

# Tectonic framework of Laccadive Ridge in Western Continental Margin of India



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## ABSTRACT

From the analysis of the satellite derived high resolution free air gravity data it is inferred that the evolutionary history of the Western Continental Margin of India to north and south of Goa appears to be totally different. The shelf edge is continuous and not disturbed in the northern part whereas to the south (south of 16°N) it has been affected by the onshore tectonics. It is hotly debated if the Laccadive Ridge (northern part of the Chagos-Laccadive Ridge) is continental or oceanic in nature or just of volcanic origin. From the filtered maps of the free air gravity anomalies, sources at different depths can be deciphered that help build an evolutionary model of the much debated Laccadive Ridge. The low pass filtered maps depicting deeper features, show a persistence of NW–SE to NS Dharwarian trends and it appears that the Laccadive Ridge to the north of around 8.5°N is of continental origin being bounded to the south and north by the offshore extension of the Bhavani Shear and Chapporo lineament respectively. It may have separated from India along with Madagascar during Cretaceous. At the Cretaceous Tertiary boundary as Laccadive-India passed over the Reunion hotspot, the pre-existing faults on the Laccadive Ridge were re-activated and the hotspot trace was left behind in the intermediate/shallow wavelength of the anomalies, as intrusives in the Laccadive Ridge. These are reflected in the High Pass filtered maps, depicting shallow to intermediate wavelength anomalies, which show NE–SW structures. The crustal structure derived from the 2D model of the satellite derived free air gravity data and a representative gravity-magnetic profile from ship borne data also depict continental nature of the Laccadive Ridge with emplacement of volcanic intrusives as it passed over the Reunion hotspot.

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## 1. Introduction

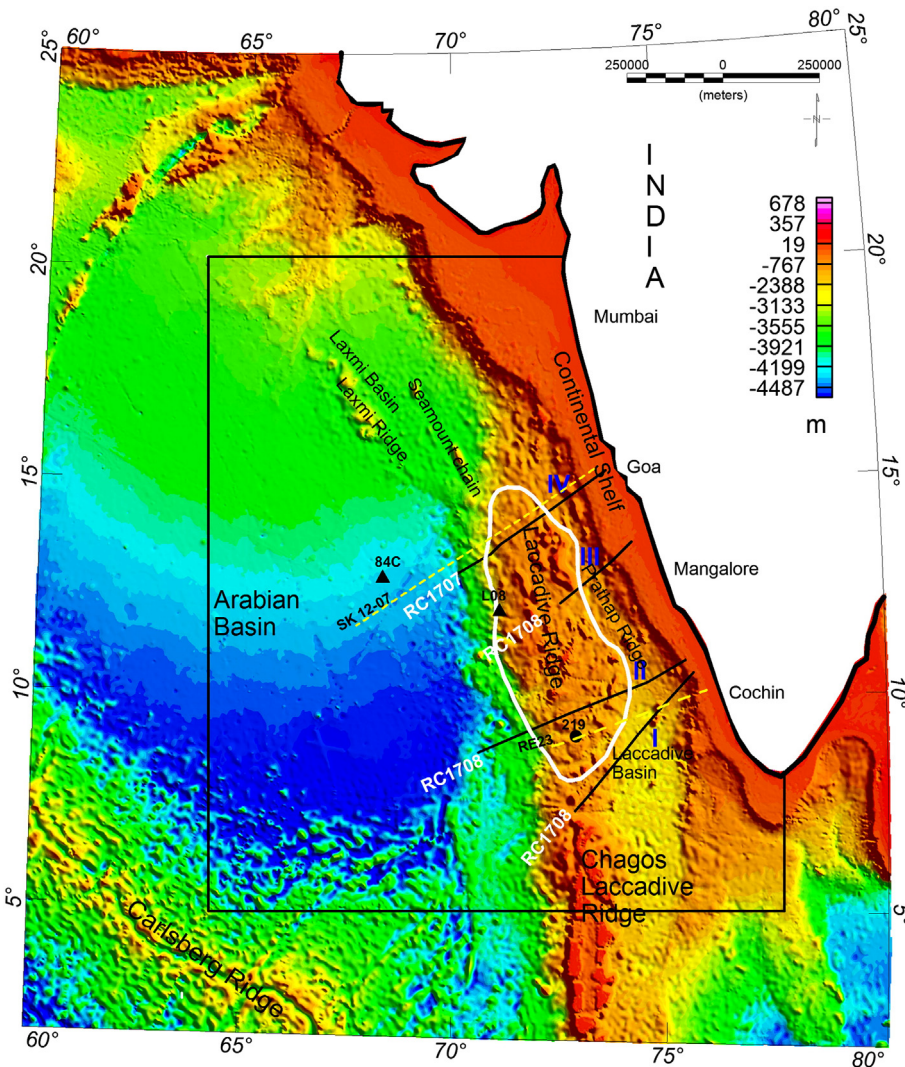
The evolution of passive continental margins, including the Western Continental Margin of India (WCMI), has received much attention owing to their economic potential, in particular hydrocarbons. There have been several studies on the tectonic history of Indian margins and detailed seismic reflection investigations of the margin are mostly confined to the shelf region for hydrocarbon exploration by the Indian oil industries. Most of the studies conducted over the WCMI are along profiles and these profiles are widely spaced and mainly cut across isolated bathymetric highs. It is now understood that the WCMI has undergone a lot of tectonic deformations from the time of its origin and this has resulted in complicated structures of its tectonic elements. Fig. 1 depicts the tectonic elements of the western offshore of India superposed on the bathymetry of the region. To have a better understanding of the evolution of the entire margin, it would require critical assessment of the crustal structure and tectonics of the margin and abyssal plain; a detail study of the shelf, shelf margin basin, Laccadive Ridge and Arabian Basin is essential. To have an unbiased understanding of the tectonic elements of the western offshore region it is essential to utilize uniform

high resolution 2D-data e.g. satellite derived Free Air Gravity (FAG) data and aeromagnetic data. In the absence of aeromagnetic data, satellite derived free air gravity data is used for the present study.

Continental rifting and breakup involve complex interactions of tectonic, magmatic, geodynamic and sedimentary processes. The gravity anomaly at a continental margin can be regarded as the result of all the processes that have shaped it through time including rifting, drifting, sedimentation, magmatic under-plating, passage over hotspot etc. (Watts and Fairhead, 1999). Each process will leave its signature on the underlying crust and hence will have a component in the observed gravity anomaly. Applying the principle of superposition, the older episodes will be relatively deeper compared to intermediate and recent ones that have taken place over the continental margin. Wavelength filtering is a process by which it is possible to separate out the anomalies in terms of their wavelengths; the shorter the wavelength the shallower will be the sources and hence may relate to relatively recent activity while longer wavelength usually represents deeper sources and possibly older activity. In the present paper, wavenumber domain filters have been utilized to separate out the gravity anomalies in terms of their wavelengths and an attempt is made to identify gravity sources and to throw light on the evolution of the Western Continental Margin of India with special emphasis on Laccadive Ridge. The region of study in the present paper has been demarcated by a rectangle on Fig. 1.

