | P57145 | 50 g | Gabbro xenolith in alkali basalt | SCA, WSU | 34.78 | 1.99 | 10.04 | 10.55 | 0.14 | 10.47 | 16.97 | 2.61 | 1.41 | 0.93 | 9.3 | 99.19 | | 386.44 |
| GEORSTOM 346 D1 Norfolk Ridge | P78644 | 200 g | Vesicular ol-plag basalt | OU | 47.02 | 2.44 | 19.84 | 10.14 | 0.16 | 2.87 | 9.63 | 3.53 | 1.38 | 0.9 | 2.15 | 100.06 | | |
| DRASP d02C Aotea Seamount | P83160 | 500 g | Fresh ol+cpx lava. Minor clay alteration. | SCA | 39.87 | 3.77 | 11.69 | 15.39 | 0.18 | 8.65 | 12.2 | 4.26 | 1.44 | 1.27 | 1.04 | 99.75 | 5 | 432 |
| DRASP d19C Reinga Basin | P83198 | 500 g | Dark brownish grey olivine micro-phyric basalt. Cc amygdules | SCA | 45.06 | 2.07 | 13.49 | 13.8 | 0.16 | 8.76 | 10.32 | 2.79 | 0.95 | 0.63 | 1.33 | 99.36 | 2 | 281 |
| DRASP d27C Aotea Basin | P83226 | 2 kg | Sparsely cpx porphyritic, highly vesicular basalt. Clay altered | SCA | 42.95 | 2.11 | 15.95 | 12.61 | 0.26 | 3.12 | 11.19 | 3.75 | 1.28 | 2.7 | 2.96 | 98.88 | 51 | 346 |
| IPOD DR4-VRAC2 New Caledonia | P84022 | >100g | Sparsely plag-cpx porphyritic amygdaloidal dacite fresh glass | SCA, OU | 65.07 | 0.49 | 13.41 | 5.87 | 0.16 | 1.51 | 3.8 | 2.98 | 1.65 | 0.12 | 4.33 | 99.39 | 3 | 60 |
| ECOSAT DR08Ai Loyalty Ridge | P82194 | >100g | Ol-plag pptic basalt clast in breccia. Cc & zeol amygdules | WSU | 53.4 | 3.27 | 16.86 | 7.27 | 0.08 | 2.16 | 9.72 | 2.35 | 0.38 | 1.26 | 2.92 | 99.68 | 51 | 142 |

| Ce | Cr | Cs | Cu | Dy | Er | Eu | Ga | Gd | Hf | Ho | La | Lu | Nb | Nd | Ni | Pb | Pr | Rb | Sc | Sm | Sr | Ta | Tb | Th | Tm | U | V | Y | Yb | Zn | Zr | GNS # |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 38.3 | | 0.43 | | 5 | 2.63 | 1.86 | | 5.12 | 4.88 | 1.01 | 17 | 0.33 | 22.85 | 18.37 | | 7.04 | 4.13 | 10.7 | 33.3 | 4.91 | 431 | 2.21 | 0.85 | 2.23 | 0.36 | 1.13 | | 29.86 | 2.15 | | 195 | P82218A |
| 39.12 | | 0.5 | | 5.58 | 2.76 | 2.02 | | 6 | 5.84 | 1.07 | 23.95 | 0.33 | 27.56 | 23.46 | | 21.2 | 5.42 | 12 | 32.4 | 5.96 | 446 | 2.58 | 0.96 | 2.43 | 0.37 | 1.62 | | 24.19 | 2.25 | | 269 | P82218B |
| 29.92 | | 0.89 | | 6.03 | 3.13 | 1.94 | | 6.06 | 3.4 | 1.21 | 17.97 | 0.39 | 14.82 | 21.08 | | 1.34 | 4.7 | 11.1 | 33.6 | 5.41 | 334 | 1.02 | 0.98 | 1.28 | 0.43 | 0.64 | | 36.03 | 2.47 | | 131 | P82221 |
