Plate-Tectonic Evolution of the Deep Ocean Basins Adjoining the Western Continental Margin of India—A Proposed Model for the Early Opening Scenario

G.C. Bhattacharya and V. Yatheesh

Abstract The available plate-tectonic evolution models suggest that the deep ocean basins adjoining the western continental margin of India have evolved largely due to break-up and dispersal of India, Seychelles and Madagascar continental blocks since Late Cretaceous. Mainly owing to the availability of large number of well identified magnetic anomaly picks, the evolution of the region from chron C28ny (~62.5 Ma) and younger times is better constrained than the preceding period of its early evolution. Using constraints of several recently mapped regional scale tectonic features, a plausible model for that early evolution is proposed in this paper. Around 88.0 Ma the involved continental blocks were in their immediate pre-drift configuration where a wide continental rift zone existed between India and Madagascar. Seafloor spreading in the Mascarene Basin commenced shortly before 83.0 Ma. A ternary rift system off Saurashtra peninsula of western India, formed shortly before 68.5 Ma, reached seafloor spreading stage in the Laxmi and Gop basins around 67.6 and 64.7 Ma respectively. Around 62.5 Ma the ancestor of the Carlsberg Ridge spreading center developed between the Seychelles Plateau and the Laxmi Ridge while spreading in the northern Mascarene Basin ceased and spreading in the Laxmi and Gop basins continued at very slow rate. Between 60.9 and 57.9 Ma the spreading in the southern Mascarene Basin also ceased and the spreading center jumped north between the Laccadive Plateau and the northern boundary of the Mascarene Basin. The divergence regimes of the Gop, Laxmi and Laccadive basins ceased between 57.6 and 56.4 Ma, and the Laccadive Plateau and the Laxmi Ridge got welded to the Indian plate.

Keywords Plate-tectonic reconstruction · Early oceanic opening · Western Indian Ocean · Laxmi Basin · Gop Basin · Réunion hotspot · Marion hotspot · Laxmi Ridge · Seychelles Plateau · Madagascar

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1 Introduction

The broad plate-tectonic evolutionary model for the Indian Ocean region first emerged through three pioneering studies (McKenzie and Sclater 1971; Norton and Sclater 1979; Besse and Courtillot 1988) published during 1970s and 1980s. According to those studies, the western region (Fig. 1) of the Indian Ocean [hereafter referred as the Western Indian Ocean (WIO)] evolved by rifting and drifting of the major Gondwanaland fragments of Africa (AFR), Madagascar (MAD), Seychelles (SEY) and India (IND) from each other. Those studies also proposed that the eastern part of WIO, which is the area of focus of the present paper (i.e. the deep ocean basins (WCMI-ADOB) that lie between the Laxmi Ridge and the western continental margin of India–Pakistan subcontinent) evolved in two stages mainly by rifting and drifting of MAD, SEY and IND continental blocks. In the first stage a conjoined IND–SEY block drifted from Madagascar since ~chron C34n, which formed the Mascarene Basin. In the second stage, IND drifted from SEY since chron C28ny creating the conjugate Arabian and Eastern Somali basins. These broad models however did not accommodate vast oceanic areas adjacent to the continental margins apparently due to paucity of appropriate geophysical data from those regions. With the availability of newer and denser coverage of geophysical transects and advanced tools for plate-tectonic reconstructions, those initial models for the Indian Ocean region as a whole continues to improve through large number of subsequent studies (e.g. Naini 1980; Schlich 1982; Naini and Talwani 1982; Royer and Schlich 1988; Bhattacharya et al. 1992; Chaubey et al. 1993, 1995, 1998; Dyment 1998; Krishna et al. 2012; Gibbons et al. 2013 and references therein; references cited in Yatheesh et al. 2013a; Jacob et al. 2014; see Misra and Mukherjee 2015) in different parts of the Indian Ocean area. However, till date, the nature and genesis of the crust underlying the WCMI-ADOB region remained vague. Naini and Talwani (1982) and Kolla and Coumes (1990) opined that the WCMI-ADOB areas are underlain by thinned continental crust, while Biswas and Singh (1988) opined that the underlying crust is oceanic. However, for many years subsequent researchers did not consider the possibility of oceanic crust underlying the WCMI-ADOB areas, and instead based their models with the assumption of an underlying thinned continental crust. The idea of oceanic crust underlying the WCMI-ADOB areas gained strength with an apparent breakthrough few years later, when Bhattacharya et al. (1994a) reported the presence of short sequence of two-limbed seafloor spreading type magnetic anomalies in the Laxmi Basin sector of the WCMI-ADOB. Subsequently, Malod et al. (1997) reported the presence of two-limbed seafloor spreading type magnetic anomalies in the Gop Basin sector of WCMI-ADOB. In the subsequent years several publications (Reeves and Leven 2001; Chatterjee et al. 2006, 2013; Bastia et al. 2010; Calvès et al. 2011; Gibbons et al. 2013; Torsvik et al. 2013) presented models for the evolution of the WIO region with the consideration that the WCMI-ADOB region represents extinct oceanic spreading regime. A recent study of Misra et al. (2015) treated various geophysical data over a large part of the WCMI-ADOB region. Their interpretations (Figs. 5 and 9 of Misra et al. 2015) of

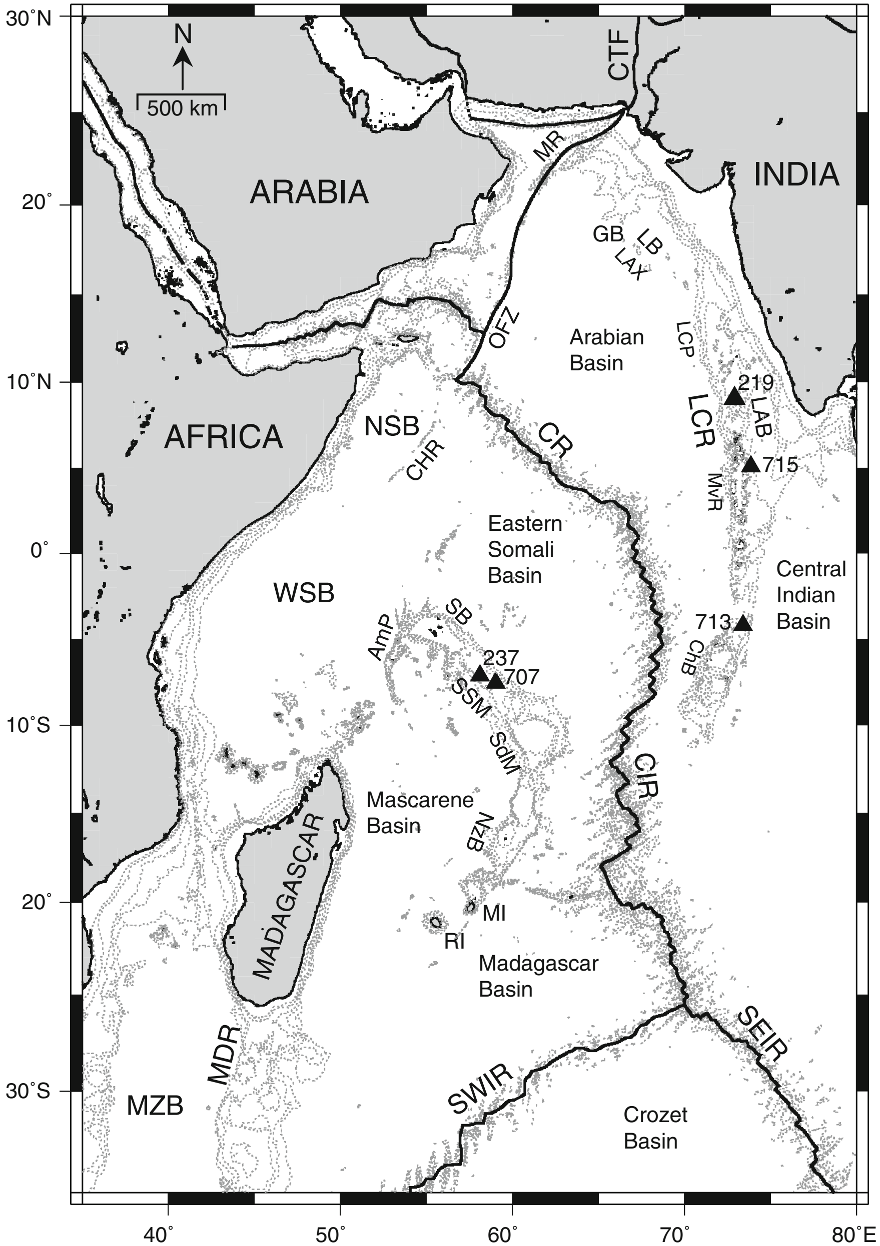


Fig. 1 Generalized map of a part of the Western Indian Ocean area depicting various major tectonic elements referred in the text. *Thin dotted lines* are selected (200, 1000, 2000, 2500 and 3000 m) isobaths from GEBCO digital data set (IOC-IHO-BODC 2003). Abbreviations used are as in Table 1

Table 1 List of selected abbreviations used to refer various tectonic elements and domains in this study

Abbreviations	Tectonic elements and domains	Abbreviations	Tectonic elements and domains
Indian side		***Seychelles side***	
BH	Bombay High	AmP	Amirante Plateau
CG	Cambay rift graben	MI	Mauritius Island
ChB	Chagos Bank	NzB	Nazareth Bank
CKE	Chain Kairali Escarpment	RI	Réunion Island
CTF	Chaman Transform fault	SB	Seychelles Bank
DFB	Deccan Flood Basalt	SMP	Seychelles-Mascarene Plateau Complex
ESC	Extinct Spreading Centre	SdM	Saya de Malha Bank
GB	Gop Basin	SEY	Seychelles Plateau
IND	Indian continental block	SSM	Seychelles—Saya de Malha saddle
IPS	Indian Peninsular shield	ESB	Eastern Somali Basin
KG	Kutch rift graben	***Madagascar side***	
LAB	Laccadive Basin	AnE	Angavo Escarpment
LAX	Laxmi Ridge continental sliver	MAD	Madagascar continental block
LB	Laxmi Basin	MDB	Madagascar Basin
LCP	Laccadive Plateau	MDR	Madagascar Ridge
LCR	Laccadive-Chagos Ridge	MhnFZ	Mahanoro Fracture Zone
MvR	Maldive Ridge	MSB	Mascarene Basin
NG	Narmada rift graben	MauFZ	Mauritius Fracture Zone
NPB	Northern Indian Protocontinental block	Rg	Ranotsara Gap
		African side	
P	Panikkar Seamount	AFR	African continental block
PB	Padua Bank	MZB	Mozambique Basin
Pg	Palghat Gap	NSB	Northern Somali Basin
PTR	Palitana Ridge	WSB	Western Somali Basin
R	Raman Seamount	***Deep oceanic regions***	
Sau	Saurashtra Peninsula	CR	Carlsberg Ridge
SPB	Southern Indian Protocontinental block	CIR	Central Indian Ridge
		CHR	Chain Ridge
SVP	Saurashtra volcanic Platform	MR	Murray Ridge
W	Wadia Guyot	OFZ	Owen Fracture Zone
WgE	Western Ghat Escarpment	SEIR	Southeast Indian Ridge
		SWIR	Southwest Indian Ridge

high quality deep penetration seismic reflection data of recent vintage apparently supported the oceanic nature of the Laxmi Basin. However, despite those advancements, the geodynamic evolution of the WIO region particularly for the period prior to chron C28ny ($\sim$62.5 Ma[1]) has not yet been well constrained. In this paper, we propose a plausible plate-tectonic evolutionary model of the WCMI-ADOB region, for its early opening period, i.e. from the time of initiation of the India-Madagascar break-up ($\sim$88.0 Ma; Late Cretaceous) to chron C25no ($\sim$56.4 Ma; Late Paleocene). Before proceeding to present our proposed model, in the following section, we will discuss the constraints and implications of the relevant tectonic elements and geological events, which in our opinion should be considered for constructing models for early plate-tectonic evolution of the WCMI-ADOB region. It may be mentioned here that some of these aspects have not been holistically considered in any such model for the region so far.

2 Relevant Tectonic Elements and Geological Events

Since the evolution of the WCMI-ADOB region began with separation of India and Madagascar; therefore our description will include the relevant features from the Indian side as well from the Madagascar counterpart. However, the emphasis will be for the features from the land and offshore areas of the eastern part of Madagascar and its conjugate western part of India.

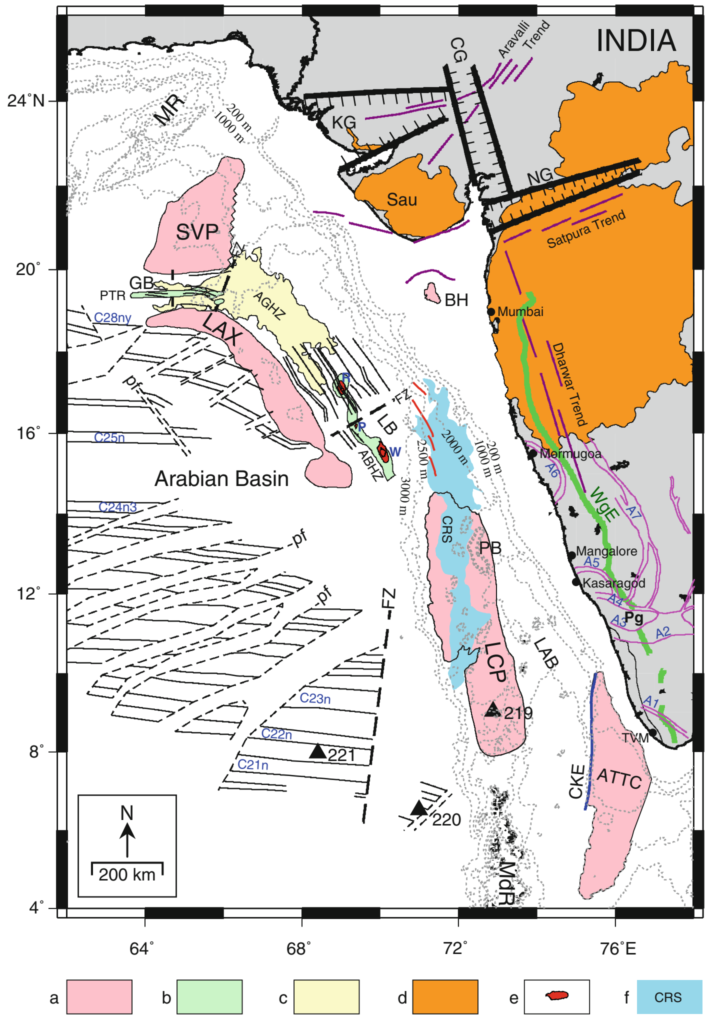
2.1 Features on the Western Part of the Indian Peninsular Shield and Adjacent Continental Margin

The geological formation of the southernmost region of the western part of Indian peninsular shield (IPS), approximately south of Kasaragod (Fig. 2), is the Southern Granulite Terrain (SGT), which is a Neoproterozoic mobile belt, made mainly of granulite facies rocks (age range of 700–500 Ma). North of this area, approximately between Kasaragod and north of Goa, is the western part of Dharwar Craton, where linear belts of Late Archaean schistose rocks (age range of 2800–2600 Ma) overlie a basement of Archaean gneisses (age of >3000 Ma) with an unconformity (Sharma 2009). Further north the deeper geology lie hidden under Deccan Flood Basalts (DFB), the commonly known Deccan Traps, of Late Cretaceous to Early Paleocene age (Radhakrishna and Vasudev 1977; Subrahmanya 2001; Chenet et al. 2007). Probably much of the terrain onto which the DFB were erupted consisted of the Dharwar Craton (Jerram and Widdowson 2005). The Saurashtra Peninsula, a region almost in the northwestern limit of DFB province, represents a cratonic horst-like

[1]Ma: millions of years before present.

uplift, which appear to be bordered in the north, east and south by continental rift grabens or their offshore extensions. Here again the deeper geology lie hidden under DFB. However, from some deep drill wells at Lodhika and Dhanduka it was inferred that DFB in the Saurashtra region overlie Createceous/Jurassic sediments, volcanic tuffs and possibly another sedimentary layer, which overlie a Precambrian crystalline basement. The central western part of the Saurashtra Peninsula also contains several volcanic plugs (Singh et al. 1997; Rao and Tewari 2005).

