

Re-examination of geophysical data off Northwest India: Implications to the Late Cretaceous plate tectonics between India and Africa

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ABSTRACT

The Gop and Laxmi Basins lying off Northwest India have been assigned ambiguous crustal types and evolution mechanisms. The Chagos-Laccadive Ridge (CLR) complex lying along the southwest coast of India has been attributed different evolutionary processes. Late Cretaceous seafloor spreading between India and Africa formed the Mascarene Basin, and the plate reconstruction models depict unequal crustal accretion in this basin.

Re-interpretation of magnetic data in the Gop and Laxmi Basins suggests that the underlying oceanic crust was accreted contemporaneously from 79 Ma at slow half spreading rates (0.6 to 1.5 cm/yr) separating the Seychelles-Laxmi Ridge complex from India. The spreading ridge became extinct at 71 Ma in the central region between 19-20°N and 65.5-67°E, and at 68.7 Ma in the Gop Basin. Extinction progressed southwards with time until 64.1 Ma at ~14.5°N in the Laxmi Basin. This spreading probably limited the seafloor spreading in the northern Mascarene Basin, while normal to fast spreading continued in the south. The fracture zone FZ2 acted as a major boundary between the northern and southern Mascarene Basin, and may have also restricted the southward propagation of the Laxmi Basin spreading ridge.

Plate reconstruction models generated in this study accommodate several microplates between Madagascar and India, and trace their movements over time within the India-Africa spreading corridor. Furthermore, these models suggest the formation of the Seychelles-Laxmi Ridge microplate by 79 Ma in a complex three plate system. This microplate may have existed up to 64.1 Ma and experienced an anticlockwise rotation of about 50°. Under the influence of the Deccan hotspot activity, the Laxmi Basin spreading ridge jumped southwestward splitting the Seychelles-Laxmi Ridge complex and initiating the Carlsberg Ridge. The presence of about 160 km of oceanic crust in the Gop and Laxmi Basins partially reduces the space problem faced in the earlier plate reconstruction models.

Keywords: West coast of India, Mascarene Basin, Laxmi Ridge, Seychelles, plate reconstructions, magnetic anomalies, Gop Basin

1. Introduction

The Western Continental Margin of India is characterized by i) a remarkably straight shelf edge limited by ~200 m isobath, ii) NW-SE trending continental shelf, ~300 km wide off Mumbai narrowing gradually southward to ~50 km off Cochin, iii) continental slope bounded between 200 and 2000 m isobaths, narrow in the north and wide towards south iv) deep sedimentary basins, and v) several structural features (Fig. 1). The shelf area is composed of four offshore basins, i.e. Kutch, Saurashtra, Bombay and Konkan-Kerala (Fig. 2), characterized by horst-graben structures (Biswas, 1987). The major structural features include the midshelf high, Pratap Ridge complex (Naini, 1980; Subrahmanyam et al., 1995), aseismic Laxmi Ridge (Naini and Talwani, 1982) and the Chagos-Laccadive Ridge (CLR) System (Duncan, 1990). The deep-water sedimentary basins include the Western and Eastern Arabian Basins separated by the Laxmi and northern CLR Ridges. The extensions of the onshore structural lineaments such as the Precambrian Dharwarian trends into the Western Continental Margin of India have been delineated (Naini, 1980; Kolla and Coumes, 1990). The Narmada-Son lineament, an old Precambrian feature (Powar, 1981) was reactivated in the Late Cretaceous. During its initial marine sedimentation stage, regional uplift caused by Deccan volcanism abruptly ended its activity resulting in a failed rift (Biswas, 1988).

The Western Arabian Basin is bounded to the west by the Owen Fracture Zone, to the south by the NW-SE trending active Carlsberg Ridge and, to the north and east by the Laxmi and CLR Ridges respectively (Fig. 1). The underlying basement is oceanic associated with oldest seafloor spreading magnetic anomalies decreasing in age from anomaly 28n in the north to 22 in the south (Mckenzie and Sclater, 1971; Naini and Talwani, 1982; Miles and Roest, 1993; Dymant, 1998; Chaubey et al., 2002a; Royer et al., 2002; Collier et al., 2008). The Eastern Arabian Basin lying between the eastern end of the Laxmi and northern CLR Ridges and the adjacent continental slope of India consists of the Laxmi and Laccadive Basins (Fig. 2). The Pratap Ridge composed of a chain of shallow basement highs along the western offshore has been related to Deccan-Reunion hotspot activity (Krishna et al., 1992), and rifting between India and Madagascar (Subrahmanyam et al., 1995).

2. Morpho-tectonic Features

The approximately N-S trending CLR system is a positive topographic feature extending from about 10°S to 15°N (Fig. 1). The ridge consists of several irregular blocks separated by relatively deep east-west trending channels and a considerable length of its crest is composed of shoals, banks, coral reefs and atolls. The free-air gravity signature is positive (~25 mGal) when compared with that of the surrounding regions (Kahle and Talwani, 1973; Naini and Talwani, 1982). The origin of the CLR system is attributed to various processes such as transform faulting (McKenzie and Sclater, 1971), microcontinent tectonics (Avraham and Bunce, 1977) and hotspot volcanism (Dietz and

Holden, 1970; Whitmarsh, 1974). Based on crustal structure and lack of appreciable magnetic anomalies, Naini and Talwani (1982) and Gopala Rao et al. (1987) favored a continental origin for this ridge. DSDP and ODP drilling suggest that the Deccan Trap province on the Indian peninsula and the CLR system were formed by volcanic activity during the northward motion of the Indian plate over the Reunion hotspot (Duncan, 1990). The CLR system can be divided into the northern Laccadive Ridge, the middle Maldives block and southern Chagos Bank. The northern Laccadive Ridge is bounded by the offshore extensions of the onshore lineaments- Chapporo and Bhavani Shear zones (Fig. 2), and is associated with deep N-S to NW-SE Dharwarian trends (GSI, 2001; Nair et al., 2013). Different opinions prevail on the nature and origin of the Laccadive Ridge. It is considered as a continental sliver (Naini and Talwani (1982), alternately it is attributed to hotspot volcanism (Biswas, 1988). Chaubey et al. (2002b, 2008) suggested that the Laccadive Ridge is a thinned continental fragment intermingled with volcanic intrusives and locally compensated according to the Airy model of isostasy (Ajay et al., 2010).

The NW-SE trending Laxmi Ridge located 300 km off the west coast of India has an average water depth of about 2.8 km (Fig. 2). It is an aseismic basement high with a relief of about 2 km and mainly buried under thin sediment cover. Contrary to its positive topography, the ridge is associated with a broad negative free-air gravity anomaly (-50 mGal). Based on its characteristic gravity low and adjacent magnetic signature, it veers in a nearly E-W direction at about 19°N (Naini and Talwani, 1982; Miles and Roest, 1993; Malod et al., 1997). It has been inferred to be a continental sliver (Naini and Talwani, 1982; Talwani and Reif, 1998). Todal and Eldholm (1998) suggested that the Laxmi Ridge is a partly isostatically compensated marginal high, with an inner component underlain by faulted continental blocks and an outer component of oceanic crust. Lower crustal high velocities observed beneath the Laxmi Ridge indicate that the ridge is a heavily intruded thinned continental block (Minshull et al., 2008). The crust of the ridge is 9-16 km thick and can be considered to be thinned continental crust of Neoproterozoic age juxtaposed to Seychelles and Malani province of India (Torsvik et al., 2013). Using high resolution, deep seismic data Misra et al. (2015) suggested that the Laxmi Ridge is composed of oceanic crust and acted as a fossil spreading centre.

2.1 Laxmi and Gop Basins

The Laxmi Basin lying between the west coast of India and the Laxmi Ridge, north of the CLR system has water depths of 3000 to 4000 m (Fig. 2). The underlying crust was found to be thicker than normal oceanic crust, but thinner than normal continental crust (Naini and Talwani, 1982) hence it was inferred to be transitional crust formed during the initial phase of rifting. Furthermore, Talwani and Reif (1998) advocated that the Laxmi Basin crust is "initial oceanic crust" similar to the crust underlying the US East Coast margin (Talwani et al., 1995). Identification of seafloor spreading marine magnetic anomalies in the Laxmi Basin prompted Bhattacharya et al. (1994a) to

suggest that the underlying crust is oceanic. Distinctive characteristics of oceanic crust with seaward dipping reflectors on either side were noted in the 160 km wide Laxmi Basin (Corfield et al., 2010). The observed high velocity (>7 km/s) layer beneath the Laxmi Basin was attributed to underplating of the thinned continental crust (Miles et al., 1998; Radhakrishna et al., 2002). The crust underlying the Laxmi Basin was considered as extended continental based on irregular basement relief as well as indications of rotated fault blocks (Todal and Eldholm, 1998) and 3-D modeling of gravity anomalies (Arora et al., 2012). The high amplitude magnetic anomalies in the Laxmi Basin were attributed to the presence of intrusive bodies (Krishna et al., 2006).

The magnetic lineations in the Laxmi Basin were found to be symmetric about a central negative magnetic anomaly and were identified as chrons 28-33 with half spreading rates of <1 cm/yr (Bhattacharya et al., 1994a). The central anomaly associated with a gravity low and a linear seamount chain was considered as an extinct spreading ridge (Bhattacharya et al., 1994b). Todal and Eldholm (1998) inferred fan shaped seafloor spreading in the southern Laxmi Basin based on the identification of magnetic anomalies 31 and younger. Furthermore, Eagles and Wibisono (2013) suggested that the magnetic anomalies in the Laxmi Basin could be a two-sided sequence of chrons 29-28-29 indicating fast half spreading rates of ~8.5 cm/yr consistent with those in the Mascarene Basin.

Magnetic analysis in the Gop Rift or Basin (we use the term 'Basin' henceforth) indicated the presence of three positive lineations related to oceanic spreading (Malod et al., 1997). The central negative anomaly of 29n flanked by two positive 29r anomalies in the Gop Basin were correlated with those inferred by Bhattacharya et al. (1994a) in the Laxmi Basin. Fan shaped seafloor spreading was inferred in the Gop Basin based on the identification of magnetic anomalies 31 and younger (Todal and Eldholm, 1998). Seismic reflection and magnetic data suggested that the center of the ~120 km wide Gop Basin is a reversely magnetized extinct spreading ridge (Collier et al., 2008). They proposed that the central anomaly could be 28r, 29r or 31r, but their preferred magnetic model for the three-polarity sequence (RNR) symmetric about the extinct spreading ridge is 31r-32n.1n-32n.1r with high half spreading rates of 6.8 cm/yr.

Yatheesh et al. (2009) inferred the presence of oceanic crust in the Gop Basin with the reversely magnetized Palitana Ridge as the extinct spreading ridge. Two models were inferred depicting symmetric magnetic anomaly sequence of 31r-25r or 29r-25r. The first model has a low half spreading rate of <0.6 cm/yr and indicates that seafloor spreading began prior to the Deccan Trap emplacement and these two events are unrelated. The second model has a high half spreading rate of 3 cm/yr and suggests seafloor spreading started at the time of the Deccan Trap emplacement. Thus, there is no consensus on the timing and mode of evolution of the crust in the Gop and Laxmi Basins until date.