| 22.97 | | 0.53 | | 8.13 | 3.9 | 2.86 | | 9.37 | 3.11 | 1.61 | 26.99 | 0.43 | 13.63 | 34.02 | | 1.48 | 7.43 | 21.6 | 34.6 | 8.49 | 291 | 1.59 | 1.4 | 1.38 | 0.51 | 0.59 | | 49.89 | 2.79 | | 111 | P82224 |
| 73.4 | 160 | 0.08 | 51 | 5.66 | 2.56 | 2.74 | 25.2 | 6.95 | 6.3 | 1.03 | 36.7 | 0.29 | 41.1 | 35.1 | 72 | 7 | 8.83 | 27.3 | 19 | 7.66 | 690 | 2.3 | 1 | 3.81 | 0.35 | 0.9 | 275 | 27.4 | 2.06 | 102 | 270 | GD6060 |
| 11.12 | | 17.48 | | 2.78 | 1.59 | 0.88 | | 2.64 | 1.23 | 0.6 | 5.51 | 0.21 | 1.36 | 8.46 | | 5.31 | 1.76 | 78.2 | 23.2 | 2.35 | 402 | 0.99 | 0.44 | 1.02 | 0.22 | 0.81 | | 16.68 | 1.38 | | 46 | P82232 |
| 30.58 | | 5.78 | | 5.5 | 2.94 | 1.72 | | 5.65 | 3.12 | 1.12 | 13.18 | 0.4 | 3.98 | 21.77 | | 12.41 | 4.71 | 74.8 | 37.8 | 5.76 | 258 | 2.36 | 0.91 | 2.82 | 0.43 | 1.02 | | 30.95 | 2.56 | | 122 | P82233 |
| 11.48 | 61 | 0.23 | 77 | 2.95 | 1.9 | 0.9 | 19 | 2.85 | 0.97 | 0.66 | 7.15 | 0.27 | 0.81 | 9.6 | 65 | 4.5 | 2.01 | 3.6 | 14.4 | 2.51 | 115 | 0.06 | 0.45 | 1 | 0.27 | 0.39 | 174 | 23.92 | 1.59 | 92 | 39 | P82239 |
| 52.49 | | 24.65 | | 4.47 | 2.34 | 1.9 | | 5.69 | 2.18 | 0.87 | 31.07 | 0.28 | 1.36 | 36.73 | | 6.87 | 8.9 | 207.2 | 22.8 | 7.1 | 512 | 0.08 | 0.8 | 4.8 | 0.31 | 1.07 | | 26.37 | 1.76 | | 80 | P82240 |
| 19.7 | | 5 | | 4.95 | 3.18 | 1.22 | | 5.24 | 1.73 | 1.14 | 20.36 | 0.41 | 1.04 | 19.23 | | 8.67 | 4.16 | 69.1 | 30.2 | 4.32 | 114 | 0.07 | 0.77 | 1.79 | 0.44 | 1.59 | | 46.76 | 2.55 | | 72 | P82246 |
| 63.2 | 7.5 | 6.8 | 248 | 11.2 | 6.73 | 1.5 | 24.8 | 11.1 | 10.4 | 2.32 | 34.8 | 0.88 | 7.77 | 43.9 | 22.1 | 21.9 | 10.2 | 113 | 10.8 | 10.7 | 153 | 0.63 | 1.75 | 13.1 | 0.94 | 3.43 | 136 | 71.1 | 6.16 | 232 | 374 | na |
| 63.1 | 2.6 | 5.7 | 433 | 10.2 | 5.71 | 1.61 | 27.4 | 11.2 | 15.4 | 2.04 | 24.6 | 0.64 | 10.01 | 40.5 | 5.5 | 36.2 | 8.91 | 115 | 17.6 | 10.4 | 134 | 0.69 | 1.66 | 12.7 | 0.75 | 2.42 | 96 | 54.3 | 4.68 | 555 | 606 | na |
| 49.96 | 6 | 2.39 | 18 | 2.49 | 1.45 | 0.75 | 14 | 2.65 | 5.23 | 0.5 | 23.07 | 0.26 | 7.94 | 18.45 | 7 | 11.05 | 5.11 | 122.2 | 3.4 | 3.39 | 181 | 0.64 | 0.41 | 11.39 | 0.23 | 1.91 | 38 | 13.44 | 1.55 | 55 | 195 | P81396 |