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**Fig. 1.** Bathymetry of the Western offshore region of India. The study area has been demarcated by a rectangle. The Laccadive Ridge as defined in the present study has been superposed in white on this map. The location of the ship profile data used in Fig. 2 is superposed in black and the seismic reflection section used in the calculated model is superposed in yellow. The location of seismic refraction L08V34 and 84C17 and DSDP site 219 are also superposed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 2. Morpho-tectonic elements of the WCMI

The WCMI has evolved due to the break-up of Indian sub-continent from Madagascar in mid-Cretaceous and later from Seychelles micro-continent at the end of the Cretaceous (Norton and Sclater, 1979; Courtillot et al., 1988; White and McKenzie, 1989). This has led to the formation of numerous NW–SE and NNW–SSE trending structural features almost parallel to the western margin of India. Numerous regional structures and sedimentary basins are located along the continental margin of western India and the contiguous Arabian Sea. Most prominent among these are the Chagos Laccadive Ridge (CLR), Laxmi Ridge, Prathap Ridge, Laxmi basin and the chain of seamounts termed Laxmi Basin seamount chain (Bhattacharya and Chaubey, 2001) (location superposed on Fig. 1). The region between the CLR and the Indian margin south of Goa consists of a complex bathymetry with numerous topographic highs and lows. The shelf edge limited by the 200 m isobath, results in the width of the shelf varying from 350 km off Bombay to 60 km towards south of Cochin (Naini and Kolla, 1982). Between Goa and Cochin, numerous topographic highs complicate the nature of continental rise. The CLR is formed by the Laccadive and Maldive island groups and the Chagos Archipelago and extends from about 10°S to

15°N latitudes; it is an asymmetrical ridge with a steeper eastern flank. The ridge on an average is less than 1000 m deep with occasional coral atolls and volcanic islands. Gravity data over CLR indicates that the free-air gravity anomaly is broadly varying and subdued (Bhattacharya and Chaubey, 2001; Radha Krishna et al., 2002). Ben Avraham and Bunce (1977) mentioned that north of 8°N the Laccadive Ridge (LR) is associated with large negative magnetic anomalies (which support the idea of volcanic composition for this region) suggesting that it was formed south of magnetic equator or north of equator during period of reversed magnetic polarity; it appears that there is a fault scarp on the east from 8 to 12°N. Verzhbitsky (2003) believed that the heat flow distribution along the Chagos-Laccadive Ridge is in accordance with the theory of the oceanic lithospheric evolution and further from an analysis of the geothermal regime and of the age of the basalts relate the genesis of the CLR to the hot spot hypothesis. According to Pushcharovsky (1996, 2011) the Chagos Laccadive Ridge consists of three extending blocks the Southern, Middle and Northern blocks corresponding to Chagos, Maldives and Laccadive blocks respectively with continental structure in the north and oceanic in the other two blocks. The deep sea holes drilled in the Southern and Middle blocks penetrated basalts and they are dated at 47 Ma and 55–60 Ma respectively.

Seismic refraction studies (Babenko et al., 1981) indicate that the Moho lies at a depth of about 18–19 km, which suggests that the crustal thickness of the Laccadive Ridge (northern part of CLR) is thicker than the normal oceanic crust. Some believe it has originated from a hot spot (Biswas, 2001) and others believe it may be a continental sliver that resulted from rifting along western margin (Talwani and Reif, 1998). Based on admittance analysis of gravity and bathymetry data, Chaubey et al. (2008) suggested that the Laccadive Ridge comprises thinned continental crust that is locally compensated by the Airy model of isostasy. From the study of Multi channel seismic reflection data, Ajay et al. (2010) identified Seaward Dipping Reflectors (SDR) along the western flank of the Laccadive Ridge and their 2D crustal model deduced from free air gravity data suggest that the SDRs are genetically related to incipient volcanism during rifting and the Ocean Continent Boundary (OCB) lies at the western margin of the Laccadive Ridge suggesting continental nature of the Laccadive Ridge. Sinha Roy (2001) believed the rifting failed to produce oceanic crust between India and Laccadive Ridge and therefore the continental margin lies to the west of the ridge. In a close fit India–Madagascar configuration, obtained for an 86.5 Ma reconstruction, Yatheesh et al. (2006) found that the model appeared to accommodate Seychelles, Laxmi Ridge, Saya de Malha and Laccadive Plateau between the 2000 m isobaths of India and Madagascar as intervening micro-continental slivers.

The Laccadive Basin – a narrow triangular shaped basin – is located between the Laccadive Ridge in the west and the south-western continental slope of India in the east. The seismic reflection studies (Bhattacharya and Chaubey, 2001 and references therein) suggest that the sediment thickness in this basin increases from south to north. Along the western margin, several basement highs (arches) trending perpendicular to the coast divide the shelf region into various thick sediment filled basins. From north to south, they include Bombay, Konkan and Kerala basins. The south-westerly plunging Vengurla arch (near Goa) separates the Bombay basin and the Konkan basin whereas the Tellicherry arch demarcates the Kerala and Konkan basins further south. Although the morphology of the western offshore of India is quite well known, there is much debate on the tectonic evolution of this region.

### 3. Methodology and data analysis

High-resolution gravity database (Sandwell and Smith, 2009) and bathymetric database (Sandwell and Smith, 1997) generated from re-tracked Seasat, Geosat GM, ERS-1/2 and TOPEX/POSEIDON altimeters data of the Arabian Sea are used as the primary data in the present work to investigate the tectonics and continental margin structure. Satellite altimetry has emerged as an efficient alternative for ship-borne gravity survey since the data collected on board ship was along widely spaced profiles. The Free Air Gravity data set version 18, (Sandwell and Smith, 2009) is obtained from a 1' by 1' grid (approximately 1.75 km in the study area) and has an improved spatial resolution of 24 km compared to the initial version (Sandwell and Smith, 1997). All the gravity values were referenced to the WGS84 horizontal datum with reference to the IGSN-71 system. Currently a new version of the Sandwell and Smith satellite gravity V20.1 is available on the ftp site [http://topex.ucsd.edu/cgi-bin/get\\_data.cgi](http://topex.ucsd.edu/cgi-bin/get_data.cgi). This is based on about twice as much satellite altimetry data and so has a nearly factor of 2 reduction in noise level (personal communication, Sandwell). In the present study we have used this improved version 20.1 satellite derived FAG data. A comparison of the satellite free air data was made with the available ship borne gravity data from the NOAA/NGDC, Marine Track-line Geophysics data set, version 5.0.11 and it was found that for the scale of structural features in the study region, the satellite gravity data are comparable with the ship borne measurements. Fig. 2 gives a plot of the comparison of ship borne data and satellite derived FAG data along four profiles; location of these profiles is superposed on Fig. 1. Though several

National and International agencies have collected ship borne gravity data in the Arabian Sea and WCMI, the satellite derived gravity data provide better coverage. Seafloor topography (version 15.1) derived from satellite altimetry with a resolution of 1' grid was used as bathymetric data for the present study. Bansal et al. (2005) used geoid derived Free air gravity data and compared it to the satellite-derived gravity (using slope to gravity method) of Sandwell and Smith (1997), v. 9.2. On comparing the power spectra of the FAG generated from their studies with the one from Sandwell and Smith (1997, v.9.2), it was found that the spectral behavior of the Sandwell and Smith (1997, v.9.2) data was far from ideal. Power spectra were computed using the version 20.1 data set and also the FAG derived from geoid (Sreejith et al., 2013) for the same region considered by Bansal et al. (2005) and the results are presented as an insert in Fig. 2; we found that the spectral behavior of both the data sets is comparable (see inset of Fig. 2) and considerably improved in data quality compared to Bansal et al. (2005). The free air gravity anomaly map generated using the above discussed data set (slope to gravity method) is represented in Fig. 3 as histogram equalized color shaded image in which the warm and cool colors represent highs and lows respectively. The tectonic elements of the WCMI are superposed on Fig. 3.

Free air gravity anomalies along the continental margin off western India and the adjoining deeper Arabian Sea form sub-linear belts of alternate positive and negative anomalies trending in NW–SE direction suggesting the control of the Precambrian Dharwarian tectonics. The region, in general, is characterized by broad to intermediate wavelength anomalies with isolated high wavenumber anomalies. The continental shelf of western offshore is characterized by strong signature of shelf edge gravity high probably representing sea ward thinning/attenuation of continental crust. The inner continental shelf exhibits gravity anomalies ranged from 0 to 20 mGal while the slope region is characterized by negative anomalies of the order of 60 mGal with steep gradients, except for the region west of Goa. The steep gravity gradients associated with the slope region coincide with the steep bathymetric variation that can be marked as the major continental shelf break. North of Goa, the shelf appears broader compared to the narrow region to the south. The free air anomaly along the shelf margin basin within the continental shelf ranged from –10 to –60 mGal. Some isolated gravity lows are prominent within the shelf margin and the one off Mumbai identified Bombay High (anticline) sedimentary basin. Towards the northern part of the study area, along the Laxmi Basin, the gravity anomaly ranges from +10 to +30 mGal whereas within the Laxmi Ridge, the anomaly varies from –10 to –60 mGal, implying major density variations within the crust associated with Laxmi Ridge. This gravity variation matches well with the rugged topography of the Laxmi Ridge region. Within the broad gravity high associated with Laxmi Basin are isolated seamounts (known as Laxmi Basin seamount chain) whose gravity anomaly ranges from 10 to 40 mGal. The Laccadive basin, towards the southwest of the shelf edge, is characterized by long wavelength gravity low in which are seen several high wavenumber high amplitude near circular gravity anomalies. According to Gopala Rao et al. (2010) the Prathap Ridge falls in this region but there is no continuous expression of this ridge in the FAG anomaly map (Fig. 3), rather it is represented by isolated high frequency, high amplitude, and circular anomalies. The Laccadive Ridge appears as a high amplitude broad NNW–SSE trending feature. Further west of the Laxmi and Laccadive Ridges, the anomalies along the Arabian Basin appeared flat and subdued varying from –10 to –30 mGal.

