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Evidence of 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 southern part of the margin, which is known to be the conjugate segment of the Madagascar, has been least studied. 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 the post-breakup extension between the Laccadive Ridge and the West coast of India. We further propose that the anti-clockwise rotation of India and the passage of the Reunion 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-rift juxtaposition of the continental blocks fairly established from the magnetic anomaly identifications and geochronology (Collier et al., 2008). Earlier reconstruction studies place the southwestern margin of India close to the southeastern margin of Madagascar (Katz and Premoli, 1979), whereas, more recent studies (Torsvik et al., 2013;

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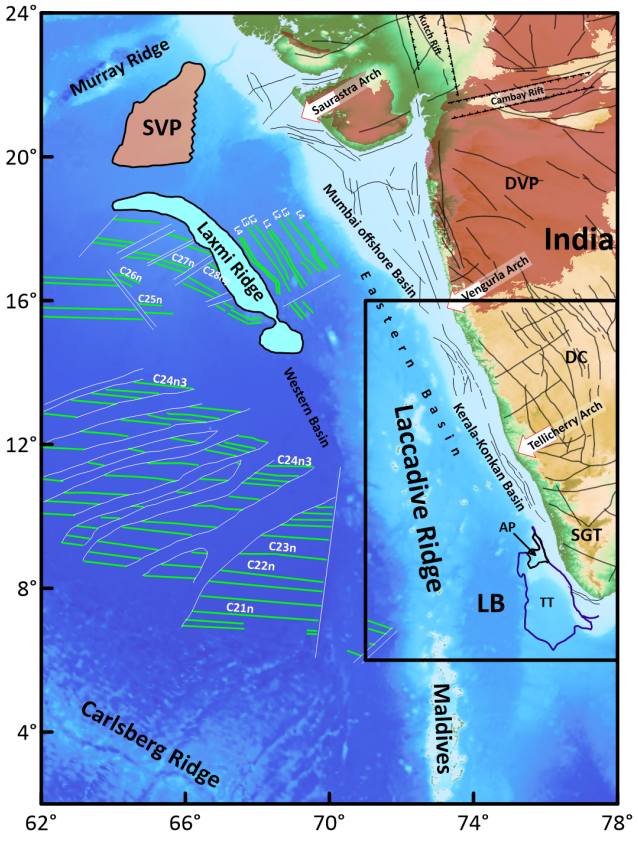

Figure 1. Regional tectonic map of the western continental margin of India (Smith and Sandwell, 1997). Solid green coloured lines represent the mapped seafloor spreading type magnetic lineations (Bhattacharya and Yatheesh, 2015, and references therein) . Solid white lines represent the mapped fracture 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. MR: Murray Ridge; SVP: Saurashtra volcanic province; DVP: Deccan Volcanic Province; DC: Dharwar Craton; SGT: Southern Granulite Terrain; LB: Laccadive Basin; AP: Alleppey Platform; TT Trivandrum Terrace.

Bhattacharya and Yatheesh, 2015) incorporate continental fragments like Laccadive Ridge and Mauritius between India and Madagascar, and suggest a breakup timing around 83 Ma.

The evolution of the southern part of the WCMI, south of the Tellichery Arch (fig. 1), comprising the Laccadive Ridge and Laccadive Basin is more complex and poorly studied segment (Yatheesh, 2020). Presence of thin Tertiary sediment cover and wide-spread occurrence of volcanic trap layer below these sediments as evidenced by drilled-wells made it less attractive for hydrocarbon exploration (Singh et al., 2007; Singh and Lal, 1993) for a long time. However, the recent high-resolution deep penetrating seismic data provided some new insights on the pre-Tertiary history of the southwest margin as the thick trap layer masked the underlying rift features. The origin of the volcanic trap layer is attributed to the passage of India over the Reunion hotspot (Singh and Lal, 1993).

