

Conjugate nature of the Alleppey-Trivandrum Terrace Complex with the Northern Madagascar Ridge in the early opening model of the Arabian Sea: Evaluation based on an integrated geophysical investigation

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Abstract

The southwestern continental margin of India reveals the presence of an anomalous bathymetric high feature located in the mid-continental slope region off Trivandrum. Based on the analysis of the available geophysical data and plate tectonic reconstruction, this feature was interpreted as a scar of India-Madagascar separation, with its conjugate identified on the Northern Madagascar Ridge. Although the conjugate nature of the Alleppey-Trivandrum Terrace Complex and the Northern Madagascar Ridge was postulated, this inference has not yet been evaluated by comparing their geophysical signatures and crustal structure. The present study is aimed to derive and compare the crustal configuration of these two features using an up-to-date compilation of the bathymetry, gravity and magnetic data, and by employing integrated forward modelling of gravity and magnetic anomalies. Our derived crustal models for the Alleppey-Trivandrum Terrace Complex and the Northern Madagascar Ridge suggest that both these features can be explained in terms of thinned continental crust intermingled with volcanic intrusives. The crustal thicknesses of the Northern Madagascar Ridge and Alleppey-Trivandrum Terrace Complex at their conjugate continent-ocean boundaries are ~17 km and both these features are associated with high amplitude magnetic anomalies whose genesis is attributed to the volcanism caused by the Marion hotspot activity. Therefore, based on our integrated interpretation of the geophysical data, we support the earlier interpretation on conjugate nature of the Northern Madagascar Ridge and the Alleppey-Trivandrum Terrace Complex that was proposed based on the fitting of shape and size of the bathymetric notch observed in the southeastern continental margin of Madagascar with a bathymetric protrusion observed in the southwestern continental margin of India in the India-Madagascar pre-drift scenario. These features remained as a single unit prior to ~88 Ma and subsequently got separated during the India-Madagascar breakup.

Key words: Alleppey-Trivandrum Terrace Complex, Northern Madagascar Ridge, crustal configuration, gravity and magnetic anomalies, Marion hotspot

1. Introduction

The bathymetric map of the southwestern continental margin of India reveals the presence of an anomalous bathymetric high feature in the mid-continental slope region off Trivandrum (Figs. 1a, b). Based on the analysis of limited single beam bathymetry transects available over this feature, and the isobaths available from GEBCO database (IOC-IHO-BODC, 2003), Yatheesh et al. (2006) inferred this feature to represent a “terrace” defined by a conspicuously wide low gradient zone between the 1000 and 2000 m isobaths, and referred it to as the ‘Terrace Off Trivandrum (TOT)’. Using the available paleogeographic reconstruction models depicting the evolution of the Western Indian Ocean and updated compilation of identified offshore tectonic elements, Yatheesh et al. (2006) further inferred that the southern part of the TOT fits well in shape and size with bathymetric notch on the Northern Madagascar Ridge (NMR), implying the conjugate nature of TOT with NMR. Subsequently, Yatheesh et al. (2013) carried out detailed investigation on the TOT region using a new set of sea-surface gravity, magnetic and single beam bathymetry data, and inferred that the above anomalous topography feature consists of two contiguous terraces (Fig. 1b), the Alleppey Terrace (defined by 300 m and 400 m isobaths) and the Trivandrum Terrace (defined by 1500 m and 1900 m isobaths), together referred to as the Alleppey-Trivandrum Terrace Complex (ATTC). They further provided gravity and magnetic characteristics of the ATTC and derived detailed crustal configuration model for the Alleppey Terrace and Trivandrum Terrace, based on forward modelling of gravity and magnetic profiles. Based on all these constraints from the southwestern continental margin of India, complemented with the magnetic anomaly interpretations in the Mascarene Basin, Bhattacharya and Yatheesh (2015) provided a revised plate tectonic evolution model for the Western Indian Ocean, where the anomalous feature defined by 2000 and 2500 m isobath from the southwestern continental margin of India was found to fit with the bathymetric notch in the Northern Madagascar Ridge. Therefore, this feature also is considered to form a part of the Alleppey-Trivandrum Terrace Complex (Fig. 1b), which is believed to have broken away from the Northern Madagascar Ridge. Even though the conjugate nature of the Northern Madagascar Ridge with ATTC is inferred from the plate tectonic reconstruction model and the detailed crustal structure of the ATTC was derived based on forward modelling, the comparison of geophysical signatures and the crustal architecture of these two postulated conjugate features are yet to be examined. Therefore, in the present paper, an attempt is made to derive the crustal configuration of the Northern Madagascar Ridge and compare this with crustal configuration of the ATTC, using an up-to-date compilation of the marine geophysical data available from the southeastern continental margin of Madagascar and its conjugate southwestern continental margin of India.

