Late Cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana

N. Mortimer, P. van den Bogaard, K. Hoernle, C. Timm, P.B. Gans, R. Werner, F. Riefstahl

PII: S1342-937X(18)30228-4
DOI: doi:10.1016/j.gr.2018.07.010
Reference: GR 2017

To appear in: *Gondwana Research*

Received date: 25 January 2018
Revised date: 25 July 2018
Accepted date: 25 July 2018

Please cite this article as: N. Mortimer, P. van den Bogaard, K. Hoernle, C. Timm, P.B. Gans, R. Werner, F. Riefstahl , Late Cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana. Gr (2018), doi:10.1016/j.gr.2018.07.010

Late Cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana

N. Mortimer[a], P. van den Bogaard[b], K. Hoernle[b,c], C. Timm[d], P.B. Gans[e], R. Werner[b] F. Riefstahl[f]

[a]GNS Science, Dunedin 9054, New Zealand
[b]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
[c]Christian-Albrechts University of Kiel, Germany
[d]GNS Science, Lower Hutt 5040, New Zealand
[e]University of California, Santa Barbara, CA 93106, USA
[f]AWI Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

Highlights

- New $^{40}Ar/^{39}Ar$ dates from SW Pacific and Zealandia igneous rocks form the basis of a revised tectonic model
- Intraplate lavas erupted onto continental, LIP and oceanic crust from 99 to 78 Ma
- Spreading ridges and transforms adjusted themselves around a collided Hikurangi Plateau
- Kinematically stable Pacific-Antarctic spreading became established from c. 84 Ma
- Osbourn Trough Sea floor spreading possibly ceased at c. 79 Ma

Keywords
Igneous rocks, $^{40}Ar/^{39}Ar$ geochronology, Cretaceous, Gondwana, Zealandia, Pacific Plate

Abstract

New $^{40}Ar/^{39}Ar$ ages of igneous rocks clarify the nature, timing and rates of movement of the oceanic Pacific, Phoenix, Farallon and Hikurangi plates against Gondwana and Zealandia in the Late Cretaceous. With some qualifications, cessation of spreading at the Osbourn Trough is dated c. 79 Ma, i.e. 30-20 m.y. later than 110-100 Ma Hikurangi Plateau-Gondwana collision. Oceanic crust of pre-84 Ma is confirmed to be present at the eastern end of the Chatham Rise, and a 99-78 Ma intraplate lava province erupted across juxtaposed Zealandia, Hikurangi Plateau and oceanic crust. We propose a new regional tectonic model in which a mechanically jammed Hikurangi Plateau resulted in the dynamic propagation of small, kinematically misaligned short-length 110-84 Ma spreading centres and long-offset fracture zones. It is only from c. 84 Ma that geometrically stable spreading became localized at what is now the Pacific-Antarctic Ridge, as Zealandia started to split from Gondwana.

1. Introduction

The SW Pacific region (Fig. 1) underwent major tectonic and geological change in the Cretaceous Period (145-66 Ma). For much of the Mesozoic, the continent-ocean margin between SE Gondwana and the crust of the paleo-Pacific was convergent and characterised by the development of Cordilleran batholiths and accretionary complexes (Mortimer et al., 2014). Sometime between 110 and 85 Ma this tectonic regime was interrupted and/or replaced by a passive margin and widespread intracontinental rifting and volcanism (Bradshaw, 1989; Luyendyk, 1995; Tulloch et al., 2009). This intracontinental rifting culminated in the breakup of Gondwana, such that by 83 Ma (anomaly 34ny; Seton et al., 2014) new oceanic crust had started to form between the continents of Australia, Antarctica and Zealandia (Stock and Cande, 2002; Wright et al., 2016; Mortimer et al., 2017a). Meanwhile, in the ocean basins the eruption of 125-115 Ma large igneous provinces (LIPs) such as Ontong Java, Manihiki and Hikurangi Plateaus took place, likely as a single superplateau (Taylor, 2006; Davy et al., 2008; Hoernle et al., 2010; Timm et al., 2011; Chandler et al., 2012; Hochmuth et al., 2015).

There has been much speculation on the cause and effect between rapid Cretaceous spreading, LIP eruption, LIP collision, and the change in continental tectonic regime (Luyendyk, 1995; Mortimer et al., 2006; Downey et al., 2007; Davy et al. 2008; Tulloch et al. 2009; Davy, 2014; Hochmuth and Gohl, 2017). Satellite gravity maps (Sandwell and Smith, 1997) have provided extremely useful insights into kinematic aspects of oceanic crust tectonics. But the dearth of sampled rocks, particularly from the widespread oceanic crust of Cretaceous Normal Superchron (121-83 Ma) age (Fig. 1), has hindered our ability to date the age of events, and hence define spreading rates and tectonic events.

This paper increases our knowledge of SW Pacific tectonics by providing new $^{40}Ar/^{39}Ar$ ages of igneous rocks, particularly in the critical parts of the large and difficult-to-access oceanic crust northeast and east of Zealandia (Fig. 1). The direct dating provides a critical check on oceanic crust ages inferred from magnetic reversals. This paper is relevant to, and develops, themes of Ontong Java Nui Large Igneous Province (LIP) breakup and collision (Larson et al., 2002; Taylor, 2006; Davy et al., 2008, Hoernle et al., 2010; Chandler et al., 2012; Hochmuth and Gohl, 2017; Barrett et al. 2018), SW Pacific volcanism (Mortimer et al., 2006, 2017b; Tulloch et al., 2009; Timm et al., 2010; van der Meer et al., 2016), and SW Pacific-Zealandia-Antarctica Cretaceous tectonics (Luyendyk, 1995; Sutherland and Hollis, 2000; Larter et al., 2002, Eagles et al., 2004; Wright et al., 2016). Our data clarify the age and rate of breakup of the Hikurangi Plateau part of the Ontong Java Nui LIP and our tectonic model emphasises the role of LIP collision in controlling subsequent continental and oceanic magmatic and tectonic events. This is a companion paper to Homrighausen et al. (2018) in which trace element and isotopic data for some of the dated samples are described and discussed.

2. Geological background

2.1 Oceanic crust east of Zealandia

Lying east of the Kermadec Trench, the Osbourn Trough is an east-west trending fossil spreading ridge that split the once contiguous Hikurangi and Manihiki Plateau LIPs (Fig. 1; Billen and Stock, 2000; Taylor, 2006, Downey et al., 2007). Rocks dredged from the Osbourn Trough axial valley and drilled at International Ocean Discovery Program (IODP) Site U1365 are altered lavas of normal mid-ocean ridge basalt (N-MORB) composition (Worthington et al., 2006; Zhang et al., 2012). All or most of the oceanic crust between the two LIPs is believed to have formed c. 118-83 Ma during the Cretaceous Normal Superchron (e.g., Seton et al. 2014, fig. 1), but the exact time of inception, rates of spreading and time of cessation of spreading at the Osborn Trough have been the subject of debate. Geophysical estimates of the age of cessation of spreading at the Osbourn Trough range between 105 and 71 Ma, and are based on magnetic anomaly interpretations, abyssal hill fabrics and/or regional tectonic considerations (Billen and Stock, 2000; Worthington et al., 2006; Downey et al., 2007; Davy et al., 2008).

There are no published dates of rocks directly dredged from the Osbourn Trough. However, rocks at DSDP site 595 and the adjacent IODP site U1365, both c. 250 km north of the Osbourn Trough (Fig. 1) have been dated and potentially offer an important age constraint on the spreading history of the Osbourn system. Montgomery and Johnson (1987) reported $^{40}Ar/^{39}Ar$ whole rock total fusion ages of 96.8 ± 0.6 and 101.5 ± 0.6 Ma (DSDP 595B, 4-2, 13-16), which they regarded as minimum eruptive ages. In contrast, Sutherland and Hollis (2000) reported radiolarians of late Berriasian-Valanginian age (144-132 Ma) from near the base of the sedimentary section in DSDP 595 and of Cenomanian age (99-94 Ma) in nearby DSDP 596. More recently, Zhang and Li (2016) reported a 103.7 ± 2.3 Ma Re-Os isochron age for basalts in U1365. Previous estimates of the geological age of basement at DSDP 595/U1365 therefore range from c. 132 to c. 104 Ma.

The oldest ocean floor marine magnetic anomaly that is recognised along the entire length of the southern Zealandia margin and through to the Tasman Sea is 33ry (74 Ma; Stock and Cande 2002). Northeast of Bollons Seamount (Fig. 1), there is general agreement that anomaly 34ny (83 Ma) is present (Stock and Cande, 2002; Larter et al., 2002; Davy, 2006; Wright et al., 2016) and that, to the east, it connects with the trace of the Tongareva Triple Junction (TTJ) (Larson et al., 2002). A large triangular area between the TTJ, Manihiki Scarp and Bollons Seamount is poorly surveyed and its age and spreading patterns are undemonstrated.

2.2 Zealandia intraplate lavas

The Zealandia continent has a geological record of scattered, low-volume intraplate volcanism over the last c. 100 Ma that is not related to subduction or to hotspot tracks (e.g., Weaver and Smith, 1989; Panter et al., 2006; Hoernle et al., 2006; Tulloch et al., 2009; Timm et al., 2010; Mortimer et al., 2017b; van der Meer et al., 2017). This intraplate volcanism - the Horomaka Supersuite (Mortimer et al., 2014) - shares some common ages and compositions with intraplate volcanism in formerly adjacent West Antarctica and Australia (Finn et al., 2005). The initial eruption of intraplate (mainly alkaline) lavas, and intrusion of associated plutons has long been recognised to be associated with the syn-rift (c. 105-85 Ma) phase of South Gondwana breakup (e.g., Bradshaw, 1989; Tulloch et al., 2009, and references therein).

3. Samples and methods

Samples were obtained from several sources including Sonne 168 dredges, the International Ocean Discovery Programme core repository, newly collected onland samples and existing samples in the GNS Petrology Collection (Table 1; Fig. 2). All samples prefixed "P" refer to the GNS Science Petrology Collection. Sample data are lodged in the PETLAB database (http://pet.gns.cri.nz; Strong et al., 2016).

