# Isotopic and Geochemical Evidences from 85°E Ridge: Implications on Kerguelen Hotspot Linkage

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## Summary

Two prominent N-S trending structural lineaments have been observed in the basement topography of Bay of Bengal and the northeastern Indian Ocean. One is the northernmost portion of the Ninetyeast Ridge which is totally buried by sediments north of 10° N, whereas the other one is the 85°E ridge running parallel to the 85°E meridian in the Bay of Bengal. The 85°E ridge is a prominent linear aseismic ridge, which can be visualized extending from the Afanasy Nikitin Seamounts northward to the Mahanadi basin along the ECMI. The ridge is associated with two contrasting gravity anomalies: negative anomaly over the north part (up to 5°N latitude), where the ridge structure is buried under thick Bengal Fan sediments and positive anomaly over the southern part, where the structure is intermittently exposed above the seafloor. The origin of the 85°E ridge has been a subject of debate, with opinions ranging from an abandoned spreading center to a hotspot track. The present study supports the hotspot hypothesis and incorporates new isotopic and geochemical evidences from the analysis of basaltic rocks encountered in the basements of two deep water wells A1 and A2, drilled on the western flank of 85°E ridge in the Kakinada graben of the Krishna-Godavari basin in the Eastern Offshore of India. The study correlates the isotopic and geochemical signatures of the basalt samples from the two deep water wells representing 85°E basalts and from Afanasy Nikitin Seamounts to those from onland Rajmahal and Sylhet traps and to the South and Central Kerguelen Plateau Basalts and establishes their isotopic and geochemical similarity in favour of Kerguelen hotpot origin of the ridge, and proposes a plausible model for the origin of the structure.

## Introduction

The breakup of greater India from the Eastern Gondwanaland during the early Cretaceous and subsequent tectonic events that resulted in the evolution of the Bay of Bengal also marks the construction of two well-known aseismic ridges, the Ninetyeast Ridge, which is now believed to have evolved due to the Kerguelen hotspot as an oceanic trail when the Indian plate moved northward over it (Weis and Frey, 1991; Weis et al., 1991; Klootwijk et al., 1992; Duncan and Storey, 1992), and the 85°E ridge, whose origin is less understood, and is buried under thick sediments of the Bengal fan to the west of the Ninetyeast Ridge. This submerged ridge trends N10°W between 6° and 16°N and takes an arcuate shape off the southeast coast of Sri Lanka and appears to abut the northward extension of the Afanasy-Nikitin seamounts situated around 2°S latitude (Krishna, 2003; Bansal and Dimri, 2005). The ridge appears as an intrusive peak and broad basement rise around 10°N (Curray et al., 1982) and as a double humped feature around 13°N and 12°N latitudes (Gopala Rao et al., 1994; Ramana et al., 1997b). It has also been observed that the northern part of this buried ridge, in contrast to the Ninetyeast Ridge, shows a negative free-air gravity anomaly of about -60 mGal (Ramana et al., 2000; Sar et al., 2009) which disappears at about 5°N (Liu et al., 1982). Liu et al. (1982) have modelled the negative gravity anomaly of the 85°E ridge and suggested a two stage loading; emplacement of the ridge on a weak lithosphere (5-15 m.y) leading to excess thickening of the crust and subsequent loading of sediments on a stronger lithosphere of 40-18 m.y old. Later, Krishna (2003) proposed an alternate model in which he explained the negative gravity anomaly of the 85°E ridge as result of the density contrast between the metasediments and less dense ridge material and a broader Moho depression beneath the ridge. Sreejith et al. (2011) carried out a comprehensive process-oriented gravity modelling for the ridge and concluded that the negative gravity anomaly is due to the combined effect of thick sedimentary column, presence of metasediments at the basal level and flexure of the Moho boundary.

