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Mantle melting and magma supply to the Southeast Indian Ridge: The roles of lithology and melting conditions from U-series disequilibria

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ABSTRACT

Intermediate-spreading Southeast Indian Ridge (SEIR) basalts display geographic gradients from 90°E to 118°E in Th/U, (^{230}Th/^{232}Th) and ^{238}U–^{230}Th–^{226}Ra disequilibria (^{230}Th-excesses of 1 to 21% and ^{226}Ra-excesses of 0 to 160%). Highly correlated (^{238}U/^{232}Th) and (^{230}Th/^{232}Th) (r^2=0.94) span nearly the entire global MORB range; basalts from three of four ridge morphologies form subparallel, vertically stacked arrays on an equiline diagram. (^{226}Ra/^{230}Th) is inversely correlated with (^{230}Th/^{238}U) within sub-regions of the study area. There is a convex (^{230}Th/^{238}U) along-axis pattern (lower ^{230}Th-excesses in the west and east, at shallowest and deepest depths), such that (^{230}Th/^{238}U) does not correlate with axial depth as described elsewhere, despite the ~2300 m west-to-east axial depth increase. κ and κ_{Pb} also vary along axis from $\kappa<\kappa_{Pb}$ in the west to $\kappa \cong \kappa_{Pb}$ in the east.
Variations in axial depth, crustal thickness, U-series disequilibria, κ and κ_{Pb} are best explained by forward model scenarios in which the physical characteristics of melting (such as melting rate, degree of melting, porosity and melt initiation depth) vary along axis in response to an inferred long wavelength temperature gradient and small variations in the underlying source lithology (pyroxenite veins). This leads to decreased melt supply from west to east, a concomitant change in axial morphology and axial magma chamber depth, and systematic long wavelength geochemical gradients. Melting rate covaries with melt supply in the western and central regions, decreasing eastward along the SEIR, but supply and rate vary inversely from the central to the eastern regions, because cooler eastern mantle contains a few percent of fusible pyroxenite veins that melt productively to generate melts with high Th–U–Ra concentration but low ^{230}Th-excess and ^{226}Ra-excess. The veins contribute only a small proportion of the total melt volume from mantle that is >95% peridotite. Th, Pb and He isotopic gradients are consistent with a changing proportion of enriched pyroxenite veins along axis having a roughly 0.5 to 1 Gyr reservoir age.

1. Introduction

Magmas produced beneath mid-ocean ridges (MORs) are indirect probes of upper mantle composition and melting conditions. Geographic variations in the conditions and extent of melting, and their linkages to mantle temperature, lithology and chemical composition are central to an understanding of mantle evolution and the origin of mid-ocean ridge basalts (MORBs). Important patterns in melt generation are revealed by the relations between MORB chemistry and physical attributes of MORs (e.g., Klein and Langmuir, 1987; Langmuir et al., 1992; Niu and Batiza, 1993; Shen and Forsyth, 1995; Bourdon et al., 1996b; Niu and Hekinian, 1997; Rubin and Sinton, 2007; Niu and O'Hara, 2008). Global studies of MORB composition must often make simplifying assumptions to relate compositional variations to changes in a particular physical characteristic, such as axial depth or spreading rate (Klein and Langmuir, 1987; Bourdon et al., 1996a; Lundstrom et al., 1998). This approach makes it difficult to decipher the competing effects of several independent parameters on MOR magmatism.

Regional scale studies are a useful complement to global studies, particularly in regions with a limited variation in one or more key variables (e.g., spreading rate, axial depth), or where physical, morphologic and/or chemical gradients in ridge character result from a coherent geologic history. Here we present results of a regional scale U-series isotopic and geochemical study of melting conditions at the intermediate spreading rate Southeast Indian Ridge (SEIR) between 90°E and 118°E, an ~2100 km long region displaying significant along-axis physical and chemical variations that can be used to constrain mantle melting and source lithology.

Uranium series disequilibria in MORBs record variations in U–Th–Ra elemental fractionation due to the type (e.g., fractional, batch), extent, rate and depth of melting beneath MORs (e.g., McKenzie, 1985, 2000; Williams and Gill, 1989; Spiegelman and Elliott, 1993; Bourdon et al., 1996a,b; Stracke et al., 1999; Spiegelman, 2000; Sims et al.,

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2002). U-series disequilibria also reflect MORB source mineralogy (e.g., garnet modal abundance, which dominates U–Th fractionation, and clinopyroxene mode, which largely controls fertility and thus melting rate; Beattie, 1993; LaTourette et al., 1993; Pertermann and Hirschmann, 2003). There is a temporal aspect to observed U-series disequilibria, because parent-daughter activity ratios relax to a state of secular equilibrium at a rate governed by their half-lives following U–Th–Ra fractionation. We use these attributes in conjunction with chemical (Sours-Page, 2000) and radiogenic isotope compositions (Graham et al., 2001, 2006; Mahoney et al., 2002) of the same SEIR samples to test scenarios for physical variations in melting conditions of a heterogeneous mantle source.

