Geophysical and geological characterisation of dredge locations from RV *Southern Surveyor* voyage ss2012_v06 (ECOSATI): hotspot activity in northern Zealandia

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SUMMARY

In October-November 2012 a geophysical mapping and dredging campaign in the eastern Coral Sea was conducted on the RV *Southern Surveyor* during voyage ss2012_v06 (ECOSATI). Part of this campaign was focussed in northernmost Zealandia where volcanic seamounts and uplifted portions of the Lord Howe Rise were targeted to determine the age and location of the northern portion of the Lord Howe Seamount Chain. Geophysical and geological analysis of the dredge sites from the southernmost South Rennell Trough and Chesterfield Plateau confirm the extension of the Lord Howe Seamount Chain ~200 km northward than previously identified, with an age-progression extending to ~27-28 Ma. These new samples, together with previously published samples from the youngest part of the chain, show consistency with both Indo-Atlantic and Pacific hotspots. The average magma flux rate of the Lord Howe hotspot is estimated at 0.4 m^3/s, which is similar to the rates of crustal production at the South Rennell Trough, A peak in magmatism along the trail in the late Oligocene may be related to a slowdown in the motion of the Australian plate sometime between 27-23 Ma. The results of the geophysical and geological sampling and estimates of magma flux from the Lord Howe Seamount Chain will assist in thermal history modelling in the sedimentary basins of northern Zealandia and will help provide a geological framework for frontier resource exploration in this region.

Key words: Zealandia, Lord Howe Seamount Chain, hotspots, magma flux, plate motion, RV *Southern Surveyor*

INTRODUCTION

Zealandia is a predominantly submerged continent lying to the east of Australia (Mortimer et al., 2017a). It comprises the landmasses of New Zealand and New Caledonia and several submerged plateaus, ridges and basins including the Lord Howe Rise, Dampier Ridge, New Caledonia Basin, Fairway Ridge and Basin, Aotea Basin, Challenger Plateau, Reinga Basin, Norfolk and West Norfolk Ridge, Loyalty Ridge and Kenn Plateau (northern Zealandia) and the Campbell Plateau and Chatham Rise (southern Zealandia) (Fig. 1). Northern Zealandia was isolated from eastern Australia in the Cretaceous during the final phase of Gondwana break-up, leading to extensive continental stretching and culminating in the initiation of seafloor spreading in the Tasman Sea (Gaina et al., 1998; Norvick et al., 2008; Tulloch et al., 2009). The largest continental block within Zealandia is the Lord Howe Rise where crustal thickness estimates range from 8-25 km (Grobys et al., 2008). A characteristic of this highly extended continent is that, together with eastern Australia, it hosts one of the world's largest intraplate volcanic fields (Johnson et al., 1989). In Zealandia, this volcanism can be separated into:

1. The age-progressive Tasmantid and Lord Howe Seamount chains (Slater and Goodwin, 1973; Vogt and Conolly, 1971; Wellman and McDougall, 1974) (Fig. 1).
2. Three unnamed linear trends of volcanism, which have no age control to determine if they are age-progressive (Mortimer et al., 2017b) (Fig. 1)
3. Randomly distributed volcanism with no age-progression and varying geochemical signatures, some of which may form regional clusters (Finn et al., 2005; Mortimer et al., 2017b; Timm et al., 2010) (Fig. 1).

In October-November 2012, a geophysical mapping and dredging campaign in the eastern Coral Sea was conducted on the RV *Southern Surveyor* during voyage ss2012_v06 (ECOSATI). As part of this survey, samples were collected from the northern reaches of Zealandia to identify the northern part of the Lord Howe Seamount Chain (Fig. 1). Here, we present the results from two site locations along the Lord Howe Seamount Chain and calculate the magma flux along the entire chain. The geophysical and geological sampling and volume flux estimates in the northern part of Zealandia will help in assessing the spatio-temporal thermal history of the sedimentary basins due to the influence of a mantle plume in this frontier exploration area.

