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A common parentage for Deccan Continental Flood Basalt and Central Indian Ocean Ridge Basalt? A geochemical and isotopic approach

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ABSTRACT

A comparison of geochemical and Sr–Nd–Pb isotopic compositions for Deccan Continental Flood Basalts (CFBs) and Central Indian Ridge (CIR) Basalts is presented: these data permit assessment of possible parental linkages between the two regions, and comparison of their respective magmatic evolutionary trends in relation to rift-related tectonic events during Gondwana break-up. The present study reveals that Mid-Ocean Ridge Basalt (MORB) from the northern CIR and basalts of Deccan CFB are geochemically dissimilar because of: (1) the Deccan CFB basalts typically show a greater iron-enrichment as compared to the northern CIR MORB, (2) a multi-element spiderdiagram reveals that the Deccan CFBs reveal a more fractionated slope ($Ba/Yb_N > 1$), as compared to relatively flat northern CIR MORB ($Ba/Yb_N < 1$), (3) there is greater REE fractionation for Deccan CFB than for the northern CIR MORB (i.e., $La/Yb_N \sim 2.3$ and 1 respectively) and (4) substantial variation of compatible–incompatible trace elements and their ratios among the two basalt groups suggests that partial melting is a dominant process for northern CIR MORB, while fractional crystallization was a more important control to the geochemical variation for Deccan CFB. Further, incompatible trace element ratios (Nb/U and Nb/Pb) and radiogenic isotopic data (Sr–Pb–Nd) indicate that the northern CIR MORBs are similar to depleted mantle [and/or normal (N)-MORB], and often lie on a mixing line between depleted mantle and upper continental crust. By contrast, Deccan CFB compositions lie between the lower continental crust and Ocean island basalt. Accordingly, we conclude that the basaltic suites of the northern CIR MORB and Deccan CFB do not share common parentage, and are therefore genetically unrelated to each other. Instead, we infer that the northern CIR MORB were derived from a depleted mantle source contaminated by upper continental crust, probably during the break up of Gondwanaland; the Deccan CFB are more similar to Ocean island basalt (Reunion-like) composition, and perhaps contaminated by lower continental crust during their evolution.

1. Introduction

Continental Flood Basalt (CFB) and Ocean-Floor Basalt (OFB) eruptions are the two singlemost important magmatic processes that contribute large volumes of basaltic magma to the surface of the Earth. The former occurs before and during continental rifting (e.g. Jerram and Widdowson, 2005; Saunders et al., 2007), whereas the latter is associated with sea-floor spreading (BVSP, 1981). The Deccan Traps basalt of India (Fig. 1) is an important example of a CFB province, which covers an area of 1.5 million km^2 over western India (Bakshi, 1994). It is characterized by multiple basaltic magma eruptions, within a continental extension – rifting framework that took place between 68 and 62 Ma. This process is believed to have resulted in the formation of the Deccan tholeiitic volcanic edifice onshore, and the separation of the Seychelles micro-continent from India, and culminated in sea-floor spreading related to the opening of the Indian Ocean Ridge(s) (e.g., Courtillot et al., 1999; Collier et al., 2008; Hooper et al., 2010; Ganerød et al., 2011).

However, the origin of CFB, such as the Deccan Traps, is a matter of debate, and two contrasting hypotheses presently exist: (a) partial melting of deep mantle plumes at shallower crustal depth (e.g., White and McKenzie, 1989; Courtillot et al., 2003; Ernst and Buchan, 2003), and (b) decompression melting of the shallow non-plume asthenosphere or sub-continental lithosphere (e.g., Anderson, 1994, 2000; King and Anderson, 1995; Sheth, 2005). In a comprehensive review, White and McKenzie (1995) opined that the peak extrusive activity in any CFB province on a rifted continental margin shortly predates the oldest magnetic anomaly, and marks the onset of seafloor spreading. It has long been debated