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One of the questions that remains to be resolved is the long time gap of more than 20 Ma 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 (Singh and Lal, 1993). The geochronological (Valsangkar, 1981; Storey et al., 1995; Torsvik et al., 2000; Pande et al., 2001; Melluso et al., 2009; Radhakrishna and Joseph, 2012) and geophysical (Eagles and Wibisono, 2013) evidences indicate that the basin opened during late Cretaceous time. This indicates that the southwest margin comprises either Mesozoic sediments below the trap cover or post-Madagascar breakup activity within the Laccadive basin. Further, the accommodation of the continental fragments between India and Madagascar (Bhattacharya and Yatheesh, 2015; Torsvik et al., 2013) brings new complicity to the geodynamics of this area, as how this separation has taken place, and provides some insight into the state of the lithosphere that existed before. Hence, studying the opening of the Laccadive Basin area will shed light on the margin's evolution post-India-Madagascar separation. 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 shed more light on the evolution of the western continental margin of India and help in tight-fit reconstruction studies.

2 Tectonics of the study area

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). Naini and Talwani (1982) considered that the Laxmi-Laccadive Ridge system divides the western offshore basin into western and eastern basins which are underlain by oceanic crust and extended continental crust respectively (Bastia and Radhakrishna, 2012).

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.

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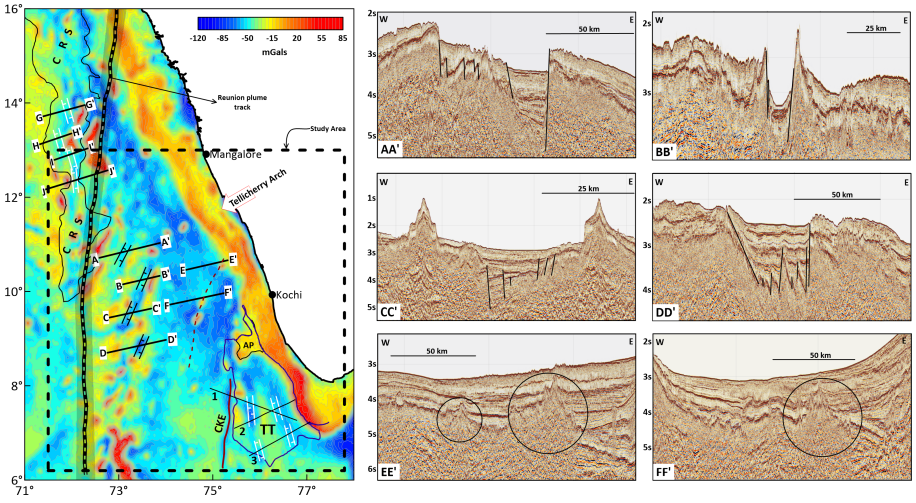

Figure 2. Satellite-derived free-air anomaly map of the study area showing the location and orientation of identified extensional features, grabens and intrusives. Black solid lines represent the location of the profiles. The grabens marked in white are given in fig. S2. Interpreted seismic sections 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 for more seismic sections). CRS represents the Cannanore Rift System as identified by DGH. CKE: Chain-Kairali Escarpment; AP: Alleppey Platform; TT: Trivandrum Terrace

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 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 ten interpreted seismic sections which reveal horst-graben structures and extensional features in the Laccadive Ridge area (see fig. 2 & fig. S2). The orientation of the identified structural features and faults in these sections reveal two prominent extensional directions along the Laccadive Ridge. The prominent ENE-WSW extension observed in the northern