A ~200°C hot, 50 km thick mantle layer was inferred using seismic constraints below the Gop Basin when seafloor spreading initiated at 71 Ma (Armitage et al., 2011) emplacing up to 12 km of igneous material beneath the Indian subcontinent, Laxmi Ridge and Seychelles Bank, and generating ~9 km thick oceanic crust (Minshull et al., 2008). Recent crustal studies using gravity inversion indicate that the Laxmi Basin crust is 5-7 km thick and the crust beneath the extinct spreading ridge up to 9 km thick (Torsvik et al., 2013).

2.2 Mascarene Basin and Seychelles-Mascarene Plateau

The Mascarene Basin lying between Madagascar and the Seychelles-Mascarene Plateau (Fig. 1) has formed due to the separation of India from Africa-Madagascar between 83.5 and 61 Ma (Norton and Sclater, 1979; Schlich, 1982; Masson, 1984; Dyment, 1991; Plummer and Belle, 1995; Storey et al., 1995; Lawyer et al., 1998; Bernard and Munsch, 2000). Hence, the evolutionary history in time and space, and tectonics of this basin are relevant to the present study. The oldest magnetic anomaly 34 lies within 50 km and subparallel to the Madagascar coast. Magnetic anomalies ranging from 34 to 30 are observed in the north of the basin off Madagascar, while a symmetric sequence of anomalies 34 to 27 is observed in the south (Dyment, 1991; Bernard and Munsch, 2000). NE-SW trending fracture zones offset these magnetic lineations depicting the direction of spreading. A series of southward progressing ridge jumps caused seafloor spreading to stop in the Mascarene Basin and transferred the Seychelles-Mascarene Plateau complex to the Africa-Madagascar plate. The northern Mascarene Basin has a prominent NNW-striking bathymetric feature, the Amirante Arc, with a trough along its median valley (Fisher et al., 1968; Miles, 1982; Mart, 1988). Furthermore, the northern basin has a width of about 500 km less than the southern basin (Masson, 1984). A transtensional boundary between the eastern and western Mascarene Basins has been inferred based on plate reconstruction models (Talwani and Reif, 1998).

The Seychelles –Mascarene Plateau is an arc of wide, isolated shallow banks and small islands between Madagascar and the Carlsberg-Central Indian Ridges (Fig. 1). It consists of the Amirante Arc, Seychelles Bank, Mascarene Plateau (Saya de Malha Bank, Nazareth Bank, Cargados Carajos Bank), and Mauritius and Reunion Islands (Fisher et al., 1968). The topographic continuity of this plateau complex is interrupted by several deep saddles and channels. The Seychelles-Mascarene Plateau was suggested to form the continental conjugate to eastern Madagascar and isolated by ridge jumps or propagation events associated with the Deccan volcanism (Francis and Shor, 1966; Plummer and Belle, 1995; Muller et al., 2001; Torsvik et al., 2013). The Seychelles Bank has been identified as a continental fragment (Besse and Courtillot, 1988; Torsvik et al., 2001; Collier et al., 2009) which has experienced rotation as an independent plate (Cande et al., 2010; Ganerod et al., 2011; Eagles and Hoang, 2013). Rapid anticlockwise rotation of the Seychelles plate began around 64 Ma and stopped at 59 Ma when the spreading ridge in the Mascarene Basin became extinct (Eagles and Hoang, 2013). The Seychelles Bank is underlain by 32 km thick continental crust

having a thin oceanic crust on its northern margin (Collier et al., 2009). The presence of a layer of lower crustal intrusions beneath Seychelles suggests that it lay at the edge of the Reunion plume during the emplacement of the Deccan Traps (Hammond et al., 2013).

The narrow, arcuate Amirante Arc is bounded to the west and south by the Amirante Trough and to the east by the Amirante Basin (Mart, 1988). Francis and Shor (1966) proposed that the Amirante Basin is underlain by intermediate crust, while Miles (1982) suggested the crust to be continental. The age of the tholeiitic basalts (82 Ma) of the Amirante Arc (Fisher et al., 1968) is compatible with the age of the oldest magnetic anomaly 34 found in the Mascarene Basin (Masson, 1984). Miles (1982) further suggested that the Amirante Arc is a zone of minor compression/limited subduction. Recently, a continental sliver has been recognized beneath the northern Amirante Arc (Hammond et al., 2013).

The Saya de Malha, Nazareth and Cargados Carajos Banks comprising the Mascarene Plateau have shallow bathymetry with coral reefs and steep scarps. The Saya de Malha Bank is considered either as a submerged southeastward extension of the Seychelles microcontinent (Mckenzie and Sclater, 1971) or a volcanic platform formed due to Deccan volcanism (Courtillot et al., 1986). Furthermore, the Saya de Malha Bank is considered conjugate to the Chagos Bank, the southern part of the CLR system (Mckenzie and Sclater, 1971). Drilling results at various locations on the Mascarene Plateau indicate the presence of basalts below the carbonate rocks (Duncan and Hargraves, 1990). Thus, the Mascarene Plateau along with CLR has been formed due to volcanic activity of the Reunion hotspot (Duncan, 1990). Recent crustal studies suggest that Mauritius too has anomalously thick crust of up to 30 km and may belong to a Precambrian microcontinent termed Mauritia (Torsvik et al., 2013).

Thus there are several tectonic features involved in the Late Cretaceous to Early Cenozoic breakup and seafloor spreading between India and Africa. In the present study, the geophysical datasets were re-examined to ascertain the exact nature, age and evolution of the underlying crust in the Laxmi and Gop Basins. Plate reconstruction models for different chrons were generated to validate our results and establish the evolutionary and tectonic history between India and Africa.

3. Data and Methodology

Magnetic data along 17 profiles amounting to 8500 km in the Laxmi and Gop Basins were extracted from the NIO and NGDC (Colorado) databases (Fig. 3). The magnetic anomalies were initially identified along the key profiles using the synthetic seafloor spreading modeling technique and the geomagnetic polarity time scale of Gradstein et al., (2004). Synthetic seafloor spreading models were generated assuming the source layer of 500 m thickness is located ~1.5 km below the seabed. This depth to the source layer is deduced from the seismic profiles published in the Gop Basin (Malod et al., 1997) and Laxmi Basin (Krishna et al., 2006). It is noted here that the identifications

may be influenced by the unknown basement topography due to limited seismic data in these basins. A mostly good correlation between the observed magnetic anomalies and synthetic models facilitated the identification of the magnetic anomalies and inference of half spreading rates (Fig. 4). A central anomaly is seen bounded by symmetric magnetic anomalies and associated with a gravity low. A gravity low which cannot be explained by the gravity effect of the topography and its compensation, may result from the presence of a rift valley and may represent an extinct spreading ridge. Thus the central anomaly characterized by a gravity low was considered as an extinct spreading ridge. For example, the extinct spreading ridge in Labrador Sea (Kristofersen and Talwani, 1977). Further, the magnetic anomaly identification process was carried out for all the profiles (Fig. 5). The identified magnetic anomalies were then plotted onto the track map and the age of the underlying oceanic crust was deduced (Fig. 6). Fracture zones were inferred based on the offset in the anomalies, while their trend was deduced using the satellite gravity map (Sandwell and Smith, 2009). Likewise, the boundaries of the gravity low separating the older and younger regions were inferred using the satellite gravity map. The likely seaward edge of the continent-ocean transition is assumed based on the major variation in the gravity values and inferred crustal thickness (Torsvik et al., 2013).

A series of regional plate reconstruction models were generated to explain the evolution of the Gop and Laxmi Basins off Northwest India (Fig. 7, Table 1) using the GPlates software (Boyden et al., 2011) based on the East Gondwana breakup models (Gibbons et al., 2013). The magnetic anomaly identifications and fracture zones inferred in this study together with the published results in the Mascarene Basin (Bernard and Munsch, 2000), Eastern Somali Basin and Western Arabian Basin (Collier et al., 2008) were used to recalculate the rotation poles keeping Africa and Madagascar in their present day position. The Laccadive Ridge, Saya de Malha Bank and Laxmi Ridge were considered as continental slivers in addition to the Seychelles, and restored to their paleopositions to propose a plausible plate kinematic scenario.

Since the initial breakup between Madagascar and Seychelles-India occurred during Turonian time (88.5-91 Ma; Torsvik et al., 2000), the pre-breakup scenario was generated at 90 Ma and compared with the published models (Gibbons et al., 2013). This model (Fig. 7a) is constrained by the tight fit between the Trivandrum terrace and the bight in Madagascar Ridge (Yatheesh et al., 2006). The location of the Seychelles along with the Laxmi Ridge was based on the models of Plummer and Belle (1995). The identifications of the magnetic anomaly 34 off eastern Madagascar together with the fracture zone trends (Bernard and Munsch, 2000) constrained the 84 Ma reconstruction (Fig. 7b), and this model was compared to the earlier models (Yatheesh et al., 2006; Calves et al., 2011; Torsvik et al., 2013). The magnetic anomaly identifications 33r and 31r on either side of the spreading center in the Mascarene Basin together with our identifications in the Gop and Laxmi Basins tightly constrained the 79 Ma and 68.7 Ma reconstructions respectively (Fig. 7c & d). The

63.1 and 58.4 Ma reconstructions were built with magnetic anomaly constraints 28n and 26n respectively in the Eastern Somali Basin and Western Arabian Basin (Collier et al., 2008) in addition to the magnetic anomalies 30 to 27 in the Mascarene Basin (Fig. 7e & f).

Integrated analysis of the geophysical dataset indicated contemporaneous seafloor spreading in the Laxmi and Gop Basins from 79 to 64.1 Ma. The extinction of seafloor spreading got younger from 71 to 64.1 Ma southwards and to 68.7 Ma westwards. Plate reconstruction models generated in this study accommodated several microplates between Madagascar and India, and demonstrated that the oceanic crust in the Gop and Laxmi Basins partly reduces the space problem faced by the earlier models.

4. Results

4.1 Magnetic analysis

Detailed magnetic analysis using synthetic seafloor spreading modeling technique facilitated the identification of magnetic anomalies, fracture zones and an extinct spreading ridge in the Gop and Laxmi Basins, off Northwest India (Figs. 3 to 6). A symmetric magnetic anomaly pattern about a central anomaly was observed on all of the profiles. The central anomaly was associated with a typical gravity low prompting us to infer the presence of an extinct spreading ridge. Along some profiles, a high is seen within the gravity low which is associated with positive bathymetry. Similar extinct spreading ridges are reported in Labrador Sea (Kristoffersen and Talwani, 1977), Norway Basin (Talwani and Eldholm, 1977) and Coral Sea Basin (Weissel and Watts, 1979). Extinct spreading ridges have been inferred in the Laxmi and Gop Basins earlier (Bhattacharya et al., 1994a; Collier et al., 2008; Yatheesh et al., 2009).