The crystalline terrain of the southern region of IPS is dissected by several shear zones, the most prominent of which are the Achankovil Shear Zone, the Palghat-Cauvery Shear Zone, Bhavani Shear Zone and the Moyar Shear Zone (Kroner and Brown 2005). These shear zones are important in the context of India-Madagascar



◀ **Fig. 2** Generalized map of the western continental margin of India and the adjoining land and deep ocean basin areas for depicting the locations of various onshore and offshore tectonic elements referred in the text. The continuous *black lines* in the offshore areas represent the mapped seafloor spreading type magnetic lineations. *Dashed lines* orthogonal to magnetic lineations represent fracture zones (labeled FZ). In the Arabian Basin area the *thin dashed lines* (labeled pf) oblique to the magnetic lineations are the inferred pseudo-faults related to propagating ridges. Hachured *thick black lines* represent postulated boundaries of rift graben basins onland. *Pink lines* over southwestern India represent the inferred shear zones. *A1* Achankovil Shear Zone; *A2* Palghat-Cauvery Shear Zone; *A3* Bhavani Shear Zone; *A4* Moyar Shear Zone; *A5* Coorg Shear Zone; *A6* Kumta Shear Zone; *A7* Chitradurga Shear Zone. *Thick green line* (labeled WgE) along the western edge of Indian mainland represents Western Ghat Escarpment (digitized from satellite imagery available at http://commons.wikimedia.org/wiki/File:South_India_satellite.jpg). The *red lines* located north of the Laccadive Plateau represent the segments of the Ratnagiri Fracture Zone postulated by Misra et al. (2015). ATTC: Alleppey-Trivandrum Terrace Complex; *ABHZ* Axial basement high zone coinciding with the inferred extinct spreading axis of the Laxmi Basin. Solid annotated black triangles are DSDP/ODP drill hole sites annotated with site numbers. Explanation of items of the legend—(a) Continental slivers; (b) Extent of ABHZ in Laxmi Basin and PTR in Gop Basin; (c) anomalous gravity high zone (AGHZ); (d) extents of Deccan Flood Basalts; (e) Seamounts in the Laxmi Basin. *R* Raman seamount; *P* Panikkar seamount; *W* Wadia Guyot; (f) Cannanore Rift System. Tectonic elements were compiled from several sources (Biswas 1982; Bhattacharya et al. 1994a, b; Chaubey et al. 2002a; Srinivas 2004; Yatheesh 2007; Calvès et al. 2011; Yatheesh et al. 2013b; DGH 2014; Ishwar-Kumar et al. 2013 and Ratheesh-Kumar et al. 2014). Other abbreviations used are as in Table 1 and the other details are as in Fig. 1

pre-drift juxtaposition, as they are often considered as conjugate of several comparable shear zones in the Madagascar and therefore used as constraints by researchers (e.g. Crawford 1978; Katz and Premoli 1979; Windley et al. 1994; Menon and Santosh 1995; Yoshida et al. 1999). However, opinions differ amongst researchers about the exact conjugate correspondence of these onshore shear zones. The recently identified Kumta Suture (Ishwar-Kumar et al. 2013) and Mercara (Coorg) Suture (Santosh et al. 2014) in western India and their continuation to eastern Madagascar as the Betsimisarka-Kumta-Coorg Suture (Ishwar-Kumar et al. 2013), appears to have provided valuable constraint to establish more reliable conjugate correspondence of other shear zones of India and Madagascar as well as best fit reconstruction of India and Madagascar. The three major Precambrian tectonic trends, which predominate this western part of IPS are; the NNW-SSE Dharwar trend, the NE-SW Aravalli trend and the ENE-WSW Satpura trend (Fig. 2). These three major tectonic trends were the zones of deformed and weakened crust along which later Phanerozoic rifting was facilitated. The three intra-continental rift basins which formed by rifting along these trends are the; Kutch, Cambay and Narmada rift basins. The geological history of these intra-continental rift basins indicates that they were formed sequentially from north to south around the Saurashtra horst by reactivation of primordial faults. The Kutch rift basin opened up first during Jurassic—Early Cretaceous along the Aravalli trend and was aborted in Late Cretaceous. The Cambay rift basin opened in the Early Cretaceous along the Dharwar trend and was aborted in Late Cretaceous. The Narmada rift basin opened in the Late Cretaceous time along the Satpura trend and was aborted in Late Cretaceous—early Paleocene time (Biswas 1982, 1987, 1988;

Gombos et al. 1995). This Narmada rift basin has been considered as an important aulacogen in our reconstruction model. The Narmada rift basin zone is considered to be a prominent, ancient line of weakness which developed along a Proterozoic protocontinental suture between two protocontinents of the Indian shield; a northern, Aravalli protocontinent and a southern, Dharwar protocontinent (Naqvi 2005; Sharma 2009). One major geomorphic feature of the western part of Indian peninsular shield, which we have considered in our model, is the Western Ghats Escarpment (or, Sahyadri Escarpment). This great escarpment is manifest as a coast parallel precipitous terrain separating the coastal lowlands and the eastward sloping central highlands of the peninsular India. The westward (seaward) facing Western Ghats Escarpment, which is clearly discernible in the satellite imagery, is a continental scale ($\sim$1500 km long) lineament, with only a prominent breach in its continuity at one place, known as the Palghat Gap. Considering the earlier mentioned description of the western part of IPS, the geological formations and age vary along the length of the Western Ghats Escarpment, although morphologically the feature is continuous. This escarpment is believed to represent the easterly, possibly uplifted, rift shoulder related to India—Madagascar rifting episode that was much older than the time of DFB event. The present day location and morphology of this escarpment possibly are the outcome of various processes, such as, denudation, scarp retreat and marine regression (Radhakrishna 2001; Subrahmanya 2001; Gunnell and Harbor 2008).

The shelf break in the western continental margin of India (Fig. 2) occurs at an average depth of about 200 m (Naini 1980). Towards north this shelf is relatively wider, being more than 300 km in the areas off Mumbai, whereas towards south this width gradually narrows down to about 50 km off Trivandrum. In contrast to this, the continental slope is narrow in the north but widens towards south (Biswas 1989). The paleo-shelf edge is situated (Raju et al. 1981; Rao and Srivastava 1981) much landwards of the present day shelf edge. A system of nearly coast parallel narrow horst and graben structures characterizes the basement trends of the shelf area approximately up to the northern limit of the Bombay High. This horst—graben system also had the same trend as the NNW-SSE Dharwar trend and perhaps is related to the Dharwarian basement grain parallel rifting event that preceded separation of Madagascar from India (Biswas 1989; Gombos et al. 1995). A conspicuous positive basement feature off Saurashtra Peninsula is the Saurashtra Arch. This ENE–WSW trending arch is a broad structural high on a regional scale and extends from the shelf across the slope to deep sea areas. The continental shelf part of the arch is manifest as a simple anticline, but its deepwater part contains a horst and graben structure at the crestal region (Sriram et al. 2006). As evidenced by the continuation of the Narmada and Kutch rifts and Saurashtra Arch onto the continental shelf (Biswas 1982; Bhattacharya and Subrahmanyam 1986), it appears that, in the areas northwards of Mumbai the basement trends are nearly orthogonal to the coast.

A prominent and anomalous lateral bathymetric protrusion in the form of two contiguous terrace-like features, named 'Alleppey-Trivandrum Terrace Complex (ATTC)', exists in the mid-continental slope region off southwest coast of India. A conspicuous, nearly 500 km long, steep escarpment named 'Chain-Kairali Escarpment (CKE)', demarcates the westward limit of the ATTC. The crust of this region was inferred to be thinned continental type that was intermingled with extensive volcanic intrusive emplacements, perhaps related to Marion hotspot volcanism. This ATTC region and a bathymetric notch in the northern Madagascar Ridge was postulated as conjugate features related to India-Madagascar separation, where the 'Chain-Kairali Escarpment (CKE)' forms a sheared continental margin segment along which the continental margin off the nearly straight southeast coast of Madagascar glided past India (Yatheesh et al. 2006, 2013b).

2.2 Laxmi Ridge and Laccadive Plateau

The Laxmi Ridge, located in the deep (average water depth ~2.8 km) offshore region of west coast of India (Figs. 1 and 2), is a prominent aseismic basement high feature. At seafloor the Laxmi Ridge is expressed as thin sediment covered basement high having a maximum relief of only ~0.7 km. However, as its flanks are covered by thick sediments hence the actual relief of this basement high is ~2.0 km. This ridge is expressed as NW–SE trending bathymetric high in its southern end, while its bathymetric expression is not discernible northwards beyond 18°30′N. Further, even though this ridge is a positive basement feature all along its extent and a positive seafloor feature in its southern end, it is associated with a characteristic broad negative free-air gravity anomaly (~50 mgal). However, based on associated characteristic gravity anomaly and adjacent magnetic anomalies (Fig. 3), it appears that around 65°30′E this ridge turns nearly E-W and extends westwards at least up to 63°40′E (Miles and Roest 1993). As will be discussed later (in Sect. 2.4.3), in our opinion this bight of the Laxmi Ridge provides important clue for the early evolution of the WCMI-ADOB region. The southward extent of the seafloor expression of the NW-SE trending most prominent southerly segment of the Laxmi Ridge appears to terminate abruptly against an oceanic crust containing east–west trending small segment of magnetic lineation, which is identifiable as anomaly C27n (Chaubey et al. 1998; Bhattacharya and Chaubey 2001). Based on seismic refraction studies, Naini and Talwani (1982) proposed a continental sliver genesis of the Laxmi Ridge. Todal and Eldholm (1998) opined that it is a marginal high complex, comprising both continental and oceanic crust, where inner part of the ridge is underlain by faulted continental blocks. From identified seafloor spreading magnetic anomalies, it was established that the Laxmi Ridge is that conjugate continental sliver, which was severed from the Seychelles when

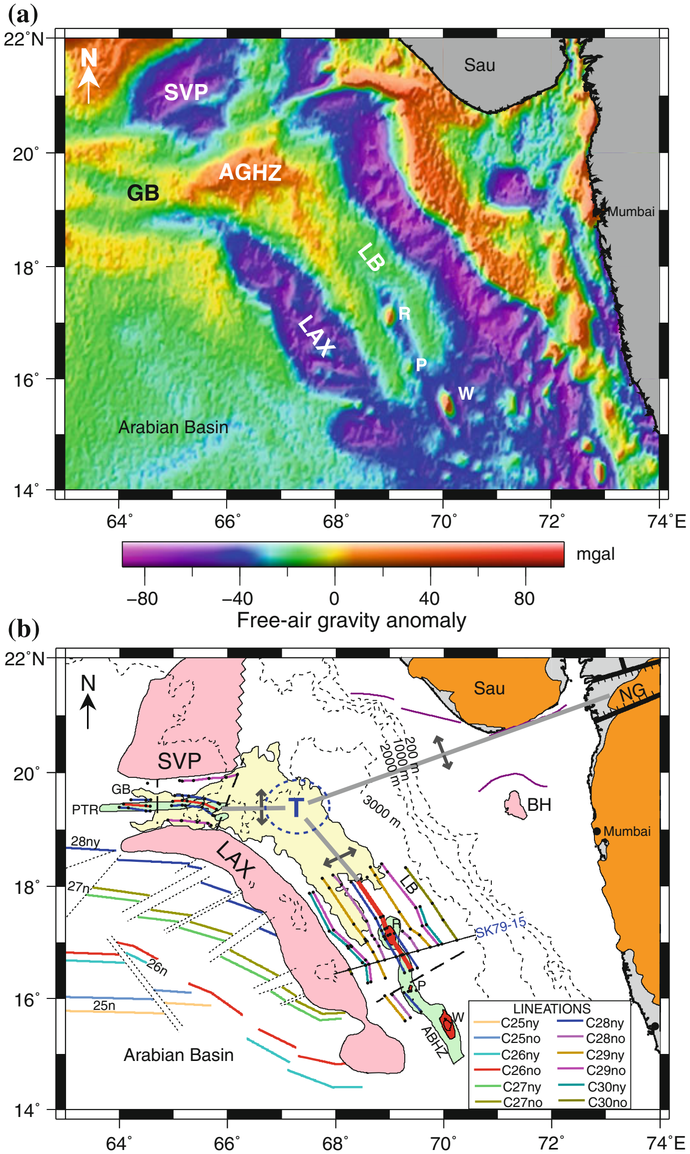


Fig. 3 Tectonic elements of the deep offshore regions adjoining northern part of the western continental margin of India. **a** Colour shaded-relief image of the satellite derived free-air gravity anomalies version 23.1 (Sandwell et al. 2014). **b** Major tectonic elements on a generalized map of the region. Location of profile SK79-15 used for magnetic anomaly modelling in this study is shown as *annotated line*. *Solid coloured lines* represent the mapped seafloor spreading type magnetic lineations inferred in the Laxmi Basin (after Bhattacharya et al. 1994a; Yatheesh 2007), in the Gop Basin (after Yatheesh et al. 2009), and in the Arabian Basin (after Chaubey et al. 2002a). *Thin dotted lines* are pseudofaults. *T* postulated Gop-Narmada-Laxmi (GNL) fossil triple junction off Saurashtra peninsula; *AGHZ* anomalous gravity high zone. Other abbreviations used are as in Table 1 and the other details are as in Figs. 1 and 2

spreading was initiated along the Carlsberg Ridge sometimes during the younger part of anomaly C28n. Collier et al. (2004) reported the presence of seaward dipping reflectors (SDRs) on the southwards regions of the Laxmi Ridge. It may be mentioned here that Misra et al. (2015) reported to have identified several geological/geophysical signatures over the Laxmi Ridge, which according to them suggest that the ridge is composed of oceanic crust formed at an abandoned oceanic spreading centre. They (ibid.) however candidly admitted that the debate on the crustal nature of the Laxmi Ridge would still remain owing to the non-uniqueness of geophysical analyses. In our opinion, although genesis of the Laxmi Ridge as an abandoned oceanic spreading centre could be a possibility, but that does not appear to have been firmly established in this study. In view of this we maintain what the researchers in general agree—that the Laxmi Ridge is a continental sliver.

The Laccadive-Chagos Ridge (LCR) is a prominent aseismic bathymetric high feature of the Western Indian Ocean (Fig. 1). The LCR is a slightly arcuate elongated feature, which extends for about 2500 km between 12°S and 14°N. This feature appears to be divided into three main segments by the presence of several relatively deep saddle-like features. These three main segments, from north to south have been referred by Bhattacharya and Chaubey (2001) as the Laccadive Plateau, the Maldives Ridge and the Chagos Bank. The genesis of the LCR still remains an enigma. The proposed views about its genesis are varied, such as, it is: a leaky transform fault, a hotspot trail, a composite structural elements of various origins etc. (references cited in Bhattacharya and Chaubey 2001). Out of these, the hotspot trail genesis appears to have broad acceptance, but as have been discussed later in this paragraph, we believe that at least the northern part of the LCR, i.e. the Laccadive Plateau (LCP) region is a continental sliver. The linearity of the LCR and the inferred age progression along its extent were considered as evidences for its hotspot trail genesis (Morgan 1972, 1981; Whitmarsh 1974; Duncan 1981). This age progression was inferred from the basement age determinations at the DSDP site 219 and ODP sites 713 and 715 (Fig. 1). Out of these three sites, the basement ages for sites 713 and 715 are radiometric ages of the basement basalts (Duncan and Hargraves 1990), and for site 219 it is an estimate from the bio-stratigraphic age (Whitmarsh et al. 1974) of the oldest sediment overlying the basement. Even though the radiometric ages for sites 713 and 715 were qualified as imprecise by a later researcher (Baksi 2005), still the ages of the three sites together do appear to suggest a pattern of increasing age of basement northward along the LCR. We, however believe that this observation of age progression on its own do not rule out the possibility that the Laccadive Plateau is a continental sliver. The reasons for believing so are two; firstly, the ODP sites 713 and 715 are not located over the Laccadive Plateau and volcanics were not sampled at DSDP site 219, which appears to lie at the southern fringe of the Laccadive Plateau. Secondly, mere existence of age progressive volcanics along parts of LCR do not indicate anything unequivocal about the nature of the country rocks, because volcanics along the trail of a hotspot are expected to show evidence of age progression, irrespective of whether those volcanics are intrusives/extrusives over continents/continental slivers or are manifested as volcanic islands in the oceanic area. On the other hand, there are several observations, which strongly suggest that the Laccadive Plateau region may be a continental sliver. For example, based on estimation of crustal thickness from seismic refraction experiments, Naini and Talwani (1982) arrived at crustal thickness (~15 km) of the Laccadive Plateau region, which is higher than normal oceanic crust. This prompted them to suggest a continental fragment nature of the Laccadive Plateau. Some insight about the geological configuration of the Laccadive Plateau perhaps can be obtained from the situation at Padua Bank—a shallow carbonate bank atop the northern part of the Laccadive Plateau (Fig. 2). It was reported (Murty et al. 1999; Kothari et al. 2001) that industry well drilled over the Padua Bank reached basalt layer underlying the tertiary sedimentary section. If this drilled basalt forms the basement then this is the only well to have sampled basaltic basement over the Laccadive Plateau or in its near vicinity. Unfortunately, no results of further studies of those basalts are available in public domain. Further, based on study of seismic reflection sections, presence of clearly identifiable rotated fault blocks have been observed by Murty et al. (1999) on either side of the Padua Bank. They (ibid.) considered those fault blocks are akin to typical stretched continental crust. It may be mentioned here that rotated fault blocks represent extensional tectonic event, but on their own they cannot be considered to represent only stretched continental crust, because rotated fault blocks were also reported (Salisbury and Keen 1993) from the regions of oceanic crust. In view of this we feel the presence of rotated fault blocks in the Padua Bank region can only be considered as a possible indicator of the continental nature of the Laccadive Plateau, not as an evidence to confirm that nature. Therefore, considering the drilled basalts and the basement characteristics we surmise that the Padua Bank and its vicinity represent an area of stretched crust, possibly of continental affinity, which is overlain by basaltic rocks. It has been reported (DGH 2014) that the Laccadive Plateau area has a complex basement structure, comprising of single normal faults, half grabens and grabens, which as a whole appear as a rift system. This rift system, named as 'Cannanore Rift System' (Fig. 2), extends along eastern part of the ridge in N-S direction from ~17°N to 9.5°N. Yatheesh et al. (2006) have shown that in a close fit India—Madagascar juxtaposition in their immediate pre-drift scenario, there is space to accommodate the Laccadive Plateau region as a continental sliver in between India and Madagascar. Later, Yatheesh (2007) made a more detail examination of the Laccadive Plateau as a possible continental sliver in the perspective of plate-tectonic evolution of the Western Indian Ocean. It may be mentioned here that most of the plate-tectonic reconstruction models, which included the period of early evolution of the WCMI-ADOB region (e.g. Norton and Sclater 1979; Besse and Courtillot 1988; Reeves and Leven 2001), considered the hotspot trail genesis for the LCR. Therefore in those models the LCR appeared into the reconstructions of periods younger than ~65 Ma, i.e. since the postulated time of peak of Réunion hotspot volcanism on Indian mainland. Whereas, some other reconstructions of recent vintage (e.g. Torsvik et al. 2013; Calvès et al. 2011; Ganerød et al. 2011) appear to consider the Laccadive Plateau region as continental sliver. In view of above, in our present model we have assumed that the Laccadive Plateau part of the LCR is a continental sliver that was severed from the western Indian Peninsula by a regime of crustal divergence and was intruded by volcanics as the area passed over the Réunion hotspot.

