Cretaceous-Paleocene extension at the southwest continental margin of India and opening of the Laccadive Basin: Constraints from geophysical data

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Abstract. Previous geophysical investigations of the Western Continental Margin of India (WCMI) confirm the double breakup history of the margin with the first breakup taking place between India and Madagascar in Late Cretaceous and the second breakup event in early Paleocene with Seychelles separation from India. Despite numerous geoscientific studies along the WCMI, the opening of the Laccadive Basin, lying along the southern part of the margin, is not discussed. In this study, we evaluate the multi-channel seismic reflection and gravity anomalies at the margin to identify the early rift signatures in conjunction with the magnetic anomaly identifications in the Mascarene Basin. The analysis led to the identification of two extensional directions, a ENE-WSW oriented extension over the Laccadive Ridge north of Tellicherry Arch, and the NW-SE extension in the Laccadive Basin region towards south. Plate reconstruction models of the Mascarene Basin suggest the ENE-WSW extension observed over the Laccadive Ridge could be related to the India-Madagascar separation. However, the sediment deposition pattern and the presence of Paleocene trap associated with the NW-SE extensional grabens observed in the Laccadive Basin region has been attributed to extension between the Laccadive Ridge and the West coast of India after the separation of Madagascar from India. We further propose that the anti-clockwise rotation of India and the passage of the Réunion plume have facilitated the opening of the Laccadive Basin.

1 Introduction

The Western Continental Margin of India (WCMI) formed through the breakup and separation of India and Madagascar in the late-Cretaceous (Storey et al., 1995; Pande et al., 2001). The northern part of the margin then experienced another breakup event when the Seychelles block separated from the Laxmi Ridge and India in the early Paleocene time. The second breakup event is well studied with the pre-drift juxtaposition of the continental blocks fairly established from the magnetic anomaly identifications and geochronology (Collier et al., 2008; Chaubey et al., 2002; Ganerød et al., 2011; Shellnutt et al., 2015, 2017). Earlier reconstruction studies place the southwestern margin of India close to the southeastern margin of Madagascar (Katz and Premoli, 1979), whereas, more recent studies incorporate continental fragments like Laccadive Ridge (Bhattacharya and Yatheesh,