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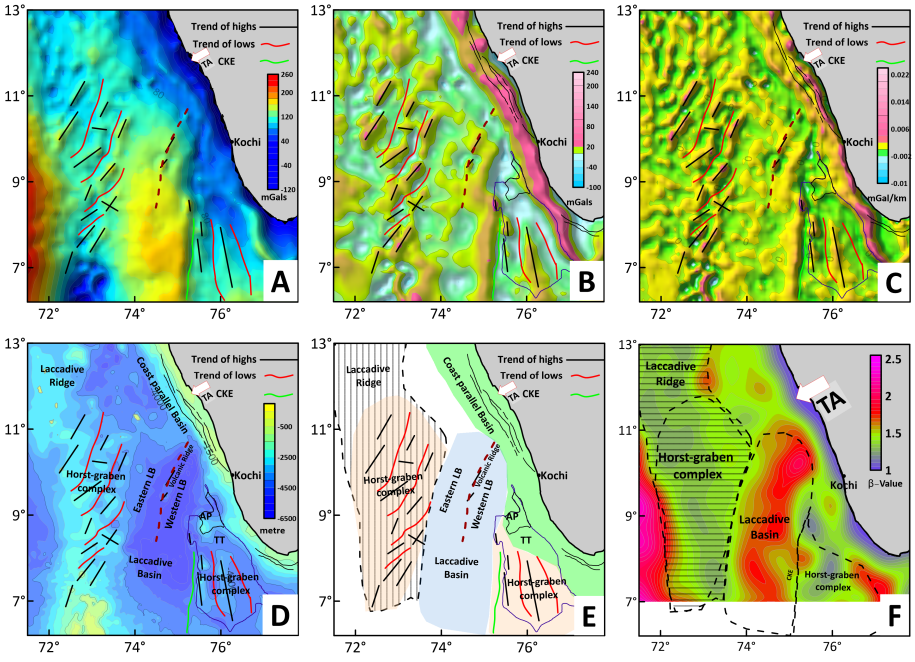

Figure 3. A) Crustal Bouguer anomaly, B) Band-pass filtered crustal Bouguer anomaly, C) First vertical derivative (FVD) of band-pass filtered crustal Bouguer anomaly, D) Depth to the basement map with all identifications, E) Proposed Tectonic map of the study area, F) β-value map (Adapted from Unnikrishnan et al. (2023). The black arrows 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.

part of the ridge changes to NW-SE extension in the region south of Tellicherry Arch. Interestingly, the identified extensional structures were eminently revealed as low gravity anomaly trends, the continuity of which can be traced as gravity lows surrounded by gravity highs in the anomaly maps (fig. 2 & fig. 3A-C). This correlation is more prominent at the margin south of the Tellicherry Arch. Further, a curvilinear trend of volcanic intrusive features is identified in the centre of the Laccadive Basin parallel to the identified extensional trend (fig. 2). This trend is also observed in the gravity anomaly map as a broken chain of highs (fig. 2 & 3).

In order to further constrain the post-rift evolution and probable timing for opening of the Laccadive Basin, the isochron maps available for early Paleocene- early Eocene, early Eocene-early Miocene and early Miocene- recent have been analysed. 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 sediment deposition has shifted towards deep offshore with significant deposition taking place in the Laccadive Basin on either side of the identified volcanic ridge (fig. 4B). During Early Miocene to recent time, the sedimentation became uniform in the Laccadive Basin (fig. 4C). The maps also reveal

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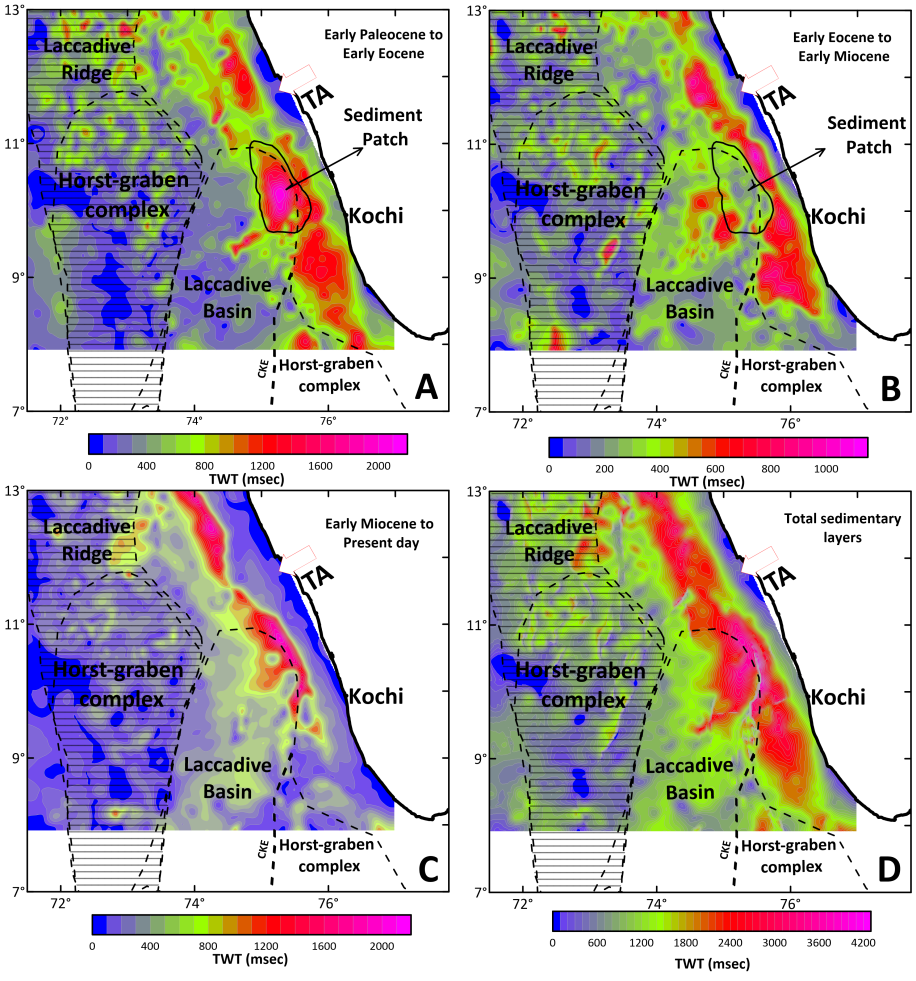