The origin of 85°E ridge is much debated over the time, as no published data from drilled wells was available to confirm its origin. Liu et al. (1982) modelled the observed steep gradient of the negative free-air gravity anomaly associated with the 85°E ridge and interpreted it in terms of lithospheric flexure. Subsequently, Mukhopadhyay and Krishna (1991) suggested that the ridge consists of thick oceanic crustal material with its underlying root in the lithosphere. Different theories, such as an abandoned spreading center (Mishra, 1991), as a result of volcanism from a weak zone within a short period of time (Chaubey et al., 1991), a northward continuation of the 86°E fracture zone (Kent et al., 1992), or shearing or sagging of crust by horizontal stretching/ compressional forces (Ramana et al., 1997) have been proposed for the origin of the 85°E ridge. Curray and Munasinghe (1991) suggested that the 85°E ridge was a trace of the Crozet hotspot which also formed the Rajmahal traps. On the other hand Muller et al. (1993) suggested that the 85°E ridge between 10°N and Afanasy Nikitin seamounts might have been formed by a hotspot now located underneath the eastern Conrad Rise on the Antarctica plate. Based on interpretation of geophysical data, many later workers supported the hot spot theory as the most plausible mode of emplacement of the ridge (Gopala Rao et al., 1997; Subrahmanyam et al., 1999, 2008; Krishna, 2003; Krishna et al., 2009; Bastia et al., 2010), though the source of the plume emplacing the ridge is still debated.

Michael and Krishna (2011) identified distribution of normal and reversed magnetization patterns through the analysis of marine magnetic data of the 85°E ridge, and concluded that the ridge was formed during the period of rapid changes in the Earth's magnetic field, earlier to that, the underlying oceanic crust was created in the Cretaceous super-long normal polarity phase (~35 Ma). On correlation of the ridge's magnetization pattern to the geomagnetic polarity timescale, they suggested that the 85°E ridge volcanism started at anomaly 33r time (~80 Ma) in the Mahanadi Basin by a short lived hotspot activity, and continued towards south and finally ended at ~55 Ma in the vicinity of the Afanasy Nikitin Seamounts.

From the hydrocarbon exploration point of view, the 85°E ridge, especially its western flank has been considered important as the age from 87 Ma to 118 Ma relates to the syn-rift sediments of KG basin, the Onshore Mahanadi basin as well as the Albian-Aptians of Cauvery basin. In fact, the sediments all along the East Coast from Barremian to Albian in age have been deemed potential in terms of hydrocarbon exploration. Younger than Albian age of the ridge (100 Ma) would provide the possibility of syn-rift sediments beneath the ridge, provided the activity took place on a conventional continental lithosphere. Also, the ridge might be associated with reasonable atolls around it for the time younger than 100 Ma if it was above the MSL, as rim carbonates have been reported in several wells of Mahanadi and KG basin, although none have shown good reservoir qualities.

We present here the isotopic and geochemical evidences, for the first time, from the analysis of basaltic rocks encountered in the basements of two deep water wells A1 and A2, drilled on the western flank of 85°E ridge in the Kakinada graben of the Krishna-Godavari basin in the Eastern Offshore of India, proposing the hotspot origin of the 85°E ridge from the Kerguelen hotspot system.

**Methodology and Data Analysis**

The basalt cutting samples from two deep water wells A1 and A2 have been taken up for multi-isotopic and trace elemental analysis. Location of studied wells is shown in Figure 1. The wells A1 and A2 were drilled to a depth of 4802 m and 5690 m at a water depth of 2442 m with trap thickness of 517 m and 282 m respectively.

For major and 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 $HNO_3$ 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% $HNO_3$ and was filtered to remove any undissolved particles. The trace element analysis was carried out on ICP-AES in the Hydrogeochemistry lab of KDMIPE, Dehradun.

For Sr and Nd isotopic analysis, about 100 mg powder sample was digested in a mixture of acids as per the procedure detailed above.

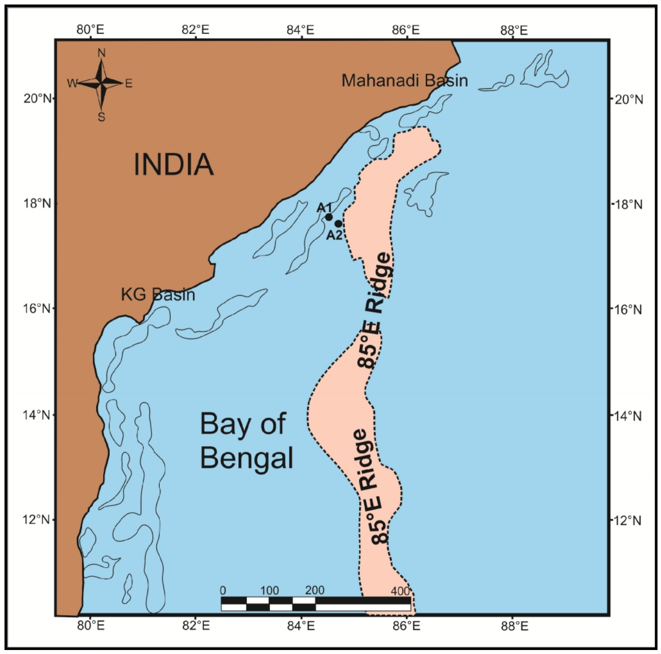


Figure 1: Map of the eastern offshoret of India showing the location of studied wells A1 and A2 in KG Basin.