The mostly good correlation between the observed and synthetic anomalies aided in identifying the magnetic anomalies along the key profiles (Fig. 4). These identifications were then extended to all the profiles with sufficient clarity (Fig. 5). The magnetic anomaly location map (Fig. 6) revealed anomaly 33r (79 Ma) as the oldest anomaly along all of the northern profiles (north of 17°N). The synthetic models facilitated the identification of symmetric magnetic anomalies from 33r about a central anomaly 32n (71 Ma) in the region between 19-20°N and 65.5-67°E. Furthermore, symmetric magnetic anomalies from 33r to 31r (68.7 Ma) were identified in the Gop Basin, while conjugate magnetic anomalies from 33r about a central anomaly having an age from 31r up to 28r (64.1 Ma) were inferred in the Laxmi Basin north of 14.5°N. The region south of 14.5°N (profile rc1707-e; Fig. 6) is highly disturbed and no seafloor spreading magnetic anomalies could be identified.

The models further indicated that the oceanic crust in the Gop and Laxmi Basins was initially created with a low half spreading rate of ~0.6 cm/yr from anomaly 33r to 32n. Thereafter, slow seafloor spreading at a half spreading rate of 0.8 cm/yr occurred in the central region until spreading

ceased at anomaly 32n (profile 1902-a; Fig. 4). In the Gop Basin, the half spreading rates increased to 1.1 cm/yr until spreading ceased at anomaly 31r, while in the Laxmi Basin, the half spreading rates gradually increased to 1.5 cm/yr until spreading ceased at anomaly 28r (Fig. 4).

A number of fracture zones were inferred, of which FZA and FZB appear to be the dominant ones. They not only offset the anomalies, but also demarcate the central region (19-20°N and 65.5-67°E) having the earliest extinction time (71 Ma). The extinction of seafloor spreading progressed towards the west from 71 to 68.7 Ma in the Gop Basin (Fig. 6). South of FZB, spreading ceased progressively southwards from 71 to 64.1 Ma in the Laxmi Basin. Thus different ages of extinction of the spreading ridge are inferred off Northwest India.

4.2 Plate reconstruction models

Plate reconstruction models for different ages (90, 84, 79, 68.7, 63.1 and 58.4 Ma) revealed a complex evolutionary history of the India-Africa spreading corridor (Fig. 7, Table 1). Initial fit conditions at 90 Ma constrained by the Trivandrum terrace and bight in Madagascar Ridge (Yatheesh et al., 2006) allowed the placement of a number of microplates -Seychelles (S); Laxmi Ridge (LR); Saya de Malha Bank (SMB); Laccadive Ridge (LaR) between Madagascar and India (Fig. 7a). These microplates belong/are in addition to the Seychelles-Mascarene Plateau which is considered to form the continental conjugate to eastern Madagascar (Francis and Shor, 1966; Plummer and Belle, 1995; Muller et al., 2001; Torsvik et al., 2013). This model also preserved the alignment of the Wallaby-Zenith Fracture Zone with the northern extent of Greater India, and that of the fracture zones west of Madagascar with those in the Dronning Maud Land, off Antarctica (Gibbons et al., 2013).

The 84 Ma reconstruction depicts that seafloor spreading was initiated and progressed obliquely in an ~NW-SE direction in a two plate (Africa-Madagascar and India-Seychelles-Laxmi Ridge-Saya de Malha Bank-Laccadive Ridge) system (Fig. 7b). All the microplates remained attached to the Indian subcontinent. The model also matched the anomaly 34 identifications in the Central Indian Ocean Basin and Enderby Basin (Gibbons et al., 2013). The 79 Ma reconstruction model (Fig. 7c) depicts nearly symmetric seafloor spreading in the Mascarene Basin. The occurrence of anomaly 33r in the Gop and Laxmi Basins indicates the opening of these basins. Thus, by 79 Ma, with the Seychelles-Laxmi Ridge complex separating from India, a three plate system was initiated. The Seychelles-Laxmi Ridge complex behaved as a microplate while Saya de Malha Bank and Laccadive Ridge remained attached to India.

The 68.7 Ma reconstruction model (Fig. 7d) suggests simultaneous seafloor spreading occurred in the Mascarene Basin, and the Laxmi and Gop Basins. The unequal width of oceanic crust generated in the northern (~820 km) and southern (~1050 km) Mascarene Basin suggests that seafloor spreading was restricted in the northern Mascarene Basin, while unhindered spreading

continued in southern Mascarene Basin. Saya de Malha Bank and Laccadive Ridge still remained attached to India.

The 63.1 Ma reconstruction depicts a complex tectonic scenario probably caused by the arrival of the Deccan hotspot (Fig. 7e). By 65.8 Ma, seafloor spreading had stopped in the northern Mascarene Basin, but spreading continued in the south. Furthermore, seafloor spreading stopped in the Laxmi Basin by 64.1 Ma, and the spreading center jumped southwest splitting the Seychelles-Laccadive Ridge microplate to form the nascent Carlsberg Ridge. The Laxmi Ridge was transferred to the Indian plate and the Seychelles to the African plate. The model allows the presence of the Amirante Ridge unlike the earlier ones indicating that it may have formed by this time. The model further suggests that the Saya de Malha Bank has separated from the Indian plate.

The 58.4 Ma reconstruction depicts the extinction of seafloor spreading in the southern Mascarene Basin. Saya de Malha Bank merged with the Africa-Madagascar plate while Laccadive Ridge remained attached to the Indian Plate and may have drifted to its present day position only after Saya de Malha Bank moved away from it. The Carlsberg Ridge became the dominant spreading ridge and the India-Africa spreading once again became a two plate system (Fig. 7f). The Mascarene Plateau may have emplaced by this time as indicated by the drilling results (Duncan and Hargraves, 1990). This reconstruction depicts a two plate system with all the microplates in their ultimate positions (Laxmi and Laccadive Ridges in the present day position relative to India, and the Seychelles-Mascarene Plateau-Saya de Malha Bank relative to Africa-Madagascar, Fig. 7f).

5. Discussion

The present study suggests that seafloor spreading started contemporaneously in the Gop and Laxmi Basins by 79 Ma and progressed at half spreading rates of 0.6 to 1.5 cm/yr (Fig. 4). Seafloor spreading began to stop at 71 Ma at the junction between the Gop and Laxmi Basins (Fig. 6). This Central region between fracture zones FZA and FZB probably represents the location of a RRR type triple junction at that time. A similar triple junction connecting the Laxmi Basin, Narmada-Son lineament and the Gop Basin prior to chron 28 has been proposed by Malod et al. (1997) and Yatheesh et al. (2009). The extinction progressed with time from the Central region at 71 Ma, westwards to 68.7 Ma in the Gop Basin and southwards to 64.1 Ma in the Laxmi Basin. It is interesting to note that our opening and extinction timings for the Laxmi and Gop Basins differ significantly from the numerous variable timings inferred earlier (Table 2).

The extinct spreading ridge inferred in this study in the Gop Basin is the same as inferred by Collier et al. (2008) and has a positive anomaly, i.e. reversely magnetized. Their favored model assigned the central anomaly as 31r and the oldest identified anomaly as 32n.1r with high half spreading rates of 6.8 cm/yr. Further, the presence of an axial high rather than an axial valley along their transect corroborates with these high spreading rates. We have also assigned our central anomaly

as 31r but preferred our oldest identification to be 33r. Thus our spreading rates are lower (<1.1 cm/yr) and the oceanic crust has an age of 68.7 to 79 Ma. Our low spreading rates cannot fully explain the presence of the axial high (Collier et al., 2008), but similar axial volcanic ridges can be present at slow spreading ridges (Smith and Cann, 1993). Our inferences on the extinct spreading ridge and identified chrons in the Gop Basin differ considerably from Yatheesh et al. (2009).

In the Laxmi Basin, our identifications (Fig. 5) match very well with that of Bhattacharya et al. (1994a). We have identified their central anomaly L1 as anomaly 29n which represents the extinct spreading ridge between 16 and 18°N (Fig. 6). All the seamounts identified in the Laxmi Basin (Bhattacharya et al., 1994b) represent the extinct spreading ridge in this study as in Bhattacharya et al. (1994a). Further south, we have identified the age of the extinct spreading ridge as 64.1 Ma. Here too, the extinct spreading ridge aligns along the positive topography of the Wadia guyot (Fig. 6). Thus the present study endorses that the oceanic crust in the Gop and Laxmi Basins evolved contemporaneously as inferred by Malod et al. (1997). The timing of the oldest magnetic anomaly 33r suggests that the initial rifting occurred prior to Deccan Trap volcanism (Courtilot et al., 1986) and these two events are not related.

Pre-Deccan Campanian to Maastrichtian-Danian volcanism (~75 to 65.5 Ma) resulted in extension between the Seychelles, Laxmi Ridge and India (Calves et al., 2011) and is seen as basaltic dykes on Seychelles Bank (Dickin et al., 1986), offshore Seychelles (Plummer and Belle, 1995) and Bibai volcanics (Mahoney et al., 2002). The opening of the Gop and Laxmi Basins can be linked to this volcanism. The spreading ridge in these basins created seafloor from 79 to 64.1 Ma before its relocation to form the Carlsberg Ridge dividing the Seychelles-Laxmi Ridge complex. The varying timing of extinction of spreading from 68.7 to 64.1 Ma (chrons 31r to 28r) in these basins precedes and concurs with the younger Tertiary magnetic anomalies identified west of the Laxmi Ridge. In the Gop and northern Laxmi Basin, where spreading extinction occurred by chron 29r, the southwestward ridge jump generated oceanic crust as early as chron 28n in the Western Arabian Basin (Dyment, 1998; Collier et al., 2008). Whereas in the southern Laxmi Basin, where extinction occurred later up to chron 28r, oceanic crust younger to 27n was formed in the Western Arabian Basin (Chaubey et al., 2002a; Royer et al., 2002).

Seafloor spreading initiated by 84 Ma in the Mascarene Basin progressed obliquely in an ~NW-SE direction (Norton and Sclater, 1979; Schlich, 1982) at slow half spreading rates of up to 2.7 cm/yr in the entire basin (Bernard and Munschy, 2000). Seafloor spreading initiated in the Gop and Laxmi Basins by 79 Ma (Fig. 7c), limited the spreading in the northern Mascarene Basin, while unobstructed spreading continued in the southern Mascarene Basin. This is evident from the inferred spreading rates which remained stagnant at 3.0 cm/yr in the northern Mascarene Basin but increased in the southern Mascarene Basin to 5.7 cm/yr until 68.7 Ma (Fig. 7d). Continued slow spreading in the Gop and Laxmi Basins ultimately resulted in the extinction of the spreading center

in the northern Mascarene Basin by 65.8 Ma (Fig. 7e). Further seafloor spreading in the Laxmi Basin up to 64.1 Ma resulted in compression/convergence probably leading to the formation of the Amirante Ridge. The initiation of seafloor spreading in Laxmi and Gop Basins at 79 Ma before the inferred ridge extinction in the northern Mascarene Basin at 65.8 Ma suggests these two events may be casually related.