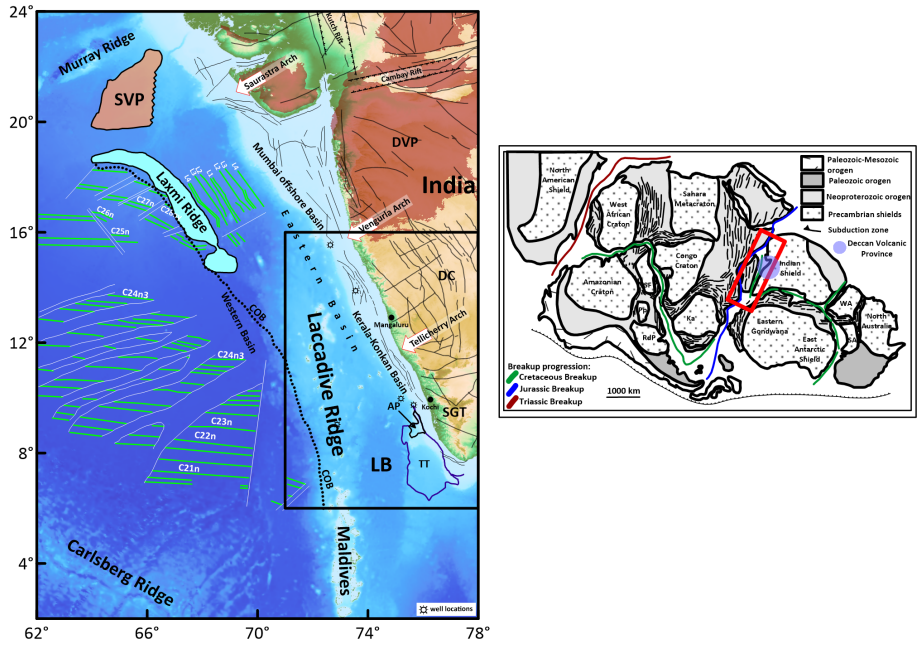

Figure 1. Regional tectonic map of the western continental margin of India (Smith and Sandwell, 1997) on the left. Solid green coloured lines represent the mapped seafloor spreading type magnetic lineations (Bhattacharya and Yatheesh, 2015, and references therein) . Solid white lines represent the mapped fracture zones or pseudo-faults. Black solid lines in the offshore region represent shear zones and faults. The larger study area is marked in a black rectangle.The map on the right shows the position of India relative to Madagascar and Deccan Volcanic Province in late Paleozoic fit (Lovecchio et al., 2020, modified after). The area of intrest is marked in red rectangle. SVP: Saurashtra volcanic province; DVP: Deccan Volcanic Province; DC: Dharwar Craton; SGT: Southern Granulite Terrain; LB: Laccadive Basin; AP: Alleppey Platform; TT Trivandrum Terrace.

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2015) or Mauritia, consisting of Mauritius, Southern Mascarene Plateau, Laccadive Plateau and Chagos Bank (Torsvik et al., 2013) between India and Madagascar in the India-Madagascar pre-drift scenario, and suggest a breakup timing around 83 Ma.

Since the Laccadive Basin and the adjoining southwest margin lying south of the Tellicherry basement Arch is the conjugate segment of the Madagascar, the margin is important in terms of examining the early breakup history. Also, the basin was affected by Réunion plume volcanism towards the end of Cretaceous (Singh and Lal, 1993). Further, due to the presence of wide-spread trap layer below the thin Tertiary sediment cover at the margin (Singh et al., 2007; Singh and Lal, 1993), the vintage seismic data was not of much help to decipher the basin architecture. However, the recent high-resolution seismic data could image the deeper parts of the basin more clearly and provided some new insights on the pre-Tertiary history of the margin.

One of the key questions that remain to be resolved is the absence of Late Cretaceous sediments in the basin, that is the long-time gap of more than 20 m.y.r between the India-Madagascar breakup at 83 Ma and the oldest sediments of 65 Ma

encountered in almost all wells except at CH-1-1 well which could penetrate through Santonian formations (Singh and Lal, 1993). This long-time gap indicates either the presence of older sediments below the Paleocene trap layer or the opening of the Laccadive basin subsequent to the Madagascar separation. Further, the accommodation of the continental fragments between India and Madagascar (Bhattacharya and Yatheesh, 2015; Torsvik et al., 2013) brings new complexity to the geodynamics of this area, as how this separation took place, and therefore provides some insight into the inheritance of the lithosphere that existed before. Hence, examining the Laccadive Basin formation will provide important constraints on the early breakup evolution of the margin. In this study, we present evidence of a major extensional event that occurred at the southwest margin that cannot be correlated with the India-Madagascar separation or the India-Seychelles separation. This helped us to present an evolutionary model that explains the formation of extensional features and the opening of the Laccadive Basin. Understanding and time-stamping this major extensional event will provide important constraints on the evolution of the western continental margin of India and help in tight-fit reconstruction studies.

2 Description of tectonic elements

The area under investigation falls towards south of Tellicherry Arch and contains the southern part of the Laccadive Ridge and the Laccadive Basin in the offshore. The major geomorphic features present in the study area from west to east are the Laccadive Ridge, the Laccadive Basin, the Alleppey Platform and Trivandrum Terrace together called the Alleppey-Trivandrum Terrace Complex (ATTC), and the continental shelf (fig. 1). The ATTC is bounded to the west by the Chain-Kairali Escarpment (CKE) and shows the horst-graben structures within it (Yatheesh et al., 2006, 2013; Nathaniel, 2013) as revealed in the seismic sections (See fig. S1). There are numerous seamounts/guyots/knolls present in the Laccadive Basin which lies between the Laccadive Ridge and the continental shelf (Bijesh et al., 2018). In addition to this, the entire region is characterized by several intrusive structures within the Tertiary sediments (Unnikrishnan et al., 2023).