By and large the FAG anomaly map shows different wavelength components suggesting different depth levels for the causative sources. Different spectral components of Free Air Gravity anomalies correspond to varied magnitude geological features lying at different depth levels (Majumdar et al., 2006). To have an understanding of the distribution of shallow level gravity sources, an analytic signal

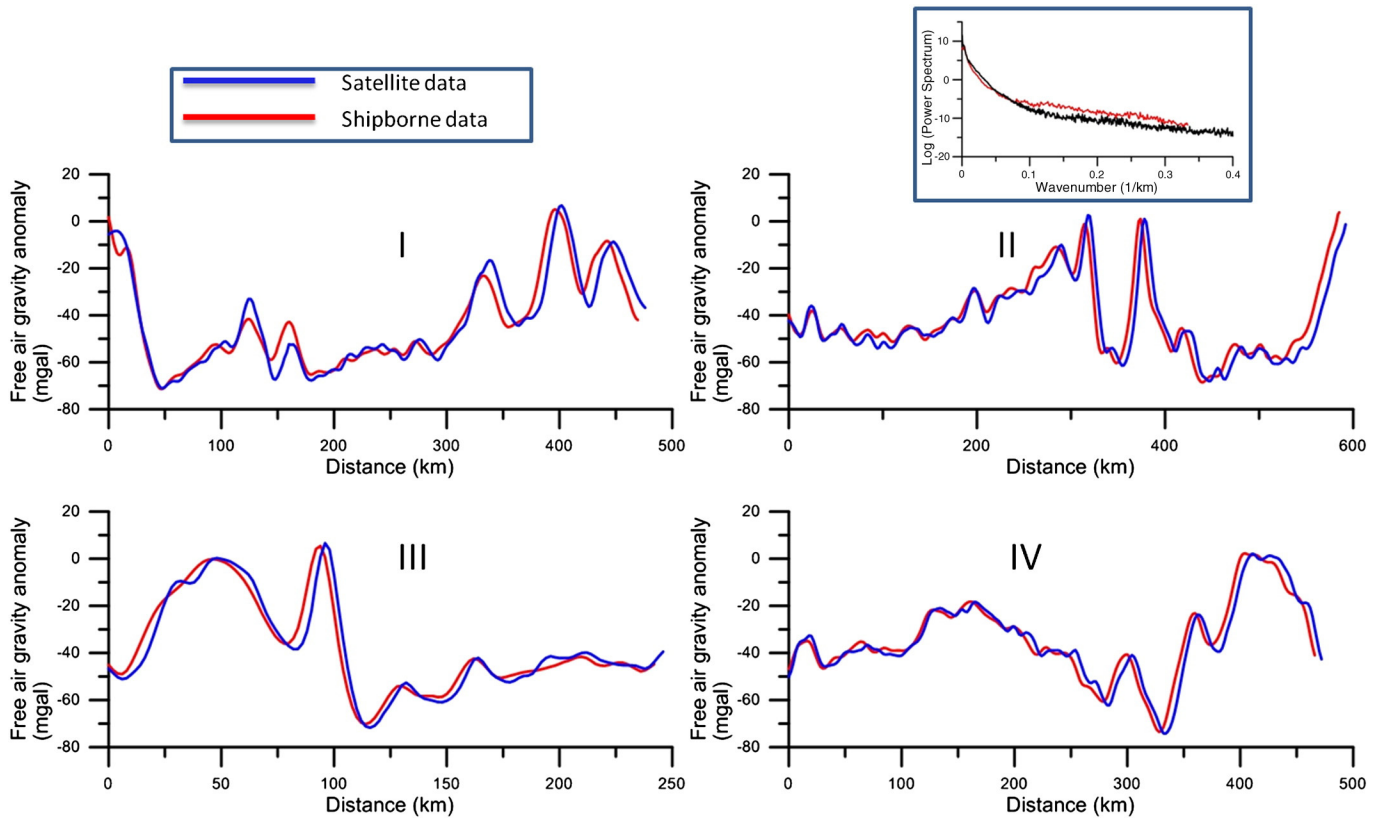


Fig. 2. Comparison of Ship borne and Satellite FAG Data (version 20.1) in the WCMI along four profiles; location of the profiles is demarcated in Fig. 1. Inset shows Log power spectrum of the Satellite derived gravity data using slope to gravity method (represented in black) and using geoid to Gravity method (Sreejith et al., 2013) in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

map was generated from the free air gravity data high pass filtered at 180 km (Watts and Fairhead, 1999) to help define the Ocean Continent Boundary and is reproduced in Fig. 4. The analytic signal method (the total gradient method) is used for defining the edges (boundaries) of geologically anomalous density or magnetization distributions (Nabighian, 1972, 1974). Mapped maxima (ridges and peaks) in the calculated analytic signal of a gravity anomaly map locate the anomalous source body edges and corners (e.g., basement fault block boundaries, basement lithology contacts, fault/shear zones, igneous and salt diapirs, etc.). It is assumed that the Ocean Continent Boundary (OCB) lies at the edge of the sources and has been superposed on Fig. 4 in white at the location showing the maximum gradient change in the FAG anomalies. As mentioned earlier, in a profile modeled by Ajay et al. (2010) cutting across the OCB, the location of the OCB as modeled by them matches with that in Fig. 4 lending credence to the deduced OCB. The location of the SDR and OCB in their modeled profile is superposed on Fig. 4.

### 3.1. Filtered FAG maps

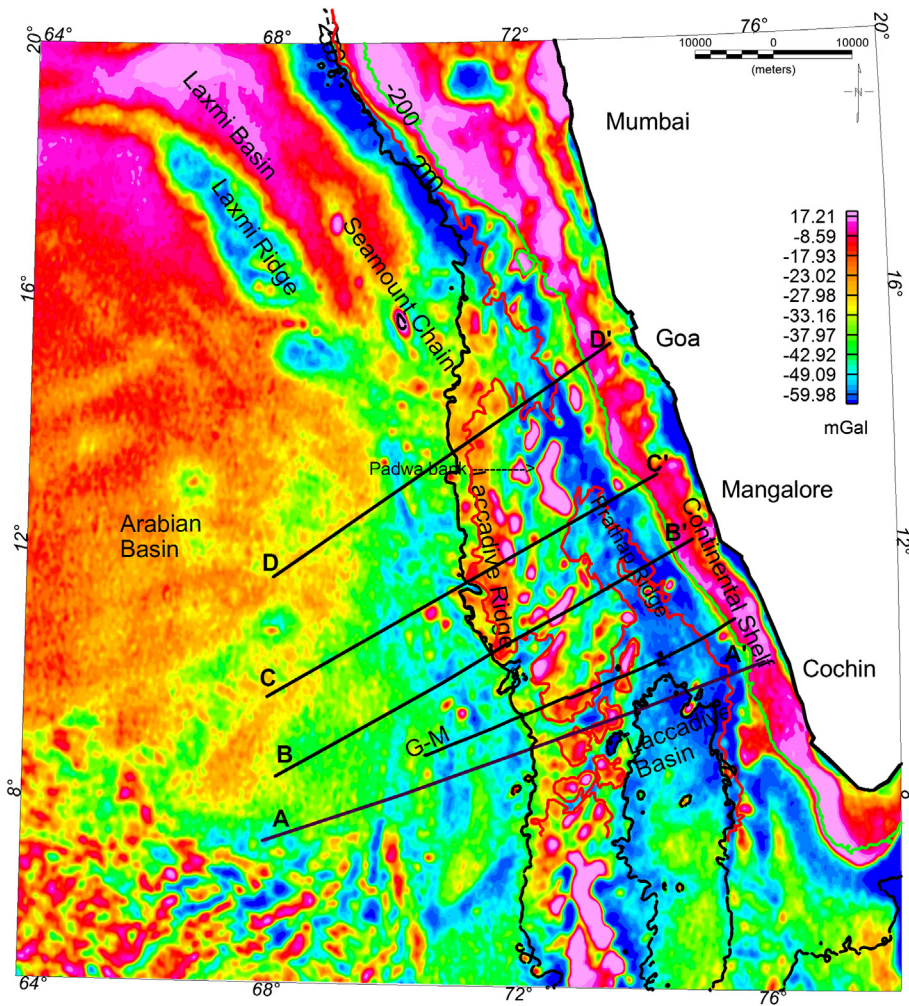
The FAG anomaly map was subjected to high pass filtering for cut-off wavelengths of 20 km, 30 km, 40 km, 50 km, 80 km, 100 km and 180 km to depict shallow/intermediate level features, and to low pass filtering at 50 km, 80 km, 100 km, 125 km and 200 km to understand the deeper features. In this paper the high pass filtered maps at 50 km and 100 km wavelengths have been reproduced in Fig. 5a and b respectively, and low pass filtered maps at 80 and 100 km wavelength in Fig. 6a, b; also superposed on Fig. 6a are the bathymetry contours at 200 m (in green), 2000 m (in red) and 2500 m

