Did Madagascar and Seychelles Separate Simultaneously from India?

S.Rangarajan
KDM Institute of Petroleum Exploration, Oil & Natural Gas Corporation Ltd., Dehradun 248195 India.
E-mail: rangarajans_@hotmail.com

Summary

The controversial subject of Continent to Oceanic Boundary (COB) off the western continental margin of India is addressed through a study of gravity and magnetic data. Published free-air gravity and magnetic anomaly data along with a few regional scale magnetic anomaly profiles acquired by ONGC constitute the database for the study. Analysis of gravity data indicates that the COB is located near the shelf edge. A set of seafloor spreading-type lineations roughly parallel to the west coast and running along its entire length are observed in the composite magnetic anomaly map. Comparison with a simple synthetic seafloor spreading magnetic anomaly profile indicates that these lineations are probably generated by seafloor spreading just to the west of shelf edge. The study brings out a simple scheme of one-stage breakup of India from Madagascar and Seychelles starting from about 89 Ma without ridge jumps. Consequently, there is a necessity for re-examination of geological events hitherto associated with India's breakup from Gondwanaland.

Introduction

Continent to oceanic boundary (COB) in Eastern Arabian Sea has been a contentious issue for more than two decades. Based on bathymetry, gravity, magnetic and refraction seismic data, Naini and Talwani (1982) concluded that the area west of the imaginary curvilinear axis connecting Laxmi Ridge with Chagos-Laccadive Ridge (Fig. 1) is underlain by oceanic crust and proposed that the crust east of the axis is of intermediate type. However, Biswas and Singh (1988), on the basis of character of seismic reflections, proposed that the crust to the west of shelf is oceanic. Studying the geophysical data in the northwestern part of Eastern Arabian Sea, Miles and Roest (1993) inferred that India separated from Seychelles at 65 Ma and that the resultant COB is located just to the west of Laxmi Ridge. Bhattacharya et al. (1994) reported seafloor spreading-type magnetic anomaly lineations in Laxmi Basin and inferred them to indicate extinct seafloor spreading that was active from roughly about 84 Ma to 65 Ma. Malod et al. (1997) acquired magnetic and seismic data north of Laxmi Ridge and reported that the lineations continue northwest. They proposed that (i) there was a limited seafloor spreading between Laxmi Ridge and India around 89 Ma, (ii) the spreading ceased by 65 Ma and (iii) simultaneously breakup between Seychelles and India was initiated. Todal and Eldholm (1998), Talwani and Reif (1998), Radhakrishna et al. (2002) and Choubey et al. (2002) conducted gravity modeling studies constrained by velocity from refraction seismic data. While Todal and Eldholm (1998) and Choubey

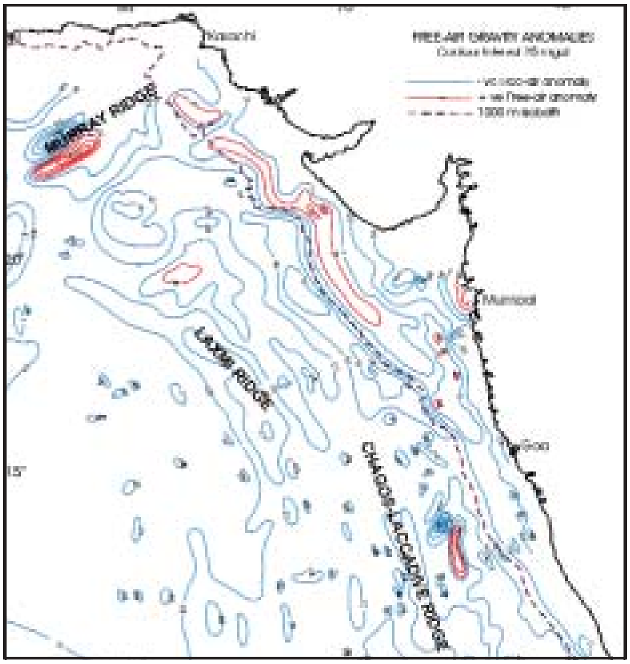

Fig.1. Free-air anomaly map of a part of Eastern Arabian Sea depicting the major morphological features (source: Naini & Talwani, 1982)

et al. (2002) inferred altered continental crust between Laxmi-Chagos-Laccadive ridges and shelf, Talwani and Reif (1998) and Radhakrishna et al. (2002) favored oceanic crust. The present study attempts to contribute to the issue through a study of Free-air gravity anomaly and magnetic anomaly data.