| 48.66 | 5 | 2.53 | 5 | 5.63 | 3.29 | 1.34 | 16 | 5.57 | 6.29 | 1.18 | 23.34 | 0.53 | 8.97 | 26.48 | 5 | 12.91 | 6.49 | 107.7 | 12.7 | 6.02 | 293 | 0.65 | 0.92 | 9.5 | 0.52 | 2.45 | 45 | 29.66 | 3.31 | 105 | 239 | P81397 |
| 35.66 | 29 | 0.2 | 70 | 3.82 | 2.12 | 1.46 | 18 | 4.16 | 3.7 | 0.78 | 18.82 | 0.29 | 5.92 | 24.01 | 34 | 5.24 | 5.68 | 10.9 | 13.7 | 4.85 | 1402 | 0.39 | 0.64 | 2.01 | 0.31 | 0.43 | 167 | 26.14 | 1.81 | 173 | 122 | P81400 |
| 106.45 | 526 | 0.42 | 38 | 8.07 | 2.64 | 4.18 | 18 | 11.62 | 8.19 | 1.28 | 55.2 | | 73.23 | 54.69 | 61 | 3.7 | 12.62 | 31.55 | 17.23 | 13.29 | 917.46 | 4.56 | 1.68 | 6.67 | 0.3 | 1.77 | 136 | 33.11 | 1.56 | 135 | 346.97 | P57145 |
| 57.12 | | 0.4 | | 8.92 | 5.87 | 3.3 | | 8.47 | 4.4 | | 56.16 | 0.57 | 39.9 | 41.4 | | | 9.86 | | | 8.29 | | 2.7 | | 4.8 | | 2.4 | | 63.4 | 4.55 | | 186.8 | P78644 |
| 207 | 205 | | 71 | | | | 24 | | | | 120 | | 128 | | 184 | 9 | | 40 | 16 | | 800 | | | 13 | | 4 | 253 | 42 | | 155 | 458 | P83160 |
| 104 | 345 | | 74 | | | | 19 | | | | 57 | | 62 | | 236 | 6 | | 24 | 20 | | 579 | | | 6 | | 1 | 174 | 27 | | 121 | 208 | P83198 |
| 43 | 272 | | 172 | | | | 19 | | | | 33 | | 41 | | 114 | 3 | | 19 | 28 | | 629 | | | 4 | | 5 | 225 | 32 | | 153 | 149 | P83226 |
| 11.1 | <1.0 | 0.58 | 4 | 4.12 | 2.81 | 0.75 | 13 | 3.31 | 2.41 | 0.93 | 4.25 | 0.46 | 0.62 | 8.57 | 9 | 3.69 | 1.63 | 14.7 | 20 | 2.57 | 117 | 0.05 | 0.61 | 0.61 | 0.42 | 0.36 | 24 | 24.5 | 3.04 | 81 | 83.9 | P84022 |
| 14.72 | 395 | 0.1 | 7 | 2.06 | 0.96 | 1.1 | 16 | 2.24 | 6.94 | 0.39 | 5.39 | 0.12 | 54.57 | 8.45 | 25 | 0.85 | 1.8 | 3.9 | 29.8 | 2.14 | 787 | 4.22 | 0.36 | 2.4 | 0.13 | 0.23 | 209 | 9.1 | 0.8 | 45 | 350 | P82194 |

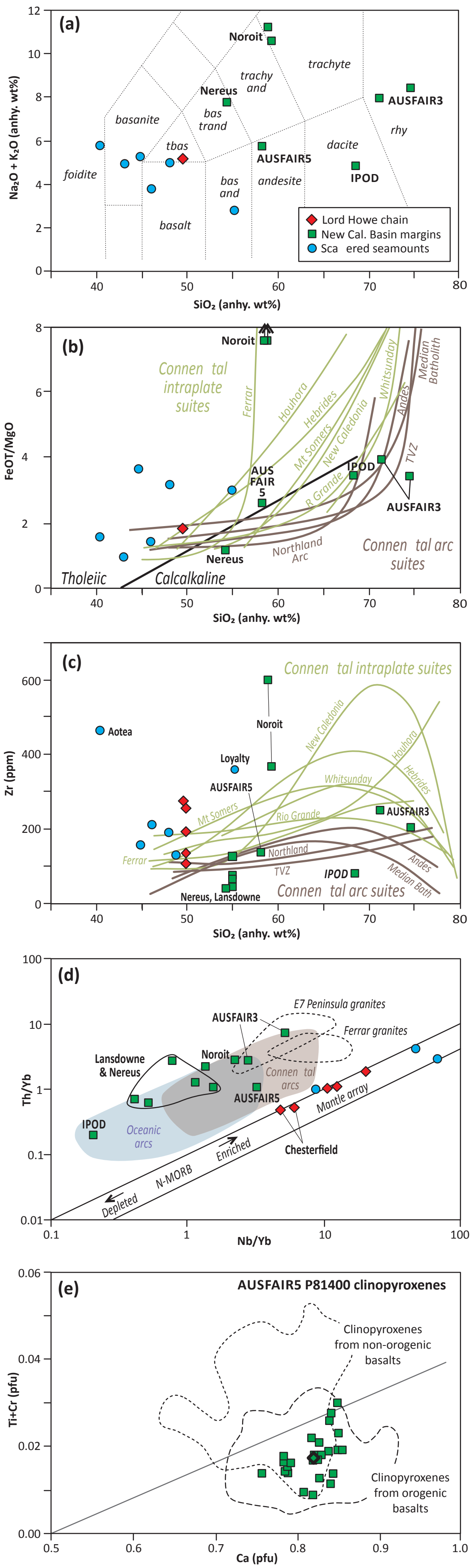
| Location | Dredge | GNS # | 147Sm/144Nd | 143/144Nd meas | ±2se | Age (Ma) | 143Nd/144Nd init |
|---|---|---|---|---|---|---|---|
| ***Lord Howe Seamount Chain*** | | | | | | | |
| Horsehead | ECOSAT DR15Bi | P82218A | 0.1609 | 0.512739 | 7 | 28 | 0.512711 |
