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The Norfolk Ridge seamounts: Eocene–Miocene volcanoes near Zealandia's rifted continental margin

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Abstract :

New age and geochemical data are used to investigate the origin of a ~670 km-long line of eight seamount volcanoes along the western side of the Norfolk Ridge between New Caledonia and New Zealand. Altered lavas and limestones were dredged from three volcanoes during the 2015 Volcanic Evolution of South Pacific Arcs cruise of N/O l'Atalante, so a total of four, including the northernmost and southernmost, have now been directly sampled and analysed. Dating of lava and volcanic breccia clasts by Ar–Ar methods gives north-to-south ages from these sites of 31.3 ± 0.6, 33 ± 5, 21.5 ± 1.0 and 26.3 ± 0.1 Ma. These ages, along with supporting stratigraphic data on a fifth seamount from IODP borehole U1507, provisionally refute the hypotheses that the seamounts represent a southward-younging, age-progressive, intraplate volcanic chain on the Australian Plate or a subduction-related chain of restricted age range. Geochemically, the upper Eocene to lower Miocene lavas have alkaline and subalkaline basaltic compositions, and some could be shoshonitic. The location of the volcanoes along the western side of the Norfolk Ridge suggests an origin related to late Eocene and early Miocene melting near an intracontinental lithosphere–asthenosphere step. Involvement of a deep slab in petrogenesis is also possible.

Key points

1. Eight seamounts form a line along the Norfolk Ridge.
2. Dating and geochemistry indicate the seamount line is not a hotspot track.
3. A rift-related origin, possibly with influence by subduction, is proposed.

Keywords : Southwest Pacific, Zealandia, Norfolk Ridge, seamounts, guyots, volcanoes, geochronology, geochemistry, Cenozoic

Introduction

The Norfolk Ridge is a major bathymetric feature of the northern part of the Zealandia continent (Figure 1a) (Mortimer *et al*., 2017). It is a prominent 1000 km-long bathymetric ridge that links New Zealand and New Caledonia and separates the probable oceanic Norfolk and probable intracontinental New Caledonia basins (Figure 1). The only emergent part of the ridge is Norfolk Island, which is an eroded Pliocene intraplate volcanic edifice (Jones & McDougall, 1971). Compared with other Southwest Pacific submarine features, the Norfolk Ridge is little-studied, undrilled, and not much has been written about it since the summaries by Dupont *et al*. (1975), Eade (1988) and Rigolot (1989). Based on exposures in New Caledonia and New Zealand, the basement rocks of the Norfolk Ridge are presumed to be Mesozoic greywackes and/or schists, correlative with those in New Zealand's and New Caledonia's basement terranes (Adams *et al.*, 1998; Campbell *et al.*, 1985, 2001). Reflection seismic profiles suggest that the Norfolk Ridge has a thin Upper Cretaceous to Neogene sedimentary cover (Collot *et al.*, 2019; Dupont *et al.*, 1975; Patriat *et al.*, 2018), and the age and petrology of some dredged northern Zealandia Cenozoic limestones have been reported by Lawrence *et al.* (2020).

Late Cretaceous-Cenozoic volcanoes and volcanic fields are widespread across northern Zealandia's continental crust basement and its sedimentary basin cover (Mortimer & Scott, 2020). Some of these form prominent curvilinear alignments (Figure 1). Two such alignments, the Tasmantid and Lord Howe seamount chains (green dashed lines at longitude *ca* 158°E and *ca* 160°E in Figure 1b), have been demonstrated to be age-progressive chains of alkali basalts. These so-called hotspot tracks record the northward movement of the Australian Plate over a presumed deep mantle plume source (Crossingham *et al.*, 2017; Seton *et al.*, 2019 and references therein). A hotspot track on the eastern Norfolk Ridge proposed by Rigolot (1988) (white dashed lines at *ca* 168°E in Figure 1b) was disproved by Mortimer *et al.* (2014). Another hotspot track along the Lord Howe Rise, at *ca* 163°E, has been proposed but remains unproven (Dadd *et al.*, 2011; Exon *et al.*, 2004). Other major volcanic alignments (yellow lines in Figure 1b) have been shown to be subduction-related volcanic arcs. These include the Three Kings-Loyalty Ridge arc, the Colville-Lau arc and the Kermadec-Tonga arc (Collot *et al.*, 2020).

The purpose of this paper is to evaluate the origin of another linear alignment of northern Zealandia volcanoes, a *ca* 670 km-long, north-south group of eight seamounts on the western side of the Norfolk Ridge near longitude 167°E (orange dashed lines in Figure 1b, detail in Figure 1c). Did these Norfolk Ridge seamounts originate as (1) a Paleogene-Neogene, age-progressive chain of volcanoes on the Australian Plate (Exon *et al.*, 2004), (2) a Paleogene subduction-related volcanic arc, possibly the westernmost and oldest such arc in the Southwest Pacific (Mortimer *et al.*, 1998), or (3) a non-age progressive group of intracontinental volcanoes with a different origin (*e.g.* Mortimer *et al.*, 2018)? To answer these questions we present analyses of rock dredges from the 2015 VESPA (Volcanic Evolution of South Pacific

Arcs) cruise of N/O *l'Atalante*, part of which targeted the Norfolk Ridge seamounts for study.

This paper builds on earlier work on the Norfolk Ridge and New Caledonia Basin regional geology and stratigraphy by Eade (1988), Rigolot (1989), Patriat *et al*. (2018), Collot *et al*. (2019) and Lawrence *et al*. (2020). It also supplements the Jones and McDougall (1973) account of Norfolk Island volcanism, and the Mortimer *et al*. (2018) summary of northern Zealandia intraplate volcanism.

Methods

Samples were obtained by standard rock dredging methods. None of the eight Norfolk Ridge seamounts have formal names, and the sites and rocks are referred to in this paper by their dredge numbers (Figure 1c). The southernmost seamount was sampled during the GEORSTOM III SUD cruise of N/O *Le Noroît* (dredge GO348; Monzier & Vallot, 1983) and three new dredges of seamounts further north were made during the VESPA cruise of N/O *l'Atalante* (dredges DR1, DR4 and DR7; Mortimer & Patriat 2016). During the cruise, examination and description of rocks was facilitated by use of a diamond rock saw and binocular microscope. An Olympus DP-6050-C portable X-Ray fluorescence (pXRF) analyser was used to obtain preliminary geochemical information. Samples prefixed P are archived in GNS Science's National Petrology Reference Collection and Petlab database (https://pet.gns.cri.nz; Strong *et al*. 2016).

After the cruise, samples were dispatched to various laboratories for more thorough investigation. Prior to thin sectioning, crushing and mineral separation, all samples were soaked in deionised water to remove sea salt. The major element composition of clinopyroxene in two lavas from VESPA dredges DR1A and DR4B was determined by a Cameca Camebax SX100 electron microprobe at the Laboratoire Domaines Océaniques (University of Brest) using a 15 kV and 10 nA beam focused to a spot of *ca* 2 µm in diameter.

Whole rock geochemical analyses of three lavas from VESPA dredges DR1A, 4B and 7C were made in January 2017 using Jobin Yvon Ultima 2 ICP-AES and

Thermo Element2 HR-ICP-MS instruments for major and trace elements respectively at the Institut Universitaire Européen de la Mer, Brest, following protocols described by Agranier *et al*. (2019). A wide beam (*ca* 25 µm) electron microprobe analysis was made of breccia matrix in GO348 (see Mortimer *et al*., 1998). The sample stage was moved during analysis; the major element concentrations of GO348 should be regarded as approximate only.

Ar–Ar dating was done at the University of California Santa Barbara, with laboratory methods and interpretive workflows identical to those described in Mortimer *et al*. (1998, 2014). The Ar–Ar ages for VESPA dredges DR1A, 4B and 7C were obtained in October 2016 and the Ar–Ar biotite age for GO348D1 is from Mortimer *et al*. (1998). Quoted precision in this paper is effectively at the two-sigma level but the error bars on gas release steps in Figure 5 are one sigma. Micropaleontological dating methods are explained in Crundwell *et al*. (2016) and Lawrence *et al*. (2020). Ages are reported in terms of the New Zealand timescale of Raine *et al*. (2015). The VESPA cruise data that support the findings of this study are openly available in the SISMER repository at http://doi.org/10.17600/15001100 .

