

Integrated geophysical study off Goa, Central West Coast of India

M. V. Ramana¹, Maria Ana Desa^{*2} and T. Ramprasad²

¹ Sagarika Apartments, Nagali Hills, Dona Paula, Goa 403 004

² CSIR-National Institute of Oceanography, Dona Paula, Goa, India-403 004

*Corresponding Author: mdesa@nio.org

ABSTRACT

The western Indian offshore is characterized by several tectonic elements along its entire length. The prominent ones include the Laxmi Ridge (LR) and the Chagos-Laccadive Ridge (CLR) in the north and south, respectively. These ridges divide the western offshore into the western and eastern Arabian Basins, and have been attributed different evolution mechanisms and crustal types.

The Goa offshore (14.7 - 15.7°N and 70.3 -71.2°E), between the Laxmi Basin in the north and the CLR complex in the south, off the Central West Coast of India, may hold some clues of the connection/boundary between these diverse crustal domains. About 1550 km of gravity, magnetic, single and multibeam bathymetry data has been analyzed in the present study. The results indicate that the water depth varies between 2450 and 4000 m, and the region is characterized by ~NW-SE to NNW-SSE trending broad wavelength gravity and magnetic anomalies. Forward modeling of the geophysical data under seismic constraints highlight the presence of ~6-9 km thick oceanic crust, while towards the east, the crust is thicker and contaminated with Deccan volcanic intrusions. Magnetic data analysis suggests that the age of the underlying oceanic crust varies between 63.9 and 68.7 Ma (Chron 29n to 31r).

The present study indicates that the Goa offshore is an integral part of the Laxmi Basin. As such it is interpreted that a tectonic boundary between the oceanic crust in the north and the CLR complex in the south lies south of the study area. Further, this boundary may be associated with the Vengurla Arch and may have restricted the southward propagation of the Laxmi Basin spreading ridge.

Key words: West Coast of India, Goa offshore, Laxmi Basin, geophysical data, Chagos-Laccadive Ridge

INTRODUCTION

The Western Continental Margin of India is characterized by a NW-SE trending continental shelf, which narrows from ~300 km wide off Mumbai to ~50 km south off Cochin (Figure 1). The shelf area is characterized by several horst-graben like features resulting in Kutch, Saurashtra, Bombay and Konkan-Kerala offshore basins, and Saurashtra, Vengurla and Tellicherry arches (Biswas, 1987). In contrast to the continental shelf configuration, the slope bounded between 200 and 2000 m isobaths is narrow in the north and wide towards south. Beyond the slope lie the abyssal depths of the Arabian Sea. Major structural features in the western offshore include the midshelf high, Pratap Ridge complex (Naini, 1980; Subrahmanyam et al., 1995), aseismic Laxmi Ridge (Naini and Talwani, 1982) and Chagos-Laccadive Ridge (CLR) complex (Heezen and Tharp, 1964; Duncan, 1990).

The NW-SE trending Laxmi Ridge (LR, Figure 1) is an aseismic basement high located approximately 300 km off the northwest coast of India with a relief of about 2 km and carpeted by a thin veneer of sediments. Contrary to its positive topography, the ridge is associated with a negative (-50 mGal) free-air gravity anomaly (Naini and Talwani, 1982). The LR has been inferred as a continental sliver (Talwani and Reif, 1998), while Todal and Eldholm (1998) suggested that it is a partly isostatically compensated

marginal high. Due to ~9-16 km crustal thickness, the LR has been considered as a thinned continental crust of Neoproterozoic age juxtaposed to Seychelles and Malani province of India (Torsvik et al., 2013). High resolution, deep seismic data indicated that the ridge is composed of oceanic crust and acted as a fossil spreading center (Misra et al., 2015). Based on crustal studies, the LR has been divided into: E-W trending segment with thick lower crust and NW-SE segment with underplated material (Nair et al., 2015).

The ~N-S trending CLR complex is a positive broad topographic feature conspicuous between 10°S and 15°N latitudes (Figure 1). This CLR complex consists of several irregular blocks separated by relatively deep E-W trending channels and considerable length of its crest is composed of shoals, banks, coral reefs and atolls. It is associated with positive (~25 mGal) free-air gravity anomalies (Kahle and Talwani, 1973; Naini and Talwani, 1982). The origin of this complex is attributed to various processes such as continental tectonics, transform faulting and hotspot trace (Mckenzie and Sclater, 1971; Naini and Talwani, 1982; Gopala Rao et al., 1987). The DSDP and ODP drilling results indicated that the CLR complex evolution is due to volcanic activity during the northward migration of the Indian plate over the Reunion hotspot (Duncan, 1990).

The CLR complex consists of the northern Laccadive Ridge, middle Maldives Block and southern Chagos Bank.