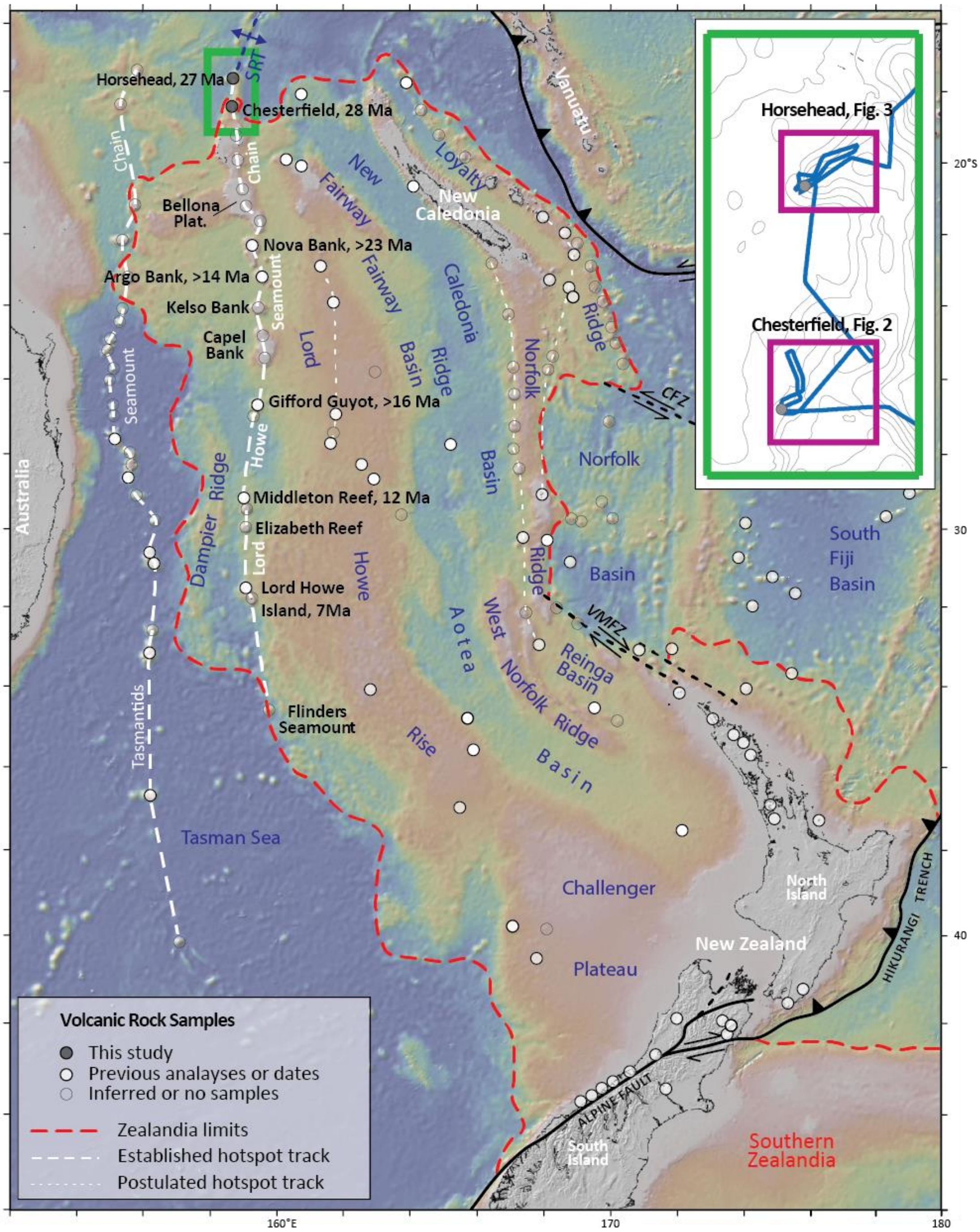

Figure 1: Regional bathymetry of northern Zealandia showing known volcanic rock samples. The seamounts of the Lord Howe chain are labelled with ages taken from Mortimer et al. (2017b). Green box denotes the area shown in the insert. Inset shows bathymetry contours in grey, ECOSATI ship track in blue, dredge sites as grey symbols and the frames of Fig. 2-3 as pink boxes. Figure modified from Mortimer et al. (2017b).