3 Data and Methods

In this study, we used the satellite-derived free-air gravity (Sandwell et al., 2014) and bathymetry from General Bathymetric Chart of the Oceans (GEBCO, 2020) for comparative analysis with the long-offset multichannel seismic reflection profiles. The large volume of industry seismic reflection data at this margin provided information on the sediment thickness above the Paleocene trap layer and the intermediate horizons (Unnikrishnan et al., 2023). We also compiled a few published seismic sections (Nathaniel, 2013; Yatheesh et al., 2013) within the study area.

The crustal Bouguer anomaly is calculated by removing the gravity effects of bathymetry and sediments from the satellite-derived free-air anomaly. High-resolution sediment thickness derived from TWT maps is used to calculate the gravity effect of the sediments. The two-way travel time (TWT) maps are available for three different times: the early Paleocene, early Eocene, early Miocene. These maps were converted to depth with respective interval velocities (after Unnikrishnan et al., 2023) and the total sediment layer is used to calculate the gravity effect of sediments by assigning the densities of 2.3 g/cc for sediments

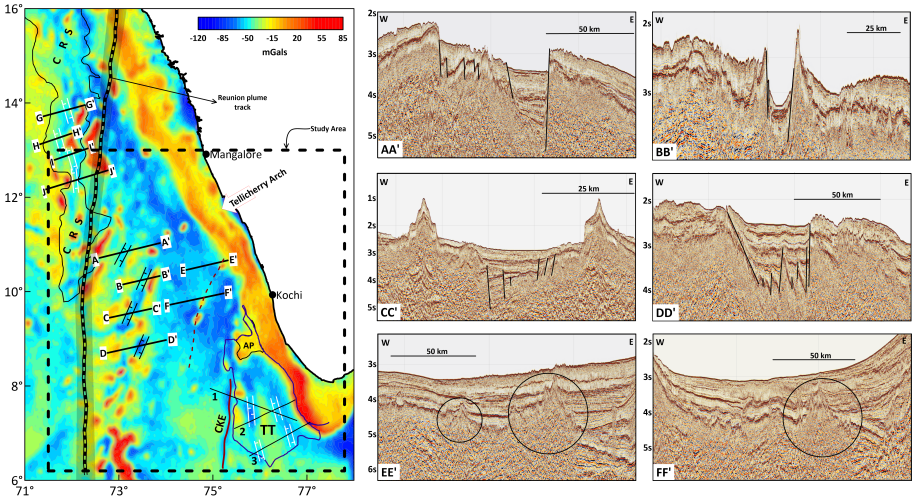

Figure 2. Satellite-derived free-air anomaly map of the study area showing the location and orientation of identified extensional features, grabens and intrusives. Black solid lines represent the location of the profiles. The grabens marked in white are given in fig. S2. Interpreted seismic sections are shown on the right. The faults are marked and the intrusives are shown in circles. The locations of seismic sections is marked in the free-air anomaly diagram. The broken brown line in the centre of the basin represents the identified volcanic ridge. (refer to fig. S2 & S3 for more seismic sections). CRS represents the Cannanore Rift System as identified by DGH. CKE: Chain-Kairali Escarpment; AP: Alleppey Platform; TT: Trivandrum Terrace

and 1.03 g/cc for the water column. For the crustal rocks, an average density of 2.8 g/cc was considered as the study area lies within the extended continental crust (Unnikrishnan et al., 2023). A band-pass filter of 10-200 km wavelengths was applied to the crustal Bouguer anomaly map to highlight the crustal heterogeneities. This map's first vertical derivative (FVD) was also prepared to identify shallow structural features. The identified features in the seismic section are then transferred to these gravity anomaly maps and their continuity is mapped.