Characteristics of Continental and Oceanic crusts

Continental and oceanic crusts are characterized by distinct physical parameters. Continental crust is generally made up of a mélange of sedimentary, igneous and metamorphic rocks of about 35 km thickness. The thickness of oceanic crust is about 12 km and is dominantly made up of basic volcanics. The oceanic crust is considered to be made up of five layers namely, water, sediment, layer2, layer3 and mantle (Worzel, 1974). The average seismic velocity in layer 2 is about 5.12 km/sec and that in layer 3 is 6.7 km/sec. There exists a layer having velocity of 5.0 – 5.5 km/s at only a few kilometers beneath the surface layer of continental crust, which gives way to a layer with velocity 6.5-7.2 km/sec at about one third of the way to the mantle. The average density of continental crust is about 2.67 gm/cc while that of oceanic crust is about 2.85 gm/cc. The average magnetic susceptibility of continental crust is about 2.5×10^{-4} cgs units while that of oceanic crust is about 2.5×10^{-3} cgs units. In general, parameters for oceanic crust have higher magnitude than those of continental crust.

Characteristics off western continental margin of India

The Eastern Arabian Sea is characterized by negative free-air gravity anomaly (Fig. 1). Superposed on this regional negative field are relatively negative and positive linear anomaly features, ranging from about –75 to 50 mGal, parallel to the shelf edge. The shelf is characterized by positive anomalies, flanked on the west by negative anomaly features. The crestal region of Chagos-Laccadive ridge is characterized by relatively positive anomaly closures. Laxmi Ridge has a conspicuous NW-SE tending negative anomaly belt of about –25 mGal. Between this feature and the negative anomaly located over the continental slope and rise is a belt of NW-SE tending positive anomaly features.

Isostatic gravity anomaly in Eastern Arabian Sea ranges from less than -75 mGal to more than 25 mGal and the regional field is negative (Naini and Talwani, 1982). Superposed on this regional field are relative positive and negative anomaly features. An approximately N-S belt of relative positive and negative isostatic anomalies, south of 10ºN, are associated with the crest and flanks of the Chagos-Laccadive ridge. Belts of relative positive and negative anomalies are approximately parallel to the trend of the present day shelf. A negative isostatic anomaly belt of about 30 mGal, located between 14ºN to 19ºN and 65ºE to 69ºE, is coincident with the Laxmi ridge.

The average seismic velocity structure of the Eastern Arabian Sea is depicted in Fig. 2.

Analysis of Gravity and Magnetic Data

Gravity data:

Passive margins are characterized in general by free-air gravity highs over the shelf break, lows over the continental slope/raise, and in places, relative highs farther seaward. In addition, an isostatic gravity anomaly is usually present. These features are linked to the presence of oceanic crust adjacent to continental crust (Fig. 3). When such gravity anomaly features of shelf are associated with the onset of typical sequence of long wavelength – high amplitude magnetic anomalies, ocean-continent boundary is inferred thereat. Given the free-air and isostatic anomaly features described in the previous section, the COB off the