2.3 Conjugate Arabian and Eastern Somali Basins

The Arabian and Eastern Somali basins are two large conjugate ocean basins, which formed by seafloor spreading across the still active Carlsberg Ridge (Fig. 1). The conjugate seafloor spreading magnetic anomalies of these basins were mapped way back in 1960s with limited magnetic traverses and later with some additional magnetic data McKenzie and Sclater (1971) identified them as anomalies sequence C28n–C23n. In the subsequent years, large amount of magnetic profiles were acquired by various agencies in this area and study of those magnetic profiles enabled to establish the tectonic framework of these basins. However, we will restrict our discussion only to those aspects which are relevant to our reconstruction model. Now we know that these conjugate Arabian and Eastern Somali basins were formed within the broad geographical bounds of the submarine Laxmi Ridge in the north and the Seychelles Plateau in the south. The Chain Ridge—Owen Fracture Zone system marks the western boundary of these basins and the northern portion of the LCR marks their easterly boundary. Recent seismic investigations (Collier et al. 2004, 2009) across the conjugate Seychelles—Laxmi Ridge continental margins appears to have firmly established the northerly and southerly bounds of these two basins. So far the oldest confidently identified magnetic anomalies in these two basins are the anomaly C27n lineations. However, the younger ends of anomaly C28n lineations are considered to be present in the Arabian Basin immediately south of the Laxmi Ridge (Miles and Roest 1993; Chaubey et al. 1998, 2002a). These two basins appear to have experienced long sustained spreading ridge propagation activities. The Spreading ridge propagation is one of the processes by which spreading ridges reconfigure their geometry and this process, also consistent with rigid plate hypothesis, is different from ridge jump. In case of ridge jump, the ridge segments relocate as a whole on one of the flanks. In ridge propagation a new spreading ridge segment with new trend gradually advances into the crust previously created by the adjacent retreating ridge segment and in due course replaces the ridge with old trend. Oblique offsets of magnetic lineations in the ocean basins are considered (Hey 1977; Hey et al. 1980) as the diagnostic feature of the propagating spreading ridges. Miles and Roest (1993) were the first to report the existence of ridge propagation in the northern sector of the Arabian Basin. Later, independent as well as collaborative studies by Indian and French research groups (Bhattacharya et al. 2001, 2003a, b; Chaubey et al. 1998, 2002a; Dyment 1998; Dyment et al. 2001; Royer et al. 2002) thoroughly established the ridge propagation pattern that took place during the accretion of oceanic crust in these conjugate basins during their first ~16 myr[2] (i.e. chron C28ny–chron C21ny) of formation. According to these studies, there were three major stages of ridge propagation during that period with dominant propagation pattern characterizing each stage. The first stage of propagation commenced at about chron C28ny (~62.5 Ma) and continued at least till chron C27ny (~60.9 Ma). The propagation in this stage was along short segments and the direction of propagation was dominantly westward. The second stage of propagation, which started some time during chron C26r (~57.9–60.9 Ma) was characterized by a general eastward propagation, and the propagation of this stage continued in the same direction at least till chron C25n (~55.9 Ma). The third and last stage of propagation commenced some time during chron C24r (~53.3–55.9 Ma) and ended gradually around chron C21ny (~46.3 Ma). Propagation direction during this last stage was systematically towards west along all the spreading ridge segments. The crust generated during each of these propagation stages is delimited by unique tectonic boundaries, which are even decipherable from satellite gravity anomaly data (see Fig. 8 of Chaubey et al. 2002a). The ridge propagation system resulted in an asymmetric crustal accretion in these conjugate basins with gross additional crust in the Arabian Basin. Several processes, such as thermal triggering by Réunion hotspot, attempt by ridge segments to remain in proximity of the hotspot or its trailing thermal anomaly, and the processes of lengthening of short ridge segments formed along an initially curved margin, are suggested to have causal relationship with these ridge propagation events.

2.4 Laxmi and Gop Basins

The Laxmi and Gop basins are the two relatively narrow deep sea basins, which exist within the bounds of the Laxmi Ridge and the India-Pakistan continental margin. These two basins (Figs. 2 and 3) assume significance in our study, because we believe they contain valuable clues regarding the early opening history of the WCMI-ADOB region.

2.4.1 The Laxmi Basin

The Laxmi Basin is the ~250 km wide deep offshore region lying approximately between the NW-SE trending southern part of the Laxmi Ridge and the continental slope off western India. Bhattacharya et al. (1994a) were the first to recognize and designate the distinct entity of the Laxmi Basin. Towards south, this basin abuts the

[2] myr: millions of years.

northern extremity of the Laccadive Plateau, while towards north this basin appears to merge with the E-W trending Gop Basin.

Differences of opinions appear to exist regarding the nature of the crust underlying the Laxmi Basin. Some believe, the underlying crust is thinned and volcanics intruded continental crust (Naini and Talwani 1982; Kolla and Coumes 1990; Rao et al. 1992; Todal and Eldholm 1998; Krishna et al. 2006). On the other hand, Biswas and Singh (1988) favoured an oceanic nature, because they observed hyperbolic reflection pattern, which is typical for an oceanic crust, in the seismic reflection from basement in the region. Subsequently, Bhattacharya et al. (1994a) mapped the existence of well-correlatable NNW-SSE trending linear axi-symmetric magnetic anomalies in this basin (see Figs. 4 and 5 of Bhattacharya et al. 1994a), and inferred them to represent a two-limbed seafloor spreading anomaly sequence. Several subsequent studies (e.g. Talwani and Reif 1998; Bernard and Munschy 2000; Eagles and Wibisono 2013) favoured oceanic nature of the crust underlying the Laxmi Basin. However, Krishna et al. (2006) opined that the magnetic anomalies in the Laxmi Basin, that Bhattacharya et al. (1994a) interpreted as seafloor spreading magnetic anomalies, could best be explained as volcanic intrusives within the stretched continental crust. We agree that volcanic intrusives within the stretched continental crust can generate magnetic anomalies. However, we do not think any physical model can rationally explain the formation of several hundreds of kilometers long axi-symmetric linear magnetic anomalies within such stretched continental crust. The seaward dipping reflectors (SDRs) are considered as a veritable clue to demarcate continent ocean transition (Mutter et al. 1982). Of late, based on high quality 2D seismic reflection imaging, presence of such SDRs was reported (Corfield et al. 2010; Siawal et al. 2014) on both the easterly and westerly margins of the Laxmi Basin. Misra et al. (2015) have further distinguished the SDRs of the Laxmi Basin region as Outer SDRs and indicated (Fig. 2 and 5b of Misra et al. 2015) that the Laxmi Basin is flanked on both sides by Outer SDRs and normal oceanic crust exists basinwards beyond the termination of the Outer SDRs. In view of above we maintain that the Laxmi Basin is underlain by oceanic crust.

It cannot be denied, that dating of seafloor spreading type magnetic anomalies of the Laxmi Basin is very difficult due to their short extent. The problem gets further compounded as no characteristic signatures of those anomalies, which can aid their identification with respect to geomagnetic timescale, have been detected so far. Age constraints from drill hole samples or seismic stratigraphic data from the area are also not available so far. The preferred interpretation of Bhattacharya et al. (1994a) suggested a slow spreading (<10 mm/yr Half Spreading Rate) C33n-C28n-C33n sequence (corresponding ~79.5 to ~62.5 Ma) aged oceanic crust for the Laxmi Basin. Recently, Eagles and Wibisono (2013) opined that the smooth nature of the acoustic basement of the area as inferred from seismic reflection data, is not compatible with such a slow spreading model, and instead they (ibid.) proposed a C29n-C28n-C29n sequence (corresponding ~64.7 to ~62.5 Ma) to the Laxmi Basin magnetic lineations. In view of this wide variation in interpreted age bounds of the Laxmi Basin oceanic accretion, we carefully examined the interpretations of Bhattacharya et al. (1994a) *vis-à-vis* the interpretations of Eagles and Wibisono

(2013). We viewed their (ibid.) magnetic profile along with the large amount of magnetic profiles available with us, and observed that the magnetic profile (apparently a R.S.S. Shackleton cruise profile of 1975 vintage) used by them (ibid.) for modelling can not be considered to represent the two limbs of the Laxmi Basin anomalies sequence properly. This is because their (ibid.) profile is located near the northern limit of the Laxmi Basin, where the magnetic lineations start veering towards the Gop Basin. Further, the westerly part of their (ibid.) profile actually merges with the strike of an E-W trending magnetic anomaly high that lies over the Laxmi Ridge. In view of these we could not agree with the C29n-C28n-C29n age bound assigned by them (ibid.) for the Laxmi Basin. Nevertheless, we revisited the interpretation of Bhattacharya et al. (1994a) by taking cognizance of other inconsistency, such as smooth basement despite slow spreading rate, pointed out by Eagles and Wibisono (2013). Further, this revisit also became necessary as C33n-C28n-C33n age of Laxmi Basin oceanic accretion as assigned by Bhattacharya et al. (1994a) was quite at variance with the C31r-C25r-C31r or C29r-C25r-C29r interpretation of Yatheesh et al. (2009) for sequence of anomalies of the neighbouring Gop Basin. We re-modelled the same Laxmi Basin magnetic profile (SK 79-15) used by Bhattacharya et al. (1994a) to find out the possibility of other interpretation options. While doing this re-modelling we considered that the spreading pattern of the Laxmi Basin was similar to that assumed for the Gop Basin, i.e. a reasonable slow to intermediate Half Spreading Rate (HSR) for most of the period and a gradually decreasing very slow (<10 mm/yr) HSR during the waning phase commencing at chron C28ny. Our modelling (Fig. 4) under these two conditions yielded three possible interpretations of the Laxmi Basin anomalies sequence, i.e. either as C33n-C25r-C33n or C31n-C25r-C31n or C30n-C25r-C30n sequences. However, out of these three possible interpretations we favour the C30n-C25r-C30n sequence as it involves least variation of spreading rates for consecutive blocks and the HSR remains in the level of about 20 mm/yr for most of the time only to drop at a very low level (<5 mm/yr) during a waning phase (Fig. 5). This model also suggested a drop in the HSR after the time of peak[3] of DFB volcanism. We believe this reinterpretation also reconciles many other perceived inconsistencies about the situation in the Laxmi Basin. First of all, with this model, there will not be much difference in the ages of the Laxmi Basin and Gop Basin spreading regimes. Secondly, the conjoined Seychelles-Laxmi Ridge block will not be very far from western Indian land mass at the time of DFB event. Thirdly, this higher HSR will be compatible with the relatively smooth nature of the basement. In view of these, for the reconstruction models proposed in the present study, we used the constraints of this revised interpretation of the Laxmi Basin magnetic anomalies.

[3]The peak, i.e. the main phase of DFB volcanism (as will be discussed in a later section), which most likely was around 65–66 Ma.

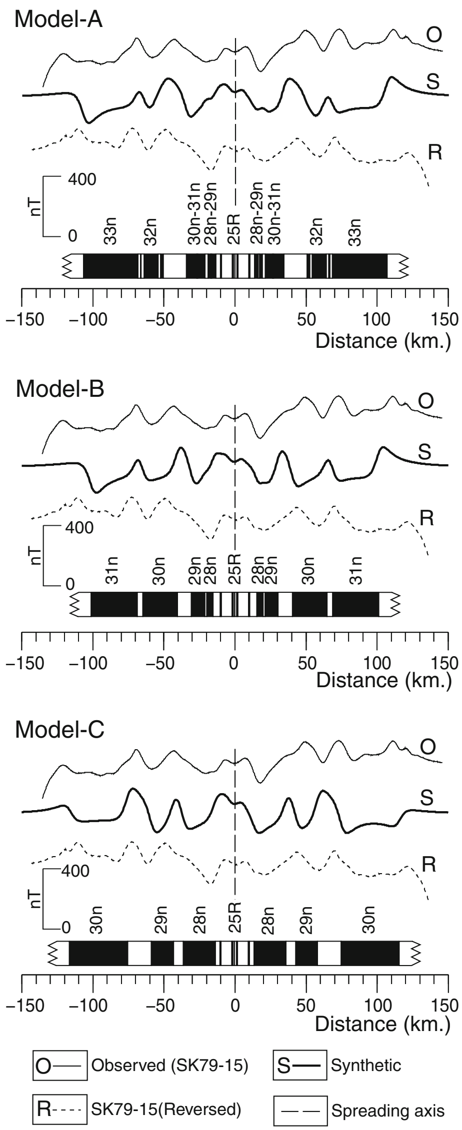


Fig. 4 Interpretative modelling of magnetic lineations of the Laxmi Basin. Three alternative models for interpretation. *Model-A* corresponds to anomaly sequence C33n-C25r-C33n; *Model-B* corresponds to anomaly sequence C31n-C25r-C31n and *Model-C* corresponds to anomaly sequence C30n-C25r-C30n. The simulated magnetic anomalies are shown along with observed anomalies (projected to an azimuth of 60°) along profile SK79-15 of Bhattacharya et al. (1994a). Simulated magnetic profiles were generated for a ridge formed near 15°S, 53°E and presently located near 17°N, 69°E as a N30°W striking body. Assumed magnetized layer (susceptibility 0.01 cgs units) is considered to be flat, 2.0 km thick, and its top lies at 5.5 km below the sea surface. Normally magnetized blocks are indicated with *black*. *Thin dashed line* represents the axis of the Laxmi Basin now extinct oceanic spreading center. *Model-C* is our preferred interpretation

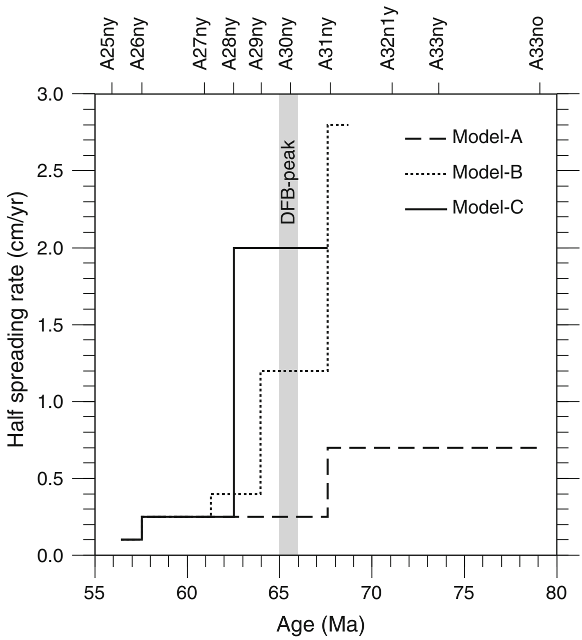


Fig. 5 Variation of half spreading rates yielded by three alternative models proposed (presented in Fig. 4) in the present study for interpretation of magnetic lineations of the Laxmi Basin. *Dashed line* corresponds to *Model-A* (i.e. anomaly sequence C33n-C25r-C33n), *dotted line* corresponds to *Model-B* (i.e. anomaly sequence C31n-C25r-C31n) and *continuous line* corresponds to *Model-C* (i.e. anomaly sequence C30n-C25r-C30n). *Grey shaded limit* (labeled DFB-peak) corresponds to the timing of the peak of Deccan Flood Basalt volcanism on the adjacent western Indian mainland

It may be mentioned here that, Bhattacharya et al.'s (1994a) interpretation of chron C33n (~79.5 Ma; Late Cretaceous) opening of the Laxmi Basin implied two things. Firstly, it suggested that the opening of the Laxmi Basin was older than the peak of DFB volcanism. Secondly, it implied existence of Mesozoic basins on the flanks of the Laxmi Basin. We noted that a study (Roberts et al. 2010) of specially processed high quality seismic reflection data reported existence of Mesozoic basins underlying basalt (DFB?) layer on the continental margin off Mumbai (i.e. on the eastern flank of the Laxmi Basin). If this interpretation is correct, then it confirms our implied suggestions. The chron C30no (~67.6 Ma) opening of the Laxmi Basin, as revised in the presented study, also conform to those implied suggestions.

The axial part of the Laxmi Basin is characterized by a narrow quasi-linear NNW-SSE trending basement high zone (Fig. 2), which at places is expressed (Bhattacharya et al. 1994b) as subtle subcrop and at few places the basement high zone is overlain by large seamounts. Rao et al. (1992) inferred this axial basement high zone as a ~360 km long feature and named it as the Panikkar Ridge. Interestingly, the inferred extinct spreading centre of the Laxmi Basin (Bhattacharya et al. 1994a) was observed to approximately coincide with this basement high zone.

2.4.2 The Gop Basin

The Gop Basin (Figs. 2 and 3) is the ~100 km wide deep offshore region located immediately north of the E–W trending northerly segment of the Laxmi Ridge (Yatheesh et al. 2009). The Gop Basin can be considered as a sub-basin of the larger Offshore Indus Basin (Miles et al. 1998; Bhattacharya and Chaubey 2001) i.e. the large deepwater area lying between the landward boundary of the Laxmi Ridge and the India–Pakistan continental shelf. Malod et al. (1997) were the first to recognize the Gop Basin (referred by them as Gop Rift) as a distinct entity in view of its basement fabric and conspicuous magnetic lineations. They (ibid.) inferred that the basement of the Gop Basin forms a sediment-filled E-W graben with a prominent central E–W trending basement high zone. They (ibid.) designated this basement high feature as 'Palitana Horst'; however following Yatheesh et al. (2009) hereafter we refer this feature as 'Palitana Ridge'.

Most researchers agree that the Gop Basin represents an oceanic crust formed by an extinct seafloor spreading regime. However, opinion varies regarding the location of the extinct spreading center (ESC) and thereby the identification of the conspicuous magnetic lineations (see Fig. 6a of Yatheesh et al. 2009) of the basin. Yatheesh et al. (2009) proposed that the Palitana Ridge represents the ESC of the Gop Basin and opined that magnetic anomalies across the Palitana Ridge ESC can be reasonably explained as the axi-symmetric magnetic anomalies sequence, either C31r–C25r-C31r or C29r–C25r-C29r. On the other hand, Minshull et al. (2008) and Collier et al. (2008) placed the ESC of the Gop Basin to a different basement high about ~50 km north of the Palitana Ridge and thereby considered a different segment of the magnetic lineations as representing the axi-symmetric magnetic anomalies sequence of the Gop Basin. Collier et al. (2008) arrived at three different possible sequences to explain the axi-symmetric magnetic anomalies of the Gop Basin (corresponding to their ESC), such as, C29r–C28r-C29r, or C31r–C29r-C31r, or C32n.1r–C31r-C32n.1r. In contrast to this, Minshull et al. (2008) opined that the entire sequence of the same axi-symmetric magnetic anomalies segment can be due to basement relief on a single reversed polarity block (C29r or C31r) and the edge effects at the margins of such a block. Detail critique of these various interpretations is beyond the scope of this paper. However, we would like to mention that, we have thoroughly examined (Bhattacharya and Yatheesh under preparation) the location of the extinct spreading center proposed by Collier et al. (2008) and Minshull et al. (2008), in the backdrop of large magnetic database of the area available with us and the published seismic reflection data (Calvès et al. 2011; Gaedicke et al. 2002) of various vintage acquired by different organizations. From this examination, we came to the conclusion that, the magnetic anomaly, which Collier et al. (2008) and Minshull et al. (2008) considered as axial anomaly (corresponding to their ESC) actually coincides with the zone of SDRs identified (Calvès et al. 2011) at the southern edge of the Saurashtra Volcanic Platform (SVP), which as will be discussed later, represents a thinned continental crust region north of the Gop Basin. We are not aware that an extinct spreading center was found to be associated with SDRs anywhere in the world oceans. Further, we also observed that the basement high, which was considered by Collier et al. (2008) and Minshull et al. (2008) as the ESC, actually is a NE-SW trending isolated basement high trend of limited extent and that trend also is not parallel to the distinct E-W trending magnetic lineations of the Gop Basin. In view of these shortcomings, we could not agree with Collier et al. (2008) and Minshull et al. (2008) location of ESC and their consequent identifications of magnetic anomalies sequence of the Gop Basin. Instead, we maintained the conclusion of Yatheesh et al. (2009) that the Palitana Ridge is the ESC of the Gop Basin. Further, out of the two possible identification of the anomalies sequence of Gop Basin proposed by Yatheesh et al. (2009), we adopted the C29r-C25r-C29r model as it provides a reasonable high Half Spreading Rate (HSR) of ~30 mm/yr for most of the period and a gradually decreasing very slow (<10 mm/yr) HSR during its waning phase of Gop Basin spreading center since chron C28ny (~62.5 Ma). Admittedly like the situation in the Laxmi Basin, the magnetic anomalies sequence in the Gop Basin also is very short, hence their unique identification is difficult. Therefore these identifications will remain tentative till some other constraints are available to confirm them.