2. Tectonic framework

The revised plate tectonic reconstruction model (Fig. 2) for the Western Indian Ocean (Bhattacharya and Yatheesh, 2015; Shuhail et al. 2018; Yatheesh, 2020; Yatheesh et al. 2020) suggests that the western continental margin of India and its conjugate regions were formed by the continental breakup among the Southern Indian Protocontinent (SIP), Northern Indian Protocontinent (NIP), Seychelles (SEY), Madagascar (MAD), Laxmi Ridge (LAX), and the Laccadive Plateau (LCP). In this context, the Alleppey-Trivandrum Terrace Complex and the Northern Madagascar Ridge were juxtaposed and existed as the intervening continental slivers between the major continental blocks of India and Madagascar in the south prior to 88.0 Ma. Followed by this, the rifting between Madagascar and conjoint SIP-NIP-LAX-LCP-SEY block has occurred due to the influence of Marion hotspot at around 88.0 Ma (Fig. 2a), followed by the initiation of seafloor spreading in the Mascarene Basin shortly before 83.0 Ma (Fig. 2b). The shapes of the ATTC as a protrusion on the Indian side and as a notch in the Madagascar side appear to have been created by the spreading and transform segments of the initial spreading geometry. As a result, the western limit of the Alleppey-Trivandrum Terrace Complex is defined by a ~500 km long steep linear escarpment, known as the Chain-Kairali Escarpment, coinciding with the transform boundary. The southern limit of the ATTC is marked by the feature defined by the 2500 m isobath, which is located immediately east of the southernmost spreading centre segment.

3. Data and Methodology

The main data used in the present study are sea-surface multibeam bathymetry, gravity and magnetic data collected by National Centre for Polar and Ocean Research (NCPOR), Goa, and CSIR - National Institute of Oceanography (CSIR-NIO), Goa, under the project “Geoscientific Studies of Exclusive Economic Zone of India”, complemented with those available from Yatheesh et al. (2013) and National Centres for Environmental Information (<https://www.ngdc.noaa.gov/ngdc.html>). Multibeam bathymetry data over the ATTC region were acquired through four expeditions (MGS-03, MGS-04, MGS-08 and SSD-059) and are archived as grids in 100 m spatial resolution, after systematic post-processing. Sea-surface gravity and magnetic data were reduced to gravity and magnetic anomalies, after applying the respective corrections. For understanding the sub-seafloor characteristics of the ATTC, we used multichannel seismic reflection data (profiles SWC-01 and SWC-24) acquired by the Directorate General of Hydrocarbon (DGH), India, and published seismic sections (Nathaniel, 2013; Yatheesh et al. 2013; Shuhail et al. 2018). Further, to aid our analysis and interpretation, we used satellite derived free-air gravity anomalies (Sandwell et al. 2014), GEBCO global bathymetry grid (GEBCO Compilation Group, 2020), and EMAG2 magnetic anomaly grid (Maus et al. 2009), in the

areas where sea-surface data is not available. The locations of sea-surface gravity, magnetic, multibeam and seismic reflection profiles used in the present study are shown in Fig. 3.