| Chesterfield | ECOSAT DR16Ai | P82221 | 0.1545 | 0.512826 | 7 | 27 | 0.512799 |
| Lord Howe Island | na | GD6060 | 0.1303 | 0.512735 | 6 | 7 | 0.512729 |
| Middleton Reef | NORFANZ DR49 | P69722 | 0.1271 | 0.512883 | 8 | 12 | 0.512873 |
| ***New Caledonia Basin margins*** | | | | | | | |
| Le Noroit | ECOSAT DR11Fi | P82196 | 0.1283 | 0.512917 | 6 | 64 | 0.512863 |
| Lansdowne Bank | ECOSAT DR17Aiv | P82232 | 0.1672 | 0.512896 | 7 | 100 | 0.512787 |
| Nereus Reef | ECOSAT DR18Bi | P82239 | 0.1574 | 0.512847 | 6 | 100 | 0.512744 |
| Nereus Reef | ECOSAT DR18Bi | P82239 dup | 0.1574 | 0.512837 | 8 | 100 | 0.512734 |
| Nereus Reef | ECOSAT DR18Bii | P82240 | 0.1164 | 0.512951 | 9 | 100 | 0.512875 |
| Nereus Reef | ECOSAT DR18Bii | P82240 dup | 0.1164 | 0.512950 | 8 | 100 | 0.512874 |
| ***Eocene-Oligocene backarc basin basalts*** | | | | | | | |
| Rennell Ridge SW side | GEORSTOM3 DR301A | P78604 | 0.2537 | 0.513012 | 8 | 38 | 0.512949 |
| South Rennell Trough | GEORSTOM3 DR308A | P78613 | 0.2018 | 0.512996 | 8 | 28 | 0.512959 |
| D'Entrecasteaux Ridge | GEORSTOM3 DR316-23 | P78622 | 0.1669 | 0.513101 | 9 | 40 | 0.513057 |
| Rennell Ridge NE side | ECOSAT DR03Ai | P82182 | 0.1503 | 0.512798 | 8 | 40 | 0.512759 |
| West Torres Plateau | ECOSAT DR04Aii | P82188 rind | 0.2006 | 0.512881 | 7 | 35 | 0.512835 |
| West Torres Plateau | ECOSAT DR04Aii | P82188 inside | 0.1973 | 0.512804 | 6 | 35 | 0.512759 |
| East Laperouse Ridge | ECOSAT DR06A | P82193 | 0.1606 | 0.512727 | 8 | 35 | 0.512690 |
| South Rennell Trough | ECOSAT DR14Ei | P82204 | 0.1916 | 0.51264 | 7 | 28 | 0.512605 |
| South Rennell Trough | ECOSAT DR14Eiii | P82206 | 0.1539 | 0.512659 | 8 | 28 | 0.512631 |



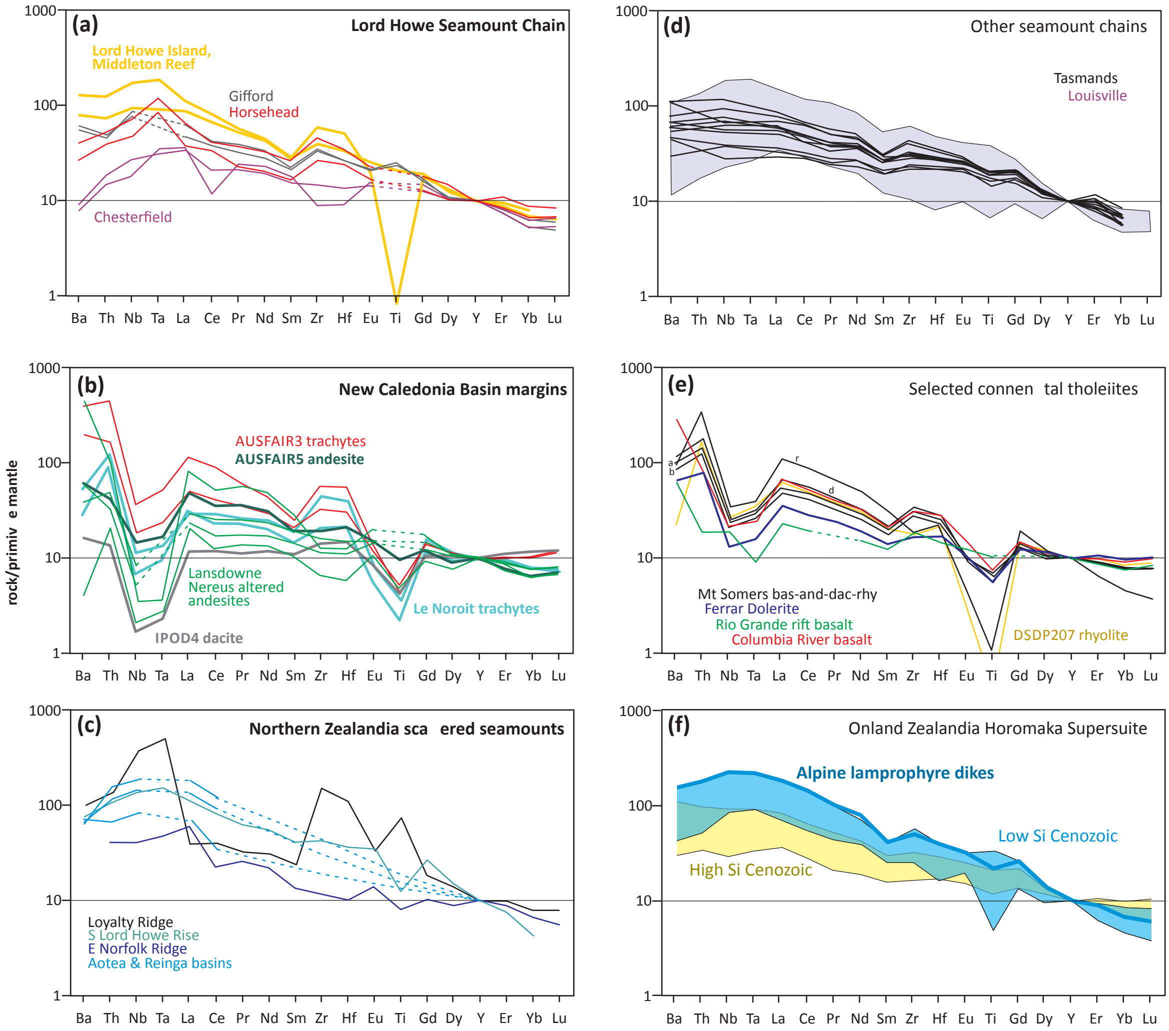
Zealandia
Vanuatu
New Caledonia
Loyalty
New Caledonia Basin
Fairway Ridge
Lord Howe Rise
Norfolk Ridge
Norfolk Basin
South Fiji Basin
Tasman Sea
Tasmantid Seamount Chain
Lord Howe Seamount Chain
Dampier Ridge
West Norfolk Ridge
Reinga Basin
Aotea Basin
Challenger Plateau
New Zealand
North Island
South Island
Southern Zealandia
HIKURANGI TRENCH
ALPINE FAULT
SRT
CFZ
VMFZ
Australia
Mellish Rf
Horsehead
Chesterfield Is.
