



## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India and its Implications on Exploration

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Immobile trace elements, Strontium-Neodymium isotopes, Kerala-Konkan Offshore Basin, E-type MORB, Exploration

### Summary

This paper presents immobile trace elemental and Strontium-Neodymium (Sr-Nd) isotopic signatures of basalts encountered in Kerala-Konkan Offshore Basin of India. The results are compared with the basalts from Kutch and Mumbai Offshore Basins, Onland Deccan traps as well as Chagos Laccadive Ridge (CLR) and South Mascarene Plateau. The study suggests close affinity of Kerala Konkan Offshore basalts to Chagos-Laccadive Ridge and South Mascarene Plateau basalts. Further, the basalts from Kerala Konkan Offshore and Chagos-Laccadive Ridge/South Mascarene Plateau show Enriched Mid-Ocean Ridge Basalt (E-MORB) characteristics, a very significant finding being reported for the first time, while the basalts from Kutch and Mumbai Offshore fall in Within Plate Basalts (WPB) category similar to the on-land Deccan Traps. The geochemical and isotopic studies of basalts from Kerala Konkan Offshore suggest different petrogenetic history as compared to the basalts from Kutch and Mumbai Offshore and appear to have been derived from a more primitive deep mantle plume source. The Ar-Ar dating of basalts from wells KKD-AA and K-A-A of Kerala Konkan Offshore indicate their emplacement ~62 Ma which is coeval with the formation of northern part of Chagos-Laccadive Ridge. The magmatic episode in both the regions postdate the Deccan activity and were emplaced possibly by the interaction of the Reunion Plume and newly formed Carlsberg Ridge. In such kind of settings, the probability of occurrence of Mesozoic sediments below the E-MORB becomes meager. Present study also proposes a plausible model for emplacement of E-type MORB in the Kerala Konkan Offshore and the Chagos Laccadive Ridge.

### Introduction

It is generally accepted that India was formed initially by the progressive breakup of the Gondwana supercontinent, variously reported as starting about 150-180 my ago (i.e. in Middle to Upper Jurassic time). This resulted in the creation of West Gondwana (Africa) and East Gondwana (Madagascar, Seychelles, India, Antarctica and Australia) which itself started to break up about 128-130 my ago. This led to the rifting of India from Madagascar about 90 my ago (Middle Cretaceous) and the beginning of a number of stages of volcanism and rifting (e.g. Deccan Traps), which

shaped the present day structure of the Western Offshore of India.

The western margin of India is regarded as a rifted volcanic continental margin as opposed to a simple passive margin and extends from Kutch in the northwest to Cape Comorin in the southwest. The western margin is tectonically differentiated into horst-graben complex of ridges and depressions. The principal features observed by the seismic data include the Shelfal Horst and Graben Province, Lakshadweep Basin, Laxmi Basin, Laccadive Ridge and Arabian Cenozoic Spreading Basin. The Laxmi and Laccadive ridges are believed to be continental remnants which rifted away from the western continental margin and subsequently affected by volcanism, in the latter case by the Reunion hotspot which forms part of the Chagos-Laccadive-Maldives hotspot trail (Naqvi, 2005).

The Kutch, Mumbai and Kerala-Konkan Offshore Basins are located in the northern, central and southern part of the western margin of India. The locations of structural-tectonic features like Chagos-Laccadive ridge, South Mascarene Plateau and the study area is shown in Figure 1. The structural styles and depositional history of these basins have been studied in detail by earlier workers. The Kerala-Konkan Offshore Basin is situated along the west coast of India south of 16°N latitude, and is bounded on the eastern side by the Indian Peninsular shield; towards west and south, the basin opens up into the deep sea of the Indian Ocean. The tectonic limits for the Kerala Konkan Offshore are defined by the ENE-WSW trending Vengurla arch in the north and similar trending Trivandrum arch in the south (Figure 2). The Vengurla arch partially separates the Kerala Konkan Offshore from Mumbai Offshore Basin.

The structural styles of Kerala Konkan Offshore are similar to the Mumbai Offshore basin, however, the horst-graben structures on the continental shelf are somewhat less pronounced in the former. Instead, a series of step fault parallel to the coast are typical of this basin. The regional tectonics of this area is guided primarily by major basement lineaments (Gupta et al., 2000). The Kerala Konkan Offshore evolved mainly through two tectonic phases- an Early Cretaceous Rift phase and a Late Cretaceous-Early Tertiary Drift phase. The tectonic framework, stratigraphy, structural styles and depositional history of the Kerala

## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

Konkan Offshore have been discussed by Biswas (1982, 1987) and Mathur et al. (1993). However, information on the basement rocks that play a very significant role in the evolution of geological structures in a sedimentary basin is limited.