4. Geophysical signatures over NMR and ATTC

4.1 Seafloor and sub-seafloor topography

4.1.1 Northern Madagascar Ridge

The Madagascar Ridge represents an elongated bathymetric high feature that extends southward from the Madagascar Island (Fig. 1). This feature existing between 26°S and 36°S is defined by ~3000 m isobath, separating the Mozambique Basin in the west and the Mascarene and Madagascar basins in the east, abutting its south on the Southwest Indian Ridge. The Madagascar Ridge appears to consist of two domains – a southern domain (between 31°S and 36°S) consisting of a relatively flat area, and a northern domain (between 31°S and 26°S) consisting of complex and irregular topography (Goslin et al. 1980). Since the ATTC fits with the Northern Madagascar Ridge, we analyzed the bathymetric signatures of the northern domain using the latest available GEBCO global bathymetric data (GEBCO Compilation Group, 2020). The bathymetric map of the NMR (Fig. 4a) clearly exhibits a bathymetric notch (labelled as BN in Fig. 4a) defined by 2000 m isobath in its northeastern part, adjacent to the Mascarene Basin. The central part of the NMR is characterized by the presence of several secondary bathymetric peaks within the 2000 m water depth, between 26°S and 28°S (Fig. 4a). The NMR also exhibits an arcuate shaped saddle-like feature (labelled as SLF in Fig. 4a) along 28°S latitude, between 44°E and 48°E longitudes.

4.1.2 Alleppey-Trivandrum Terrace Complex

The morphology of the Alleppey-Trivandrum Terrace Complex was originally defined (Yatheesh et al. 2006) based on the bathymetric contours (1000 m and 2000 m) available from GEBCO digital database (IOC-IHO-BODC, 2003). Subsequently, Yatheesh et al. (2013) published an updated bathymetric contour map of the Alleppey-Trivandrum Terrace Complex, based on a new set of single beam bathymetry profiles. With an aim to carryout detailed bathymetric imaging of this region, we acquired multibeam bathymetry data for the first time over the northern part of the Alleppey-Trivandrum Terrace Complex falling between 400 m and 2000 m water depth. The updated bathymetric map (Fig. 4b) generated using this high-resolution multibeam bathymetry data (complemented by the global GEBCO bathymetry data in the nearby regions) clearly depicts the morphology qualifying to consider the ATTC as a terrace defined by low gradient zones. The map further defines the sharp drop in the depth to the seafloor defining the location of the nearly N-S trending Chain-Kairali Escarpment (CKE) that defines the western boundary of the ATTC, and the

ENE-WSW trending Quilon Escarpment (QE) south of the Alleppey Terrace. Small scale features representing slope failure events and submarine channels are also observed in the shelf/slope regions of the Alleppey and Trivandrum terraces. Trivandrum Terrace is a large feature that exists between the shelf edge in the east, CKE in the west and QE in the north, while the southern boundary of TT appears to continue towards south as the feature defined by the 2500 m isobath. As noticed by Yatheesh et al. (2013), north of 7°45'N, continental shelf-slope transition is gentle, while south of 7°45'N, this is comparatively steeper. The region in the vicinity of the CKE is characterized by the presence of several isolated bathymetric high features (Bijesh et al. 2018). Further, significant scouring/depression-like features are observed close to the CKE and in the central part of the TT that appears to have resulted due to the underwater current activity and its erosive-depositional process.

For understanding the sub-seafloor information of the ATTC, we present five multichannel seismic reflection sections (Fig. 5). In the seismic sections, the CKE is marked by a steep gradient basement topography (Fig. 5a, b). Seafloor / sub-seafloor bulging and block faulting are prominent underneath the TT region (Figs. 5b-d). The basement corresponding to the QE shows a sharp drop in the basement topography as seen from the seismic section along SWC-24 (Fig. 5e). Yatheesh et al. (2013) divided the TT into the western and eastern basins (TT-WB and TT-EB) based on the central basement high flanked by thick sediment-filled basins with block-faulted basement on either sides (Figs. 5b-d).

