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Chemical composition and Sr-Nd isotopic studies of basement rocks from Kerala-Konkan Offshore Basin of India: Implications on future exploration

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Summary

This paper presents, for the first time, chemical compositions and Sr-Nd isotopic signatures of basement rocks from Kerala-Konkan Offshore Basin (KKOB) and the results are compared with the basaltic basement of Kutch (KOB) and Mumbai (MOB) Offshore Basins of India. Petrographic studies of KKOB basement show the presence of basalt, dolerite, peridotite and trachyte/rhyolite etc. The chemical compositions and Sr-Nd isotopic signatures suggest close affinity of the KKOB basement to Mid-Ocean Ridge Basalt (MORB), a very significant observation being reported for the first time, while the KOB and MOB basements fall Within Plate Basalts (WPG) category similar to the on-land Deccan Traps. The KKOB basement seems to be an oceanic crust formed at ~62 my ago possibly by the interaction of the Reunion Plume and newly formed Carlsberg Ridge. The occurrence of peridotite in the well KKOB-4 (CC-4) possibly represents a remnant oceanic crust. In such kind of settings, the probability of occurrence of Mesozoic sediments below the oceanic crust becomes meager. However, this observation needs to be substantiated by additional studies including seismic and other geophysical tools before further exploration efforts in the KKOB are redirected. These results will be discussed and presented in the paper.

Keywords: Sr-Nd isotopic studies, Kerala-Konkan Offshore basin, Implication on future exploration

Introduction

It is generally accepted that India was formed initially by the progressive breakup of the Gondwana supercontinent, variously reported as starting ~150-180 my ago (i.e. in Middle to Upper Jurassic time). This resulted in 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 ~90 my ago (Middle Cretaceous) and the beginning of 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 southeast. 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. The structural style and depositional history of these basins have been studied in detail by earlier workers. However, information about their basement is sporadic and hence this study is a step forward to understand their petrogenetic and tectonic histories. This paper presents, for the first time, Strontium-Neodymium (Sr-Nd) isotopic signatures and bulk rock chemical compositions including immobile trace elemental data of the basement rocks drilled in the Kerala-Konkan Offshore Basin. The results thus obtained are interpreted to understand the tectonic setting,

petrogenesis and compared with the basement (basalt) of Kutch and Mumbai Offshore Basins in order to bring about any similarities or differences. This comparison will throw some light on the mode of origin and hence the evolution of the basement rocks of the western margin of India.

Regional Tectonic Settings

The Kerala-Konkan Offshore Basin (KKOB) is situated along the west coast of India south of 16°N latitude. The KKOB 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 of the KKOB are defined by the ENE-WSW trending Vengurla arch in the north and similar trending Trivandrum arch in the south (figure 1). The Vengurla arch partially separates the KKOB from Mumbai Offshore Basin.

The structural styles of KKOB are similar to the Mumbai Offshore basin. However, the horst-graben structures on the continental shelf are somewhat less pronounced in the KKOB. Instead, a series of step faults 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 KKOB 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 KKOB have been discussed by Biswas (1982, 1987). However, information on the basement rocks that play a very significant role in the evolution of geological structures in a sedimentary basin is limited.

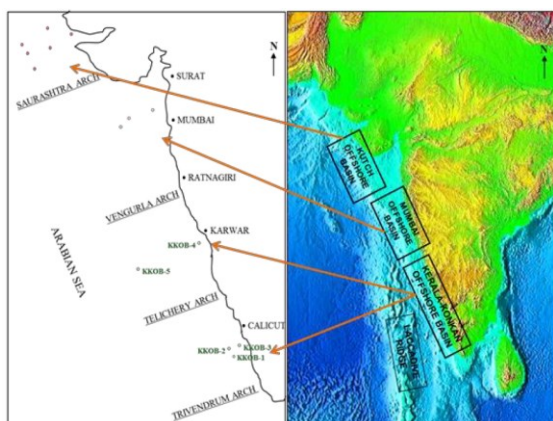


Figure 1: Location map of wells under study from Kerala-Konkan Offshore Basin. The location of earlier studied wells from Kutch and Mumbai Offshore Basins are also plotted.