Figure 4. Isochron maps prepared from the TWT for selected time intervals: A) Early Paleocene to Early Eocene; B) Early Eocene to Early Miocene; C) Early Miocene to Present day; and D) Total sedimentary layers. (Refer to text for detailed explanation and interpretation). TA: Tellicherry Arch

that sediment deposition in the coast parallel grabens remained high throughout the period. The sediment depositional pattern reveals that most of the sediments were accommodated either within the coast parallel grabens or within the Laccadive Basin (Fig. 4D).

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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 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 (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). We believe that these structural trends would have continued into the continental fragments located in between them. Due to this, the lithosphere between India and Madagascar became weaker 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 Reunion 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).

5.3 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

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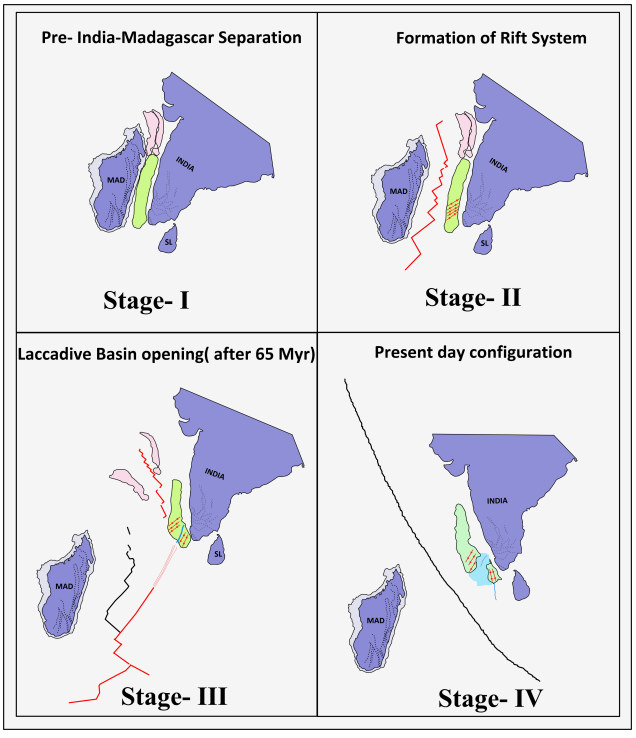

Figure 5. Map showing the evolution of the region in four stages. Stage I: The pre-rift juxtaposition of the continental fragments. Note that the Laccadive Ridge is larger since it incorporates all the fragments that are littered between India and Madagascar. Stage II: The formation of the faults system 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.

the gravity image of the area (figs. 2 & 3A-C). The trend of the intrusives and bathymetric highs in the study area follows the identified extensional trends. 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 trap depth map (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.

5.4 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 Lac-

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

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 titled 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. UK – 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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