New constraints on the age and evolution of the Wishbone Ridge, southwest Pacific Cretaceous microplates, and Zealandia–West Antarctica breakup

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ABSTRACT

We present analytical results from four dredge locations across the eastern Zealandia continental margin and adjacent ocean crust. The 115 Ma dacites dredged from the West Wishbone Ridge (WWR) are isotopically primitive, weakly adakitic, slab-derived lavas. The 97 Ma A-type granites and a basalt from the easternmost Chatham Rise enlarge the known area of postsubduction Gondwana magmatism. Amphibolite-grade schists from a fault block south of the Chatham Rise provide a critical bridge between the Zealandia and West Antarctica belts of Jurassic–Cretaceous accretionary prism rocks. The new recognition of the WWR as a remnant of a 115 Ma intraoceanic subduction system means that previous hypotheses of the WWR as a fracture zone or spreading ridge require modification. The dacite ages constrain the start of Osbourn Trough spreading, which caused breakup of the Hikurangi-Manihiki igneous plateau, to before 115 Ma. We speculate that, after 115 Ma, the WWR was rifted by an intraoceanic spreading center that developed along its southeast side. Impingement of this spreading center against the Gondwana margin led to widespread 95–100 Ma postsubduction magmatism, variable lithospheric stretching, and ultimately continental splitting of Zealandia and West Antarctica across basement trends.

Keywords: Cretaceous, southwest Pacific, Gondwana, dating, geochemistry, tectonics.

INTRODUCTION

The Wishbone Ridge is an enigmatic 2000-km-long forked gravity feature in the southwest Pacific Ocean (Fig. 1). It has variously been interpreted as an extinct spreading center (Luyendyk, 1995) or an intraoceanic fracture zone or zones across which Osbourn Trough spreading was dextrally offset to another ridge system (Billen and Stock, 2000; Sutherland and Hollis, 2001), or to a trench at the Gondwana margin (Larter et al., 2002). These tectonic models are not well constrained by magnetic anomaly data because all of the abyssal oceanic crust adjacent to the Wishbone Ridge formed in the Cretaceous normal superchron (83–118 Ma). The Hikurangi Plateau, a Cretaceous large igneous province (LIP), is another major feature of the southwest Pacific Ocean (Wood and Davy, 1994; Mortimer and Parkinson, 1996; Hoernle et al., 2004). The inferred collision of the Hikurangi Plateau with the Gondwana continental margin (Chatham Rise) has been used in a variety of speculative tectonic models, particularly those relating to the cessation of subduction and subsequent Zealandia–West Antarctica rifting (e.g., Mortimer, 2004, and references therein).

In order to provide critical geological constraints for these models, basement rocks were sampled at four sites in a transect across the eastern Zealandia continent-ocean margin during the SO168 cruise of the R/V *Sonne* (December 2002–January 2003). The radiometric age and petrological results that we present here are the first samples recovered from these remote yet major continental and oceanic features. Our results have implications for Gondwana and southwest Pacific tectonics, and shed light on a variety of general geological issues such as formation of intraoceanic subduction zones, inheritance of geochemical characteristics of lavas from old orogens, and lithospheric controls on continental breakup.

GEOCHEMICAL AND AGE RESULTS

Information about the regional setting, bathymetry, sample descriptions, and analytical methods are in Data Repository Appendix DR1.[1] Sample locations and analytical data are in Data Repository Appendices DR2–DR7. The largely monolithologic nature of the four dredges, along with broken Mn-crusted surfaces, rules out an ice-rafted origin for the rocks at each site.