Recent studies (Calvès et al. 2011; Carmichael et al. 2009; Corfield et al. 2010) of the Offshore Indus Basin area brought out the existence of a sediment covered prominent basement platform structure of large areal extent in the areas immediate north of the Gop Basin. The areal extent of the mapped portion (which is restricted within Pakistan EEZ) of this basement platform structure, was reported (Calvès et al. 2011) to be about 42,500 km^2. The structure appears to extend further eastward into Indian EEZ and thus may occupy much greater areal extent. This basement platform structure is inferred to be characterized by volcanic centres, subaerial lava flows, volcaniclastic clinoforms and marine volcaniclastic sediments. The extrusive volcanism is estimated to be at least 5 km thick in many parts of the platform. Apparently in view of the predominance of volcanic build up features, Corfield et al. (2010) referred this platform structure as Saurashtra Volcanic Platform (SVP). The northwestern boundary of the SVP is a pronounced linear NE–SW trend that separates the SVP from deep water, probably an oceanic crust strip of Offshore Indus Basin that parallels the Murray Ridge. The published seismic sections suggest that the northern boundary of the SVP is defined by a narrow, thick sediment filled, nearly E-W trending basin that abuts the Pakistan continental slope. Perhaps this E-W basin is a remnant of the fossil Kutch Rift. A prominent fault zone is inferred to exist towards the southeastern part of the SVP. This faulted area conforms to the NE-SW trending so-called Somnath Fracture Zone reported by Malod et al. (1997). The easterly boundary of the SVP is poorly constrained, apparently as the data were restricted within the EEZ of Pakistan. The crustal thicknesses of the SVP region was interpreted (Corfield et al. 2010) to be around 15 km. We observe that the basement grain of the SVP is largely NE-SW which is in clear contrast to the E-W trend of the magnetic lineations of the Gop Basin or its axial Palitana Ridge. Based on reflection seismic data, Carmichael et al. (2009) inferred presence of syn-rift sedimentary packages in the SVP region, which at places were intruded by seamount forming volcanics. Based on reflection seismic data, Calvès et al. (2011) also mapped the presence volcano-stratigraphic features of

Outer and Inner SDRs and the Outer High towards the southwestern boundary of the SVP. According to Planke et al. (2000) such volcano-stratigraphic features are associated with volcanic continental margins. Apparently aided by these identifications, Calvès et al. (2011) demarcated the continent ocean boundary coinciding with the landward edge of the Inner SDRs zone, where the SVP was inferred as an area of stretched continental crust. In view of these observations and inferences and presence of extinct spreading center in the Gop Basin, we infer that the SVP represents a conjugate continental sliver of the Laxmi Ridge in the Gop Basin sector and include the SVP element in our model accordingly.

2.4.3 Proposed Gop-Narmada-Laxmi Triple Junction

As mentioned earlier (Fig. 3), the inferred extinct spreading center of the Gop Basin region (i.e. the Palitana Ridge ESC) trends E-W and that of the Laxmi Basin region trends NW-SE. We believe these distinctly different directions of spreading between a plate pair (India and Laxmi Ridge) is inconsistent unless a third plate is involved in the scenario. We therefore look for those possible three plates, the three plate boundaries separating them and a triple junction connecting these plate boundaries. The spreading centres in the Gop and Laxmi basins obviously represent the two plate boundaries (or arms) of this triple junction. We feel that the Narmada Rift on the Indian peninsula in the east can be considered as the third plate boundary, or the third arm of the triple junction. The reasons for such a consideration are following. As mentioned earlier, three continental rift basins (Kutch Rift, Cambay Rift and Narmada Rift) exist in the western part of adjacent Indian mainland, but location and orientation wise, the Narmada Rift appears a more reasonable candidate for this third arm. The Narmada Rift is an ENE–WSW trending major basinal trend on the Indian mainland. This basin is considered to have developed within a rift graben that meets the western continental margin of India. The inferred Late Cretaceous initiation of the Narmada Rift also appear to be compatible with this three plate scenario, as the spreading/rifting in the Laxmi and Gop basins were also inferred to have commenced during the same period. In such a scenario, the extinct spreading centers of the Gop and Laxmi basins may represent the two ridge axes of an once-active ridge-rift-ridge ternary system of crustal divergence, where the Narmada Rift represented the third, rift arm. Such a proposition, have also been forwarded by Malod et al. (1997). If this assumption about the presence of a ternary system of crustal divergence is correct, then it requires the existence of two separate continental blocks of Indian peninsula across the Narmada Rift at that time. The geological scenario of Indian peninsula appears to support the existence of two such continental blocks. As discussed earlier, the Narmada Rift is considered to have developed along a prominent, ancient line of weakness, which was a Proterozoic proto-continental suture between the northern, Aravalli protocontinent and the southern, Dharwar protocontinent (Naqvi 2005; Sharma 2009). Therefore, when the Narmada Rift developed along that suture, it was causing divergence of the above mentioned two protocontinents. In view of these we feel, for our model we can reasonably assume the existence of a northern Indian protocontinental block (NPB), which is equivalent to Aravalli protocontinent and a southern Indian protocontinental block (SPB), which is equivalent to Dharwar protocontinent. Further, according to Biswas (1982) the Surat Depression is the offshore extension of the Narmada rift graben trend. In view of such assumption, the genesis of Gop and Laxmi basins can be explained as results of crustal divergences between Greater Seychelles [Seychelles + Laxmi Ridge] and NPB and Greater Seychelles and SPB, respectively. It may be mentioned here that all earlier workers explained the early evolution of the WCMI-ADOB region in terms of a two-plate system. In contrast to those models, we considered the scenario as a three-plate system.

Since this three-plate system required a triple junction to connect the intervening ternary system of crustal divergence, so we postulate the existence of such a triple junction and for ease of further reference in this article we denote that postulated triple junction as Gop-Narmada-Laxmi (GNL) Triple junction. It can be seen (Fig. 3) that, between Saurashtra peninsula and the bight of the Laxmi Ridge, there exists an anomalous wide gravity high zone (AGHZ) centered around 19°30′N, 67° 00′E. Interestingly this AGHZ has similar orientational attitude as the Laxmi Ridge, including its bight. Based on the magnetic anomaly patterns over and around this AGHZ (Yatheesh 2007), it appears that the NW-SE trending Laxmi Basin extinct spreading center and E-W trending Gop Basin extinct spreading center abut this AGHZ. We are tempted to speculate that the central part of this AGHZ perhaps represent the present day location of that postulated fossil GNL triple junction. We further believe, the bight of the Laxmi Ridge also supports the postulation of a triple junction, because such a shape can be inherited by a margin close to a triple junction, where two initial plate boundaries met at an angle. Having postulated the triple junction and its axial framework, we now examine the possible time when the GNL triple junction might have come into existence and its probable genesis.

As has been discussed earlier (in Sect. 2.4.1), an oceanic spreading in the Laxmi Basin had started by the time of C30no (~67.6 Ma), hence we believe the triple junction can not be younger than ~67.6 Ma. To guess the minimum older age bound for formation of the triple junction, we considered that the triple junction might have developed as a result of domal uplift of the crust, which preceded the Réunion hotspot related DFB volcanism. According to Basu et al. (1993) the earliest manifestations of DFB volcanism are the alkaline volcanic and intrusive complexes in extensional areas north of the main DFB province, and those volcanics are dated ~68.5 Ma. It is interesting to note that even a more recent study of Chenet et al. (2007) also identified an older pulse of DFB volcanism between 68 and 67 Ma. In consideration of these above, we believe that the triple junction off Saurashtra perhaps have developed around 68.5 Ma, i.e. contemporaneous with the earliest manifestation of DFB volcanism. We admit that this assumed time of the formation of the GNL triple junction is poorly constrained, but the existence of a ternary rift pattern off Saurashtra well before chron C30no (~67.6 Ma) appear as a reasonable assumption. Further, although the ternary rift pattern appears to be very similar to situations which lead to splitting of continents in many parts of the world (Burke and

Dewey 1973), this could have also been the outcome of a thermally-induced extensional rifting or a mantle convection induced rifting. Therefore, instead of our assumption, that the genesis of this triple junction is due to crustal doming preceding DFB volcanism, there could be other reason for the genesis of this triple junction. However, due to spatial proximity of the triple junction with the DFB province it may not be unreasonable to assume a causal relationship amongst them as we have assumed. However we feel it puzzling, that neither the pre-existing horst-graben complex closer to west coast of India nor the Cambay rift system evolved into oceanic spreading, when that area came under the influence of Réunion hotspot. Instead the regions of Laxmi and Gop basins, which were further to the west, evolved into oceanic spreading. Possibly this suggests that the Gop–Laxmi basins area, before it came under the influence of Réunion hotspot, was already experiencing some tensional stress, due to development of some pre-Deccan thermal build-up or asthenospheric convection underneath. As a result of which a “ternary rift pattern” had already developed in that region, and that could get easily accentuated under the influence of Réunion hotspot, when it arrived in the adjacent region. If our interpretation of Gop and Laxmi basins magnetic anomalies are correct, then they point towards existence of such a pre-DFB event extension regime in these two areas.

2.5 *Seamount Chain of the Laxmi Basin*

Three prominent seamounts, namely Raman Seamount, Panikkar Seamount and Wadia Guyot, exist along the axial part of the Laxmi Basin (Figs. 2 and 3). Together, these three seamounts form a ~N30°W trending linear seamount chain of about 250 km length. These seamounts are the first ones in the Arabian Sea whose detail bathymetry has been established through swath-bathymetric investigations (Bhattacharya et al. 1994b) and they were found to be considerably large in dimensions. The basal areas of these three seamounts range between 300–1200 km^2 and heights range from 1068 to 2240 m. These basal areas and heights are with reference to the surrounding seafloor. Therefore, considering the presence of 1–2 km thick sediment overburden on the surrounding areas (Naini 1980), the actual heights and basal areas of the seamounts, with respect to the basement, will be much greater. The morphology of these seamounts are characterized by relatively flat summit surface, secondary peaks, steep lower flanks with terraces at places, and an extensive pattern of dendritic gully like features. These gullies resemble a relict drainage pattern of sub-aerial erosional origin. Hence, we infer that during course of their growth, those seamounts became wholly/partially sub-aerial for some protracted period during which they experienced erosion, which resulted in the formation of dendritic drainage pattern. The seamounts subsequently subsided and during the course of subsidence, wave-base erosion caused formation of flat terraces/surfaces. Seismic reflection profiles available over Raman and Panikkar seamounts indicated (Srinivas 2004) that the top of those seamounts are covered with ~500 ms (TWT) thick acoustically transparent sedimentary unit.

This thickness is comparable with the thickness of similar acoustically transparent sedimentary unit observed in seismic records at DSDP drill site 219 in the adjacent Laccadive Plateau. Most likely, these acoustically transparent sedimentary unit over the seamounts represent the carbonate reef build up structures, when the seamount was slowly subsiding from very shallow water depths. This reef build up stopped at some stage, probably when the subsidence rate outpaced the rate of reef growth.

As mentioned in Sect. 2.4.1, this seamount chain clearly overlies the narrow quasi-linear NNW-SSE trending basement high zone, which characterizes the axial part of the Laxmi Basin. When viewed in conjunction with the interpreted magnetic lineations of the Laxmi Basin, it appears that the extents of the seamounts are restricted within the basement younger than chron C28no ($\sim$63.6 Ma). From this we infer that the formation of seamounts has started some time during chron C28n, or in other words they are not older than $\sim$63.6 Ma (i.e. chron C28no). Bhattacharya et al. (1994b) attributed the genesis of the seamount chain to an anomalous volcanism resulting from the interaction of the Réunion hotspot with the extinct or waning Laxmi Basin spreading centre, when they were in close proximity. As will be shown later from the predicted location of Réunion hotspot, the Laxmi Basin spreading center was in close proximity of the hotspot during chron C28n. Thereby, inference of Bhattacharya et al. (1994b) about the genesis of the seamounts looks reasonable.

We believe the growth of the seamounts could not have stopped before cessation of spreading along the spreading centre, because in that case the continued spreading would have caused seamount edifices to be splitted into two halves. It may be mentioned here that the seamount complex of Guadalupe Island of eastern Pacific Ocean is also located above an extinct spreading center, but there it is inferred that the building up of Guadalupe seamount complex commenced probably several million years after the spreading center became extinct (Batiza 1977). Such a post spreading-abandonment genesis can also be argued for the Laxmi Basin seamounts. But, that option appears unlikely in the case of the Laxmi Basin seamounts, because the presence of a hotspot in the vicinity and thereby hotspot–spreading ridge interaction is apparent here, whereas there is no evidence of a hotspot activity in the vicinity of Guadalupe seamount complex. From these, we infer that volcanism along the Laxmi Basin seamounts also stopped simultaneously with the extinction of Laxmi Basin spreading center during chron C25r, when the seamount area moved far away from the area of influence of the Réunion hotspot.

The dendritic gullie pattern observed over the Laxmi Basin seamounts was inferred to have been caused by sub-aerial erosion. A sub-aerial erosional origin of these gullies necessitates emergence of the entire edifices above sea level and subsequent subsidence by about 3700 m (Bhattacharya et al. 1994b). A subsidence of this magnitude appears to be anomalously high as compared to the inferred (Whitmarsh et al. 1974) subsidence of only 2075 m of the nearby DSDP Site 219 over the Laccadive Plateau. Perhaps this difference in subsidence amounts is indicative of differing lithospheric domains of the Laccadive Plateau and the Laxmi Basin. The Laccadive Plateau region subsided less as this area corresponds to thicker continental lithosphere, whereas the seamounts subsided more as their loads were emplaced over relatively thinner oceanic lithosphere of the Laxmi Basin. The sedimentary history of DSDP Site 219 over the nearby Laccadive Plateau in the south suggested that, after deposition of shallow water (water depths of less than 100 m) limestones, sandstones and siltstones of Late Paleocene age (ibid.) on a subsiding foundation, the site began to sink in Early Eocene (56.0–47.8 Ma) time. We presume that the Laccadive Plateau started subsiding only when the area was no more under the influence of Réunion hotspot, which had caused bulging of crust in that area. Further, as the location of DSDP Site 219 is much southwards of the Laxmi Basin seamounts, therefore we can also assume that the effect of Réunion hotspot on the Laxmi Basin seamounts area might have stopped before the time its influence stopped in the area of Site 219. In view of these, we infer that the seamounts started subsiding after their growth stopped some time during chron C25r (~57.6–56.4 Ma). Perusal of seismic reflection records across Raman Seamount does not indicate any deformation of the flanking sequence of Indus Fan sediments. This perhaps indicates that the subsidence of seamounts stopped before the Indus fan sediments were deposited in the Laxmi Basin area, probably around Middle to Late Oligocene time (i.e. ~23.0–28.0 Ma). Subsidence of the Laxmi Basin seamounts could have even stopped earlier, but definitely not at a time younger to this period.

It may be mentioned here that so far no plate-tectonic evolutionary model of the Western Indian Ocean has taken cognizance of these Laxmi Basin seamounts. Therefore we attempted to weave into our model the broad sequence of events, which we think are inferable from the Laxmi Basin seamounts.

2.6 The Laccadive Basin

The Laccadive Basin (LAB) is a narrow triangular shaped basin lying (Fig. 2) between the Laccadive Plateau in the west and the continental slope of south-western India in the east. Towards north, this basin appears to extend up to ~16°N, where the northern extremity of the Laccadive Plateau apparently converge with the adjacent continental slope off central part of western India. Towards south, this basin appears to open into the Central Indian Basin (Bhattacharya and Chaubey 2001). However, in consideration of a recent study (Yatheesh et al. 2013b) we consider that the southern extent of the Laccadive Basin, to a large extent, abuts the Chain–Kairali Escarpment (CKE). The water depth in this basin varies from ~2000 m in the north to ~2800 m in the south. The width of the basin gradually decreases from ~215 km in the south to ~70 km in the north. The basement of this depression is complicated by normal faulting and a series of basement tilted blocks. The total thickness of sediments varies broadly between 200 and 3200 m but at few places it reaches a maximum value of about 5500 m. The underlying basement widens and deepens towards south and is characterized by several basement high features (DGH 2014; Bhattacharya and Chaubey 2001 and references therein). As rightly pointed out by Gunnell (2001), the exact nature of the crust underlying the LAB has not been established as yet. Based on observations of rotated fault blocks akin to half-grabens, which flank a central basement high, Chaubey et al. (2002b) suggested that the basin represents a failed rift and volcanism of the stretched continental regime. While studying the morphotectonic architecture of the adjacent submarine Alleppey Trivandrum Terrace Complex (ATTC), Yatheesh et al. (2013b) have demonstrated by gravity anomaly modelling, that the crust in the LAB region could either be a much thinned continental crust or an anomalously thick oceanic crust.

So far no seafloor spreading type magnetic lineations have been reported from any part of this basin. It could be that the seafloor spreading type magnetic anomalies actually existed in the Laccadive Basin, but they were obscured by overprinting of Réunion hotspot related volcanism, when that hotspot was close to the area between ~60–55 Ma. In view of this ambiguous nature of the underlying crust and to explain its triangular shape, for the present study we consider that Laccadive Basin was formed as a result of a crustal divergence that separated Laccadive Plateau from southern Indian peninsula and the rift/spreading ridge that caused this divergence gradually progressed from south to north. Further, we also assumed that the LAB divergence system were active during the interval between stoppage of N-S trans-tensional movement along eastern Madagascar margin and initiation of margin oblique seafloor spreading between Laccadive Plateau and eastern Madagascar. We came to this conclusion because, as will be discussed later, the shear movement across CKE appears to have taken place between southern Laccadive Plateau and SE coast of Madagascar on one side and the ATTC region on the other side.