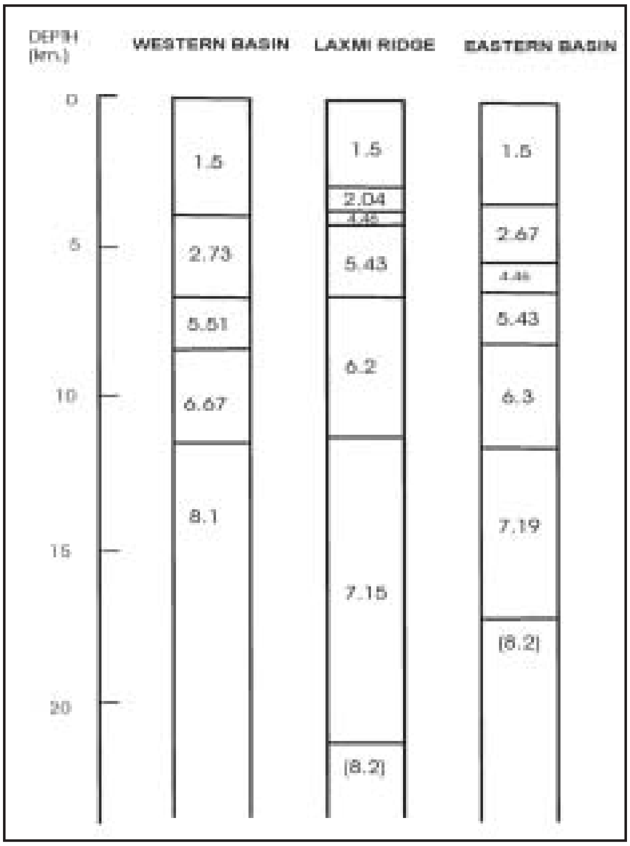

Fig. 2. The average crustal seismic velocity structure of Eastern Arabian Sea (source: Naini & Talwani, 1982)

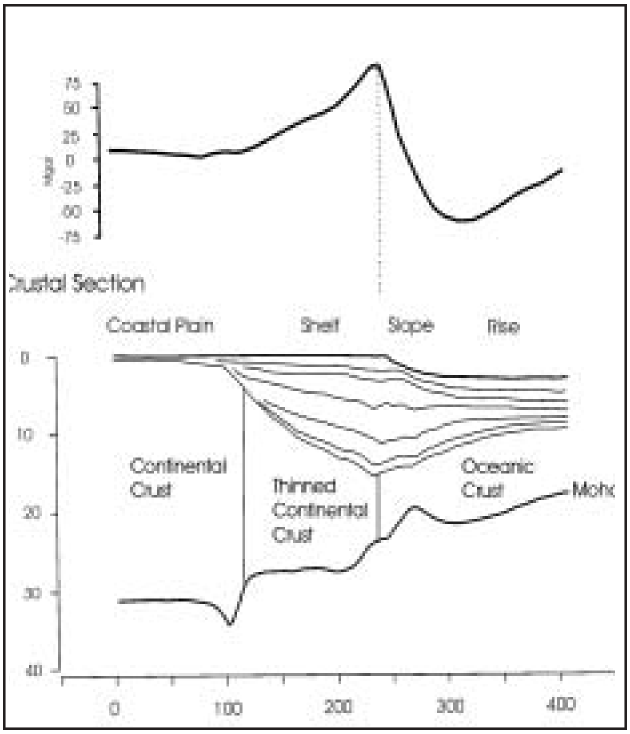

Fig. 3. The typical free-air gravity anomaly profile across a passive margin (adapted from Watts and Carr, 1995).

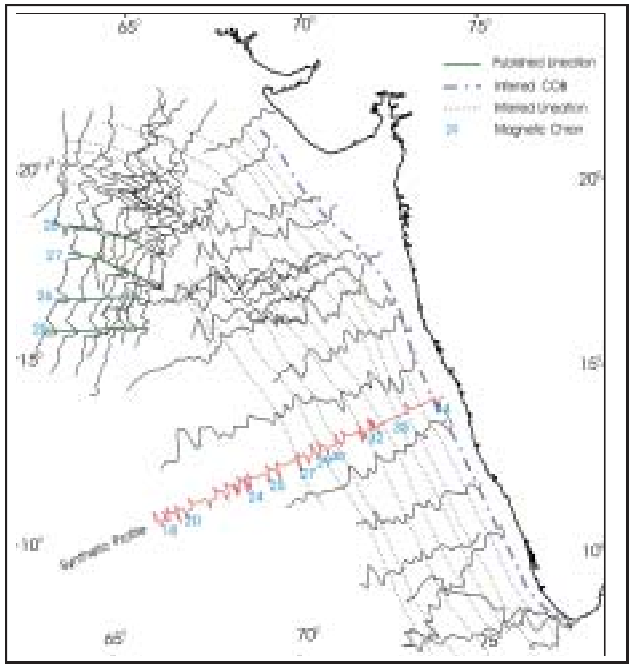

Fig. 4. The composite magnetic anomaly map of a part of Eastern Arabian Sea depicting selected profiles. The published lineation chrons are adapted from Miles & Roest, 1993). (sources: Naini & Talwani, 1982; Miles & Roest, 1993; Bhattacharya et al., 1994; Malod et al.., 1997)

westcoast of India should be near the shelf break. This is in conformity with studies in various passive margins, which show that COB is located near the shelf edge (Rabinowitz, 1982, Talwani and Eldholm, 1973; Watts and Marr, 1995, Rao et al., 1997).