West Wishbone Ridge

Siliceous lavas and associated sedimentary rocks were dredged from three sites (dredges 54, 55, and 56) within 15 km of each other on the 40° slopes of a 1-km-high southeast-facing scarp of a fault block on the Wishbone Ridge (Appendix DR1, Fig. DR1; see footnote 1). Midpoint dredge coordinates of dredge 55 are lat 40°45.05′S, long 169°49.87′W (water depth 2930 m). The lavas are medium-K, metaluminous plagioclase + biotite + oxide ± hornblende ± augite ± quartz porphyritic dacites. On a primitive mantle-normalized multielement diagram (Fig. 2), it is clear that the dacites are very depleted compared with typical siliceous igneous rocks. The troughs at the high field strength elements (HFSE: Nb, Ta, Ti) and the peaks at large ion lithophile elements (LILE: Rb, U, K, and Sr) in the multielement patterns are not observed in mid-ocean ridge and intraplate oceanic volcanic rocks, but are characteristic of subduction-zone volcanic rocks (see also Fig. 3A). The dacites have slightly elevated Sr/Y (8–34) and La/Yb, low heavy rare earth element (REE) and Y contents (Fig. 2), and high Sm/Yb compared to most arc volcanic rocks. While the extreme Sr/Y (>40) of adakites (Drummond and Defant, 1990) is not present, they have no negative Eu anomalies, and it is possible that the Wishbone dacites have mildly adakitic affinities. The U-Pb zircon ages of two Wishbone lavas and a volcaniclastic sandstone have pooled means of 115 ± 1 Ma (2σ, mean square of weighted deviates 3.1; Fig. 3B), and one of the lavas has an Ar-Ar hornblende age of 113 ± 4 Ma (Appendix DR1, Fig. DR2A). The lack of inherited substantially older zircon grains, and the mid-oceanic-ridge basalt–like initial Sr-Nd-Pb isotopic ratios (Figs. 3B, 3C; Appendix 1, Fig. DR2B) indicate

[1]GSA Data Repository item 2006035, Appendices DR1–DR7, sample and analytical data including Fig. DR1 (bathymetry of dredge sites) and Fig. DR2 (argon spectra and Pb isotope diagrams), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

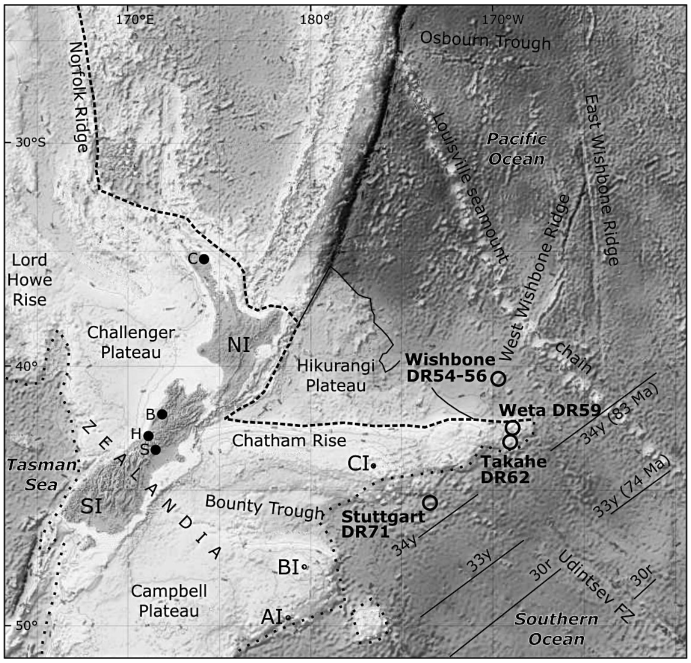

Figure 1. Map showing locations of four SO168 dredge sites (DR; black circles) in southwest Pacific Ocean. Dashed line is inferred Mesozoic convergent margin (modified by Cenozoic tectonics north of Chatham Rise). Dotted lines are ca. 85 Ma rift margins. Black dots are onland New Zealand postsubduction granite-rhyolite suites (ca. 90–100 Ma). B—Berlins Porphyry; S—Mount Somers; H—Hohonu Batholith, C—Mount Camel Complex. Base map is from Stagpoole (2002), magnetic anomalies are simplified from Larter et al. (2002). NI—North Island; SI—South Island; CI—Chatham Islands; BI—Bounty Islands; AI—Antipodes Island; FZ—fracture zone.

a local, intraoceanic source for the Wishbone lavas. The $\delta^{18}O_{magma}$ value calculated from a measurement on clinopyroxene is +5.4‰ (Appendices DR1, DR4) and suggests that there was no significant oxygen contribution from marine carbonates, pelagic clays, or weathered or hydrothermally altered oceanic crust.