Sample Details and Experimental Techniques

Conventional core samples recovered from 5 wells KKOB-1 (CC-7), KKOB-2 (CC-2), KKOB-3 (CC-1 & CC-3), KKOB-4 (CC-3 & CC-4), and KKOB-5 (CC-4, CC-6 & CC-7) from KKOB were selected for studies. The location of wells under study is marked in figure 1.

Fresh whole rock samples were chipped into small pieces, ultrasonically cleaned with Milli-Q water, dried and crushed to 2-3 mm size using a Jaw crusher and cleaned again in an ultrasonic bath and dried. The crushed samples were further powdered and sieved between 200-270 mesh size and stored in pre-cleaned sample bottles.

Chemical Analysis

For determination of bulk rock major and trace elements, excluding silica, “B” solution was prepared following the procedure of Shapiro and Brannock (1962). The final solution was prepared in 100mL 10% HNO₃. Silica was determined from solution “A” prepared by lithium metaborate fusion method. The elemental analysis was carried out on ICP-AES. REE and some immobile trace elements like Th, Ba, V, Zr, Nb, Y, Sr and Tb were analyzed by ICP-MS at the Indian Institute of Technology (IIT), Roorkee using the solution “B” as detailed above.

Isotopic Analysis

Sample digestion for Rb, Sr, Sm, and Nd isotopic analyses were carried out following the standard procedures. About 100mg of the sample powder was weighed in a Teflon beaker followed by adding known amounts of Rb-Sr and Sm-Nd mixed spikes. 3mL HNO₃ and 2mL HF were added to the sample beakers which were kept at 200°C for ~24 hours in an oven. After complete dissolution, the acids were evaporated and the residue was re-dissolved in 3mL 6N HCl and dried. The final solutions were prepared in 2mL 2N HCl and were centrifuged before loading onto the chromatographic columns for elemental separation.

Rb, Sr and REE were separated using ion exchange chromatography as per the established procedure (Rathore et al., 2013). The Rb, Sr and REE thus collected were dried on a hot plate at ~80°C. REE was re-dissolved in 0.7mL 0.1N HNO₃ of which 0.5mL was loaded onto Eichrom LnSpec columns. Nd was collected in the fractions 8-13 mL (5mL) in 0.25N HCl while Sm was collected in the fractions 2-3.5 mL (1.5mL) in 0.75NHCl.

The LnSpec column was cleaned by passing 5mL 6N HCl and then conditioned with 5mL of 0.25N HCl. Nd and Sm thus collected were dried on a hot plate at ~80°C.

Rb and Sr were loaded onto pre-degassed single Ta filaments while Sm and Nd were loaded onto pre-degassed double Re filaments. The Rb, Sr, Sm 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 < 3 ng for Sr and Nd. During the course of this study, 15 analyses of Sr reference material NIST SRM- 987 yielded an average value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710258 \pm 6$; for Nd reference materials, 6 analyses of JNdi-1 yielded an average value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512107 \pm 2$ and 7 analyses of Ames yielded an average value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.511963 \pm 2$. The results for the Sr and Nd reference standards are well within their reported values.

Results

Bulk Rock Chemical Composition

In the TAS diagram of Le Bas et al. (1986), the rocks under study show broad range of lithology from basalt to trachyte to rhyolite (figure 2). A few samples from Kutch and Mumbai offshores are also plotted in the TAS diagram for comparison. The Kutch Offshore basalts plot in alkaline region which is a characteristic of the Kutch on land Deccan Traps. However, the Mumbai Offshore basalts and Kerala-Konkan Offshore basalts, dolerites and rhyolites plot in tholeiitic region of the diagram.