Dating of most samples was done at GEOMAR, Kiel using step heating and single crystal laser fusion $^{40}Ar/^{39}Ar$ methods, as described in supplementary files of Hoernle et al. (2010) and Timm et al. (2011). Plagioclase separates were acid-leached with 5% HF prior to dating; matrix separates were ultrasonically washed in distilled H_2O. The neutron flux was monitored using Taylor Creek sanidine with an age of 27.92 Ma. K/Ca ratios, percent of atmospheric ^{40}Ar and calculated $^{36}Ar/^{37}Ar$ alteration index (AI) values (Baksi, 2007) were used to determine the degree of alteration of the laser step-heating or total fusion analyses. Inverse isochron ages were calculated to confirm both the plateau and total fusion ages and identify if the samples preserved initial atmospheric $^{40}Ar/^{36}Ar$ ratios, without the presence of extraneous ^{40}Ar components (i.e., an atmospheric $^{40}Ar/^{36}Ar$ ratio of 295.5). Statistically valid weighted mean plateau ages have a well-defined age spectrum plateau created by three or more continuous and concordant steps overlapping at the 2σ confidence level, with >50% of the cumulative ^{39}Ar, a mean square of weighted deviations (MSWD) ≤2, and probability (P) of fit is >0.05. For three samples (P63810, P63853 and P63854), $^{40}Ar/^{39}Ar$ dating was done at the University of California Santa Barbara (UCSB) using step heating methods described by Gans (1997). Major elements and Cr, Ni, Zr, Sr of whole-rock samples were determined by X-ray fluorescence methods as described in Timm et al. (2010). Raw data and plots are given in Supplementary Files. All errors in $^{40}Ar/^{39}Ar$ ages are reported at two sigma level and include errors in the J value (reactor neutron flux).

At latitudes 40°S and higher, there is the risk of dredging iceberg-rafted dropstones of Antarctic origin rather than *in situ* material (e.g., Mortimer et al., 2016). Dredges of dropstones tend to be unweathered, thinly manganese-coated and include very different rock types that are rounded or faceted in shape. The dredged samples reported in this paper showed some weathering rinds, often had thick Mn encrustations, and were single rock types that were angular in shape and/or had broken faces, all consistent with an *in situ* origin.

4. Data

4.1 Osbourn MORB lava

Whole rock chemical analysis of DSDP 595A sample P63853 confirms a Pacific N-MORB composition that matches other samples from the plate between the Osbourn Trough and Manihiki Plateau (Fig. 1; Saunders, 1987; Thomas, 2002; Worthington et al., 2006; Castillo et al., 2009; Zhang et al., 2012). This is especially evident in Fig. 3 where the basalt is seen to be subalkaline and with the moderate Ti/V of MORBs.

Our dated DSDP595 samples P63853 and 63854 are from basalt unit 2 (Saunders, 1987). This underlies unit 1 and is thus not the youngest recognised unit in the borehole. Step heating $^{40}Ar/^{39}Ar$ dating of plagioclase from P63853 at Kiel revealed a gas release spectrum in which 92% of the gas gave a statistically valid weighted mean plateau age of 84.4±3.5 Ma (Fig. 4A). Alteration indices (Baksi, 2007) for most of these steps are acceptably low (<0.001, see supplementary files). However, many of the steps in the plateau have high percentages of atmospheric argon, and we cannot entirely rule out the effects of seawater alteration. Step heating $^{40}Ar/^{39}Ar$ dating of hard, grey matrix from the same sample, P63853 at UCSB (Table 1) gave a gas release spectrum that was hump-shaped with flattish middle parts at c. 80-86 Ma (figure in Supplementary Files). K/Ca values were low (0.01-0.05). Clearly this is not a fresh basalt, as indicated by the c. 1.6 wt% loss on ignition of the whole rock (see Supplementary Data). The young apparent ages in hump-shaped spectra like this usually reflect a combination of argon loss from minerals or glass at the low temperature steps and reactor-induced recoil in the higher temperature steps. But it is impossible to evaluate how much argon loss there has been so we regard c. 82 Ma as a minimum age for the lava as established from the weighted mean of the oldest three steps. This is within error of the plagioclase age of P63853 dated at Kiel. Matrix from a lava 12 m deeper in DSDP595A (P63854) was also dated at UCSB. It has slightly higher K/Ca (0.01-0.25) than matrix from P63853. It also gave a similar gas release spectrum except that the steps at the top of the hump ranged from c. 79 to 87 Ma. We regard c. 86 Ma as a minimum age for this sample, again based on the age of the oldest three steps.

All things considered, we tentatively regard the plagioclase step-heating age of 84.4±3.5 Ma as possibly approximating the age of crystallisation of the unit 2 lava flow in DSDP 595A, an age supported by the minimum ages of matrix in two samples. A comparison of this age with other Osbourn Trough lava ages is given in the Discussion below.

4.2 Intraplate lavas: eastern Zealandia

We dated lava samples from four seamounts and one fault scarp near the eastern Zealandia margin (Table 1; Fig. 2). Three analysed samples are basaltic-basanitic and two are trachytes (Fig. 3). In simple petrotectonic terminology, they are intraplate lavas. Like Cenozoic intraplate lavas from Zealandia (Hoernle et al. 2006; Timm et al. 2009, 2010) the basalts show a range of silica saturation.

Feldspars from Kakapo, Erik, Frankfurt and Western Uprising lavas were dated by single crystal laser fusion $^{40}Ar/^{39}Ar$ methods at Kiel. Some single crystal fusion ages were excluded from weighted mean calculations because of their high $^{36}Ar/^{37}Ar$ based alteration indices (Baksi, 2007). Relatively high percentages of atmospheric ^{40}Ar in some samples, particularly 63-1fs and 67-1fs may also be indicative of seawater alteration (Baksi, 2007) but we provisionally interpret weighted mean single crystal ages as unreset eruptive ages (selected examples are shown in Fig. 4). The $^{40}Ar/^{39}Ar$ ages from the seamounts range from 85-79 Ma (Table 1; Supplementary Files).

In the Bollons Gap lava P63810, adularia (replacing plagioclase) was dated by furnace step-heating at UCSB. The spectrum is flat with single step ages ranging from 77.9 to 78.2 Ma (Fig. 4E) with very high K/Ca (30-60) and high radiogenic yields (95-96%) throughout. All of the steps define a high precision inverse isochron with an age of 77.65 ± 0.26 Ma (2σ), a trapped Ar component with a $^{40}Ar/^{36}Ar$ ratio of 337 ± 7. We interpret this age as the age of K-feldspar formation in the basalt. Because the adularia is a metasomatic mineral, this is a minimum age for the basalt eruption rather than dating the cooling of the lava flow.

4.3 Intraplate lavas and dikes: South Island

We dated material from six lavas and dikes in the northern South Island (Fig. 1), that potentially were related to the lavas described in section 4.2. Step heating methods at Kiel were employed. Chemically, the lavas are basanites, basalts and trachybasalts, and Ti/V ratios indicate an intraplate setting of eruption or intrusion (Fig. 3).

Matrix from Lottery River basanite MSI 31 gives a plateau age of 94.8 ± 1.6 Ma which we interpret as approximating the age of crystallisation of the basalt. The immediately surrounding rocks are Cookson Volcanic Group basalts, well dated as Oligocene (Rattenbury et al., 2006; Timm et al., 2010, $^{40}Ar/^{39}Ar$ ages = 31.2 ± 0.6, 26.6 ± 0.3 and 25.8 ± 0.5 Ma). Because our dated sample is a stream cobble (not *in situ*) and Cretaceous, it probably is derived from a dike cutting greywacke basement upstream in the Seaward Kaikoura Ranges (Rattenbury et al., 2006 map no volcanic rocks in the catchment). Basaltic float samples MSI 47M (coarse-grained) and MSI 46A (porphyritic) were collected from the lower Clarence River. The Clarence River drains a large area of the Seaward and Inland Kaikoura Ranges, and the samples could have come from Wallow Group lavas, numerous dikes that intrude greywacke basement or, more likely for the coarse-grained rock, the main Tapuaenuku Igneous Complex from which alkaline gabbros are reported (Rattenbury et al., 2006). Biotite in MSI 47M gave a good plateau age of 96.5 ± 0.3 Ma and plagioclase a good plateau age of 94.3 ± 0.5 Ma. We interpret the older, biotite age to approximate best the crystallisation age of the basalt (Table 1) but give data for both splits in the Supplementary Files. Plagioclase from MSI 46A gave a plateau age of 94.4 ± 0.6 Ma (Table 1).

Two samples of matrix from a basalt flow from the Lookout Formation (Wallow Group) in the Awatere Valley gave ages of 95.4 ± 0.5 Ma and 97.5 ± 0.5 Ma (Supplementary Files). The older sample had a higher % radiogenic argon and lower MSWD, and we chose that one as being closest in age to the crystallisation of the flow (Table 1; Fig. 4F). Float in Strauchon Creek on the South Island west coast contains cobbles of basanite, presumed to be float of Hohonu Dike Swarm. Amphibole phenocrysts from two separate samples, NZS1 and P45280, give analytically indistinguishable ages of 82.8 ± 0.3 Ma and 82.7 ± 0.3 and have almost identical chemistry. These ages compare with $^{40}Ar/^{39}Ar$ amphibole ages of 88 and 87 Ma for two other float sanples from Strauchon Creek (van der Meer et al., 2013).

These new South Island ages complement and add to the growing body of dated Late Cretaceous Horomaka Supersuite volcanic, hypabyssal and plutonic rocks from across the Zealandia continent (e.g., Tappenden 2003; Tulloch et al., 2009; van der Meer et al., 2016; Mortimer et al., 2017b).

5. Discussion

5.1 Osbourn Trough spreading system

DSDP 595 is in a sparsely surveyed region (Fig. 1). Available nearby multibeam bathymetry, single channel seismic reflection lines and satellite gravity maps indicate tectonic continuity, and no identifiable fracture zones, between the DSDP 595 site and the Osbourn Trough. DSDP 595 is c. 200 km off-axis from the main Osbourn Trough and knowledge of the age of the DSDP 595 basalts provide a date on the later spreading history of the ridge system. A 78.8±1.3 Ma age from Osbourn Seamount at the northwestern end of the Louisville Seamount Chain (Koppers et al., 2004) provides a minimum age for Osbourn Trough spreading.

Previous direct age interpretations of 144-132 Ma have been made on microfossils from DSDP 595 (Sutherland and Hollis, 2000): this is by far the oldest claimed age, and was used by Sutherland and Hollis as the basis for their Moa Plate, an extra Early Cretaceous oceanic microplate next to the Gondwana margin. The age is puzzling as it predates the formation of the Ontong Java Nui superplateau (Taylor, 2006; Hoernle et al., 2010; Timm et al., 2011; Chandler et al., 2012; Hochmuth et al., 2015) whereas DSDP 595 is located in the breakup region between the Hikurangi and Manihiki plateaus (Fig. 1). Following Downey et al. (2007) we explain the Early Cretaceous microfossils as being reworked, and not necessarily representative of the true stratigraphic age of DSDP 595. Speculatively, the microfossils could be derived from Early Cretaceous accretionary complexes along the Gondwana-Zealandia margin or from abyssal ooze on or near one of the LIPs.

