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Short Communication

# Oxygen isotope evidence for crustal contamination in Deccan Basalts

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ABSTRACT

A set of whole rock lava flows and dykes from the western part of Deccan Traps, Western India, was analyzed for oxygen isotope ratios. $\delta^{18}O$ stratigraphy of the upper formations in the Mahabaleshwar section of the Western Ghats area can be correlated with the Sr- and Nd-isotopic stratigraphy, in that increasing $\delta^{18}O$ is associated with increasing initial $^{87}Sr/^{86}Sr$ and decreasing initial $\varepsilon Nd$. The increases of $\delta^{18}O$ (up to +11.8‰) exceed the range of primitive mantle-derived materials, strongly suggesting that isotopic variations of these Deccan basalts are due to crustal contamination rather than input of continental lithospheric mantle as previously considered. The variations of $\delta^{18}O$–$^{87}Sr/^{86}Sr$ and $\delta^{18}O$–$\varepsilon Nd$ indicate that there are at least two contaminating domains, most likely (1) Archean granitic upper crust and (2) Archean carbonates + granulitic lower crust.



## 1. Introduction

The Deccan Traps in western India can be considered as one of the most voluminously extensive and best-exposed large igneous provinces (LIPs). Over the past few decades, they have attracted both geophysical and geochemical studies concerning their origin and related issues (e.g. Mahoney et al., 1982; Lightfoot et al., 1987, 1990; Kaila, 1988; Lightfoot and Hawkesworth, 1988; Mohan and Ravi Kumar, 2004; Sheth and Melluso, 2008; Zellmer et al., 2012). Some attention was paid on whether the voluminous outpouring of the flood basalts is associated with a mantle plume emplacement. In general, plume advocates argue that the Deccan Traps represent the arrival of a plume head and the Mascarene Islands (Mauritius, Réunion and Rodrigues) as well as Lakshadweep-Chagos ridge (presently to the SSW of India) in the Indian Ocean represent subsequent products of the tail of this plume when the Indian plate drove over the Réunion hotspot (Baksi, 1987; Jaeger et al., 1989). Plume skeptics, by contrast, question (1) the short eruptive duration and catastrophic eruption rates, (2) the presence of excess heat for the genesis of the Deccan basalts, as well as (3) the architecture of age-progressive features ("hotspot track") which may otherwise be considered as a result of large-scale fracture propagation (Sheth et al., 2001a,b; Baksi, 2005; Sheth, 2005a,b). Regardless of whether they were plume related or not, the Deccan Traps are yet of significant interest to geological studies in terms of their short eruptive duration (≤1 my at ~65–66 Ma; Baksi, 1994; Pande, 2002), huge volume, causal relationship with the Cretaceous/Tertiary (K/T) mass extinction (Courtillot et al., 1988; Jaeger et al., 1989; Swisher et al., 1992; Kelley et al., 2009; Schulte et al., 2010) and break-up with the Seychelles microcontinent (Mahoney, 1988; Collier et al., 2008).

The Deccan lava flows, of mainly tholeiitic compositions, cover >500,000 $km^2$ of the Indian subcontinent (Fig. 1). The Archean Dharwar craton, exposed in much of southern India, is thought to have continued beneath the Deccan Traps by virtue of drilling at Latur (Gupta and Dwivedy, 1996) and crustal xenolith studies (Ray et al., 2008).

A number of studies have been undertaken to resolve crust–lithospheric mantle–asthenosphere–plume contributions to continental intraplate or flood basalt volcanism (Baker et al., 1997, 2000; Ma et al., 2011a,b, 2013; Pang et al., 2012). Likewise, the Deccan basalts, as a flood basalt province, have been extensively studied to unravel such interactions and to identify the chemical character of their mantle sources (e.g. Mahoney et al., 1982; Cox and Hawkesworth, 1984; Lightfoot and Hawkesworth, 1988; Lightfoot et al., 1990; Mahoney, 1988; Peng et al., 1994). In Deccan, 11 basalt formations have been identified and grouped into three sub-groups (e.g. compilations of Subbarao and Hopper, 1988 and Sano et al., 2001). On the grounds of the geochemistry of the lava flows, Peng et al. (1994) generalized these formations as the upper formations and lower formations. A summary of the stratigraphic units of the Deccan basalts is provided in Fig. 1. One of the primary geochemical and isotopic studies of the Deccan basalts is that of Mahoney et al. (1982) who investigated the Sr–Nd isotopes of the lava flows in the Mahabaleshwar area (the upper formations reported by Peng et al., 1994). Shrivastava and Pattanayak (2002) reviewed recent studies