(in black). The filter response function of a tapered butterworth filter used for the present study was:

$$L(k) = \frac{1}{\left[1 + \left(\frac{k}{k_0}\right)^n\right]}$$

where  $k_0$  is the central wavenumber of the filter, and  $n$  is the degree of the filter,  $n = 8$  for the present study. In the region between Mangalore and Cochin (parallel to the west coast of India) and in the southern tip of India, a part of the continental shelf is clearly discernible at short wavelength anomalies, particularly in the high pass filtered map with cut off wavelength of 50 km (Fig. 5a). The presence of shelf edge is more prominent (with breaks in between) as one increases the cutoff wavelengths and appears as a continuous feature for a wavelength cutoff of 100 km (Fig. 5b) with a break south of Goa. However, this break vanishes in the low pass filtered map (Fig. 6a). Thus from a combination of high pass and low pass filtered maps, it is observed that the continental shelf is discontinuous at shallow levels and as the depth increases it is a continuous feature. To the west of continental shelf, the shelf margin basin – is a continuous NW–SE trending low all along the west coast of India (Fig. 6a).

All the high pass filtered maps depict NE–SW trends in the south eastern part of the Laccadive Ridge. Within the northern part of LR, the signatures of Padwa bank (location Fig. 3) are evident (Fig. 5a and b). Further north, the trends are subdued. From the long wavelength anomalies, the dominant structural features of the Laccadive Ridge trend are in a N–S direction (Fig. 6a, b). It is important to note that the NE–SW features dominant in the short and intermediate wavelength



**Fig. 3.** The free-air gravity anomaly map of the Western Continental Margin of India. The location of the tectonic elements, from Ajay et al. (2010) is superposed on this map. The location of the four profiles A–A', B–B', C–C' and D–D' used for modeling the crustal structure from FAG data is superposed on this map; superposed on this map are the bathymetry contours at 200 m (in green), 2000 m (in red) and 2500 m (in black). Location of GM profile used for modeling the crustal structure from ship-borne gravity-magnetic data is also superposed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

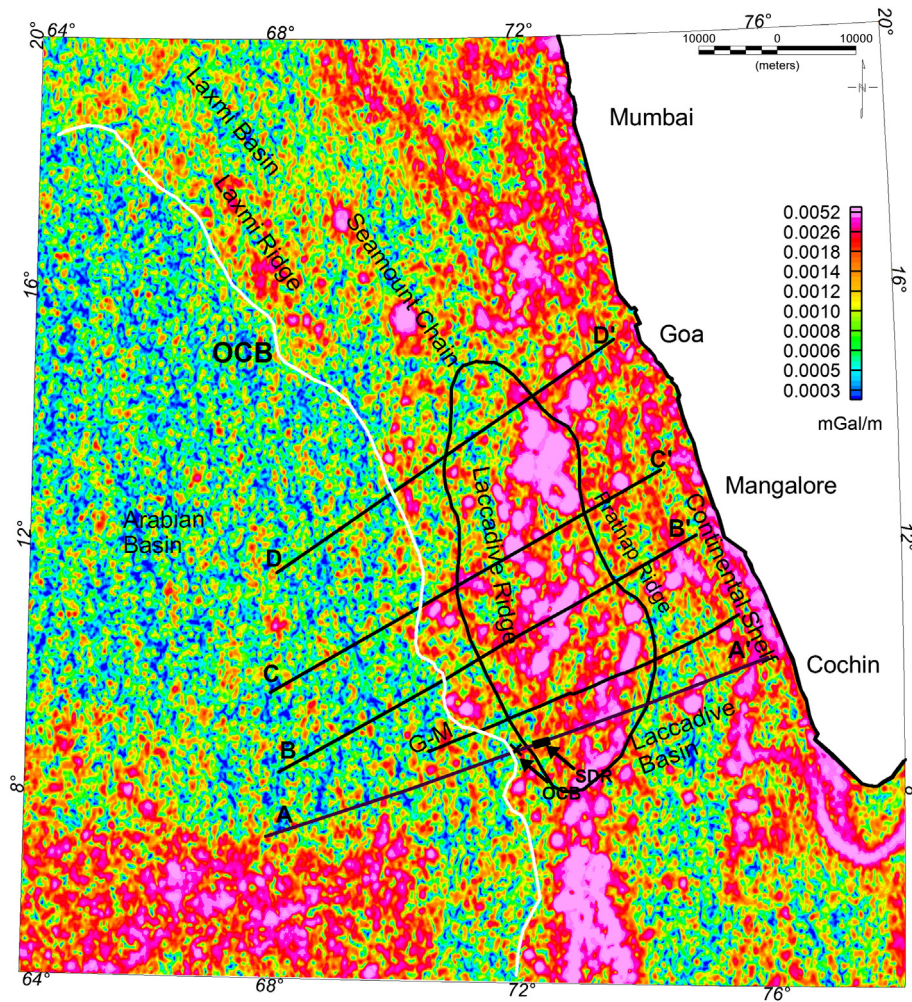
maps are totally absent in the deep features. Also, it may be noted that the main structural features of the adjacent Dharwar region on the land trend NW–SE to N–S direction implying that the deep features on the Laccadive Ridge perhaps have continental affinity. To the west of Laccadive Ridge (in south) the negative gravity anomaly continues to the north and further extends into the Laxmi Ridge. The delineated OCB as evident in Fig. 4 has been superposed on Fig. 6a, b.

### 3.2. Modeling of the crustal structure over LR

To further support our interpretations from the filtered maps of the FAG anomalies, we attempt to derive a crustal structure that best reproduces the observed FAG data. In order to understand the nature of the crust in the study region, forward modeling of the satellite derived free air gravity data was carried out along four NE–SW profiles (Profile A–A', B–B', C–C', D–D' starting from the south), with profile length varying from 730 to 940 km. The location of the profiles is superposed in Figs. 3, 4, 6b. The profiles start from the continental shelf and cut across the marginal high, Laccadive basin, Laccadive Ridge and end at the Arabian basin. To have an understanding of the nature of the crust along these profiles 2-dimensional forward modeling has been undertaken using the GM-SYS software designed for the same. The computation is based on the methods of Talwani et al. (1959) and Talwani and Heirtzler (1964) and makes use of the algorithms described

in Won and Bevis (1987). A two-dimensional flat earth model is assumed and the USGS SAKI implementation of the Marquardt inversion algorithm is used to linearize and invert the data.