More recently, Zhang and Li (2016) have reported a 12 point Re-Os whole rock isochron age of 103.7 ± 2.3 Ma (MSWD 3.2) for basalts in IODP-U1365, 15 km west of DSDP 595A (so co-located at the scale of Fig. 1). Despite the care taken by Zhang and Li (2016), dating basalts by the Re-Os isochron method is not without potential problems. We note that the MSWD of 3.2 for the Re-Os isochron of Zhang and Li (2016) is slightly high for acceptable isochrons, and there is a correlation between Re content and loss on ignition, suggesting that alteration may play a role in forming the correlation between $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ interpreted as an isochron. Furthermore, the large range of initial Os, Nd, Hf and Pb isotope ratios for U1365 basalts is not consistent with all samples having been derived from a homogeneous source and thus the criteria for original isotopic homogeneity and closed system behaviour (necessary for a positive correlation between $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ to have age significance and thus be a meaningful isochron) are not met. Anomalously old isochron ages in basalts resulting from binary mixing without complete isotopic equilibrium have been reported by Li et al. (2016). Other potential issues include 1) ultra-low concentrations of Os, resulting in the melts being particularly sensitive to crustal contamination, 2) a peridotite-pyroxenite issue that can skew the $^{187}Os/^{188}Os$ ratio, 3) possible correlated errors between $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$, and 4) lack of common Os corrections of blanks (Zimmerman et al., 2014). As noted by Zhang and Li (2016), the initial $^{187}Os/^{188}Os$ ratio of the U1365 basalts (0.196 ± 0.080) is much higher than found in fresh modern Pacific N-MORB (~0.127; e.g., Snow and Reisberg, 1995). Thus, we do not regard Zhang and Li's (2016) c. 104 Ma age of U1365 basalts as an eruptive age. Instead the $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ correlation is likely to reflect a mixing line between a MORB source mantle component and a radiogenic crustal component assimilated by the magmas during ascent (cf. Tejada et al., 2013).

Our c. 84 Ma $^{40}Ar/^{39}Ar$ plagioclase age from DSDP 595 could also be criticised as not being an eruptive age as plagioclase is regarded as being somewhat vulnerable to resetting during post-eruption alteration. However, the UCSB minimum ages are consistent with the GEOMAR age, the Baksi alteration indices are acceptably low (Supplementary Files), and there is no evidence of tectonism, reheating or later dikes at DSDP 595 (Fig. 2; Saunders, 1987). The rest of this paper is written on the basis that an 84 Ma age rather than a 104 Ma age for DSDP595/U1365 volcanism is correct. However, since lavas with MORB chemistry can erupt tens of millions of years after spreading cessation (e.g., O'Connor et al. 2015), and seawater alteration can lead to spuriously young ages, we acknowledge that further sampling and dating from this region is desirable. The assumed c. 84 Ma age for DSDP 595 basalt in this paper should be used with caution.

Taking an age of inception of Osbourn spreading as 115 Ma (Mortimer et al., 2006), an 84 Ma age for DSDP 595 and a DSDP 595-Manihiki plateau separation distance of 1200 km gives an average half spreading rate on the Osbourn system of c. 40 mm/a. This is slower than the >70 mm/a half spreading rate interpreted by Zhang et al. (2012) based on basalt compositions and c. 110 mm/a using a 104 Ma age (Fig. 6). All these spreading rate calculations are approximate as all three inputs are still poorly known: the exact timing of rifting of the Hikurangi and Manihiki plateaus, choice of distance between plateaus and Osbourn Trough, and error limits on the DSDP 595 age. The K/Ar and $^{40}Ar/^{39}Ar$ ages of oceanic crust immediately east of the Tonga Trench reported in Thomas (2002) are very scattered and do not show any clear age-latitude co-variation (Figs. 1, 6); however, they do support the general Late Cretaceous age of sea floor spreading. As previously noted, DSDP 595 is not located at the Osbourn Trough, but lies north of it. At a 40 mm/a half spreading rate, the age difference between basalts at DSDP 595 and those at the trough axis would be c. 5 m.y., so the implication is that spreading would have ceased at the Osbourn trough at c. 79 Ma. The 79 Ma age for inferred spreading cessation is younger than the age of Cretaceous Magnetic Superchron. Billen and Stock (2000) interpreted anomalies 33 and 32 to be present in the vicinity of the Osbourn Trough and thus our 84 Ma age at DSDP 595 is in agreement with their interpretation.

5.2 Oceanic crust age constraints

Two seamounts, Hünchen and Pukeko lie north of the tip of Zealandia on oceanic crust. These have been dated by Homrighausen et al. (2018) as 85.5±3.3 Ma and 81.2±0.5 Ma respectively. The ages of these seamounts are important in that they provide minimum ages for the underlying oceanic crust and independently confirm the presence of Cretaceous normal superchron, pre-86 Ma, oceanic crust immediately southeast of the West Wishbone Scarp.

About 1000 km further southwest along the Zealandia continent margin is Bollons Seamount (Fig. 1), and our dated intraplate lavas from Bollons Gap. According to Davy (2006) Bollons Seamount lies close to magnetic anomaly C34ny. If the adularia in the Bollons Gap lava either grew soon after eruption and/or is related to movement on the Bollons Fracture Zone, its 78 Ma age dates the timing of separation of Bollons Seamount from Zealandia. As such it corroborates the models of Sutherland (1999) and Davy (2006) in which Bollons Seamount (Fig. 1) is interpreted to have been stranded in its position off Zealandia by a ridge jump near the end of chron 33r to just after the start of chron 33n i.e. 78-80 Ma.

5.3 Zealandia syn-rift intraplate magmatism

The pre-breakup phase of Gondwana margin rifting is generally thought to have taken place in the interval 105-85 Ma (Bradshaw, 1989; Luyendyk, 1995; Mortimer et al., 2014 and references therein). Tulloch et al. (2009) identified silicic magmatic pulses throughout Zealandia at c. 101, c. 97 and 88-82 Ma. For the most part, our new ages data on igneous rocks from the South Island and from the eastern continent-ocean margin region, match and reinforce the two younger intraplate magmatic pulses (Figs. 1, 5). This was manifested as extensive c. 85-82 Ma tholeiitic volcanism on the Chatham Islands (Panter et al. 2006), c. 99-67 Ma seamount volcanism on the Hikurangi Plateau (Hoernle et al. 2010), 86-79 Ma volcanism around the tip of easternmost Zealandia (Homrighausen et al. 2018; this study), and 98-83 Ma ages in the South Island (e.g., van der Meer et al. 2013; this study).

5.4 Hikurangi Plateau-Gondwana collision

The collision or docking of the Hikurangi Plateau LIP against the Chatham Rise part of Zealandian Gondwana has been cited as a primary cause of numerous Cretaceous geological events including cessation of local subduction of oceanic crust beneath Gondwana, cessation of spreading at the Osbourn Trough, Alpine Schist metamorphism, exhumation of the schist basement of the Chatham Rise and localisation of the position of the Cenozoic Alpine Fault Pacific-Australia plate boundary (Vry et al., 2004; Davy et al., 2008; Reyners, 2013; Cooper and Ireland, 2013; Davy, 2014; Mortimer et al., 2016; Mortimer, 2018).

Although the Late Cretaceous plate interface is clearly imaged in seismic reflection profiles (Davy et al., 2008; Bland et al., 2015; Barrett et al., 2018), drilling and dating of critical horizons needed to directly establish the age of plateau collision against the Chatham Rise has not yet been done. The best indirect estimate for the time of collision of the Hikurangi Plateau with Gondwana, based on relatively near-field effects, is 108±11 Ma based on the rapid exhumation of a partial He retention zone in zircons of the schist basement of the Chatham Islands (Mortimer et al., 2016). This is in accord with the cessation of subduction-related magmatism and accretion in the Zealandia part of Gondwana at 110-100 Ma (Bradshaw, 1989; Mortimer et al., 2014) and widespread inception of post-subduction intraplate magmatism across Zealandia by c. 100 Ma (see section 5.3 above).

It has been implicit or stated in some earlier models that the cessation of Osbourn Trough spreading occurred simultaneously with Hikurangi Plateau-Chatham Rise collision (e.g., Worthington et al., 2006; Downey et al., 2007; Davy et al., 2008; Davy, 2014). In other words, there was an implied effect of collision causing spreading to cease almost simultaneously. If our new c. 79 Ma inferred age for the cessation of Osbourn Trough spreading is accepted (section 5.1, Fig. 6), instead suggests that sea floor spreading continued for another 20-30 m.y. after LIP-Gondwana collision.

6. Tectonic model

Our new age data require changes to previous tectonic models of the region (e.g., Bradshaw, 1989; Weaver et al., 1994; Luyendyk, 1995; Sutherland and Hollis, 2000; Larter et al., 2002; Eagles et al., 2004). Key new points in Fig. 7 are a potentially relatively young (c. 79 Ma) cessation of spreading at the Osbourn Trough and demonstration of an area of pre-83 Ma oceanic crust between the West Wishbone Scarp and magnetic anomaly C34ny.

The Ontong Java Nui superplateau formed in the Pacific Ocean basin between 125 and 117 Ma and breakup of the superplateau commenced from 117-115 Ma (Larson et al., 2002; Mortimer et al., 2006; Taylor, 2006; Davy et al., 2008; Chandler et al., 2012). At that time, the oceanic crustal plate or plates of the paleo-Pacific Basin were converging on Gondwana generating the Median Batholith and Torlesse accretionary wedge (Fig. 7A; Mortimer et al., 2014). We agree with Sutherland and Hollis (2000), Davy et al. (2008) and Davy (2014) that collision of the Hikurangi Plateau was indeed the prime cause of 110-100 Ma subduction cessation at the Zealandia part of the then Gondwana margin (Fig. 7B). However, spreading at the Osbourn Trough did not necessarily cease then but could have continued for up to another 20-30 m.y.