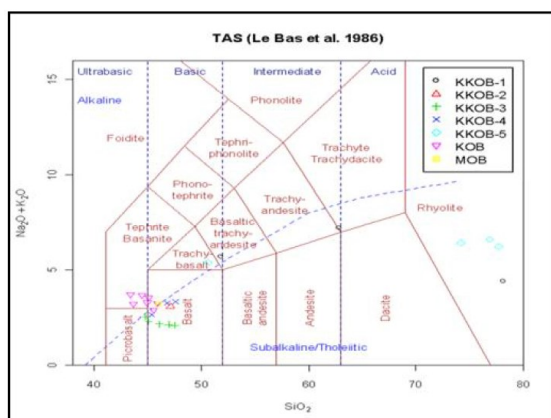


Figure 2: TAS (Total Alkali-Silica) diagram after Le Bas et al. (1986). The rocks under study plot in a broad range of lithology from basalt to trachyte to rhyolite.

In the Zr/Y versus Zr plot after Pearce and Norry (1979) (figure 3), Ti/100-Zr-3xY triangular plot after Pearce and Cann (1973) (figure 4), 2xNb-Zr/4-Y plot after Meschede (1986) (figure 5), the basalts of Kutch (KOB) as well as Mumbai Offshore Basin (MOB) indicate close affinity to Within Plate Basalt (WPB), whereas basalts and dolerites from Kerala-Konkan Offshore Basin (KKOB) show close affinity to Mid-Ocean Ridge Basalt (MORB).

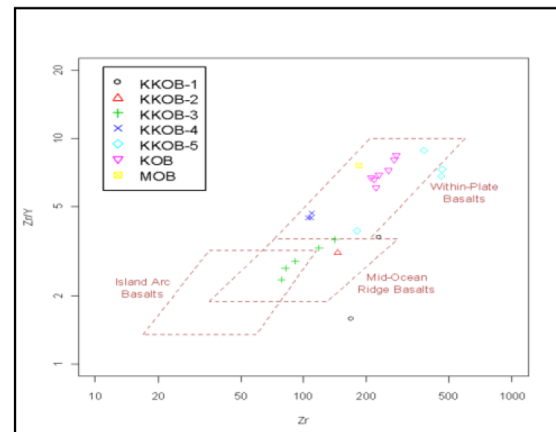


Figure 3: Zr/Y versus Zr diagram (Pearce and Norry, 1979) of basalt samples under study. The basalts of KOB and MOB plot in the field of Within Plate Basalt (WPB), whereas the basalts and dolerites of KKOB show close affinity to Mid-Ocean Ridge Basalt (MORB).

These diagrams suggest that basalts of Kutch (KOB) and Mumbai Offshore Basin (MOB) belong to the Deccan Trap main volcanic activity ~65-67 my when magma out poured through rifts in the Indian Continental crust, but prior to the separation of Seychelles from India. The basalts and dolerites of KKOB with MORB signature perhaps represent magmatic activity at the time of Carlsberg Ridge (an MORB) formation after which Seychelles and India drifted apart.

Sr-Nd Isotopic Composition

30 samples from five selected wells as detailed above were analyzed for Sr-Nd isotopic studies. In the ϵ_{Nd} versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (figure 6) the basalts, dolerites and trachytes/rhyolites (except the samples from well KKOB-4/CC-3 & 4) indicate close affinity to Mid-Ocean Ridge Basalt (MORB). The samples from KKOB-4/CC-3 (basalt) and CC-4 (peridotite) fall close to the mantle plume/deep mantle region (figure 6). This suggests that the basalt of KKOB-4/CC-3 perhaps represent the early phase of plume activity over a remnant oceanic crust (peridotite). On the other hand, the basalts from KOB and

MOB indicate wide variations in ϵ_{Nd} values as well as $^{87}Sr/^{86}Sr$ ratios.