4.2 Gravity Signatures

4.2.1 Northern Madagascar Ridge

The shipborne free-air gravity anomaly data available over the Northern Madagascar Ridge is sparse. Therefore, we also used satellite-derived free-air gravity anomalies (Sandwell et al. 2014) to understand the broader gravity anomaly signature of the NMR. For this purpose, we present the satellite-derived free-air gravity anomaly image superimposed with the available sea-surface free-air gravity anomaly profiles. The 2-dimensional free-air gravity anomaly image and the track-along profiles (Fig. 6a) exhibit several secondary positive and negative gravity anomalies superimposed over a broader dominant positive anomaly, which is correlatable with the topographic signature of the Northern Madagascar Ridge at its entire width. The boundary between the Mozambique Basin and the NMR is well defined by a sharp gradient in free-air gravity anomaly, while its eastern boundary with the Mascarene Basin is not delineable from the free-air gravity anomaly.

4.2.2 Alleppey-Trivandrum Terrace Complex

We present the free-air gravity anomaly map (Fig. 6b) of the ATTC region using the satellite-derived free-air gravity anomaly grid superimposed with the sea-surface gravity grid and selected track-along

profiles. A distinct belt of gravity high is observed on the continental shelf lying immediately east of the ATTC. A linear gravity high region is observed with an ~N-S trend in the central part of TT. This gravity high anomaly, which is wider in the south and narrower in the north, is superimposed over a high amplitude negative gravity anomaly. In addition, there exists several isolated gravity highs, which are associated with the bathymetric highs identified within the TT region and along-strike of CKE.

4.3 Magnetic signatures

4.3.1 Northern Madagascar Ridge

The shipborne magnetic data available over the Northern Madagascar Ridge is limited and therefore to have a broader picture of the magnetic signature of the NMR, we used EMAG2 magnetic anomaly grid (Maus et al. 2009) along with the available sea-surface magnetic data. The 2-dimensional magnetic anomaly image and the track-along profiles (Fig. 7a) exhibit complex magnetic anomaly pattern over the NMR that do not show any correlation from profile-to-profile. Some of these high-amplitude and short wavelength anomalies correspond to the bathymetric highs while others are not correlatable to any bathymetric features. The amplitude of the magnetic anomalies over NMR are higher compared to those in the adjacent Mozambique Basin in the west and the Mascarene Basin in the east. The amplitude of the magnetic anomalies also varies along the strike of the NMR, with highest amplitude north of 29°S.

4.3.2 Alleppey-Trivandrum Terrace Complex

We present the magnetic anomaly map (Fig. 7b) of the ATTC region using the EMAG2 magnetic anomaly grid (Maus et al. 2009) along with the up-to-date compiled sea-surface magnetic data. The magnetic anomaly map depicts the presence of complex magnetic anomalies with variable amplitudes on the ATTC and the adjoining Laccadive Basin in the west and the continental shelf in the east. The continental shelf is associated with relatively high amplitude and high frequency anomalies while the Laccadive Basin is associated with lower amplitude anomalies. The magnetic anomaly map shows the presence of several prominent high amplitude magnetic anomalies over the ATTC region and the Chain-Kairali Escarpment. In some areas of CKE, there is obvious correspondence for these magnetic anomalies with bathymetric highs.

5. Crustal configurations of NMR and ATTC

5.1 Crustal configuration of the Northern Madagascar Ridge

To derive the crustal configuration of the Northern Madagascar Ridge, we carried out integrated forward modelling of gravity and magnetic data along a representative profile, di-101 (profile location