In this paper we present Strontium-Neodymium (Sr-Nd) isotopic signatures and bulk rock chemical compositions including immobile trace elemental data of the basaltic rocks drilled in the Kerala-Konkan Offshore Basin. The results thus obtained are interpreted to understand the tectonic setting, petrogenesis and are compared with the basalts of Kutch and Mumbai Offshore Basins as well as to the basalts from Chagos-Laccadive Ridge and South Mascarene Plateau in an attempt to bring about any similarities or differences. This comparison will throw new light on the mode of origin and hence the evolution of the basaltic basement from Kerala Konkan Basin of India.



Figure 1: Map of the Western Margin of India showing structural-tectonic features along South West Indian Ocean and the locations of study area.

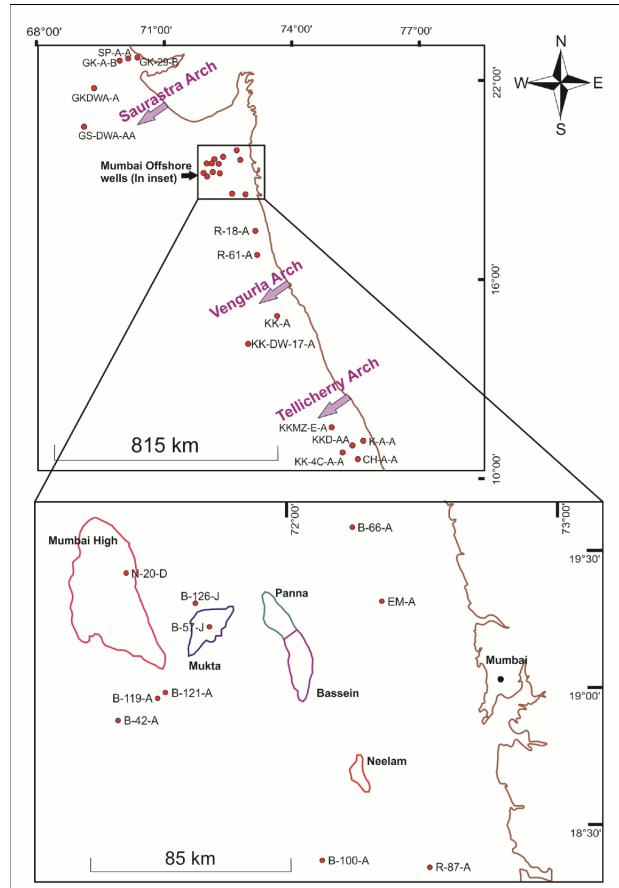


Figure 2: Map of the study area from Western Offshore of India showing locations of studied wells.

### Methodology and Data Analysis

In the present study core samples from 23 wells and cutting samples from 2 wells have been taken up for multi-isotopic and trace elemental analysis. Location of studied wells is shown in Figure 2. Five wells from Kutch Offshore, thirteen wells from Mumbai Offshore and seven wells from Kerala Konkan Offshore have been included in the study.

For trace elemental analysis, the samples were digested using a mixture of acids in steel Parr digestion bombs. About 25 mg of the sample powder was weighed in a Teflon beaker and ultrapure acids (3 mL HNO<sub>3</sub> and 2 mL HF) were added and placed in a steel Parr bomb vessel. The bomb was kept at 200°C for about 24 hours in an oven, after which the digested sample was dried and the residue was dissolved in 3mL 6N HCl and dried. The final solution was prepared in 100 mL 10% HNO<sub>3</sub> and was filtered to remove any undissolved particles. The trace element analysis was carried out on ICP-AES in the

## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

Hydrogeochemistry Lab. of KDMIPE, Dehradun and on ICP-MS in IIT, Roorkee, India.

For Sr and Nd isotopic analysis, about 100 mg powder sample was digested in a mixture of acids as per the procedure detailed above. The Rb-Sr and Sm-Nd mixed spike was added to the sample prior to the dissolution to ensure complete mixing. The Sr and Nd elements were separated using ion exchange chromatography as per the in-house established procedure (Rathore et al., 2013).