2.7 India–Madagascar–Seychelles Separation Related Volcanisms

Various researchers considered that the separations of India, Madagascar and Seychelles are causally and temporally related to two widespread and few localized volcanic emplacements evident on the land areas of these continental blocks. The older of these two widespread volcanic emplacements, considered to be related to separation of India and Madagascar, is Late Cretaceous in age and is represented by the ~83.6–91.6 Ma aged Cretaceous volcanic rocks of Eastern Madagascar, the ~85–91 Ma aged igneous rocks of southwestern India and the St. Mary Islands on the adjacent Indian offshore (Valsangkar et al. 1981; Storey et al. 1995; Torsvik et al. 2000; Pande et al. 2001; Melluso et al. 2009; Radhakrishna and Joseph 2012). These older set of igneous rocks are considered to have resulted, (i) either as direct magmatism of Marion hotspot, where thick lava piles at Volcan de l'Androy located in the southeastern Madagascar mark the focal point of the Marion hotspot activity, or (ii) from the rift related extensional processes initially induced by Marion hotspot (Torsvik et al. 2000). It may be worthwhile to note that on the Madagascar side such igneous rocks are considered to be present almost along the entire stretch of straight eastern coast of Madagascar, whereas on the Indian side such older igneous rocks could only be found in the areas of southwestern India. An explanation (Kumar et al. 2001) for this enigmatic absence of those older igneous rocks on northern and central part of western India could be that those rocks, even if exists, presently underlie the younger DFB volcanics, which almost entirely covers those regions. We think a satisfactory explanation for such a conspicuous absence is required to be found, as it may provide better understanding of the process by which the initial wide rift zone between India and Madagascar developed.

The second of these two widespread volcanic emplacements, is represented by the extensive and mainly tholeiitic Deccan Trap Flood Basalts (commonly known as Deccan Traps but referred as DFB; see Misra et al. 2014), which encompass an area of about 500,000 km^2 of the western and central India. The published literatures suggest considerable difference of opinion regarding the age, duration and even about genesis of DFB volcanism. It was generally believed (Courtillot et al. 1988; Vandamme et al. 1991; Hooper 1999; Sen 2001) that bulk of DFB erupted around 65–66 Ma within a simple C30N-C29R-C29N magnetic polarity sequence and a large fraction of the activity to have taken place during the middle reversed chron C29R. On the contrary to this general belief, Pande (2002) based on a critical evaluation of the available absolute age data and paleomagnetic constraints, concluded that DFB volcanism continued over a prolonged period from ~69 to ~62 Ma with several episodes of eruptions punctuated by periods of quiescence and the most intense pulse occurred around ~67 Ma (~chron C30R). Further, according to him (ibid.) the duration of DFB volcanic activity, instead of a simple C30N-C29R-C29N magnetic polarity sequence, appears to have continued over a longer period encompassing several N-R-N magnetic polarity sequences. In a later publication, Courtillot and Renne (2003) maintained support to the theory of short duration (~1.0 myr) of DFB volcanism and concurred with the results of Hofmann et al. (2000) that bulk of Deccan volcanics erupted close to 65.5 Ma. The more recent study of Chenet et al. (2007) identified two pulses of DFB volcanism. The smaller but significant earlier pulse of volcanism was between 68 and 67 Ma, and after a quiescence of about 2–3 Ma the major phase of volcanism occurred around 65 Ma.

The genesis of DFB is another subject of debate. Many researchers (e.g. Morgan 1981; Courtillot et al. 1986; Devey and Stephens 1991) believe this to have been caused by plume magmatism when the Indian Plate came over the Réunion hotspot. However, Sheth (2005) has contested the plume theory as far as the origin of the DFB is concerned and proposed a non-plume, plate-tectonic model involving continental break-up and related mantle convection and decompression melting. According to Bhattacharji et al. (1996), the onset of the main DFB eruptions during 67–64 Ma was with concurrent reactivation of the intra-plate Narmada Rift and N-S crustal extension. The peak of eruptive activities occurred at 65–66 Ma with propagation of dikes from a plume center located at the intersection of the present day Narmada and Cambay rifts. Some authors (Chatterjee and Rudra, 1996; Chatterjee et al. 2006) even suggested that DFB volcanics owes its origin to magma generated from melting of the lithosphere caused by a large bolidal ('Shiva bolide') impact in the areas near the present day 'Bombay High'. We do not have any evidence to support or contradict this bolidal impact theory, but some behaviours of the seafloor spreading systems of the WCMI-ADOB region appears to suggest passage of the region over the Réunion hotspot. This aspect will be discussed in a later section. Mahoney et al. (2002) concluded that the Bibai volcanics from the Quetta–Zhob area of Pakistan, dated 73.4–72.0 Ma, represents the marine phase of Réunion hotspot activity in an area northwards of the main DFB province on the Indian subcontinent. Therefore, if the genesis of DFB is attributed to Réunion hotspot, then considering their (ibid.) conclusion, the Indian subcontinent region might have experienced the effect of Réunion hotspot much earlier than believed so far. Discussion about the merits/demerits of these inferences related to age, duration etc. of DFB is beyond the scope of the present article. We mentioned these aspects only to highlight that knowledge about the age, duration, main phase of DFB volcanic activity, genesis etc. of DFB, as it stands today, is not sacrosanct and it is still evolving. Some of these changes appear to have resulted due to evolution of geochronological dating techniques or geochemical analysis tools and methodologies. In view of this situation, we urge caution while anchoring interpretation of other geophysical data, particularly related to evolution of WCMI-ADOB region on the existing knowledge about the age, duration, genesis etc. of DFB.

The other localized volcanics considered to be related to India–Madagascar–Seychelles separation, are represented by the Late Cretaceous–Paleocene volcanic rocks from the islands and offshore areas of the continental fragment of the Seychelles Plateau and the Amboronala volcanics of the northeast coast of Madagascar. Some of these volcanic occurrences of Seychelles region are the ~69–73 Ma aged tholeiitic dykes of Praslin Island, the ~60–63 Ma aged alkaline rocks of the Silhouette and North Islands (Plummer and Belle 1995 and references therein) and the 63.7 ± 1.1 Ma aged tholeiitic basalts drilled at ODP site 707 (Duncan and Hargraves 1990). It was inferred (Devey and Stephens 1991) that the tholeiitic dykes of Praslin Island are geochemically very similar to the Bushe formation magmas of the DFB. Ganerød et al. (2011) have recently provided a revised dating between 63.0 and 63.5 Ma for the alkaline rocks of the Silhouette and North Islands. From the isotopic and trace element compositions of the Seychelles alkaline suite, Owen-Smith et al. (2013) concluded that these magmas were derived from the Réunion hotspot source, equivalent to that of the DFB, with an additional minor contribution from an enriched source, likely sub-continental mantle lithosphere. Thus it can be seen that the volcanics of the Seychelles Plateau area, which are believed to be related to DFB event have a wide range of age starting from 73 Ma (which is nearly the age of Bibai volcanics mentioned earlier) to 63.0 Ma, which is the age of the oldest magnetic anomaly identified north of Seychelles. It is agreeable that this age range is nearly same as of DFB, and on that basis Late Cretaceous–Palaeocene volcanic rocks of Seychelles Plateau region can surely be considered as coeval with DFB, but it is not clear to us, how confidently one could say that this Late Cretaceous–Palaeocene volcanics of Seychelles Plateau surely were derived from the Réunion hotspot source.

The southern part of Seychelles Plateau is considered to have been separated from the northeastern continental margin of Madagascar. According to Plummer (1995) the ~91.0 Ma dated (Randrianaloso et al. 1981 cited in Plummer 1995) volcanics present at the Amboronala on the northeast coast of Madagascar relates to the short phase of transform rifting and pull-apart basin formation that separated Seychelles Plateau from Madagascar. However, volcanics are yet to be recognized in Seychelles Plateau related to the rift between Seychelles Plateau and Madagascar, which is predicted to have occurred at around 96–84 Ma (Plummer 1995).

2.8 Constraints from Madagascar

Madagascar is the largest island (Fig. 6) of the Indian Ocean area. By now it stands well established that Madagascar, Seychelles Plateau and India were once a conjoined continental landmass in the Gondwanaland framework. In that conjoined framework, the straight edges of eastern and northeastern Madagascar are considered to have been facing the western India and southern Seychelles Plateau respectively. Even though researchers agree on the concept of this conjoined Madagascar-Seychelles-India continental landmass, opinions differ regarding their exact juxtaposition, in particular in their immediate pre-drift scenario. Probably lack of distinct and dependable 'piercing points', which could have constrained these juxtapositions, is one of the reasons for such varied inferences.

Considerable research has been carried out to examine the compatibility and congruity of the onshore geological and tectonic scenario of Madagascar and India. Although, such relationship do not appear to be straightforwardly discernible, still in broad sense the Precambrian geology of Madagascar and the south Indian shield area have geological affinity in many aspects. For example both India and Madagascar are characterized by Archean-greenstone terrains to the north and the Proterozoic granulite terrains to the south (Yoshida et al. 1999 and references therein). The Precambrian terrain of Madagascar, like the Precambrian terrain of the southern India, also contains several shear zones, the most prominent of which are the Ranotsara Shear Zone and Angavo Shear Zone. Based on lithological and geochronological similarity, two cratonic strips of eastern Madagascar are considered to be 'chipped-off-parts' of the westernmost boundary of the Western Dharwar Craton (WDC) of India. These cratonic strips are the Antongil and Masora cratonic blocks, which are located close to the northern and central part of eastern coast of Madagascar (Raval and Veeraswamy 2003 and references therein). The eastern Madagascar contains a remarkable continental scale topographic scarp, which according to Subrahmanya (2001) appear as a mirror image of the Western Ghat Escarpment of western Indian Peninsula. We found this feature interesting in the context of India—Madagascar juxtaposition and rifting and therefore included in our proposed model. Gunnell and Harbor (2008) denoted this feature as 'Angavo Escarpment' and made detail examination of its morphological similarities with the Western Ghats Escarpment of India. The Angavo Escarpment (AnE) is manifest as the steep eastern edge of the westward tilting central highlands of Madagascar (Fig. 6). This AnE is nearly 1000 km long lineament that is even perceptible in the

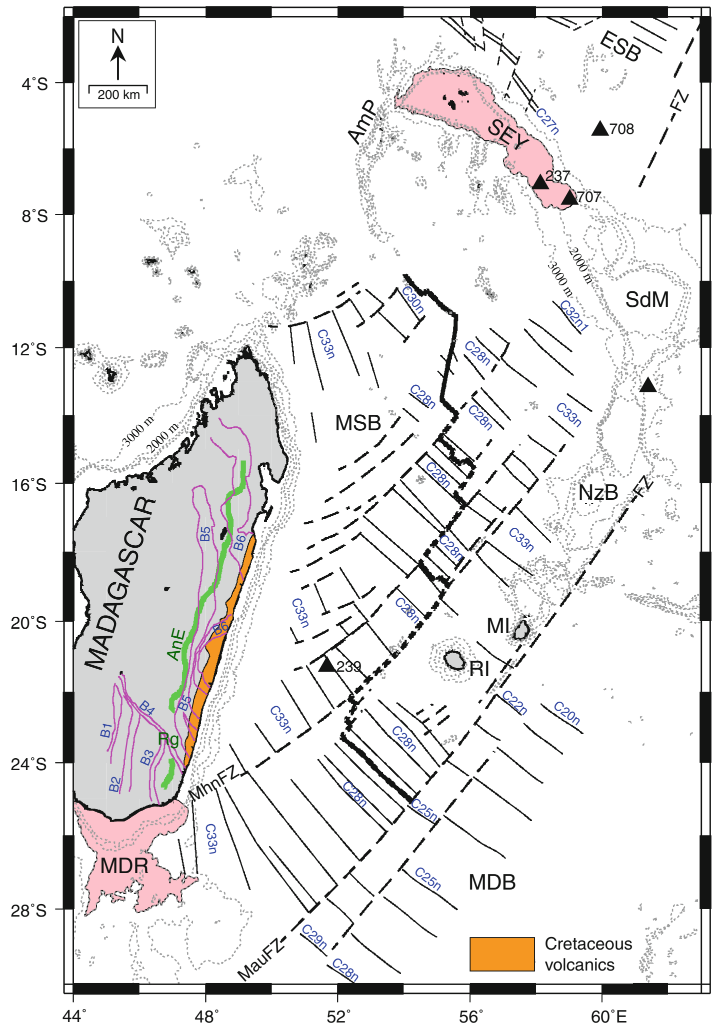


Fig. 6 Generalized map of the land and deep ocean basin areas adjoining the Seychelles–Mascarene Plateau Complex and Madagascar for depicting the locations of various onshore and offshore tectonic elements referred in the text. These tectonic elements were compiled from several publications (Eagles and Wibisono 2013; Ratheesh-Kumar et al. 2014; Matthews et al. 2011). *Thick green line* (labeled AnE) along the eastern edge of Madagascar mainland represents Angavo Escarpment (digitized from satellite imagery available at http://en.wikipedia.org/wiki/File:Madagascar_sat.png). *Pink lines* over land areas represent the inferred shear zones. *B1* Amphanihy Shear Zone; *B2* Betroka Shear Zone; *B3* Tranomaro Shear Zone; *B4* Ranotsara Shear Zone; *B5* Angavo Shear Zone; *B6* Betsimisaraka Shear Zone. Other abbreviations used are as in Table 1 and the other details are as in Figs. 1 and 2

satellite imagery. The westward tilt of the central highlands is highlighted by westward course of all major drainage systems over it. The AnE has a major topographic breach in its continuity, the Ranotsara Gap. This Ranotsara Gap (Rg) and the Palghat Gap (Pg) of India is considered to have common genesis in a cross-cut Precambrian shear zone (Palghat–Cauvery Shear Zone) structure that continued from India to Madagascar (Gunnell and Harbor 2008). The present day location and morphology of this escarpment possibly is also the outcome of various processes, such as, denudation, scarp retreat and marine regression. The eastern and north-eastern edges of Madagascar contain volcanic emplacements that are inferred to be related to separation of Madagascar from India and Seychelles and we have discussed those volcanic emplacements in the preceding section.

The continental shelf of Madagascar is generally narrow, averaging about 25 km in width. At some places, all along the northeast coast, no shelf is present. The straight east coast is bordered by the narrow shelf whose edge appears as a fault scarp (Pepper and Everhart 1963). Transform motion between India and Madagascar dating prior to the opening of the Mascarene Basin has been suggested as responsible for the linearity of the shelf, but its details are controversial. From the characteristics of gravity anomalies, a strip of extended continental crust appears to exist in the eastern continental margin of Madagascar further eastwards of the continental shelf (Eagles and Wibisono 2013). The landward terminations of fracture zone traces in satellite derived gravity anomalies map appears to suggest that such extended continental crust is predominant in the areas off the central part of eastern Madagascar.

2.9 Constraints from Seychelles

The Seychelles Bank is the northern end of a long arcuate complex [Seychelles–Mascarene Plateau complex (SMP)] of wide, partially isolated shallow banks and small islands, that is located (Figs. 1 and 6) in the areas between Madagascar Island and the Central Indian–Carlsberg ridge segments. Except the Seychelles Bank part, the genesis of other parts of SMP still remains ambiguous. Although situated in an oceanic environment, the continental character of the Seychelles Bank has been confirmed from the presence of Precambrian granitic rocks, of ~700 Ma age, as basement of many of the islands. The seismic refraction profiling also indicated a continental crustal thickness of ~33 km beneath the Seychelles Bank (Laughton et al. 1970; Khanna and Walton 1992 cited in Plummer and Belle 1995; Collier et al. 2009 and references therein). Being surrounded by oceanic crust, the Seychelles Bank thus qualified as a Precambrian continental fragment in the Western Indian Ocean. This oval shaped bank, of an area of about 80,000 km^2, has an almost flat top lying at an average water depth of 50 m. The edge of the bank is well defined by steep slopes, which drops to depths exceeding 3000 m in all directions, except for the southwest and the southeast. The Seychelles Bank is connected by a 2000 m deep saddle to the Amirante Plateau in the southwest, whereas to the southeast it abuts a 1500 m deep saddle [Seychelles-Saya de Malha saddle (SSM)] that in turn connects with the other elements of the SMP (Bhattacharya and Chaubey 2001 and references therein). The crustal nature of complete SSM up to Saya de Malha Bank is not yet established. However, the seismic data (Plummer 1996) suggested the presence of tilted fault blocks akin to rifted continental crust near the location of DSDP site 237 and ODP-707. Further, the basalts drilled at ODP site 707 (dated at 63.7 ± 1.1 Ma) was inferred to have been extruded sub-aerially or in very shallow water during a period of transition between continental rifting and the initiation of the spreading center (Duncan and Hargraves 1990; Plummer 1995). In view of these, we have considered that the continental crust regime of the Seychelles Bank area extends at least up to the location of ODP site 707 and refer that extended continental crust regime as Seychelles Plateau. The remaining part of the SMP perhaps was formed as a result of passage of the region over the Réunion hotspot (Duncan 1981; Morgan 1981). Rifting between NE Madagascar and the Seychelles Plateau was probably in the form of a pull-apart basin that was initiated between 100 and 95 Ma from a releasing bend that joined the East African–Tethyan transform fault and the transform fault adjacent to eastern Madagascar. The Amirante Plateau (AmP) is a ~400 km long arcuate conjoined ridge-trough system, which extends southwards from northwestern limit of the Seychelles Plateau. Genesis of the AmP still remains an enigma. Some researchers (Plummer and Belle 1995; Plummer 1996) opined that AmP developed due to complex geodynamics effected modification of a transform boundary that coincided with northernmost point of Madagascar and western most point of Seychelles. While Mukhopadhyay et al. (2012) suggested that AmP is the product of a short duration subduction event in the northern Mascarene Basin region, when the oceanic crust of the area experienced compression due to the combined effects of commencement of spreading of the Carlsberg Ridge and cessation of spreading in the Mascarene Basin.