As per plate tectonic models, a major part of the present-day peninsular coast of India was attached to the rather straight east coast of Madagascar prior to their separation around 84 Ma. Since the COB in eastern Madagascar is close to shelf edge (Schlich, 1982) and COB in the westcoast of India also is most likely to be near the shelf edge. Since COB is near the shelf edge, Laxmi Basin and Eastern Basin must be underlain by oceanic crust.

Magnetic data:

Fig. 4 shows the composite magnetic anomaly data in the Eastern Arabian Sea. The published magnetic anomaly profiles of Naini & Talwani (1982), Miles and Roest (1983), Bhattacharya et al. (1994) and Malod et al. (1997) and that acquired by ONGC along a few regional scale profiles in 1978-79 were digitized and re-scaled to a uniform level among the various publications. In order to avoid overcrowding in certain areas and for clarity in appearance, some of the profiles have been omitted. The figure shows many interesting features. There are a number of sub-parallel lineations starting just to the west of the shelf edge (1000 m isobath contour) continuing from latitude of 22° N up to the southernmost profile at the latitude of 8° N. The lineations are made up of long wavelength - high amplitude highs and lows and run almost parallel to the coastline. A group of them, in the middle of Laxmi Basin, brought out by Bhattacharya et al. (1994), particularly stand out. Rather, its recognition helps in the identification and correlation of the anomaly peaks and troughs on both sides in each profile. The westerly turn of the lineations north of latitude 19° is particularly noteworthy.

The anomaly corresponding to 65 Ma (Chron 29) (LaBrecque et al., 1977) is already established along the Laxmi Ridge and near the Chagos-Laccadive Ridge (Naini and Talwani, 1982; Malod et al., 1997). Hence the lineations between shelf edge and the Laxmi-Chagos-Laccadive ridge axis must correspond to the seafloor spreading episode preceding that corresponding to Chron 29. As per the presently accepted scheme of plate reconstruction between India and Madagascar, the two continental blocks broke apart at Chron 34 when the southern tips of the two continents were roughly coincident. The lineations corresponding to the range from Chron 34 to 29, which are already observed east of Madagascar (Schlich, 1982), should occur in that case between Laxmi-Chagos-Laccadive axis and shelf edge. To verify this proposition, a synthetic profile from Chron 18 to 34 was generated at latitude of 20° S with an azimuth of 215° (with a uniform spreading rate of 5 cm/yr). The resulting magnetic anomaly sequence is shown in Fig. 4. The anomaly sequence in the synthetic profile matches fairly well with the observed profiles in the figure, thus corroborating the hypothesis. It may be noticed that the characteristic sequence of Bhattacharya et al. (1994) discussed in earlier paragraph corresponds to the period from Chron 30 to 33. This indicates that the crust just to the west of shelf off the western continental margin of India has been generated by seafloor spreading. The earliest oceanic crust must have been emplaced around Chron 34, that is, about 89 Ma close to the shelf edge. This is in conformity with inference from gravity data that the COB is located near the shelf.

Discussion

The elongate Free-air anomaly high-low pair near the western continental shelf of India indicates that the COB is located near the shelf. It may, however, be argued that similar features, though not contiguous, also exist immediately to the west of Laxmi Ridge and Chagos-Laccadive Ridge. Given that the COB along the eastern margin of Madagascar is near its shelf edge, if the COB in the Eastern Arabian Sea were to be placed west of Laxmi-Laccadive Ridges, it would lead to an unacceptably exaggerated asymmetry. Such gross asymmetry among conjugate pairs of margins is not known.

Though Naini & Talwani (1982), Todal & Eldholm (1998), Choubey et al. (2002) and Radhakrishna et al. (2002) have argued against oceanic crust between Laxmi-Laccadive ridges and the shelf edge, it must be noted that their gravity and seismic velocity models indicate thinning of crust near the shelf. In order to distinguish this thinned crust from the continental crust and to avoid identifying it with oceanic crust, it was explained as intruded/modified/altered continental crust, attributing the alteration to the Reunion plume activity. This inference appears to have been influenced to a considerable extent by the presumed role of the Deccan Volcanism and Reunion Plume in the breakup of India from Gondwanaland. Once the magnetic anomaly of Chron 29, corresponding to the time of outpouring of Deccan Flood Basalts, has been identified near Laxmi-Laccadive ridge axis, it was but logical for them to infer the COB near the axis. However, it is now established that mantle plumes on their own can neither cause rift nor break continents (Ziegler, 1992; Zeyen et al., 1997). Rather, the concept of mantle plumes itself is doubted of late, with evidences building up against it (http://www.mantleplumes.org).