The Tasmantid and Lord Howe Seamount chains are collinear, broadly north-south trending age-progressive volcanic trails that have been demonstrated to record the rapid northward motion of the Australian plate over a relatively slowly moving mantle source (Knesel et al., 2008; McDougall and Duncan, 1988). The Tasmantid Chain can be traced northward just south of the Louisiade Plateau with an oldest age of > 50 Ma based on recent ^{40}Ar/^{39}Ar dating of dredge samples collected during RV *Southern Surveyor* voyage ss2012_v07 (Crossingham et al., 2017; Kalnins et al., 2015). The northernmost identified extent of the Lord Howe seamount trail was previously limited to the Bellona Plateau at the northern end of the Lord Howe Rise (Fig. 1) and tentatively dated to 25 Ma (Exon et al., 2006). However, radiometric dating of volcanic samples from the ECOSATI voyage extend the age range of the trail to ~27-28 Ma and to the southern end of the South Rennell Trough (Mortimer et al., 2017b) (Fig. 1). The southern (younger) part of the

Lord Howe Seamount Chain crosses the Middleton Basin, which may be underlain by highly thinned continental or oceanic crust (Norvick et al., 2008). The youngest dated seamount along the trail is at Lord Howe Island (~7 Ma; (McDougall et al., 1981)), but may extend as far south to the, as yet undated, Flinders Seamount (Fig. 1). The recent results from both trails are broadly consistent with northwards motion of the Australian plate over fixed or slow-moving sources of magmatism within the mantle predicted by global plate motion reconstructions (Mortimer et al., 2017b; Williams et al., 2015). The longevity of the trails suggest a deep plume source for the volcanism (Kalnins et al., 2015), possibly with a genetic relationship to volcanism recorded within eastern Australia during the Cenozoic (Davies et al., 2015; Sutherland, 1983). An implication of the above observations is that sedimentary basins in northern Zealandia, particularly on the Lord Howe Rise, have experienced time-varying influence by mantle hotspots during the last 30 Myrs.

DREDGE SITE AND SAMPLE CHARACTERISATION

Multibeam bathymetry was collected during the ECOSATI voyage using the 30 kHz Simrad EM300 multibeam echo sounder system installed on the RV *Southern Surveyor*. The data were processed and archived by the CSIRO Marine National Facility (MNF) Geophysical Survey and Mapping Team and are discoverable via the MNF Geophysics Data Portal (http://www.cmar.csiro.au/data/gsm). The multibeam data were used for targeting of dredge site locations and to determine seafloor morphology. The swath data were combined with the existing Geoscience Australia bathymetry grid of the region to complete coverage, as presented in Seton et al. (2016a). Slope and azimuth grids were derived for each dredge site location using GMT's gradient function (Wessel et al., 2013).

An A-frame and dredging equipment were used to collect rock samples during the ECOSATI survey. The dredge samples were attained at water depths ranging from 300 to 2600 m. Dredge location and sample data have been lodged in GNS Science's open file Petlab database: http://pet.gns.cri.nz/result_list.jsp?Type=Ext&Cruise=SS2012v6. Detailed descriptions of the petrology, geochemistry and geochronology of the dredge samples can be found in Mortimer et al. (2017b) and photos of the samples can be found in the post-voyage report (Seton et al., 2016b).

DREDGE SITE DR16 - CHESTERFIELD ISLANDS

The Chesterfield Islands are a small group of uninhabited islands and shallow reef systems in the northern part of the Chesterfield Plateau, which is presumed to be floored by continental crust (Terrill, 1975) (Fig. 1). Much of the complex appears to be flat and smooth topped (guyot-like), characteristic of typical carbonate reef accumulation. At our specific site location ~50 km north of the Chesterfield Islands (Fig. 2a), the highest elevation is at approximately 1300 m below sea level, forming a small ~7 km wide peak, with relatively smooth elevations ranging from 1500-1800 m in the northeast. A small knoll and ridge complex in deeper water (down to 3100 m) exists to the west of the plateau. Slopes in excess of > 30° are present (Fig. 2a).