Easternmost Chatham Rise: Takahe and Weta Seamounts

The only rock types recovered at Takahe (dredge 62, lat 43°3.71′S, long 168°45.23′W, depth 2770 m) were porphyritic biotite leucogranite (some with drusy cavities, indicating high-level intrusion), with biotite leucogranodiorites as xenoliths. The U-Pb zircon ages of samples of host rock and xenoliths indicate indistinguishable ages of 97 Ma (Fig. 3B). The Takahe geochemistry is distinctly different from the Wishbone lavas. The SiO_2 and total alkalies values indicate they are weakly peraluminous and have high potassium. On the primitive mantle-normalized multi-element diagram, Takahe rocks have pronounced negative Nb and Ta anomalies and positive Rb, K, and Pb anomalies, characteristic of subduction-related magmatism. Compared to the Wishbone dacites, the Takahe granites are relatively enriched in all incompatible elements, except Sr, P, Ti, and Eu (Fig. 2), reflecting fractionation of feldspar, apatite, and Fe-Ti oxides. The lower Sr/Y, greater heavy REE contents, and deeper (more negative) Eu anomalies (Fig. 2) indicate that the Takahe granites have no adakitic characteristics; however, they have some characteristics of A-type granites (Fig. 3A). The initial Sr-Nd-Pb isotope ratios, moderately radiogenic Sr and Nd, high $^{207}Pb/^{204}Pb$ at low $^{206}Pb/^{204}Pb$, and presence of an older zircon are consistent with the involvement of continentally derived material in the petrogenesis of the melts (Fig. 3; Appendix 1, Fig. DR2B [see footnote 1]). Collectively, these features point to distinct similarities with coeval postsubduction onland New Zealand and Antarctic suites such as Mount Somers, Berlins Porphyry, and Mount Camel Complex rhyolites and Byrd Coast granite (Figs. 1, 3A, and 4).

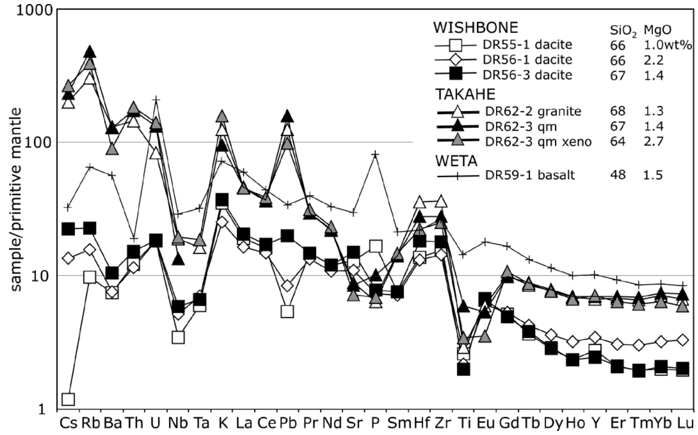

Figure 2. Primitive mantle-normalized multi-element diagram for selected Wishbone, Takahe, and Weta lavas; qm—quartz monzonite; xeno—xenolith.

These suites have mixed I- and A-type affinities; their Nb anomalies are considered to have been inherited from their source areas and/or host rocks (Ewart et al., 1992; Weaver et al., 1994; Waight et al., 1998; Tappenden, 2003).

The bathymetry of the Weta dredge site shows a flat-topped north-northeast–trending volcanic or tectonic ridge. Dredge 59, on the north side of a guyot (lat 42°16.85′S, long 168°51.03′W, depth 2671 m), yielded an altered (and undated) olivine basalt. Despite some phosphorite contamination (Fig. 2), the primitive mantle-normalized multi-element diagram is similar to an alkali olivine basalt, but shows a small subduction-like Nb and Ta anomaly.