The seaward thinning of continental crust in a passive margin is required to facilitate the transition to the thinner oceanic crust. If there were no transition, there would neither be consistent crustal thinning along the shelf nor the resultant belt of linear free-air high-low anomaly pair. It is proposed that the shelf break itself is an expression of the transition from continental to oceanic crust in passive margins. It is a morphological manifestation of the isostatic adjustment between the two crustal units of grossly different density and thickness. The permanency of the coast and shelf features (Matmon et al., 2002) and the seismic activity near the shelf edge (Sykes, 1978) indicate the continual adjustments to the changes in the topography of the region due to sedimentary input, resultant loading etc, so that isostatic balance between the continental and oceanic crusts is maintained. In the process of maintaining the isostatic balance, the shelf break feature is also preserved. The presence of shelf break is thus a diagnostic feature of crustal transition in a passive margin. Though the variations in sediment influx might displace the shelf break over time, these movements are never far removed from the margin that had come into existence at or near the time of breakup. The beginning of seafloor spreading magnetic anomalies close to the shelf edge world over independently corroborates this.

The continuity of the lineations along the entire coastline of India from 8° N to 22° N implies that there was one continuous breakup along this stretch. This implies that Seychelles must have been separated from India along with Madagascar at around Chron 34. If there was a ridge jump at 65 Ma as believed till now, we would have had two different plate dynamic situations along the western continental margin: One in the south involving separation of Madagascar from India and another to its north involving limited spreading in Laxmi Basin. Then, a large transform fault would be necessary to separate these two separations with differing dynamics. Such a transform fault would need to be situated roughly perpendicular to the coast around Mumbai, corresponding to the northern tip of the coastline attached to Madagascar. This fault would have a characteristically strong linear signature on gravity like that of Murray ridge, Owen Fracture zone, Davies Fracture zone, etc (Bird, 2001). However, no such feature is seen in the free-air anomaly map (Fig. 1). Thus, the one-stage breakup of India involving its separation from Madagascar and Seychelles at Chron 34 across the Carlsberg Ridge is a valid proposition.

Probable Implications

This alternative scheme of plate tectonic evolution of Eastern Arabian Sea has many implications, some of which are: 1. The role of Reunion plume in the breakup of India appears to be untenable. 2. Till now, Cambay Basin was perceived to be a failed rift arm of a four-way junction formed due to the impingement of Reunion Plume near the junction of Narmada Rift with Cambay Rift, during the Late Cretaceous – Early Paleocene (Burke and Dewey, 1972; Biswas, 1982). Since seafloor spreading had already set in about 30 Myr prior to this time, the failed rift concept also appears invalid. This inference necessitates a re-examination of the genesis of Cambay Basin. 3. It may be noticed that the westerly turn in the anomaly lineations to the north of latitude 19ºN and the overall curved signature of Cambay Rift on gravity data look parallel or concentric. It appears that the two are still related, but not by the way of a failed rift concept. 4. The coeval separation of Madagascar and Seychelles from India logically necessitates a re-look at the plate tectonic evolution of Gondwana blocks and plate reconstructions.

Conclusions

1. The shelf break in passive margin is a manifestation of the transition from continental to oceanic crust and is diagnostic of the location of the transition.
2. Analysis of gravity and magnetic anomaly data indicate that the Continent-Oceanic boundary in Eastern Arabian Sea is located near the shelf edge. The crust to the west of shelf edge is oceanic in nature.
3. In terms of seafloor spreading, the oceanic crust must have been generated due to the breakup of India from Madagascar and Seychelles around magnetic Chron 34, that is, about 89 Ma.
4. Contrary to the existing concepts, the breakup and seafloor spreading appears to be one continuous event, with Laxmi Ridge as a continental block/sliver buoyant on oceanic crust. There is no necessity to invoke ridge jumps for the period from Chron 34 to the present.
5. This simple scheme of breakup of India from its western neighbors will necessitate a re-examination of the concepts and timings of various other geodynamic events related to the breakup. Of particular interest will be the genesis of Cambay Basin and reconstruction of the plate tectonic evolution of India and its western neighbors.

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