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Enriching mantle melts within a dying mid-ocean spreading ridge: Insights from Hf-isotope and trace element patterns in detrital oceanic zircon

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ABSTRACT

Oceanic zircon trace element and Hf-isotope geochemistry offers a means to assess the magmatic evolution of a dying spreading ridge and provides an independent evaluation of the reliability of oceanic zircon as an indicator of mantle melting conditions. The Macquarie Island ophiolite in the Southern Ocean provides a unique testing ground for this approach due to its formation within a mid-ocean ridge that gradually changed into a transform plate boundary. Detrital zircon recovered from the island records this change through a progressive enrichment in incompatible trace elements. Oligocene age (33–27 Ma) paleo-detrital zircon in ophiolitic sandstones and breccias interbedded with pillow basalt have trace element compositions akin to a MORB crustal source, whereas Late Miocene age (8.5 Ma) modern-detrital zircon collected from gabbroic colluvium on the island have highly enriched compositions unlike typical oceanic zircon. This compositional disparity between age populations is not complimented by analytically equivalent εHf data that primarily ranges from 14 to 13 for sandstone and modern-detrital populations. A wider compositional range for the sandstone population reflects a multiple pluton source provenance and is augmented by a single cobble clast with εHf equivalent to the maximum observed composition in the sandstone (~17). Similar sandstone and colluvium Hf-isotope signatures indicate inheritance from a similar mantle reservoir that was enriched from the depleted MORB mantle average. The continuity in Hf-isotope signature relative to trace element enrichment in Macquarie Island zircon populations, suggests the latter formed by reduced partial melting linked to spreading-segment shortening and transform lengthening along the dying spreading ridge.

1. Introduction

Zircon geochemistry has proven to be an invaluable tool for assessing the provenance of sedimentary rocks, genesis of parental magmatic rocks, and timing of continental crust differentiation on early Earth (Amelin et al., 1999; Belousova et al., 2006; Heaman et al., 1990; Link et al., 2005). In particular, Hf-isotope systematics have been used in large-scale crustal evolution and provenance studies to infer model ages for the separation of melts from the depleted MORB mantle (DMM; e.g. Griffin et al., 2004; Nebel et al., 2007; Veevers et al., 2008). Doubt cast on this technique (Dhuime et al., 2011) suggests that continental crust zircons should have starting compositions more enriched (εHf = 13.2 at 0 Ma) than the average DMM (εHf = 17.0 at 0 Ma). Although this notion is inferred by many workers, few Hf-isotope compositions have been reported from “juvenile” oceanic zircon (e.g. Kostitsyn et al., 2009), thus precluding constraints on the primary isotopic composition of zircon formed from mantle melting along the mid-ocean ridge system. Filling this fundamental gap in the zircon Hf-isotope database will not only constrain inferred Hf-model ages for crustal evolution studies, but it will also improve upon the growing database of oceanic zircon trace element geochemistry (e.g. Grimes et al., 2009).

Trace element concentrations, characteristically U, Yb, Y, and Hf, in oceanic zircon show wide compositional variation (Grimes et al., 2009) and can be used to distinguish oceanic grains from continental grains (Grimes et al., 2007). The nature of this distinction with respect to the variable compositions of oceanic lithosphere (Langmuir et al., 1992; Salters and Hart, 1991; Sun and McDonough, 1989) and comagmatic basaltic rocks has not been assessed. Such an evaluation would benefit from zircon compositions analyzed from all types of oceanic crust including those more enriched and/or depleted than the average DMM reservoir (Workman and Hart, 2005). This approach is used here and stresses the significance of considering an enriched MORB mantle reservoir in provenance and crustal evolution studies and could be used for interpreting the petrogenetic–tectonic origins of obducted oceanic crust.