Dredging occurred along profile A (Fig. 2b) starting at a depth of approximately 2630 m at the base of the slope and ending at approximately 2522 m upslope. The dredge recovered pebble-sized pieces of thinly manganese-coated lava and limestone. The lavas included a 4 x 2 x 1 cm angular piece of subtrachytic, sparsely olivine-phyric basalt and three ~~1 cm pieces of olivine-plagioclase porphyritic altered basalt with a subtrachytic groundmass (see Mortimer et al. 2017b for detailed description). The geochemistry of these samples are consistent with those collected from the younger seamounts of the Lord Howe Seamount Chain (convex-up multi-element normalised patterns) (see Mortimer et al. (2017b)). A preferred Ar-Ar age for one of the samples is 28.1 ± 1.0 Ma and another gives a minimum age of 23 Ma (Mortimer et al., 2017b).

The Bellona Plateau (just to the south of the Chesterfield Islands) has previously been interpreted as the site of the northernmost part of the Lord Howe Seamount Chain and inferred as either Middle Eocene or younger (Missègue and Collot, 1987) or about 25 Ma based on hotspot migration rate estimates (Exon et al., 2006). The results of Mortimer et al. (2017b) and our study confirm that intraplate volcanism occurred on the Chesterfield Plateau with the morphology suggesting a larger volume of material was erupted at this site than at the younger seamounts that make up the Lord Howe Seamount Chain. The timing of eruption occurred sometime between 23-28 Ma, consistent with Exon et al. (2006).

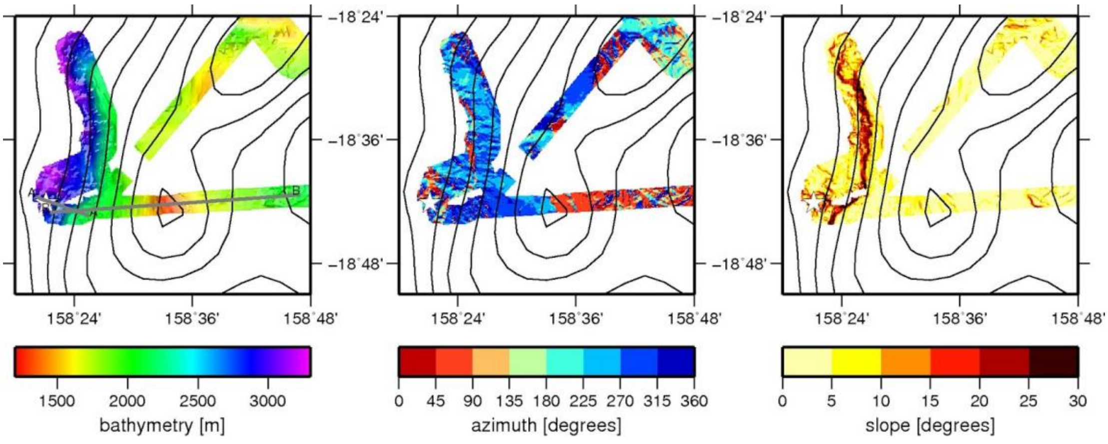

Figure 2a: Swath bathymetry, azimuth and slope grids of DR16 at the Chesterfield Islands with gravity contours in 20 mGal intervals (black lines) (Sandwell and Smith, 2009). Dredge site location (white star) and profiles along which bathymetry profiles were taken (grey lines). Letters denote profile names.

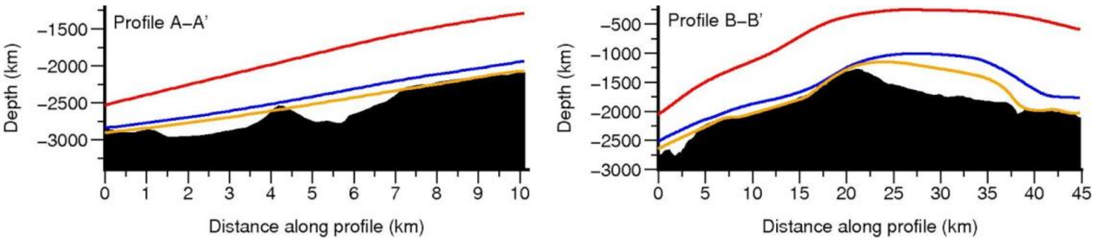

Figure 2b: Bathymetry profiles across the DR16 site location based on the swath data (black), GEBCO dataset (red), ETOPO1 (blue) and Smith and Sandwell satellite-derived bathymetry (orange). See Figure 2a for location of profiles.