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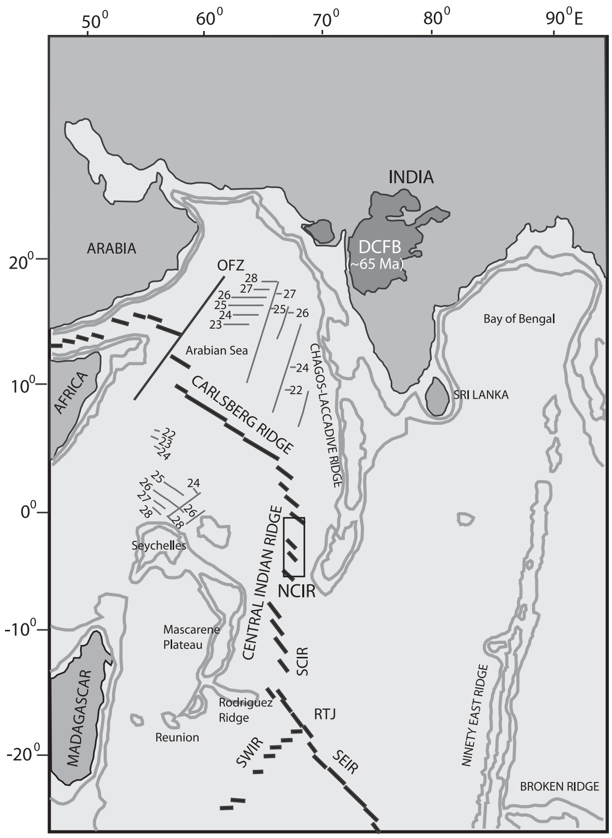

Fig. 1. Location of the Deccan CFB in western India and the northern CIR in Indian Ocean. Segments of Indian mid-ocean ridges viz. Carlsberg Ridge, Central Indian Ridge, Southwest Indian Ridge (SWIR), Southeast Indian Ridge (SEIR) and Rodriguez Triple Junction (RTJ) are also shown. Samples collected from different segments of NCIR are shown as a rectangle. Magnetic anomalies are drawn following McKenzie and Sclater (1971).

that most of the Phanerozoic CFB are closely associated with seafloor spreading, e.g. Deccan/Indian Ocean, Karoo-Ferrar/Indian Ocean, Parana-Etendeka/Southern Atlantic Ocean, etc. (Hawkesworth et al., 1999; Courtillot et al., 1999; Minshull et al., 2008). There is a general consensus that CFB activities could precede the associated seafloor spreading by a period of no more than ~30 Ma, often a few million years. This idea is based on the age difference between the oldest records of magnetic anomalies on the sea floor and the peak activities related to the CFB. Thus, CFB eruptions may have a genetic link with later basalt generated by seafloor spreading and the subsequent development of mid-ocean ridge systems.

Possible eruption mechanisms for the Deccan CFB include (a) the emplacement of a mantle plume followed by crustal extension (Courtillot et al., 2003), (b) continental extension – rifting preceding eruptions from a mantle plume (White and McKenzie, 1995), and (c) a non-plume source model related to smaller-scale upper mantle convection associated with continental and/or rift margins (Anderson, 2007; Sheth, 2007). Therefore, a comprehensive comparison of geochemical and isotopic data for basalts belonging to both a CFB province and those associated with the later MORB might lead to a better understanding of the links between the rifting process(s) at continental margin(s) and the evolution of MOR. This would also evaluate any possible genetic relationship between the two types of magmatic activity.

The Deccan CFB erupted across the Cretaceous-Tertiary (KT) boundary between 67 and 64 Ma, with peak volcanism occurring within 1 Ma, just prior to the KT boundary (Hofmann et al., 2000; Courtillot et al., 2000; Widdowson et al., 2000; Courtillot and Renne, 2003; Pande et al., 2004). Recent work suggests that these eruptions occurred as a series of distinct 'pulses', each lasting only a few hundred thousand years. The first and most extensive phase occurred at c. 67.5 Ma, at the northern half of the present Deccan outcrop, and the final volcanism phase, predominantly located in the southern region, at c. 65 Ma, just prior to the KT boundary (Chenet et al., 2007). Extension and rifting of the western Indian margin began in the later stages of the Deccan CFB evolution. During this time erupting tholeiitic magmas produced spilites, pillow lavas and hyaloclastites within a shallow marine gulf environment near present day Mumbai (Cripps et al., 2005). The separation of the Seychelles micro-continent from India occurred because of seafloor spreading along the Carlsberg Ridge (CR). Initial ocean floor spreading and opening of the northern Arabian Sea took place at c. 62–64 Ma (Chrons 27–28; Fig. 1, Collier et al., 2008; Ganerød et al., 2011).