The Rb-Sr and Sm-Nd mixed spike was added to the sample prior to the dissolution to ensure complete mixing. After complete dissolution, the acids were evaporated and the residue was re-dissolved in 3 mL 6N HCl and dried. The final solutions were prepared in 2 mL 2N HCl and were centrifuged before loading onto the chromatographic columns for elemental separation. The Sr and Nd elements were separated using ion exchange chromatography as per the in-house established procedure (Rathore et al., 2013).

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 $^{86}Sr/^{88}Sr$ = 0.1194 and $^{146}Nd/^{144}Nd$ = 0.7219, respectively. Average blank levels were found to be <25 ng for Sr and Nd. During the course of this study, 13 analyses of Sr reference material SRM-987 yielded an average value of $^{87}Sr/^{86}Sr$ = 0.710257±7; for Nd reference materials, 6 analyses of JNdi-1 yielded an average value of $^{143}Nd/^{144}Nd$ = 0.512107±2 and 4 analyses of La Jolla yielded an average value of $^{143}Nd/^{144}Nd$ = 0.511846±2. The results for the Sr and Nd standards were well within their reported values. Results of isotopic analyses of basalt samples from wells A1 and A2 have been presented in Table 1.

**Results and Discussions**

Petrographic evaluation of samples from wells A1 and A2 from KG basin indicates the occurrences of ophitic to sub-ophitic, iron rich basalt having clino-pyroxene and laths of plagioclase embedded in fine grained Fe-rich groundmass as the dominant lithology and show low to moderate degree of alterations of plagioclase into clay minerals and pyroxenes into Fe-oxides to some extent.

Figure 2 shows the major element data for basalts samples from A1 and A2 from KG basin representing 85°E ridge basalts plotted on the Total Alkalis-Silica (TAS) diagram of Le Bas et al., (1986), along with major element data from Afanasy Nikitin Rise (Borisova et al., 2001; Mahoney et al., 1996), Rajmahal Tholeiites (Baksi et al., 1995) and most enriched basalts from Site 747, 748 and 749 of Kerguelen Islands (Storey et al., 1992). The A1 basalt samples appear to be mostly alkaline whereas those from well A2 range from alkaline to subalkaline/tholeiitic in nature. Most of the basalts show a similar range of composition compared with Afanasy Nikitin Rise basalts and trachybasalts and also with some of the Kerguelen basalts and Rajmahal Tholeiites, showing an overlap in the basalt field of the TAS plot.