2.10 Constraints from Mascarene Basin

The Mascarene Basin (Fig. 6) is bordered on the west by the steep and linear eastern margin of the Madagascar Precambrian massif and to the east by the arcuate Seychelles–Mascarene Plateau complex. The northerly extent of the Mascarene Basin is considered to be defined by a boundary joining the northern tip of the Madagascar Island, the Farquhar Group of Islands, the Amirante Plateau and the Seychelles Plateau, while the NE-SW trending Mauritius Fracture Zone is considered to define its southerly boundary. The fact that Mascarene Basin represents an oceanic domain formed by an extinct seafloor spreading regime was recognized during the initial magnetic studies of the region (Schlich 1982 and references therein). However, apparently due to paucity of data and complexity of magnetic fabric, the identifications of anomalies and fracture zones at that time were restricted only to the southern part of the basin. Several subsequent studies (Dyment 1991; Sahabi, 1993; Bernard and Munschy 2000; Bissessur et al. 2009; Eagles and Wibisono 2013) aided with more magnetic transects, satellite derived gravity anomalies and other tectonic informations, improved the identifications of magnetic lineations and fracture zones and extended many of those identifications even to the northerly part of the basin. The present understanding is that the Mascarene Basin contains two-limbed magnetic anomalies sequence C34ny through C27ny and the spreading became extinct some time shortly after chron C27ny. Further, the extinction appeared to have progressed gradually from the north across the basin. The magnetic lineations trend approximately northwest-southeast and series of northeast-southwest trending fracture zones offset the magnetic lineations. The Mascarene Basin is considered to be divided into northern and southern parts. The geometrical relationship of the magnetic lineations with the adjacent Madagascar continental margin is different in these two parts. The southern Mascarene Basin is adjacent to the straight eastern edge of the Madagascar and the oldest magnetic lineations are oblique to this straight margin. The northern Mascarene Basin lies eastwards of the straight north-eastern edge of the Madagascar peninsula and the magnetic lineations in that area are margin parallel. The widths of the oceanic crusts accreted during same periods are also different in these two parts. The oceanic crust of the southern Mascarene Basin is relatively wider as compared to contemporary oceanic crust of northern Mascarene Basin. It has been earlier believed that the northern Mascarene Basin sector evolved due to ocean crust accretion between the Seychelles Plateau and the north-eastern edge of the Madagascar peninsula, whereas the southern Mascarene Basin evolved by ocean crust accretion between the continental margins off western India and the eastern Madagascar. The Mascarene Basin appears as the northwestern continuation of the Madagascar Basin. However these two basins, despite geographical contiguity, are considered as two separate entities due to following reasons. The Madagascar Basin does not represent an extinct spreading regime oceanic crust like Mascarene Basin. Rather, the spreading in the Madagascar Basin, which commenced around chron C30ny, was a separate spreading ridge segment; where the conjugate of oceanic crust accreted during C30ny-C20ny period formed part of the Central Indian Basin in the north and the oceanic crust of further younger accretion till present lies across the Central Indian Ridge (Schlich 1982). Since anomaly C34ny (83 Ma) is the oldest identified anomaly in the Mascarene Basin off Madagascar margin, hence it is believed that the seafloor spreading in the Mascarene Basin commenced sometime during Late Cretaceous (Norton and Sclater 1979; Besse and Courtillot 1988).

However, as this time falls under the Cretaceous long normal superchron, the precise age of the rift-drift transition could not be determined from the magnetic lineations.

3 Data and Adopted Methodology

The main continental blocks/slivers, which have been considered in our reconstruction models, are India (IND), Madagascar (MAD), Seychelles Plateau (SEY), Laxmi Ridge (LAX) and Laccadive Plateau (LCP). For reference to various features in this study, we have used the nomenclatures proposed by Bhattacharya and Chaubey (2001). The term India unless specified refers to Indian subcontinent that includes the geographical and political regions of India and Pakistan.

The continent-ocean boundary in the study area is poorly constrained; as a result, the extents of the continental blocks under consideration were defined by various researchers using different criteria. Following Norton and Sclater (1979), we used the 2000 m isobaths to define the boundaries of India and Madagascar continental blocks. We defined the extent of the Seychelles Plateau by the 2000 m isobath surrounding the Seychelles Bank and part of the SSM up to the location of ODP drill well 707. The basement high feature of the Laxmi Ridge is buried under sediment and its physiographic expression lies at depths greater than 2000 m. Therefore we approximated the outline of the Laxmi Ridge based on the extents of the characteristic gravity anomaly low as decipherable from image and contours of the satellite-derived free-air gravity anomalies and the mapped seafloor spreading magnetic lineations in the surrounding Arabian (Chaubey et al. 2002a), Gop (Yatheesh et al. 2009) and the Laxmi (Bhattacharya et al. 1994a; Yatheesh 2007) basins. In this study we considered the Laccadive Plateau as a continental sliver and used the surrounding 2000 m bathymetry contour to approximate its extent. However, its southern extent have been extended (by including few isolated 2000 m contour closures in such a way that the extent of Laccadive Plateau touches the Chain-Kairali Escarpment in the reconstruction of immediate pre-drift juxtaposition.

During the course of discussion in this article, as far as possible the event timings have been mentioned with reference to an integrated geologic time scale (Table 2). The directions, wherever mentioned are with respect to present day orientations of the concerned features, they will be somewhat different if viewed in the context of their paleo-position. All the plate-tectonic reconstructions presented in this paper were computed with the software package ROTPXY (Bhattacharya and Yatheesh 2013) and the Euler rotation parameters wherever estimated in this study were made using GPlates package (Boyden et al. 2011). Finite rotation parameters describing

Table 2 Integrated geologic time scale for the period under consideration in this study. The ages of stratigraphic boundaries are based on Walker et al. (2013) and the ages of seafloor spreading magnetic anomalies are based on the geomagnetic time scale of Cande and Kent (1995)

Era	Period	Epoch		Age (Ma)	Anomaly number and Age (Ma)
CENOZOIC	Paleogene	Eocene	Middle		
				47.8	
			Early		C24n (52.36-53.35)
				56.0	C25n (55.90-56.39)
		Paleocene	Late		C26n (57.55-57.91)
				59.2	
			Middle		C27n (60.92-61.28)
				61.6	
			Early		C28n (62.50-63.63) C29n (63.98-64.75)
				66.0	C30n (65.58-67.61)
MESOZOIC	Cretaceous	Late			C31n (67.74-68.74) C32n (71.07-73.00) C33n (73.62-79.08)
				100.0	C34n (83.00-118.0)
		Early			
				145.0	

relative motions between various plates/continental slivers used for making plate-tectonic reconstruction maps in the present study are given in Table 3.

All the reconstructions presented in this study (Figs. 7a–i) are in fixed African (now Somali) plate reference frame. Earlier, in absence of directly estimated Indian–African plate Euler rotation parameters, reconstructions of India with respect to African plate were achieved by following the Indian–Antarctic and then Antarctic–African plate rotation circuit. Euler rotation parameters estimations for Indian–African plate relative motion during chron C27ny–chron C21ny, are now available (Royer et al. 2002) directly from conjugate Arabian and Eastern Somali basins magnetic picks. Similarly, Eagles and Wibisono (2013) provided the Euler rotation parameters estimations for Indian–African plate relative motion during chron C34ny to ~60.25 Ma (i.e. time of abandonment of Mascarene Basin

Table 3 Finite rotation parameters describing relative motions between various plates used for making plate-tectonic reconstruction maps in the present study. Angle is positive when the motion of the moving plate is counter clockwise with respect to the fixed plate when viewed from outside the earth. Ages are after Cande and Kent (1995). CST Cessation of spreading/rifting; INT Initiation of spreading/rifting

Chron	Age (Ma)	Finite rotation parameters			Reference
		Lat. (deg.)	Long. (deg.)	Angle (deg.)	
(a) ***Seychelles block to Laxmi Ridge*** ($_{\mathbf{LAX}}$ $\mathbf{ROT}_{\mathbf{SEY}}$)					
C25ny	55.904	19.41	29.02	30.111	Royer et al. (2002)
C26ny	57.554	19.61	25.62	30.729	Royer et al. (2002)
C27ny	60.920	18.83	24.86	35.411	Royer et al. (2002)
C28ny	62.499	23.57	−20.08	23.799	This study
Close-fit	62.800	20.75	−47.00	24.750	This study
(b) ***Laxmi Ridge to Southern Indian Protocontinent*** ($_{\mathbf{SPB}}$ $\mathbf{ROT}_{\mathbf{LAX}}$)					
CST	56.400	−8.95	78.79	0.000	This study
C26no	57.911	−8.95	78.79	−0.100	This study
C28ny	62.499	−8.95	78.79	−0.460	This study
C28no	63.634	−8.95	78.79	−1.000	This study
C29ny	63.976	−8.95	78.79	−1.740	This study
C29no	64.745	−8.95	78.79	−2.700	This study
C30ny	65.578	−8.95	78.79	−3.020	This study
C30no	67.610	−8.95	78.79	−4.200	This study
INT	68.500	−8.95	78.79	−7.500	This study
(c) ***Saurashtra Volcanic Platform to Laxmi Ridge*** ($_{\mathbf{SVP}}$ $\mathbf{ROT}_{\mathbf{LAX}}$)					
CST	56.400	20.68	56.77	0.000	This study
C28ny	62.499	20.68	56.77	−1.280	This study
C29no	64.745	20.42	60.79	−9.760	This study
INT	68.500	19.22	70.28	11.114	This study
(d) ***Laccadive Plateau to Southern Indian Protocontinent*** ($_{\mathbf{SPB}}$ $\mathbf{ROT}_{\mathbf{LCP}}$)					
CST	56.400	15.26	68.32	0.000	This study
C28ny	62.499	15.26	68.32	10.000	This study
C34ny	83.000	15.26	68.32	18.000	This study
INT	88.000	15.26	68.32	20.000	This study
(e) ***Northern to Southern Indian Protocontinent*** ($_{\mathbf{SPB}}$ $\mathbf{ROT}_{\mathbf{NPB}}$)					
CST	56.400	26.00	94.00	0.000	This study
INT	68.500	26.00	94.00	1.000	This study
(f) ***Southern Indian Protocontinent at 60.25 Ma to Madagascar*** ($_{\mathbf{MAD}}$ $\mathbf{ROT}_{\mathbf{SPB}}$)					
CST	60.250	−15.91	−163.75	0.000	Eagles and Wibisono (2013)
C27ny	60.920	−15.99	−163.66	0.570	Eagles and Wibisono (2013)
C28ny	62.499	−18.09	−160.76	2.060	Eagles and Wibisono (2013)
C28no	63.634	−17.26	−161.82	3.050	Eagles and Wibisono (2013)
C29no	64.745	−17.11	−162.41	5.060	Eagles and Wibisono (2013)

(continued)

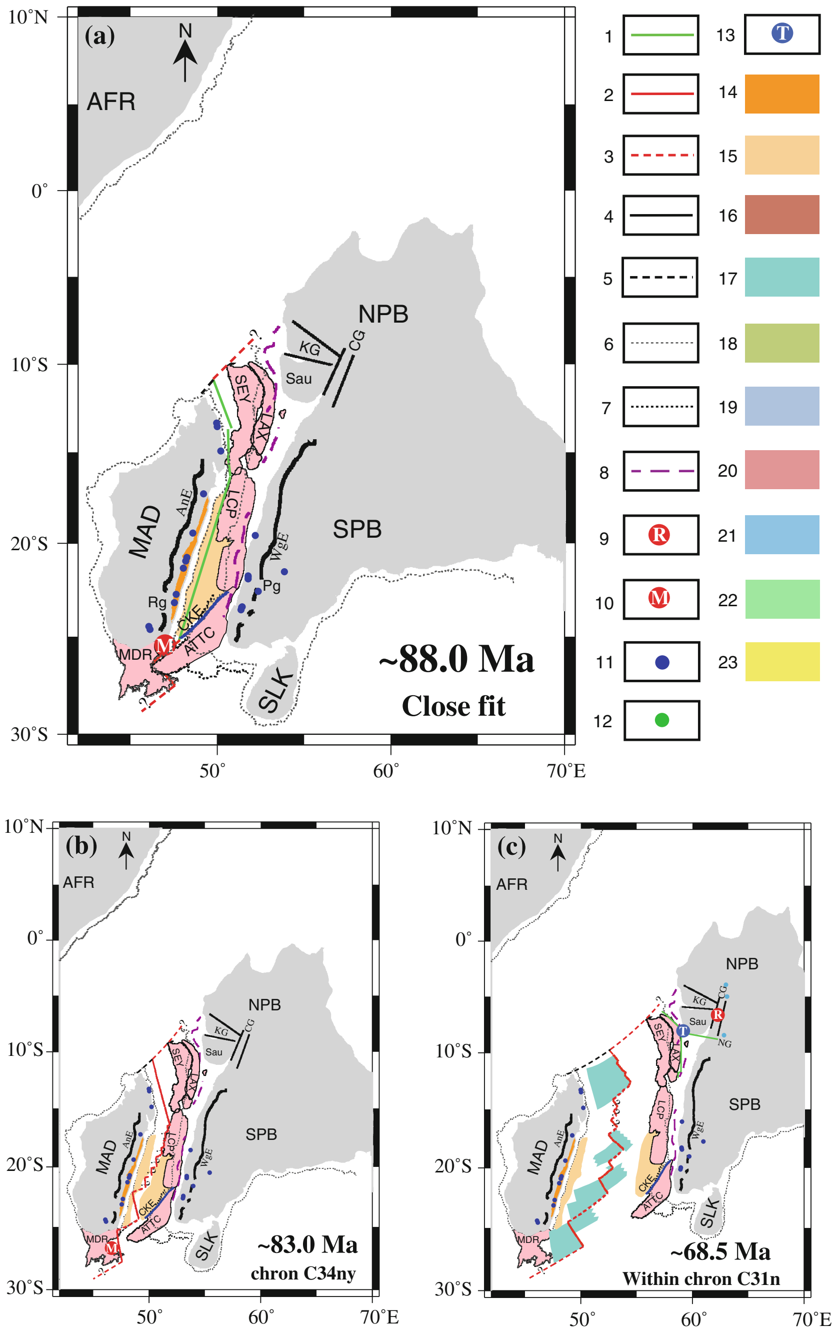
Table 3 (continued)

Chron	Age (Ma)	Finite rotation parameters			Reference
		Lat. (deg.)	Long. (deg.)	Angle (deg.)	
C30ny	65.578	−15.06	−158.30	6.940	Eagles and Wibisono (2013)
C30no	67.610	−16.73	−158.93	9.590	Eagles and Wibisono (2013)
C31no	68.737	−18.51	−160.06	10.270	Eagles and Wibisono (2013)
C32n1y	71.071	−20.29	−160.67	11.960	Eagles and Wibisono (2013)
C33ny	73.619	−22.42	−162.39	13.120	Eagles and Wibisono (2013)
C33no	79.075	−31.59	−171.23	13.580	Eagles and Wibisono (2013)
C34ny	83.000	−21.19	−152.99	18.000	This study
Close-fit	88.000	−21.19	−152.99	20.270	This study

spreading modified as per Cande and Kent 1995 timescale), directly from conjugate anomaly picks of the Mascarene Basin. Therefore we have carried out the required reconstructions in fixed African plate reference frame by using these two direct estimations of Indian–African plate relative motions. By following this route, we could also avoid the effect of deformation in the Central Indian Basin. We however adopted the Indian–African plate rotation parameters of Eagles and Wibisono (2013) for period younger to chron C34ny. We felt that the chron C34ny rotation parameters estimate of Eagles and Wibisono (2013) is not well-constrained as they had chron C34ny pick only in one flank of the Mascarene Basin. Therefore, we estimated the Indian–African plate rotation parameters for the chron C34ny and further close-fit by trial and error until we got an improved fit for the ATTC and the bathymetric notch of the northern Madagascar Ridge. For reconstructions of continental slivers (including Seychelles Plateau), we followed the following approach: (i) reconstructed sliver to India for close fit and considered that close fit sliver position as sliver's new position, (ii) reconstructed that sliver's new position to desired reconstruction time using appropriate sliver—India rotation parameters, (iii) considered those reconstructed sliver positions as fixed to Indian plate and achieved their further reconstruction with respect to African plate in the same way as was done for Indian plate.

4 Proposed Plate-Tectonic Evolution Model

We describe our views about the plate-tectonic evolution of the eastern part of the Western Indian Ocean for the period ~88.0 to ~56.4 Ma, through a sequence of plate-tectonic reconstruction maps made in fixed Africa reference frame (Figs. 7a–i). We consider this period to correspond to the early evolution of the western


(a)
AFR
NPB
KG
CG
Sau
SEY
LAX
MAD
AnE
LCP
WgE
SPB
Rg
Pg
CKE
ATTC
MDR
SLK
~88.0 Ma
Close fit
(b)
~83.0 Ma
chron C34ny
(c)
NG
~68.5 Ma
Within chron C31n

◀ **Fig. 7** Simplified plate-tectonic reconstruction maps (in fixed Africa reference frame) of the Western Indian Ocean region depicting evolution of the ocean basins and associated tectonic features discussed in this study. **a** Reconstruction for a close-fit juxtaposition of involved continental blocks at 88.0 Ma (Late Cretaceous). **b** Reconstruction for chron C34ny (~83.0 Ma, Late Cretaceous). **c** Reconstruction at 68.5 Ma (within chron C31n; Late Cretaceous). **d** Reconstruction for chron C30no (~67.6 Ma, Late Cretaceous). **e** Reconstruction for chron C29no (~64.7 Ma, Early Paleocene). **f** Reconstruction for chron C28ny (~62.5 Ma, Early Paleocene). **g** Reconstruction for chron C27ny (~60.9 Ma, Middle Paleocene). **h** Reconstruction for chron C26no (~57.9 Ma, Late Paleocene). **i** Reconstruction for chron C25no (~56.4 Ma, Late Paleocene). *NG* Narmada rift graben dividing the Indian continental areas into northern (NPB) and southern (SPB) proto-continental blocks: Explanation of items of the legend—*1* Rift axis; *2* Ridge axis; *3* Transform fault; *4* Extinct spreading centre; *5* Paleo Transform fault; *6* 2000 m isobath; *7* 2500 m isobath; *8* Paleo shelf edge; *9* Réunion hotspot location for the time of the presented reconstruction. Trailing open circles corresponds to the predicted Réunion hotspot locations for times of successive previous reconstructions; *10* Marion hotspot location for the time of the presented reconstruction; Rift stage crust; *11* Locations of 80.0–92.0 Ma volcanics; *12* Locations of 60.0–70.0 Ma volcanics; *13 T* postulated Gop-Narmada-Laxmi (GNL) fossil triple junction off Saurashtra peninsula (Sau); *14* Deccan Trap volcanics; *15* Ultra thinned continental crust; *16* Oceanic/rift stage crust of the Laccadive Basin; *17* Oceanic crust formed during 83.0–68.5 Ma; *18* Oceanic crust formed during 68.5–67.6 Ma; *19* Oceanic crust formed during 67.6–64.7 Ma; *20* Oceanic crust formed during 64.7–62.5 Ma; *21* Oceanic crust formed during 62.5–60.9 Ma; *22* Oceanic crust formed during 60.9–57.9 Ma; *23* Oceanic crust formed during 57.9–56.4 Ma. Other abbreviations used are as in Table 1. Note that the comprehensive legend of symbols, shades, designs given in Fig. 7a as well the abbreviations provided in this caption are common to the reconstruction maps 7a–i for denoting/labelling various features. Oceanic crust was shaded only at places where identified magnetic lineations are available. Other details are as in Figs. 1, 2, 3 and 6

continental margin of India and the adjacent deep offshore basins. The reconstructions presented are for 88.0 Ma (close-fit), 83.0 Ma (chron C34ny), ~68.5 Ma (within chron C31n), ~67.6 Ma (chron C30no), ~64.7 Ma (chron C29no), ~62.5 Ma (chron C28ny), ~60.9 Ma (chron C27ny), ~57.9 Ma (chron C26no) and ~56.4 Ma (chron C25no). Recently Gibbons et al. (2013) forwarded an updated model of East Gondwanaland breakup, wherein they have incorporated several of the constraints from the Cretaceous ocean basins around India, which were not considered in earlier reconstructions. However, our model somewhat differs from theirs (ibid.) in a way, because of our detail treatment of the constraints from the WCMI-ADOB region.