Forward modeling involves creating a hypothetical geologic model and calculating the geophysical response to that earth model. Gravity and magnetic models are not unique and as a consequence the process is non-linear and the final result depends on the initial model: the better the starting model, the better the final result. Hence the initial model should be well constrained. In the present modeling the initial model was constrained using the available bathymetry, isopach (Balakrishnan, 1997) and published reflection/refraction seismic data (Naini and Talwani, 1982). The densities of different geological units were obtained from refraction seismic velocities (Naini and Talwani, 1982) using the Nafe–Drake curve; the location of the seismic refractions used, L08V34 for Laccadive Ridge and 84C17 for Arabian Ocean, is superposed on Fig. 1 and Table 1 gives the density values used in the forward model. Since density–velocity relation is non-linear, it possesses limitations on the direct use of density obtained from an assumed linear density–velocity relationship. Therefore, we selected mean density within the given range of densities for a particular seismic velocity. The response of the gravity was calculated for a four layer model assuming: first layer water column the thickness of which was constrained from the bathymetry data, second layer: the sediment thickness derived from isopach map, third layer: the continental/oceanic crust the top of which was taken from the available

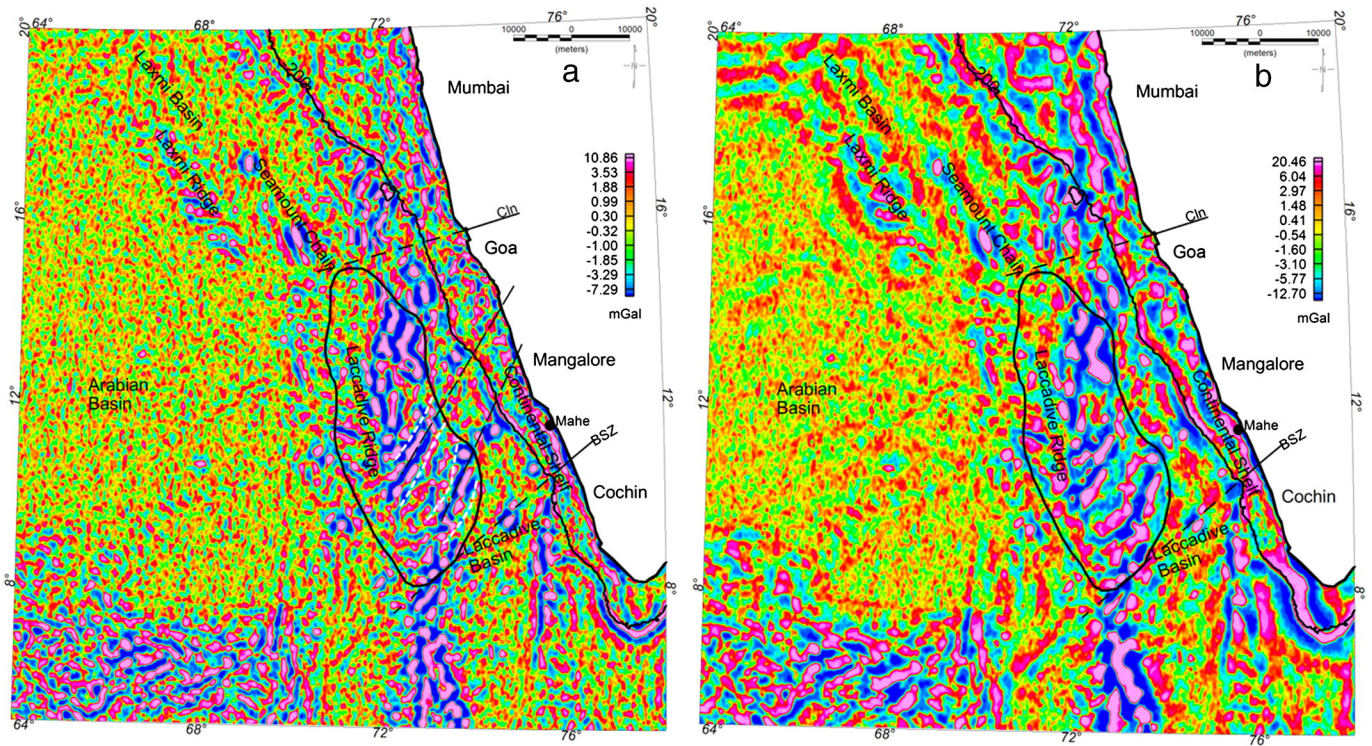


**Fig. 4.** Analytic Signal map of the free-air gravity anomaly (high pass filtered at 180 km wavelength) of the Western Continental Margin of India. The interpreted Ocean Continent Boundary is superposed on this map in white. Location of modeled profiles as is stated in Fig. 3 and the position of the SDR and OCB derived from the seismic section A–A' (RE23) by Ajay et al. (2010) is also shown.

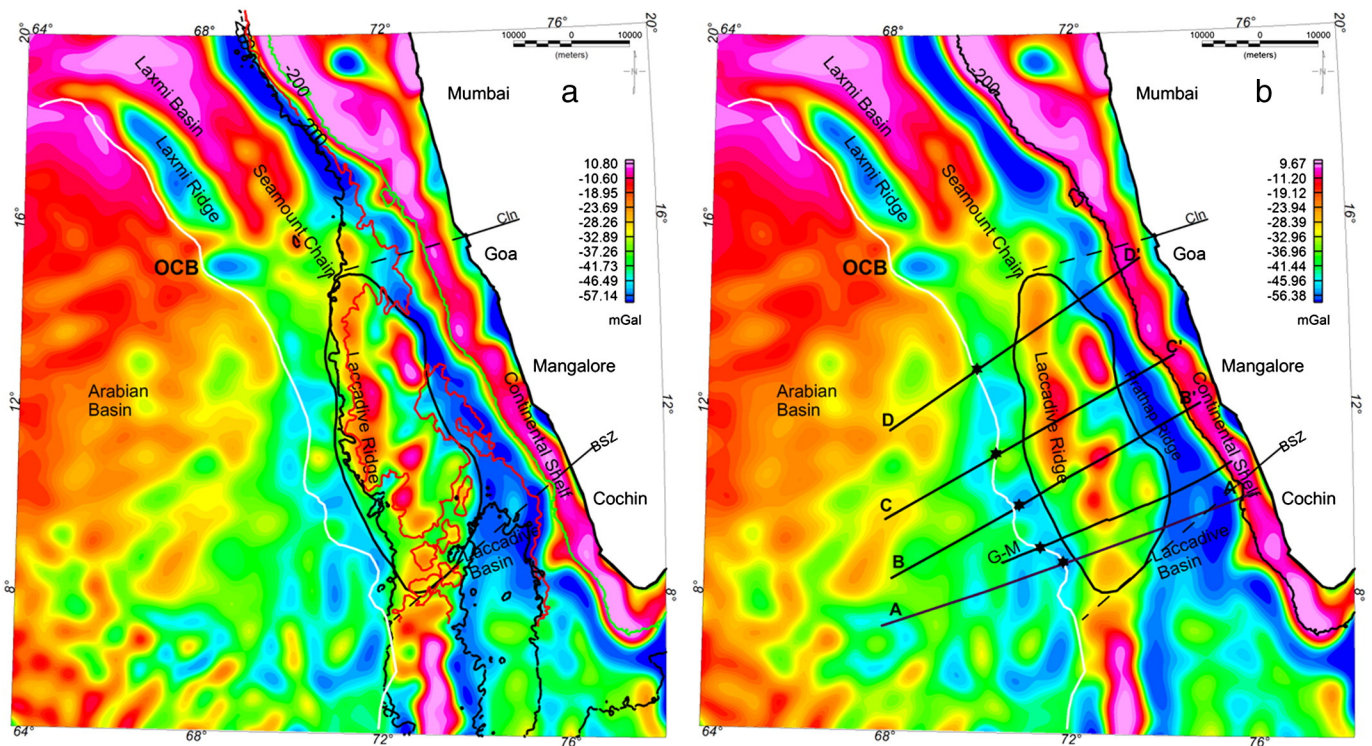
seismic sections and fourth layer: Mantle below the Moho. The gravity anomaly of the crustal model thus generated is calculated and compared with the observations; the depth to the top of the crustal layers and Moho was iteratively adjusted to minimize the error. The crustal model obtained with minimum RMS error is considered as the final crustal model and the crustal model derived from the four gravity profiles are shown in Fig. 7.