Dredge sites

VESPA dredge DR1 was made on the lower northeast flank of a *ca* 12 km diameter guyot, presumed to be a stratovolcano eroded at or near wave base (Figure 2a). The guyot top lies at *ca* 130 m water depth, *i.e.* the same as the last glacial low sea-level stand. The base of the guyot rises from *ca* 1000 m on its eastern (Norfolk Ridge) side and *ca* 2000 m on its western (New Caledonia Trough) side. The dredge is estimated to have been on the sea bottom at 1000–1200 m water depth and dragged across a point at 166.9707°E, 24.2118°S (WGS84 coordinates). A *ca* 150 m vertical height of seafloor ridges and hills was sampled. Approximately 5 kg of rock in two pieces was recovered in the dredge: DR1A was a large piece of Mn-crusted olivine basalt and DR1B an altered hyaloclastite breccia (Figure 3a–c).

VESPA dredge DR4 was made on the south side of an east-west trending canyon incised into the west flank of the Norfolk Ridge (one of many such canyons thereabouts; Figure 2b). The dredge is estimated to have been dragged up a steep canyon wall varies from 2500 to 2200m depth, across a point at 167.1490°E, 27.6086°S. The dredge was intended to target rocks close to a major regional unconformity, the so-called TECTA (Tectonic Event of the Cenozoic in the Tasman Area; Sutherland *et al*. 2017). Approximately 100 kg of rock was obtained in DR4. Most of this was cobbles and a boulder of soft ashy mudstone (DR4A) that was only very slightly calcareous. Another distinctive rock type was thickly Mn-coated amygdaloidal olivine basalt occurring as several cobbles up to 15 cm in size (DR4B) (Figure 3). About a third of the dredge consisted of slabs of Mn crust up to 6 cm thick (DR4C), many containing attached substrate of olivine basalt similar to DR4B. Minor rock types were ashy mudstone like DR4A but containing clasts of basalt of similar characteristics to DR4B (DR4E, 4F; Figure 3d–f). The dredge site is *ca* 30 km south of a *ca* 25 km diameter guyot at 27.3°S, a presumed eroded stratovolcano, whose top is at a water depth of *ca* 500 m (Figures 1c and 2b). We regard this guyot as the likely source of the DR4 volcanic rocks, matrix and clasts. Facies models of submarine volcanoes (*e.g.* Allen *et al.*, 2007; Bischoff *et al.*, 2020) involve sector collapse and parasitic vents that can form breccias tens of km from central volcanoes. Alternatively, the DR4 volcano may have been a much smaller cone along the same general north-south Norfolk seamounts trend. The DR4 dredge site is also *ca* 10 km west (downslope) of a previously unrecorded north-south trending *ca* 60 km long seafloor lineament, which passes across the top of the guyot at 27.3°S. We provisionally interpret this feature as a down-to-the west, post-volcanic normal fault trace (Figure 2b).

VESPA dredge DR7 was carried out on the possibly collapsed lower northwest flank of the guyot near 28°S (Figure 2c). The guyot is *ca* 25 km in diameter; its top lies at *ca* 1000 m water depth, and base at *ca* 1600 m. The approximate centre point of the track of the dredge on the sea floor is estimated to be 167.2407°E, 28.3018°S, at 1500–600 m water depth. About 60 kg of rock was dredged. Approximately a third of this was manganese crusts up to 4 cm thick (DR7A). Two angular boulders and two cobbles consisted of light brownish-red, moderately sorted volcaniclastic breccia with typical clast size 1 cm (DR7B). One *ca* 50 x 40 x 40 cm boulder (DR7C) consisted of volcanic breccia similar to DR7B except for being more poorly sorted and containing fresher olivine basalt clasts up to 7 cm in size (Figure 3g, h).

GEORSTOM dredge 348 was made near the crest of a broad seamount on the Norfolk Ridge (Monzier & Vallot, 1983). This is the southernmost of the eight identified volcanic seamounts. No detailed multibeam bathymetry exists for this feature except a single multibeam track acquired in 1993. Bathymetry reveals a *ca* 10 km guyot-like feature with its top at *ca* 700 m water depth (Figure 2d). Small, shallower water spots indicated that there may be several small outlying volcanic cones around the guyot. The approximate dredge coordinates are 167.4965°E, 30.1219°S, water depth 900–1400 m, and about 30 kg of volcanic breccia, some cemented by carbonate, was recovered (Figure 3i) (Monzier & Vallot, 1983).

Petrology and geochemistry

One sample from each of VESPA dredges DR1, 4 and 7, and GEORSTOM 348 was selected for further work. All rocks are texturally pristine in that original phenocryst, vesicle and clast outlines are still clearly visible. However, all show extensive secondary mineralogical alteration as revealed by their brownish colour, absence of relict glass, olivine pseudomorphed by clay minerals, and presence of visible calcite, zeolite, clay and manganese oxides. Some samples have relict clinopyroxene (Table 1). In keeping with the abundant secondary minerals, the whole rock chemical analyses (Table 2) reflect a high degree of alteration with loss on ignition (LOI), CaO and P_2O_5 contents that exceed those for normal igneous rocks; this has led to addition and dilution of various minor and trace elements. However, contamination by Mn crusts in all analysed samples appears minimal. The high secondary carbonate and phosphate indicated by the major element analyses explains the high light rare-earth element (*e.g.* La, Ce, Eu) and alkaline earth (*e.g.* Sr, Ba) concentrations. Instead of rejecting these altered rocks for study, we have interpreted their geochemical characteristics with caution and circumspection, and attempted to use trace elements and their ratios, that are generally thought to be less mobile during low-grade alteration processes. In the lower part of Table 2, major elements have been recalculated on an anhydrous basis with CaO = 9 wt% and P_2O_5 = 0.5 wt%, values typical of less altered basaltic rocks.

DR1A (P84582) is an altered vesicular to amygdaloidal basalt with *ca* 2 % olivine and *ca* 10 % clinopyroxene microphenocrysts set in a very fine-grained groundmass. Olivine is completely altered to clay minerals and many vesicles contain calcite (Figure 3c). The clinopyroxenes have green cores and colourless rims but there is no consistent chemical difference between them. Compositions are diopsidic, and high Ti (and Al) contents match those from alkaline suites (Table 1, Figure 4a; Supplemental File 2). One of the thin sections of DR1A contained a 2 mm long xenolith composed of polygonal quartz grains (Figure 3c; quartz was confirmed by electron microprobing). On balance, petrographic features such as euhedral cloudy quartz facets abutting anhedral clear quartz patches, and healed fractures crossing between grains, point to a probable quartz vein rather than an ortho- or meta-quartzite origin for the xenolith. Speculatively, the vein may have originated from schists that make up part of the basement in eastern Zealandia terranes (*e.g.* Adams et al. 1998). In terms of whole rock chemistry, alteration notwithstanding, DR1A seems to have most of the anhydrous normalised SiO_2, TiO_2, MgO and Cr characteristics of a subalkaline to marginally alkaline basalt or basaltic andesite (Table 2, Figure 4b). On a multi-element normalised diagram (Figure 4c), there is decoupling between relatively low values of high field strength elements (HSFE, *e.g.* Ta, Nb, Ti, Zr, Hf) and relatively high values of light and middle rare-earth elements (REE, *e.g.* La, Ce, Nd, Sm, Gd). In intra-oceanic settings, these features are typical of subduction-related lavas. However, the intracontinental setting of the seamount offers other possibilities (Li *et al.*, 2015) and the DR1A composition also lies in the range of continental intraplate and subduction-related lavas (Figure 4c, d). The K_2O and Ba contents are relatively high for a basalt; if they approximate to igneous values then, very tentatively, a shoshonitic composition might be indicated. In this regard we note that the multi-element pattern of DR1A with its high Th/Nb and La/Nb also resembles lower Miocene shoshonites from the Three Kings Ridge described by Mortimer *et al.* (1998, 2007).

DR4B (P84590) is an altered amygdaloidal basalt with *ca* 10% olivine and *ca* 10% clinopyroxene phenocrysts set in an extremely fine-grained groundmass. Olivine is completely altered to clay minerals, but augite is fresh. Amygdules contain neoformed calcite and zeolite, probably phillipsite (Figure 3f) and there has also been some carbonate and phosphatic sediment infiltration. Clinopyroxenes span the same compositional range as those from DR1A, and show no clear core-rim compositional trends, although overall they are slightly more magnesian (Table 1, Figure 4a). Geochemically, DR4B has the lowest LOI of our analysed samples and is clearly the most alkaline and ocean island basalt-like of the analysed samples, especially in its high TiO_2, Cr and Nb contents, high Nb/Y ratio, convex-up and generally smooth normalised trace element pattern and its Th/Yb and Nb/Yb ratios (Figure 4). It lacks the negative Nb and Ta anomalies of DR1A and DR7Ci.