In this study, we present Hf-isotope and trace element geochemistry from first generation detrital zircon populations collected from the Macquarie Island ophiolite in order to determine the utility of oceanic zircon as a recorder of mantle melting conditions. Detrital zircon is utilized in order to obtain large sample datasets that represent spatially expansive igneous source regions and consequently a wide range in

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oceanic zircon geochemistry. Such an approach is now widely used (see Link et al., 2005 and references therein) and deemed to be reliable in studies where provenance is well constrained. Detrital oceanic zircon populations from Macquarie Island separated from Miocene gabbroic sandstone–breccia sequences and modern gabbroic colluvium represent igneous rocks that formed 33–27 Ma and 8.5 Ma along a now-extinct spreading ridge south of Australia (Portner et al., 2011). This range in zircon crystallization ages records magmatic conditions in the spreading system prior-to and during transformation of the ridge into the modern transpressional Australia–Pacific plate boundary (Mosher and Massell-Symons, 2008).

2. Regional setting

Macquarie Island is the sole subaerial exposure of non-plume-related in-situ oceanic crust in the world and preserves pristine remnants of the undeformed seafloor (i.e. pillow cones; Varne et al., 2000). The island emerged 700–600 kyr ago (Adamson et al., 1996) 1500 km south of Australia due to transpression along the Pacific–Australia plate boundary southwest of New Zealand (Macquarie Ridge Complex in Fig. 1A). Sixty five percent of the island exposes pillow basalt with localized thin intercalations of volcaniclastic and sedimentary rocks (Fig. 2A). This extrusive sequence is juxtaposed against lower crustal sheeted dolerite dykes, gabbro and/or peridotite across major spreading-related faults (Fig. 2B). The isolated position of the island in the Southern Ocean, relatively recent emergence from the seafloor, and 400–200 m high plateau ensure that panned heavy minerals from gabbroic colluvium on the central plateau, including modern-detrital zircon analyzed in this study, were derived from surrounding gabbro exposures (Fig. 2B) and not from Antarctic ice-rafted material or other erratic sources (e.g. Paduan et al., 2007).

Shipboard geophysical data recovered from the Southern Ocean seafloor show that the oceanic crust surrounding and making up Macquarie Island formed along a slow mid-ocean spreading ridge, the proto-Macquarie spreading ridge (PMSR), which rifted the Campbell Plateau and Resolution Ridge conjugate margins (Fig. 1B) apart from the Middle Eocene (ca. 42 Ma) until the Late Miocene (~6 Ma; Sutherland, 1995; Varne et al., 2000). Plate reorganization from ca. 27 Ma caused rift segment shortening, transform lengthening and clockwise rotation of spreading directions through the Miocene (Mosher and Massell-Symons, 2008), which is expressed by curved fracture zones in PMSR crust (Fig. 1B). This reorganization eventually culminated with the cessation of spreading by 6 Ma and the formation of the currently active transpressional Macquarie Ridge Complex (Fig. 1C; Daczko et al., 2003).

Geodynamic modeling, radiometric ages from basalt (whole rock K/Ar and ^{40}Ar/^{39}Ar) and gabbro (zircon U–Pb), and microfossil biostratigraphy indicate that the oceanic crust making up Macquarie Island formed 11.5–6.1 Ma (Armstrong et al., 2004; Duncan and Varne, 1988; Quilty et al., 2008; Varne et al., 2000; Wertz, 2003), thus coinciding with the final stages of spreading along the PMSR. The large majority of basalts on the island have unusual MORB compositions that are more enriched than typical EMORB suites (Fig. 3A; Kamenetsky et al., 2000). Although the highly enriched composition of basalt is also shared by other plutonic rocks (i.e. zircon-bearing gabbro), exposed mantle peridotites bear no melt-residue chemical relationship to other igneous rocks on the island (Christodoulou, 1990; Dijkstra et al., 2010; Varne, et al., 2000; Wertz, 2003). Basalt isotopes show a strong resemblance to Pacific MORB rather than Indian MORB and bear no