DREDGE SITE DR15 - HORSEHEAD SEAMOUNT

At the southern termination of the South Rennell Trough, an Oligocene extinct spreading centre (Larue et al., 1977; Mortimer et al., 2014), lies a flattish, slightly convex feature with two distinct elevated areas separated by a featureless (perhaps highly sedimented) ~2300 m deep trough. This site location has been unofficially named the Horsehead seamount by Mortimer et al. (2017b) due to its shape in regional bathymetry compilations. The elevated area to the northeast is characterised by a small (15 km wide) swell that defines a top peak elevation of 1300 m below sea level. The elevated area to the west and south is a flattish feature between 1700-1900 m (Fig. 3). This plateau may have been built up over time with the edges of several terrace-like features at depths of 2800 and 3100 m (Fig. 3a), similar to those that exist on carbonate platforms, appearing in both the bathymetry and slope grids. The gradual slope in the southwest corner appears to be a debris flow sourced from the platform.

DR15 targeted a steep slope in the southwestern corner (Fig. 3), hitting bottom at 2537 m at the base of the slope and dragged upslope along profile A (Fig. 3b) to approximately 1900 m. The dredge yielded predominantly hard cream-colored shallow water limestone, manganese crusts and small (0.5-3 cm diameter) pieces of lava. The lavas were age-dated using the Ar-Ar method and analysed for their geochemistry (see Mortimer et al. (2017b) for detailed descriptions). In summary, the geochemistry of the lavas indicates a basaltic composition, with multi-element normalised patterns typical of intraplate basalts (Mortimer et al., 2017b). Ar-Ar dates from the lavas give a preferred (igneous) age of 27.24 ± 0.24 Ma. Clasts embedded in the hard limestone produce a late Early Miocene age, which is consistent with the older ages of the lavas found at this site.

The morphology of the dredge site and the intraplate basaltic composition of the lavas indicate that there is likely to be a volcanic edifice that underlies the platform with extensive carbonate platform growth, erosion and subsidence (of at least 1500 m) at this site. The geochemical signatures and ~27 Myr old age are broadly consistent with age estimates based on hotspot trail modelling (Mortimer et al., 2017b).

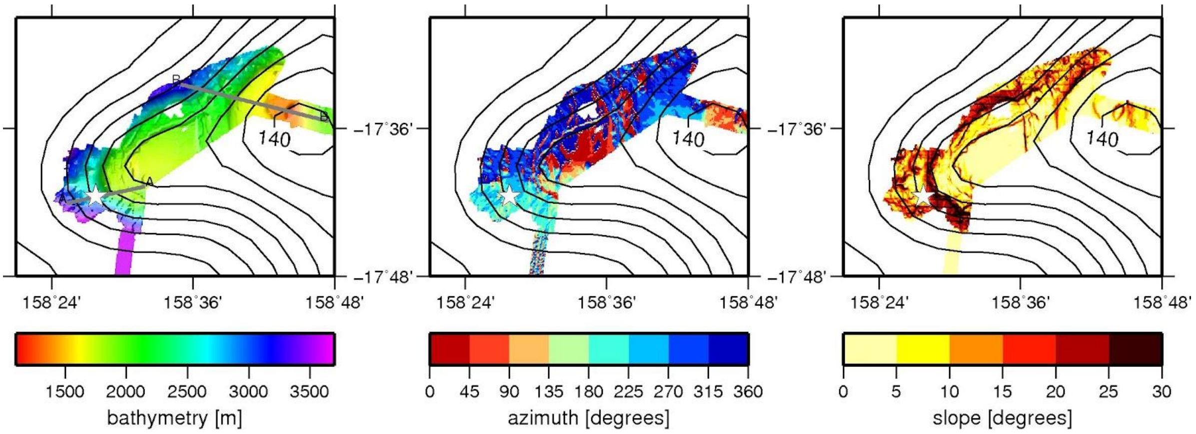

Figure 3a: Swath bathymetry, azimuth and slope grids of DR15 at the Horsehead. Lines, symbols and annotations same as in Fig. 2a.