Le Noroit
ECOSAT8
Lansdowne
Nereus
IPOD4
Lifou
Maré
Kenn
Bellona Plat.
Wreck
Nova Bank
Cato
Argo Bank
ZONE CO5 Smts
Kelso Bank
Fraser
Recorder
Capel Bank
Moreton
Gifford Guyot
Brisbane
Capel-Faust Smts
AUSFAIR5
Queensland
Britannia
AUSFAIR3
Stradbroke
Middleton Reef
FR9/01DR05
Elizabeth Reef
Norfolk Is.
GO346
Derwent-Hunter
Lord Howe Island
Barcoo
Taupo
NORFANZ85
Three Kings Is.
Flinders Seamount
DRASP27
DRASP19
GO357
Gascoyne
DSDP 207
Aotea Smt
Coquille
Marion
Mascarin
Matahourua
Devonport
Margot
Houhora
Bay of Islands
Puhipuhi
Whangarei
Auckland
Mayor Is.
S. Auckland
Mt Spong
Megabrick
DSDP 593
Palliser
Ngahape
Buller
Lookout
Tapuaenuku
Hohonu
Gridiron
Whataroa
Canavans
Otumotu
Tokakoriri
Arno,Oa
Mt Somers
20°S
30
40
160°E
170
180
Volcanic rock samples
This study
Previous analyses or dates
Inferred / no samples
Zealandia limits
Active volcanic arc
Established
Postulated
'Hotspot tracks'



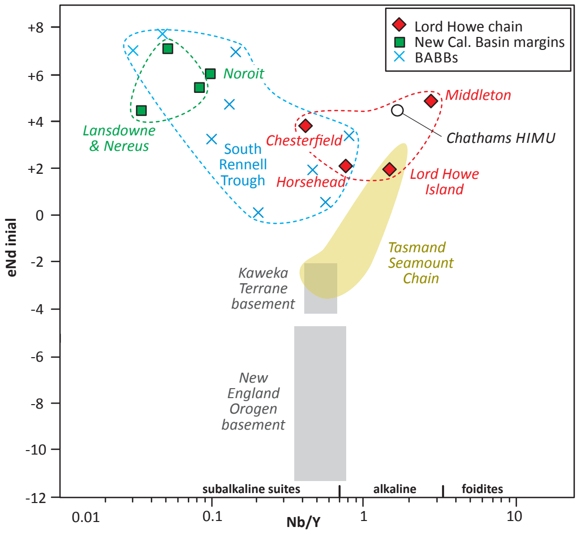
(a)
Horsehead ECOSAT DR15C (P82218C)
basalc gr oundmass
TFA = 24.7±0.3 Ma
'WMPA' = 27.2±0.3 Ma
(b)
Lansdowne ECOSATDR17Aii (P82230)
altered andesite groundmass
TFA = 76.7±0.3 Ma
'WMPA' = 78.1±0.4 Ma
(c)
AUSFAIR DR5 (P81400) andesite
hornblende
TFA = 72.5±0.3 Ma
'WMPA' = 73.8±0.3 Ma
(d)
GEORSTOM 357 (P57145) gabbro xenolith
plagioclase
TFA = 27.0±0.1 Ma
WMPA = 27.0±0.1 Ma
(e)
Aotea Smt DRASPd2 (P83160) basalt
groundmass
TFA = 21.7±0.1 Ma
'WMPA' = 22.5±0.1 Ma
apparent age (Ma)
cumulav e ³⁹Ar



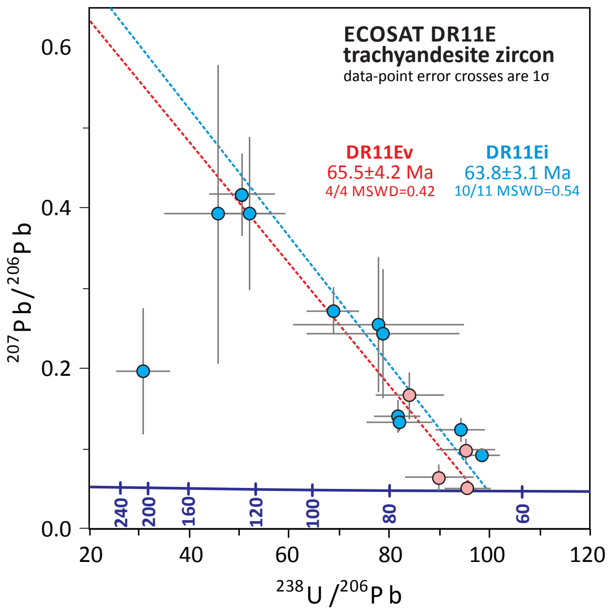
(a)
Noroit
trachyte
trachy and