Simultaneous seafloor spreading in the Mascarene Basin, and the Gop and Laxmi Basins from 79 to 64.1 Ma resulted in the formation of a third plate – the Seychelles-Laxmi Ridge complex. Thus two coeval seafloor spreading ridges created seafloor between west India and East Madagascar in a parallel, three-plate system separating India, Seychelles-Laxmi Ridge and Madagascar as mentioned by Gibbons et al. (2013). Similar coeval, close-set seafloor-spreading ridges exist in the North Fiji Basin (Lagabrielle et al., 1997). The spreading ridge extinction initiated at around 65.8 Ma in the northern Mascarene Basin and progressed southwards to 58.7 Ma (Masson, 1984; Dymant 1991; Bernard and Munsch, 2000; Cande et al., 2010; Torsvik et al., 2013). Likewise, progressive southward extinction of the spreading ridge is seen from 71 to 64.1 Ma in the Laxmi Basin. Similar progressive extinction of the Mathematician spreading ridge is seen in southeast Pacific Ocean (Mammerickx and Naar, 1988) and was attributed to mantle source depletion/failure related to hotspot motion. Here too, coeval spreading ridges operated at slow rates creating a short-lived Mathematician microplate. One of the ridges got abandoned due to the disappearance of the shallow crustal magma chamber and the other one assumed full spreading (Hey et al., 1985).

Several studies have been carried out regarding the existence of the Seychelles microplate. Late Cretaceous anticlockwise rotation has been inferred based on the triangular shape of the Mascarene Basin (Plummer and Belle, 1995) and paleomagnetic studies (Torsvik et al., 2001). The crust around the Seychelles shows evidence of deformation both to the north and south. Cande et al. (2010) reported independent motion of the Seychelles microplate from 58.3 to 49.4 Ma and suspected that this motion might have started earlier. The fan shaped trends of the magnetic anomalies north of the Seychelles depict anticlockwise rotation between 64.1 and 63 Ma (Ganerod et al., 2011). Visual-fit modeling of conjugate magnetic anomaly data around the Seychelles and Laxmi Ridge indicated rapid anticlockwise motion with respect to the African plate about nearby Euler poles between 64 and 59 Ma (Eagles and Hoang, 2013).

The present study suggests that Seychelles-Laxmi Ridge complex behaved as a microplate from 79 Ma when seafloor spreading initiated in the Gop and Laxmi Basins. This microplate experienced an anticlockwise rotation of about 50° between fracture zones FZ1 and FZ2 until about 64.1 Ma when spreading in the Laxmi Basin ceased (Fig. 7). Its boundaries changed with time and included the Amirante Arc. At 63.1 Ma, when Laxmi Ridge separated from the Seychelles, the Seychelles Bank may have continued behaving as a microplate individually (Cande et al., 2010; Ganerod et al., 2011; Eagles and Hoang, 2013).

5.1 Plate kinematic models

Several plate kinematic models have been generated to explain the evolution of the India-Africa spreading corridor (Norton and Sclater, 1979; Morgan, 1981; Besse and Courtillot, 1988; Cochran, 1988; Muller et al., 1993). Most models place the west coast of India against Madagascar and invoke random strike-slip motions to fit Madagascar within the global plate model (Gaina et al., 2007). In contrast, the Seychelles-Mascarene Plateau is considered as the continental conjugate to eastern Madagascar (Francis and Shor, 1966; Plummer and Belle, 1995; Muller et al., 2001; Torsvik et al., 2013). Majority of the models are plagued by unequal crustal accretion of up to 500 km width in the Mascarene Basin and advocate the presence of oceanic crust in the Gop and Laxmi Basins (Bernard and Munsch, 2000; Eagles and Wibisono, 2013).

Bernard and Munsch (2000) proposed that the Laxmi and Mascarene Basins formed at the same spreading system between 67 and 59 Ma. But no evidence of a plate boundary required to join the spreading axis in the Laxmi Basin and the axis remaining in the southern Mascarene Basin was offered. Calves et al. (2011) placed the Mascarene Plateau and Chagos-Laccadive Ridge between India and Madagascar in their 99 Ma reconstruction and invoked dextral strike-slip motion from 95 to 84 Ma. The placement and subsequent motion of the Mascarene Plateau does not match with the inferred fracture zones in the Mascarene Basin (Bernard and Munsch, 2000).

Eagles and Wibisono (2013) postulated that a ridge jump at 67 Ma of >600 km from the Mascarene Basin towards northeast into the Laxmi Basin was followed by another ridge jump of 100 km towards the southwest at 64.1 Ma, initiating the Carlsberg Ridge. The plate kinematics involved for a ridge to jump further east and then back to the west need to be established. Eagles and Hoang (2013) suggested that the extinction of the Mascarene Ridge may have occurred geologically instantaneously at 58.7 Ma and not diachronously as inferred by earlier workers.

Torsvik et al. (2013) placed several microcontinents (Seychelles, Laxmi Ridge, Laccadive Ridge, Saya de Malha Bank in addition to Chagos Bank, Nazareth Bank and Mauritius) between Madagascar and India in their reconstruction models. The models of Gibbons et al. (2013) did not accommodate any microcontinents between India and Madagascar, while the Seychelles-Laxmi Ridge was placed at the northernmost tip of Madagascar. Thus the existing plate kinematic models describing the evolution of the India-Africa spreading corridor were speculative and needed refinement.

Our plate reconstruction models allow the placement of the microplates between India and Madagascar as done by Plummer and Belle (1995); Calves et al. (2011) and Torsvik et al. (2013). Hence the pole used to generate the 90 Ma reconstruction (Fig. 7a) depicting the pre-breakup scenario differs considerably from that of Gibbons et al. (2013). Thus though India is placed slightly east in comparison to that of Gibbons et al. (2013), all the tectonic features located further east are

well aligned . Our location of the Seychelles along with the Laxmi Ridge based on Plummer and Belle (1995) matches with Calves et al. (2011) and Torsvik et al. (2013), but differs to some extent with that of Gibbons et al. (2013). Our 84 Ma model (Fig. 7b) is similar to most of the earlier published models and matched the anomaly 34 identifications in the Central Indian Ocean Basin and Enderby Basin (Gibbons et al., 2013). Our models postulate that the spreading ridge in the Laxmi and Gop Basins has not formed due to a ridge jump from the northern Mascarene Basin as inferred by Bernard and Munsch (2000) and Eagles and Wibisono (2013). Furthermore, our models are a refinement over those of Gibbons et al. (2013) in terms of the timings of opening and extinction of the two coeval spreading systems, and the characteristics of the third plate between these systems. Our reconstruction models are simple and realistic, and can explain better the evolution and tectonics of many features such as the Laxmi and Gop Basins, and the Laxmi and Laccadive Ridges.

5.2 Seafloor spreading stages

Most of the earlier models explain the plate kinematics in the India-Africa spreading corridor in three stages (Masson, 1984; Talwani and Reif, 1998; Todal and Edholm, 1998). The first stage is a two-plate configuration between India-Seychelles-Mascarene Plateau and Africa-Madagascar with seafloor spreading in the Mascarene Basin. A complex three-plate configuration is inferred in the second stage due to the opening of the Gop/Laxmi Basins separating Seychelles-Mascarene Plateau from India. The third stage reverts back to the simple two plate system formed at the initiation of the Carlsberg Ridge and extinction of seafloor spreading in the Mascarene Basin (Schlich, 1982).

We too concur a three-stage evolutionary history for the India-Africa spreading corridor (Fig. 7, Table 3). The first stage occurred from 84 to 79 Ma between Africa-Madagascar and India-Seychelles-Laxmi Ridge-Laccadive Ridge-Saya de Malha Bank and resulted in the formation of the Mascarene Basin. In the second stage, the three plate system formed at 79 Ma when the Gop and Laxmi Basins opened. The Seychelles-Laxmi Ridge block behaved as a third plate until 64.1 Ma when spreading ceased in the Laxmi Basin. The Laxmi Basin spreading ridge jumped southwestward and separated the Laxmi Ridge from the Seychelles. Seychelles individually behaved as the third plate until it merged with Africa-Madagascar by 63.1 Ma. Additionally, the Saya de Malha Bank and Laccadive Ridge may have also behaved as microplates during this period. With the extinction of the spreading ridge in the Mascarene Basin by 58.7 Ma, the India-Africa spreading system once again became a two plate system.

5.3 Evolutionary tectonics between India and Africa

A multiphase breakup history between Africa, Madagascar, Seychelles and India has been proposed (Mckenzie and Sclater, 1971; Norton and Sclater, 1979; Schlich, 1982). India-

Madagascar-Seychelles separated from Africa in the Late Jurassic, forming the Mozambique, western and northern Somali Basins. In the Cretaceous (M0 time), spreading in the western Somali and Mozambique Basins stopped and a plate reorganization resulted in Madagascar attaching to the African plate. The initial breakup between Africa-Madagascar and Seychelles-India (Torsvik et al., 2000) during Turonian time (88.5-91 Ma) was accompanied by magmatism probably from the Marion hotspot and is recorded in the stratigraphy of the Madagascar sedimentary basins, Morondava volcanic rocks on Madagascar and St. Mary's islands on the west coast of India (Mahoney et al., 1991; Storey et al., 1995). The opening was diachronous and oblique to the coast, and seafloor spreading initiated since 84 Ma progressed with low to intermediate spreading rates in the Mascarene Basin in a two plate system (Schlich, 1982; Storey et al., 1995; Bernard and Munsch, 2000; Gibbons et al., 2013). The microplates such as Laxmi Ridge, Laccadive Ridge and Saya de Malha Bank formed the continental conjugate to eastern Madagascar along with Seychelles-India (Francis and Shor, 1966; Plummer, 1996; Muller et al., 2001; Torsvik et al., 2013).

The Pre-Deccan volcanism (~75 to 65.5 Ma) weakened the Indian western continental margin (Muller et al., 2001; Calves et al., 2011) and isolated several microcontinents such as the Seychelles-Laxmi Ridge, Saya de Malha Bank and the Laccadive Ridge. This volcanism also resulted in the opening of the Gop and Laxmi Basins in a three plate setting (Talwani and Reif, 1998). The present study suggests this opening occurred contemporaneously from 79 Ma and seafloor spreading progressed with low half spreading rates of up to 1.5 cm/yr in both of the basins. Continued spreading in these basins limited the seafloor spreading in the northern Mascarene Basin, while spreading continued freely in the southern Mascarene Basin. The fracture zone FZ2 acted as a major boundary between the northern and southern Mascarene Basin and may have also restricted the southward propagation of the Laxmi Basin spreading ridge resulting in a failed rift between India and Laccadive Ridge as inferred by Nair et al. (2013).

Simultaneous seafloor spreading in the Mascarene and Laxmi-Gop Basins created the Seychelles-Laxmi Ridge microplate since 79 Ma. This microplate bounded by the fracture zones FZ1 and FZ2 underwent anticlockwise rotation of about 50° between the spreading ridges on either side (Figs. 7c - e). Seafloor spreading ceased in the Gop Basin by 68.7 Ma, while it ceased in the northern Mascarene Basin just after 65.8 Ma. Further spreading in the Laxmi Basin until its extinction at 64.1 Ma (Fig. 6) resulted in compression/convergence in the northern Mascarene Basin and formation of the Amirante Ridge.

The arrival of the Deccan hotspot caused destabilization of the entire region resulting in changes in plate boundaries, spreading rates and directions, and spreading ridge extinctions. These include the splitting of the Seychelles-Laxmi Ridge block, separation of Saya de Malha Bank and Laccadive Ridge from India, emplacement of the Mascarene Plateau and initiation of the Carlsberg Ridge.