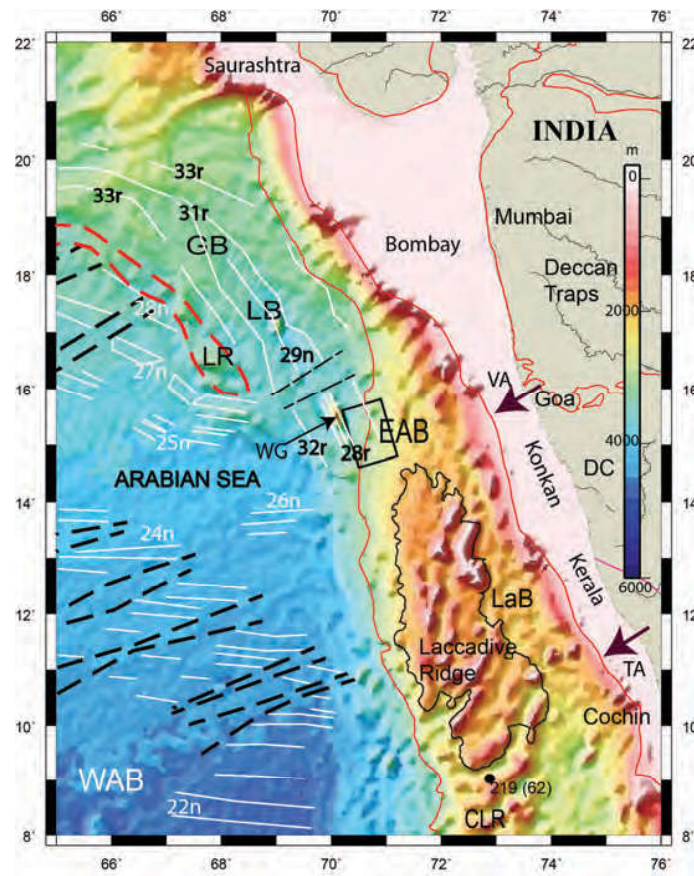


Figure 1. General bathymetry map of the Arabian Sea showing the main tectonic and structural features. Pseudofaults (black dashed lines) and magnetic lineations (white thin lines, some are annotated) are from Chaubey et al., (1998) and Ramana et al., (2015). Location of DSDP site 219 (Whitmarsh, 1974) is shown as a black circle with basement age in bracket. The extent of the Deccan volcanism is shown in red outline (Coffin and Eldholm, 1994). The 2000m isobath of the Laccadive Ridge is shown as a black outline. The extent of the gravity low of the Laxmi Ridge (LR) is shown as red dashed outline. Study area is marked with a black box. CLR: Chagos-Laccadive Ridge; DC: Dharwar Craton; EAB: Eastern Arabian Basin; GB: Gop Basin; LB: Laxmi Basin; LaB: Laccadive Basin; WG: Wadia Guyot; WAB: Western Arabian Basin. The Vengurla Arch (VA) and Tellicherry Arch (TA) are shown as brown arrows.

Gravity modeling study (Radhakrishna et al., 2002) suggested that the Laccadive Ridge was emplaced on pre-existing oceanic crust. Using seismic constraints and isostatic response, Chaubey et al., (2002a; 2008) postulated that the Laccadive Ridge is a thinned continental fragment intermingled with volcanic intrusives. The NW-SE trends associated with the Laccadive Ridge were linked to the Precambrian trends of the Dharwar Craton (Nair et al., 2013). Some recent plate reconstruction models highlighted that the Laccadive Ridge is a continental fragment (Yatheesh et al., 2006; Torsvik et al., 2013; Ramana et al., 2015; Bhattacharya and Yatheesh, 2015).

The Eastern Arabian Basin comprising the Laxmi and Laccadive Basins lies between the Laxmi and northern CLR Ridges and the adjacent continental slope of India (Figure 1). The Laxmi Basin occupies an area within the water depths of 3000 to 4000 m between the West Coast

of India and the Laxmi Ridge. Contrasting opinions prevail over the nature of the crust underlying the Laxmi Basin. For example, the crust underlying the Laxmi Basin has been inferred as transitional crust formed during initial phase of rifting (Naini and Talwani, 1982), while Todal and Eldholm (1998) are of the view that the northern Laxmi Basin is underlain by an extended continental crust. The crust underlying the Laxmi Basin has been considered as underplated and thinned continental (Radhakrishna et al., 2002), and ~14 km thick stretched continental (Krishna et al., 2006). Further, a 3-D modeling study of gravity anomalies indicated that the basin developed over an extended continental crust (Arora et al., 2012).

On the other hand, Talwani and Reif (1998) believed the crust underlying the Laxmi Basin as "initial oceanic crust", while Todal and Eldholm (1998) inferred the southern Laxmi Basin to be underlain by oceanic crust.

The Laxmi Basin crust has been suggested as oceanic (Bhattacharya et al., 1994a; Malod et al., 1997), and a linear seamount chain identified in the center of the basin represents an extinct spreading ridge (Bhattacharya et al., 1994b). Corfield et al., (2010) deduced that the 160 km wide Laxmi Basin shows distinctive characteristics of oceanic crust with seaward dipping reflectors on its either side. Recent crustal studies confirmed the oceanic nature of the Laxmi Basin, with 5-7 km thickness in the basin and up to 9 km thickness of the extinct spreading ridge (Torsvik et al., 2013). Contemporaneous seafloor spreading has been inferred in the Gop and Laxmi Basins since 79 Ma with progressive southward extinction of the spreading center by ~64 Ma (Ramana et al., 2015).

The Laccadive Basin, south of the Laxmi Basin is a narrow triangular shaped basin located between the Laccadive Ridge and the Kerala-Konkan Basin (Figure 1). It is confined between 2000 and 2800 m water depths with gravity field varying between -40 and -60 mGal. Naini and Talwani (1982) postulated that the Laccadive Basin is underlain by transitional crust with down faulted basement and decreasing sediment thickness from north to south. A chain of shallow basement highs form an approximately NNW-SSE trending lineament known as the Pratap Ridge (Naini and Talwani, 1982). Biswas (1988) suspected that part of the basin lying west of the Pratap Ridge is oceanic in nature, while the part of the basin east of the ridge evolved during the early rift phase. The Pratap Ridge has been related to Deccan-Reunion hotspot activity (Krishna et al., 1992), and rifting between India and Madagascar (Subrahmanyam et al., 1995). Gravity model suggests that the Laccadive Basin is underlain by thinned/extended continental crust (Radhakrishna et al., 2002; Arora et al., 2012). Presence of oceanic crust has been inferred from deep seismic data (Das, 2013). Yatheesh et al., (2013) suggested that the Laccadive Basin crust could be either much thinned continental or anomalously thick oceanic crust, and the Laccadive Ridge separated from the Indian continent by crustal divergence from the southern end (Bhattacharya and Yatheesh, 2015).

The Western Arabian Basin is bounded to the west by the Owen Fracture Zone, the NW-SE trending active Carlsberg Ridge towards south, and the Laxmi and CLR Ridges towards the north and east respectively. Tertiary magnetic anomalies 28n and younger in age are inferred (Chaubey et al., 1998; 2002b; Collier et al., 2008).