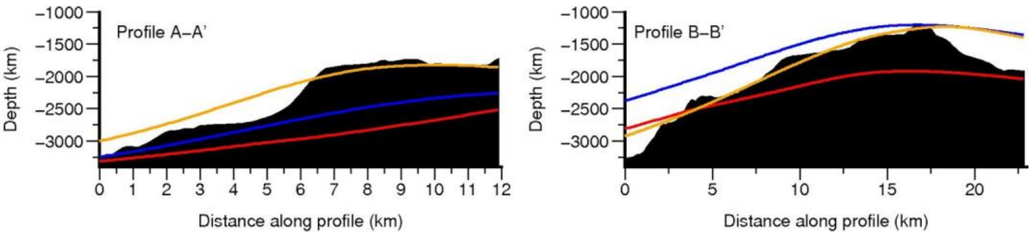

Figure 3b: Bathymetry profiles across the DR15 site location. Lines are the same as in Fig. 2b. See Figure 3a for location of profiles.

MAGMA PRODUCTION ALONG THE LORD HOWE SEAMOUNT CHAIN

Volume calculations of the volcanic edifices along a hotspot trail can provide an important first-order relationship between the mantle and surface plate motions. Previous studies have outlined methods to estimate the variation of volume flux of a plume through time (Wessel, 2015; White, 1993). These methods utilise bathymetry data to define the size of plume-related volcanic edifices, together with radiometric dates from individual seamounts and reconstructions of absolute plate motion relative to the underlying mantle. Studies of volume flux for the Hawaiian seamount trail illustrate the need to consider both the volcanic edifices and a longer wavelength bathymetric swell (Vidal and Bonneville, 2004; Wessel, 2015). The superposition of these two signals amounts to a regional-residual separation problem, and where the swell amplitude is significant (as is the case for Hawaii), the precise choice of methodology to achieve this separation will strongly influence the derived flux values. The Lord Howe hotspot, in common with the nearby Tasmantid hotspot, is not associated with any clear bathymetric swell either at the inferred present-day hotspot location or along their trails, resulting in zero or negligible estimates of present-day buoyancy flux (King and Adam, 2014). Regional seismic tomography (Fichtner et al., 2010) shows that the present-day plume location does not correspond to a pronounced low velocity zone in the upper mantle. Thus, we have chosen to disregard any swell component within our analysis and focus solely on the volcanic edifices. The analysis is further complicated by variations in the nature of the crust into which volcanic material has been emplaced. In the case of the Lord Howe Seamount Chain, this spans both oceanic and stretched continental lithosphere and includes regions such as the Middleton Basin where the nature of the crust remains unclear. Given these complexities, we adopt a deliberately simplistic approach, excluding flexural effects. As illustrated by Wessel (2015) for the Hawaiian trail, the absolute values of flux estimates are significantly influenced by the methods and assumptions used to derive them - however, the first-order trends in terms of periods of relatively high or low flux rate are generally consistent between different studies.

To make basic estimates of magma production along the Lord Howe Seamount Chain, we used bathymetry derived from satellite altimetry (Smith and Sandwell, 1997). Using this bathymetry, we calculated variations in Moho depth assuming Airy isostasy, using densities of 2800 kg/m^3 for the volcanic load, 3300 kg/m^3 for the mantle, and 1030 kg/m^3 for seawater. We manually defined a polygon around the regions of excess volcanism associated with the Lord Howe Seamount Chain (Fig. 4a), generated a bathymetry grid in which the observed bathymetry values within the polygon are masked and filled by smoothly interpolating values from the surrounding area - this constitutes the regional grid for the regional-residual separation. The difference between the observed and regional bathymetry yields a map of volcanic edifice thickness; combining this with the estimates of Moho depth yield a map of the total excess crustal thickness (edifice plus compensating crustal root, Fig. 4b). As a sensitivity study, this process was repeated using a regional bathymetry compilation (Seton et al., 2016a), which included the detailed swath data from our dredge sites. As expected, our results show negligible difference in the resultant crustal thickness estimates between the two datasets, consistent with the small difference observed along profiles at the dredge sites (Fig. 2b and 3b).