DR7Ci (P84597) is the largest and least altered clast from the DR7 volcanic breccia. It is another very fine-grained, altered vesicular to amygdaloidal basalt with *ca* 5% olivine phenocrysts and *ca* 5% plagioclase microphenocrysts. Clinopyroxene is absent. Olivine is completely altered to clay minerals (Figure 3h). Despite being the freshest clast in the DR7 breccia, it has a loss on ignition of 11 wt% and is the most altered of the three analysed lavas. Both petrographically (*i.e.* with plagioclase phenocrysts) and geochemically (lowest Nb/Y, low overall normalised trace element contents) it has the features of a subalkaline basalt and plots distinctly away from DR1A and DR4B on all geochemical plots (Figure 4). However, like DR1A it has relatively low normalised values of high field strength elements (*e.g.* Zr, Nb, Hf, Ti) compared to light and middle rare-earth elements. The same ambiguous issues of interpretation apply to DR7Ci as to DR1A: it may have a subduction-related or an intraplate continental origin.

GO348D1 (P57118) is an altered, clast-supported volcanic breccia (Mortimer *et al.*, 1998). Phenocrysts of biotite and greenish clinopyroxene are prominent within the clasts (Figure 3i). Petrographically identifiable secondary minerals include clay and zeolite. The presence of biotite (confirmed by electron microprobe; Mortimer et al. 1998) indicates that the lava clasts are not basalts. Pyroxene analyses reported by Mortimer *et al*. (1998) have higher Si, and lower Ti and Al than pyroxenes from DR1A and DR4B (Table 1, Figure 4a). These concentrations, along with an Mg# of 80, indicate a likely subalkaline andesitic affinity for the parent igneous rock. Mortimer *et al*. (1998) noted the similarity of GO348D1 pyroxene compositions to Southwest Pacific Miocene shoshonites. Wide beam electron microprobe analyses of GO348D1 breccia matrix (Table 2) very tentatively support a trachyandesitic, possibly high-K to shoshonitic, composition.

Dating

New Ar–Ar and micropaleontological ages

The absence of potassic phenocrysts in DR1A, DR4B and DR7Ci meant that groundmass from these three rocks had to be used for Ar–Ar dating. Analysis of groundmass separates of these three new VESPA samples gave reasonable K/Ca ratios and radiogenic yields (Supplemental File 3). However, all three samples had complex degassing spectra (Figure 5). As is expected for fine-grained groundmass samples, hump-shaped spectra result from substantial reactor-induced recoil. No statistical plateaus are present, so accuracy of ages is highly interpretive, and precision is based on conservative estimates (see Mortimer *et al*., 2014 for discussion).

VESPA DR1A (P84582, SB69-11) groundmass Ar–Ar ages range from 30–32 Ma for first 70% of gas then lower to <30 Ma, suggestive of recoil in this very fine-grained rock. K/Ca is high throughout the spectrum. The middle part of the spectrum is flattest, but there is no statistical plateau or isochron. We use the weighted mean of the three middle steps (*ca* 39 % of gas) to generate an interpreted pseudoplateau age of 31.3 ± 0.6 Ma. We interpret this age to approximate to the age of eruption and crystallisation of the lava.

VESPA DR4B (P84590, SB69-6) groundmass shows a highly disturbed hump-shaped spectrum. Ar–Ar ages climb stepwise from 27 to 38 Ma, then drop stepwise to

<25 Ma; no two contiguous steps are concordant. This behaviour is characteristic of major recoil in the extremely fine-grained rock, along with some low temperature argon loss. K/Ca ratios and % radiogenic yield are satisfactory. A weighted mean of the middle eight steps of the spectrum (most of the gas) gives an age of *ca* 33 Ma with a conservative precision estimate of ± 5 Ma. Although this age is imprecise, it is supported by micropaleontological dating of two mudstones from DR4. Sample DR4A is an early Whaingaroan (34.6–29.8 Ma) ashy, yellowish-grey sandy mudstone (Lawrence *et al*., 2020); the sand grains in the mudstone are orange sideromelane glass and variably altered lava. Sample DR4F (SE27167/f003; F49679) is a volcanic breccia with an ashy mudstone matrix which contains moderately well-preserved microfauna, mostly planktic foraminifera. The adopted age of the DR4F matrix is middle to late Eocene, Zone P14 to P16 (39.1–29.8 Ma). The age is based on the presence of the foraminifera *Globigerinatheka index* in combination with the absence of *Acarina*, especially *Acarina primitiva* and *Bulimina bortonica*. Paleo-water depth was bathyal (>200 m) based on presence of *Pleurostomella* and (?)*Dentalina*. Because of the angular- to irregular-shaped margins of the hyaloclastite clasts, we interpret this as a syn-eruptional age. Thus, the Ar–Ar age of the lava and the biostratigraphic ages of the two mudstones from DR4 are all in agreement, although none are especially precise.

VESPA DR7Ci (P84597, SB69-14) groundmass shows a disturbed argon release spectrum, with evidence for low temperature argon loss and recoil (Figure 5). Ages climb from 24–27 Ma at low temperature, then drop and flatten out in three steps at *ca* 21.5 Ma and then drop to *ca* 17 Ma at the highest temperature steps. K/Ca ratios are moderately high and there is abundant radiogenic gas; fine grain size and alteration are the biggest problem. For a crystallisation age we calculated a pseudoplateau weighted mean age of the 920–1040°C steps but increased the uncertainty as the steps are not concordant. Consequently, we interpret the eruption age of the lava as 21.5 ± 1.0 Ma.

Other ages

Fresh biotite from the GO348D1 volcanic breccia (P57118, SB9-18) was dated as 26.3 ± 0.1 Ma by Mortimer *et al.* (1998). This is the most precise age obtained from the Norfolk Ridge volcanoes and is important because it is the southernmost one in the linear group of eight. Norfolk Island is the only emergent part of the Norfolk Ridge (Figure 1). K–Ar ages and magnetostratigraphic ages from Norfolk Island lavas lie in the range 2.4–3.2 Ma (Jones & McDougall, 1973, recalculated using new decay constants).

The largest guyot in the group of eight Norfolk Ridge seamounts is the 35 km diameter feature at 26.5°S (Figure 1c, labelled SS01/2003). The flanks are dissected by canyons and the guyot top is possibly tilted from *ca* 700 m water depth in the east to *ca* 1200 m in the west. Several small post-guyot cones are visible on this tilted plateau. The northern part of the seamount was sampled by dredge 10 of the SS01/2003 voyage of the R/V *Southern Surveyor* and andesitic to trachyandesitic lavas were recovered (Crawford, 2004). Dating and analytical results have not yet been published but we suggest a relationship to rocks in International Oceanic Discovery Programme hole U1507. This was drilled *ca* 50 km west of the large volcano at 26.5°S (Figure 1c) and penetrated 864 m of strata of middle Eocene to Pleistocene age comprising mainly nannofossil chalks and foraminifer limestones (Sutherland *et al.*, 2019). In U1507, late Eocene through early Oligocene (*ca* 36–28 Ma) chalk is interbedded with volcaniclastic breccia, conglomerate and sandstone (subunit Ic) and late Oligocene to early Miocene (*ca* 28–19 Ma) chalk with thinner and fewer beds of tuff (subunit Ib). At the time of writing of this manuscript, there is no precise radiometric dating or geochemical information for these U1507 volcaniclastic rocks and tuffs. We speculate that the most likely source of the volcanic breccias was the guyot volcano at 26.5°S, hence the guyot at 26.5°S is possibly dated as *ca* 36–28 Ma.

Tectonic models of Norfolk seamounts volcanism

The above age and geochemical data allow testing of the various hypotheses of origin of the linear alignment of seamounts along the western flank of the Norfolk Ridge. They permit discrimination between age progressive hotspot track, subduction-related arc and other volcanotectonic settings. We are very much aware that direct sampling of any submarine volcano, be it by drilling or dredging, is necessarily limited, incomplete and possibly biased (*e.g.* to younger ages). This is especially the case with reconnaissance-level sampling as reported in this paper.