4.1 From Gondwanaland to India-Madagascar Break-up, the Evolution in Brief

It is generally believed that arrangement of continents, continental fragments and ocean basins as we see today in the Indian Ocean area is related to the fragmentation and dispersal of components of the Gondwanaland. The Gondwanaland was comprised of present-day South America, Africa, Arabia, Madagascar, Seychelles, India, Sri Lanka, Antarctica, Australia and New Zealand. The fragmentation of

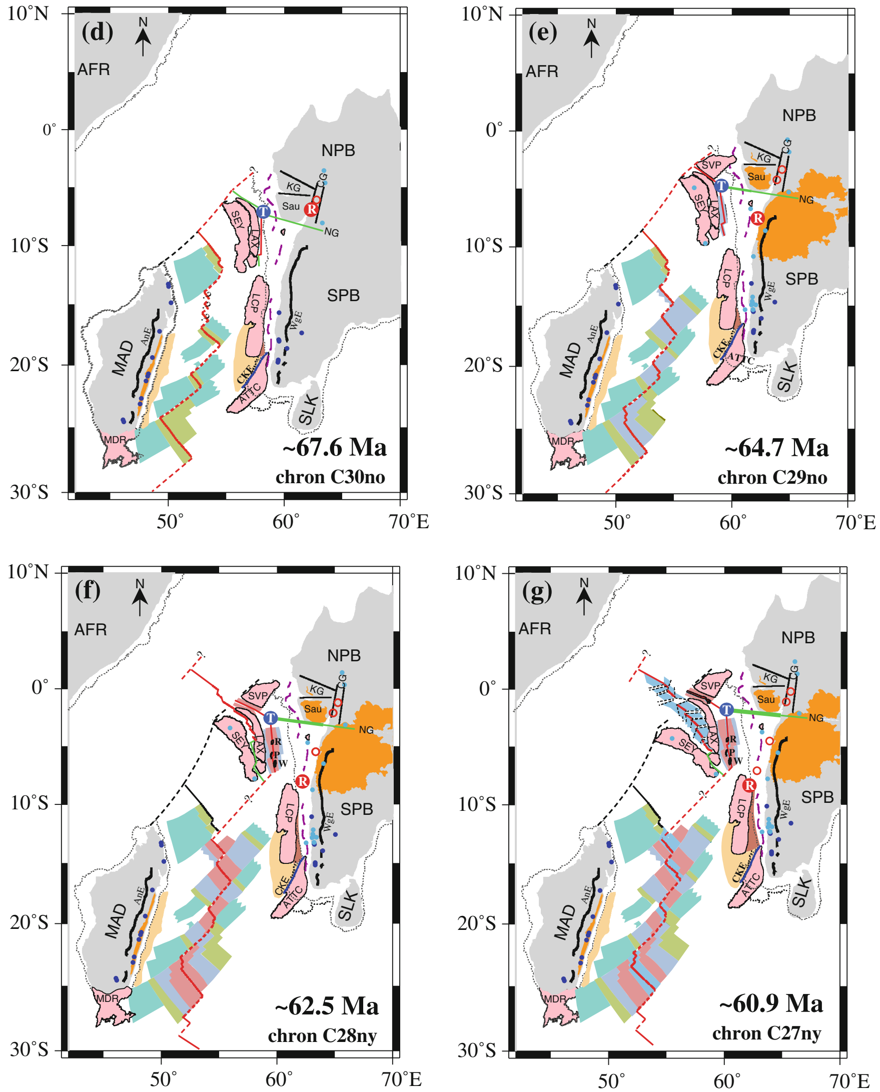


Fig. 7 (continued)

Gondwanaland seems to have resulted from its interaction with a series of hotspots or mantle plumes and the Karoo mega-plume effect is considered to be the cause (Lawver et al. 1998) of the first split of the Gondwanaland into two halves, the east Gondwanaland and the west Gondwanaland. This split was manifested with the commencement of seafloor spreading at ~150 Ma (chron M22, Late Jurassic) between those two halves along short E-W trending spreading segments offset by long N-S trending transform faults. This seafloor spreading ultimately resulted in

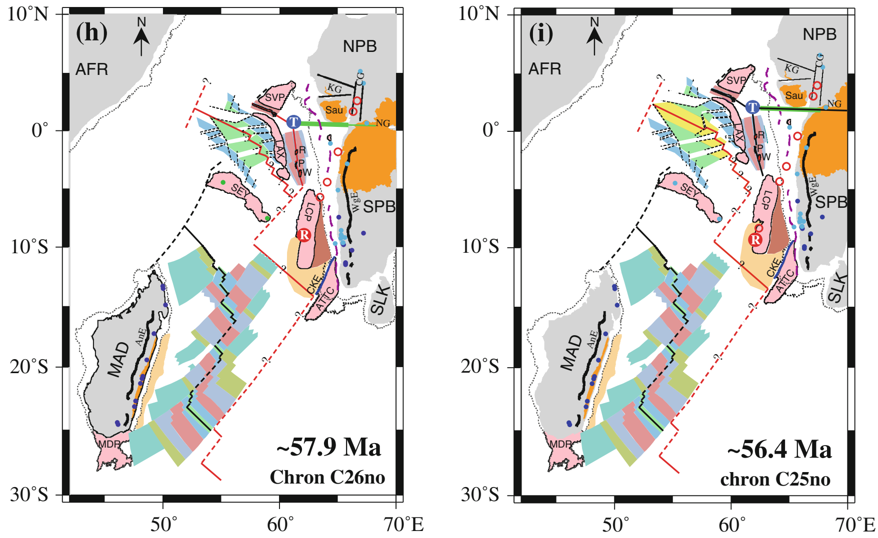


Fig. 7 (continued)

the formation of Mozambique, Western Somali and probably Northern Somali basins and thus marked the opening of the Indian Ocean. The rifting episode, which preceded this split, might have been initiated several million years before this time. After the first split, the east Gondwanaland moved south with respect to west Gondwanaland and both the Gondwanaland halves witnessed further splits in the subsequent period. The evolution of the Indian Ocean area is related to further break-up of east Gondwanaland, which consisted of Antarctica, Australia, New Zealand, Madagascar, Seychelles, India and Sri Lanka. Around 136 Ma (chron M11n, Early Cretaceous) a conjoined Madagascar-Seychelles-India-Sri Lanka continental block rifted and drifted away from conjoined Antarctica-Australia. Following separation of Madagascar-Seychelles-India-Sri Lanka block from Antarctica-Australia block, a uniform pattern of seafloor spreading continued for the subsequent ~15 myr. However, after this period the spreading pattern between Africa-Arabia and Madagascar-Seychelles-India-Sri Lanka blocks experienced a change. In the changed scenario, shortly after the time of anomaly M0 (~118 Ma, Early Cretaceous), spreading stopped in Western Somali and Northern Somali basins, while it continued in the Mozambique Basin. As a result of this spreading center reorganization, the conjoined Madagascar-Seychelles-India-Sri Lanka block got attached to African plate (Rabinowitz et al. 1983; Bhattacharya and Chaubey 2001 and references therein). The subsequent rifting and drifting of Madagascar-Seychelles-India-Sri Lanka block closely relates to the early evolution of the WCMI-ADOB region, the focus of the present paper and we discuss that part in detail in the following sections.

4.2 India-Seychelles-Madagascar Pre-break-up Close Fit Scenario (~88.0 Ma; Late Cretaceous)

Our model of early evolution of the WCMI-ADOB region begins with the presentation of a reconstruction (Fig. 7a) at about 88.0 Ma, which we infer was the time when all the continental blocks/slivers under consideration were juxtaposed in their immediate pre-drift close fit configuration. However, at that time Sri Lanka, which was attached to southeastern coast of India in Gondwanaland configuration, attained its present position with respect to India probably being separated from India by an aulacogen (Bhattacharya and Chaubey 2001 and references therein). Earlier, Yatheesh et al. (2006) ascribed this close fit time as 86.5 Ma, but we revise that time to 88.0 Ma in consideration of the average 88.0 Ma ages of the rift related volcanics emplaced on the eastern edge of the Madagascar.

At that time a wide continental rift zone of hitherto obscure origin existed between the larger continental blocks of India and Madagascar. This rift zone developed in a direction parallel to the pre-Cambrian Dharwarian basement grain and was flanked on the west by the eastern edge of Madagascar and on the east by the western edge of the Indian peninsula. In appreciation of suggestions of Gunnell and Harbor (2008) and Subrahmanya (2001) perhaps it can be assumed that the western shoulder of this major rift zone was expressed on the eastern Madagascar as the Angavo Escarpment and the conjugate eastern shoulder of the rift was in the western India as the Western Ghat Escarpment. The horst graben complex, which characterizes a major part of the present day continental shelf of western India perhaps was another contemporary feature related to that rifting parallel to Dharwarian basement grain. The thinning crust of the wide rift zone was the parental material from which the smaller continental blocks/slivers of Seychelles Plateau, Laxmi Ridge, Laccadive Plateau, etc., had developed. The Seychelles Plateau and Laxmi Ridge at that time was not separate entities, and we refer that conjoined continental sliver as Greater Seychelles. The major southerly part of the Laxmi Ridge area of the Greater Seychelles and the Laccadive Plateau were juxtaposed to western India perhaps with a Dharwarian basement grain parallel NNW-SSE trending zone of crustal weakness in between. The northwestern part of the Laxmi Ridge area of Greater Seychelles was adjacent to that part of the Saurashtra Arch, which forms its deep water part at present. Further, the area situated between this northwestern part of the Laxmi Ridge and the northwestern Indian peninsula perhaps contained the remnants of pre-existing older (of Jurassic age) Kutch rift and/or relatively younger (of Late Cretaceous age) Narmada rift.

With all those zones of weaknesses, initially between $\sim$100 and $\sim$88 Ma, the movement of crustal blocks across the major rifts between India and Madagascar were N-S translational, perhaps to accommodate the reorganized direction of relative plate motions across the incipient southeast Indian Ridge. During this period of translational motion, a major transform fault existed along the eastern edge of Madagascar, along which the Madagascar was gradually sliding with respect to continental slivers of Laccadive Plateau and southerly part of Greater Seychelles.

This transform fault adjacent to eastern Madagascar was connected to an East African–Tethyan transform fault system via a releasing bend passing between Seychelles continental block and the northeastern Madagascar (Plummer 1996; Plummer and Belle 1995). During the relative movement of these continental blocks across this transform boundary, a remarkably straight eastern continental edge developed between eastern Madagascar and opposing continental slivers while the releasing bend between Seychelles and the northeastern Madagascar evolved into a pull-apart basin. In the 88 Ma juxtaposition model, the southern extent of ATTC region fitted into the bathymetric notch of the northern Madagascar Ridge and the conjoined Seychelles Plateau-Laxmi Ridge and the Laccadive Plateau have been accommodated with nearly their present outlines. It may be mentioned here that we have been guided by this 88.0 Ma juxtaposition to iteratively arrive at the assumed southern limit of the Laccadive Plateau. We believe this 88.0 Ma reconstruction (Fig. 7a) clearly suggests that the southern limit of the continental sliver of the Laccadive Plateau can be considered to extend only up to the northern boundary of ATTC, which in turn is defined by the Chain-Kairali Escarpment. With these outlines, at places some overlaps could be seen onto the present day continental shelf areas, which we believe, do not pose serious challenge to our proposed juxtaposition model. This is because the extent of these continental slivers surely were much less in their original pre-thinning state and considering the much landward location of the seismically imaged paleo-shelf edge, a tighter fit also looks feasible. It is agreeable that these blocks would have fitted slightly better and closer within their un-stretched dimension but the overall scenario would have remained the same. It may be worthwhile to mention here that all existing plate-tectonic models suggest that, except the conjugate areas of Seychelles, the remaining part of western margin of India was conjugate to eastern margin of Madagascar. Whereas according to our proposed model the conjugate of eastern Madagascar was not the western margin of India, rather it was mostly the western margin of the continental sliver of the Laccadive Plateau.

4.3 Reconstruction at Chron C34ny (~83 Ma; Late Cretaceous)

The chron C34ny ($\sim$83.0 Ma) reconstruction (Fig. 7b) corresponds to 5.0 myr younger time than the previous reconstruction. Shortly before this time, a seafloor spreading system (Mascarene Basin spreading system (MBSS)) had developed between the northeastern margin of Madagascar and the Seychelles Plateau in the north, and the eastern margin of Madagascar and the Laccadive Plateau in the south. The MBSS thus initiated the formation of the Mascarene Basin and separation of Madagascar from SEY + LAX + LCP + SPB + NPB blocks. Based on extents and orientations of the magnetic lineations of chron C34ny, which is the oldest identified magnetic lineation of the Mascarene Basin, we infer that in the northern Mascarene

Basin area (i.e. between Seychelles and northeastern Madagascar, the MBSS was margin parallel. Whereas in the southern Mascarene Basin (i.e. between eastern margin of Madagascar and the Laccadive Plateau) the MBSS at that time was comprised of short, oblique to the margin segments, which were connected by en-echelon short transform offsets. The margin-oblique southern segment of MBSS developed within the thinned continental crust lying between Madagascar and the Laccadive Plateau. With the commencement of oceanic opening, part of that thinned crust got attached to Madagascar as its continental margin and part got attached to Laccadive Plateau as its continental margin. The existence of margin-oblique spreading segments in the southern Mascarene Basin at chron C34ny and a transform fault in the same locale prior to initiation of spreading, perhaps suggest a leaky transform fault origin of that spreading system. Perhaps, the transform fault, that earlier existed east of Madagascar gradually developed into leaky transform fault and then into spreading ridge segments, as the area came under the influence of Marion hotspot in the southern vicinity and the spreading commenced in a direction compatible with the contemporary regional relative plate motion direction.

At this time under the influence of Marion hotspot or due to some other tectonic stress, a northward propagating rift was initiated in the regions between the Laccadive Plateau and the southern Indian Protocontinental block (SPB) and as a result the SPB started slowly sliding north-eastwards with respect to Laccadive Plateau. This sliding probably was accommodated along a pre-existing line of weakness, which later evolved into the Chain-Kairali Escarpment (CKE) on the southwestern continental margin of India. Further southwestward extension of this line of weakness appear to align with a transform offset trend, which in due course will evolve into the Mahanoro FZ of the Mascarene Basin. We would like to mention here that, earlier Yatheesh et al. (2013b) inferred that CKE is a major sheared margin segment of the Indian continental margin along which the continental margin off the nearly straight southeast coast of Madagascar glided past India. Now, we revise that inference slightly to propose that the shear movement across CKE appear to have taken place between southern Laccadive Plateau and SE coast of Madagascar on one side and the ATTC region on the other side. Similar shearing along another pre-existing line of weakness, which was inherited by another transform offset of the Mascarene Basin, might have separated Laccadive Plateau from its northern neighbour of Greater Seychelles.

4.4 Reconstruction at 68.5 Ma (Within Chron C31n; Late Cretaceous)

The ~68.5 Ma reconstruction (Fig. 7c) is for a time falling within the normal chron C31n and it corresponds to 14.5 myr younger time than the previous reconstruction. We propose that by this time a ternary rift system (rift-rift-rift) with a triple junction (GNL Triple junction) came into existence off Saurashtra peninsula of western India. Whatever may be the mode of genesis or timing of formation, we propose that at

68.5 Ma the southern arm of this rift system was propagating southward and was causing gradual divergence of the conjoined Seychelles-Laxmi Ridge and the SPB. The eastern arm of this rift system was propagating eastward as the Narmada rift, which was causing gradual divergence of the NPB and SPB. The western arm of this rift system was propagating westward and was causing gradual divergence of the conjoined Seychelles-Laxmi Ridge from NPB. The southern arm of the rift system in due course will give rise to the oceanic Laxmi Basin, hence we refer this rift arm as Laxmi Basin axis of divergence (or Laxmi Basin AoD). The western arm of the rift system in due course will give rise to the oceanic Gop Basin, hence we refer that western rift arm as Gop Basin axis of divergence (or Gop Basin AoD). The Narmada Rift arm of the system in due course will become a failed rift (aulacogen).

By this time the rift between SPB and Laccadive Plateau, referred hereafter as the Laccadive Basin axis of divergence (or Laccadive Basin AoD), also might have propagated some distance further northward and caused further crustal divergence between SPB and the Laccadive Plateau. On the Madagascar side, Marion hotspot moved away southwards and seafloor spreading continued in both the northern and southern Mascarene Basin.

4.5 Reconstruction at Chron C30no (~67.6 Ma; Late Cretaceous)

The chron 30no ($\sim$67.6 Ma) reconstruction (Fig. 7d) corresponds to 0.9 myr younger time than the time of previous reconstruction. At that time on the Indian side, the Laxmi Basin AoD reached the stage of seafloor spreading in its northerly part and thus commenced the formation of the oceanic Laxmi Basin between the continental margins adjacent to the SPB and the NW-SE trending southern segment of the Laxmi Ridge. However, towards south the Laxmi Basin AoD might have still continued as a southward propagating rift. We inferred this situation based on our proposed revised identification (discussed in an earlier section) of the oldest and conjugate seafloor spreading magnetic lineations of chron C30no ($\sim$67.6 Ma) in the Laxmi Basin. Crustal extension and outward propagation might have continued at that time along the Gop Basin AoD and easterly Narmada arm of the rift. On the Madagascar side, seafloor spreading continued in both the northern and southern Mascarene Basin. The Laccadive Basin AoD continued its northward propagation resulting further divergence between SPB and the Laccadive Plateau.