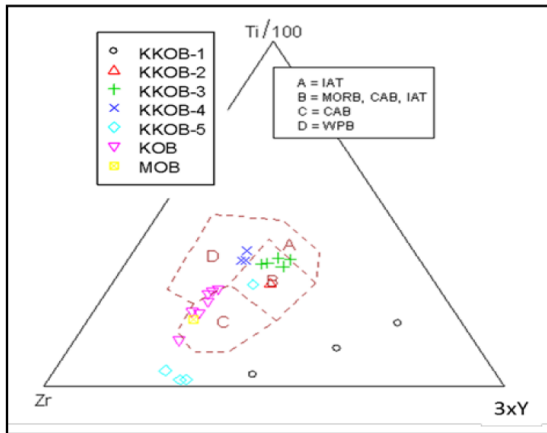


Figure 4: Ti versus Zr diagram (Pearce and Cann, 1973) for basalt samples under study. The basalts and dolerites of Kkob show close affinity to Mid-Ocean Ridge Basalt (MORB).

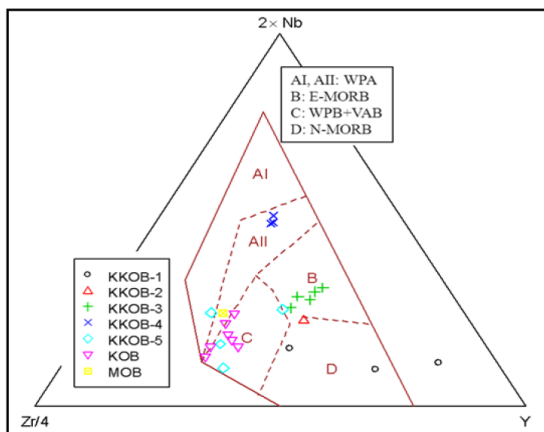


Figure 5: $2xNb- Zr/4-Y$ triangular plot (Meschede, 1986) for basalt samples under study. The basalts of Kob and Mob plot in the field of Within Plate Basalt (WPB) whereas the basalts and dolerites of Kkob show close affinity to Mid-Ocean Ridge Basalt (MORB).

This is because of significant inputs/contamination from a variety of crustal materials, which is typical of continental flood basalts where hot magma incorporates pre-existing rocks through which they extrude to the surface.

In the ϵ_{Nd} versus $^{87}Sr/^{86}Sr$ plot specific to the onland Deccan Traps (after Peng et al., 1994), the rocks from the Kkob (except the well Kkob-4/CC-3 & 4) plot close to the Central Indian Ridge region, which is an MORB (figure 7), whereas the data points from Kutch and Mumbai offshores plot in the different fields specific to

Deccan Traps. The above discussion clearly indicates that the mode of origin for the MOB and KOB basalts was different from the Kkob basalts, dolerites and trachytes/rhyolites.

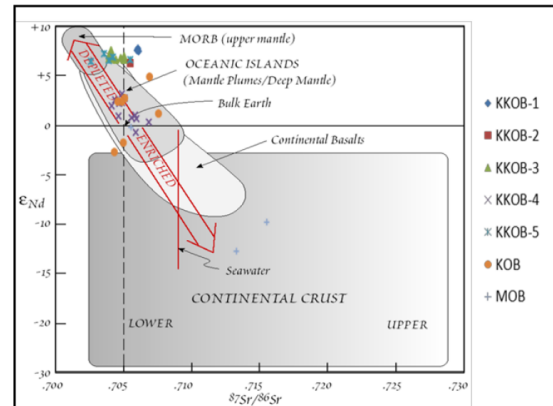


Figure 6: ϵ_{Nd} versus $^{87}Sr/^{86}Sr$ diagram of samples under study. The basalts from Kob and Mob show wide variations. The basalts, dolerites and trachytes/rhyolites from Kkob (except the well Kkob-4/CC-3 & 4) show close affinity to Mid-Ocean Ridge Basalt (MORB). The basalt and peridotite from Kkob-4/CC-3 & 4, respectively, plot close to mantle plume/deep mantle region.