The Sr and Nd isotopic ratios were measured using multi-collector TRITON-TIMS. The measured data for Sr and Nd isotopes were corrected for mass fractionation by normalizing to  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$  and  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ , respectively. Average blank levels were found to be within nanogram range for Sr and Nd. The results for the Sr and Nd standards were well within their reported values.

### Results and Discussions

Petrographic evaluation of the core samples from Kerala Konkan Offshore reveals varying rock types. Samples from well KK-A (CC-3) appears to be *vesicular basalt* with fine grained porphyritic texture containing micropheocrysts of plagioclase, clinopyroxene and minor olivine in a very fine grained groundmass of plagioclase laths and clinopyroxene with abundance of vesicles. However, another core of the same well (CC-4) cut at a deeper depth is found to be medium to coarse grained *serpentinized peridotite* containing rounded grains of high relief olivine, garnet, minor labradorite and spinel and appears to be derived from deep mantle. Samples from well K-A-A are found to be *dolerite* with equigranular, interlocking grains of plagioclase and clinopyroxene. Core samples from wells KKD-AA and KKMZ-E-A appear to be *fine-grained basalts* whereas rocks from wells CH-A-A and KKDW-17-A represent acidic volcanism and are *rhyolites/trachytes* in lithology.

The geochemical behavior of basalts from Kerala Konkan, Mumbai and Kutch Offshore is discussed here. For comparison, the trace element data from basalts encountered in least contaminated Deccan Traps of Mahabaleshwar and Ambenali formations (Data source: Mahoney et al., 1982; Ray et al., 2014), and from Site 713, 715 (Chagos-Laccadive Ridge) and Site 706, 707 (South Mascarene Plateau) of ODP Leg 115 (Fisk et al., 1989) have also been used from published domain.

The Ti-Zr plot (Pearce, 1981) is widely used to geochemically distinguish various kinds of volcanic settings involving Within Plate Volcanics and Arc lavas, and also to demarcate affinity of MORB lavas whose signatures could be preserved both in Within Plate Basalts (WPB) as well as Volcanic Arc lavas. The Ti-Zr plot for basalts/dolerites encountered in wells of Kerala Konkan Offshore as well as those from Mumbai and Kutch

Offshore, along with Deccan Traps, Chagos-Laccadive Ridge and South Mascarene Plateau (Figure 3) suggests

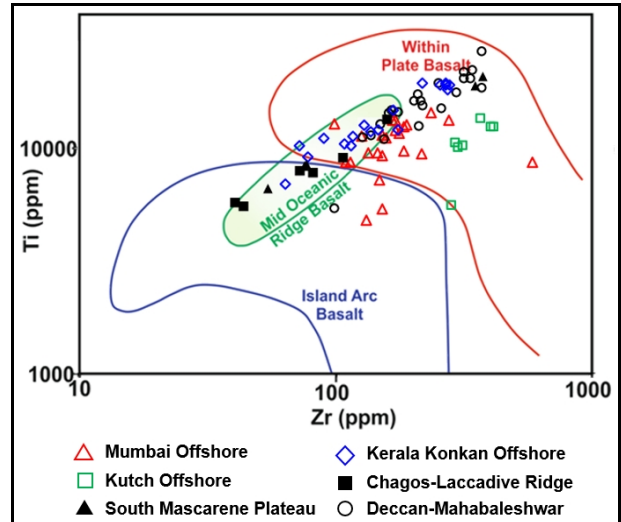


Figure 3. Zr-Ti discrimination plot of studied samples (After Pearce, 1981)

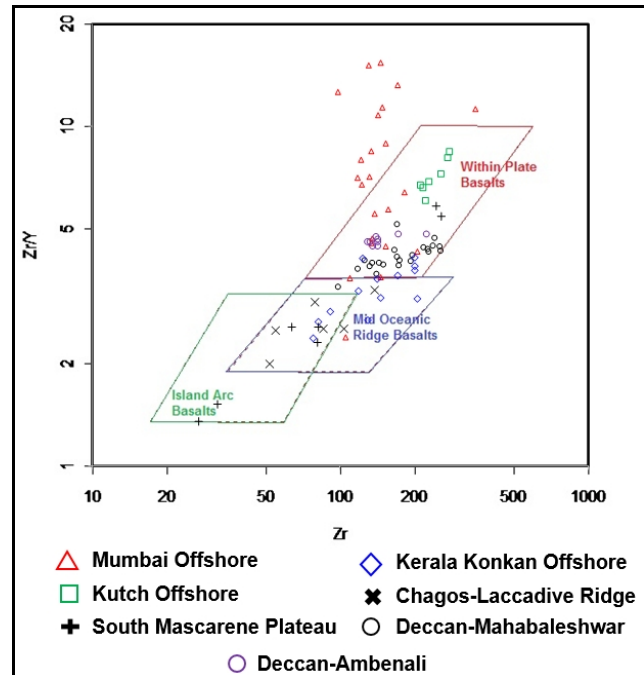


Figure 4. Zr/Y vs. Zr diagram of studied samples (After Pearce and Norry, 1979)