The persistence or resumption of spreading around the jammed Hikurangi Plateau took place to the east of the plateaus (present day geographic coordinates). The Manihiki Scarp is a rift edge feature with oceanic crust to the SE and dates from c. 119 Ma (Larson et al., 2002). Mortimer et al. (2006) proposed that, from 115 Ma, the West Wishbone Scarp was, likewise, a SE-facing intra-oceanic rift edge and was obliquely cut by the East Wishbone Ridge and a parallel, un-named fault (Fig. 1). Eagles et al. (2004) were the first to suggest that the West Wishbone Scarp was formerly co-linear and conjoined with the Manihiki Scarp, a proposition with which we agree. By c. 105 Ma the West Wishbone and Manihiki scarps had started to move apart on the East Wishbone Scarp which transferred motion from the Osbourn Trough and of the Tongareva Triple Junction (Fig. 7B). The 86-81 Ma ages of intraoceanic seamounts around the eastern tip of the Chatham Rise allow assignment of minimum ages to the Cretaceous Normal Superchron crust SE of the West Wishbone Scarp. From 95-80 Ma, progressive mechanical misalignment of the SEmigrating spreading system along the long-offset Wishbone Scarp eventually led to abandonment of the Osbourn Centre spreading and all Pacific-West Antarctica plate motion was taken up on the more southerly spreading system that broke Zealandia off Gondwana (Fig. 7C). The best constraint on the age of new seafloor between the eastern Chatham Rise and West Antarctica is the K-feldspar age of 83.9 ± 0.1 Ma from trachyte DR66-1 from Erik Seamount, representing a minimum age for the inception of seafloor spreading in this region. In the interval 80-60 Ma, Bollons Seamount was initially attached to West Antarctica but a ridge jump stranded it in its present position as, with time, spreading propagated to the SW further splitting Zealandia from West Antarctica and establishing the spreading system that persists today (Fig. 7D).

The tectonic events to the west of the Hikurangi Plateau are necessarily more speculative because that crust has since subducted beneath the Kermadec Arc (Fig. 1). The full and original size of the Hikurangi Plateau is inferred to be about double its present day exposed area (Hoernle et al. 2010; Reyners et al., 2011; Timm et al., 2014). The Osbourn Trough likely continued west (present day coordinates) and it is possible that the west side of the Hikurangi Plateau was the site of a major transform, possibly a subduction-transform edge propagator (STEP) fault (Govers and Wortel, 2005). Conceivably, the spreading systems to the west of the Hikurangi Plateau were as complex as those to the east.

7. Conclusions

New geochronological data from Late Cretaceous igneous rocks in the SW Pacific-New Zealand region highlight regional changes in tectonomagmatic regime from subduction to a rift and intraplate setting to stable seafloor spreading. Cessation of long-lived subduction at the SE Gondwana margin is reasonably attributed to collision of the Hikurangi Plateau at 110-100 Ma. Widespread but low-volume intraplate volcanic rocks erupted in the interval 99-78 Ma across Gondwana/Zealandia continental lithosphere, oceanic crust and Hikurangi Plateau. Based on new dating of DSDP 595 basalts, we propose that Osbourn Trough spreading could have ceased at c. 79 Ma rather than earlier as proposed by previous workers. However, more material and more dating will be needed before this result can be used with confidence. Following collision, a regime of dynamically changing ridge and transform spreading patterns was arrayed around the east edge of the collided Hikurangi

Plateau. From c. 84 Ma the spreading pattern became simplified and focussed on the Pacific-Antarctic ridge that split Zealandia away from Gondwana.

Acknowledgments

We thank the Captain and crew of F/S *Sonne* 168 "Zealandia" cruise for dredged rocks and the IODP/DSDP core repository for providing the DSDP 595 samples. The New Zealand Ministry of Foreign Affairs and Trade gave permission to use the data obtained from Bollons Gap. We also thank John Simes, Belinda Smith Lyttle and Jenny Black for technical assistance, and Karsten Gohl, Bryan Davy and Hamish Campbell for discussions. An earlier version of the manuscript was improved by comments from Quinten van der Meer and an anonymous referee. The German Ministry of Education and Research (BMBF; grant SO168 Zealandia), the DFG (grants HO18/12-1 and 2), GEOMAR Helmholtz Centre for Ocean Research and the New Zealand Government (core grant to GNS Science), are gratefully acknowledged for providing funding for this project.

References

Baksi, A.K., 2007. A quantitative tool for detecting alteration in undisturbed rocks and minerals - I: water, chemical weathering, and atmospheric argon. Geological Society of America Special Paper 430, 285–303.

Barrett, R.S., Davy, B., Sterm, T., Gohl, K., 2018. The strike-slip Wishbone Ridge and the eastern margin of the Hikurangi Plateau. Geochemistry, Geophysics, Geosystems 19, doi.org/10.1002/2017GC007372

Billen, M.I., Stock, J., 2000. Morphology and origin of the Osbourn Trough. Journal of Geophysical Research 105, 13481–13489.

Bland, K.J., Uruski, C.I., Isaac, M.J., 2015. Pegasus Basin, eastern New Zealand: a stratigraphic record of subsidence and subduction, ancient and modern. New Zealand Journal of Geology and Geophysics 58, 319–343.

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

Castillo, P.R., Lonsdale, P.F., Moran, C.L., Hawkins, J.W., 2009. Geochemistry of mid-Cretaceous Pacific crust being subducted along the Tonga–Kermadec Trench: implications for the generation of arc lavas. Lithos 112, 87–102.

Chandler, M.T., Wessel, P., Taylor, B., Seton, M., Kim, S.-S. and Hyeong, K., 2012. Reconstructing Ontong Java Nui: implications for Pacific absolute plate motion, hotspot drift and true polar wander. Earth and Planetary Science Letters 331–332, 140–151.

Cooper, A.F., Ireland, T.R., 2013. Cretaceous sedimentation and metamorphism of the western Alpine Schist protoliths associated with the Pounamu Ultramafic Belt, Westland, New Zealand. New Zealand Journal of Geology and Geophysics 56, 188–199.

Davy, B., 2006. Bollons Seamount and early New Zealand–Antarctic seafloor spreading. Geochemistry, Geophysics, Geosystems 7, Q06021, doi:10.1029/2005GC001191

Davy, B., 2014. Rotation and offset of the Gondwana convergent margin in the New Zealand region following Cretaceous jamming of Hikurangi Plateau large igneous province subduction. Tectonics 33, 1577–1595, doi:10.1002/2014TC003629.

Davy, B., Hoernle, K., Werner, R., 2008. The Hikurangi Plateau - crustal structure, rifted formation and Gondwana subduction history. Geochemistry, Geophysics, Geosystems 9 (7) Q07004, doi:10.1029/2007GC001855.

Downey, N.J., Stock, J.M., Clayton, R.W., Cande, S.C., 2007. History of the Cretaceous Osbourn spreading center. Journal of Geophysical Research 112, B04102, doi:10.1029/2006JB004550

Eagles, G., Gohl, K., Larter, R.D., 2004. High-resolution animated tectonic reconstruction of the South Pacific and West Antarctic margin. Geochemistry, Geophysics, Geosystems 5, 7 doi:10.1029/2003GC000657.

Finn, C.A., Müller, 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.

Gans, P.B., 1997. Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwest Mexico. Tectonics 16, 388–408.

Govers, R., Wortel, M.J.R., 2005, Lithosphere tearing at STEP faults: response to edges of subduction zones. Earth and Planetary Science Letters 236, 505–523.

Hochmuth, K., Gohl, K., 2017. Collision of Manihiki Plateau fragments to accretional margins of northern Andes and Antarctic Peninsula. Tectonics 36, 229–240 doi:10.1002/2016TC004333

Hochmuth, K., Gohl, K., Uenzelmann-Neben, G., 2015. Playing jigsaw with Large Igneous Provinces - a plate tectonic reconstruction of Ontong Java Nui, West Pacific. Geochemistry Geophysics Geosystems 16, 3789–3807, doi:10.1002/2015GC006036

Hoernle, K., Hauff, F., van den Bogaard, P., Werner R., Mortimer N., Geldmacher, J., Garbe-Schönberg, D., Davy, B., 2010. Age and geochemistry of volcanic rocks from the Hikurangi and Manihiki oceanic plateaus. Geochimica et Cosmochimica Acta 74, 7196–7219.

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.

Homrighausen, S., Hoernle, K. Hauff, F., Geldmacher, J., Wartho, J-A., van den Bogaard, P., Garbe-Schönberg, D. 2018. Global distribution of the HIMU end member: formation through Archean plume-lid tectonics. Earth-Science Reviews in press. doi.org/10.1016/j.earscirev.2018.04.009

Koppers, A.A.P., Duncan, R.A., Steinberger, B., 2004. Implications of a nonlinear $^{40}Ar/^{39}Ar$ age progression along the Louisville seamount trail for models of fixed and moving hot spots. Geochemistry, Geophysics, Geosystems 5, Q06L02, doi:10.1029/2003GC000671.

Larson, R.L., Pockalny, R.A., Viso, R.F., Erba, E., Abrams, L.J., Luyendyk, B., Stock, J.M., Clayton, R.W., 2002. Mid-Cretaceous tectonic evolution of the Tongareva triple junction in the southwestern Pacific Basin. Geology 30, 67–70.

Larter, R.D., Cunningham, A.P., Barker, P.F., Gohl, K., Nitsche, F.O., 2002. Tectonic evolution of the Pacific margin of Antarctica: 1. Late Cretaceous tectonic reconstructions. Journal of Geophysical Research 107, 2345, doi:10.1029/ 2000JB000052.

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

Li, J., Wang, X.-C., Xu, J.-F., Xu, Y.-G., Tang, G.-J., Wang, Q., 2016. Disequilibrium-induced initial Os isotopic heterogeneity in gram aliquots of single basaltic rock powders: implications for dating and source tracing. Chemical Geology 406, 10–17.

Luyendyk, B.P., 1995. Hypothesis for Cretaceous rifting of East Gondwana caused by subducted slab capture: Geology 23, 373–376.

Montgomery A.F., Johnson, H.P., 1987. Paleomagnetic studies of Leg 91 basalts and sediments. Initial Reports of the Deep Sea Drilling Project 91, 475–482.

Mortimer, N., 2018. Evidence for a pre-Eocene proto-Alpine Fault through Zealandia. New Zealand Journal of Geology and Geophysics, in press. doi.org/10.1080/00288306.2018.1434211

Mortimer, N., Hoernle, K., Hauff, F., Palin, J.M., Dunlap, W.J., Werner, R., Faure, K., 2006. New constraints on the age and evolution of the Wishbone Ridge, southwest Pacific Cretaceous microplates, and Zealandia-West Antarctica breakup. Geology 34, 185–189.