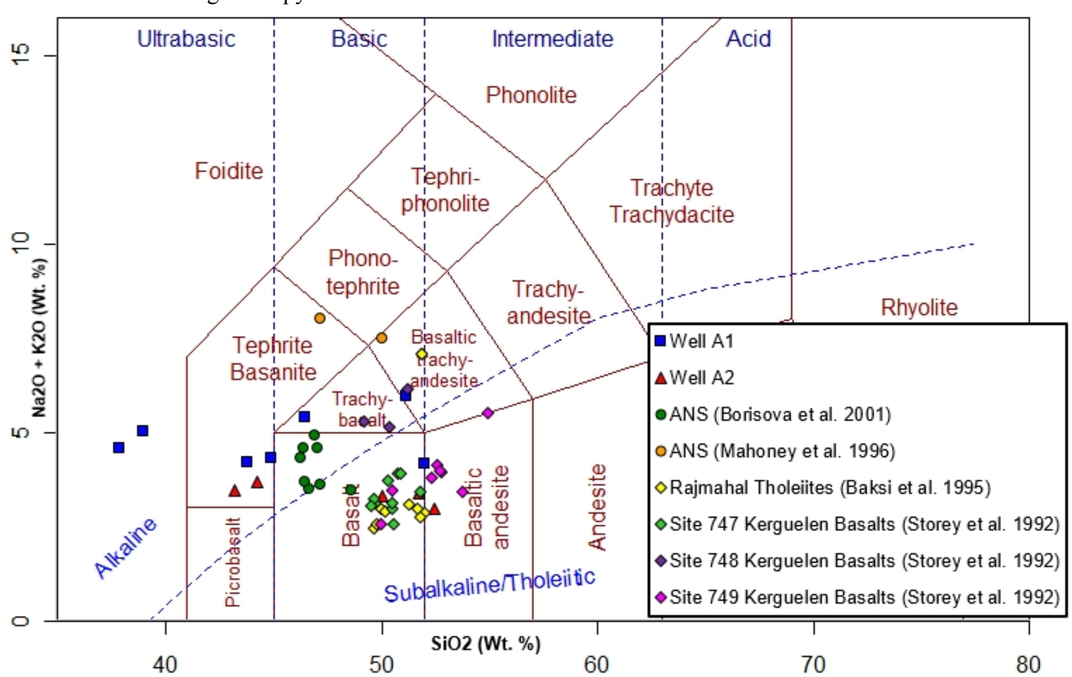


Figure 2. Total Alkalis-Silica (TAS) diagram (after Le Bas et al., 1986) of the basalts samples from wells A1 and A2 from study area. Data from Afanasy Nikitin Seamounts (ANS) (Borisova et al., 2001; Mahoney et al., 1996), Rajmahal Tholeiites (Baksi et al., 1995) and most enriched basalts from Kerguelen Islands (Site 747, 748 and 749) (Storey et al., 1992) are also shown for comparison.

Primitive mantle normalized incompatible element patterns of our samples reveal an overall enrichment in highly incompatible elements relative to less incompatible elements; in this respect they resemble most oceanic island basalts (OIB) (Figure 3). However, they are quite distinct in having prominent peaks at Rb and La; a mostly positive slope from Nb to La; and low Ti (Figure 3). The samples display much larger ratios, for example, of Ba/Nb, La/Nb, Ba/Th, Nb/Th and Ti/Y (respectively 17.2-18, 0.9-1.3, 218-238, 12.2-13.9 and 597-736) compared to modern oceanic island basalts (e.g., 7.3, 0.77, 88, 12 and 593, respectively) (Sun and McDonough, 1989; Mahoney et al., 1996). These ratios are found to be similar to those from average Rajmahal basalts (e.g. 19.0, 1.2, 225, 12.4 and 426, respectively) (Baksi, 1995) and Sites 747, 748 and 749 of Kerguelen basalts (22.8-12-21, 1.6-0.9-1.0, 174-141-188, 8.4-11.3-12.5 and 611-987-496, respectively) (Storey et al., 1992). Thus, the samples from 85°E ridge appear to have similar characteristics in their overall enrichment in incompatible elements to some of the Rajmahal and South and Central Kerguelen basalts, although the studied samples from 85°E ridge have been affected by moderate levels of low temperature sea water alteration. Isotopically, the basalts from wells A1 and A2 are found to possess low $\varepsilon Nd_{(t)}$ (~ -2.7) and high $87Sr/86Sr_{(t)}$ (~0.705913) with an age correction t = 117 Ma, however, the age corrections are small and the values do not change significantly if the lower age limit of 80 Ma is used. Although, broadly similar and often more extreme compositions are found in some continental flood basalts, this combination of values is unique among ocean islands, seamounts and ridge basalts found to be present in some of the most enriched basalts from Kerguelen Islands. Moreover, the isotopic data also corresponds to Rajmahal tholeiites (II) (Storey et al., 1988, 1992). 14 analyses from wells A1 (05) and A2 (09) were carried out and their results are presented in Table 1.

Tectonic reconstructions made by Royer et al. (1991) and Royer and Coffin (1992) indicate that the Ninetyeast Ridge, Broken Ridge and the Kerguelen LIP have originated from a single hotspot in the Indian Ocean, now sitting beneath the Antarctic plate.

