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Melt extraction and mantle source at a Southwest Indian Ridge Dragon Bone amagmatic segment on the Marion Rise

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ABSTRACT

This paper works on the trace and major element compositions of spatially associated basalts and peridotites from the Dragon Bone amagmatic ridge segment at the eastern flank of the Marion Platform on the ultraslow spreading Southwest Indian Ridge. The rare earth element compositions of basalts do not match the pre-alteration Dragon Bone peridotite compositions, but can be modeled by about 5 to 10% non-modal batch equilibrium melting from a DMM source. The Dragon Bone peridotites are clinopyroxene-poor harzburgite with average spinel Cr# ~ 27.7. The spinel Cr# indicates a moderate degree of melting. However, CaO and Al_2O_3 of the peridotites are lower than other abyssal peridotites at the same Mg# and extent of melting. This requires a pyroxene-poor initial mantle source composition compared to either hypothetical primitive upper mantle or depleted MORB mantle sources. We suggest a hydrous melting of the initial Dragon Bone mantle source, as wet melting depletes pyroxene faster than dry. According to the rare earth element patterns, the Dragon Bone peridotites are divided into two groups. Heavy REE in Group 1 are extremely fractionated from middle REE, which can be modeled by ~7% fractional melting in the garnet stability field and another ~12.5 to 13.5% in the spinel stability field from depleted and primitive upper mantle sources, respectively. Heavy REE in Group 2 are slightly fractionated from middle REE, which can be modeled by ~15 to 20% fractional melting in the spinel stability field from a depleted mantle source. Both groups show similar melting degree to other abyssal peridotites. If all the melt extraction occurred at the middle oceanic ridge where the peridotites were dredged, a normal ~6 km thick oceanic crust is expected at the Dragon Bone segment. However, the Dragon Bone peridotites are exposed in an amagmatic ridge segment where only scattered pillow basalts lie on a partially serpentinized mantle pavement. Thus their depletion requires an earlier melting occurred at other place. Considering the hydrous melting of the initial Dragon Bone mantle source, we suggest the earlier melting event occurred in an arc terrain, prior to or during the closure of the Mozambique Ocean in the Neproterozoic, and the subsequent assembly of Gondwana. Then, the Al_2O_3 depleted and thus buoyant peridotites became the MORB source for Southwest Indian Ridge and formed the Marion Rise during the Gondwana breakup.

1. Introduction

Abyssal peridotites and mid-ocean ridge basalts (MORB) are considered complementary products of mantle melting and melt extraction that creates the ocean crust (Alard et al., 2005; Dick et al., 1984; Handler et al., 2005; Roy-Barman and Allègre, 1994; Snow and Reisberg, 1995). If the mantle source beneath the mid-ocean ridges was homogeneous, the abyssal peridotites show complementary variations, in terms of their mineralogy and chemistry, with the chemistry of spatially associated MORB (Dick and Natland, 1996; Johnson et al., 1990; Kelemen et al., 1997; Niu, 1997; Snow et al., 1994). These coherent features of abyssal peridotites and MORB suggest at least some of the melting is very recent. Then, it is reasonable to use $Na_{8.0}$ and $Fe_{8.0}$ ($Na_{8.0}$ and $Fe_{8.0}$ were calculated from the reported analyses after correction to 8.5 wt.% MgO by removal of Fo_{90} olivine. $Na_{8.0} = Na_2O + 0.373 * MgO-2.98$. $Fe_{8.0} = FeO + 1.664 * MgO-13.313$.) in MORB melts to infer the extent of mantle melting and thickness of oceanic crust (Klein and Langmuir, 1987). However, it is increasingly clear that the upper mantle is heterogeneous with pyroxenite or eclogite layers in all parameters at all scales (Dick et al., 1984; Niu et al., 2002; Salters and Dick, 2002; Seyler et al., 2003; Stracke, 2012). The preferential melting of pyroxenite and eclogite will mess up to estimate the thickness of oceanic crust. Moreover, remelting a previously depleted source would also yield low melt volumes, low sodium basalts, highly incompatible element depleted peridotites, and thin crust (Dick and Zhou, 2015; Dick et al., 1984; Niu, 2004). In the last two decades, Re–Os isotopic studies have indicated that some abyssal peridotites may have experienced multiple ancient melt extraction episodes (Alard et al., 2005; Brandon et al., 2000; Harvey et al., 2006; Ishikawa et al., 2011; Lassiter et al., 2014; Liu et al., 2008;

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Roy-Barman and Allègre, 1994), and some trace element variations in MORB can only explained by a previously depleted source (Hofmann, 1997). However, where this ancient melting occurred is generally not explained.