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., 2014. High-level stratigraphic scheme for New Zealand rocks. New Zealand Journal of Geology and Geophysics 57, 402–419.

Mortimer, N., Kohn, B., Seward, D., Spell, T., Tulloch, A.J., 2016. Reconnaissance thermochronology of southern Zealandia. Journal of the Geological Society of London 173, 370–383.

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., 2017a. Zealandia: Earth's hidden continent. GSA Today 27(3), 28-35, doi: 10.1130/GSATG321A.1

Mortimer, N., Gans, P.B., Meffre, S., Martin, C.E., Seton, M., Williams, S., Turnbull, R.E., Quilty, P.G., Micklethwaite, S., Timm, C., Sutherland, R., Bache, F., Collot, J., Maurizot, P., Rouillard, P., Rollet, N., 2017b. Regional volcanism of northern Zealandia: post-Gondwana breakup magmatism on an extended, submerged continent. Geological Society (London) Special Publication 463.9 doi: 10.1144/SP463.9.

O'Connor, J.M., Hoernle, K., Müller, R.D., Morgan, J.P., Butterworth, N.P., Hauff, F., Sandwell, D.T., Jokat, W., Wijbrans, J.R., Stoffers, P., 2015. Deformation-related volcanism in the Pacific Ocean linked to the Hawaiian-Emperor bend. Nature Geoscience 8, 393–397 doi:10.1038/NGEO2416

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.

Rattenbury, M.S., Townsend, D.B., Johnston, M.R. (compilers), 2006. Geology of the Kaikoura area, scale 1: 250,000. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 13.

Reyners, M., Eberhart-Phillips, D., Bannister, S., 2011. Tracking repeated subduction of the Hikurangi Plateau beneath New Zealand. Earth and Planetary Science Letters 311, 165–171.

Reyners M., 2013. The central role of the Hikurangi Plateau in the Cenozoic tectonics of New Zealand and the Southwest Pacific. Earth and Planetary Science Letters 361, 460–468.

Sandwell, D.T., Smith, W.H.F., 1997. Marine gravity anomaly from Geosat and ERS I satellite altimetry. Journal of Geophysical Research 102, 10039–10054.

Sandwell, D.T., Müller, R.D., Smith, W.H., Garcia, E., Francis, R., 2014, New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. Science 346 (6205), 65–67. doi: 10.1126/science.1258213.

Saunders, A.D., 1987. Geochemistry of basalts from Mesozoic Pacific Ocean crust; Deep Sea Drilling Project Leg 91. Initial Reports of the Deep Sea Drilling Project 91, 483–494.

Seton, M., Whittaker, J.M., Wessel, P., Muller, R.D., DeMets, C., Merkouriev, S., Cande, S., Gaina, C., Eagles, G., Granot, R., Stock, J., Wright, N., Williams, S.E. 2014. Community infrastructure and repository for marine magnetic identifications. Geochemistry Geophysics Geosystems 15, 1629–1641, doi: 0.1002/2013GC005176.

Shervais, J., 1982. Ti-V plots and the petrogenesis of modern ophiolitic lavas. Earth and Planetary Science Letters 59, 101–118.

Snow, J.E., Reisberg, L., 1995. Erratum of "Os isotopic systematics of the MORB mantle: results from altered abyssal peridotites" [Earth Planet. Sci. Lett. 133 (1995) 411–421]. Earth and Planetary Science Letters 136, 723–733.

Stock, J.M., Cande, S.C., 2002. Tectonic history of Antarctic seafloor in the Australia-New Zealand-South Pacific sector: implications for Antarctic continental tectonics. Royal Society of New Zealand Bulletin 35, 251–259.

Strong, D.T., Turnbull, R.E., Haubrock, S., Mortimer, N., 2016. Petlab: New Zealand's national rock catalogue and geoanalytical database. New Zealand Journal of Geology and Geophysics 59, 475–481.

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., Hollis, C., 2000. Cretaceous demise of the Moa plate and strike-slip motion at the Gondwana margin. Geology 29, 279–282.

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, New Zealand.

Taylor, B., 2006. The single largest oceanic plateau: Ontong Java-Manihiki-Hikurangi. Earth and Planetary Science Letters 241, 372–380.

Tejada, M.L.G., Suzuki, K., Hanyu, T., Mahoney, J.J., Ishikawa, A., Tatsumi, Y., Chang, Q., Nakai, S. 2013. Cryptic lower crustal signature in the source of the Ontong Java Plateau revealed by Os and Hf isotopes. Earth and Planetary Science Letters 377-378, 84–96.

Thomas, C.L., 2002. Geochemistry of the Pacific lithosphere being subducted along the Tonga-Kermadec trench. Unpublished M.Sc. thesis, University of California, San Diego, 63 pp.

Timm, C., Hoernle, K., van den Bogaard, P., Bindeman, I., Weaver, S.D. 2009. Geochemical evolution of intraplate volcanism at Banks Peninsula, New Zealand: interaction between asthenospheric and lithospheric melts. Journal of Petrology 50, 989–1023.

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

Timm, C., Hoernle, K., Werner, R., Hauff, F., van den Bogaard, P., Michael, P., Coffin, M.F., Koppers, A., 2011. Age and geochemistry of the oceanic Manihiki Plateau, SW Pacific: new evidence for a plume origin. Earth and Planetary Science Letters 304, 135–146.

Timm, C., Davy, B., Haase, K., Hoernle, K.A., Graham, I.J., de Ronde, C.E.J., Woodhead, J., Bassett, D., Hauff, F., Mortimer, N., Seebeck, H.C., Wysoczanski, R.J., Caratori-Tontini, F., Gamble, J.A., 2014. Subduction of the oceanic Hikurangi Plateau and its impact on the Kermadec arc. Nature Communications 5, 4923, doi10.1038/ncomms5923.

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., Scherstén, 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 der Meer, Q.H.A., Storey, M., Scott, J.M., Waight, T.E., 2016. Abrupt spatial and geochemical changes in lamprophyre magmatism related to Gondwana fragmentation prior, during and after opening of the Tasman Sea. Gondwana Research 36, 142–156.

van der Meer, Q.H.A., Waight, T.E., Scott, J.M., Münker, C. 2017. Variable sources for Cretaceous to recent HIMU and HIMU-like intraplate magmatism in New Zealand. Earth and Planetary Science Letters 469, 27–41.

Vry, J.K., Baker, J., Maas, R., Little, T.A., Grapes, R., Dixon, M., 2004. Zoned (Cretaceous and Cenozoic) garnet and the timing of high grade metamorphism, Southern Alps, New Zealand. Journal of Metamorphic Geology 22, 137–157.

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 and S. R. Taylor. Cambridge University Press.

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

Worthington, T.J., Hekinian, R., Stoffers, P., Kuhn, T., Hauff, F., 2006. Osbourn Trough: Structure, geochemistry and implications of a mid-Cretaceous paleospreading ridge in the South Pacific. Earth and Planetary Science Letters 245, 685–701.

Wright, N., Seton, M., Williams, S.E., Muller, R.D., 2016. The Late Cretaceous to recent tectonic history of the Pacific Ocean basin. Earth-Science Reviews 154, 138-173.

Zhang, G., Smith-Duque, C., Tang, S., Li, H., Zarikian, C., D'Hondt, S., Inagaki, F., IODP Expedition 329 scientists, 2012. Geochemistry of basalts from IODP site U1365: Implications for magmatism and mantle source signatures of the mid-Cretaceous Osbourn Trough. Lithos 144–145, 73–87.

Zhang, G., Li, C., 2016. Interactions of the greater Ontong Java mantle plume component with the Osbourn Trough. Scientific Reports 6:37561 doi:10.1038/srep37561

Zimmerman, A., Stein, H.J., Morgan, J.W., Markey, R.J., Watanabe, Y., 2014. Re–Os geochronology of the El Salvador porphyry Cu–Mo deposit, Chile: tracking analytical improvements in accuracy and precision over the past decade. Geochimica et Cosmochimica Acta 131, 13–32.

Figure captions

Fig. 1. Present day map of the Zealandia continent and adjacent SW Pacific Ocean crust showing major tectonic features and sample sites referred to in the text. The Ontong Java Plateau lies NW of the area of the figure. White lines and labels = Cenozoic features, black and blue lines and labels = Cretaceous features. Numbers are ages of lavas (in Ma) from Thomas (2002), Tappenden (2003), Mortimer et al. (2006), Panter et al. (2006), Hoernle et al. (2010), and Homrighausen et al. (2018). Sample sites from this study are shown as in larger symbols with names. Lineation Z is from Eagles et al. (2004).

Fig. 2. Seafloor bathymetry of the sample sites at the same scale. Inferred dredge on bottom tracks shown by arrows, DSDP 595 drill site shown by yellow dot. Isobath interval 100 m; the bathymetry scale is the same for all panels.

Fig. 3. Compositions of dated lavas on plots to define rock names and simple petrological affinity (A) anhydrous-normalised SiO_2 vs total alkalies (Le Maitre 1989), (B) Ti vs V (Shervais, 1982).

Fig. 4. Selected $^{40}Ar/^{39}Ar$ ages (A) DSDP 595, (B) Kakapo seamount, (C) Frankfurt seamount, (D) Western Uprising seamount, (E) Bollons Gap, (F) Awatere Valley. Shaded bars used in age calculations, white ones not used because of high alteration indices. Complete data and plots for all dated samples are given in Supplementary Files.

Fig. 5. Interpretation of four main tectonic blocks in and near present day eastern Zealandia along with dated lavas and magnetic lineations. Background is gravity gradient map from Sandwell et al. (2014). The prominent NW-SE trending line of black dots is the Louisville Seamount Chain, a Late Cretaceous to Cenozoic hotspot track superimposed on the Cretaceous crust of the region.