Not a hotspot track

Islands, seamounts and guyots in the Tasmantid and Lord Howe seamount chains become younger consistently to the south (Figures 1a and 6). The age progressions track the northward motion of the Australian Plate over fixed or semi-fixed deep mantle plumes and indicate a rate of *ca* 60 mm/a. The line of eight volcanoes along the Norfolk Ridge has the same azimuth as the Lord Howe and Tasmantid chains and is thus a plausible additional hotspot track. However, as shown in Figures 1c and 6, ages from four lavas along the Norfolk Ridge, including the northernmost and southernmost, do not become consistently younger to the south, despite the variability in age precision. This is even the case if some allowance is made for restricted age sampling at each Norfolk seamount (dating of individual Tasmantid seamounts suggest volcano lifetimes of up to 3 m.y.; Crossingham *et al*. 2017). The lack of age progression is reinforced if the U1507 volcaniclastic rocks are taken as dating the age of the volcano at 26.5°S. Two combinations of two data points permissibly lie on a 60 mm/a slope in Figure 6 namely GO348 and DR4 and, separately, DR1 and DR7. However no three points are co-linear and, as such, we consider the hypothesis that all eight volcanoes along the Norfolk Ridge are an age progressive hotspot track is provisionally refuted.

Not a coeval volcanic arc

In the Southwest Pacific region there are several known and inferred Cenozoic volcanic arcs – curvilinear chains of volcanoes that formed above subducting slabs. These progressively get older towards the west (Figure 1a), having been stranded by backarc basin formation as the Pacific slab and its trench rolled back to the east. In such a migrationary model of subduction, the line of volcanoes on the Norfolk Ridge, being the westernmost, might be expected to be the oldest, perhaps related to Eocene subduction initiation or to volcanism above a Pacific slab deeper than (and down dip from) the more normal 100–125 km depth of slab dehydration below volcanic arc axes. The oldest known subduction-related igneous rocks from the Three Kings-Loyalty arc are a *ca* 36 Ma boninite (Meffre *et al*., 2002) and a 40 Ma andesite on Bougainville Seamount (Mortimer *et al*., 2014).

One of the simplest observations that suggests the Norfolk seamount lavas are not subduction related is their overall low phenocryst content and near absence of plagioclase; island arc lavas tend to be highly porphyritic (*e.g.* Ewart, 1982). Immobile trace element abundances and ratios in whole rock samples are potentially another way to interpret if ancient volcanic rocks erupted above subduction zones (*e.g.* Pearce 2014). The highly altered condition of the Norfolk Ridge samples have been explained above. And it should be borne in mind that many of the seemingly authoritative tectonic discrimination diagrams of past decades simply do not work as intended, particularly where continental crust is involved (*e.g.* Li *et al*., 2015).

From a geochemical point of view, the best quality sample is the 33 ± 5 Ma DR4B basalt, which has ocean island basalt (OIB) like Nb contents of >60 ppm and therefore no negative Nb or Ta anomaly on a multi-element normalised diagram (Figure 4c); as such it is clearly not subduction related. As cautioned by Li *et al.* (2015) and Mortimer *et al.* (2018), lavas with negative Nb and Ta anomalies like DR1A and DR7C that erupt through continental crust can either be intraplate continental tholeiites or subduction-related lavas. The two alternatives cannot readily be distinguished based on geochemistry alone. That said, most subduction-related basalts have bulk Nb contents <5 ppm (McCulloch & Gamble, 1991); basalts like DR1A and DR7C with un-normalised Nb of 29 and 13 ppm occur only very rarely in subduction zones (*e.g.* Castillo *et al*., 2007 Sulu arc; Sorbadere *et al*., 2013 Vanuatu arc). Although no trace element analyses are available for GO348D1, analyses of pyroxene phenocrysts and presence of biotite phenocrysts (Mortimer *et al*., 1998) suggest this could be a shoshonitic breccia; as noted above, DR1A also has some shoshonitic geochemical features. Mortimer *et al*. (1998) suggested GO348D could have erupted in a backmost arc position above a deep slab. Even if a tentative, loose or broad subduction-influenced (rather than a directly slab-related) origin for DR1A, DR7Ci and GO348D1 is accepted, their age range from 33–21 Ma does not represent an arc of volcanoes that erupted in a limited time range such as either late Eocene or early Miocene.

An intracontinental rift?

The spatial coincidence of the north-south alignment of the eight volcanoes with the pronounced bathymetric edge between the Norfolk Ridge and the New Caledonia Trough suggests the two may be related. A seismic refraction line shot near the VESPA DR1 volcano revealed a *ca* 5 km step in the Moho between the Norfolk Ridge and New Caledonia Trough (Klingelhoefer *et al*., 2007); a corresponding step in the lithosphere-asthenosphere boundary can reasonably be assumed. We suggest that the origin of the eight Norfolk Ridge volcanoes can best be explained in terms of a combination of three previously-proposed petrological and tectonic models: (1) the New Caledonia Trough was a Upper Cretaceous intracontinental rift basin that was substantially deepened during Eocene subduction initiation by foundering of a relict slab (Baur *et al*., 2014; Etienne *et al*., 2018; Sutherland *et al*., 2010, 2020); (2) melting anomalies beneath Zealandia are generated by lithosphere-asthenosphere discontinuities and disturbances and result in widespread, low-volume, intracontinental volcanism (Gamble *et al*., 2018; Hoernle *et al*., 2006); (3) shoshonitic lavas in and around South Fiji Basin, Three Kings Ridge and Norfolk Ridge have distinctively high K and low Nb and Ta, and can be related to rifting of arcs (Gill & Whelan 1989; Mortimer *et al*., 2007, 2014).

Our new, combined model is illustrated in Figure 7. This explains the location, variable age and variable chemistry of the sampled 167°E Norfolk Ridge seamounts

(Figures 4–6). It can also be used as an explanation for the linear alignment of volcanoes along and near the eastern Norfolk Ridge at 168°E (Figure 1b) identified by Rigolot (1988) and dated by Mortimer *et al.* (2014). The first key element is the permanent Paleogene subsidence of the north-south striking New Caledonia Trough with its highly localised deformation (Hackney *et al.*, 2012; Sutherland *et al.*, 2010, 2020) that would have generated steps (relief) in the lithosphere-asthenosphere boundary. In the models of Farrington *et al.* (2010), Conrad *et al.* (2011) and Davies & Rawlinson (2014) (and many others), such steps induce asthenospheric shear which introduces hot mantle which, in turn, melts. Further asthenospheric shear might be introduced by Oligocene–Miocene rifting and opening of the Norfolk and South Fiji basins (Mortimer *et al.* 2014) although the precise position of plate and microplate boundaries at that time is unknown.

That the Norfolk Ridge volcanoes have a range of ages rather than representing a sharp pulse is explained by repeated asthenospheric shear disturbances in the background context of steady northward motion of the Australian lithosphere. The variable chemistry (sodic alkali basalts, tholeiitic basalts and subalkaline potassic shoshonites) is explained by heterogeneous mantle domains in the vicinity of the melting anomalies. High potassium is either a signature of continental crust, metasomatised continental lithospheric mantle, or of deep contemporary slab involvement in petrogenesis. The precise involvement of each geochemical reservoir in the case of the Norfolk Ridge volcanoes is speculative but, since the volcanoes lie close to a continent-ocean boundary, our model can accommodate any of these (Figure 7).

We have moderate rather than complete confidence that our model is correct, but it is testable with more sampling and analysis. The small number of current samples, their altered condition and the wide range in age and chemistry means that it is difficult to convincingly isolate individual igneous processes (which are more numerous than our samples). Volcanic rocks erupted in extensional intracontinental settings such as the Rio Grande, East African, Rhine and Baikal rifts are known to comprise more varied compositional suites than those found in intraoceanic settings (*e.g.* Thompson & Gibson, 1994). The Norfolk Ridge seamount lavas certainly are varied in age and composition. It is, of course, possible that the match between the location of the eight volcanoes and seafloor bathymetry could simply be a coincidence; as shown by Mortimer and Scott (2020), there are vast numbers of other scattered Cenozoic volcanoes and volcanic fields across Zealandia that are seemingly unrelated to bathymetric and lithospheric relief.