Progressive extinction of the spreading center southward (from 71 to 64.1 Ma) in the Laxmi Basin is probably linked to the relative southward motion of the Deccan hotspot as suggested by Talwani and Reif (1998). This spreading center east of the Seychelles-Laxmi Ridge block relocated to form the Carlsberg Ridge breaking the Seychelles-Laxmi Ridge microplate. Seychelles merged with the Africa-Madagascar plate and Laxmi Ridge merged with the India-Laccadive Ridge-Saya de Malha Bank plate. Seafloor spreading started along the Carlsberg Ridge forming the Western Arabian Basin by 63.1 Ma (Dyment, 1998; Collier et al., 2008) with a half spreading rate of 6 cm/yr (Chaubey et al., 2002a; Royer et al., 2002; Collier et al., 2008). When spreading finally ceased in the southern Mascarene Basin around 58.7 Ma (Dyment, 1991; Bernard and Munsch, 2000), Saya de Malha Bank merged with the Africa-Madagascar plate. Laccadive Ridge remained attached to the Indian plate with minimal motion resulting in its present day position. Continued Reunion hotspot activity produced the Mascarene Plateau as suggested by drilling results (Duncan and Hargraves, 1990).

6. Conclusions

Detailed magnetic anomaly analysis off Northwest India suggests that seafloor spreading initiated contemporaneously in the Gop and Laxmi Basins from 79 Ma. Symmetric magnetic anomalies about a central anomaly associated with a gravity low and occasionally with positive topography, indicate the presence of an extinct spreading ridge in these basins. The central region between 19-20°N and 65.5-67°E is characterized with symmetric magnetic anomalies from 33r about a central anomaly 32n, while the Gop Basin is associated with symmetric magnetic anomalies from 33r to 31r. Symmetric magnetic anomalies from 33r about a central anomaly ranging from 31r up to 28r are seen in the Laxmi Basin suggesting progressive southward extinction of the spreading center. The central region was probably the location of a RRR type triple junction having the Gop Basin, Laxmi Basin and the Narmada-Son lineament as its arms. Half spreading rates were initially low (~0.6 cm/yr) between anomalies 33r and 32n. These rates increased to 1.1 cm/yr in the Gop Basin until seafloor spreading ceased at 68.7 Ma, while the rates gradually increased to 1.5 cm/yr until spreading ceased at 64.1 Ma in the Laxmi Basin.

Our plate reconstruction models suggest that the two plate India-Africa spreading system since 84 Ma was transformed into a complex three plate system by 79 Ma with the contemporaneous opening of the Gop and Laxmi Basins, and the formation of the Seychelles-Laxmi Ridge microplate. Further seafloor spreading in these basins caused limited spreading in the northern Mascarene Basin, while normal to fast spreading continued in the southern Mascarene Basin. The fracture zone FZ2 acted as a major boundary between the northern and southern Mascarene Basin, and may have restricted the southward propagation of the Laxmi Basin spreading ridge. The Seychelles-Laxmi Ridge microplate may have undergone anticlockwise rotation of about 50°

between 79 and 64.1 Ma. About 160 km of oceanic crust generated in the Gop and Laxmi Basins alleviates partially the space problem faced in the earlier plate reconstruction models.

The progressive southward extinction of the spreading center in the Laxmi Basin and the corresponding southwestward ridge jump separating the Seychelles and Laxmi Ridge were controlled by the relative southward motion of the Deccan hotspot. The Carlsberg Ridge was initiated by 63.1 Ma prior to the extinction of seafloor spreading in the southern Mascarene Basin at 58.7 Ma. With the Seychelles and Saya de Malha Bank microplates attaching to the African plate, and the Laccadive and Laxmi Ridges attaching to the Indian plate, the India-Africa spreading system became a two plate system once again.

Acknowledgment

We sincerely thank Director, NIO for granting the necessary permission. The officers, crew, scientific and supporting staff of the concerned cruises are duly acknowledged. We are grateful for the constructive reviews of Tim Minshull, Deborah Smith and one anonymous reviewer that greatly improved the manuscript. GMT software (Wessel and Smith, 1998) was used to generate the figures. This is NIO contribution no. .

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Figure Captions

1. Satellite gravity of the western Indian Ocean (Sandwell and Smith, 2009) showing the various tectonic elements referred in the present study. The present day mid-oceanic ridge system is shown as a black line. The red outline denotes the Large Igneous Provinces (Coffin and Eldholm, 1994). Black dots show the present day location of the hotspots. AR: Amirante Arc; CLR: Chagos-Laccadive Ridge; GB: Gop Basin; LB: Laxmi Basin; LR: Laxmi Ridge; Mabt: Madagascar Bight; MaR: Madagascar Ridge; MP: Mascarene Plateau; MuR: Murray Ridge; S: Seychelles; SEIR: Southeast Indian Ridge; SL: Sri Lanka; SMB: Saya de Malha Bank; SWIR: Southwest Indian Ridge.

2. Bathymetry map of the Arabian Sea (Smith and Sandwell, 1997) 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 Bhattacharya et al. (1994a). The yellow dashed and thin lines indicate fracture zones and magnetic lineations respectively (Todal and Eldholm, 1998). The pink continuous line and dashed lines represents the Gop Rift and fracture zones respectively (Malod et al., 1997). Location of DSDP sites (Whitmarsh, 1974) are shown as black circles with basement age in Ma in bracket. The extent of the onshore Deccan volcanism is shown in red outline. The extent of the Dharwar Craton is shown in purple outline. Reunion hotspot track shown as thick red dashed line and its initial age are from Duncan (1990). The 2000 m isobath of the Laccadive Ridge is shown as thin black outline. The extent of the gravity low of the Laxmi Ridge is shown as thick black outline. The axis of the Palitana Ridge (PR) is shown in brown. Dashed brown lines represent the shear zones on Indian mainland. The Narmada-Son lineament (NSL) is shown as thick green dashed line. The Trivandrum Terrace (TT) is shown as a thick blue outline. BSZ: Bhavani Shear Zone; CSZ: Chapporo Shear Zone; EAB: Eastern Arabian Basin; LR: Laxmi Ridge; LaB: Laccadive Basin.

3. Magnetic anomaly dataset used in the present study are plotted in different colours along the tracks. Bathymetry is shown as thin black dashed lines. The extent of the gravity low of the Laxmi Ridge is shown as thick black outline.

4. Synthetic seafloor spreading models (black) generated using the geomagnetic polarity time scale of Gradstein et al. (2004) for the key profiles (red). Gravity and bathymetry along these profiles is plotted in green and blue respectively. Half-spreading rates in cm/yr are indicated. Dashed line represents the extinct spreading ridge axis having different timings of extinction. Models have been generated assuming 500 m thick source layer at a paleolatitude of 19°S (Bhattacharya et al., 1994a) now observed at 17°N, 70°E. The spreading ridge strike is N20°W with a remanent magnetization of 0.05 A/m. Normally magnetized blocks are shown in black. R is the location of the Laxmi Ridge.

5. Interpretation of the magnetic profiles used in the present study. The identified magnetic anomalies are shown in different colours as per legend. The extent of the Laxmi Ridge is shown as black dashed outline. The boundaries of the gravity low separating the older and younger regions, and the likely seaward edge of the continent-ocean transition (COT) are also marked (Sandwell and Smith, 2009).

6. Magnetic anomaly identifications made in the present study are shown as per legend on the track map. The extent of the gravity low of the Laxmi Ridge is shown as black outline. The extent of the low gravity signature bounding the older and younger regions and the likely seaward edge of the continent-ocean transition (COT) is indicated. Fracture zones are marked as thick black dashed

lines. The pseudofaults (thin black dashed lines) and magnetic lineations (red lines) are from Chaubey et al. (1998). The 2000 m isobath of the Laccadive Ridge is shown as green outline. The extent of the onshore Deccan volcanism is shown in red outline. The thick brown line represents the Chapporo Shear Zone (CSZ). The Narmada-Son lineament (NSL) is shown as green dashed line. FZA and FZB are the inferred fracture zones bounding the central zone where extinction took place at 71 Ma.

7. (a to f) Plate reconstruction models for different timings depicting the evolution of the study area. The isochrons of Gibbons et al. (2013) are shown in pink in the first three reconstructions to demonstrate the preservation of the fit of the surrounding plates. The prominent fracture zones in the Mascarene, Laxmi and Gop Basins are shown as black lines. Magnetic anomalies in the Mascarene Basin (Bernard and Munsch, 2000) are shown in different colours as per legend, some are annotated. Magnetic identifications inferred in the present study in the Gop and Laxmi Basins are shown as dots, blue - on the Indian plate and red on the Seychelles-Laxmi Ridge microplate. Black arrow depicts the direction of initiation of seafloor spreading. The shear zones in the Indian subcontinent are shown as dashed lines. A: Africa; AR: Amirante Arc; GB: Gop Basin; I: India; LR: Laxmi Ridge; LaR: Laccadive Ridge; LB: Laxmi Basin; M: Madagascar; MB: Mascarene Basin; MP: Mascarene Plateau. NSL: Narmada Son Lineament; S: Seychelles; SL: Sri Lanka; SMB: Saya de Malha Bank; TT: Trivandrum Terrace; WZFZ: Wallaby-Zenith Fracture Zone. For every chron, the region in the blue box is enlarged separately for clarity purpose.

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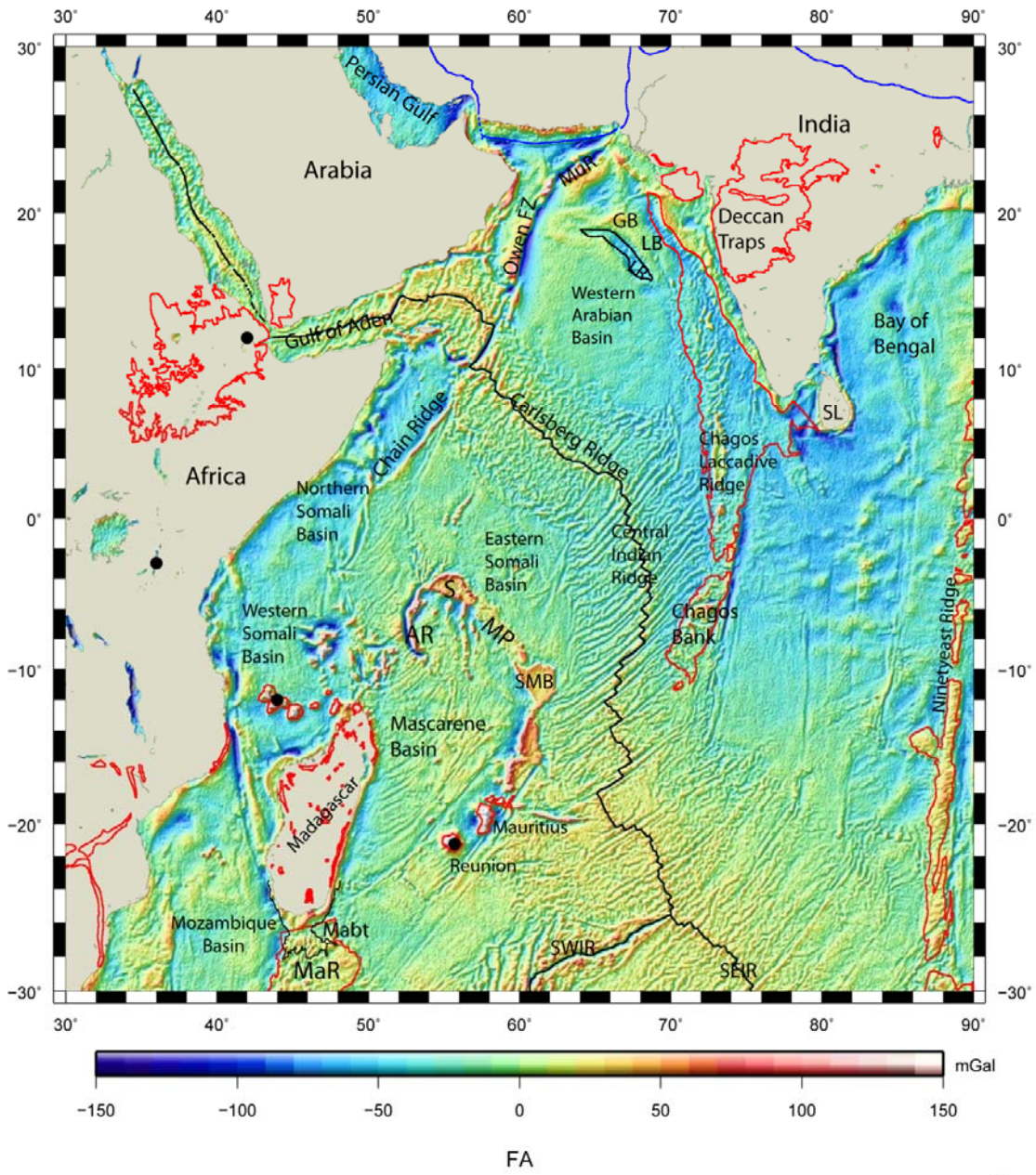