4 Results

We present thirteen interpreted seismic sections which reveal horst-graben structures and extensional features in the Laccadive Ridge area (see fig. 2 & fig. S2-S3). In the area north of the Tellicherry Arch, the grabens are oriented in the NNW-SSE direction interpreted as a ENE-WSW extension and towards the south, the grabens are oriented in NNE-SSW direction which is interpreted as extension is in the NNW-SSE direction. These identified extensional structures show low gravity anomalies, the continuity of which can be traced as gravity lows surrounded by gravity highs in the anomaly maps (fig. 2 & fig. 3A-C). This is particularly true towards the south of the Tellicherry Arch. A volcanic intrusive is identified in the centre of the Laccadive Basin which is traced almost parallel to the identified extensional trend in the south and to CKE (fig. 2). This is seen in the gravity anomaly map also as a broken chain of highs (fig. 2 & 3).

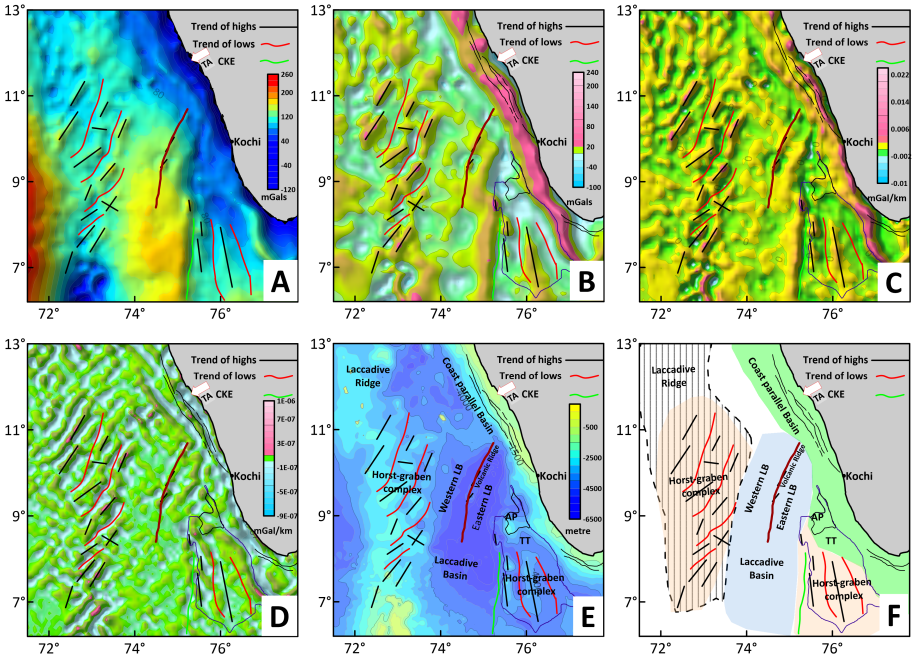

Figure 3. A) Crustal Bouguer anomaly, B) Band-pass filtered crustal Bouguer anomaly, C) First vertical derivative (FVD) of band-pass filtered crustal Bouguer anomaly, D) Depth to the basement map with all identifications, E) Proposed Tectonic map of the study area, F) β-value map (Adapted from Unnikrishnan et al. (2023). The black lines show the structural highs and the red lines show the continuity of rift basins identified. The green solid line represents the Chain-Kairali escarpment (CKE). The broken brown line represents the identified volcanic ridge. Shelfal tectonic elements shown are from Singh and Lal (1993). TA: Tellicherry Arch.

The isochron map for the early Paleocene to early Eocene time interval shows significant deposition of sediments parallel to the coast with very less sedimentation in the Laccadive Basin. During this period, maximum deposition occurred in the area between Tellicherry Arch and Kochi (marked sediment patch in fig. 4A) with a minor sediment channel extending into the basin (fig. 4A). During the Early Eocene to Early Miocene time interval, the deposition within the sediment patch is almost absent, whereas, significant deposition is observed in the Laccadive Basin on either side of the identified volcanic ridge (fig 4B). During Early Miocene to recent time, the sedimentation is uniform in the Laccadive Basin (fig. 4C). The sediment deposition in the coast parallel grabens remained high throughout the time intervals (fig 4A-C). The total sediment deposition pattern shows that most of the sediments were accommodated parallel to the coast and towards the south there is an axis of high sediment deposition into the Laccadive Basin (Figure 4D).