To illustrate how the magmatism has varied in space and time, we plot the volume of excess estimated volcanic crust in latitudinal bins (5 arc-minutes, ~8 km in width). This provides a first-order impression of the volume of magmatism versus time, since the overall absolute motion of the Australia plate in a mantle reference frame has been consistently northwards over the last >30 Myr, at an average velocity of ~60 mm/yr. However, this figure does not directly account for changes in plate motion during this time period (Fig. 4c). The age progression from the more highly sampled Tasmantid trail, and Australian onshore volcanism, is interpreted to show a transient deceleration in Australia's northward motion in the late Oligocene, lasting 3-6 Myrs (Crossingham et al., 2017; Knesel et al., 2008). The new age constraints from the Horsehead and Chesterfield sites support the view that the kinks in the Tasmantid and Lord Howe trails formed roughly contemporaneously. The volume versus latitude plot for the Lord Howe Seamount Chain (Fig. 4c) shows a pronounced peak that broadly corresponds to this time of interpreted transient plate motion change. This may reflect slower motion of the plate over a hotspot source, enhanced volcanic flux triggered by changes in plate motion and intraplate stress fields, or some combination of these processes. Another alternative to explain the peak in magma flux is that it is associated with plume temperatures at the start-up phase of volcanism, as has been documented in Iceland (Spice et al., 2016). However, it is unknown whether the Horsehead and Chesterfield sites mark the start-up phase of volcanism along this trail and secondly, edifice volumes along the Tasmantid trail calculated by Crossingham et al. (2017) also peak in the late Oligocene suggesting that the increase in magma flux may be more regional in nature.

Over the last >20 Myr, the dominant trend within the Lord Howe trail is one of decreasing output, consistent with a waning plume not associated with any swell or strong mantle seismic velocity signature at the present day. The trail is characterised by individual seamounts whose size generally diminishes and spatial separation increases with decreasing latitude and emplacement age. Variations in magma output within the >25 Myr lifespan of the trail may result from plume pulsation, changes in plate motion, or spatial variations in the lithosphere (Davies et al., 2015; Sreejith and Krishna, 2015; Wessel, 2015). A gap of 250 km (~4 Myr) exists between the Gifford and Middleton sites in which negligible magmatism is suggested based on both bathymetry and from seismic profiles that image undisturbed sediments where the trail would have passed under the Middleton Basin (Norvick et al., 2008). Our estimate for the total volume of volcanic crust emplaced along the entire trail is around 320,000 km^3, which equates to an average flux rate of 0.4 m^3/s. While only a tentative estimate, this flux is an order of magnitude smaller than the present flux at Hawaii (e.g. Wessel (2015)), but closer to fluxes calculated for sections of the Hawaiian trail >30 Myr old. The total volume of magmatism produced along the Lord Howe trail suggests a similar rate of crustal production to the South Rennell Trough, which ceased spreading roughly contemporaneously with the initiation of Lord Howe trail 'intraplate' volcanism. One hypothesis consistent with these observations is that mantle upwelling associated with the Lord Howe trail is genetically related to upwelling beneath the South Rennell Trough spreading centre. When spreading at the South Rennell Trough ceased due to the soft collision of the Ontong Java Plateau (Seton et al., 2016a), the upwelling could no longer find an outlet at a divergent plate boundary and switched into an intraplate hotspot mode.