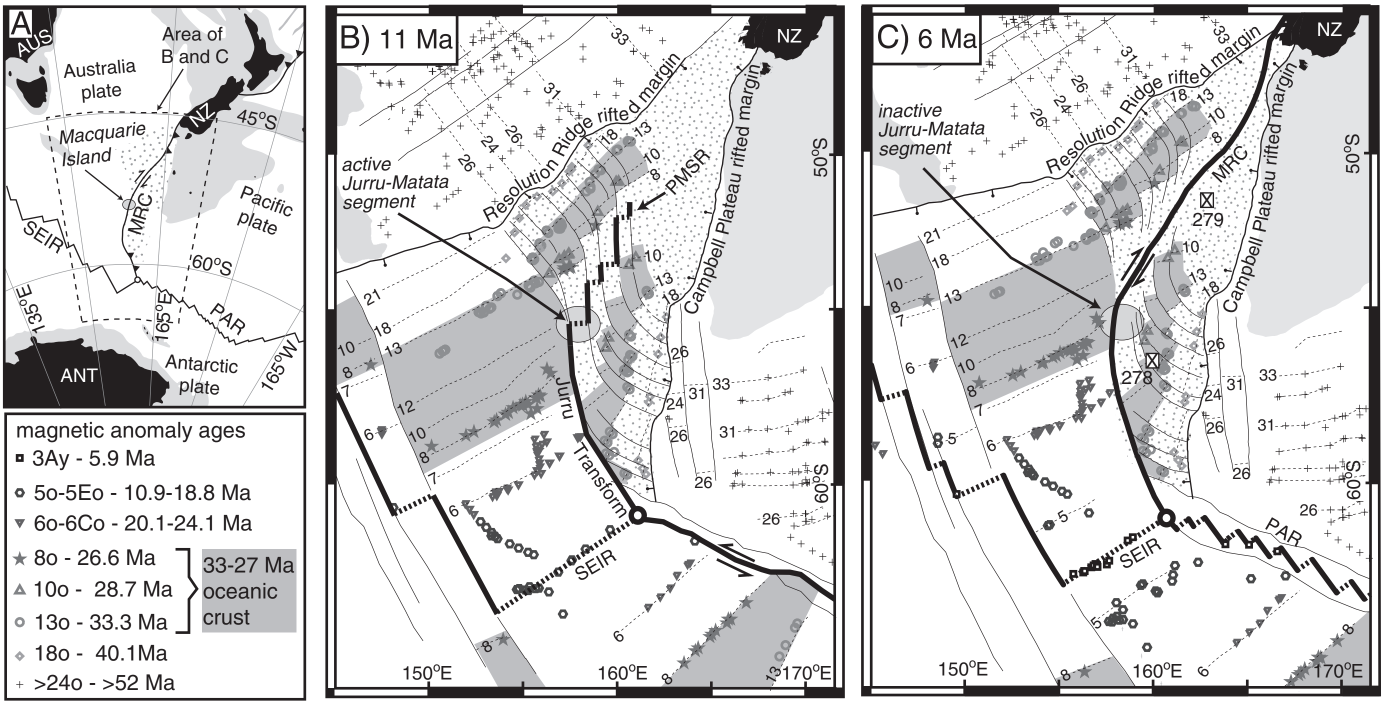

Fig. 1. Present day and Late Miocene paleogeographic reconstruction maps of proto-Macquarie spreading ridge (PMSR) oceanic crust (stippled pattern) in the Southern Ocean. Paleogeographic maps hold the Pacific plate fixed and are modified from Meckel (2003) and Portner et al. (2011). A) Present position of Macquarie Island along the transpressional Macquarie Ridge Complex (MRC). The MRC forms the Australia–Pacific plate boundary south of New Zealand and joins with the Southeast Indian ridge (SEIR) and Pacific–Antarctic ridge (PAR) at a triple junction (62° S–161° E). Light gray regions indicate continental shelf/slopes. B) Reconstruction for ca. 11 Ma. Rocks making up Macquarie Island formed within the Jurru–Matata spreading segment (circled) of the westernmost PMSR. The easternmost segment of the SEIR connected to the PMSR across the Jurru transform. Transforms are delineated by bold (active) and thin (inactive) solid lines. Bold dashed lines represent active spreading axes. Thin dashed lines represent the older boundaries (anomaly 3Ay is a younger boundary) of normal polarity magnetic isochrons (numbered; after Weissel et al., 1977; Meckel, 2003; Keller, 2004). Relative ages of selected isochrons (legend) are after Cande and Kent (1995). C) Reconstruction for ca. 6 Ma, which marks the end of rifting along the PMSR and its transition to a through going transform boundary. Approximate restored positions of DSDP holes 278 and 279 from leg 29 are shown with boxed X's (Pyle et al., 1995).