Here, we report whole-rock major and trace element compositions of abyssal peridotites, and spatially associated basalts from the Dragon Bone amagmatic segment of the Southwest Indian Ridge (SWIR). The extremely fractionated heavy rare earth elements (HREE) and pyroxene-poor of the peridotites suggest that the Dragon Bone mantle source was previously depleted in garnet stability field in an arc setting prior to or during the assembly of Gondwana.

2. Geological setting

The SWIR is a highly oblique ultra-slow spreading ridge with a full spreading rate of ~14 mm/year, extending 7700 km from the Bouvet to the Rodriguez Triple Junction. The ridge crosses over the northern side of the large southern oceans geoid high centered over Marion and Crozet islands and the Conrad Rise (Fig. 1A). This 3400 km portion of the SWIR is the Marion Rise, a large region of elevated ridge axis that represents a 2.1 km along-axis depth anomaly equal in size to the Icelandic Rise (Zhou and Dick, 2013). The Marion Rise steadily shoals from just east of the Melville FZ (Fracture Zone) to the Discovery FZ, where it plateaus all the way to the Prince Edward FZ before dropping precipitously across the Andrew Bain FZ.

The Dragon Bone amagmatic segment is located at 53°E Southwest Indian Ridge, approximately halfway between the Melville and the Discovery FZ's on the Marion Rise (Fig. 1A). It would be expected to have fairly thick crust if a mantle plume supports the rise as at Iceland (Weir et al., 2001). The segment was originally described as the Godzilla Megamullion, but as it turns out mantle rock is being emplaced simultaneously on either side of the rift mountain. Thus it has been renamed, as it does not represent a simple asymmetrically spreading ridge segment. The Dragon Bone amagmatic segment is nearly non-volcanic, representing essentially 100% tectonic accretion by direct exposure of the mantle to the seafloor. There partially serpentinized mantle peridotite is sampled over large regions from the rift valley floor to the rift mountains with only scattered basalts (Fig. 1B) (Zhou and Dick, 2013). However across the 107 km Gallieni FZ, the western adjacent ridge segment appears to be volcanically robust, with a crust up to ~10 km thick (Zhao et al., 2013).

In 2010 the R/V Dayangyihao of the China Ocean Mineral Research and Development Association surveyed the ~90 km long Dragon Bone amagmatic segment (Fig. 1). The rift valley lacks an axial neovolcanic high, and is ~3900 m deep near its center, plunging to >5000 m at the Gallieni FZ. For ~50 km, its western half is flanked by a series of parallel E–W domed ridges shoaling to 1000 to 2800 m depth. These are distinct from more regularly lineated, presumably volcanic, terrains to the southeast and northeast (Zhou and Dick, 2013). Along the western rift, tectonic blocks exposing mantle peridotite are actively emerging from beneath the valley floor to form this terrain (Fig. 1B), which was mapped for ~67 km to the south.

Eleven dredges and three television grabs collected ~1938 kg rocks from the rift valley and the northern and southern rift mountains. Seven stations, concentrated near the transform (Fig. 1B), contained serpentinized peridotite, while earlier the RV Marion Dufresne dredged a single dunite with basalt near the center of the rift valley. Only minor gabbro was sampled as veins in peridotites at two localities (D4-2, and D9), and in one large block from the eastern ridge-transform high (TVG2–3), consistent with the general scarcity of gabbro along the SWIR (Zhou and Dick, 2013). The Dayangyihao rock dredge and TV-grab locations are shown in Fig. 1B.