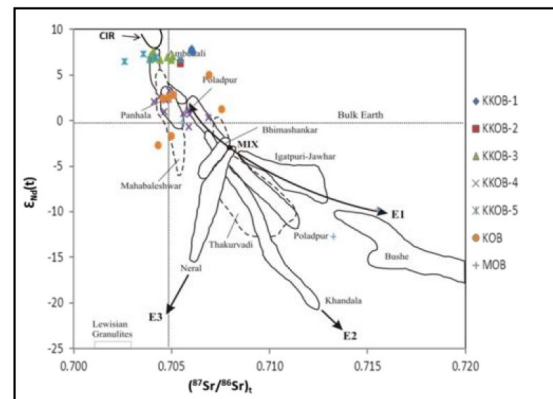


Figure 7: ϵ_{Nd} versus $^{87}Sr/^{86}Sr$ plot specific of onland Deccan Trap (Peng et al., 1994) for samples under study. The basalts of Kob and Mob show wide variations. The basalts, dolerites and trachytes/rhyolites of Kkob (except the well Kkob-4/CC-3 & 4) show close affinity to Central Indian Ridge

Discussion

The distance from Kutch Offshore to the southern part of Kerala-Konkan Offshore via Mumbai Offshore is more than 2000 km. The information collected so far from the wells drilled in these three basins suggests a broad spectrum of geological history. Their depositional histories differ from one another as reflected from their

lithostratigraphic columns. The basement rocks over which these sedimentation occurred also show a wide lithological spectrum, the most widespread being basaltic rocks.

The Deccan Trap basalts are continental basalts (WPB) where the magma extruded via fissures developed in the Indian continental crust. The extrusion occurred both over land and under the sea, overlying pre-existing igneous and/or sedimentary covers. The thickest part recorded in the Deccan Traps (>2000m) on land is found in the state of Maharashtra. Hence, it is likely that the thickest part of Deccan Traps under the sea may be found in and around MOB and gradually thinning out away from it. The thickness of Deccan Traps recorded in the wells drilled in the KOB is found to be up to 500 or 1000m. The KOB basin was in existence even prior to the Deccan Trap eruption at ~67 Ma as evidenced by the wells drilled through the basement in this region. Similar conditions may have existed in the MOB region but the thickness of Deccan Trap here is likely to be >1500m.

There is no direct evidence for the main Deccan Trap eruption in the KKOB at ~65-67 my ago. Nevertheless, all basement rocks encountered in the wells drilled so far in the KKOB are designated as Deccan Trap in the Well Completion Reports (WCR). This report, for the first time, presents bulk rock chemical composition as well as Sr-Nd isotopic signatures for the basement/basalt drilled in the KKOB and then compares them with the basalts encountered in the KOB and MOB. The main objective of this comparison is to derive vital information with regards to the tectonic set of the KKOB during or after the Deccan Trap activity.

The dolerite samples from well KKOB-3/CC-1 and CC-3 (figure 8) appear similar in hand specimen as well as in thin section. Moreover, their ϵ_{Nd} and $^{87}Sr/^{86}Sr$ values are very similar to each other. These signatures point to the fact that both CC-1 and CC-3 perhaps represent a single time event in the form of intrusions. If this is true, then the actual basement in the well KKOB-3 is yet to be encountered. The trachyte/rhyolite samples from well KKOB-1/CC-7 have a different chemical composition as well as isotopic signatures than the above discussed wells.

Figure 8 is a generalized stratigraphic column of wells under study from KKOB. Data have been compiled from their respective Well Completion Reports. Igneous rocks encountered in these wells have been indexed in green