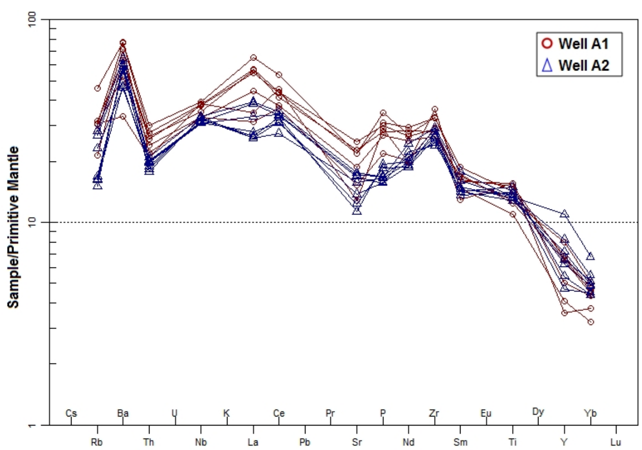


Figure 3. Incompatible element patterns of basalts encountered in wells A1 and A2 in multivariate spider diagram, normalized to Primitive Mantle (after Sun and McDonough, 1989)

The initial $\varepsilon Nd_{(t)}$ values for well A2 range from –1.5 to –3.7 with an average value of –2.1, whereas basalts from well A1 show more negative $\varepsilon Nd_{(t)}$, ranging between –1.4 to –5.3, with an average value of –3.8, with an exception of sample 1479 which exhibits $\varepsilon Nd_{(t)} = -1.4$ (Table 1). The initial $^{87}Sr/^{86}Sr_{(t)}$ values of A2 basalts range from 0.705367 to 0.706614, with a lower average ratio of 0.705849 (Table 2). The A1 basalts show more radiogenic ratios ranging from 0.705314 to 0.707126 (average = 0.706027), which indicates their alteration due to the effects of sea water.

In Figure 4, the $\varepsilon Nd_{(t)}$ and $^{87}Sr/^{86}Sr_{(t)}$ data of basalts from present study are compared with those from Site 747 and 748 of Central and South Kerguelen basalts and Rajmahal Group II tholeiites (after Storey et al., 1992) and their relationship with the most enriched basalts from Kerguelen Islands is investigated. Sr-Nd Isotopic data for some of the tholeiitic basalts and trachybasalts from Afanasy-Nikitin Rise, which is believed to be the southern extremity of 85°E ridge (Curray and Munasinghe, 1991), is also plotted along with the present data to investigate their relationship with the analyzed samples from two wells and with the Kerguelen and Crozet basalts (Data source: Borisova et al., 2001; Mahoney et al., 1996) (Figure 4).

Figure 4 suggests a remarkable similarity of $\varepsilon Nd_{(t)}$ and $^{87}Sr/^{86}Sr_{(t)}$ signatures between basalt samples from studied wells A2 and A1 and most enriched basalts from Kerguelen Islands, Site 747 and 748 and Rajmahal Group II tholeiites. The basalts and trachybasalts from Afanasy-Nikitin Rise also appear to be falling on and close to the Site 747 along with A2 basalts. On comparing these basalts from studied wells and from Afanasy-Nikitin Rise, with the isotopic data from Crozet basalts (Mahoney et al., 1996), it is observed that samples from 85°E ridge (drilled wells in the north, i.e., A2 and A1, and Afanasy-Nikitin Rise in the south) do not fall on or near Crozet data field (Figure 4).

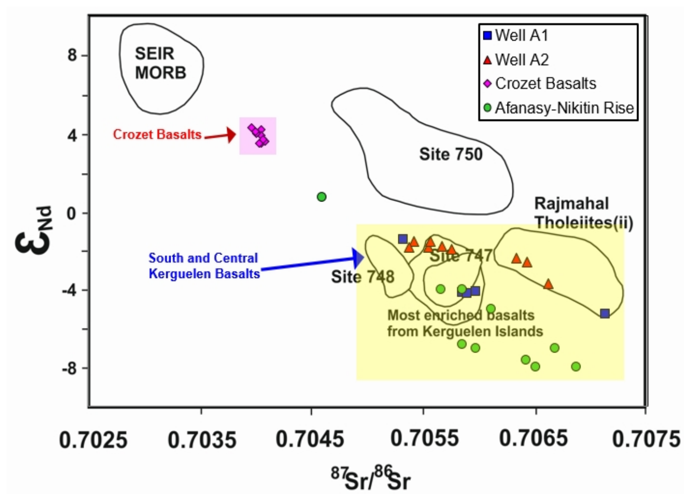


Figure 4. εNd(t) and 87Sr/86Sr(t) plot (After Storey et al., 1992) of basalts from present study. Also shown for comparison: data from Crozet basalts and Afanasy-Nikitin Seamounts (Borisova et al., 2001; Mahoney et al., 1996)

Therefore, in all probability, the strong affinity of basalts from drilled wells A2 and A1, and those from Afanasy-

Nikitin Rise suggests these to be derived from the Kerguelen plume source and not from the Crozet source.