The present study area (Figure 1) lying between the Laxmi Basin in the north and the CLR complex in the south has not been investigated in detail earlier. The results of the present study are important to infer the existence/absence of any connectivity between these two diverse crustal domains.

Integrated analysis of the geophysical datasets along with multichannel seismic data facilitated to infer the nature and structure of the underlying crust in Goa offshore. The salient result from the present study is that the crust is oceanic in nature, evolved from 63.9 to 68.7 Ma (29n to 31r), and towards east, the crust is thicker by ~4 km and associated with magmatic intrusions.

DATA AND METHODOLOGY

About 1550 km of total intensity magnetic, gravity and bathymetry collected during the cruise SK180 (August 2002) onboard ORV Sagar Kanya in the Goa offshore are used in the present study (Figure 2). A Proton Precession type Magnetometer (G876) and a Bodenseewerk Sea Gravimeter (GSS30) were used to acquire total intensity magnetic and gravity data respectively. The Honeywell Elac echosounder was operated along with the Hydrosweep system manufactured by M/s Atlas Elektronik GMBH, Germany to obtain the bathymetry/swath bathymetry data. The geophysical tracks were planned along the NNW-SSE direction to obtain 100% swath coverage of an area of 5500 square km. (Figure 2A). The dense and high quality geophysical data thus obtained were converted into grids, and the contour maps of geophysical anomalies were generated (Figure 2B-D).

In addition, a 62 line km long Multichannel Seismic (MCS) reflection profile acquired onboard ORV Sagar Kanya (sk501) was used to strengthen the interpretation (Figure 3), and this profile lies towards north of the study area. Prominent seismic sequences have been inferred along this profile from the reflection pattern. Gravity and magnetic anomalies extracted from the grids along this seismic profile are subjected to forward modeling using the GM-SYS software under seismic constraints (Figure 4; Table 1). The GM-SYS software is primarily based on the method/algorithms of Talwani et al., (1959) and Talwani and Heirtzler (1964). The gravity response has been computed using variable densities for the sediments and the underlying crust. For modeling the magnetic anomaly data, the three-layer model of Kent et al., (1993) was adopted to generate the seafloor spreading magnetic anomalies by incorporating the remnant magnetization with inclination 52° and declination 300° (Bhattacharya et al., 1994a) as the oceanic crust evolved in the southern latitudes (~50°S) during the Late Cretaceous. It was considered that the intrusive bodies formed around 65 Ma at 29°S (Courtillet et al., 1986). Several iterations were performed during modeling by assigning appropriate density, susceptibility and magnetization values for the sedimentary column and crustal configuration, till the best fit between the observed and computed anomalies was achieved.

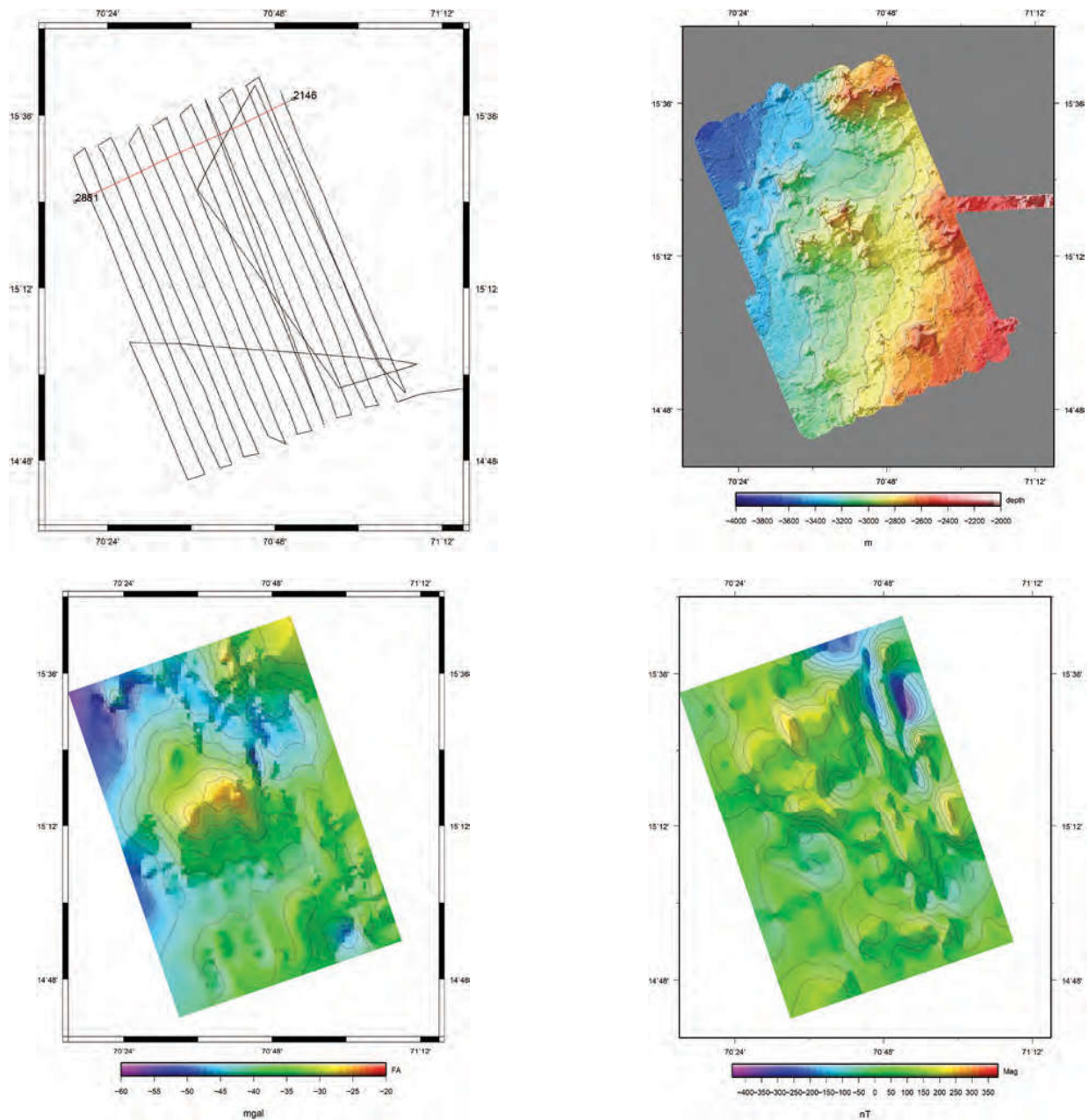


Figure 2. (A) Tracks along which gravity, magnetic and single and multibeam swath bathymetry data have been collected in the study area are shown as black lines. Multichannel seismic reflection data track is shown as a red line. (B) Map showing the detailed bathymetry of the study area generated using multibeam swath bathymetry data. (C) Free air gravity anomaly contour map of the study area. Contour interval is 4 mGal. (D) Magnetic anomaly contour map of the study area. Contour interval is 50 nT.