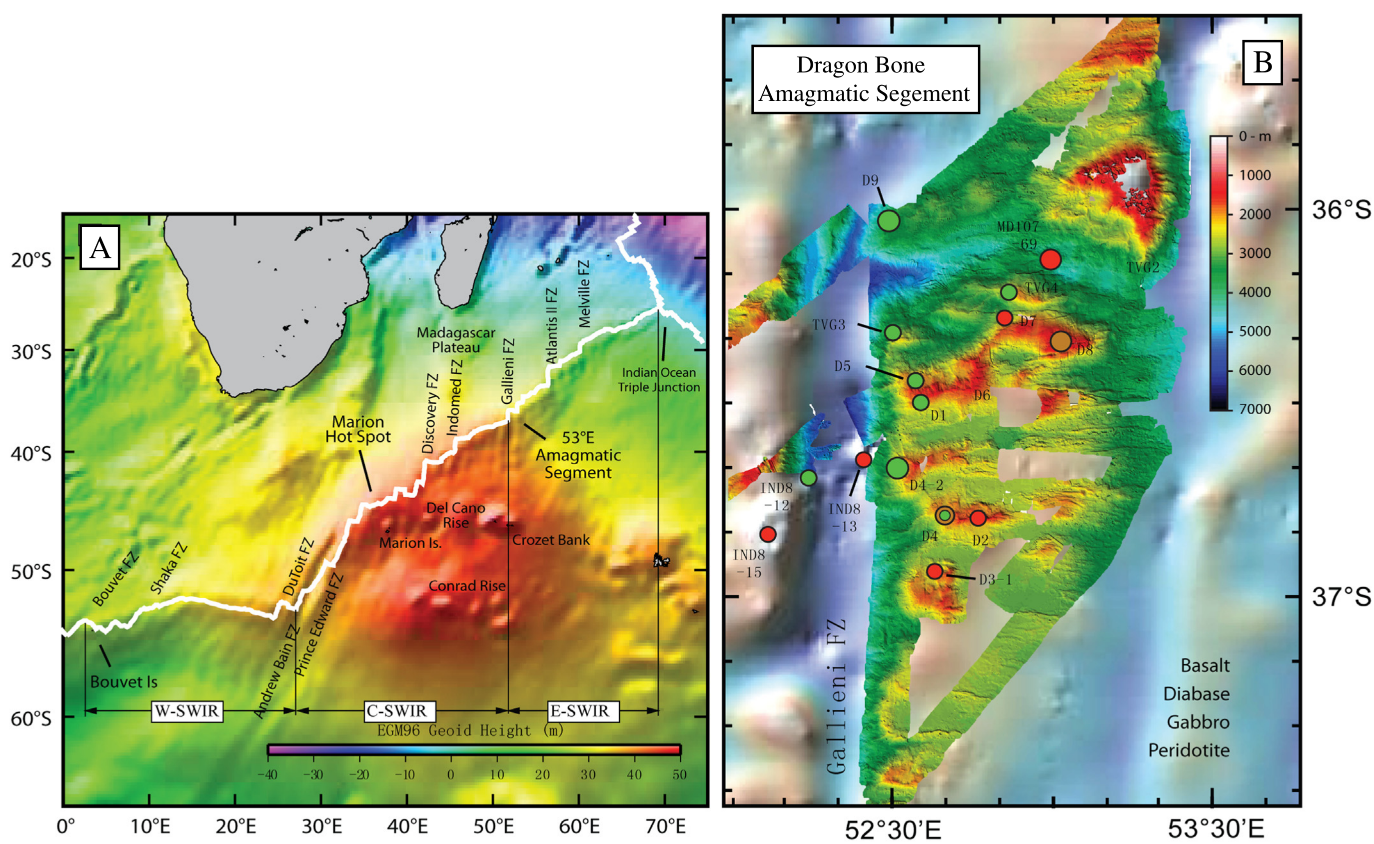

Fig. 1. A: Geoid map of the Southern Ocean plotted on a 0.25 ∗ 0.25 degree grid; B: Seabeam map of the Dragon Bone amagmatic segment with sample locations modified from Zhou and Dick (2013). The green circles are peridotites; the red circles are basalts; and the orange circles are gabbros. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)