Raju et al. (2013) have done extensive work related to the stratigraphic information on Cretaceous volcanism encountered in wells A1 and A2 based on Foraminiferal age markers in the intra-trappeans as well as formations overlying the basalts. Their study suggests a younger Coniacian age not older than 87 Ma for volcanism in well A2 based on FAD of Foram Archaeoglobogerina blowi immediately above the basalts. This age correlates with the geomagnetic polarity age for the northernmost part of the 85°E ridge given by Michael and Krishna (2011) falling close to 33r chron (~80 Ma).

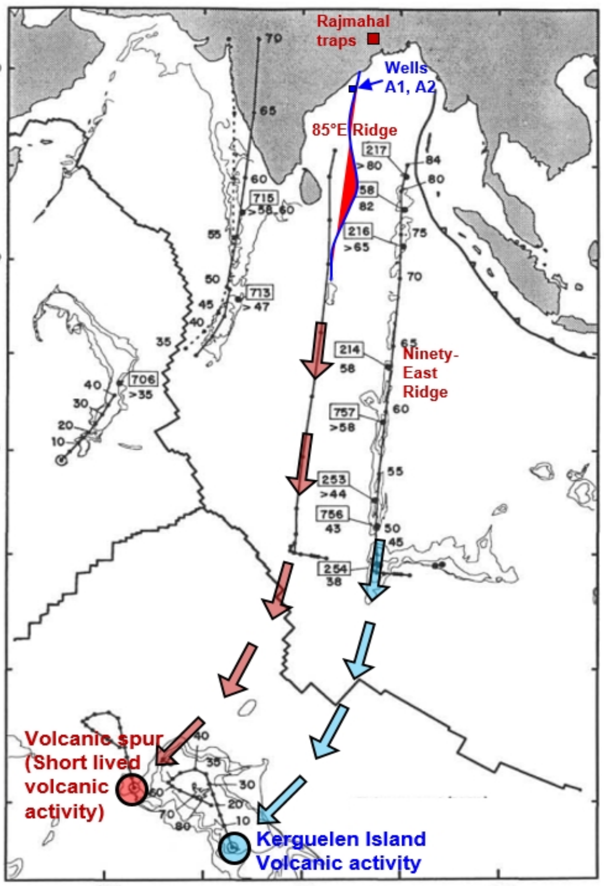


Figure 5. Possible mode of emplacement of 85°E ridge from Kerguelen hotspot from the 'volcanic spur' located to the west of Kerguelen Island (After Royer et al., 1991)

Further, Bastia et al. (2010) also established the presence and continuation of 85°E ridge below the Mahanadi shelf through the continental slope using newly acquired high resolution and close grid 2-D seismic reflection data, possibly connecting to the volcanics to the Rajmahal Traps (117 Ma) in the north via age progression, as seen in most hotspot trails (e.g. Ninetyeast ridge, Chagos-Laccadive Ridge).

The connection between the Rajmahal Traps exposed in the eastern part of India and the Kerguelen Plume has been established in the past by several authors based on geochemical and isotopic data, and plate reconstructions of the Indian plate (Baksi et al., 1987; Frey et al., 1996; Kent et al., 2002). Further, Royer et al. (1991) suggests the presence of a 'volcanic spur' to the west of present day Kerguelen Island and commented on the need to examine its relation to the McDonald Island Volcano in terms of its age and duration of volcanic activity. Their reconstruction of the hotspot migration with respect to the Atlantic and the Western Indian hotspot, requires the mirror image of the Kerguelen Island/'volcanic spur' to be present at a position west of the Ninety East Ridge, which would correspond with the trace of 85°E ridge. In all probability the two features present on the Kerguelen LIP i.e. the Kerguelen Island and the associated 'volcanic spur'–McDonald Island Volcano, could represent two heads of the Kerguelen Plume (Bastia et al., 2010) (Figure 5). This would be consistent with the volcanic hotspot related origin for both the Ninetyeast Ridge and 85°E ridge, from the Kerguelen hotspot, as suggested by isotopic and geochemical similarity of studied samples from 85°E ridge and those of south and central Kerguelen plateau.