RESULTS

The water depth in the study area ranges from 2450 to 4000 m, increasing from southeast towards northwest (Figure 2B). A predominant WNW-ESE trending positive topographic feature occurs in the central part of the study area, which shallows to 2700 m creating ~20 km wide

basin-like depressions towards northeast and southwest. The depth to the seabed shallows to 2600 m towards northeast.

The free-air gravity anomaly amplitudes vary between -56 and -28 mGal, and the anomalies in general mimic the seafloor topography. A deviation between the gravity and bathymetry is observed towards southeast where a

Table 1. Physical properties of the various bodies inferred using forward modeling of the geophysical data under seismic constraints.

Body	Density	Magnetisation
water	1.03	0
sediment	1.8 to 2.2	0
Chert layer	2.3 to 2.45	0
Intrusives	2.7-2.8	0.001 to 0.006 A/m 0.001 to 0.01 S cgs units
Upper Crust	2.7-2.75	0.001 to 0.019 A/m 0.001 to 0.01 S (cgs units)
Middle Crust	2.8-3	0
Lower Crust	2.9-3.15	0
Mantle	3.3	0

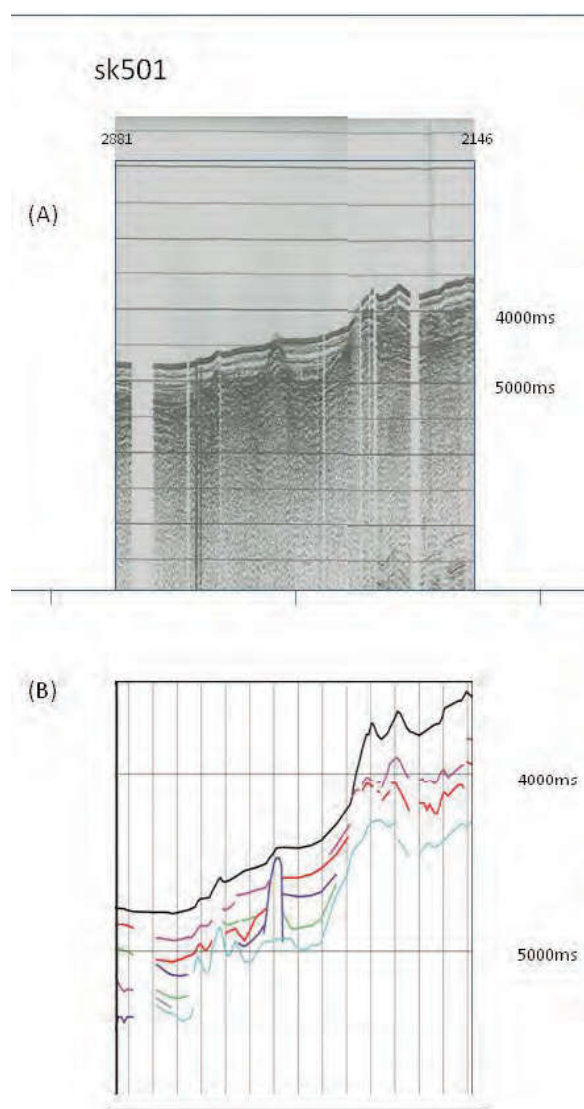


Figure 3. Multichannel seismic section along the profile sk501 (A) Uninterpreted, and (B) Line drawing. Acoustic basement is marked in light blue, while prominent horizons within the sediment column are marked in different colours. Location of the profile is shown in Figure 2A.