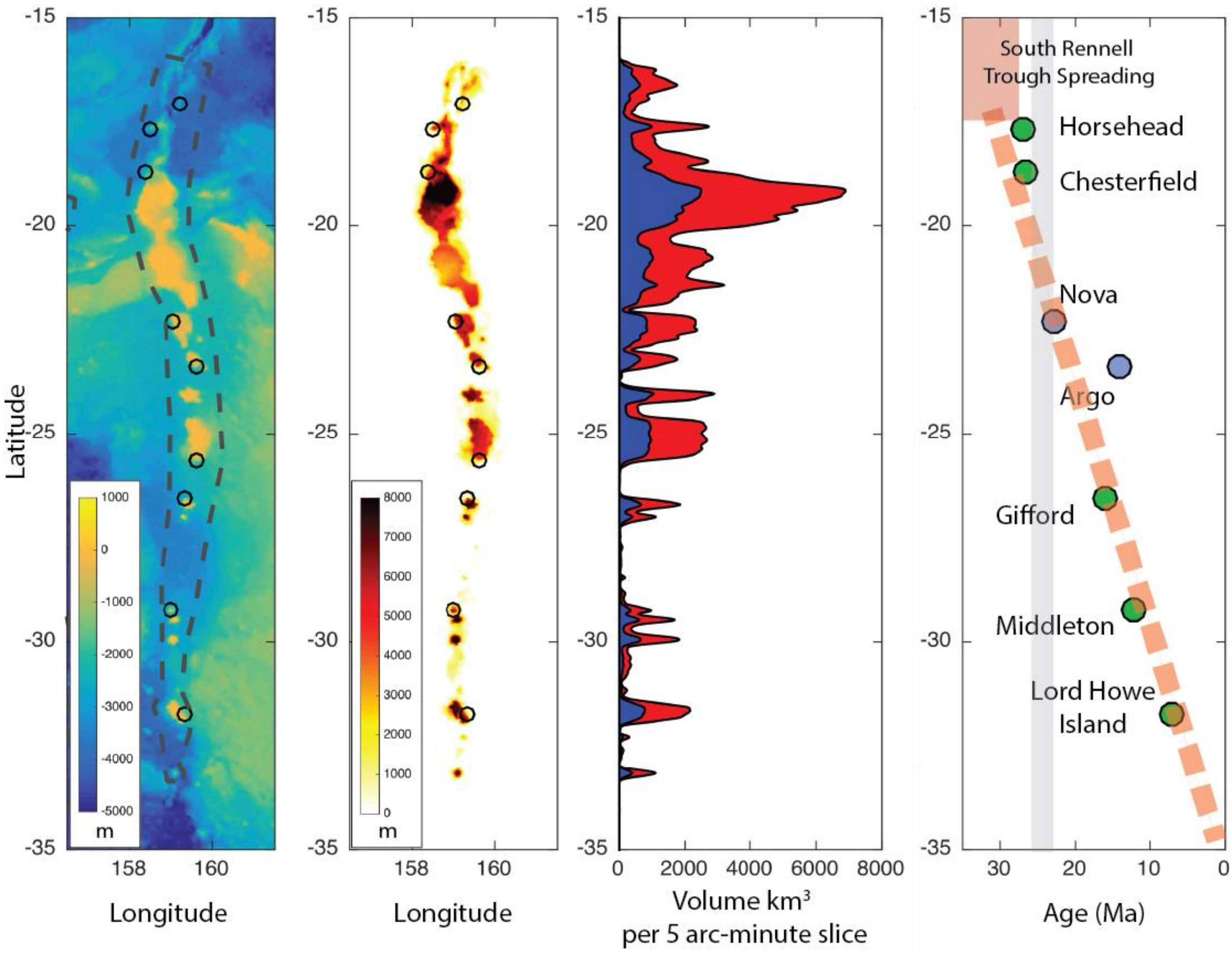

Figure 4: Estimates of volume of volcanism along the Lord Howe hotspot trail. (a) Bathymetry data (Smith and Sandwell, 1997) - the dashed grey line shows the polygon to perform the regional-residual separation (b) Residual crustal thickness derived by subtracting regional bathymetry (with seamounts removed) from the crustal thickness assuming Airy isostasy, (c) volume of crust within 5 arc-minute latitude slices; blue region shows volume of edifice, red area shows area of edifice plus compensating crustal root (d) geological ages for samples from Lord Howe trail seamounts, with green symbols denoting radiometrically-dated volcanic samples and blue symbols denoting limestones (see Mortimer et al. (2017b)). Faint grey stripe denotes approximate time range of transient slowdown in Australia's northward motion (Knesel et al., 2008).

CONCLUSIONS

The results from the ECOSATI research voyage on the RV *Southern Surveyor* have shown that the Lord Howe Seamount Chain extends north at least as far as the southern termination of the South Rennell Trough. The age of the oldest part of the chain is dated at ~27-28 million years, consistent with models of Australian plate motion. The average flux rate of the trail is estimated at 0.4 m^3/s, with similar rates to crustal production at the South Rennell Trough. A peak in magmatism in the late Oligocene, also a characteristic of the Tasmantid trail, may be related to a slowdown in Australian plate motion. Although there are many sources for intraplate volcanism within northern Zealandia, especially volcanism with no spatio-temporal relationships, the calculation of extent, timing and average flux rates from the Lord Howe Seamount Chain has important implications for assessing the thermal history and transient uplift of the sedimentary basins of northern Zealandia and should be incorporated into basin models in this frontier exploration area.

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