Nereus
AUSFAIR3
basanite
bas trand
rhy
tbas
dacite
AUSFAIR5
foidite
bas and
andesite
IPOD
basalt
Lord Howe chain
New Cal. Basin margins
Sca ered seamounts
Na₂O + K₂O (anhy. wt%)
SiO₂ (anhy. wt%)
(b)
Noroit
Connen tal intraplate suites
Ferrar
Houhora
Hebrides
Mt Somers
New Caledonia
Whitsunday
Andes
Median Batholith
TVZ
AUS FAIR 5
IPOD
R Grande
AUSFAIR3
Nereus
Northland Arc
Connen tal arc suites
Tholeiic
Calcalkaline
FeOT/MgO
SiO₂ (anhy. wt%)
(c)
Connen tal intraplate suites
Noroit
Aotea
Loyalty
New Caledonia
Houhora
Whitsunday
Hebrides
AUSFAIR5
Mt Somers
Rio Grande
AUSFAIR3
Northland
Ferrar
TVZ
IPOD
Andes
Median Bath
Nereus, Lansdowne
Connen tal arc suites
Zr (ppm)
SiO₂ (anhy. wt%)
(d)
E7 Peninsula granites
AUSFAIR3
Ferrar granites
Noroit
Lansdowne & Nereus
Connen tal arcs
AUSFAIR5
Mantle array
IPOD
Oceanic arcs
Enriched
Chesterfield
N-MORB
Depleted
Th/Yb
Nb/Yb
(e)
AUSFAIR5 P81400 clinopyroxenes
Clinopyroxenes from non-orogenic basalts
Clinopyroxenes from orogenic basalts
Ti+Cr (pfu)
Ca (pfu)



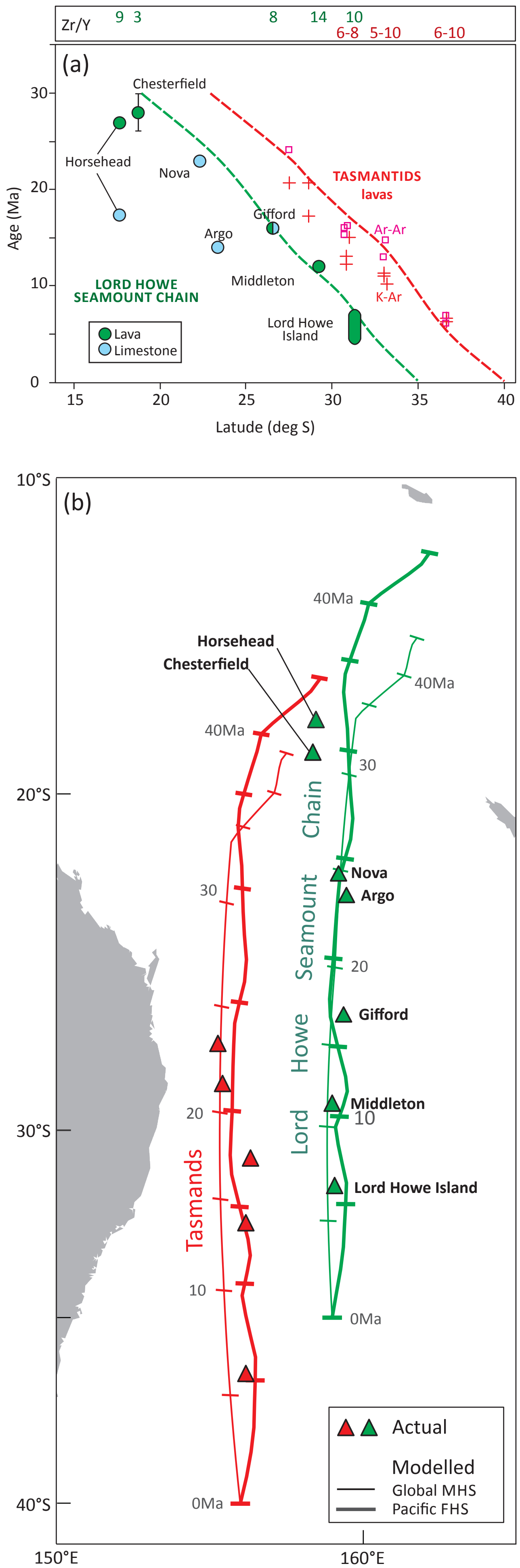
(a) Lord Howe Seamount Chain
Lord Howe Island, Middleton Reef
Gifford
Horsehead
Chesterfield
(b) New Caledonia Basin margins
AUSFAIR3 trachytes
AUSFAIR5 andesite
Lansdowne Nereus altered andesites
IPOD4 dacite
Le Noroit trachytes
rock/primitive mantle
(c) Northern Zealandia scattered seamounts
Loyalty Ridge
S Lord Howe Rise
E Norfolk Ridge
Aotea & Reinga basins
(d) Other seamount chains
Tasmands
Louisville
(e) Selected continental tholeiites
Mt Somers bas-and-dac-rhy