Conclusions

Several north-south alignments of volcanoes are present in the northern Zealandia region (Figure 1). Tasmantid and Lord Howe seamount chains are confidently identified as age-progressive intraplate volcanoes, with a deep mantle hotspot-type origin (*e.g.* Seton *et al.*, 2019). Three Kings-Loyalty Ridge is thought to be an Eocene-Miocene subduction-related volcanic arc *(e.g.* Mortimer *et al.*, 2007). We have investigated the origin of eight large seamount volcanoes which form a *ca* 670 km long line along the western flank of the Norfolk Ridge. Ages of dredged rocks from four sites (and volcaniclastic rocks drilled in U1507) range from 33–21 Ma and compositions range from alkali basalt to subalkaline basalt to shoshonitic trachyandesite. Despite the limited sampling, and poor quality of volcanic rocks recovered, we show that the Norfolk Ridge volcanoes probably represent neither an age-progressive hotspot track nor a simple subduction-related volcanic arc. We combine earlier petrological and tectonic models to explain the location of the Norfolk Ridge seamounts by mantle melting near a step in the lithosphere-asthenosphere boundary created during and after the Eocene foundering of the New Caledonia Trough. The variable age and chemistry result from shear-induced melting of heterogeneous mantle, possibly with a subducted slab being involved in the petrogenesis of some of the lavas.

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Data availability statement

Supplementary data are openly available at http://doi.org/10.17600/15001100.

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Figure and Table captions

Figure 1. Location maps. (a) Zealandia. (b) Northern Zealandia. Yellow dashed lines=subduction-related arcs, green dashed lines=confirmed age-progressive chains, thin white dashed lines=refuted and unconfirmed age-progressive chains, orange dashed lines=Norfolk Ridge seamounts (topic of this paper), BS=Bougainville Seamount, LHI=Lord Howe Island, NI=Norfolk Island. (c) Detail of the eight Norfolk Ridge seamounts with dates reported in this paper. On all panels solid red line=continent-ocean boundary.

Figure 2. Bathymetric maps of the four dredge sites at the same scale and with the same colour ramp (a) VESPA DR1. (b) VESPA DR4 (possible fault trace arrowed). (c) VESPA DR7. (d) GEORSTOM 348. Triangles show estimated seabed positions of dredge sites and white lines are ship tracks. For bathymetry data sources see Supplemental File 1.

Figure 3. Selection of hand sample and thin section images of rocks from the four Norfolk Ridge seamount dredge sites. (a-c) VESPA DR1, (d-f) VESPA DR4, (g-h) VESPA DR7, (i) GEORSTOM 348.

Figure 4. Geochemical plots. (a) clinopyroxene Ca+Na vs Ti diagram from Leterrier *et al*. (1982); concentrations per formula unit using six oxygens. Red numbers on figure are mean compositions from Table 1. (b) whole rock Nb/Y vs Ti/Zr rock classification diagram from Pearce (1996). Filled symbols are ICPMS analyses done at Brest (Table 2), open symbols are pXRF analyses done on board *l'Atalante* (data in Mortimer & Patriat, 2016). (c) whole rock multi-element double-normalised diagram using elements, element order and reference samples from Li *et al*. (2015). Primitive mantle normalising values from Sun & McDonough (1989). Elements have also been normalised to Yb_N=10 in order to partially correct for the effects of metasmomatic dilution and magmatic fractionation. (d) whole rock Th/Yb vs Nb/Yb diagram of Pearce (2014) with additional reference fields from Li *et al*. (2015). Grey bar is global MORB-OIB (mid-ocean ridge basalt-ocean island basalt) array. See Supplemental File 2 for raw data tables

Figure 5. Ar–Ar degassing spectra of dated samples (a) VESPA DR1A, (b) VESPA DR4B, (c) VESPA DR7C, (d) GEORSTOM 348. Age uncertainties are ±1 sigma; red portions of spectra are used in age calculations. P57118 is from Mortimer *et al*. (1998). See Supplemental File 3 for raw data tables.

Figure 6. Summary of ages from three northern Zealandia seamount chains. Tasmantid and Lord Howe seamount chain data from Crossingham et al. (2017) and Seton *et al*. (2019); the north-south linear age progression of these Australian Plate seamount chains is *ca* 60 km/m.y. (red and blue dashed lines). The four dated Norfolk Ridge seamounts (black bars, this study) and volcaniclastic strata in the nearby IODP borehole U1507 (grey bar, Sutherland *et al*., 2019) show no such linear age progression.

Figure 7. Generalised and schematic west-east section across northern Zealandia in the Oligocene. Not to scale. Three different regimes of volcanism are shown by colours as in Figure 1: Lord Howe age-progressive chain=green, Three Kings-Loyalty subduction-related=yellow, Norfolk Ridge seamounts intracontinental rift-related (this study)=orange.

Table 1. Average (mean) compositions of clinopyroxenes. GO348D1 data are from Mortimer *et al*. (1998). Individual analyses and means are plotted in Figure 4a. na=not analysed.

Table 2. Whole rock geochemical data. VESPA samples analysed by inductively coupled plasma mass spectrometry and inductively coupled atomic emission spectrometry. GEORSTOM sample analysed by electron probe. wr=whole rock, gmass=groundmass, LOI=loss on ignition.

Table 1. Average (mean) compositions of clinopyroxenes.

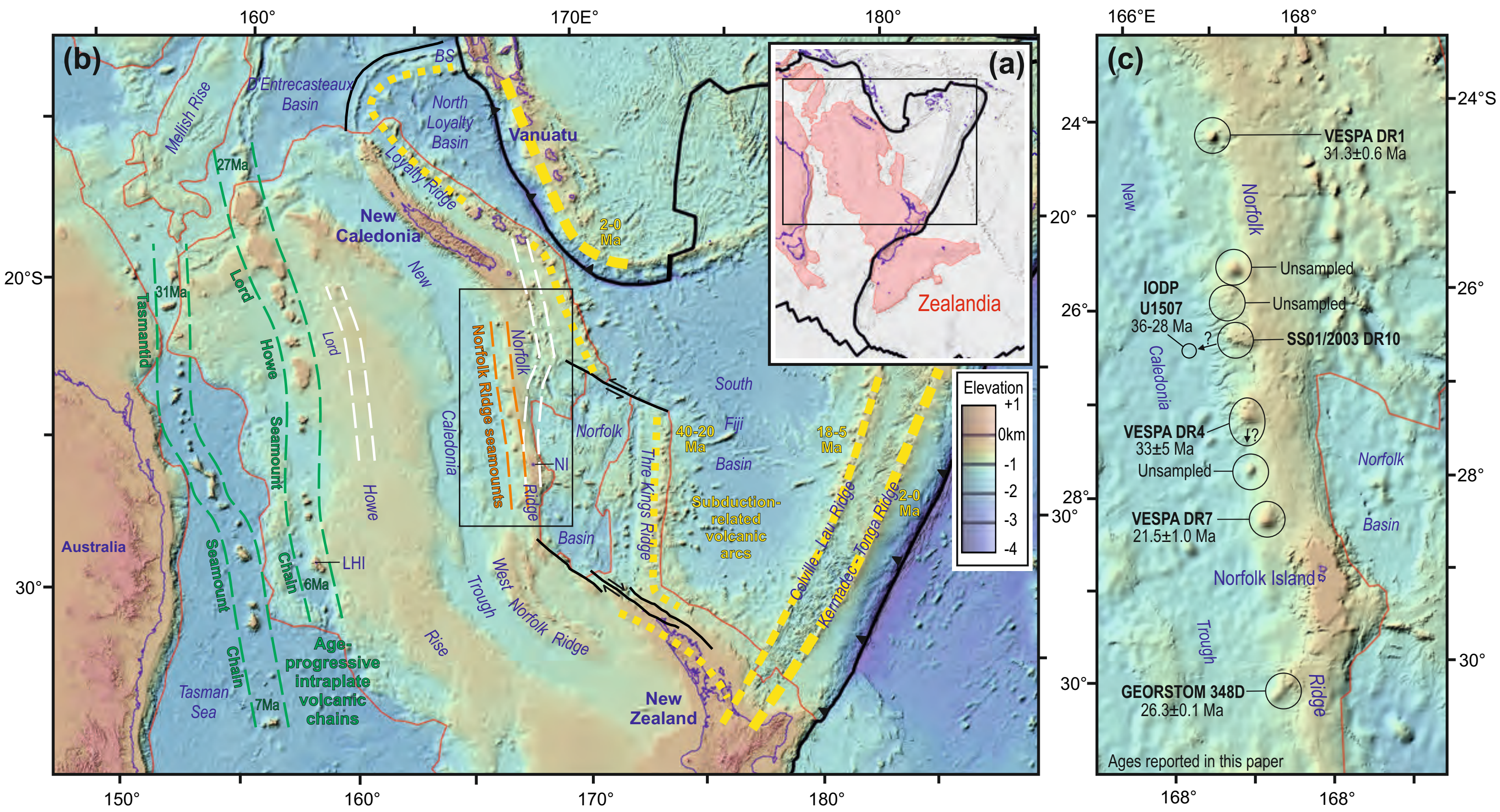
Cruise	VESPA	VESPA	GEORSTOM
Sample	DR01A	DR04B	348D1
GNS P#	84582	84590	57118
# of analyses	17	7	12
SiO_2	48.4	48.6	52.8
TiO_2	1.1	1.1	0.7
Al_2O_3	6.4	5.2	2.0
FeOT	8.6	5.9	7.2
MnO	0.2	0.1	0.2
MgO	12.3	14.1	14.4
CaO	22.9	23.6	22.5
Na_2O	0.6	0.3	0.5
Cr_2O_3	0.1	0.4	na
Total	100.6	99.3	100.3
Mg#	81	92	80
Wo	53	52	48
En	39	44	42
Fs	8	4	10