that, Mumbai and Kutch Offshore basalt samples fall mostly in the field of Within Plate Basalts (WPB) and are comparable with least contaminated Deccan Basalts. On the

## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

other hand, Kerala Konkan samples remain confined in the overlapping field of MORB and WPB, with slight anomaly in case of KKMZ-E-A, which cluster on the higher side of Ti-Zr plot. However, Kerala Konkan samples maintain close affinity to Chagos-Laccadive Ridge and South Mascarene Plateau basalts in terms of their Ti-Zr concentration which also fall mostly in the field of MORB (Figure 3).

Figure 4 is a plot of Zr vs. Zr/Y (Pearce and Norry, 1979) which was used to further characterize the different suites of volcanics in the study area. It is shown that Zr/Y ratios of Deccan samples from Kutch Offshore lie the field of

high Zr/Y, exhibiting signatures of Within Plate basalts, similar to those of Mahabaleshwar and Ambenali formations. Mumbai Offshore basalts too lie in the range of Within Plate basalts, although there is a considerable scatter in the Zr/Y ratio crediting to varied degree of crustal contamination and alteration due to seawater during emplacement (Figure 4). Kerala Konkan samples have entirely different Zr/Y signatures and almost all the samples fall in the range of MORB, suggesting either a different magma source or a different petrogenetic history that differs these lavas from that of the Kutch and Mumbai Offshore and Deccan volcanism (Mahabaleshwar and Ambenali formations).

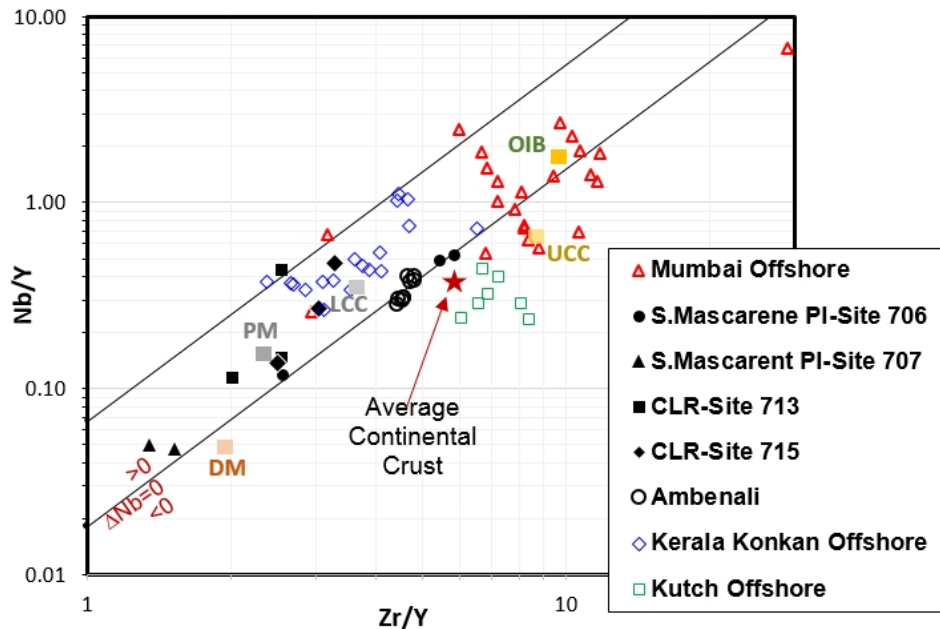


Figure 5. Binary plot of studied basalt samples in Zr/Y vs. Nb/Y space. Parallel lines define the lower and upper bounds of mantle plume array.

Further, the Kerala Konkan Offshore samples appear to show close affinity to basalts from Chagos-Laccadive Ridge (Site 713 and 715) and South Mascarene Plateau (Site 706 and 707) of ODP 115 in terms of their Zr/Y signatures and thus possibly in their petrogenesis.