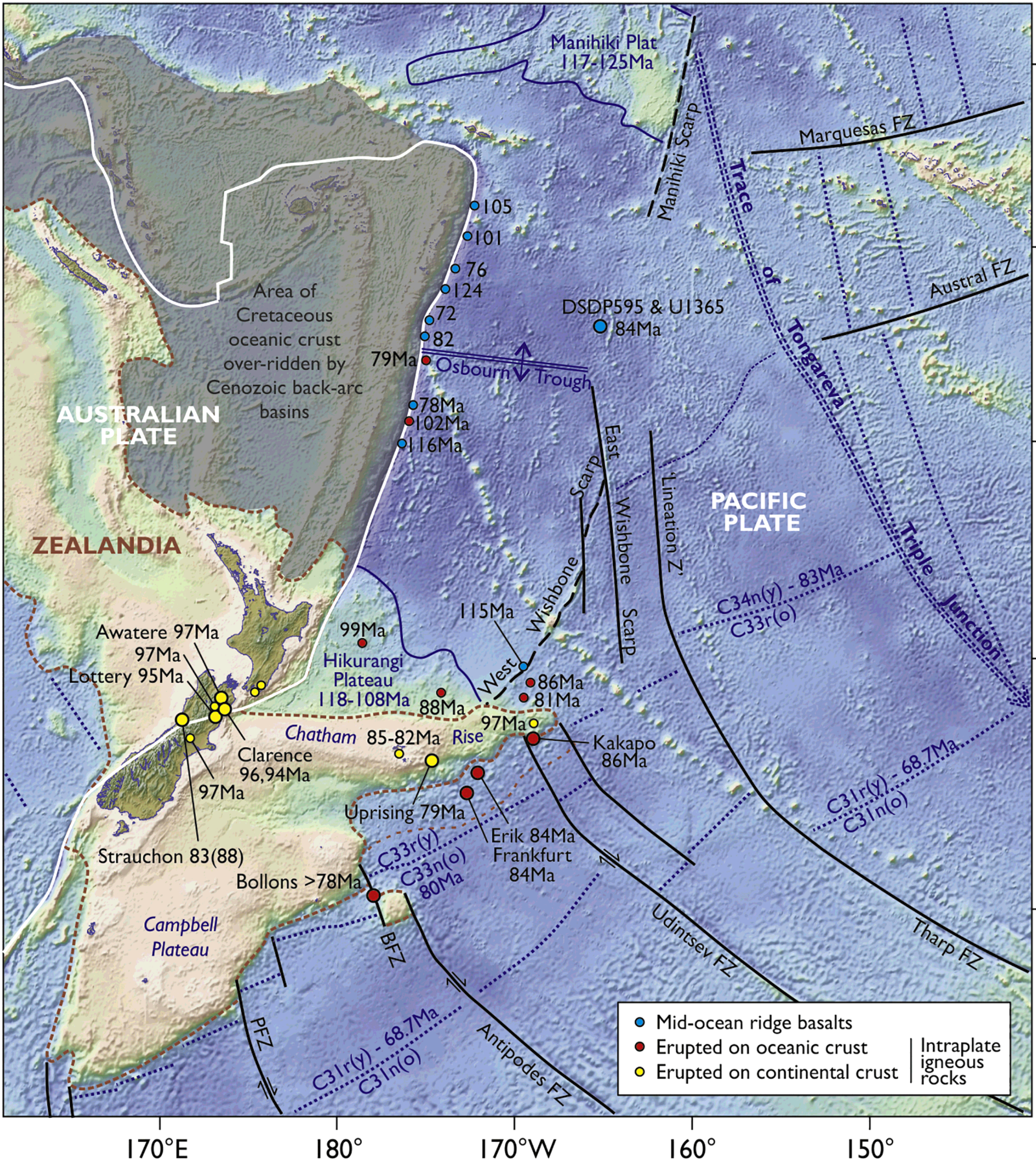
Fig. 6. Plot of age versus present day latitude for lavas related to Osbourn Trough spreading system. Outer Tonga Trench ages (tholeiites only) from Thomas (2002), Manihiki and

Hikurangi plateau ages from Hoernle et al. (2010) and Timm et al. (2011), DSDP595 microfossil ages from Sutherland and Hollis (2000).

Fig. 7. New model for Late Cretaceous magmatic and tectonic change in and near the Zealandia continent-ocean margin: (A) Early Cretaceous subduction phase; (B) superplateau breakup, collision of Hikurangi Plateau with Gondwana and subduction cessation; (C) spreading ceases at Osbourn Trough but continues east of Hikurangi Plateau; (D) establishment of kinematically stable spreading in Southern Ocean. EAnt=East Antarctica, WAnt=West Antarctica, PAC=Pacific Plate, FAR=Farallon Plate, HIK=Hikurangi Plate, PHO=Phoenix plate, OJNP=Ontong-Java Nui Plateau, OJP=Ontong Java plateau, MP=Manihiki Plateau, HP=Hikurangi Plateau, TTJ=Tongareva Triple Junction, OT=Osbourn Trough, MS=Manihiki Scarp, EWS=East Wishbone Scarp, WWS=West Wishbone Scarp, UFZ=Udintsev Fracture Zone, HFZ=Heezen Fracture Zone. The time span of panels C and D is too broad to show the short-lived Bellingshausen Plate near West Antarctica (Eagles et al., 2004). Elements of model based on Larson et al. (2002), Larter et al. (2002), Mortimer et al. (2006) and Reyners et al. (2011).

Table 1
Sample location data and interpreted Ar-Ar ages and two-sigma errors. Abbreviations smt, seamount; Hwy, Highway; Fmn, Formation; Trachybas, trachybasalt; xtal, crystal; Plag, Plagioclase; Kspar, K-feldspar; Prob, probability.

Sample number	Location / Method	Rock / Material	Lat (°S) / Age (Ma)	Long (°) (west – ve)	Depth (m) / MSWD	Lab number / Prob	%^{39}Ar or xtals
MORB: Osbourn Trough area							
P63853	Drill core 595A,10,1,101-109	Basalt	23.8223	-165.5271	70.81 bsf	Kiel 30 63852fss	
	Step heat	Plag	84.4 ± 3.5		1.5	0.11	82
P63853	Drill core 595A,10,1,101-109	Basalt	23.8223	-165.5271	70.81 bsf	UCSB 57-03	
	Step heat	Matrix	> c. 82	-	-		75
P63854	Drill core 595A,11,2,116-124	Basalt	23.8223	-165.5271	82.06 bsf	UCSB 57-04	
	Step heat	Matrix	> c. 86	-	-		74
Intraplate: Eastern Zealandia region							
P67444	SO168-DR63-1. Kakapo smt	Basanite	43.4923	-168.5473	2830-3220	Kiel 26 63-1fs	
	Single xtal	Plag	85.5 ± 2.6		1.1	0.36	6/12
P67448	SO168-DR66-1. Erik smt	Trachyte	44.7570	-172.0952	2530-2950	Kiel 26 66-1fs	
	Single xtal	Kspar	83.9 ± 0.1		1.7	0.08	10/12
P67450	SO168-DR67-1. Frankfurt smt	Basalt	45.6912	-172.5988	3560-4030	Kiel 26 67-1fs	
	Single xtal	Plag	84.5 ± 5.2		1.2	0.32	9/10
P67467	SO168-DR73-1. W Uprising smt	Trachyte	44.2175	-174.4759	870-960	Kiel 26 73-1fs	
	Single xtal	Plag	79.3 ± 0.4		1.1	0.42	14/14
P63810	TAN0006-D4-1B. Bollons Gap	Trachybas.	44.2175	-174.4759	870-960	UCSB 36-38	
	Step heat	Kspar	>77.6 ± 0.3		-	-	96
Intraplate: South Island New Zealand							
MSI 31	Lottery River, North Canterbury	Basalt float	42.5301	173.0557	na	Kiel 28 MSI31mxs	
	Step heat	Matrix	94.8 ± 1.6		1.7	0.11	56
MSI 46A	Clarence River at State Hwy 1	Basalt float	42.1609	173.9094	na	Kiel 28 MS46Afss	
	Step heat	Plag	94.4 ± 0.6		1.6	0.10	81
MSI 47M	Clarence River at Waiautoa Road	Basalt float	42.1106	173.8413	na	Kiel 28 MS47Mbt2	
	Step heat	Biotite	96.5 ± 0.3		1.2	0.30	63
MSI 54A	Awatere River, Lookout Fmn	Basalt	41.9617	173.4571	na	Kiel 28 MS54Amx2	
	Step heat	Matrix	97.5 ± 0.5		1.4	0.22	64
NZS1	Hohonu Dike, Strauchon Creek	Basalt float	42.6425	171.4736	na	Kiel 30 NZS1hbs	
	Step heat	Amph	82.8 ± 0.3		1.2	0.27	96
P45280	Hohonu Dike, Strauchon Creek	Basalt float	42.6432	171.4695	na	Kiel 28 45280hbs	
	Step heat	Amph	82.7 ± 0.3		1.4	0.23	77



Manihiki Plat
117-125Ma
Manihiki Scarp
Marquesas FZ
Trace of Tongareva Triple Junction
Austral FZ
Area of Cretaceous oceanic crust over-ridden by Cenozoic back-arc basins
105
101
76
124
72
82
79Ma
Osbourn Trough
DSDP595 & U1365
84Ma
78Ma
102Ma
116Ma
AUSTRALIAN PLATE
East Wishbone Scarp
Scarp
'Lineation Z'
PACIFIC PLATE
ZEALANDIA
West Wishbone
115Ma
C34n(y) - 83Ma
C33r(o)
99Ma
Hikurangi Plateau
118-108Ma
Awatere 97Ma
97Ma
Lottery 95Ma
86Ma
81Ma
88Ma
97Ma
Chatham Rise
85-82Ma
Kakapo
86Ma
Clarence
96,94Ma
97Ma
Uprising 79Ma
Erik 84Ma
Frankfurt
84Ma
C31r(y) - 68.7Ma
C31n(o)
Strauchon 83(88)
C33r(y)
C33n(o)
80Ma
Bollons >78Ma
Campbell Plateau
BFZ
Udintsev FZ
Tharp FZ
PFZ
Antipodes FZ
C31r(y) - 68.7Ma
C31n(o)
Mid-ocean ridge basalts
Erupted on oceanic crust
Erupted on continental crust
Intraplate igneous rocks
10°S
20°
30°
50°
170°E
180°
170°W
160°
150°