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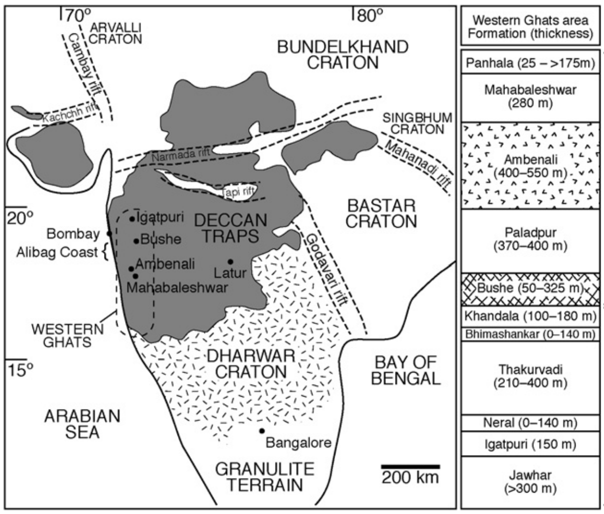


**Fig. 1.** Schematic map of the Deccan Traps and locations of the Precambrian terrains (after Ray et al., 2008). Stratigraphy of the Western Ghats area is shown in the adjacent column (after Subbarao and Hopper, 1988; Sano et al., 2001). The division of upper and lower formations is from Peng et al. (1994).

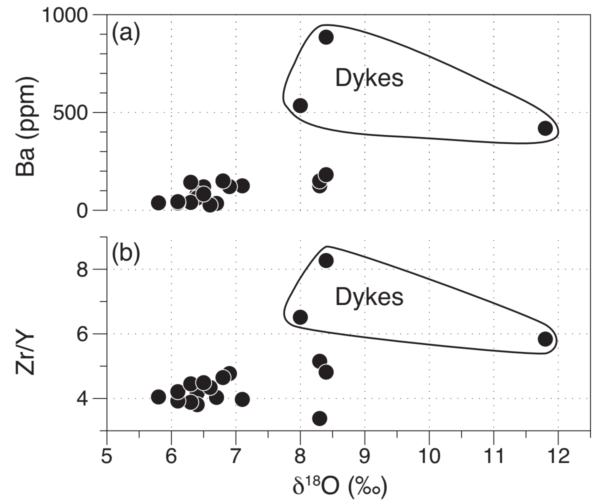


**Fig. 2.** (a) Fluid mobile element Ba and (b) immobile element ratio Zr/Y vs $\delta^{18}O$ for the Deccan basalts analyzed in this study.

of the Deccan Traps and demonstrated that the lavas from the Mahabaleshwar sequence are unique in that they comprise some of the widest Nd and Sr isotopic variations among the Deccan lavas. Such wide variations have been interpreted (e.g. Mahoney et al., 1982) as a result of either crustal contamination or partial melting of an ancient enriched mantle with high Rb/Sr and low Sm/Nd. Other authors (e.g. Peng et al., 1994), however, have contended that the diverse isotopic ranges of the Deccan lavas are mainly a result of crustal contamination in which at least two components have been identified—(1) an ancient crust with high $^{206}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$ and low $\varepsilon Nd$ (time-integrated high U/Pb, Rb/Sr and low Sm/Nd), likely of granitic compositions, and (2) a low-$^{206}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$ and $\varepsilon Nd$ material (time-integrated U-, Rb-, and Sm-poor), likely of granulitic lower crust. To resolve crustal and mantle contributions to the Deccan lavas, oxygen isotope analysis has been employed in this study for some of the lavas studied by Mahoney et al. (1982). The notion of using oxygen isotope in this study is compromised by the fact that uncontaminated, primitive lavas should retain a mantle value of ∼+5 to+6‰, whereas crustal rocks, in general, are relatively enriched in heavy isotopes due to low temperature surface processes.