Figure 1

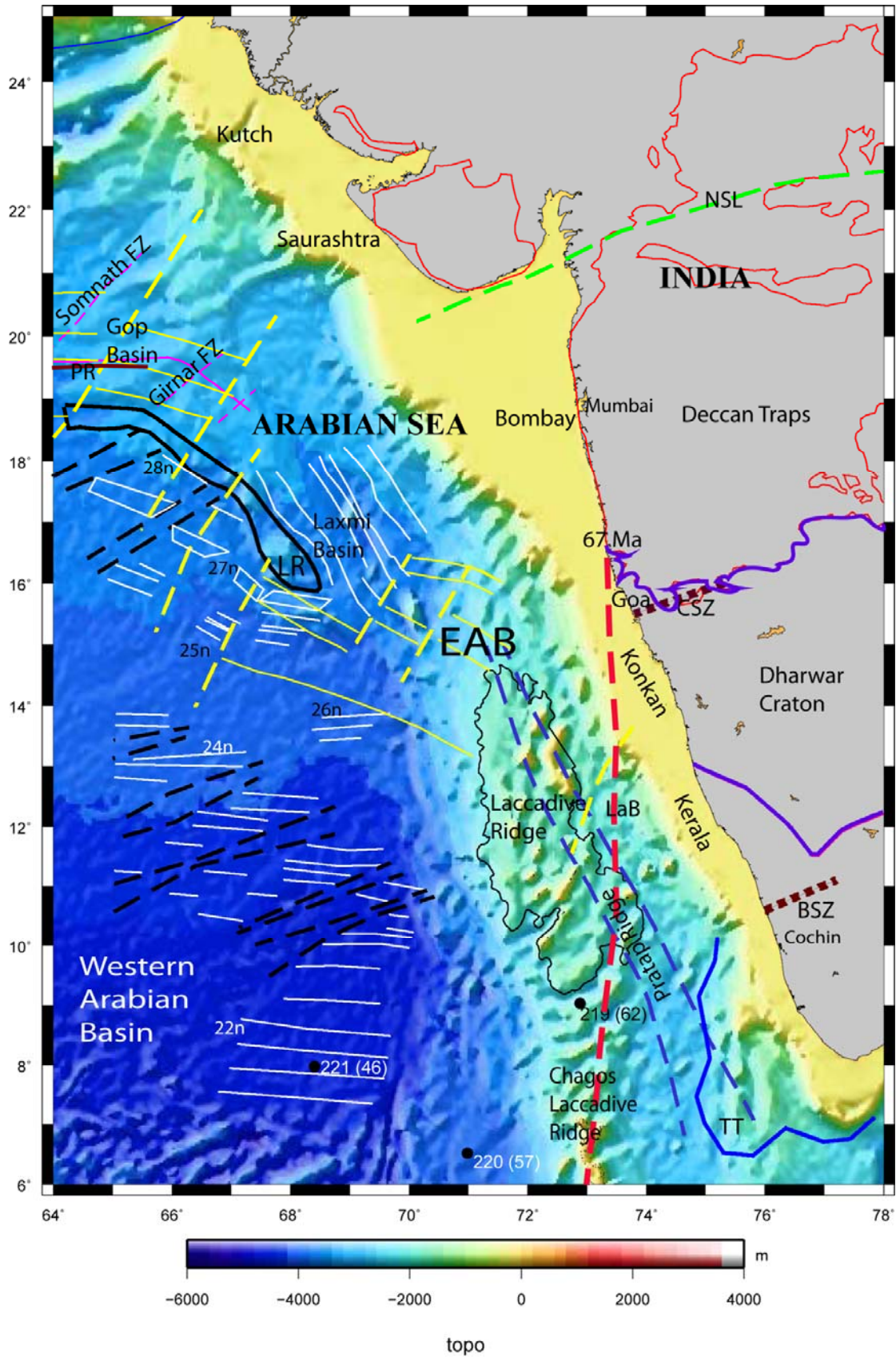


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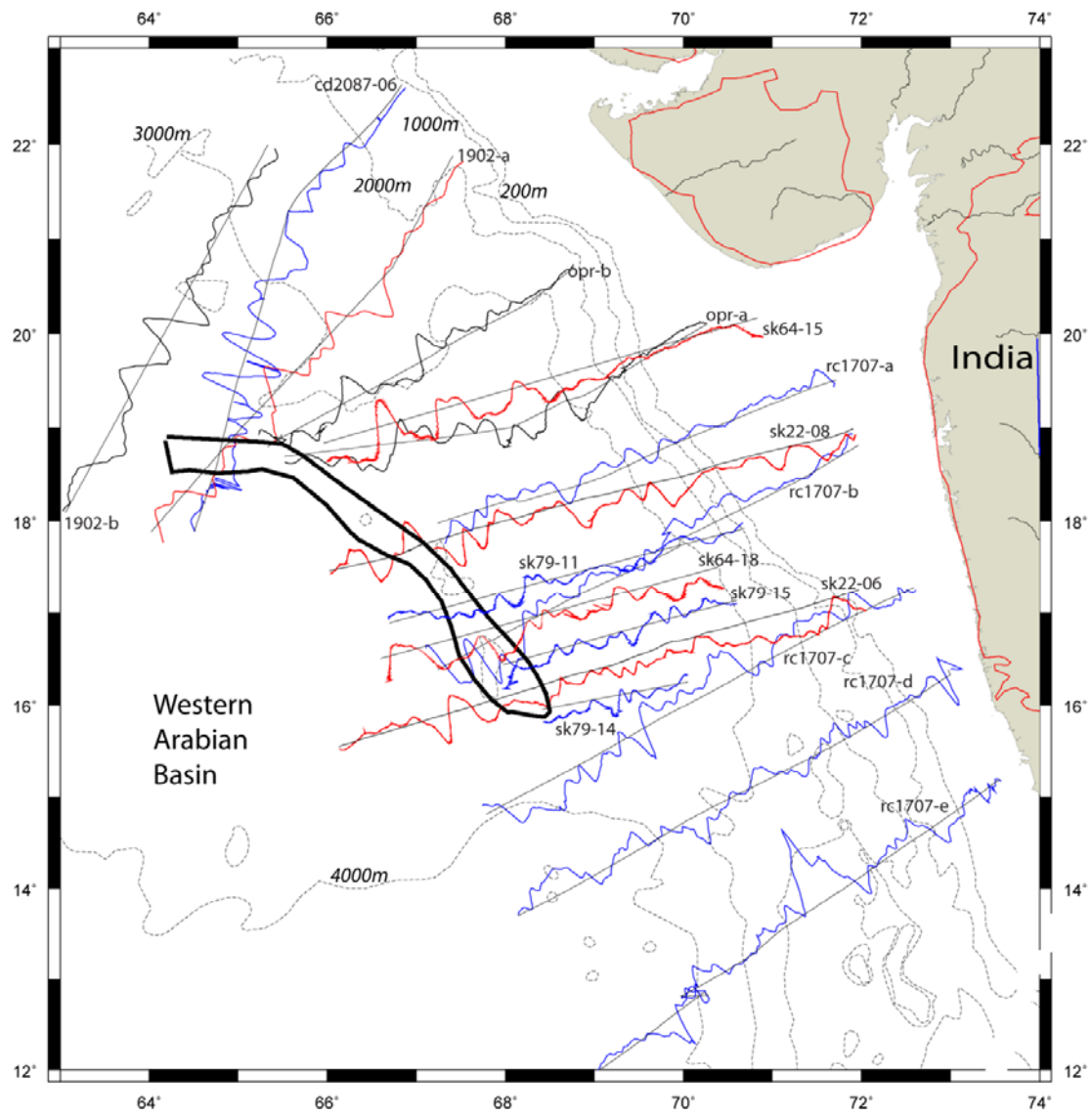