Figure 1

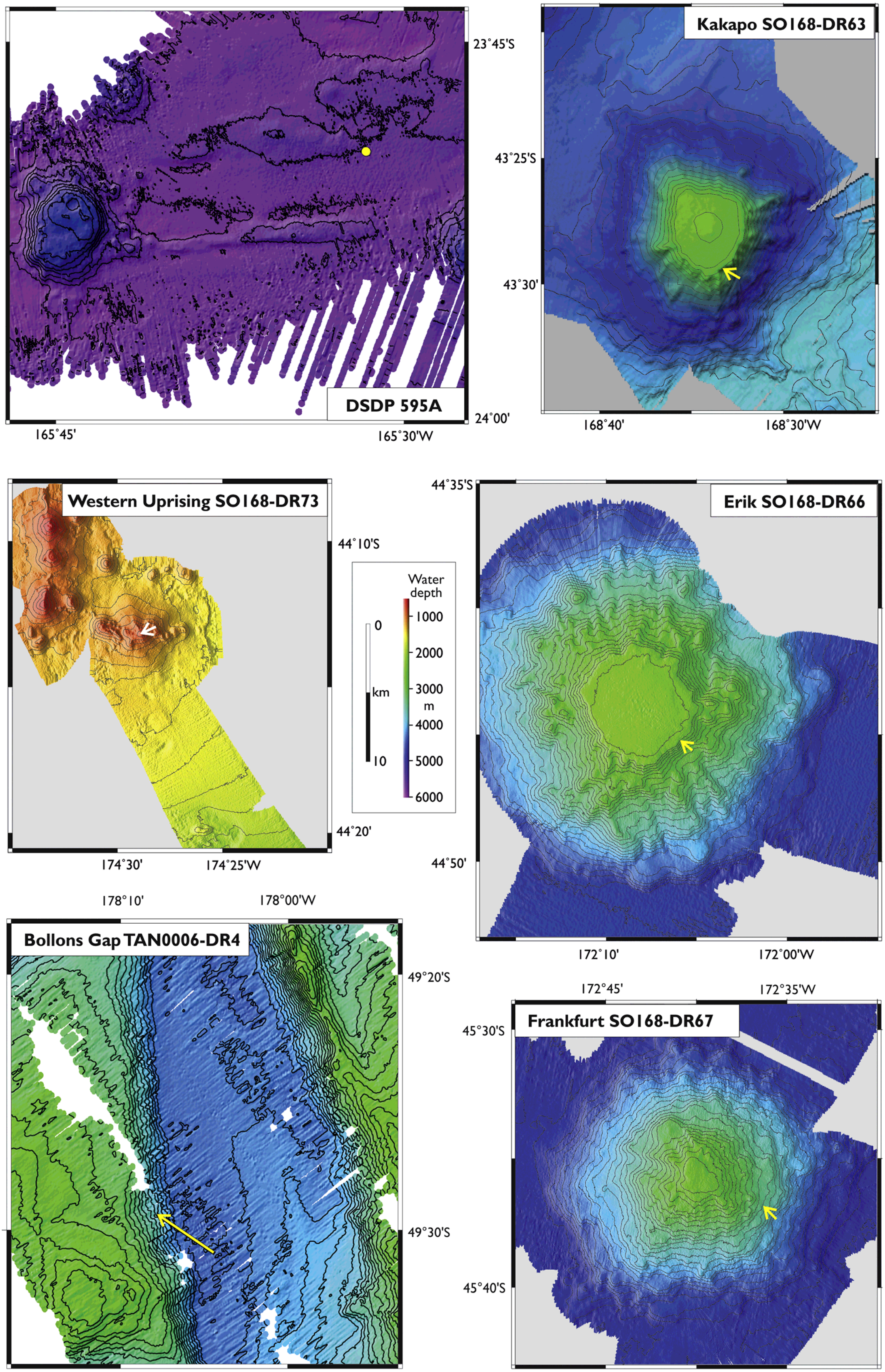

DSDP 595A
23°45'S
24°00'
165°45'
165°30'W
Kakapo SO168-DR63
43°25'S
43°30'
168°40'
168°30'W
Western Uprising SO168-DR73
44°10'S
44°20'
174°30'
174°25'W
Water depth
1000
2000
3000
m
4000
5000
6000
0
km
10
Erik SO168-DR66
44°35'S
44°50'
172°10'
172°00'W
178°10'
178°00'W
Bollons Gap TAN0006-DR4
49°20'S
49°30'S
172°45'
172°35'W
Frankfurt SO168-DR67
45°30'S
45°40'S

Figure 2

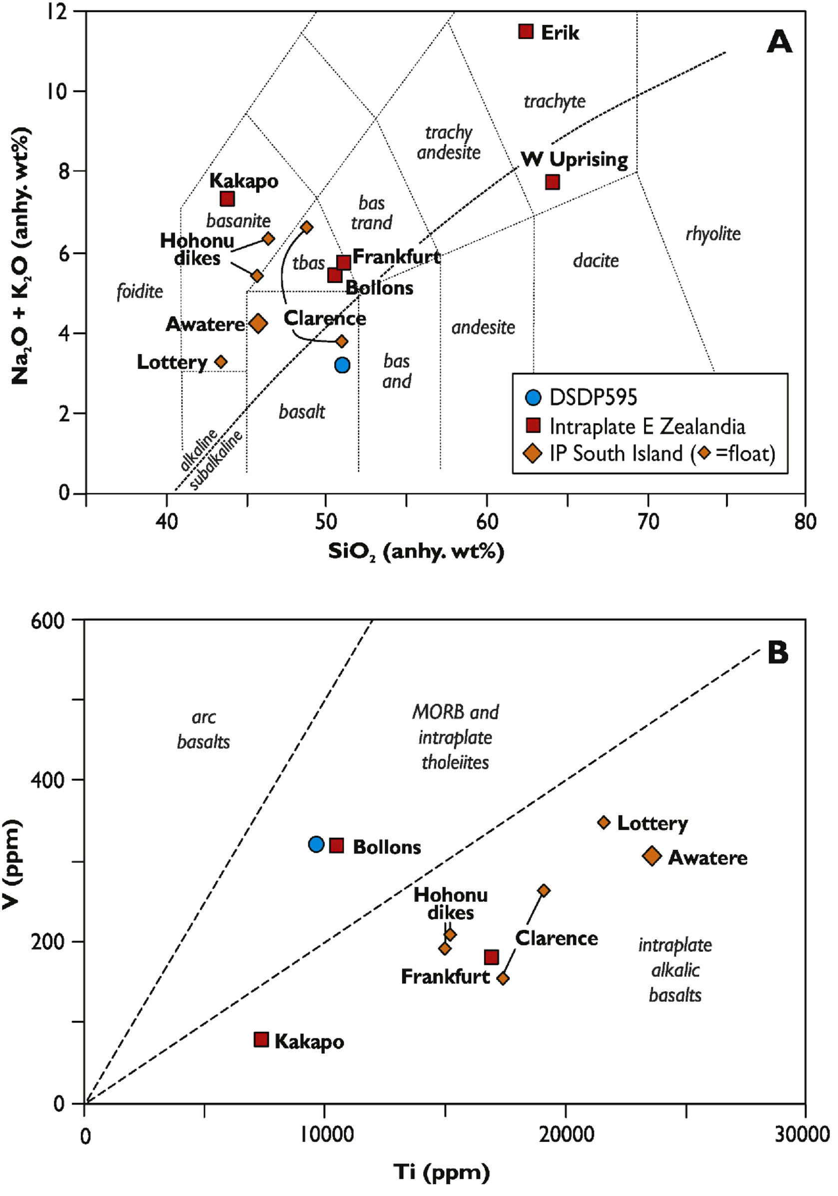

A
Erik
trachyte
trachy andesite
W Uprising
Kakapo
basanite
bas trand
Hohonu dikes
tbas
Frankfurt
Bollons
foidite
Awatere
Clarence
andesite
dacite
rhyolite
Lottery
bas and
basalt
alkaline
subalkaline
DSDP595
Intraplate E Zealandia
IP South Island (◆ =float)
$Na_2O + K_2O$ (anhy. wt%)
SiO_2 (anhy. wt%)
B
arc basalts
MORB and intraplate tholeiites
Lottery
Awatere
Bollons
Hohonu dikes
Clarence
Frankfurt
intraplate alkalic basalts
Kakapo
V (ppm)
Ti (ppm)