The final crustal structure resulted from the forward modeling of the gravity anomaly along these profiles represents a typical passive continental margin structure. From the multi channel seismic reflection studies in the region, (Nair et al., 2009; DGH-[www.dghindia.org/15.aspx](http://www.dghindia.org/15.aspx)) revealed that the basement in the Laccadive Basin to the east of Laccadive Ridge is down-faulted corroborated by a low free air gravity anomaly in comparison to the ridge crest. To achieve a good fit between the observed and calculated values, it was necessary to include intrusives in the region characterized by high wavenumber anomalies (along NE–SW trends in Fig. 5a and b) in the model. The presence of these intrusives was modeled by using either densely spaced igneous–intrusive type sources or both flows and intrusions (Chaubey et al., 2002). The presence of volcanic flows along with intrusions was incorporated in the profile models A–A', B–B' and C–C' (Fig. 7) for a better fit. The locations for these intrusions were picked up from the free air gravity anomaly map (Fig. 3) and high pass filtered map (Fig. 5a) which enhanced the short wavelength anomaly sources. Profile D–D', appeared to be devoid of any significant volcanic intrusive; inclusion of intrusive caused an increase in the RMS error.

To further support the crustal structure derived from satellite derived gravity data and the presence of intrusives, an additional profile (GM profile) was selected from ship-borne gravity and magnetic data (obtained from NOAA/NGDC, Marine Track-line Geophysics data set). The location of the profile is shown in Figs. 3, 4, 6b. At first, for modeling gravity data, the densities used for the layers below the Laccadive Ridge and Arabian Basin were selected as the same values as those for the other four profiles. The location of intrusives were picked from the high pass filtered maps (Fig. 5a and b) and incorporated into the model. The crustal structure derived appeared similar to the other four profiles and the location of OCB derived from the crustal model (shown in Fig. 6b) matched well with that delineated from analytic signal (Fig. 4). For modeling the magnetic data, we started with the 2D crustal structure derived from gravity data and were guided by the method used by Anand et al. (2009) for modeling the 85 E Ridge; magnetic susceptibilities for the continent and ocean were taken as 0.035SI and 0.04SI respectively (Rajaram et al., 2009) while a value of 0.035SI was introduced for the intrusives. The lower crust below the Laccadive Ridge was devoid of remanence. The upper crust below the Laccadive Ridge was given a magnetic susceptibility of 0.03SI and magnetization of about ~3.2 (A/m) while the volcanic layer identified from the refraction seismic velocities (Naini and Talwani, 1982) above the Laccadive crust had a higher magnetization (5–6 A/m). For the oceanic crust we assumed a model of Kent et al. (1993) with higher magnetization (~5.8 A/m) in the extrusive upper layer and magnetization of ~1.1 A/m below the extrusive layer



**Fig. 5.** High-pass filtered maps of the free-air gravity anomaly of the Western Continental Margin of India with cut-off wavelength of (a) 50 km and (b) 100 km. In Fig. 5a white dashed lines demarcate the NE–SW trends observed and the off-shore extension of the NE–SW lineaments (observed within the Indian landmass) are shown as dashed black lines. Cln and BSZ represent Chapporo lineament and Bhavani shear zone and their offshore extension respectively. We have outlined the continental part of the Laccadive Ridge as deduced from the filtered maps.



**Fig. 6.** Low-pass filtered map of the free-air gravity anomaly of the Western Continental Margin of India with cut-off wavelength: (a) 80 km and (b) 100 km. The OCB as demarcated in Fig. 4 has been superposed in white. We have outlined the continental part of the Laccadive Ridge as deduced from the filtered maps. The proposed extension of the NE–SW Chapporo lineament (Cln) and Bhavani shear zone (BSZ) into the offshore area is also indicated by dashed line. In Fig. 6a we have superposed the bathymetry contours: 200 m (in green), 2000 m (in red) and 2500 m (in black). The location of the five profiles A–A', B–B', C–C', D–D' and G–M utilized for the 2D crustal model is superposed on Fig. 6b. The location of the OCB delineated from the modeled profiles is also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**  
Densities (obtained from Nafe–Drake curve) used for the various structures of the 2D gravity models.

Description	Velocity (km/s)	Density (kg/m <sup>3</sup> )
Sea water		1030
Sediments	1.76–3.7	2200
Chert	4.4	2450
Volcanics	5.5	2600
<i>Laccadive Ridge (L08V43)</i>		
U.C	6.3	2750
L.C	7.2	2950
<i>Arabian Basin (84C17)</i>		
Layer 2	5.5	2600
Layer 3	6.6	2850
Mantle	8.2	3300
SDR		2650
Intrusives		2800

which encompasses layer of sheeted dykes and gabbros. The intrusives within the Laccadive Ridge had a higher magnetization (~6–7 A/m) compared to the Laccadive crustal layers. The magnetizations were iteratively adjusted to minimize the error difference between the observed and calculated magnetic anomalies. The 2D combined gravity-magnetic model thus obtained with the minimum error is shown in Fig. 8 and the location of OCB delineated is marked in Fig. 6b.

The constrained best fit (with minimum RMS error) geologic model derived from free air gravity data, revealed the following subsurface structure. The Moho depth below the Laccadive Ridge varied from ~17 km to ~24 km along all the five profiles. It may be noted that the crustal thickness values and the densities used in the model for the Laccadive Ridge are representatives of continental crust. The Moho beneath oceanic crust appeared to vary from 8 to 11 km as one moved northwards from A–A' to D–D' (Fig. 7) with the crustal thickness below the sediments varying from 2 km to 5 km. The basic crustal layer structure appeared to be the same along all the profiles. The basement high structures observed at the eastern side of the Laccadive Ridge (in profile D–D'), can be interpreted as the Marginal high. The presence of Marginal highs was almost absent in the rest of the profiles A–A', B–B' and C–C' (Fig. 7). The oceanic crust–continental crust boundary was marked by an abrupt change in the free air gravity anomaly. The Moho depth also changes very rapidly suggesting a major change in the crustal structure. The Ocean Continent Boundary (OCB) delineated from the five modeled profiles matches reasonably well with the OCB deduced from the analytic signal map (superposed on Fig. 6b). Seaward Dipping Reflectors (SDR), having an average density of 2650 kg/m<sup>3</sup>, observed in seismic section (Ajay et al., 2010) was incorporated in the model for profiles A–A' and D–D', along the western flank of the Laccadive Ridge at an average depth of ~6.5 km which improved the final model fit. It may be noted that the OCB lies to the seaward side of the SDRs as observed by Corfield et al. (2010). The RMS error along profiles B–B' and C–C' increased on introducing SDR's along these profiles and hence was not included. Compared to the crustal model by Ajay et al. (2010) and Arora et al. (2012), the present modeling did not require any high density underplated material in the lower crust to obtain a best fit. Along profile D–D' a layer of chert of density 2450 kg/m<sup>3</sup> (velocity 4.4 km/s in L08V34) had to be introduced in the lower part of the sedimentary layer for obtaining a reasonable fit between the calculated model and the observation. The chert layer is seen in seismic section SK1207 (Chaubey et al., 2002).

#### 4. Results

High resolution Satellite derived Free Air Gravity (FAG) data has been analyzed to throw light on the evolution of different tectonic

elements associated with the WCMI with special emphasis on Laccadive Ridge. Wavelength filtering has been performed on the FAG anomaly map to isolate the sources at different depth levels and integrating this information with available geophysical data an attempt has been made to build the tectonic history of the WCMI. Different trends including NW–SE, NNW–SSE, NS & NE–SW and several high amplitude circular to semi-circular anomalies have been delineated in the study region. On isolating the anomalies using the wavelength filters, it is observed that within the Laccadive Ridge, NE–SW trends are seen at shallow to intermediate level while the deeper levels depict NS trend; within the shelf region NW–SE trends are seen at the deeper levels. This suggests that different tectonic evolutionary processes have taken place on the WCMI which finally resulted in the present structural configuration.