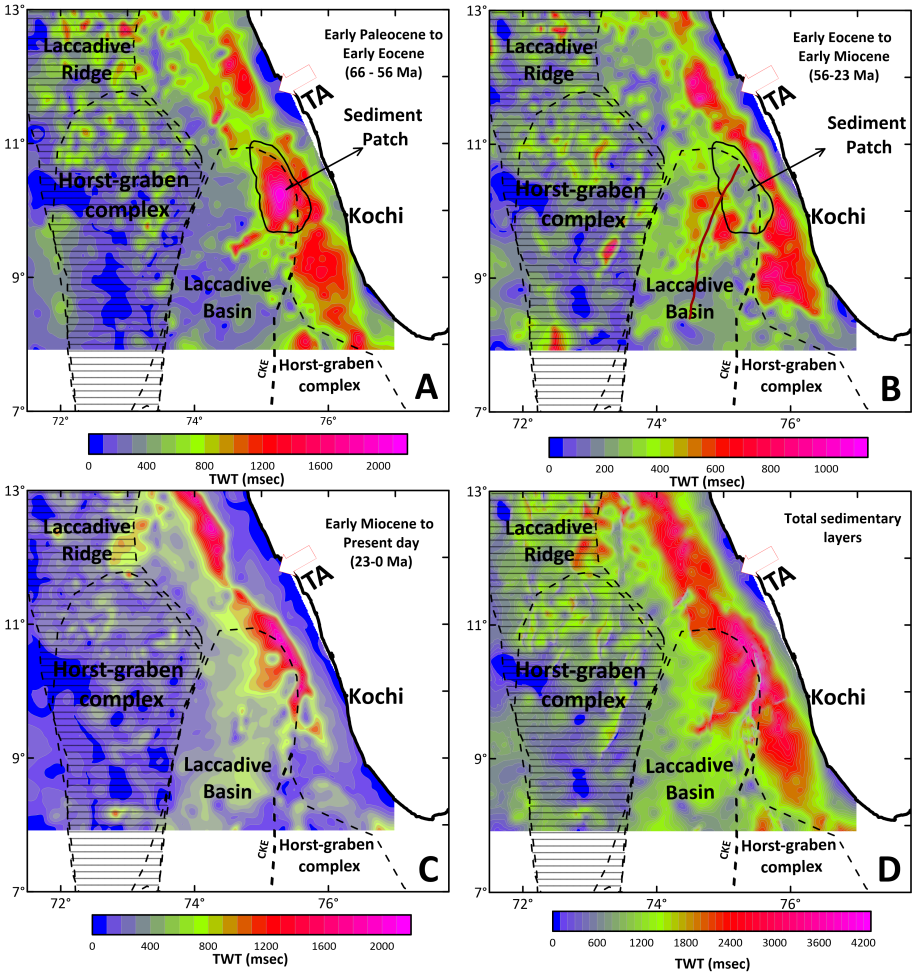

Figure 4. Isochron maps prepared from the TWT for selected time intervals: A) Early Paleocene to Early Eocene; B) Early Eocene to Early Miocene; C) Early Miocene to Present day; and D) Total sedimentary layers. The brown line in B represents trend of the identified volcanic Ridge. (Refer to text for detailed explanation and interpretation). TA: Tellicherry Arch

5 Discussions

5.1 Development of Cannanore Rift System (CRS)

The above analysis indicates that subsequent to the India-Madagascar breakup, the southwest margin of India encountered a passive extensional event which resulted in the separation of Laccadive ridge from the mainland. However, the change in the extensional direction from ENE-WSW in the northern part of Tellicherry Arch to NW-SE in south which facilitated the opening of the Laccadive Basin needs to be considered in the generation of tight-fit reconstruction models for this part of the margin. The seafloor spreading magnetic lineations in the Mascarene Basin (fig. S1) provide some insights on the Indian-Madagascar

separation. The identified anomalies clearly reveal that during the initial stages, the separation was E-W (83-79 Ma and then it changed to NE-SW (73 Ma) (Shuhail et al., 2018). During this period, the Cannanore Rift System (CRS) had developed due to continued extensional activity in the Eastern Basin of western margin of India. It is to be noted that the CRS extends southward till the Tellicherry Arch and ceases to exist further south (fig. 2). Normally one would expect this trend to continue southwards but a change in the direction of extension in the southern part signifies that this region may have a different evolutionary history compared to the northern part.