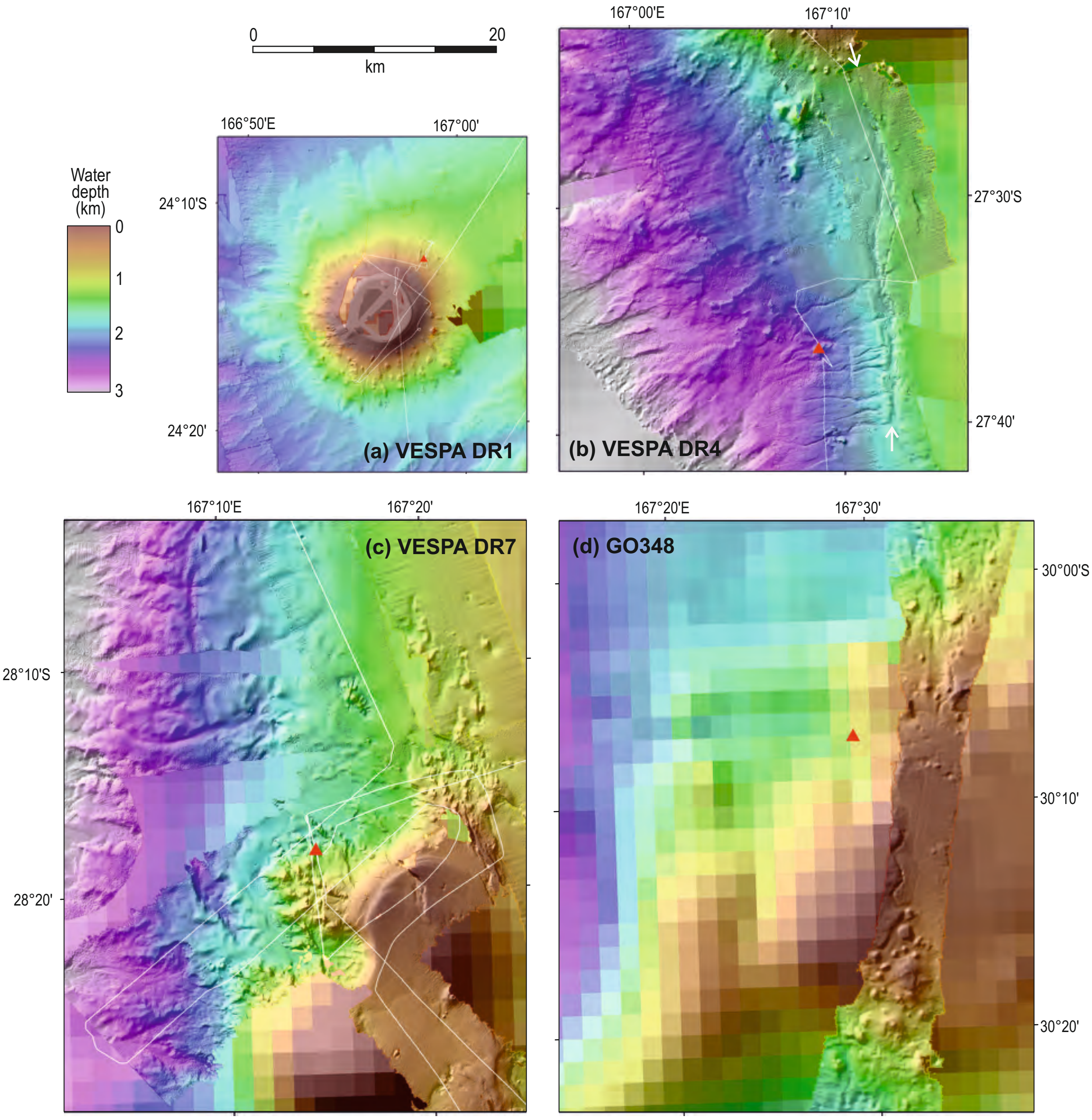
GO348D1 data are from Mortimer et al. (1998). na=not analysed.

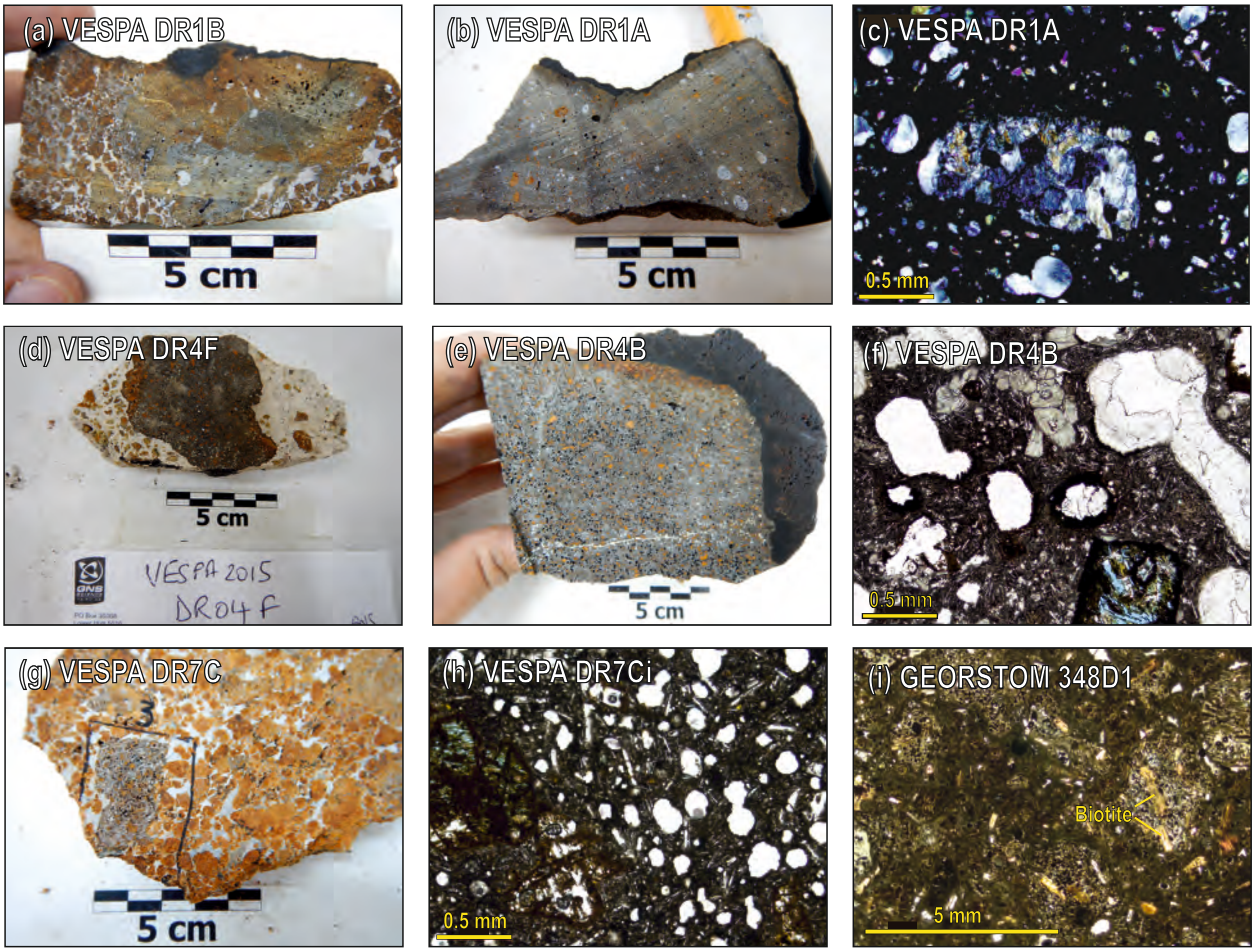
Table 2. Whole rock geochemical data.