From the filtered anomaly maps, it appears that the shelf edge towards the north and south of Goa has different tectonic setup and has undergone varied evolutionary history. The continental shelf edge, roughly coinciding with 200 m isobaths, north of Goa is continuous and the continental shelf is wide within which lies the anomalous gravity low associated with the Mumbai high anticline (Fig. 3). The shelf edge to the north of Goa depicts continuous signatures with no breaks in the intermediate levels (Fig. 5b). This suggests that there was no major tectonic activity affecting the shelf edge, north of Goa, after its formation due to rifting of Madagascar and Seychelles from India. South of Goa, at the intermediate level (high pass 100 km) in Fig. 5b, the gravity anomaly high associated with the shelf edge is visible only between south of Goa and off Mahe. From the analysis it appears that the continental shelf in the region between south of Goa and off Mahe is an up lifted block compared to region south of Mahe, as there is no signature of the shelf edge either to the north or south. It is worth mentioning here that some of the wells drilled by oil exploration companies including ONGC encountered basaltic flows at a depth of 4.6 km near Cochin while the wells south of Goa encountered basalts at a depth of 3.2 km (Source: DGH, Directorate General of Hydrocarbons India <http://www.dghindia.org/15.aspx>). Thus it appears that onshore tectonics had an impact on the shallower continental shelf south of Goa. In the deeper levels (Fig. 6a and b), the shelf edge appears to be a continuous structure right up to 20°N.

The LR is demarcated from a combination of the bathymetry, 2D-crustal structure model and various filtered maps. We started with the 2000 m bathymetry for the outline of the LR; then from the 2D crustal structure model we delineated the east and west edges of the LR along the profiles. And then from the low pass filtered map (Fig. 6a) depicting the deep continental features, we marked the entire smoothed edge of the Laccadive Ridge. The Ridge thus delineated has been superposed on all the filtered maps. In the region occupied by Laccadive Ridge anomalies at all the different wavelength levels are observed. The shallowest (Fig. 5a) to intermediate wavelength (Fig. 5b) anomalies especially at the southern part of LR, trend in the NE–SW direction, originating at the western margin of the Laccadive Ridge and continue up to its eastern boundary. There is no evidence of these trends in the Laccadive Basin, shelf margin and the continental shelf. On comparison with the lineament map of Peninsular India (GSI, 2001) it is found that several NE–SW major and minor lineaments as well as shear zones cut across the Dharwar craton and Southern Granulite terrain. Some of these lineaments/shears redrawn from GSI (2001) along with their off shore extension into the Laccadive Ridge is shown in Fig. 5a. It is observed that most of the NE–SW trending anomalies seen over the Laccadive Ridge in the shallow and intermediate levels fall on the extended part of these onshore lineaments. It is possible that as Laccadive-India passed over the Reunion hotspot these pre-existing NE–SW faults got reactivated and acted as conduits for the upward movement of magma, that left its signature in form of intrusives into the Laccadive Ridge appearing as high amplitude, high to intermediate wavenumber anomalies in the FAG anomaly map. The semi circular high amplitude long wavelength anomaly seen within the Laccadive Ridge falls directly over the Padwa Bank. This anomaly is seen even in



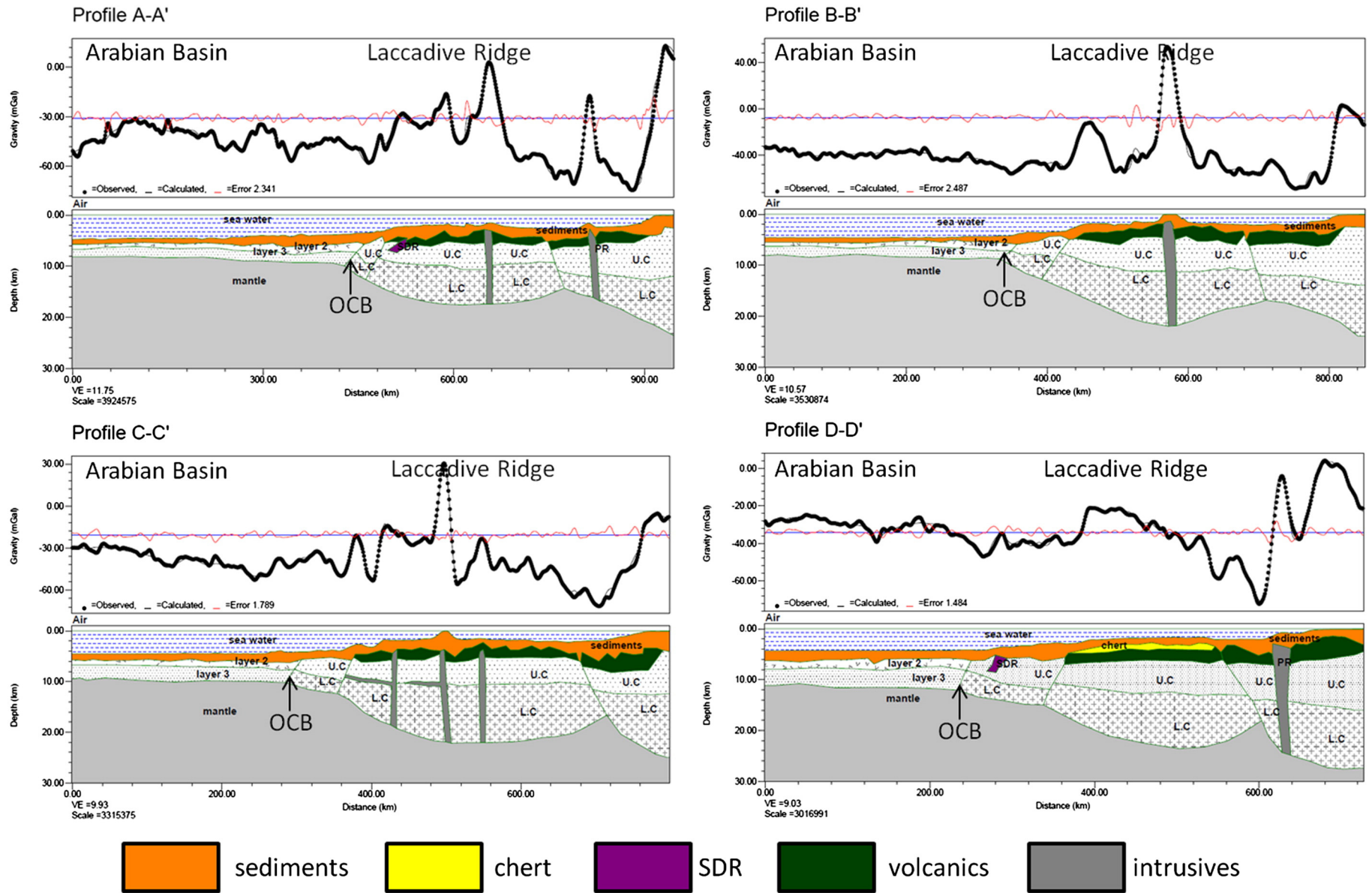
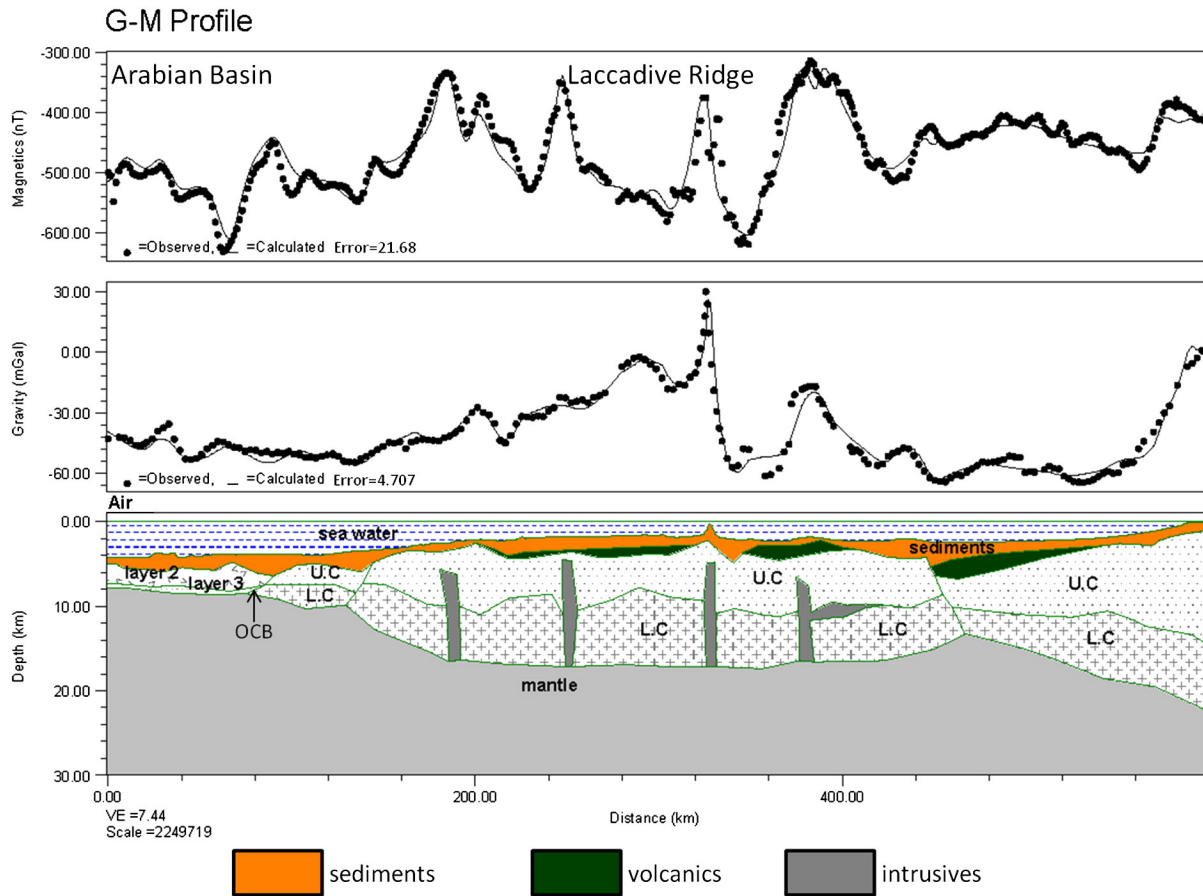