is shown in Fig. 3a) that cut across the Mozambique Basin, Northern Madagascar Ridge and the Mascarene Basin. As a first step, forward modelling of gravity anomalies has been performed based on the method of Talwani et al. (1959). We constructed an initial model by considering all the geological and geophysical constraints available from different domains within the study area. The seafloor depth has been obtained from the sea-surface bathymetry data available along the profile. Since there is no basement information available along the profile or its nearby areas, we used the sediment thickness information from the global 5-arc-minute total sediment thickness grid (Straume et al. 2019) to constrain the basement. While constructing the initial model, we used the published velocity-depth information derived based on the seismic refraction studies carried out in the Mozambique Basin (Leinweber et al. 2013) and NMR (Goslin et al. 1981) for getting the constraints in deeper layers. Since no seismic information is available for the Mascarene Basin, we used the velocity-depth information for a standard oceanic crust (Fowler, 2005). Based on the geophysical and geological framework of the study area, we considered two-layered oceanic crust for Mozambique and Mascarene basins and two-layered continental crust under NMR. Seismic velocity information is converted into density values using the velocity-density relationship (Brocher, 2005). The model is refined further keeping these density values and seafloor depth unchanged, and by changing the Moho depth and thickness of different layers slightly to get a reasonably good fit with computed and observed gravity anomalies.

Once a reasonably good fit for the gravity model is obtained, attempt has been made to derive the magnetic source bodies fitting within the crustal configuration derived from the gravity anomalies. This is achieved by carrying out the forward modelling of magnetic data based on Talwani and Heitzler (1964) method. For this, we considered that the magnetic anomalies are resulted due to the presence of volcanic intrusives present in the crust, in light of the understanding on tectonic framework of the study area. The paleomagnetic studies (Storey et al. 1995; Torsvik et al. 1998) carried out in the Madagascar mainland and coastal regions revealed the wide-spread volcanism during the Late Cretaceous. Based on the radiometric age determination (~84-90 Ma), the genesis of these volcanics has been attributed to the Marion hotspot volcanism (Storey et al. 1995; Torsvik et al. 1998). Since this timing falls within the Cretaceous normal superchron, the volcanic intrusives are of normal polarity (Torsvik et al. 1998). We have taken the average values of inclination and declination (Average Remnant Inclination = -65° ; Average Remnant Declination = 358°) derived from the paleomagnetic data (Torsvik et al. 1998). The magnetic susceptibility values are considered within the range of 2.5-4.0 A/m. Once these parameters are fixed, the shape and extent of the intrusive bodies are adjusted to obtain a good fit between observed and calculated magnetic anomalies through several

iterations. The derived crustal model (Fig. 8) suggests that the crust underlying the Mozambique and Mascarene Basin can be explained in terms of two-layered oceanic crust with an average thickness of 6-7 km. The model suggests a crustal thickness of ~16-17 km for the Northern Madagascar Ridge, with its moho located at ~22 km. The magnetic anomalies over the Northern Madagascar Ridge can be explained in terms of volcanic intrusions occurred during a normal polarity. Therefore, considering the density and magnetic structures and the thickness of the crustal layers, we infer that the crust underlying the Northern Madagascar Ridge can reasonably be explained in terms of thinned continental crust intermingled with volcanic intrusives.

5.2 Crustal configuration of the ATTC

To derive the crustal configuration of the ATTC, a profile ABC (profile AB extracted from satellite-derived free air gravity anomalies / global bathymetry and profile BC representing shipborne data along SK221-03) has been selected that cut across a portion of the Laccadive Basin, ATTC and continental shelf (Fig. 3b). While constructing the initial model along this profile, we adopted all the constraints from the crustal model derived for ATTC and the adjacent regions along SK221-05 from Yatheesh et al. (2013). As in the case of Northern Madagascar Ridge, as first step, we carried out forward modelling of gravity data and then incorporated the magnetic source bodies based on forward modelling of magnetic data. The prominent magnetic anomalies along the profile SK221-03 can be considered to have caused by volcanic intrusives within the ATTC region since a large number of volcanic rocks formed by Marion hotspot volcanism have been identified within the proximity of this region. This constraint is adopted from the paleomagnetic studies carried out in the Indian mainland (Radhakrishna and Joseph, 2012) as well as the St. Mary Island (Torsvik et al. 2000), which revealed the normal magnetization characteristics of the volcanic intrusives. The volcanic intrusives are included as dykes and sills, in which dyke is extended to the Moho derived through modelling. Besides, the magnetic properties of the intrusives are limited to a depth of ~22 km, based on the Curie point temperature of ~580°C. All intrusive bodies are considered with an average remanent inclination of -56° and declination of 315°, by averaging of all normally magnetized bodies.