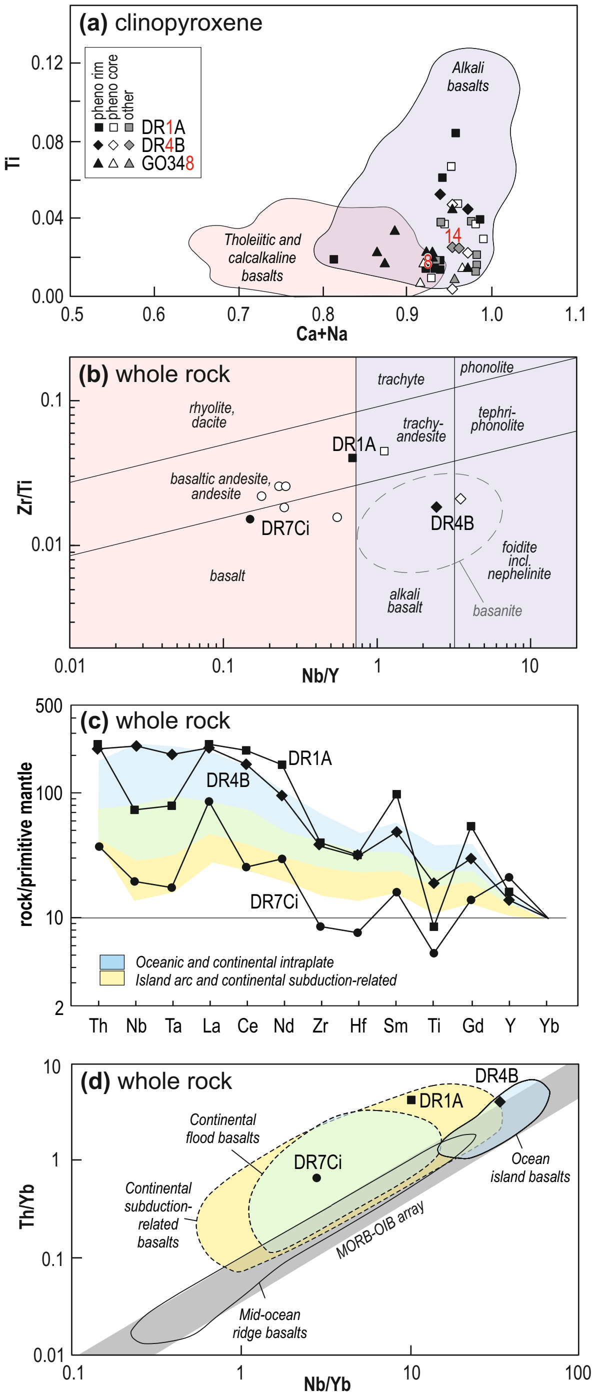
Cruise	VESPA	VESPA	VESPA	GEORSTOM
Sample	DR01A	DR04B	DR07Ci	348D1
GNS P#	84582	84590	84597	57118
Material	wr	wr	wr	gmass
SiO_2 (wt%)	40.69	42.58	31.22	41.1
TiO_2	1.04	1.64	1.06	0.7
Al_2O_3	14.40	15.65	14.09	14.3
FeOT	-	-	-	1.3
Fe_2O_3T	8.61	11.40	10.48	-
MnO	0.15	0.10	0.08	0.1
MgO	6.16	4.87	0.85	2.5
CaO	15.28	12.85	16.44	0.6
Na_2O	2.67	2.46	4.05	3.1
K_2O	2.40	0.99	2.01	3.1
P_2O_5	0.93	1.43	7.92	na
LOI	7.20	5.63	10.93	na
Total	99.55	99.62	99.11	66.8
Li (ppm)	24.5	28.3	6.53	
Be	2.20	1.26	1.52	
Sc	27.6	35.6	44.1	
V	212	248	228	
Cr	374	681	388	
Co	34.4	23.4	20.7	
Ni	145	57.9	88	
Cu	57.9	100	110	
Zn	55.1	96.7	95.0	
Ga	19.8	19.1	12.1	
Ge	3.54	2.51	1.63	
Rb	52.0	16.1	24.8	
Sr	1780	993	737	
Y	41.5	25.2	89.1	
Zr	254	170	87.8	
Nb	29.0	67.6	12.8	
Cs	0.869	0.257	0.076	
Ba	924	584	175	
La	94.0	63.1	54.2	
Ce	218	122	40.9	
Pr	30.1	12.6	8.53	
Nd	130	49.4	36.9	
Sm	24.9	8.71	6.72	
Eu	6.28	2.60	2.20	
Gd	18.5	7.19	7.58	
Tb	2.25	1.00	1.08	
Dy	10.1	5.27	6.78	
Ho	1.48	0.896	1.56	
Er	3.52	2.30	4.71	
Tm	0.453	0.319	0.680	
Yb	2.79	1.96	4.46	
Lu	0.402	0.287	0.739	
Hf	5.65	3.88	2.13	
Ta	1.86	3.29	0.664	
Pb	15.0	5.00	2.29	
Th	11.7	7.83	2.93	
U	2.76	1.77	4.65	
Normalised to LOI=0.0, CaO=9.0, P_2O_5=0.5 wt%				
SiO_2N	48.3	48.5	44.4	56.2
TiO_2N	1.3	1.9	1.5	1.0
Al_2O_3N	17.1	17.7	20.0	19.5
Fe_2O_3TN	10.2	12.9	14.8	1.8
MnON	0.2	0.1	0.1	0.0
MgON	7.3	5.5	1.2	3.4
CaON	9.0	9.0	9.0	9.0
Na_2ON	3.2	2.8	5.7	4.3
K_2ON	2.9	1.1	2.8	4.3
P_2O_5N	0.5	0.5	0.5	0.5

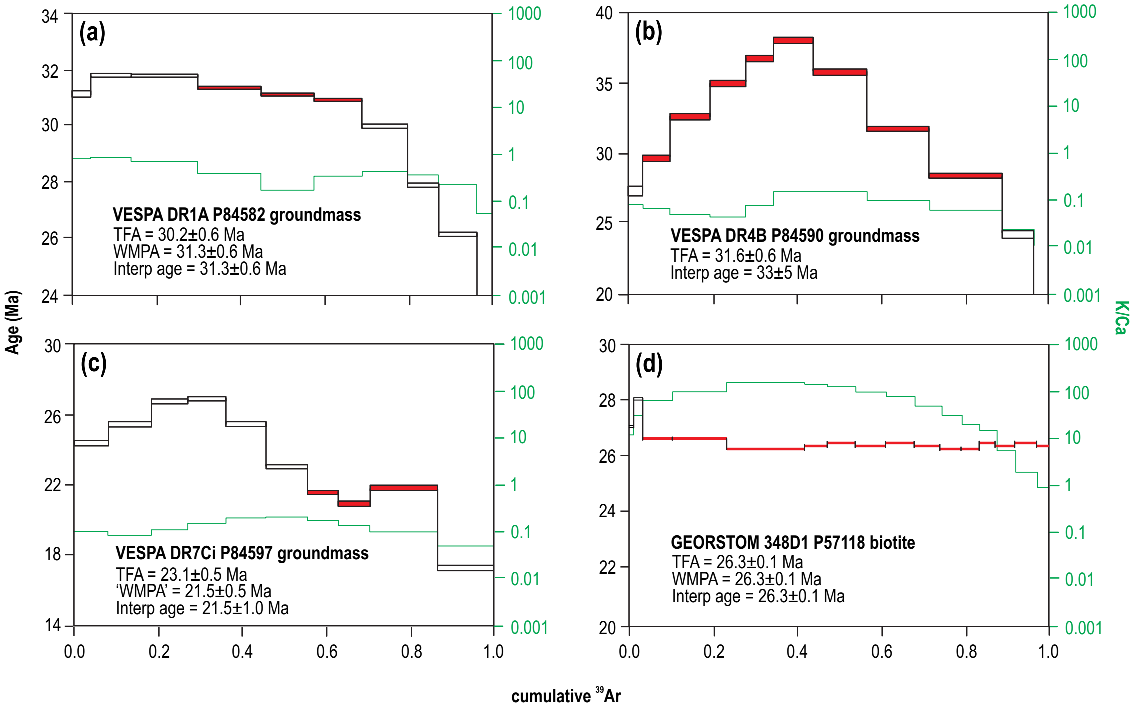
VESPA samples analysed by inductively coupled plasma mass spectrometry and inductively coupled atomic emission spectrometry. GEORSTOM sample analysed by electron probe. wr=whole rock, gmass=groundmass, LOI=loss on ignition.