Southern Ocean Rifted Margin: Stuttgart Seamount

Recovery of banded greenish-gray oligoclase + albite + quartz + biotite + muscovite + ilmenite ± garnet ± hornblende ± epidote ± titanite schists at dredge 71 on Stuttgart seamount, 380 km east-southeast of the Chatham Islands (lat 45°29.32′S, long 173°15.67′W, depth 3950 m; Fig. 1; Appendix DR1), along with swath mapping, reveal a faulted block of continental crust surrounded by Southern Ocean abyssal plain on all sides. Ar-Ar step heating of two white micas and one hornblende separate from the Stuttgart schists did not yield statistical plateaus (Appendix DR1, Fig. DR2). However, both mica samples behave similarly, in that most of the gas gives ages of 140–150 Ma. Jurassic–Cretaceous white mica ages are typical of the onland Haast Schist of New Zealand (e.g., Adams and Robinson, 1977; Gray and Foster, 2004), including schist basement on the Chatham Islands (Fig. 1).

The mafic volcaniclastic protolith of the Stuttgart schists and the high metamorphic grade suggest a match with the Caples terrane–Haast Schist belt of onland New Zealand.

DISCUSSION

West Wishbone Ridge: Intraoceanic Subduction at 115 Ma

The Wishbone lavas are unlike any siliceous igneous rocks found in ocean crust formed at mid-ocean ridges or in intraplate oceanic volcanic settings (e.g., East Pacific Rise, Iceland, and Galapagos), but are similar to those in intraoceanic subduction zone settings (e.g., Smith et al., 2003). It seems reasonable that the location and subduction-related, weakly adakitic chemistry of the dacites, the igneous provenance of the sandstones, the cataclastic deformation, and bathymetric evidence for faulting (Appendix DR1; see footnote 1) are all intimately related to the origin and evolution of the 1800-m-high WWR. We see no way to explain the HFSE anomalies except through slab dewatering, a petrologic process that accompanies plate convergence (Tatsumi and Eggins, 1995).