2. Regional geologic background

The modern SEIR (Fig. 1) marks the Australian-Antarctic plate boundary between the Rodrigues triple junction (25°S, 70°E) and the Macquarie triple junction (62°S, 151°E). This section of MOR contains no large transform offsets and exhibits a west-to-east gradient in axial depth, from ~2300 m to >4500 m (Cochran et al., 1997). The SEIR full spreading rate is nearly constant, from ~72 to 76 mm/yr across our study area (Cochran et al., 1997). The SEIR has a bathymetric high at the Amsterdam-St. Paul Plateau (ASP, 76°–78°E; Graham et al., 2001) and unusually deep, magma-starved ridges within the Australian-Antarctic Discordance (AAD; e.g., Klein et al., 1991; Sempéré et al., 1991). The west to east axial depth increase has been attributed to a long wavelength decrease in mantle temperature (Cochran et al., 1997; Sempéré et al., 1997), estimated to be ~80–150 °C using major element variations in >3,000 SEIR MORB glasses from the ASP (Douglas-Priebe, 1998) to the AAD (Klein et al., 1991; Pyle, 1994; Sours-Page, 2000).

2.1. Along-axis morphologic variations

Ridge morphology and crustal thickness variations indicate changes in melt supply along this portion of the SEIR. Three distinct axial morphological ‘zones’ were discovered by a detailed geophysical survey in 1994/1995 (Cochran et al., 1997; Sempéré et al., 1997). Most western zone ridge segments (C17–C13; Fig. 1) have axial-high morphology, similar in dimension and shape to many segments of the fast-spreading East Pacific Rise (EPR). Segments C12–C4 have a ‘transitional’ morphology typical of other intermediate-spreading ridges (e.g., Canales et al., 1997). Cochran et al. (1997) subdivided the transitional morphologies into: (a) rifted axial highs in the west (segments C12–C9), and (b) shallow axial valleys in the east (segments C8–C4). SEIR segments C3 and C2 have a deep axial valley, similar to much of the mid-Atlantic ridge (MAR). We use the following abbreviations throughout this paper to refer

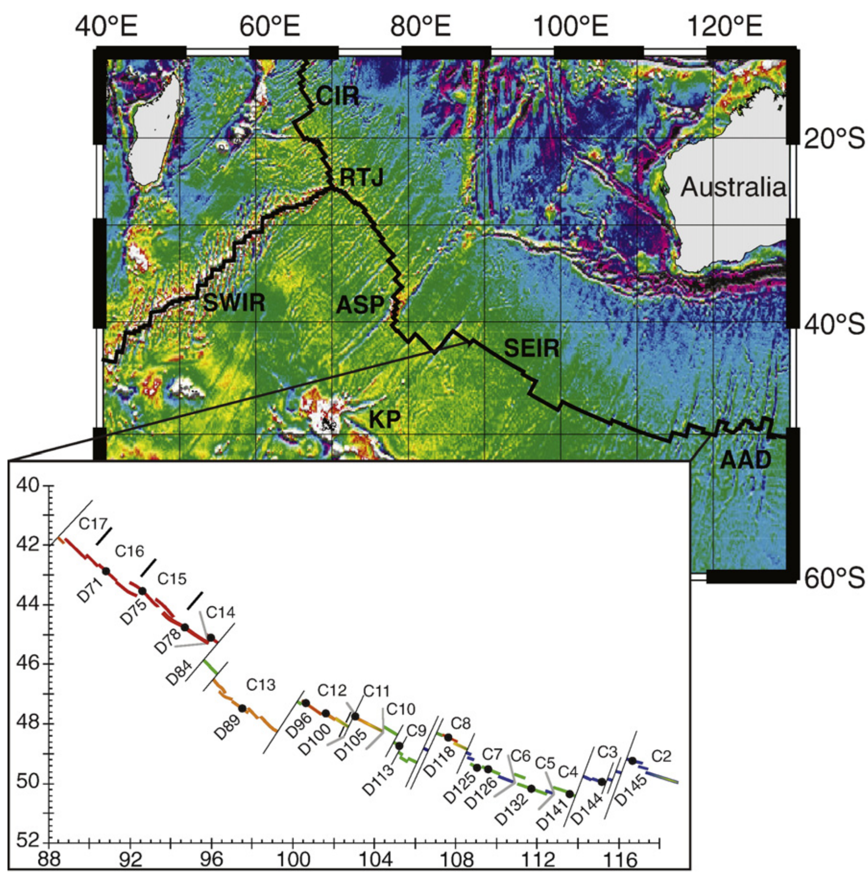

Fig. 1. Satellite altimetry of the Indian Ocean basin between 40°E and 130°E and sample location map. Labeled features include: the Southwest Indian Ridge (SWIR), Central Indian Ridge (CIR), Rodrigues Triple Junction (RTJ), Amsterdam-St. Paul Plateau (ASP), Kerguelen Plateau (KP), Southeast Indian Ridge (SEIR), and the Australian-Antarctic Discordance (AAD). Enlarged panel defines ridge-axis trace of the SEIR from 40°S to 52°S and from 88°E to 118°E. Individual ridge segments are identified above the axial trace (C17 through C2), dredge locations for samples in this study are shown by black dots along the ridge-axis and are labeled below the axial trace (D71 through D145). Ridge-axis color in the online version indicates depth variation with red shades representing the shallowest segments and blue the deepest. We consider three geographical regions in this study (western, WG, central, CG, and eastern, EG, groups). The transform fault separating segments C13 and C12 forms a natural WG-CG divide. MORBs west of this transform tend to have higher $^{3}He/^{4}He$, and different Sr, Nd, Pb isotope compositions, suggesting different mantle geochemical histories east and west of 100°E (Mahoney et al., 2002). The transition into deep-axial valley morphology between segments C3 and C4 forms the EG and CG divide.