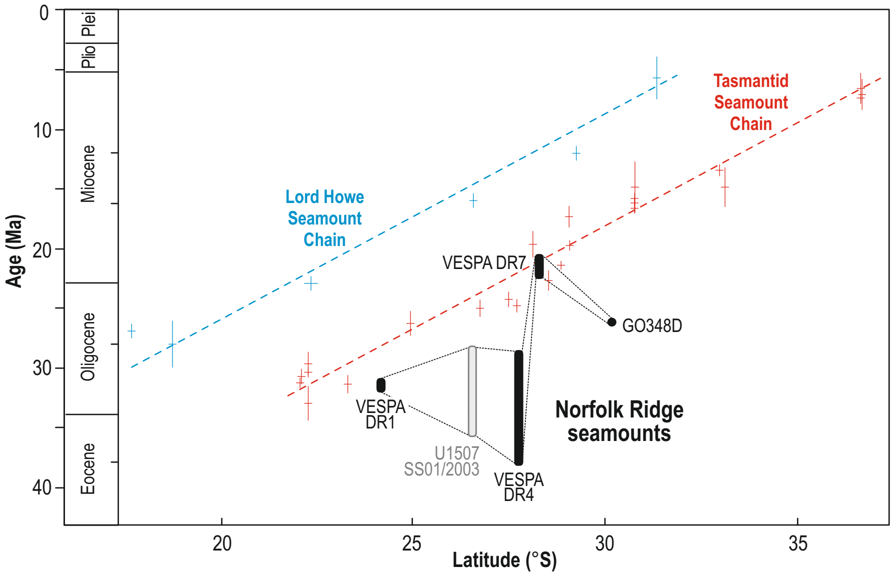
(b)
(a)
(c)
160°
170E°
180°
20°S
30°
150°
160°
170°
180°
24°
20°
26°
28°
30°
BS
D'Entrecasteaux Basin
North Loyalty Basin
Vanuatu
Mellish Rise
27Ma
Loyalty Ridge
New Caledonia
2-0 Ma
31Ma
Tasmantid
Lord
Howe
Seamount
Chain
Lord
Howe
New
Caledonia
Norfolk Ridge seamounts
Norfolk
Ridge
NI
Norfolk
Basin
Thre Kings Ridge
40-20 Ma
South
Fiji
Basin
Subduction-related volcanic arcs
18-5 Ma
Colville - Lau Ridge
Kermadec - Tonga Ridge
2-0 Ma
Australia
Seamount
Chain
Chain
6Ma
LHI
Trough
West Norfolk Ridge
Rise
Tasman Sea
7Ma
Age-progressive intraplate volcanic chains
New Zealand
Zealandia
Elevation
+1
0km
-1
-2
-3
-4
166°E
168°
24°S
26°
28°
30°
168°
168°
VESPA DR1
31.3±0.6 Ma
New
Norfolk
Unsampled
IODP U1507
36-28 Ma
Unsampled
?
SS01/2003 DR10
Caledonia
VESPA DR4
33±5 Ma
?
Unsampled
Norfolk
Basin
VESPA DR7
21.5±1.0 Ma
Norfolk Island
Trough
GEORSTOM 348D
26.3±0.1 Ma
Ridge
Ages reported in this paper

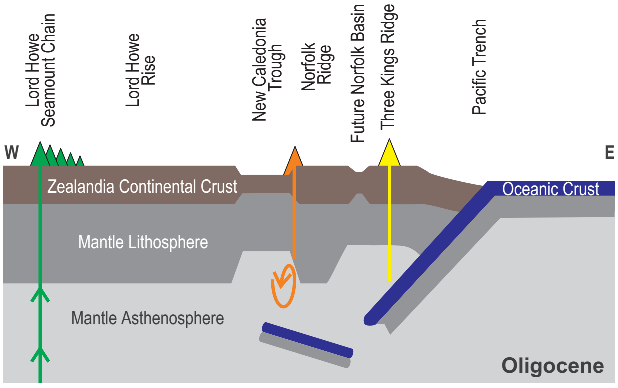

0
20
km
Water depth (km)
0
1
2
3
166°50'E
167°00'
24°10'S
24°20'
(a) VESPA DR1
167°00'E
167°10'
27°30'S
27°40'
(b) VESPA DR4
167°10'E
167°20'
28°10'S
28°20'
(c) VESPA DR7
167°20'E
167°30'
30°00'S
30°10'
30°20'
(d) GO348


(a) VESPA DR1B
5 cm
(b) VESPA DR1A
5 cm
(c) VESPA DR1A
0.5 mm
(d) VESPA DR4F
5 cm
VESPA 2015
DR04 F
(e) VESPA DR4B
5 cm
(f) VESPA DR4B
0.5 mm
(g) VESPA DR7C
3
5 cm
(h) VESPA DR7Ci
0.5 mm
(i) GEORSTOM 348D1
Biotite
5 mm


(a) clinopyroxene
pheno rim
pheno core
other
DR1A
DR4B
GO348
Alkali basalts
Tholeiitic and calcalkaline basalts
14
8
Ti
0.12
0.08
0.04
0.00
Ca+Na
0.5
0.6
0.7
0.8
0.9
1.0
1.1
(b) whole rock
rhyolite, dacite
trachyte
phonolite
trachy-andesite
tephri-phonolite
DR1A
basaltic andesite, andesite
DR7Ci
DR4B
foidite incl. nephelinite
basalt
alkali basalt
basanite
Zr/Ti
0.1
0.01
Nb/Y
0.01
0.1
1
10
(c) whole rock
DR1A
DR4B
DR7Ci
rock/primitive mantle
500
100
10
2
Oceanic and continental intraplate
Island arc and continental subduction-related
Th
Nb
Ta
La
Ce
Nd
Zr
Hf
Sm
Ti
Gd
Y
Yb
(d) whole rock
DR4B
DR1A
Continental flood basalts
DR7Ci
Ocean island basalts
Continental subduction-related basalts
MORB-OIB array
Mid-ocean ridge basalts
Th/Yb
10
1
0.1
0.01
Nb/Yb
0.1
1
10
100


(a)
VESPA DR1A P84582 groundmass
TFA = 30.2±0.6 Ma
WMPA = 31.3±0.6 Ma
Interp age = 31.3±0.6 Ma
34
32
30
28
26
24
1000
100
10
1
0.1
0.01
0.001
(b)
VESPA DR4B P84590 groundmass
TFA = 31.6±0.6 Ma
Interp age = 33±5 Ma
40
35
30
25
20
(c)
VESPA DR7Ci P84597 groundmass
TFA = 23.1±0.5 Ma
'WMPA' = 21.5±0.5 Ma
Interp age = 21.5±1.0 Ma
30
26
22
18
14
(d)
GEORSTOM 348D1 P57118 biotite
TFA = 26.3±0.1 Ma
WMPA = 26.3±0.1 Ma
Interp age = 26.3±0.1 Ma
30
28
26
24
22
20
Age (Ma)
K/Ca
0.0
0.2
0.4
0.6
0.8
1.0
cumulative ^{39}Ar


Age (Ma)
0
10
20
30
40
Plei
Plio
Miocene
Oligocene
Eocene
Lord Howe
Seamount
Chain
Tasmantid
Seamount
Chain
VESPA DR7
GO348D
VESPA
DR1
U1507
SS01/2003
VESPA
DR4
Norfolk Ridge
seamounts
20
25
30
35
Latitude (°S)


Lord Howe Seamount Chain
Lord Howe Rise
New Caledonia Trough
Norfolk Ridge
Future Norfolk Basin
Three Kings Ridge
Pacific Trench
W
E
Zealandia Continental Crust
Oceanic Crust
Mantle Lithosphere
Mantle Asthenosphere
Oligocene