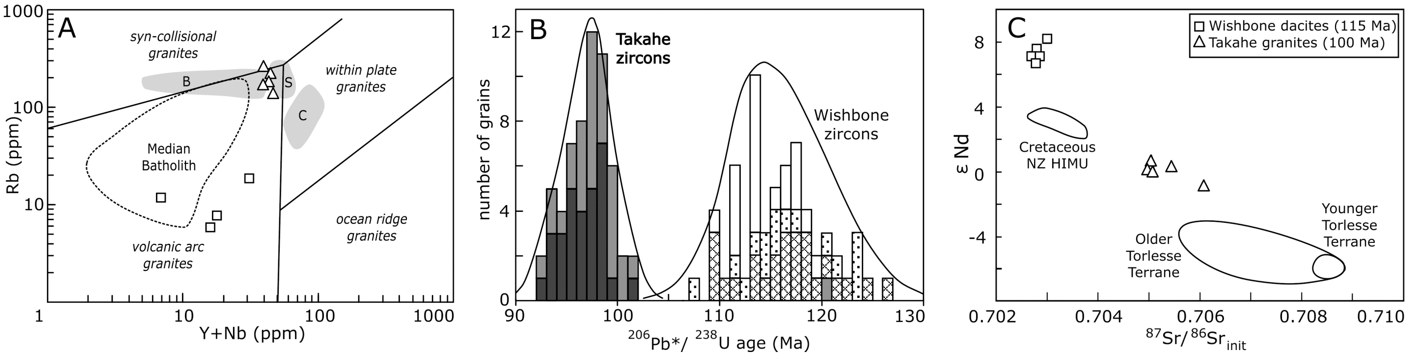

Figure 3. A: Comparison of Wishbone (squares), Takahe (triangles), and onland New Zealand syn-subduction Median Batholith and post-subduction suites on granite trace element diagram of Whalen et al. (1987); B—Berlins Porphyry; S—Mount Somers; C—Mount Camel Complex (see Fig. 1). Reference field data are from Palmer et al. (1995), Mortimer et al. (1999), and unpublished analyses of Institute of Geological and Nuclear Sciences. B: Zircon age histograms and cumulative probability curves from two Takahe (gray) and three Wishbone (other patterns) samples; all data shown; shading and patterns correspond to different analyzed samples. Typical two sigma errors on individual grain ages are ±3 m.y. (Takahe) and ±5 m.y. (Wishbone). C: Sr-Nd isotope correlation diagram. NZ HIMU—New Zealand high μ lavas.

The WWR probably developed as a major pre-115 Ma intraoceanic fracture zone, across which highly oblique convergence proceeded to the stage where dehydration-induced melting of peridotitic and/or eclogitic material took place. The presence of lavas effectively at the fracture zone may suggest a subvertically dipping slab, but the WWR geometry may have been severely modified by later rifting (Fig. 4). The WWR probably developed to a more advanced stage than the present-day Hjort-Macquarie-Puysegur Ridge (Reay and Parkinson, 1997; Meckel et al., 2003), but further sampling is needed to assess the age range, degree of maturity, and polarity of our putative ''Wishbone Arc.'' The Wishbone zircon data hint at the existence of older volcanism (Fig. 3B). Given the proximity of the Hikurangi Plateau to the Wishbone dredge site, it is possible that the thermal pulse that generated the LIP (≥118–93 Ma; Hoernle et al., 2005) was also partly responsible for generating the Wishbone Ridge melts and/or for initiating the subduction (e.g., Niu et al., 2003).

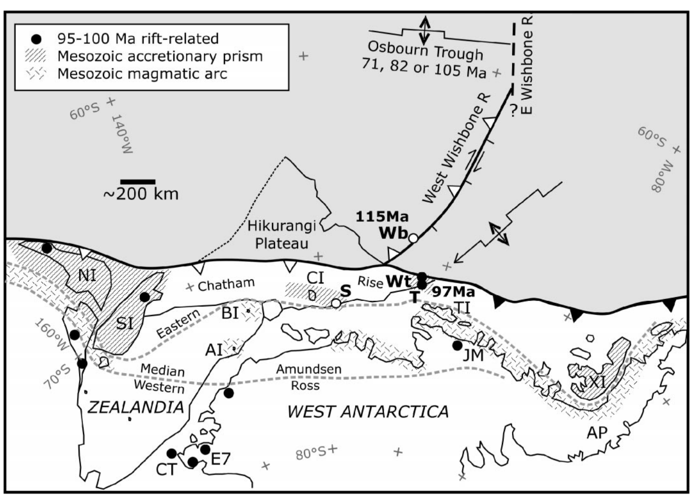

Figure 4. Cretaceous (ca. 90 Ma) tectonic reconstruction showing West Wishbone Ridge as pre-115 Ma fracture zone, 115 Ma arc, and post-115 Ma rift feature (sense of strike- slip motion and arc polarity are speculative). Takahe and Weta are most trenchward postsubduction igneous suites on Gondwana margin and Stuttgart is part of Mesozoic accretionary prism belt. Modern coastlines are projected on 90 Ma reconstruction from Eagles et al. (2004, their Fig. 4). Oceanic plate features (gray) are shown schematically. Sites of active and former subduction are shown by black and white triangles, respectively. Geology is from Maslanyj et al. (1991), Bradshaw et al. (1997), Pankhurst et al. (1993), and Mortimer (2004). R—ridge; Wb—Wishbone; Wt—Weta; T—Takahe; S—Mt. Stuttgart; AP—Antarctic Peninsula; XI—Alexander Island; TI—Thurston Island; JM—Jones Mountains; E7—Edward VII Peninsula; CT—Colbeck Trough; other abbreviations as in Figure 1.