| Sample | A1 1479 | A1 1480 | A1 1483 | A1 1484 | A1 1485 | A2 1486 | A2 1488 |
|---|---|---|---|---|---|---|---|
| Depth(m) | 4460-65 | 4510-15 | 4580-85 | 4760-65 | 4720-25 | 5500-05 | 5525-30 |
| Sr (ppm) | 398.69 | 497.57 | 564.43 | 567.54 | 570.98 | 455.01 | 402.65 |
| Nd (ppm) | 29.06 | 48.11 | 47.94 | 49.25 | 51.56 | 38.09 | 35.82 |
| $^{87}Sr/^{86}Sr(t)$ | 0.715314 | 0.707126 | 0.705842 | 0.705968 | 0.705886 | 0.705663 | 0.705413 |
| $^{143}Nd/^{144}Nd_{(t)}$ | 0.512414 | 0.512218 | 0.512274 | 0.512276 | 0.512272 | 0.512394 | 0.512409 |
| $\varepsilon Nd_{(t)}$ | –1.4 | –5.3 | –4.2 | –4.1 | –4.2 | –1.8 | –1.5 |
| $T_{DM}$ (Ma) | 1387 | 1439 | 1242 | 1235 | 1228 | 1271 | 1241 |

| Sample | A2 1489 | A2 1490 | A2 1491 | A2 1492 | A2 1493 | A2 1494 | A2 1495 |
|---|---|---|---|---|---|---|---|
| Depth(m) | 5535-40 | 5535-40 | 5680-85 | 5565-70 | 5645-50 | 5505-10 | 5640-45 |
| Sr (ppm) | 358.40 | 351.20 | 409.04 | 368.38 | 405.82 | 410.86 | 351.44 |
| Nd (ppm) | 35.42 | 40.09 | 40.91 | 34.08 | 37.03 | 34.00 | 36.07 |
| $^{87}Sr/^{86}Sr(t)$ | 0.705367 | 0.706327 | 0.705747 | 0.705536 | 0.706614 | 0.705554 | 0.706424 |
| $^{143}Nd/^{144}Nd_{(t)}$ | 0.512393 | 0.512363 | 0.512389 | 0.512392 | 0.512298 | 0.512408 | 0.512355 |
| $\varepsilon Nd_{(t)}$ | –1.8 | –2.4 | –1.9 | –1.9 | –3.7 | –1.5 | –2.6 |
| $T_{DM}$ (Ma) | 1261 | 1427 | 1308 | 1302 | 1575 | 1255 | 1466 |

Table 1. Isotopic composition of analyzed basalt samples from study area.

## Conclusions

Numerous theories have been postulated by different workers in the past for the nature and origin of 85°E ridge, based on sparse and low resolution geophysical data, although the origin of the ridge could not be explained satisfactorily due to the lack of geochemical and isotopic data. Newly acquired Sr-Nd isotopic and geochemical data from two deep water wells drilled on the western flank of the 85°E ridge, in conjunction with existing geomagnetic polarity timescale ages and paleontological evidences point towards following evidences in favour of Kerguelen hotspot origin of the ridge as an oceanic trail on a young underlying oceanic crust of Bay of Bengal:

1. Isotopic data similarity of samples from the North (wells A2, A1) and South (Afanasy-Nikitin Rise) of the Ridge with Kerguelen Basalts and Rajmahal Tholeiites.
2. Geochemical data similarity (major and trace elements) of wells A2, A1 with Rajmahal and Kerguelen Basalts.
3. Age progressiveness (younging of age) towards south, established by Geomagnetic Polarity data (Michael and Krishna, 2011), along with supporting paleontological evidences (Raju et al., 2013) for the given ages in the northernmost part of the ridge (<87 Ma for Well A2).
4. Possibility of a 'volcanic spur' (McDonald Island Volcano) towards the west of Kerguelen Island, representing to be another short lived 'head' of the Kerguelen hotspot, accounting to the 'mirror image' of the Ninetyeast Ridge towards the west.

On the basis of above evidences, 85°E ridge appears to be formed as a hotspot trail from a short lived volcanic activity from one of the heads of Kerguelen Plume (McDonald Island) present towards the west of Kerguelen Islands. However, considering the long trace of the ridge up to the Afanasy Nikitin Rise, many complexities are yet to be unravelled with regard to the time and mode of emplacement of the ridge during the evolution of the Indian Ocean. The region of the bend in the 85°E ridge needs to be surveyed in more detail to confirm the correlation between the buried volcanic hills and the Afanasy Nikitin Rise.

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