and their lithological as well isotopic summaries are highlighted within pink boxes. It is seen that the basement of three wells (KKOB-1, KKOB-2 and KKOB-3) drilled south-west of Calicut (figure 1) contain rocks that have no similarities in lithology, but their Sr-Nd isotopic signatures are quite similar. The basement samples from well KKOB-1/CC-7 are trachyte/rhyolite with $\epsilon_{Nd} = 7.6$ and $^{87}Sr/^{86}Sr = 0.706168$; samples from well KKOB-2/CC-2 are fine basalt with $\epsilon_{Nd} = 6.3$ and $^{87}Sr/^{86}Sr = 0.705550$; samples from well KKOB-3/CC-1 are dolerite with $\epsilon_{Nd} = 6.9$ and $^{87}Sr/^{86}Sr = 0.704563$; and samples from well KKOB-3/CC-3 are dolerite with $\epsilon_{Nd} = 7.0$ and $^{87}Sr/^{86}Sr = 0.704427$. Dolerites generally form dykes or sills in geological formations.

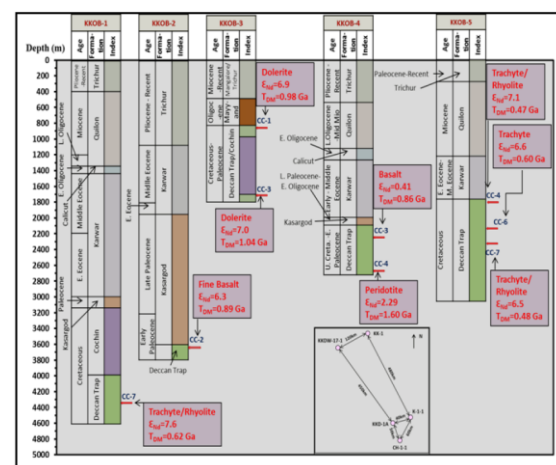


Figure 8: Stratigraphic profile of wells under study from KKOB. Data have been compiled from Well Completion Reports. Igneous rocks encountered in these wells are indexed in green. Lithological and isotopic summary of conventional cores from igneous rocks are highlighted in pink boxes. The inset picture shows the actual ground distance of the stated wells.

The basement samples of well KKOB-4/CC-4 are peridotite with $\epsilon_{Nd} = 2.29$ and $^{87}Sr/^{86}Sr = 0.704881$, while the samples of well KKOB-4/CC-3 are basalt with $\epsilon_{Nd} = 0.41$ and $^{87}Sr/^{86}Sr = 0.706174$. The evidence of transition from basalt to peridotite during drilling is reflected by increase in the average ROP as reflected in the Master Log (figure 9a). The average resistivity from peridotite to basalt increases (figure 9b) because of a very high content of magnesium ($MgO > 30$ wt.%) in the peridotite. Figure 9c is a schematic NE-SW cross-section map of the KKOB. The reflector shown within the Deccan Trap is probably due to the density change from basalt (top) to peridotite (bottom) as has been observed in the well KKOB-4.

Figure 10 is a plot of ϵ_{Nd} versus Nd (ppm) as an index of crustal contamination (after Stevenson et al., 2004). The basement samples of Kkob (except the well Kkob-4) are well constrained within MORB component, while the Kob and Mob basalts show variable contamination. These observations were also supported by earlier discussions on their bulk rock chemical compositions as well as Sr-Nd isotopic signatures. Basalt samples of well Kkob-4/CC-3 cluster around basalts of Kob (figure 10), thus indicating similar degree of contamination. Peridotite is the least contaminated rock but contain very low amount of Nd, which once more indicate a deep mantle source.