5.2 Distribution of Bathymetry highs and intrusives

A striking feature along this margin is the presence of many intrusives and bathymetric highs observed in the seismic and bathymetry data, respectively (Unnikrishnan et al., 2023; Bijesh et al., 2018). These features have very clear expressions on the gravity image of the area (figs. 2 & 3A-C). The intrusives and bathymetric highs in the study, south of Mangaluru (fig. 1) appear to be elongated roughly parallel to the trend of the Laccadive Basin. In the centre of the Laccadive Basin, we noticed a series of volcanic mounds with a trend almost parallel to the CKE (fig. 2), which are clearly expressed in the seismic sections. The observed trend correlates well with the crustal Bouguer anomaly map (fig. 3A) as well as the depth to basement map prepared by removing the sediment thickness from sea bottom (fig. 3D). This trend divides the Laccadive Basin into eastern and western basins. The composite tectonic map of the study area is shown in fig. 3E.

Further, the β-value (crustal stretching factor) map (fig. 3F) calculated clearly reveals the extensional structures in the study area (Unnikrishnan et al., 2023). The high β-values in the centre of the Laccadive Basin indicate maximum thinning, confirming our observation in this study.

5.3 Timing of opening

The sediment deposition in the basin is interpreted from the perspective of the creation of accommodation space and sediment supply. The available high-resolution time-structure maps (fig. 4A-C) provide insights on the timing of opening of the Laccadive Basin. These maps clearly reveal significant sediment deposition along the coast parallel grabens within the shelfal part of the margin in all time periods. Further, during the Paleocene-Eocene period, sediment deposition was very significant on the northern fringe of the Laccadive Basin (sediment patch in fig. 4A) with negligible sediments elsewhere in the basin. During Eocene to Miocene the sediment deposition shifted further offshore into the Laccadive Basin (Fig. 4B). The development of the median high within the basin is also noticed. This indicates that the basin opened sometime after Eocene as a result of which accommodation space was created and all the incoming sediments migrated southward into the basin. Note that the sediment deposition occurred on either side of the identified volcanic ridge. A small channel of sediment deposition into the Laccadive Basin towards the southwest of the sediment patch in Fig. 4A may represent the initial stage of opening of the basin. During the Miocene to recent period (Fig. 4C), the sediment deposition is more or less uniform throughout the basin. The western edge of the western basin has relatively less deposition which may be due to the area's location far from any sediment supply. By this time, the basin attained the present-day configuration. Unnikrishnan et al. (2018) identified the Alleppy platform