The opening of the Central Indian Ridge (CIR) to the south occurred later (anomaly 16) at c. 38–39 Ma (Norton and Sclater, 1979; Patriat and Segoufin, 1988; Dyment, 1993) during the separation of the Mascarene Plateau and Chagos–Laccadive Ridge (Schlich, 1982). Magnetic anomalies older than 5 Ma (i.e., lower Miocene) have not yet been confirmed from the CIR, though data from DSDP 238 suggests a lower Oligocene basement age. The plate opening direction in the northern CIR (NCIR) has not changed significantly during the last 4 Ma, and there is a less than 2% deviation during the last 7 Ma (Bull et al., 2010; Kamesh Raju et al., 2012). It is clear, therefore, that the events of Deccan CFB significantly predate the eruption of the CIR MORBs.

The geochemistry of the Deccan CFB from the Western Ghats, Kutch, and Narmada-Tapi areas has been intensively studied (e.g., Cox and Hawkesworth, 1984; Devey and Lightfoot, 1986; Mitchell and Widdowson, 1991; Subbarao et al., 1994; Peng et al., 1998; Mahoney et al., 2000; Melluso et al., 2004; Jay et al., 2009; Sheth et al., 2004, 2009) and the petrogenesis and chemostratigraphy are now well established (Cox and Hawkesworth, 1985; Sano et al., 2001). It is also well established that those Deccan flows that comprise the thick, and regionally extensive, Ambenali Formation are the least crustally contaminated members of the Deccan Traps (Widdowson et al., 2000 and references therein). By contrast, the petrochemical studies of the NCIR have been very limited due to lack of samples. However, recent studies on samples of basalt and associated gabbroid rock obtained by drilling and dredging from the NCIR aid in uravelling the evolutionary magmatic history of these MORB (Ray et al., 2007, 2011, 2013).

Here, we undertake a comparative geochemical and isotopic investigation of the basalts from the Deccan CFB province and NCIR MORB from the region between 5°S/68°E and 10°S/66°35′E (the latter collected during expeditions of the research survey vessel *Sagar Kanya* 125 and 165). The ages of the CIR MORBs are thought to be within the magnetic anomaly 2A (<3.5 Ma). Despite the differences in geological age between the samples from the NCIR (~5–10°S, slow spreading ridge ~26–38 mm/yr; Kamesh Raju et al., 2012), and the relatively uncontaminated Deccan Ambenali Formation lavas, a comparative geochemical study of the two cannot only identify the similarities and differences in the igneous processes involved in their petrogenetic evolution, but also aid in tracing the mantle characteristics to identify and constrain any possible genetic linkage (Fig. 1). The basalts from the Ambenali Formation show a restricted composition of $TiO_2 \sim 2$–4 wt%, Ba < 100 ppm, Sr ~ 175–230 ppm, Zr/Nb ~ 12–18, $^{87}Sr/^{86}Sr < 0.7050$ and $\varepsilon_{Nd} > 3.0$ indicating that they are among those Deccan magma compositions least contaminated by continental crust and/ or continental lithospheric mantle (Cox and Hawkesworth, 1984; Mahoney, 1988; Peng et al., 1998; Sano et al., 2001). The Ambenali Formation basalts with the highest $\varepsilon^{143}Nd(t)$ ratios ($^{143}Nd_{65Myr}$ = +5.5 to +5.6) are considered representative of the regional mantle composition (Lightfoot et al., 1990).