## 2. Samples and methods

Aliquots of 15 samples of the Mahabaleshwar sequence previously studied by Mahoney et al. (1982) were selected. They belong to the Upper Formation (Bushe, Poladpur, Ambenali and Mahabaleshwar) ranging in elevation from 54 m to 1125 m. Other samples comprise two lava flows from the Thakurvadi formation in Igatpuri (lower formation; 200 km north of Mahabaleshwar) and three dykes from Alibag Coast. Their major-element, trace-element and Sr–Nd–(Pb) isotopic data have been reported in Mahoney (1984) and Peng et al. (1994). We report new oxygen isotopes for these 20 samples.

Only the freshest portions of samples devoid of weathering products were used for the analysis. The powdered samples were processed using the standard $BrF_5$ method following the procedure of Clayton and Mayeda (1963). Briefly, a few mg of the powder is loaded in a nickel reaction tube in a dry box and the tube is closed with metal stopcock and metal ferrule. Several such tubes containing samples and NBS 28 standard are then placed in the all metal vacuum line and slowly evacuated. A small amount of $BrF_5$ is allowed to react at room temperature for 1 h to remove any adsorbed moisture. After pumping to high vacuum the tube is again loaded with $BrF_5$ (about five times more than required by stoichiometry) and heated to 600 °C for several hours. Finally, the oxygen formed is collected by expansion in a glass sample tube and converted to $CO_2$ in a graphite reactor, collected back and analyzed in a dual inlet isotope ratio mass spectrometer (MAT 250) at the Geological Survey of Japan, Tsukuba. The standard NBS 28 ($\delta^{18}O$ = +9.58‰ relative to VSMOW) was used for converting the measured delta values to VSMOW scale. The estimated analytical precision is about 0.1‰.

## 3. Results and discussions

Analogous to the Sr–Nd isotopic systematics, the samples exhibit a wide range of $\delta^{18}O$: +5.8 to +8.3‰ for the upper formations, +6.8‰ and +8.4‰ for the two lower-formation samples and +8.0 to +11.8‰ for the Alibag Coast dykes (Table 1). Among the upper formations, lavas of the Ambenali formation define the lowest range of $\delta^{18}O$ between +5.8‰ and +6.6‰, close to the values for most fresh, uncontaminated basalts (∼+5.4 to +6.1‰; Ito et al., 1987; Eiler, 2001 and references therein), and two lavas of the Bushe and Mahabaleshwar formations exhibit the highest value of +8.3‰. It is worthy noting that some of the $^{18}O$ enhanced samples are characterized by elevated fluid-mobile incompatible elements, such as Ba (Fig. 2a), which at first sight may indicate weathering. However, the increases of mobile incompatible elements are mimicked by immobile incompatible elements or ratios such as Zr/Y (Fig. 2b) suggesting that high $\delta^{18}O$ is not a result of weathering, although we cannot totally exclude minor variations of $\delta^{18}O$ due to weathering. The primary cause of the $\delta^{18}O$ variations is explored below.

### 3.1. Oxygen isotope stratigraphy

Delta $^{18}O$ stratigraphy of the upper formations is shown in Fig. 3 along with Nd and Sr isotopic data from Mahoney et al. (1982). The radiogenic isotopic values used here have been recalculated to the initial values at 66 Ma and the Nd isotopic values recalculated to $\varepsilon Nd_{(t)}$ relative to the Chondritic Uniform Reservoir of Wasserburg et al. (1981) ($^{143}Nd/^{144}Nd$ = 0.512638 and $^{147}Sm/^{144}Nd$ = 0.1967). The variations observed in the $\delta^{18}O$ stratigraphy are analogous to the $^{87}Sr/^{86}Sr_{(t)}$ and $\varepsilon Nd_{(t)}$ stratigraphy. In places of elevated $\delta^{18}O$, the samples are also characterized by higher $^{87}Sr/^{86}Sr_{(t)}$ and lower $\varepsilon Nd_{(t)}$, consistent with a model for crustal contamination. The pattern of variations may be used to infer the dynamics of the magma plumbing system in Deccan. There are at least three cycles of eruptive successions in the Mahabaleshwar lava sequence (upper formations), each can be correlated to one previously identified formation. Lavas at the top or bottom of any of the formations are characterized by increases in $\delta^{18}O$ and $^{87}Sr/^{86}Sr_{(t)}$ and a decrease in $\varepsilon Nd_{(t)}$, and these anomalies are smoothed out, to some degree gradually, away from the boundary of two formations. These features