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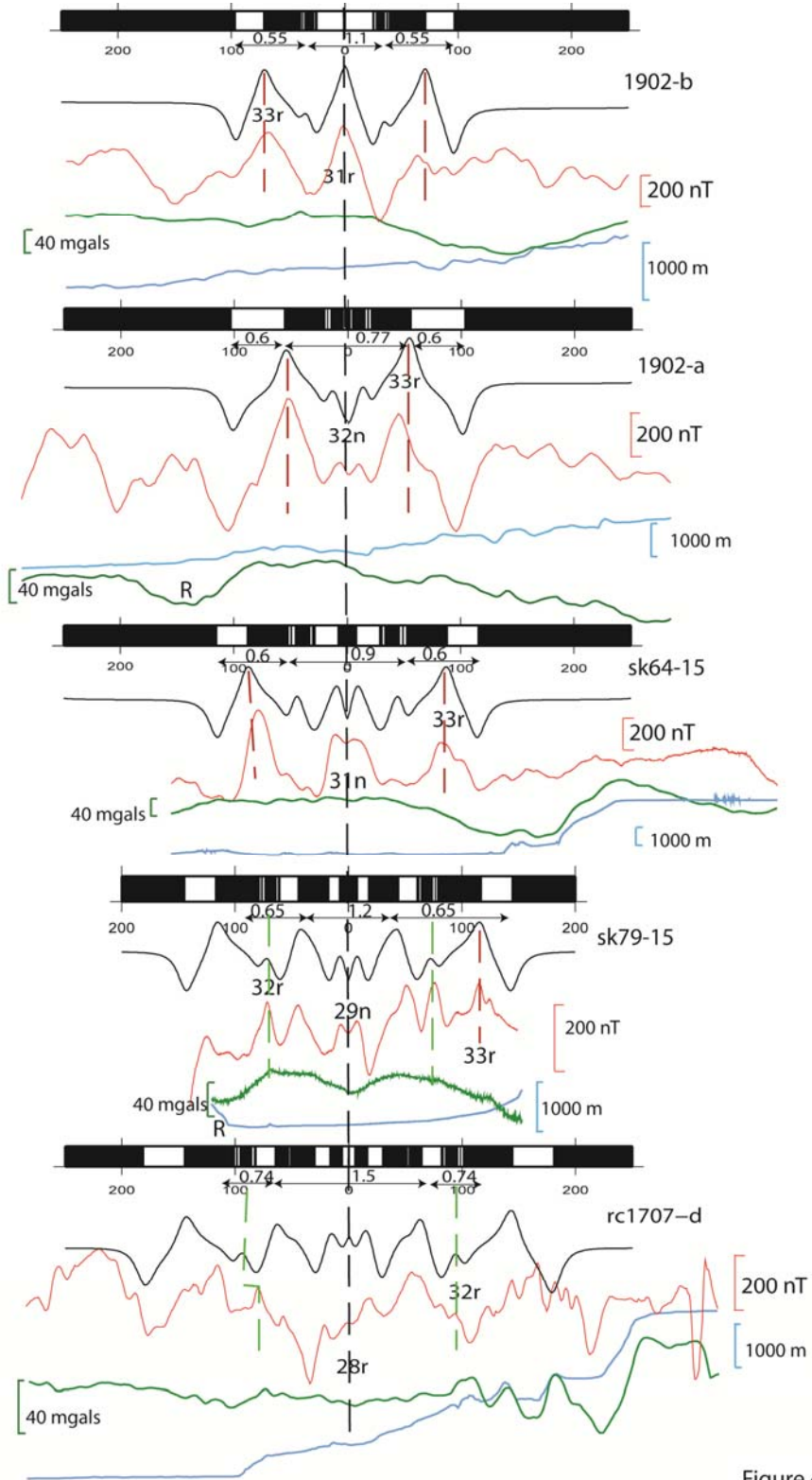


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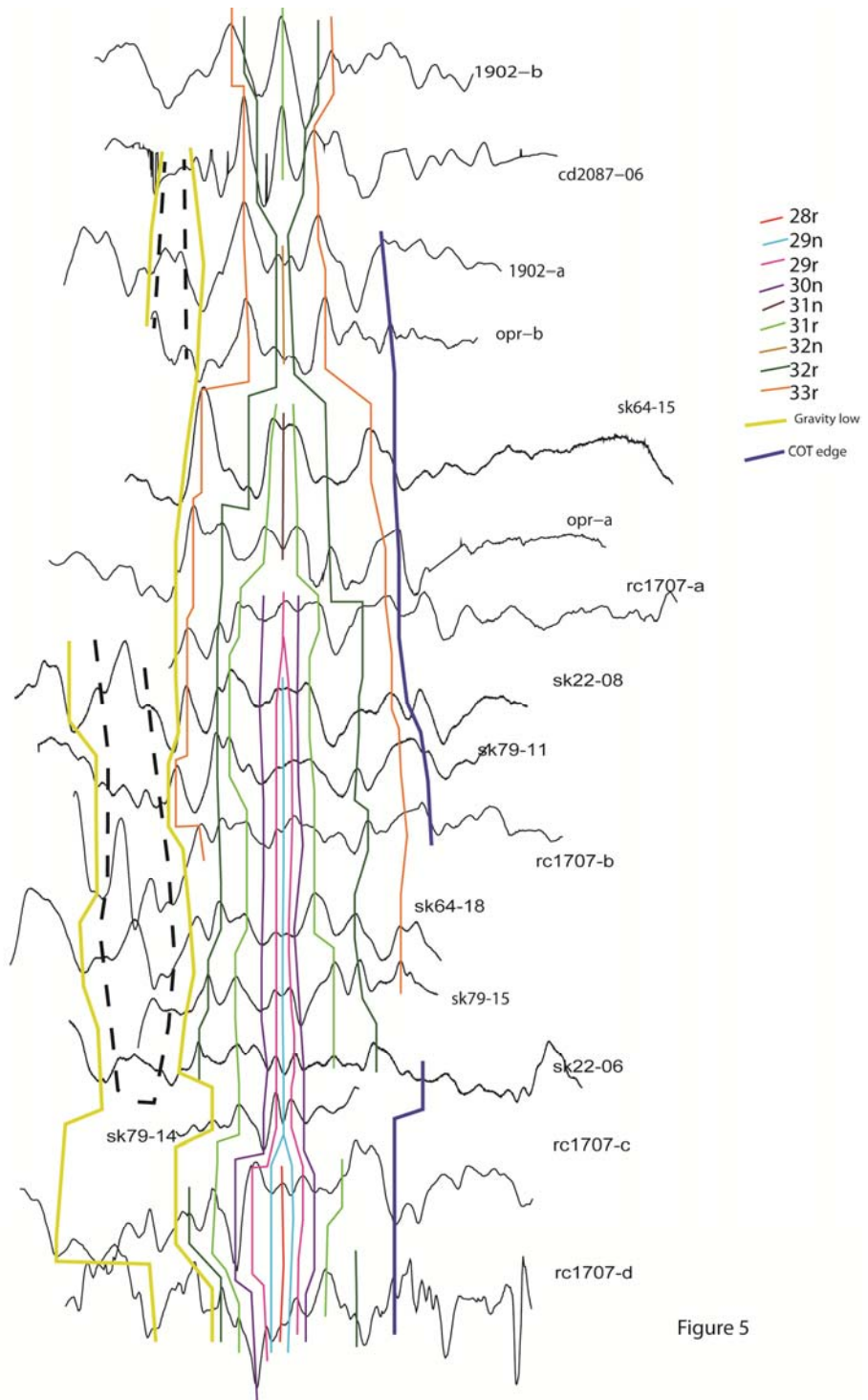