In Figure 5, basalt data from wells of Kerala Konkan, Mumbai and Kutch Offshore basins are compared with data from Site 713 and 715 (Chagos-Laccadive ridge), Site 706 and 707 (South Mascarene Plateau) and the least contaminated Deccan basalt samples (Ray et al., 2014) from Ambenali Formation on a Zr/Y vs. Nb/Y binary plot (Fitton et al., 1997; Condie, 2003) to investigate plume vs. non-plume component and the source of magma. Parallel lines represent the lower and upper bounds of the Icelandic plume array in such a way that rocks plotted between these

lines display a deep-mantle signature that essentially signifies a plume source (Fitton et al., 1997; Fitton, 2007).

Fitton et al. (1997) also defined a parameter, Nb, which expresses the excess or deficiency in Nb respective to the lower line ( $Nb=0$ ) such that the composition of primitive mantle (PM) lies within the Iceland array ( $Nb>0$ ) and both normal MORB (N-type MORB) and average continental crust plot below it ( $Nb<0$ ). Nb is unaffected by degree of melting (or partial melting) and also by fractional crystallization, which controls the position of a sample along the array (Fitton, 2007).

The basalt samples from Mumbai Offshore mostly lie within the 'plume source field', albeit close to the discrimination boundary ( $Nb=0$ ) (Figure 5). These data points cluster near the region of Ocean Island Basalts (OIB) and are also affected by Upper Crustal Contamination

## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

(UCC) during their emplacement. Deccan samples from Kutch Offshore Basin plot below the lower boundary of the Icelandic plume array in the region of average continental

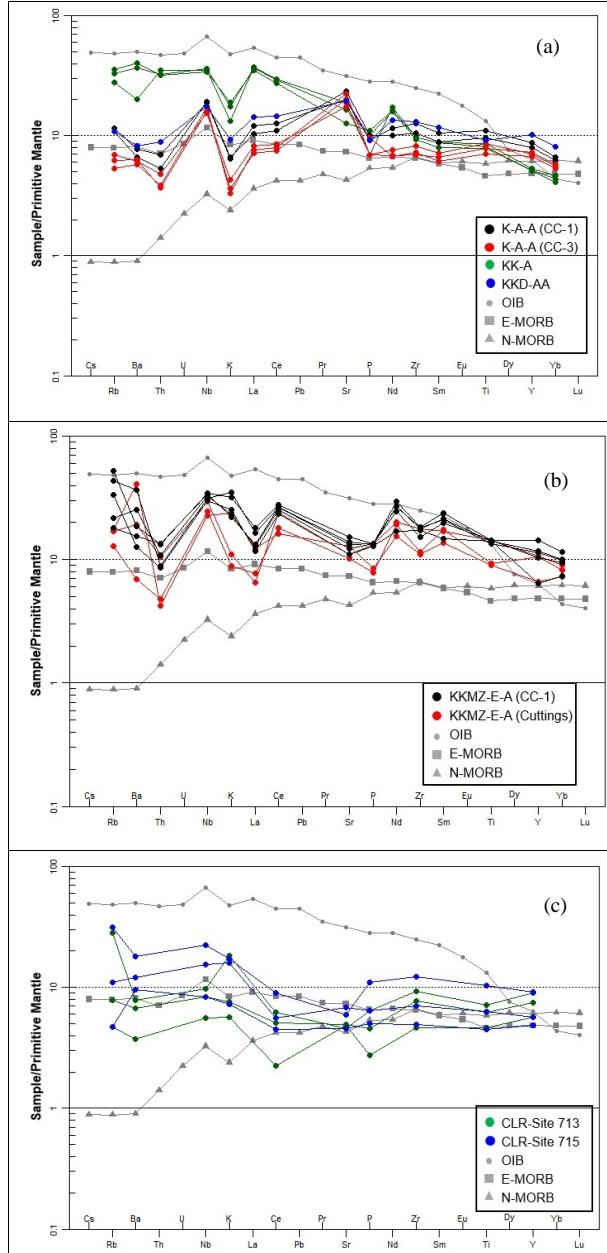


Figure 6. Incompatible element patterns of basalts encountered in Kerala Konkan Offshore in multivariate spider diagram, normalized to Primitive Mantle. Also shown here the compositions of Ocean Island Basalt (OIB), E-MORB and N-MORB (After Sun and McDonough, 1989).