Ferrar Dolerite
Rio Grande rift basalt
Columbia River basalt
DSDP207 rhyolite
(f) Onland Zealandia Horomaka Supersuite
Alpine lamprophyre dikes
Low Si Cenozoic
High Si Cenozoic
Ba Th Nb Ta La Ce Pr Nd Sm Zr Hf Eu Ti Gd Dy Y Er Yb Lu



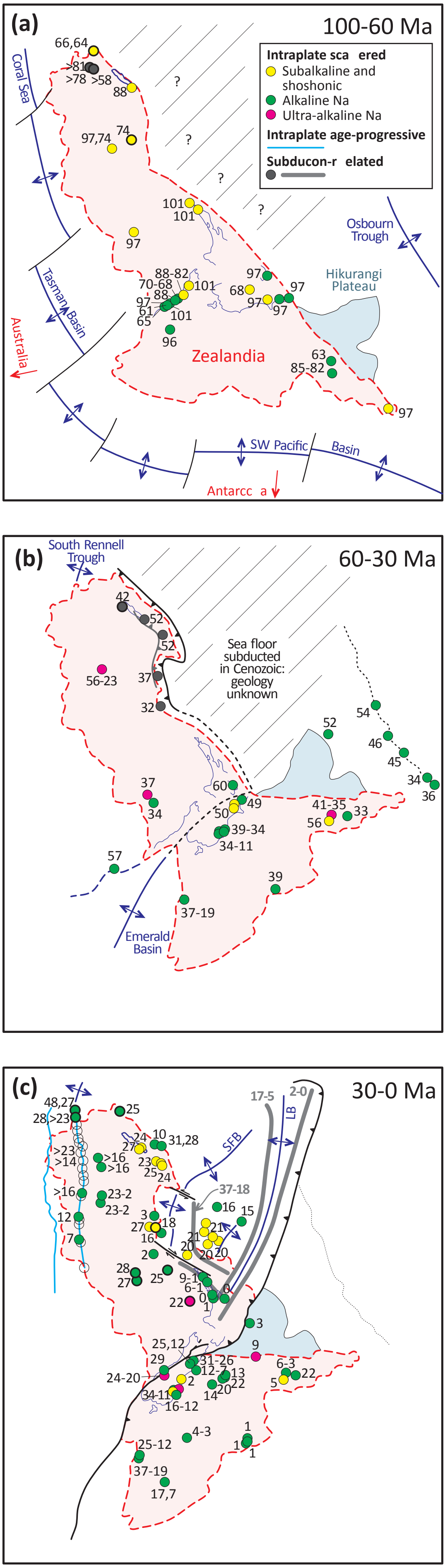
Lord Howe chain
New Cal. Basin margins
BABBs
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
-12
eNd inial
Noroit
Middleton
Lansdowne
& Nereus
Chesterfield
Chathams HIMU
South
Rennell
Trough
Horsehead
Lord Howe
Island
Tasmand
Seamount
Chain
Kaweka
Terrane
basement
New
England
Orogen
basement
subalkaline suites
alkaline
foidites
0.01
0.1
1
10
Nb/Y

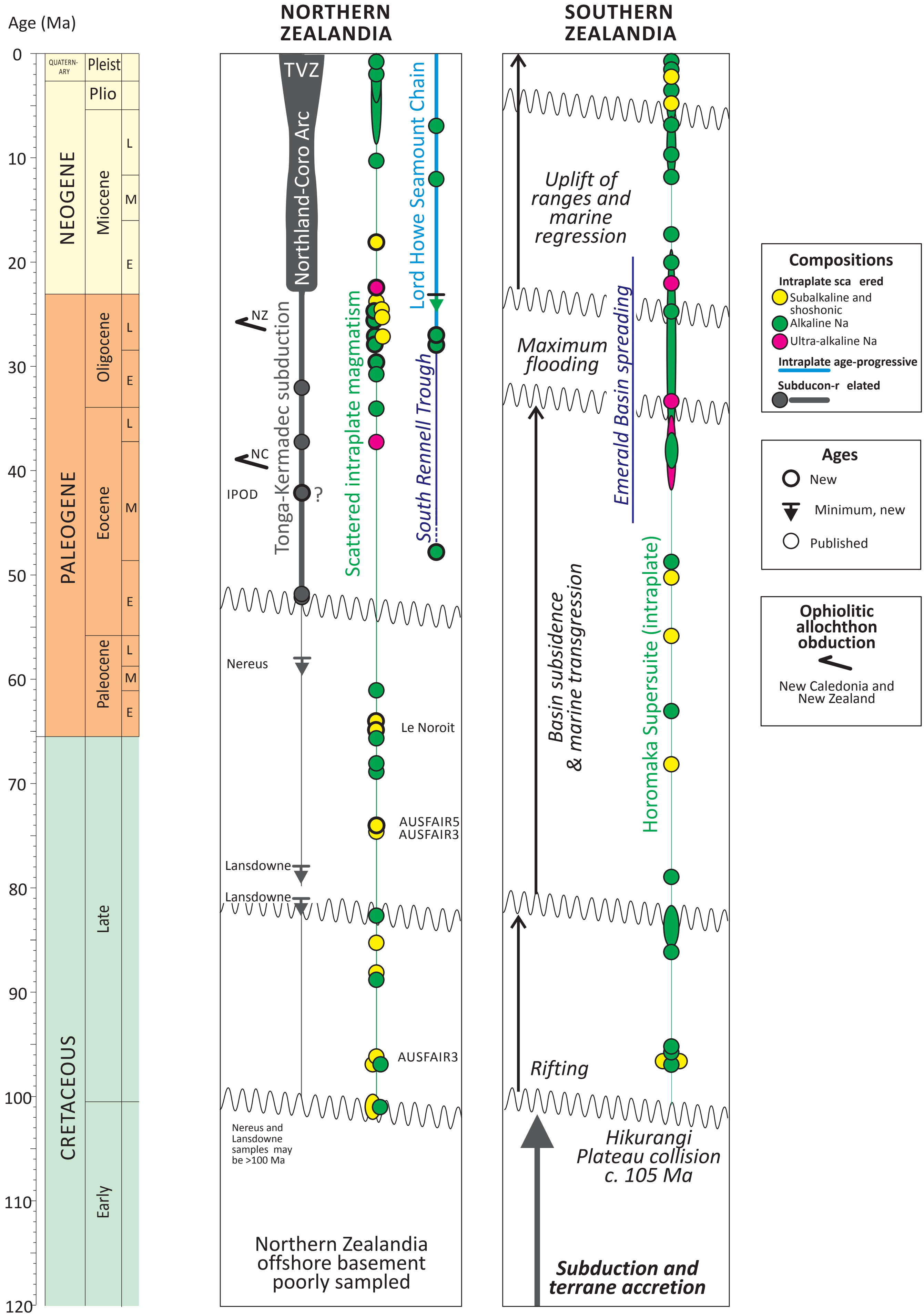


ECOSAT DR11E
trachyandesite zircon
data-point error crosses are 1σ
DR11Ev
65.5±4.2 Ma
4/4 MSWD=0.42
DR11Ei
63.8±3.1 Ma
10/11 MSWD=0.54
0.6
0.4
0.2
0.0
240
200
160
120
100
80
60
20
40
60
80
100
120
207Pb/206Pb
238U/206Pb



Zr/Y
9 3 8 14 10
6-8 5-10 6-10
(a)
Chesterfield
Horsehead
Nova
Gifford
Argo
Middleton
Lord Howe Island
TASMANTIDS lavas
Ar-Ar
K-Ar
LORD HOWE SEAMOUNT CHAIN
Lava
Limestone
Age (Ma)
Latude (deg S)
(b)
10°S
20°S
30°S
40°S
150°E
160°E
Horsehead
Chesterfield
40Ma
30
20
10
0Ma
Nova
Argo
Gifford
Middleton
Lord Howe Island
Lord Howe Seamount Chain
Tasmands
Actual
Modelled
Global MHS
Pacific FHS


(a)
100-60 Ma
Intraplate sca ered
Subalkaline and shoshonic
Alkaline Na
Ultra-alkaline Na
Intraplate age-progressive
Subducon-r elated
Coral Sea
Tasman Basin
Australia
Zealandia
Osbourn Trough
Hikurangi Plateau
SW Pacific Basin