Fig. 7. Crustal model derived from the free air gravity data analysis along four profiles A-A', B-B', C-C' and D-D' respectively; location of the profiles is given in Figs. 3, and 6b. The water depths and sediment thickness have been obtained from the bathymetry and isopach maps. Dotted lines represent the observed while the full lines depict the calculated values and the thin red lines depict the errors. The assumed density used for the calculation is shown in Table 1. The inferred OCB is shown by a bold arrow in each profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 8.** Crustal model derived from the ship-borne gravity and magnetic data along profile G–M, location of the profile is given in Figs. 3, 4 and 6b. The water depths and sediment thickness have been obtained from the bathymetry and isopach maps. Dotted lines represent the observed while the full lines depict the calculated values. The assumed density used for the calculation is shown in Table 1. The inferred OCB is shown by a bold arrow in the profile.

high pass filtered map and may possibly be associated with intrusives. As the trend and nature of this intrusive is different from the earlier discussed intrusives having NE–SW trend, it is inferred that this may be related to an episode prior to the passage of India over the Reunion plume (possibly related to the Marion hotspot activity).

One of the most conspicuous features in the long wavelength map is the NW–SE to NS trending high on the Laccadive Ridge that was not evident in the shallow and intermediate depth levels. Also, these anomalies are not seen north of Goa and south of 8.5°N. From satellite imageries, GSI (2001) identified NE–SW trending lineament, Chapporo lineament (Cln) in the onshore region near Goa, and the Deccan traps are not found to the south of this lineament on land. The NE–SW trending Chapporo lineament represents a lithological contact between the trap flows towards to the north and the Archean greenstone and allied supracrustal rocks to the south (GSI, 2001). It appears that the offshore extension of this lineament is responsible for the termination of Laccadive Ridge south of Goa. Further, towards the south an apparent break of the NS trending high amplitude low wavenumber anomalies (Fig. 6a, b) can be identified. The NW–SE Moyar and the NE–SW trending Bhavani are the two inland major shear zones together with the Palghat–Cauvery Shear defining the boundary between the Dharwar craton and the Pandyan Mobile belt (Ramakrishnan and Vaidyanathan, 2008). If the NE–SW Bhavani shear is extended offshore it passes through the region where the long wavelength NS features associated with the Laccadive Ridge are terminated. Hence we believe that the Bhavani Shear forms the southern limit of the Laccadive Ridge. We believe that the LR to the north of this shear is continental in origin and to the south of this shear may probably be oceanic in nature with trace of the hotspots overlying it (Pushcharovsky, 1996,

2011). Thus from the present study we find that the Laccadive Ridge north of around 8.5°N is bounded by the offshore extension of the onshore lineaments viz. Chapporo lineament and the Bhavani Shear zone. We believe that the LR was a part of the Dharwar craton (Indian landmass) and the deeper features reflect these trends. It is worth mentioning that the NE–SW (Fig. 5a, b), NS/NW–SE (Fig. 6a, b) trends are not seen to the east or west of LR i.e. these signatures do not exist in the Laccadive basin, Shelf Margin basin and the Arabian basin but only on the LR.

## 5. Discussion

The present study attempts at resolving several apparent controversies existing in the understanding of the evolution of the Laccadive Ridge. Results obtained from both 2D forward modeling of the crustal structure and wavelength filtering suggests that the Laccadive Ridge north of around 8.5°N is continental in nature. Synthesizing the results obtained from the present analysis viz a) the NE–SW trending intrusives found associated with the Laccadive Ridge are formed as a result of the reactivation of the pre-existing faults as the Indian plate moved over the Reunion plume b) the Laccadive Ridge is constrained to lie within the offshore extension of Chapporo lineament and the Bhavani shear c) the main anomalies (deeper) associated with Laccadive Ridge are trending NS, it can be inferred that the Laccadive Ridge was a part of the Dharwar craton (NS to NW–SE is the typical Dharwarian trend) before it moved away. According to Mallik (2001) sedimentation history of the Laccadive Ridge suggests that the ridge was once close to Indian landmass or perhaps a part of the main landmass. We believe the LR was part of India and rifted

along with Madagascar from India in late Cretaceous (Yatheesh et al., 2006). Several wells drilled in the continental shelf region (DGH, <http://www.dghindia.org/15.aspx>) in the Kerala-Konkan basin have shown that basaltic flows of Late Cretaceous age (97.5 to 66 Ma) overlie the basement. The continental nature of the Laccadive Ridge (northern part of CLR) finds support from Pushcharovsky (1996, 2011); multi-channel seismic reflection studies (Chaubey et al., 2002; Ajay et al., 2010) and Moho depth of around 19 km from seismic refraction data (Naini and Talwani, 1982) in northern part of CLR indicate that Laccadive Ridge is of continental origin. It may be noted that the geological cross section from 10°S to 20°N constructed using DSDP and ODP well data (Verzhbitsky, 2003) in support of the oceanic origin of CLR, does not lie on LR but reflects data points that lie on the Maldives and Chagos sections of the CLR which are expected to be of oceanic origin (Pushcharovsky, 1996, 2011).

Further, from the 2D crustal structure we find that the shallow to intermediate wavelength NE–SW anomalies are caused by the intrusives related to the hot spot trace as India passed over the Reunion, during the Cretaceous–Tertiary Boundary. These volcanics are responsible for the observed magnetic signatures (Ben Avraham and Bunce, 1977). These volcanic rocks appear as intrusive and sill into the continental part of the LR as seen in our 2D model derived from both gravity and magnetic data; the location of these intrusives is possibly related to sites of pre-existing faults within the LR that got reactivated during the passage of India over the Reunion hotspot.

## 6. Conclusions

Several theories have been propounded for the tectonic evolution of the Laccadive Ridge based mainly on profile data analysis. In the present study, the tectonic evolution of the Laccadive Ridge has been deduced from an analysis of the 2D satellite derived free air gravity data and by utilizing wavelength filtering to resolve different depth structures representing different epochs. From such an analysis together with 2D modeling of the crustal structure it has been possible to identify:

- 1) the Ocean Continent Boundary for the whole region
- 2) the continental nature of the deeper layers of the Laccadive Ridge to the north of around 8.5°N constrained by the offshore extension of the Chapporo lineament to the north and the Bhavani shear to the south.
- 3) The Laccadive Ridge was part of the Dharwar craton (Indian land-mass) until the Cretaceous when it rifted from India along with Madagascar.
- 4) Shallow to intermediate wavelength NE–SW anomalies caused by intrusives related to the reactivation of pre-existing faults, as a result of the trace of the Reunion hotspot near the Cretaceous Tertiary Boundary.
- 5) The eastern and western boundaries of the Laccadive Ridge are faulted.

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