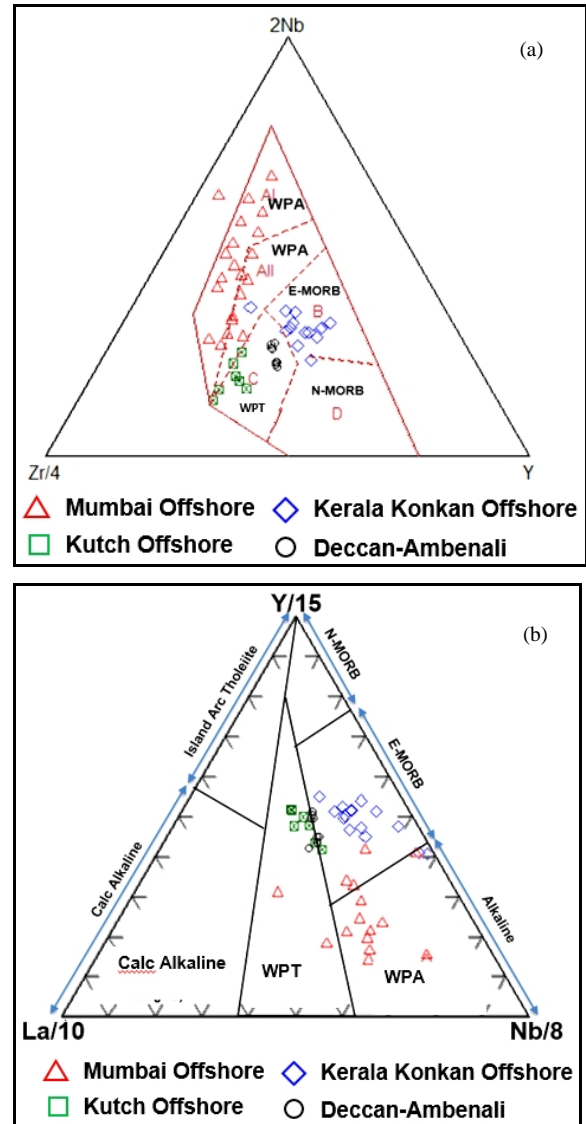


Figure 7 (a)  $2xNb-Zr/4-Y$  triangular plot (After Meschede, 1986) and (b)  $La/10-Y/15-Nb/8$  triangular plot (After Cabanis and Lecolle, 1989) for basalts under study.

crust and hence appear to have been affected by crustal contamination as well. The basalt samples from Deccan-Ambenali formation (Ray et al., 2014) fall on the lower boundary of the array ( $Nb=0$ ) indicating mantle plume signature.

All the Kerala Konkan Offshore data points cluster within the bounds of the deep mantle plume array and close to the region of primitive mantle (PM) component ( $Nb>0$ ) in close association with the basalts from Site 713 and 715 of Chagos-Laccadive ridge and Site 706 and 707 of South

## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

Mascarene Plateau of ODP Leg 115 (Fisk et al., 1989). This observation strongly suggests that the basalts from Kerala Konkan Offshore Basin could be related to those from Chagos-Laccadive Ridge in terms of their mantle component and the samples have not been affected by Upper Crustal contamination, contrary to the basalts from Mumbai and Kutch Offshore, and lie in close vicinity of LCC regime (Figure 5).

For detailed investigation of the mantle source for the basalts/dolerites from Kerala Konkan Offshore, multivariate plots of incompatible trace elements (spider-diagrams, normalized to primitive mantle (Sun and McDonough, 1989) have been used (Figure 6). Dolerites from well K-A-A and basalts from KKD-AA (Fig. 5a) show enrichment of incompatible elements similar to E-type MORB (Sun and McDonough, 1989). Basalts from well KK-A, however, show higher enrichment of incompatible elements, still exhibiting E-MORB characteristics (Fig. 6a) towards the lesser incompatible elements (P to Yb). Similar observation is derived from well KKMZ-E-A (core and cutting samples), which shows a mostly overlapping trend compared to the E-MORB (Fig. 6b). Basalts from Chagos-Laccadive ridge (Fisk et al., 1989) too exhibit typical E-MORB trend when plotted on primitive mantle normalized spider diagram (Figure 6c).