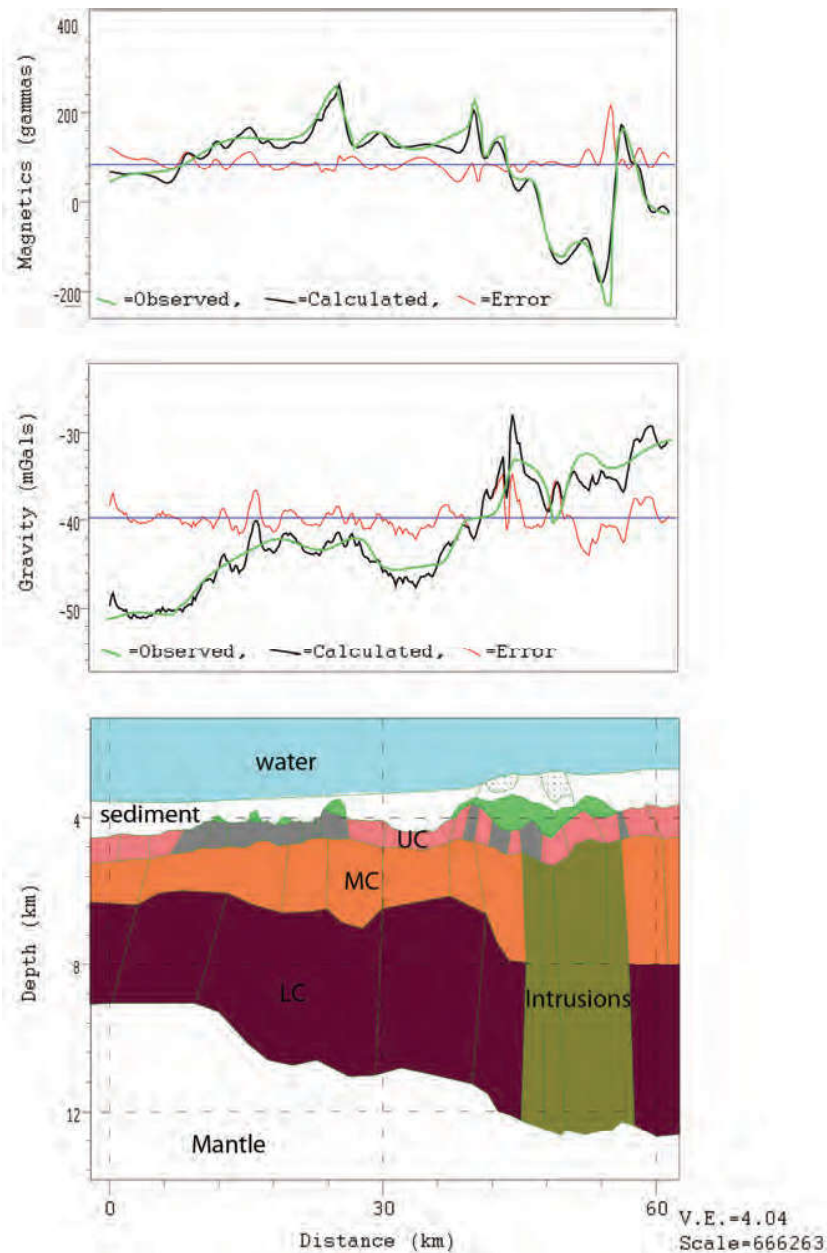


Figure 4. Forward modeling of the potential data under seismic constraints along the profile sk501. Physical properties of the sediment overburden and underlying crust are given in table 1. Normal and reversed magnetic crust are shown in red and grey respectively. Chert layer is shown in green. Intrusions are shown in olive green. UC: Upper oceanic crust; MC: Middle oceanic crust; LC: Lower oceanic crust.

gravity low is seen despite positive topography. In general, the gravity anomaly contour map depicts ~NW-SE trend (Figure 2C).

The amplitude of the magnetic anomalies (Figure 2D) varies between -400 and $+250$ nT, and the magnetic anomaly closures depict a general NW-SE to NNW-SSE trend throughout the study area. Towards the northeast, magnetic anomaly closures are dense, with large variation

in the amplitude. Towards the southwest, the closures are widely spaced.

The seismic section (Figure 3) shows the presence of at least 1 s TWT thick sediments over the acoustic basement. The basement is undulatory in nature and associated with intrusives reaching the seabed.

Forward modeling studies under seismic constraints reveal the presence of oceanic crust (Figure 4) with

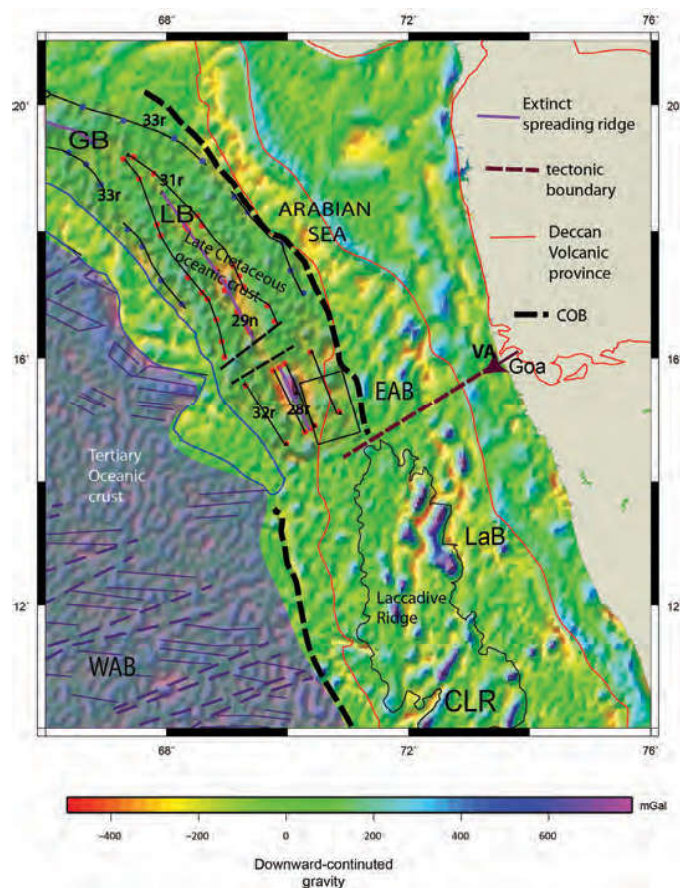


Figure 5. Map depicting the different tectonic domains in the Arabian Sea superimposed on the downward continued gravity (Whittaker et al., 2008). The Tertiary oceanic crust in the Western Arabian Basin (WAB) is shaded dark, while the Late Cretaceous oceanic crust in the Laxmi Basin (LB) is lightly shaded. The extinct spreading ridge and isochrones in the Laxmi and Gop Basins are from Ramana et al., (2015). The blue outline demarcates the gravity low around and south of the Laxmi Ridge. The red outline demarcates the extent of the Deccan volcanic province (Coffin and Eldholm, 1994). The thick black dashed line represents the COB, east of LB (Ramana et al., 2015) and west of CLR complex (Chaubey et al., 2002a). The tectonic boundary continuing into the Vengurla Arch (VA) separates the oceanic crust in the north from the CLR complex in the south. Annotations are same as in Figure 1.

thickness increasing from ~6 km to 9 km towards east. This oceanic crustal layer can be classified into the upper crust (layer 2A), middle crust and lower crust. The basement peaks are characterized by relatively low density material probably chert (Table 1). The upper crustal layer depicts the presence of the reversal blocks of the earth's magnetic field. Towards east, the undulations in the magnetic and gravity signature correspond to intrusive bodies with varying densities and magnetizations within the basement.