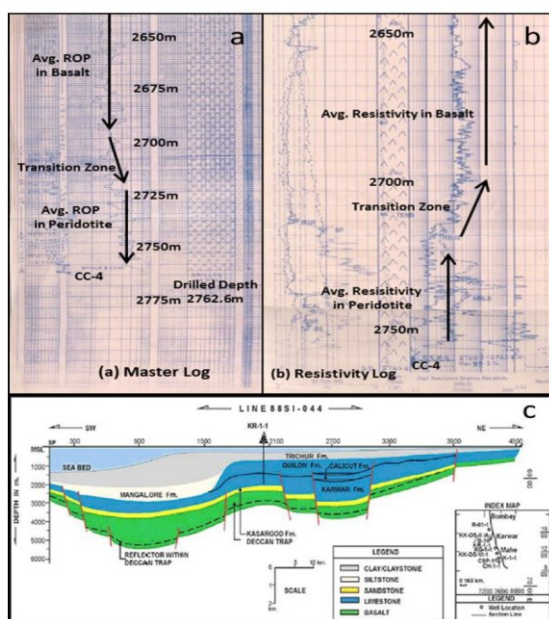


Figure 9: (a) Master Log and (b) Resistivity Log of well Kkob-4 from depth 2760 - 2650m. Average ROP increases from basalt to a very hard rock peridotite. Average resistivity increases from magnesium-rich peridotite ($MgO > 30$ wt%) to basalt ($MgO < 5$ wt%), (c) Schematic NE-SW cross-section map of the Kkob. The reflector within the Deccan Trap is probably due to lithological change from basalt (top) to peridotite (bottom).

Conclusion

The evidence collected so far from the bulk rock chemical composition and Sr-Nd isotopic signatures suggest that the basement of Kob and Mob are related to the Deccan Trap volcanic eruption at $\sim 65-67$ my ago via rifts associated with Reunion Mantle Plume. This volcanic event occurred after the breakup of Madagascar (at ~ 90 my ago) but before the breakup of Seychelles (at ~ 62 my ago) from Western Indian Margin. Therefore, we do find

Mesozoic sedimentary basin in the Kob which is overlain by 500 to 1000m thick Deccan Trap. Similar Mesozoic basin may also underlie the 1000 to 2000m thick Trap in the Mob.

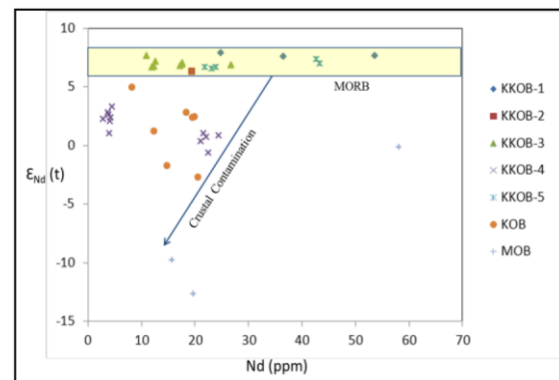


Figure 10: $\epsilon_{Nd}(t)$ versus Nd (ppm) plot (after Stevenson, 2004) as an index of crustal contamination. The basement samples of Kkob (except well Kkob-4) are well constrained within MORB component while Kob and Mob basalts show significant contamination.

The basement of Kkob (except well Kkob-4) with MORB signatures may be related to the breakup of Seychelles from Western India at $\sim 60-62$ my ago via Carlsberg Mid-Ocean Ridge. This interpretation is also supported by the Ar-Ar ages of 60-62 my (Rathore et al., 2007) for the basalt of well Kkob-2/CC-2 and dolerite of well and Kkob-3/CC-1. The basement of Kkob may have originated when the Reunion Mantle Plume passed beneath the newly formed Carlsberg Mid-Ocean Ridge. The plume then moved further south relative to the Indian Plate, leaving behind trails of aseismic ridges such as the Chagos-Laccadive Ridge (CLR).

Basement rocks of well Kkob-3/CC-1 and CC-3 are intrusions (dolerite) within the Cochin Formation and perhaps represent dykes or sills. If this is true, then the actual basement in the well Kkob-3 is yet to be encountered. Basement rocks of Kkob (wells Kkob-1, Kkob-2, Kkob-4 and Kkob-5) perhaps represent new oceanic crust, below which the possibilities of occurrences of sedimentary basins are less. This interpretation, however, is based on chemical and isotopic studies alone and needs to be substantiated by additional studies including seismic and other geophysical tools before further exploration efforts in the Kkob are redirected. This study has demonstrated remarkable use of isotopic and chemical compositions to understand petrogenetic history and tectonic settings of the basement of sedimentary basins.



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