The immobile trace element Nb is a sensitive indicator for the tectono-magmatic environment of mid-ocean ridge basalts (MORB). Meschede (1986) used Nb in combination with Zr and Y in a triangular diagram and divided basalts into four fields: "normal" mid-ocean ridge basalt (N-type MORB), basalt from plume-influenced regions (E-type MORB), tholeiitic basalts from within-plate environments (WPT) and alkali basalts from within-plate environments (WPA) in the 2Nb-Zr/4-Y triangular diagram (Figure 7a). In this ternary plot, basalts from Mumbai Offshore mostly fall under the alkali basalts from within-plate environments (WPA) whereas those from Kutch Offshore appear to have affinity to within-plate tholeiites, along with the least contaminated Deccan basalts from Ambenali formation (Data source: Ray et al., 2014).

Basalts from Kerala Konkan Offshore, however, cluster in the field of E-MORB (Fig. 6a), showing that these basalts appear to be derived from plume influenced regions owing their origin to deep enriched mantle source. The ternary diagram La/Y/Nb (Cabanis and Lecolle, 1989) also yields similar results (Figure 7b) supporting the earlier observation that Kerala Konkan Offshore basalts show strong affinity to E-MORB regime compared to Mumbai and Kutch Offshore basalts which show close relationship to Within Plate Alkaline and Within Plate Tholeiite regimes, respectively.

Results from Sr-Nd isotopic studies for the basalt samples from Western Offshore have been presented in a  $Nd(t)$  vs.

$^{87}Sr/^{86}Sr(t)$  plot of Deccan Trap (Figure 8; modified after Peng et al., 1994). Basalts from Kerala Konkan Offshore appear to be petrogenetically different from those of Mumbai and Kutch Offshore in terms of their Sr-Nd isotopic signatures as they exhibit more positive Nd values ( $\sim +4$  to  $+7$ ) and lower Sr ratios ( $< 0.705$ ) and also show an overlap with the Reunion Plume source field.

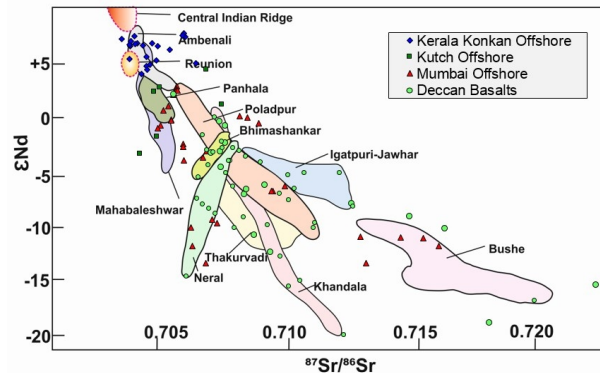


Figure 8. Nd vs.  $^{87}Sr/^{86}Sr$  plot for basalt samples under study (After Peng et al., 1994).

This strengthens the observation that basalts from Kerala Konkan Offshore appear to be derived from a more primitive deep mantle source, possibly the same plume source as of Deccan CFB (Mumbai and Kutch Offshore) but also show MORB-like isotopic signatures (High positive Nd values and low  $^{87}Sr/^{86}Sr$  ratios), supporting an E-MORB behavior, as indicated in trace element plots (Figure 6 and 7). The contamination in these basalts also appear to be very minimum compared to other basalts (Mumbai and Kutch Offshore) which otherwise show large scale scatter in the Sr-Nd plot due to varied degree of crustal contamination (Figure 8). Similar isotopic behavior is displayed by Deccan basalt samples as well (Figure 8; Data source from Peng et al., 1994)

The E-type MORB are different basalts compared to the "normal" N-type MORB as they could either be derived from a deeper more fertile mantle, or produced from the result of mixing that occurs laterally along mid-ocean ridges with material from nearby plumes (e.g., Iceland, Galapagos) (Fitton, 2007; Dymant et al., 2007). E-MORB tends to occur on elevated ridge segments close to ocean islands or large seamounts, as in southern Mid-Atlantic and southwest and central Indian ridges (Fitton, 2007) and are often believed to result from plume-ridge interaction (Douglass et al., 1999). E-MORB component has been known to occur in local intervals in all major Indian Ridges including CIR, SEIR and SWIR along with their N-MORB components (Mahoney et al., 2002; Fitton et al., 2007). They could have been associated with the presence of Reunion Hotspot which was moving relatively southwards

## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

from its location beneath the Indian subcontinent since about 62 Ma.