DISCUSSION

The Laxmi Basin, lying north of the study area has been recognized with different crustal characteristics and configuration, and evolution mechanisms (Naini and Talwani, 1982; Bhattacharya et al., 1994a; Malod et al.,

1997; Radhakrishna et al., 2002; Krishna et al., 2006; Arora et al., 2012; Ramana et al., 2015). A linear seamount chain (Wadia Guyot, Pannikar and Raman seamounts) in the Laxmi Basin has been associated with an extinct spreading ridge (Bhattacharya et al., 1994b). The Wadia Guyot lying to the west of the study area (Figure 1) has also been considered as part of the extinct spreading ridge (Ramana et al., 2015). Interestingly, the NNW-SSE and NW-SE trends depicted by the magnetic and gravity data in the study area (Figure 2) are in agreement with the NNW-SSE trending extinct spreading ridge in the Laxmi Basin (Bhattacharya et al., 1994a; Ramana et al., 2015), and these trends align in the direction of the onshore Precambrian Dharwarian lineaments (Naini, 1980; Nair et al., 2013).

The 6-9 km thick oceanic crust inferred in the present study (Figure 4) is comparable with 5-9 km crustal thickness deduced by Torsvik et al., (2013), therefore

asserting its oceanic nature. The presence of intrusive bodies towards east endorses the influence of the Reunion hotspot on the pre-existing oceanic crust. Further, the magnetic model study reveals the presence of reversal blocks corresponding to the seafloor spreading magnetic anomalies 29n to 31r (Figure 4) as inferred by Ramana et al., (2015). Thus the study area is of age 63.9 to 68.7 Ma, and lies on the eastern flank of the extinct spreading ridge.

The northern portion of the CLR complex, the Laccadive Ridge, is a thinned continental fragment intermingled with volcanic intrusives (Chaubey et al., 2002a; 2008) used in plate reconstruction models (Yatheesh et al., 2006; Torsvik et al., 2013; Ramana et al., 2015; Bhattacharya and Yatheesh, 2015). The separation of the Laccadive Ridge from India formed the Laccadive Basin. There is no unique interpretation about the underlying crust in the Laccadive Basin (Biswas, 1988; Arora et al., 2012; Das, 2013; Yatheesh et al., 2013). If the Laccadive Basin is continental in nature, then there is no scope for southward propagation of the seafloor spreading center of the Laxmi Basin (Ramana et al., 2015) towards south of the study area.

Alternately, if the Laccadive Basin is underlain by oceanic crust, then the question arises about its age and evolution mechanism. Bhattacharya and Yatheesh (2015) proposed that a northward propagating rift is responsible for the crustal divergence between Laccadive Ridge and Indian continent under the influence of the Marion hotspot, which continued till Late Paleocene. On the other hand, Ramana et al., (2015) believe that Laccadive Basin may have formed only when Laccadive Ridge moved away from India around 63.1 Ma. In both the arguments, it appears that the rifting was limited for a short period, and may not have progressed into intense and continuous seafloor spreading.

Tectonic evolution

The West Coast of India evolved as a result of multiple rifting between India, Africa, Madagascar and Seychelles. The initial breakup of Africa from India-Madagascar-Seychelles in the Late Jurassic (Mckenzie and Sclater, 1971; Norton and Sclater, 1979; Schlich, 1982) was followed by the separation of Madagascar from Seychelles-India (Torsvik et al., 2000). Pre-Deccan volcanism resulted in the opening of the Gop and Laxmi Basins by chron 33r (Talwani and Reif, 1998; Ramana et al., 2015). This opening separated Seychelles-Laxmi Ridge from India but failed to propagate south of 14.5°N. Southward progressive extinction of seafloor spreading occurred from 31r to 28r in the Laxmi Basin, and the ridge jumped southwestwards under the influence of the Reunion hotspot to form the Carlsberg Ridge (Chaubey et al., 2002b; Collier et al., 2008). Minimal motion between Laccadive Ridge and the Indian plate resulted in the formation of the present day Laccadive Basin.

A major fracture zone between the northern and southern Mascarene Basin appears to restrict the southward propagation of the Laxmi Basin spreading ridge from Late Cretaceous to Early Paleocene (Ramana et al., 2015). Due to cessation of propagation, the rifting failed between India and Laccadive Ridge (Nair et al., 2013). Hence, it is reasonable to propose that there exists a tectonic boundary south of the present study area, between the oceanic crust in the north and the CLR complex (Laccadive Ridge) in the south (Figure 5). This boundary apparently coincides with the E-W trending zone around 14°N having ~10 km thick oceanic crust (Torsvik et al., 2013). Further, this boundary probably coincides with the southwestward plunging Vengurla Arch (Figure 1; Biswas, 1987). Thus the CLR complex does not bend northwest parallel to the western Indian margin, but continues northward into India, as suggested by Talwani and Reif (1998).

CONCLUSIONS

Interpretation of integrated geophysical dataset suggests that the study area forms a vital link between the northern oceanic domain and southern partly oceanic and continental crusts. In general, the bathymetry deepens towards northwest with the central topographic high associated with relatively positive gravity anomaly. The magnetic anomalies depict ~NW-SE to NNW-SSE direction. The basement is fairly undulating and around 2 km thick sediment load overlies the basement. Forward modeling under seismic constraints reveals that crustal thickness increases towards east from 6 to 9 km. The crust is oceanic in nature of age 63.9 to 68.7 Ma (29n to 31r) and contaminated towards east due to Reunion hotspot activity.

A major tectonic boundary exists south of the study area, between the oceanic crust in the Laxmi Basin towards north and the Laccadive Ridge towards south. Further this inferred tectonic boundary coincides with the south-westerly plunging Vengurla Arch off Goa and may be associated with the major fracture zone which might have restricted the southward propagation of the Laxmi Basin spreading ridge during Late Cretaceous to Early Paleocene. Thus two distinct tectonic settings prevail in the eastern Arabian Basin. North of 14° N, the Gop and Laxmi Basins including the study area are associated with oceanic crust, while towards south, the northward motion of the Indian plate over the Reunion hotspot resulted in complex tectonics.