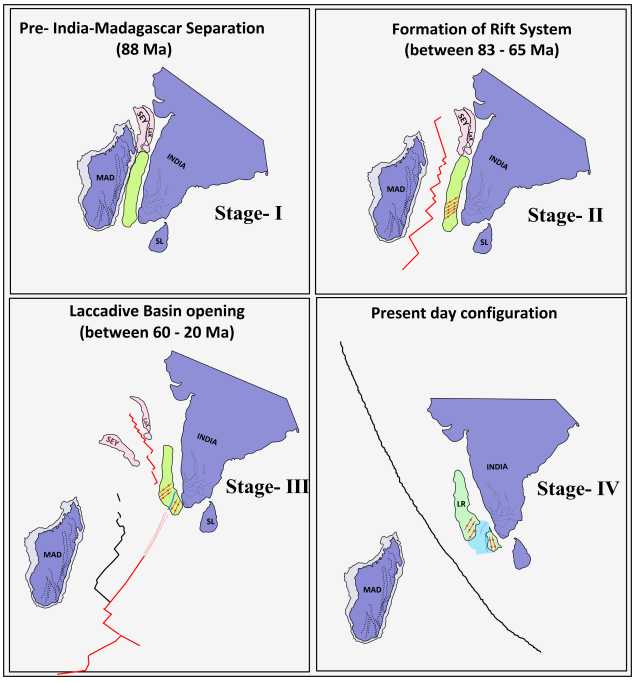

Figure 5. Map showing the evolution of the region in four stages. Stage I: The pre-rift juxtaposition of the continental fragments. Note that the Laccadive Ridge is larger since it incorporates all the fragments that are littered between India and Madagascar. Stage II: The formation of the faults system or the rifts system due to the influence of spreading in the Mascarene Basin. Stage III: The opening of the basin with CKE + ATTC and India moving away from the Laccadive Ridge. See how the orientation of the extensional feature's changes with the anticlockwise movement of India. Stage IV: The present-day configuration of the margin with all extensional features and the volcanic ridge. LaX: Laxmi Ridge; SEY: Seychelles; MAD: Madagascar; SL: Sri Lanka; LR: Laccadive Ridge

as a continental fragment and inferred its development during the Oligocene-Miocene period, which agrees with this study's observations.

5.4 Opening of the Laccadive Basin

During the India-Madagascar separation, the Laccadive area was near the fracture zones in the Mascarene Basin. It has been proposed that the CKE was connected to the spreading in the Mascarene Basin through a long transform fault (Shuhail et al., 2018). There are a large number of suture zones on land in both India and Madagascar (Bhattacharya and Yatheesh, 2015, and references therein) (fig. 1 & fig. 5 Stage I) which were earlier used to find the relative position of India and Madagascar in plate reconstruction studies (Katz and Premoli, 1979; Subrahmanyam and Chand, 2006). Earlier studies along WCMI has shown the extension of onshore structural trends into the offshore region (Subrahmanyam et al., 1994; Kolla and Coumes, 1990) and studies (Péron-Pinvidic and Manatschal, 2010) show that structural inheritance plays a role during rifting and breakup. Hence, we infer that these structural trends would have continued into the continental fragments located in between them. Due to

this, the lithosphere between India and Madagascar was weak and as a result when the area was proximal to the spreading centre in the Mascarene Basin a number of parallel trans-tensional faults may have formed on the Laccadive Ridge south of Tellicherry Arch (fig. 5 stage II). Subsequently, the entire region was flooded by Deccan volcanics during the passage of Réunion plume in the Paleocene time. Studies by Patriat and Achache (1984) and Dewey (1989) showed that the Indian plate rotated anticlockwise about 40^0 since 84 Ma, out of which, it underwent about 25^0 after the soft collision at 50 Ma (Treloar and Coward, 1991). The plume's proximity coupled with India's anti-clockwise rotation led to the reactivation and further extension in the Laccadive Basin (fig. 5 stage III). The ATTC remained attached to the Indian continent with CKE forming its western boundary. The centre of the Laccadive Basin experienced maximum crustal thinning and a series of intrusives got emplaced in the crust (fig. 5 stage IV).

6 Conclusions

The southern part of WCMI (the area south of Tellicherry Arch) has a different evolutionary history than the northern segment. The study provided evidences of pre-Deccan ENE-WSW extensional tectonics over the Laccadive Ridge north of Tellicherry Arch which were masked by volcanic traps. In the region south of Tellicherry Arch, a significant change is observed in the extensional direction to ENE-WSW in the post-Deccan period. This is evidenced by tilted intrusive features within grabens bounded by normal faults in the seismic section (Fig. 2 seismic section DD'). The Laccadive Basin opened within the post-Eocene period with maximum extension along the centre of the basin where the volcanic intrusives are emplaced. The lithosphere that existed had zones of weakness and this along with the plume led to complex rifting and evolution of the southern part of the margin.

Data availability. The authors do not have permission to share data.

Author contributions. MGG – conceptualisation, methodology, validation, formal analysis, writing (original draft and editing), visualisation. MR – conceptualisation, validation, resources, writing (review and editing), supervision. PU – conceptualisation, writing (review and editing).

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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