Antarcc a
66,64
>81
>78
>58
88
97,74
74
101
101
97
88-82
70-68
88
101
97
61
65
101
96
97
68
97
97
97
63
85-82
97
?
(b)
60-30 Ma
South Rennell Trough
Sea floor subducted in Cenozoic: geology unknown
Emerald Basin
42
52
52
56-23
37
32
52
54
46
45
34
36
60
49
50
39-34
34-11
41-35
56
33
37
34
57
39
37-19
(c)
30-0 Ma
17-5
2-0
SFB
LB
37-18
48,27
28
>23
25
24
10
31,28
27
>23
>14
>16
>16
23
25
24
>16
23-2
23-2
12
7
16
15
3
18
27
21
16
21
20
20
20
2
28
27
25
9-1
6-1
0
0
22
1
3
25,12
9
29
31-26
12-7
13
22
6-3
22
5
24-20
2
20
14
34-11
16-12
4-3
1
1
1
25-12
37-19
17,7



Age (Ma)
0
10
20
30
40
50
60
70
80
90
100
110
120
QUATERNARY
Pleist
Plio
NEOGENE
Miocene
L
M
E
PALEOGENE
Oligocene
Eocene
Paleocene
CRETACEOUS
Late
Early
NORTHERN ZEALANDIA
TVZ
Northland-Coro Arc
Tonga-Kermadec subduction
Scattered intraplate magmatism
Lord Howe Seamount Chain
South Rennell Trough
NZ
NC
IPOD
?
Nereus
Le Noroit
AUSFAIR5
AUSFAIR3
Lansdowne
Lansdowne
AUSFAIR3
Nereus and Lansdowne samples may be >100 Ma
Northern Zealandia offshore basement poorly sampled
SOUTHERN ZEALANDIA
Uplift of ranges and marine regression
Maximum flooding
Emerald Basin spreading
Basin subsidence & marine transgression
Horomaka Supersuite (intraplate)
Rifting
Hikurangi Plateau collision c. 105 Ma
Subduction and terrane accretion
Compositions
Intraplate sca ered
Subalkaline and shoshonic
Alkaline Na
Ultra-alkaline Na
Intraplate age-progressive
Subducon-r elated
Ages
New
Minimum, new
Published
Ophiolitic allochthon obduction
New Caledonia and New Zealand