ACKNOWLEDGMENTS

We sincerely thank Director, NIO for granting the necessary permission. The officers, crew, scientific and supporting staff of the concerned cruises are duly acknowledged. GMT

software (Wessel and Smith, 1998) was used to generate the Figures. We thank Chief Editor of JIGU for inviting us to contribute this article.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

REFERENCES

- Arora, K., Tiwari, V.M., Singh, B., Mishra, D.C., and Grevemeyer, I., 2012. Three dimensional lithospheric structure of the western continental margin of India constrained from gravity modeling: implication for tectonic evolution, *Geophys. J. Int.*, v.190, pp: 131-150.
- Bhattacharya, G. C., Chaubey, A. K., Murty, G. P. S., Srinivas, K., Sarma, K. V. L. N. S., Subrahmanyam, V., and Krishna, K. S., 1994a. Evidence for seafloor spreading in the Laxmi Basin, northeastern Arabian Sea, *Earth Planet. Sci. Lett.*, v.125, pp: 211-220.
- Bhattacharya, G. C., Murty, G.P.S., Srinivas, K., Chaubey, A. K., Sudhakar, T., and Nair, R. R., 1994b. Swath bathymetric investigation of the seamounts located in the Laxmi Basin, Eastern Arabian Sea, *Mar. Geol.*, v.17, pp: 169-182.
- Bhattacharya, G.C., and Yatheesh, V., 2015. Plate-Tectonic evolution of the deep ocean basins adjoining the western continental margin of India – a proposed model for the early opening scenario, In: S. Mukherjee (Ed.), *Petroleum Geosciences: Indian Contexts*, Springer Geology doi: 10.1007/978-3-319-03119-4_1.
- Biswas, S. K., 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India, *Tectonophysics*, v.135, pp: 307-327.
- Biswas, S. K., 1988. Structure of the western continental margin of India and related igneous activity, *Geological Survey of India Memoir*, v.10, pp: 371-390.
- Chaubey, A. K., Bhattacharya, G. C., Murty, G.P.S., Srinivas, K., Ramprasad, T., and Gopala Rao, D., 1998. Early tertiary seafloor spreading magnetic anomalies and paleo-propagators in the northern Arabian Sea, *Earth Planet. Sci. Lett.*, v.154, pp: 41-52.
- Chaubey, A. K., Gopala Rao, D., Srinivas, K., Ramprasad, T., Ramana, M. V., and Subrahmanyam, V., 2002a. Analyses of multichannel seismic reflection, gravity and magnetic data along a regional profile across the central-western continental margin of India, *Mar. Geol.*, v.182, pp: 303-323.
- Chaubey, A. K., Dyment, J., Bhattacharya, G.C., Royer, J-Y., Srinivas, K., and Yatheesh, V., 2002b. Paleogene magnetic isochrones and paleo-propagators in the Arabian and Eastern Somali basins, Northwest Indian Ocean, In: Clift, P. D., Kroon, D., et al., (Eds.), *The tectonic and climatic evolution of the Arabian Sea region*. *Geol. Soc. London Sp. Pub.*, v.195, pp: 71-85.
- Chaubey, A.K., Srinivas, K., Ashalatha, B., and Gopala Rao, D., 2008. Isostatic response of the Laccadive Ridge from admittance analysis of gravity and bathymetry data, *J. Geodyn.*, v. 46, pp: 10-20.
- Coffin, M.F., and Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions and external consequences, *Rev. Geophys.*, v.32, pp: 1-36.
- Collier, J.S., Sansom, V., Ishizuka, O., Taylor, R.N., Minshull, T.A., and Whitmarsh, R.B., 2008. Age of Seychelles-India break-up, *Earth Planet. Sci. Lett.*, v.272, pp: 264-277.
- Corfield, R.I., Carmichael, S., Bennett, J., Akhter, S., Fatimi, M., and Craig, T., 2010. Variability in the crustal structure of the West Indian Continental Margin in the Northern Arabian Sea, *Petrol. Geosci.*, v.16, pp: 257-265.
- Courtillot, V., Besse, J., Vandamme, D., Montigny, R., Jaeger, J.J., and Cappetta, H., 1986. Deccan flood basalts at the Cretaceous/Tertiary boundary? *Earth Planet. Sci. Lett.*, v.80, pp: 361-374.
- Das, K.C., 2013. Mesozoic enigma in Kerala-Konkan Basin: an alternate explanation for deep water sub-basalt reflections, 10th biennial international conference and exposition, Kochi, P352, pp: 1-7.
- Duncan, R. A., 1990. The volcanic record of the Reunion hot spot, In: Duncan, R.A. et al., (Eds.), *Proceedings of the ODP Scientific Results, Ocean Drilling Program, College Station* v.115, pp: 3-10.
- Gopala Rao, D., Bhattacharya, G. C., Subba Raju, L. V., Ramana, M. V., Subrahmanyam, V., Raju, K. A. K., Ramprasad, T., and Chaubey, A.K., 1987. Regional marine geophysical studies of the southwestern continental margin of India, In: Rao, T.S.S., Natarajan, R. et al., (Eds.), *Contributions in Marine Sciences*. Dr. S. Z. Qasim Sastyabdapurti Felicitation volume, National Institute of Oceanography, India, pp: 427-437.
- Heezen, B. C., and Tharp, M., 1964. Physiographic diagram of the Indian Ocean (with descriptive sheet). *Geol. Soc. Am.*, New York.
- Kahle, H. G., and Talwani, M., 1973. Gravimetric Indian Ocean geoid, *Journal of Geophysics (Z. Geophys.)* v.39, pp: 167.
- Kent, G., Harding, A., and Orcutt, J., 1993. Distribution of magma beneath the East Pacific Rise between the Clipperton Transform and the 9°17'N Deval from forward modeling of Common Depth Point data, *J. Geophys. Res.*, v.98, pp: 13945-13969.
- Krishna, K.S., Murty, G.P.S., Srinivas, K., and Rao, D.G., 1992. Magnetic studies over the northern extension of the Prathap Ridge Complex, Eastern Arabian Sea, *Geo-Mar. Lett.*, v. 12, pp: 7-13.
- Krishna, K. S., Rao, D.G., and Sar, D., 2006. Nature of the crust in the Laxmi basin (14°-20°N), western continental margin of India, *Tectonics*, v.25, doi:10.1029/2004TC001747.
- Malod, J.A., Droz, L., Kemal, B.M., and Patriat, P., 1997. Early spreading and continental to oceanic basement transition beneath the Indus deep-sea fan: northeastern Arabian Sea, *Mar. Geol.*, v.141, pp: 221-235.