The derived crustal model (Fig. 9) suggests that, in the continental shelf region, moho is at a depth of 33 km and it shallows down to ~22 km in the boundary between ATTC and the Laccadive Basin. Therefore, the derived model suggests a crustal thickness of ~30 km under the continental shelf region thinning to ~16-17 km in the westernmost extent of the ATTC. Therefore, considering the density and magnetic structures and the thickness of the crustal layers, we infer that the crust underlying the Alleppey-Trivandrum Terrace Complex can reasonably be explained in terms of thinned continental crust intermingled with volcanic intrusives.

5.3 Comparison of crustal structure of NMR and ATTC

The revised plate tectonic reconstruction model shows that the Alleppey-Trivandrum Terrace Complex fits well in a bathymetric notch on the Northern Madagascar Ridge in the immediate pre-drift scenario, at ~88.0 Ma (Fig. 10a). This implies that geometries of both these features were formed after ~88 Ma, and prior to this period, both these features form a single unit of a crustal block. If the postulated juxtaposition of these features based on plate tectonic reconstruction is correct, then both these features should show a very similar crustal structure, even though some modifications might occur due to the geodynamic events occurred after their separation.

Our exercise to derive the crustal configuration of these postulated conjugate features reveals that both these features can be explained in terms of thinned continental crust intermingled with volcanics. The derived crustal model for the Northern Madagascar Ridge suggests a two-layered continental crust with a total thickness of ~16-17 km in the eastern side at the continent-ocean boundary between the NMR and the Mascarene Basin (Fig. 10b). Similarly, the derived crustal model for the Alleppey-Trivandrum Terrace Complex suggests a two-layered continental crust with a total thickness of ~16-17 km in the continent-ocean boundary between ATTC and the Laccadive Basin (Fig. 10c). The derived model for NMR further shows that the magnetic anomalies over the Northern Madagascar Ridge can be explained in terms of volcanic intrusion within the thinned continental crust. Similarly, the derived crustal model for ATTC suggests that the magnetic anomalies over this feature also can reasonably be explained in terms of volcanic intrusion within the thinned continental crust. Therefore, the above observations, complemented by the postulated juxtaposition observed from the plate tectonic reconstruction, strongly support that both these features existed as a single unit prior to ~88.0 Ma and this feature fragmented and broke away soon after ~88.0 Ma, possibly by the Marion hotspot activity. This age constraint comes from the age of the volcanic rocks identified from Madagascar side (Storey et al. 1995; Torsvik et al. 1998; Torsvik et al. 2000) and Indian side (Valsangkar et al. 1981; Radhakrishna et al. 1994; Radhakrishna et al. 1999; Anilkumar et al. 2001; Pande et al. 2001; Melluso et al. 2009; Radhakrishna and Joseph, 2012; Mohan et al. 2016; Sheth et al. 2017).

6 Conclusion

The present study is aimed to compare the crustal configurations of the Northern Madagascar Ridge and the Alleppey-Trivandrum Terrace Complex to evaluate their postulated conjugate nature. For this, we analyzed multibeam bathymetry, gravity and magnetic data and carried out forward modelling of gravity and magnetic profiles. The derived crustal model for the NMR suggests that the moho is nearly flat at a level of ~22 km with a crustal thickness of ~16-17 km and the magnetic anomalies can be