Figure 5

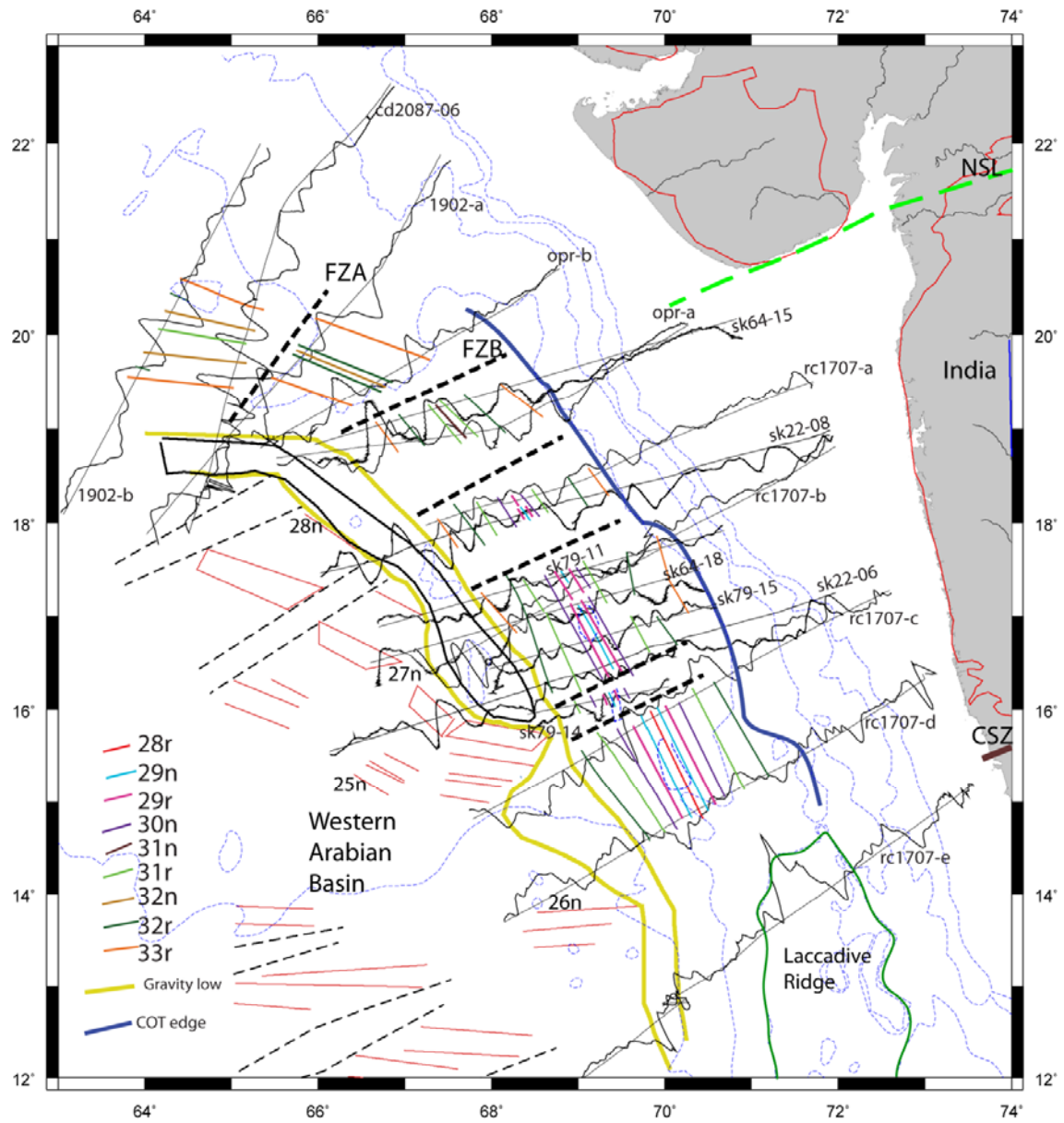


Figure 6

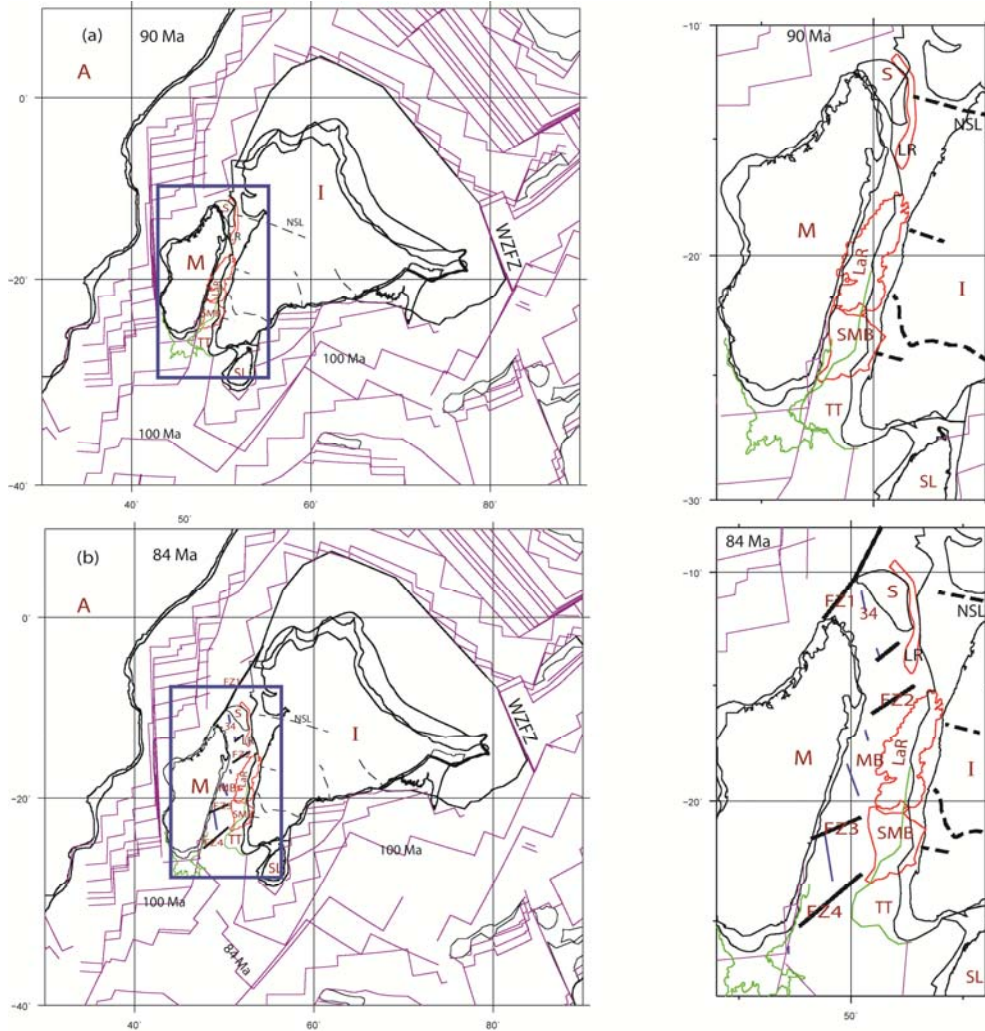


Figure 7

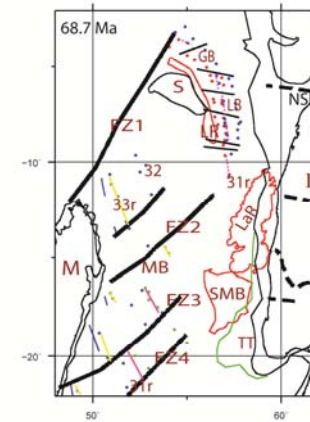
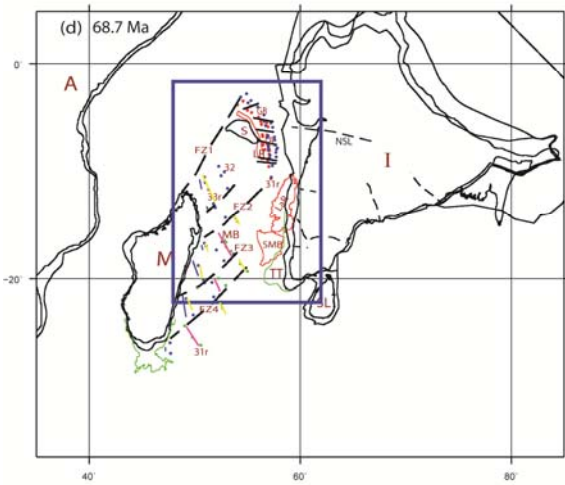
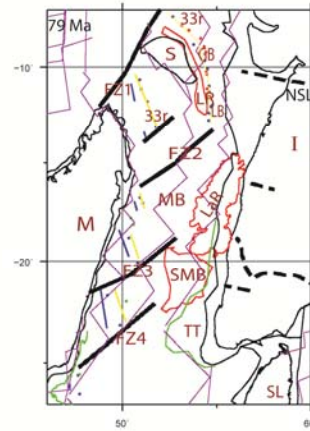
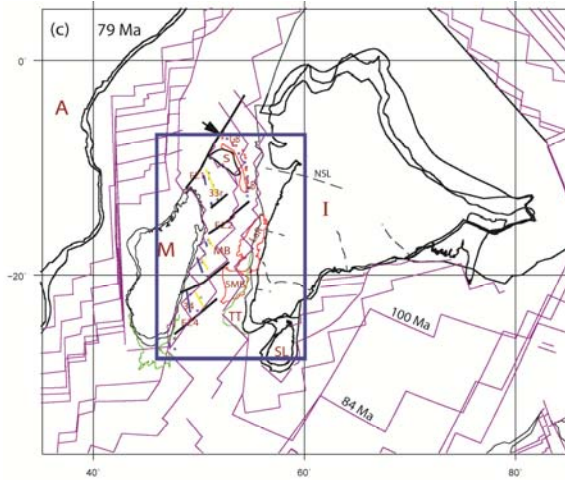


Figure 7 (contd)

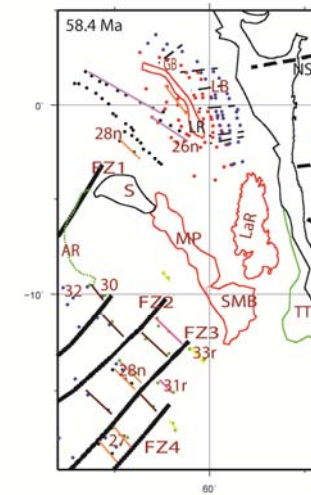
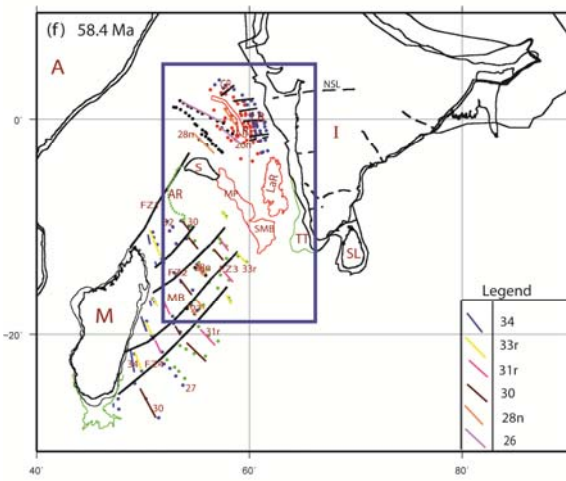
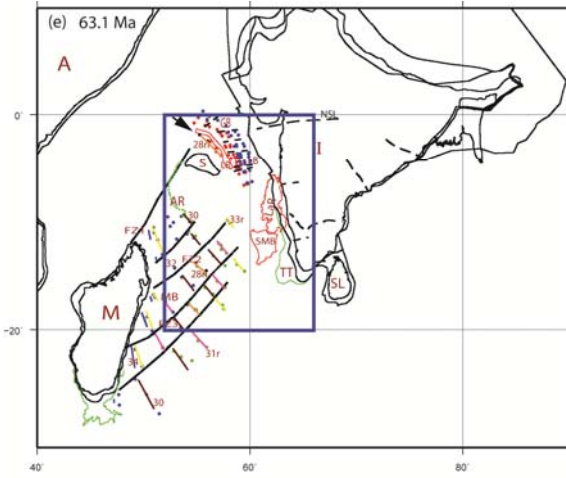


figure 7 (contd)

Table 1: Plate reconstruction parameters of relative rotations with respect to fixed Madagascar plate (702). Numbers in brackets are Plate IDs used in GPlates software, www.gplates.org (Boyden et al., 2011).

Age (Ma)	India (501)			Seychelles (704)			Saya de Malha (705)			Laxmi Ridge (570)			Laccadive Ridge (572)		
	Lat	Lon	Angle	Lat	Lon	Angle	Lat	Lon	Angle	Lat	Lon	Angle	Lat	Lon	Angle
Chron															
58.4 (26n)	24.85	13.03	-24.87	0	0	0	0	0	0	24.85	13.03	-24.87	24.85	13.03	-24.87
63.1 (28n)	24.62	6.75	-27.57	0	0	0	-12	48.49	-6.83	24.84	2.91	-26.61	21.71	15.96	-28.07
68.7 (31r)	19.58	25.1	-42.57	2.21	41.58	-7.2	5.04	31.12	-13.42	20.26	19.05	-38.09	18.16	26.62	-41.31
79 (33r)	19.05	24.24	-49.45	3.26	37.42	-16.76	4.89	31.48	-23.09	19.81	16.99	-42.34	17.69	25.64	-48.1
84 (34)	21.25	21.8	-50.1	-0.93	42.13	-31.23	8.95	27.52	-22.75	15.73	28.13	-55.93	19.32	24.86	-50.09
90	20.81	22.31	-54.95	-1.6	41.5	-38.61	5.4	31.4	-31.77	14.46	29.61	-54.95	19.16	24.68	-54.55

Table 2: Table depicting the opening and extinction timings in the Gop and Laxmi Basins inferred from earlier works and the present study.

	Timing	Reference
Gop Basin opening	65 Ma	Malod et al., 1997
	68 Ma	Todal and Eldholm, 1998
	71 Ma	Collier et al., 2008
	68/65 Ma	Yatheesh et al., 2009
	79 Ma	Present study
Gop Basin extinction	64.4 Ma	Malod et al., 1997
	No extinction	Todal and Eldholm, 1998
	68.7 Ma	Collier et al., 2008
	57.2 Ma	Yatheesh et al., 2009
	68.7 Ma	Present study
Laxmi Basin opening	74 Ma	Bhattacharya et al., 1994
	66 Ma	Todal and Eldholm, 1998
	67	Bernard and Munsch, 2000
	65.9	Eagles and Wibisono (2013)
	79 Ma	Present study
Laxmi Basin extinction	63 Ma	Bhattacharya et al., 1994
	No extinction	Todal and Eldholm, 1998
	59	Bernard and Munsch, 2000
	64.1	Eagles and Wibisono (2013)
	64.1 Ma	Present study

Table 3: Table describing the sequence of events during the three-stage evolutionary history of the India-Africa spreading corridor inferred from earlier works and the present study.

Timing chron	Event	Plate system	Reference
88.5-91 Ma	Madagascar separated from Seychelles-India	Two	Torsvik et al., 2000
84 Ma (34)	Seafloor spreading initiated in Mascarene Basin	Two	McKenzie and Sclater, 1971; Norton and Sclater, 1979; Schlich, 1982; Bernard and Munschy, 2000
79 (33r)	Gop and Laxmi Basins opened Seychelles –Laxmi Ridge microplate formed	Three	Present study
71 (32n)	Seafloor spreading stopped in the central region of Laxmi/Gop Basins	Three	Present study
68.7 (31r)	Seafloor spreading stopped in Gop Basin	Three	Present study
65.8 (30)	Seafloor spreading stopped in northern Mascarene Basin	Three	Bernard and Munschy, 2000
64.1 (28r)	Seafloor spreading stopped in Laxmi Basin	Three	Present study
63.1 (28n)	Carlsberg Ridge activity began	Three	Dyment, 1988; Collier et al., 2008
58.7 (26r)	Seafloor spreading stopped in southern Mascarene Basin	Two	Dyment, 1991; Bernard and Munschy, 2000