- Mckenzie, D., and Sclater, J.G., 1971. The evolution of the Indian Ocean since the Late Cretaceous, *Geophys. J. Royal Astron. Soc.*, v.25, pp: 437-528.
- Misra, A. A., Sinha, N., and Mukherjee, S., 2015. Repeat ridge jumps and microcontinent separation: insights from NE Arabian Sea, *Mar. Petrol. Geol.*, v.59, pp: 406-428.
- Naini, B. R., 1980. A geological and geophysical study of the continental margin of western India and the adjoining Arabian Sea including the Indus Cone, unpublished Ph. D. Thesis, Columbia University, New York, pp: 173.
- Naini, B. R., and Talwani, M., 1982. Structural frame work and the evolutionary history of the continental margin of western India, In: Watkins, J.S., Drake, C.L. (Eds.), *Studies in Continental Margin Geology*. Amer. Assoc. Petrol. Geol. Mem., v.34, pp: 167-191.
- Nair, N., Anand, S.P., and Rajaram, M., 2013. Tectonic framework of Laccadive Ridge in Western Continental Margin of India, *Mar. Geol.*, v.346, pp: 79-90.
- Nair, N., Anand, S.P., Rajaram, M., and Rama Rao, P., 2015. A relook into the crustal architecture of Laxmi Ridge, northeastern Arabian Sea from geopotential data, *J. Earth Sys. Sci.*, v.124, pp: 613-630.
- Norton, I.O., and Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of the Gondwanaland, *J. Geophys. Res.*, v.84, pp: 6803-6830.
- Ramana, M. V., Desa, M. A., and Ramprasad, T., 2015. Re-examination of geophysical data off Northwest India: Implications to the Late Cretaceous plate tectonics between India and Africa, *Mar. Geol.*, v.365, pp: 36-51.
- Radhakrishna, M., Verma, R. K., and Purushotham, A. K., 2002. Lithospheric structure below the eastern Arabian Sea and adjoining West Coast of India based on integrated analysis of gravity and seismic data, *Mar. Geophys. Res.*, v.23, pp: 25-42.
- Schlich, R., 1982. The Indian Ocean: aseismic ridges, spreading centers and oceanic basins, In: Nairn, A.E., Stehli, F.G. (Eds.), *The Ocean basins and Margins*. Plenum Press, New York, v.6, pp: 51-147.
- Subrahmanyam, V., Gopala Rao, D., Ramana, M. V., Krishna, K. S., Murthy, G. P. S., and Rao, M. G., 1995. Structure and tectonics of the southwestern continental margin of India, *Tectonophysics*, v.249, pp: 267-282.
- Talwani, M., and Reif, C., 1998. Laxmi Ridge – A continental sliver in the Arabian Sea, *Mar. Geophys. Res.*, v.20, pp: 259-271.
- Talwani, M., and Heirtzler, J.R., 1964. Computation of magnetic anomalies caused by two-dimensional bodies of arbitrary shape, In: Parks, G.A., (Ed.), *Computers in the Mineral Industries, Part 1. Geological Sciences*, Stanford University Publication, v.9, pp: 464-480.
- Talwani, M., Worzel, J.L., and Landisman, M., 1959. Rapid gravity computations for two dimensional bodies with application to the Mendocino submarine fracture zone, *J. Geophys. Res.*, v.64, pp: 49-59.
- Total, A., and Eldholm, O., 1998. Continental margin off western India and Deccan Large Igneous Province. *Mar. Geophys. Res.*, v.20, pp: 273-291.
- Torsvik, T.H., Tucker, R.D., Ashwal, L.D., Carter, L.M., Jamtveit, B., Vidyadharan, K.T., and Venkataramana, P., 2000. Late Cretaceous India-Madagascar fit and timing of breakup related magmatism, *Terra Nova*, v.12, pp: 220-224.
- Torsvik, T.H., Amundsen, H., Hartz, E. H., Corfu, F., Kuszniir, N., Gaina, C., Doubrovine, P.V., Steinberger, B., Ashwal, L.D., and Jamtveit, B., 2013. A Precambrian microcontinent in the Indian Ocean, *Nature Geosci.*, doi: 10.1038/NGEO1736.
- Wessel, P., and Smith, W. H. F., 1998. New improved version of Generic Mapping Tools released, *EOS Transactions American Geophysical Union*, v.79, pp: 579.
- Whitmarsh, R.B., 1974. Some aspects of plate tectonics in the Arabian Sea, Initial reports of the Deep Sea Drilling Project, U.S. Govt. Printing office, Washington, v.23, pp: 527-535.
- Whittaker, J.M., Müller, R.D., Roest, W. R., Wessel, P., and Smith, W. H. F., 2008. How supercontinents and superoceans affect seafloor roughness, *Nature*, v.456, pp: 938-941.
- Yatheesh, V., Bhattacharya, G.C., and Mahender, K., 2006. The terrace like feature in the mid-continental slope region off Trivandrum and a plausible model for India-Madagascar juxtaposition in immediate pre-drift scenario, *Gond. Res.*, v.10, pp: 179-185.
- Yatheesh, V., Kurian, P.J., Bhattacharya, G.C., and Rajan S., 2013. Morphotectonic architecture of an India-Madagascar breakup related anomalous submarine terrace complex on the southwest continental margin of India, *Marine and Petroleum Geology*, v.46, pp: 304-318.