Figure 3

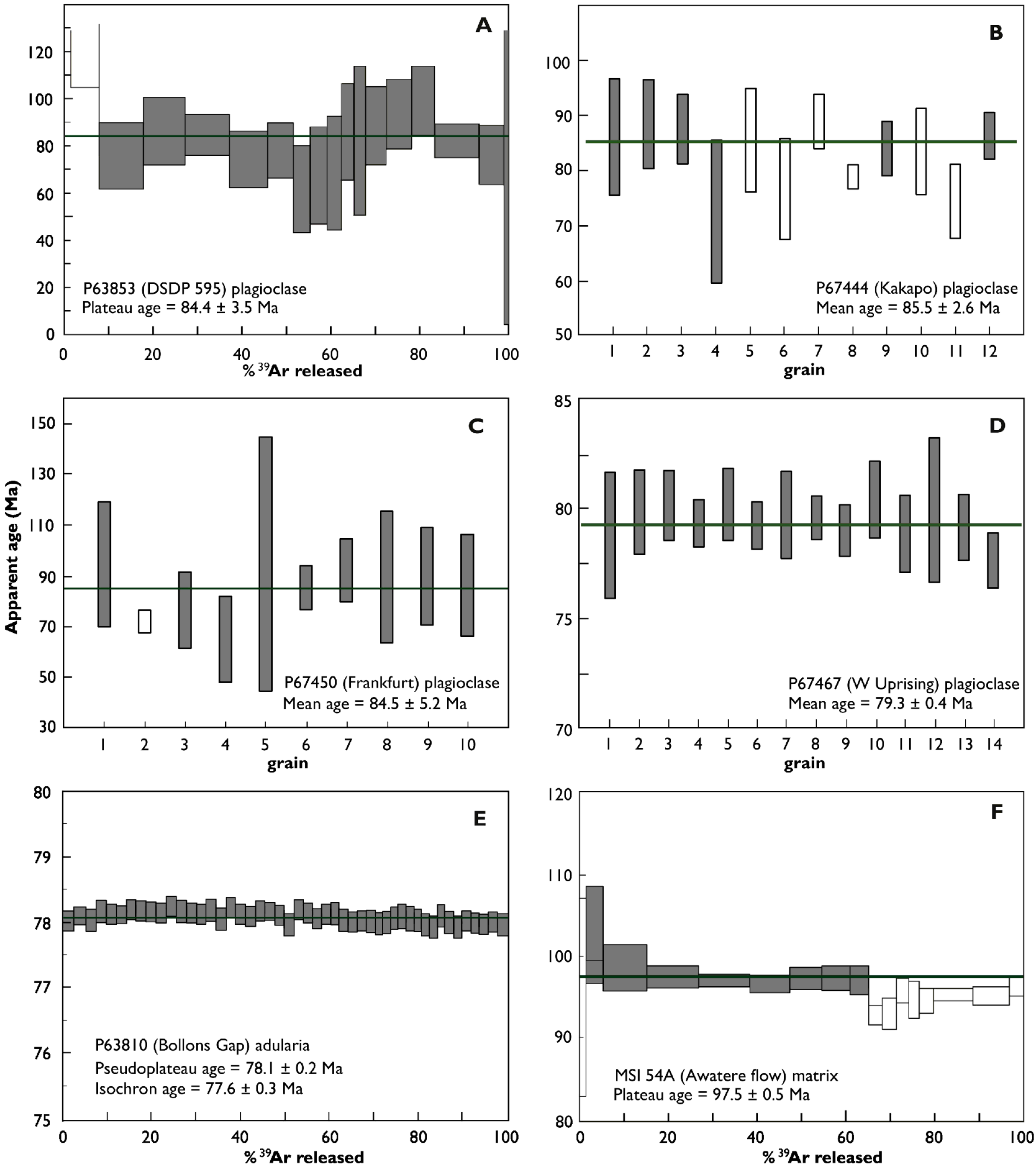
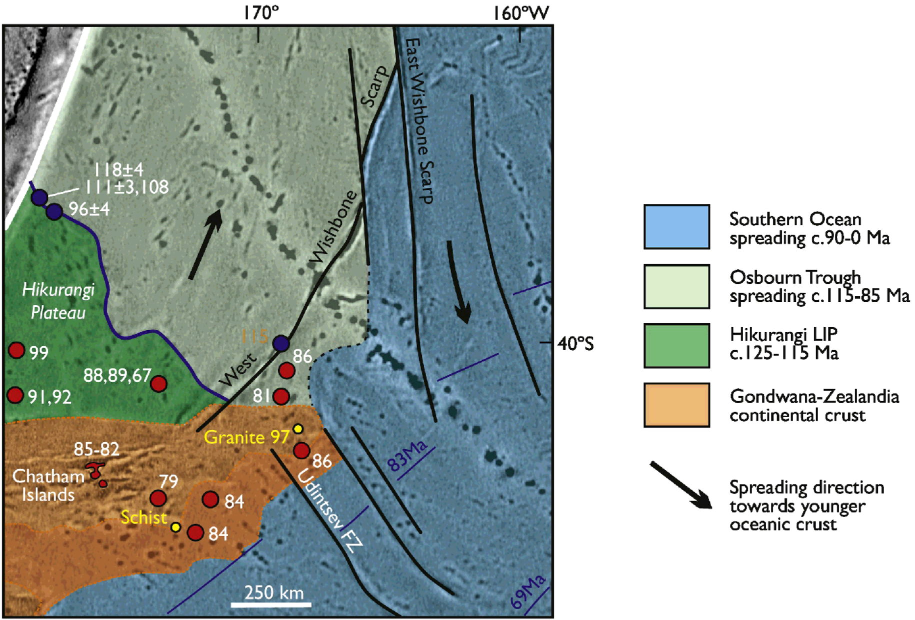
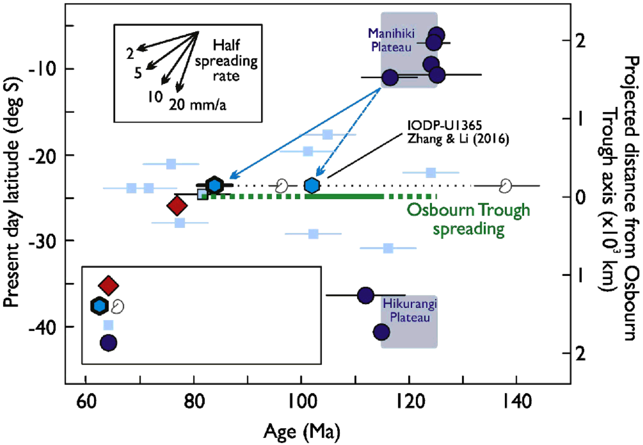

A
P63853 (DSDP 595) plagioclase
Plateau age = 84.4 ± 3.5 Ma
% ^{39}Ar released
B
P67444 (Kakapo) plagioclase
Mean age = 85.5 ± 2.6 Ma
grain
C
Apparent age (Ma)
P67450 (Frankfurt) plagioclase
Mean age = 84.5 ± 5.2 Ma
grain
D
P67467 (W Uprising) plagioclase
Mean age = 79.3 ± 0.4 Ma
grain
E
P63810 (Bollons Gap) adularia
Pseudoplateau age = 78.1 ± 0.2 Ma
Isochron age = 77.6 ± 0.3 Ma
% ^{39}Ar released
F
MSI 54A (Awatere flow) matrix
Plateau age = 97.5 ± 0.5 Ma
% ^{39}Ar released

Figure 4



170°
160°W
40°S
East Wishbone Scarp
Scarp
Wishbone
West
118±4
111±3,108
96±4
Hikurangi Plateau
115
86
81
99
88,89,67
91,92
Granite 97
86
85-82
Chatham Islands
79
84
Schist
84
Udintsev FZ
83Ma
69Ma
250 km
Southern Ocean spreading c.90-0 Ma
Osbourn Trough spreading c.115-85 Ma
Hikurangi LIP c.125-115 Ma
Gondwana-Zealandia continental crust
Spreading direction towards younger oceanic crust

Figure 5



Present day latitude (deg S)
-10
-20
-30
-40
Age (Ma)
60
80
100
120
140
Projected distance from Osbourn Trough axis (x10³ km)
2
1
0
1
2
Half spreading rate
2
5
10
20 mm/a
Manihiki Plateau
IODP-U1365
Zhang & Li (2016)
Osbourn Trough spreading
Hikurangi Plateau

Figure 6

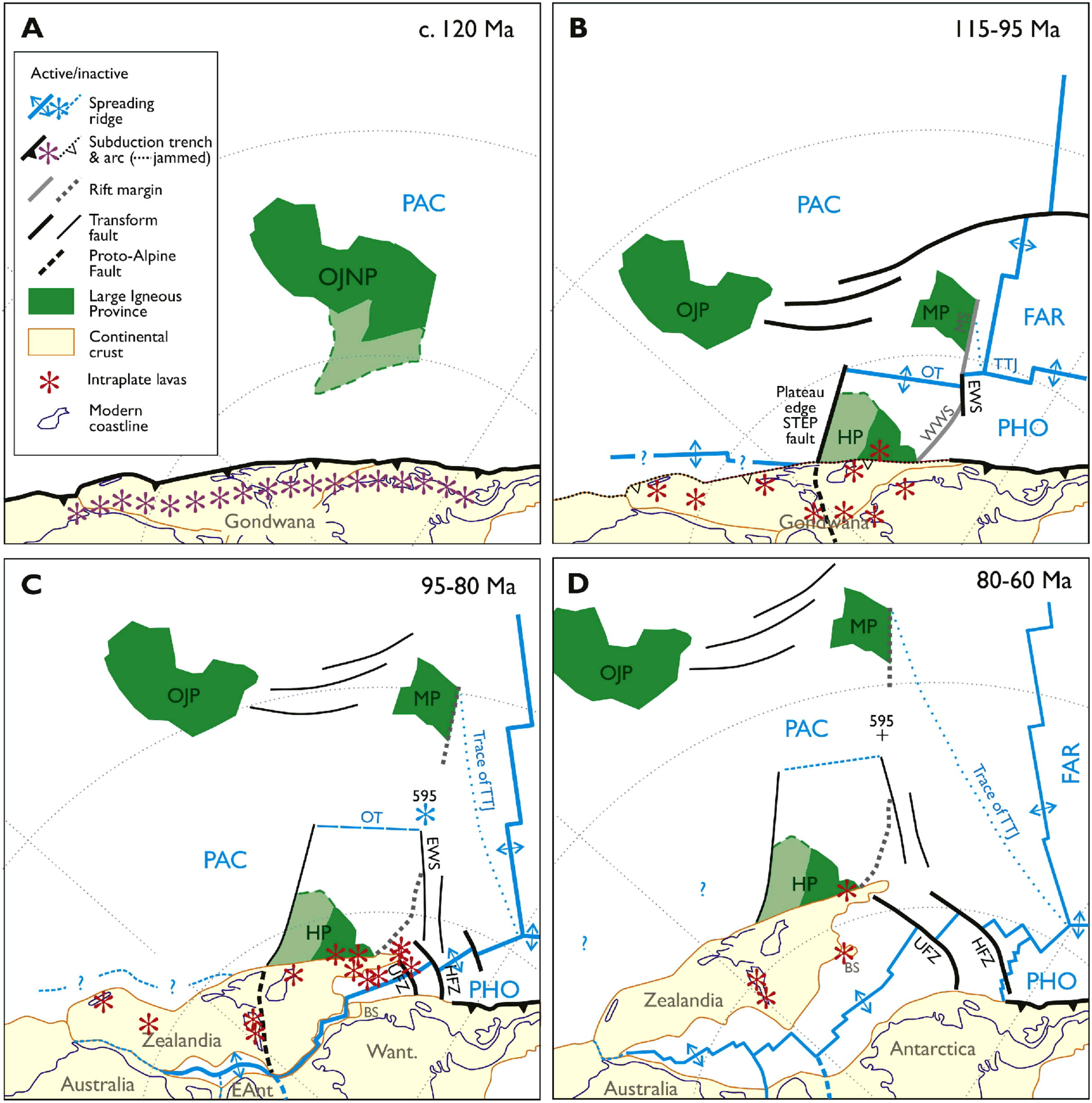

A
c. 120 Ma
Active/inactive
Spreading ridge
Subduction trench & arc (····jammed)
Rift margin
Transform fault
Proto-Alpine Fault
Large Igneous Province
Continental crust
Intraplate lavas
Modern coastline
PAC
OJNP
Gondwana
B
115-95 Ma
PAC
OJP
MP
FAR
TTJ
OT
EWS
WWS
Plateau edge STEP fault
HP
PHO
Gondwana
C
95-80 Ma
OJP
MP
Trace of TTJ
595
OT
EWS
PAC
HP
UFZ
HFZ
PHO
BS
Zealandia
Want.
Australia
EAnt
D
80-60 Ma
OJP
MP
595
PAC
Trace of TTJ
FAR
HP
UFZ
HFZ
PHO
BS
Zealandia
Antarctica
Australia

Figure 7