4.6 Reconstruction at Chron C29no (~64.7 Ma; Early Paleocene)

The chron C29no ($\sim$64.7 Ma) reconstruction (Fig. 7e) corresponds to 2.9 myr younger time than the time of previous reconstruction. By this time on the Indian side, the Gop Basin AoD reached the stage of seafloor spreading and as a result the GNL triple junction has become a ridge-rift-ridge (R-r-R) triple junction. Initiation of spreading in the Gop Basin was preceded by volcanic emplacements on the thinned continental crustal areas northwards of Gop Basin, which was identified by Calvès et al. (2011) as the Saurashtra Volcanic Platform (SVP). The SVP thus forms the conjugate of the east-west trending northerly part of the Laxmi Ridge and presence of SDRs on the southern margin of SVP (Calvès et al. 2011) perhaps indicate this margin was volcanic in nature. By this time in the Laxmi Basin area spreading ridge developed almost up to the northern extremities of the Laccadive Plateau. As the divergence continued along the Laccadive Basin AoD, the Laccadive Basin developed into a triangular shaped basin. The seafloor spreading continued in the southern Mascarene Basin but in the northern Mascarene Basin the spreading appears to have slowed down substantially after chron C30no (~67.6 Ma). Interestingly this slowing down appears to be contemporaneous with the time of initiation of seafloor spreading in the Laxmi Basin.

4.7 Reconstruction at Chron C28ny (~62.5 Ma; Early Paleocene)

The chron C28ny (~62.5 Ma) reconstruction (Fig. 7f) corresponds to 2.2 myr younger time than the time of previous reconstruction. According to us, this time corresponds to the oldest magnetic lineation inferred in the Arabian Basin. At this stage two significant developments took place; the Greater Seychelles broke into the Seychelles Plateau and the Laxmi Ridge by development of a new spreading center, while spreading in the northern Mascarene Basin ceased. This new spreading center between the Seychelles Plateau and the Laxmi Ridge will later develop into the Carlsberg Ridge. The basalts drilled at ODP site 707 (dated at 63.7 ± 1.1 Ma) on the Seychelles Plateau perhaps were emplaced shortly before this stage during the period of transition between rifting of Greater Seychelles and the initiation of this spreading center. The break-up between the Laxmi Ridge and the Seychelles Plateau started while seafloor spreading in the Laxmi and Gop basins were still continuing. Probably the proximity of the Réunion hotspot was a reason for these developments. The Seychelles Plateau and the Laxmi Ridge was getting separated by short segments of spreading centers in the westerly part and by short segments of rifts in the easterly part. This system of spreading center/rifts, of the then Carlsberg Ridge, was connected with the spreading system in the southeastern Mascarene Basin by a long transform offset. This was also the time when the first stage of unique spreading ridge propagation commenced along the short segments of the Carlsberg Ridge with a dominant westward propagation direction. Formation of the Laxmi Basin seamounts commenced some time during chron C28n perhaps as result of interaction of the waning Laxmi Basin spreading center with the Réunion hotspot in the proximity.

On the Madagascar side, seafloor spreading continued in the southern Mascarene Basin and divergence continued along the Laccadive Basin AoD.

4.8 Reconstruction at Chron C27ny (~60.9 Ma; Middle Paleocene)

The chron C27ny (∼60.9 Ma) reconstruction (Fig. 7g) corresponds to 1.6 myr younger time than the time of previous reconstruction. By this time some more rift segments in the easterly part of the Carlsberg Ridge spreading center/rifts system developed into oceanic spreading centers, as if the Carlsberg Ridge system was attempting to attain close proximity of the Réunion hotspot, which was near the northern extremity of the Laccadive Plateau. The ridge propagation, which commenced earlier during chron C28ny with a dominant westward propagation direction continued till this time and transferred crust from the Eastern Somali Basin to the Arabian Basin. Continued spreading/rifting across the Carlsberg Ridge by this time created a triangular wedge of oceanic crust between the Laxmi Ridge and the Seychelles Plateau. Based on predicted track of the Réunion hotspot, it appears that the Laxmi Basin spreading axis was in the closest proximity of the hotspot at this time. Therefore increased melt supply might have caused the seamounts to grow rapidly, even to become sub-aerial. On the Madagascar side, seafloor spreading continued in the southern Mascarene Basin and divergence continued along the Laccadive Basin AoD.

4.9 Reconstruction at Chron C26no (~57.9 Ma; Late Paleocene)

The chron C26no (∼57.9 Ma) reconstruction (Fig. 7h) corresponds to 3.0 myr younger time than the time of previous reconstruction. We consider this was the time when the waning phase of seafloor spreading, with very slow spreading rate, commenced in both the Gop and Laxmi basins spreading centers, while spreading developed along the full length of the Carlsberg Ridge. The ridge propagation along the Carlsberg Ridge continued during this time but sometime during chron C26r the propagation direction appears to have changed. At the time of C26no the Carlsberg Ridge had a long western segment and several short easterly segments and the propagation direction along these segments was broadly eastward. Since chron C27ny lineations were the youngest lineations observed on both flanks of the southern Mascarene Basin, therefore we assume that spreading in the Mascarene Basin ceased some time between chron C27ny and chron C26no. After cessation of spreading in the entire Mascarene Basin area, the spreading center probably jumped north between the southern end of the Laccadive Plateau and the northern boundary of the Mascarene Basin. This way the Mascarene Basin spreading center relocated itself closer to Réunion hotspot. Perhaps in due course of time around 45 Ma, this relocated spreading center will further relocate itself over the Réunion hotspot and will cause the formation of the Saya de Malha Bank. With cessation of spreading, the Mascarene Basin together with Seychelles Plateau became part of the African plate. Although spreading ceased in the Mascarene Basin, it continued in the Madagascar Basin. Perhaps at that time the spreading center between the Laccadive Plateau and the northern boundary of the Mascarene Basin was connected with the Madagscar Basin and Carlsberg Ridge spreading centers by long offset transform faults. The divergence continued along the Laccadive Basin AoD.

4.10 Reconstruction at Chron C25no (~56.4 Ma; Late Paleocene)

The chron C25no (~ 56.4 Ma) reconstruction (Fig. 7i) is our last reconstruction and it corresponds to 1.5 myr younger time than the time of previous reconstruction. We choose this time, because we infer that sometime during the preceding reverse geomagnetic polarity period (i.e. within C25r period (57.554 Ma–56.391 Ma)); (i) seafloor spreading in the Gop Basin ceased and the extinct spreading center of the Palitana Ridge came into existence, (ii) seafloor spreading in the Laxmi Basin ceased and the extinct spreading center of the Panikkar Ridge came into existence, (iii) the extension regimes in the Narmada Rift zone stopped and it became a failed rift (aulacogen), and (iv) the crustal divergence regime in the Laccadive Basin stopped. Stoppage of these divergence regimes caused stoppage of the drifting away of the Laccadive Plateau and the Laxmi Ridge from India and both these continental fragments reached their present position relative to India and got welded with the Indian plate. Volcanism along the Laxmi Basin seamounts also had stopped simultaneously with the extinction of Laxmi Basin spreading center during chron C25r and the Laxmi Basin area started gradually subsiding. The eastward ridge propagation which commenced at chron C26no along the Carlsberg Ridge continued in the same directional sense till this time.

4.11 Some Unresolved Problems and Demerits of the Model

The evolutionary model of WCMI-ADOB region presented in this study accommodated most of the available dependable information and integrated separate ideas into a framework of the early evolution of the region. We hope this model will stimulate further research, particularly those leading towards understanding of the processes related to the genesis and evolution of the WCMI-ADOB region. This model is also expected to provide useful constraints for improving the evolutionary model of the Indian Ocean region as a whole. This model being quantitative, can also become a very useful tool for the researchers for various related studies, such as; (i) to examine the validity of the juxtaposition of various onshore tectonic elements which are inferred as conjugate, and (ii) to study the spatial and temporal evolution of sedimentary units of the offshore basins of the region in detail. However, despite these advantages and improvements in knowledge, we also observe that there remain some crucial knowledge gaps that need to be filled. Therefore, in the following paragraphs we specifically mention the knowledge gaps about few such important tectonic elements and also mention some thinkable demerits of this model. We hope these mentions will help developing appropriate investigations in future that can fill the required knowledge gaps and achieve a better understanding of the early evolution of the study area.

4.11.1 The Age of the Laxmi and Gop Basins Oceanic Crusts

As mentioned earlier, there is a broad agreement that the Laxmi and Gop basins are underlain by oceanic crust and they contain linear magnetic anomalies, which can be equated to two-limbed seafloor spreading sequences across extinct spreading centers. However, there is considerable difference of opinion regarding the identification of those anomalies and thereby the ages related to seafloor spreading history of these basins. These age constraints are not only required for correct plate tectonic reconstructions, they are also important requirements to understand the processes related to the fragmentation of the involved continental blocks. The existence of large Deccan Flood Basalt province, which is assumed to represent the impingement of Réunion hotspot in the vicinity, appear to show bias towards implication of this hotspot while explaining the genesis and geodynamic evolution of various tectonic features of the WCMI-ADOB region. The short sequences surely are making it difficult to unambiguously identify the magnetic anomalies in terms of geomagnetic polarity time scale. Establishing the age of the underlying oceanic crust by dating the basement rocks collected at some locations through deep sea drilling can help identification of those magnetic anomalies. An alternate approach for identification of these anomalies perhaps would be to use high resolution magnetic data collected by deep tow magnetic systems. The high resolution magnetic data can provide characteristic signatures of the anomalies which can aid their identification. Until such age constraints are obtained, the early geodynamic history of the WCMI-ADOB region cannot be established in proper temporal framework.

4.11.2 Nature of Crust of the Laccadive Plateau and Laccadive Basin

One of the significant aspects of the evolutionary model of the WCMI-ADOB region presented by us is that we have considered the Laccadive Plateau as a continental fragment. As discussed earlier, the understanding about the genesis of

Laccadive Plateau is still ambiguous, and possibility of it being a continental sliver cannot be ruled out. Recent reporting (Ajay et al. 2010) of the presence of SDRs on the western edge of the Laccadive Plateau perhaps adds more credence to the continental sliver genesis of the Laccadive Plateau. Nevertheless our assumption is in variance with the commonly held belief that the Laccadive Plateau area represents the volcanic trace of the Réunion hotspot. Admittedly, we are not the first to assume Laccadive Plateau as a continental fragment for any plate-tectonic reconstruction. Earlier, Yatheesh et al. (2006) demonstrated that Laccadive Plateau can be accommodated as an intervening continental fragment in an India–Madagascar juxtaposition in immediate pre-drift scenario and Laccadive Plateau was included as a continental fragment in a model of early opening of the Arabian Sea proposed by Yatheesh (2007). Laccadive Plateau was also considered by Ganerød et al. (2011) and Torsvik et al. (2013) as a continental fragment in their reconstructions of the Western Indian Ocean that were made in different contexts. We believe, our reconstructions suggest that Laccadive Plateau as a continental sliver can be reasonably accommodated in the framework of the early evolution of the WCMI-ADOB region. Further, it can be seen from different reconstructions presented by us, that the predicted track of the Réunion hotspot passes through the region covered by the Laccadive Plateau. We believe, this situation do not contradict the continental sliver genesis of the Laccadive Plateau, because a continental sliver region, even if comes over a plume, will have volcanic emplacements, and if the plume trail covers a considerable stretch of the sliver, then the emplaced volcanics may even show age progression. A similar situation is evident in the DFB province of the western Indian peninsula, where the volcanics were emplaced over the continental basement as it passed over the Réunion hotspot and gradual younger volcanics were emplaced from north to south of the region. We agree that our model does not confirm the continental sliver genesis of the Laccadive Plateau. That confirmation has to await further studies to establish the structure and nature of the crust of the region. Till then our model can be the basis for an alternate line of thinking for further research on geodynamics of the region.

As discussed earlier, the Laccadive Basin is the narrow triangular shaped basin that lies between the Laccadive Plateau and the southwestern continental slope of India. If Laccadive Plateau is a continental sliver, then Laccadive Basin will obviously be the region of crustal divergence that separated Laccadive Plateau from southern Indian peninsula. As of now, the meagre published information do not allow to ascertain whether this region of crustal divergence of the Laccadive Basin is only an extended continental crust or it reached the stage of oceanic spreading as has been observed in the neighbouring Laxmi and Gop basins in the north. Yatheesh et al. (2013b) have demonstrated by gravity anomaly modelling, that the crust in the Laccadive Basin region could either be a much thinned continental crust or an anomalously thick oceanic crust. Our proposed evolutionary model considered this divergence, but could not resolve the ambiguity about the nature of the crust underlying Laccadive Basin. Establishing the nature of the crust of the Laccadive Basin is thus a requirement. Moreover, if an oceanic crust underlies the Laccadive Basin and that contains identifiable seafloor spreading magnetic anomalies, then we may also get some time constraints for opening of the region, which is not available at present.

4.11.3 Demerits of the Presented Evolutionary Model

Our model assumed that the Laccadive Plateau and the Laxmi Ridge are continental slivers. As discussed earlier (in Sect. 2.2), although evidences are emerging in support of a continental sliver nature of the Laccadive Plateau region, still this aspect awaits to be firmly established. Similarly, although many observations support the general belief that the Laxmi Ridge is a continental sliver, still a recent study (Misra et al. 2015) inferred that the Laxmi Ridge is composed of oceanic crust and represents an extinct spreading center. Admittedly, our model will not remain valid in its entirety, in case future studies firmly disprove the continental sliver nature of the Laccadive Plateau or confidently establish the extinct oceanic spreading center genesis of the Laxmi Ridge as a whole. Further, the Euler rotation parameters used for our quantitative reconstructions were estimated from the inferred locations and ages of various conjugate features. These rotation parameters may have to be re-estimated in case studies in future identify newer and better constrained conjugate features/piercing points or provide improved time constraints (e.g. revised ages of the magnetic lineations of the Laxmi and Gop basins). In other words the quantitative reconstructions presented in this study are sensitive to locations and age constraints of the conjugate points used for estimation of rotation parameters. We hope some future studies will carry out sensitivity analysis of such reconstruction models in relation to these variables.

In a recent study Torsvik et al. (2013) proposed the existence of ‘Mauritia’—a Precambrian micro-continent between Madagascar and southern India prior to the commencement of India–Madagascar break up during Cretaceous. They (ibid.) opined that during Cretaceous-Cenozoic times this ‘Mauritia’ micro-continent thinned, fragmented and dispersed to give rise to the present day sub-volcanic crust of Mauritius and continental fragments from the Southern Mascarene Plateau (e.g. parts of Saya de Malha, Nazareth and Cargados-Carajos Banks) and the Laccadives, Maldives and Chagos areas adjacent to Indian margin. Mauritia micro-continent is an interesting proposition and one cannot rule out such a possibility. However, in our model we have included only the Laccadive Plateau part of that proposed Mauritia mainly because, we believe the evidence of continental affinity in this region is relatively better constrained as compared to the Mauritius and southern Mascarene plateau. Further, our model suggested that the Mauritius—southern Mascarene Plateau part of Mauritia, if formed by fragmentation of Mauritia micro-continent, could have commenced only sometime between chron C27ny and chron C26no, when the spreading center from southern Mascarene Basin jumped north within a thinned continental crust zone between the southern end of the Laccadive Plateau and the northern boundary of the Mascarene Basin. Possibly this thinned continental crust region was the parental material from where at least part of Mauritius and southern Mascarene plateau region could have formed. Therefore, we believe our model retains scope to accommodate the genesis of Mauritius and southern Mascarene plateau region as continental sliver, but due to poor constraints presently we refrained from much speculation on this aspect.

5 Conclusions

This paper synthesises information from various published and unpublished studies to develop reconstructions describing the early plate-tectonic evolution of the WCMI-ADOB region from the time of initiation of the India-Madagascar break-up (~88.0 Ma; Late Cretaceous) till chron C25no (~56.4 Ma; Late Paleocene). These reconstructions provided a new view about the dispersals of Madagascar, Seychelles and India, during their early drift period wherein the Laxmi Ridge and the Laccadive Plateau have been accommodated as intervening continental slivers. The main conclusions from these reconstructions are as follows:

- Around 88.0 Ma (Late Cretaceous) the continental blocks/slivers involved in the evolution of the WCMI-ADOB region were juxtaposed in their immediate pre-drift configuration while a wide continental rift zone of hitherto obscure origin existed between the larger continental blocks of India and Madagascar.
- Shortly before chron C34ny (~83.0 Ma), the Mascarene Basin spreading system developed between the northeastern Madagascar and the Seychelles Plateau in the north, and the eastern Madagascar and the Laccadive Plateau in the south. This spreading system initiated the formation of the Mascarene Basin and separation of Madagascar from conjoined SEY + LAX + LCP + SPB + NPB blocks. Some time between 88.0 and 83.0 Ma a regime of crustal divergence also commenced between the Laccadive Plateau and the SPB.
- Around 68.5 Ma (within chron C31n) a ternary rift system came into existence off Saurashtra peninsula of western India and that system initiated divergence of the conjoined SEY + LAX from NPB and SPB. Continuation of this divergence caused commencement of seafloor spreading in the Laxmi and Gop basins around 67.6 Ma and around 64.7 Ma respectively. Seafloor spreading in the northern Mascarene Basin substantially slowed down after the commencement of spreading in the Laxmi Basin.
- Around chron C28ny (~62.5 Ma), the Greater Seychelles broke into the Seychelles Plateau and the Laxmi Ridge by development of a new spreading center (ancestor of the Carlsberg Ridge), while spreading in the northern Mascarene Basin ceased but spreading at very slow rate continued in the Laxmi and Gop basins. This was also the time of commencement of; (i) the unique spreading ridge propagation along the short segments of the then Carlsberg Ridge, and (ii) the formation of the Laxmi Basin seamounts.
- Around chron C27ny (~60.9 Ma), more rift segments in the easterly part of the then Carlsberg Ridge spreading center/rift system developed into oceanic spreading centers and continued divergence along that system created a

triangular wedge of oceanic crust between the Laxmi Ridge and the Seychelles Plateau. The Laxmi Basin spreading center, being in the closest proximity of the Réunion hotspot at that time, might have received increased melt supply and as a result the Laxmi Basin seamounts grew rapidly even to the extent of becoming sub-aerial.

- Around chron C26no ($\sim$57.9 Ma) the waning phase of seafloor spreading commenced in both the Gop and Laxmi basins spreading centers and spreading developed along the full length of the then Carlsberg Ridge. Spreading in the southern Mascarene Basin ceased some time between chron C27ny ($\sim$60.9 Ma) and chron C26no ($\sim$57.9 Ma) and the spreading center jumped north between the southern end of the Laccadive Plateau and the northern boundary of the Mascarene Basin, probably to relocate itself closer to Réunion hotspot.
- Some time during chron C25r (57.554–56.391 Ma); (i) the seafloor spreading in the Gop and Laxmi basins and volcanism along the Laxmi Basin seamounts ceased (ii) the Narmada Rift zone became a failed rift, and (iii) the crustal divergence regime in the Laccadive Basin stopped. With the cessation of these divergence regimes, the Laccadive Plateau and the Laxmi Ridge reached their present position relative to India and got welded with the Indian plate.

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