Osbourn Trough Spreading

Billen and Stock (2000) identified the Osbourn Trough as a remnant spreading center that would have split the formerly adjacent Hikurangi and Manihiki Plateaus. Our 115 Ma age from the Wishbone Ridge provides the first geological constraint on the time of initiation of that spreading (Fig. 4). Normal oceanic crust seems to abut the northwest side of the WWR and the Hikurangi Plateau and would have to be older than the 115 Ma age of the lavas erupted onto it. This means that the LIPs must have been moving apart from each other very early in their eruptive history.

WWR: Post-115 Ma Rifting?

Lyons et al. (2000) modeled a break in lithospheric elastic thickness at the WWR, consistent with older crust to the west and younger crust to the east. Figure 1 shows that anomaly 34y (83 Ma) is 300–500 km southeast of the WWR and that older crust might be expected between it and the WWR. We suggest that the southeast side of the WWR was rifted by a newly initiated <115 Ma intraoceanic spreading center (possibly part of the Pacific-Phoenix or Pacific-Charcot system of Larter et al., 2002) and that the angle between the WWR and anomaly 34y indicates southwest propagation and/or asymmetric spreading of that center. Simple extrapolation of the 33y–34y half-spreading rate (39 mm/yr) back against the WWR gives a possible rifting age of 92–98 Ma.

Tests of Southwest Pacific Tectonic Models

Our Wishbone Ridge results permit us to test and reconcile a number of earlier, apparently disparate, tectonic models of the WWR and environs. The main new ideas we propose are that the WWR is a 115 Ma intraoceanic arc and, more speculatively, that its evolution before and after 115 Ma was dominantly as a strike-slip fault and rift edge feature, respectively. Billen and Stock (2000) and Larter et al. (2002) interpreted the WWR as a fracture zone: we agree, but only for the interval before 115 Ma. Sutherland and Hollis (2001) predicted convergence across the WWR in response to Hikurangi Plateau–Gondwana margin collision: our interpretations also require convergence by ca. 115 Ma, and of sufficient amount to cause arc magmatism. Luyendyk (1995) proposed that the WWR was a remnant spreading center, but the dredging of arc rocks does not support this. Davy (2004) suggested reactivation of the WWR as an extensional feature, a hypothesis with which we agree.

From Subduction to Extension at the Gondwana Margin

Elements of the convergent Mesozoic orogen can be traced, albeit discontinuously, for more than 2000 km from the Antarctic Peninsula to New Zealand (Fig. 4). The Stuttgart schists and the single inherited 121 Ma zircon of the Takahe granite confirm that the Mesozoic accretionary prism is present between the Chatham Islands and Alexander Island.

Did collision of the Hikurangi Plateau with the Chatham Rise cause subduction to stop? The 115 Ma subduction-related dacite eruptions on the WWR are plausibly a response to oceanic microplate breakup, but it does not follow that the lavas date the timing of Hikurangi Plateau–Chatham Rise collision. Our discovery of the intra-oceanic Wishbone Arc introduces another Early Cretaceous volcano-tectonic system that could have (1) collided with the Gondwana margin independently of the Hikurangi Plateau (e.g., Muir et al., 1995) and/or (2) been an exotic source of Early Cretaceous detrital zircons to the accretionary prism (e.g., Cawood et al., 1999).

The 97 Ma Takahe granites, and the Weta basalt, are the closest examples to the paleotrench of 90–100 Ma magmatism thus far discovered. Correlative widespread A-type granites (Fig. 4) suggest that a slab window had opened up by 95–100 Ma, i.e., convergence had ceased beneath Zealandia. Sutherland and Hollis (2001) noted the need for dextral strike-slip motion along this Cretaceous continent-ocean margin, so the Hikurangi Plateau, West Wishbone arc, and the slab window could all have widened and/or migrated progressively eastward along the Zealandia margin.

The southwest projection and/or propagation of the putative younger than 115 Ma ridge system southeast of the WWR is oriented at an angle to the continent-ocean margin high enough to have initiated normal faulting across the basement trends and possibly was the principal control on Zealandia and West Antarctica splitting where and when they did (Fig. 4).

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