Subsequent to this event, the northerly movement of the Indian plate left a trail of the hotspot which at present is represented by the Laccadive-Chagos ridge and a part of the Mascarene plateau (Subrahmanya, 1998). During Eocene (~40 Ma), a major reorganization of spreading centres took place in Indian ocean, as a result of which a part of Mascarene Plateau separated from Laccadive-Chagos Ridge (Fisher et al., 1971; McKenzie and Sclater, 1971; Royer et al., 1989) and hence the youngest age of hotspot trail (40 Ma) is observed in Laccadive Chagos Ridge (Duncan and Pyle, 1988) and progressively younging of basalts is observed towards south on the Laccadive-Chagos Ridge all the way to the Reunion Islands (McDougall and Chamalaun, 1969; Duncan and Hargraves, 1990). Therefore, all stages of rifting and seafloor spreading are associated with hotspots and the Carlsberg ridge and Central Indian ridge at the time of rifting have made use of the zone of weakness created by the relative southward movement of Reunion hotspot (Subrahmanya, 1998).

Furthermore, the Chagos-Laccadive ridge postdates the India-Seychelles separation and believed to have come into existence around ~62 Ma which is temporally coinciding with the emplacement of basaltic basement in Kerala Konkan Offshore at ~62 Ma (Rathore et al., 2007).

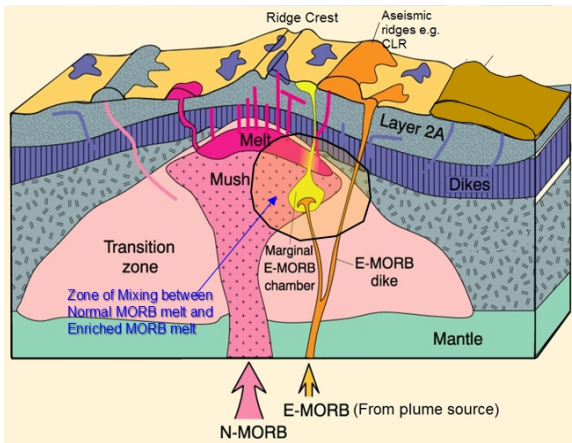


Figure 9. Schematic diagram for the emplacement of E-MORB in the study area resulting into the formation of basaltic suites (Chagos-Laccadive ridge and Kerala Konkan Offshore etc.) having E-MORB component (modified after Perfit et al., 1994).

It is possible that the asthenosphere mantle that lied beneath the Mid Oceanic Ridge (e.g. Carlsberg/CIR) and had passed near the Reunion hotspot was contaminated by hotspot material. In that case, a fraction of the hot mantle plume material (Schilling, 1991) or melt (Braun and Sohn, 2003) might have migrated toward the ridge along the base of the asthenosphere and mixed with “normal” (N-type)

melt to form “enriched” basalts (E-type) observed at the ridge axis (Figure 9). Some of this channeled hotspot material may have leaked through the overlying oceanic lithosphere to generate volcanic lineaments (Dyment et al., 2007) or intrusives in the form of E-MORB dikes (Perfit et al., 1994) (Figure 9) between CIR/Carlsberg ridge and the then location of Reunion hotspot, and may have given rise to the aseismic Chagos-Laccadive ridge and nearby Kerala Konkan basaltic province in the offshore, accounting for the occurrence of E-MORB component in their basalts.

### Conclusions

Geochemical and isotopic studies of basalts and dolerites encountered in Kerala Konkan Offshore suggests these to be of E-type MORB, similar to the basalts from Chagos-Laccadive ridge and South Mascarene Plateau, and are petrogenetically different from Deccan basalts encountered in Mumbai and Kutch Offshore. The rhyolite/trachyte samples from wells CH-A-A and KKDW-17-A in Kerala Konkan Offshore have been excluded from this observation as they belong to acidic volcanics and do not represent basaltic magmas, hence they owe their origin to an entirely different phase of acidic volcanism in Kerala Konkan Offshore.

In global examples of major E-MORB regions, e.g., Iceland, Galapagos, Foundation Seamounts near Pacific-Antarctic Ridge, Azores-Mid-Atlantic Ridge, and Reunion-Central Indian Ridge etc., no occurrences of sedimentary formations have been reported beneath the E-MORB provinces. Taking into account the similar occurrence of E-MORB in the study area in Kerala Konkan Offshore, chances of finding Mesozoic sedimentary formations below basalts are very feeble, which may have bearing on future hydrocarbon exploration.

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## Existence of Enriched Mid Oceanic Ridge Basalt in Kerala Konkan Offshore Basin of India

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