explained in terms of volcanic intrusives. Similarly, the derived crustal configuration of the ATTC suggests that the moho is at a level of ~32 km in the landward side of ATTC, shallowing to a level of ~22 km (with a thickness of ~16-17 km) at the boundary where the continental-oceanic crustal transition occurs between ATTC and the Laccadive Basin. The magnetic anomalies over the ATTC also have been interpreted in terms of volcanic intrusions. Comparison of the crustal configuration derived for these features reveal that both these features can be explained in terms of ~16-17 km thick thinned continental crust intermingled with volcanic intrusives. Therefore, based on these observations derived from the integrated interpretation of geophysical data, complemented by the postulated juxtaposition observed from the plate tectonic reconstruction, we support the earlier interpretation (Yatheesh et al., 2006; Yatheesh et al., 2013; Bhattacharya and Yatheesh, 2015) that the NMR and ATTC represent conjugate features that was proposed based on the fitting of shape and size of the bathymetric notch observed in the southeastern continental margin of Madagascar with a bathymetric protrusion observed in the southwestern continental margin of India in the India-Madagascar pre-drift scenario. These features remained as a single unit prior to ~88 Ma and subsequently got separated during the India-Madagascar breakup.

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Data availability

Datasets generated during the current study are confidential and is deposited at the Marine Geoscientific database being managed by NCPOR.

Declarations

Competing interests: The authors declare no competing interests.

Code availability: Not applicable

Ethics approval: Not Applicable

Consent to participate: Not Applicable

Consent for publication: Certified that all authors have seen and approved the final version of the manuscript being submitted.

Figure Captions

- Fig. 1** (a) Bathymetric map of the Western Indian Ocean prepared using GEBCO 2020 global bathymetric grid showing major tectonic elements. The study areas are marked as black solid boxes. Enlarged bathymetric map of the southwestern continental margin of India (b) and southeastern continental margin of Madagascar (c), along with selected GEBCO isobaths overlaid. LCP: Laccadive Plateau; MdR: Maldive Ridge; CB: Chagos Bank; CKE: Chain Kairali Escarpment; AT: Alleppey Terrace; TT: Trivandrum Terrace; LXB: Laxmi Basin; ABB: Arabian Basin; ESB: Eastern Somali Basin; WSB: Western Somali Basin; CIB: Central Indian Basin; SMP: Seychelles-Mascarene Plateau; MZB; Mozambique Basin; MC: Mozambique Channel; MDB; Madagascar Basin; MSB: Mascarene Basin; CR: Carlsberg Ridge; CIR: Central Indian Ridge; SWIR: Southwest Indian Ridge; SEIR: Southeast Indian Ridge; RTJ: Rodrigues Triple Junction; MAD: Madagascar; NMR: Northern Madagascar Ridge
- Fig. 2** Revised plate tectonic reconstruction maps of the Western Indian Ocean at (a) ~88.0 Ma; (b) ~83.0 Ma (modified after Yatheesh, 2020), in fixed Madagascar reference frame. SIP: Southern Indian Protocontinent; NIP: Northern Indian Protocontinent; SEY: Seychelles Plateau; LAX: Laxmi Ridge; LCP: Laccadive Plateau; ATTC: Alleppey-Trivandrum Terrace Complex; NMR: Northern Madagascar Ridge; SLK: Sri Lanka
- Fig. 3** Map showing locations of selected sea-surface gravity, magnetic, and bathymetry profiles and seismic sections used in the present study over (a) NMR and (b) ATTC. The gravity and magnetic anomalies along profiles di101 and ABC have been used for deriving the crustal models of NMR (in Fig. 8) and ATTC (in Fig. 9), respectively. The line labelled as N1 represents refraction profile over the Northern Madagascar Ridge (Goslin et al. 1981).
- Fig. 4** (a) Bathymetric map prepared using GEBCO 2020 grid over the NMR. (b) High-resolution bathymetric map of the ATTC region prepared using multibeam bathymetry data, presented along with the GEBCO 2020 grid in the background. Other details are as in Fig. 1
- Fig. 5** Seismic reflection sections along the profiles (a) SWC-01, (b) DN13-A (modified after Nathaniel 2013; Shuhail et al. 2018, with permission from Elsevier), (c) SST-17 (after Yatheesh et al. 2013, with permission from Elsevier), (d) SST-16 (after Yatheesh et al. 2013, with permission from Elsevier) and (e) SWC-24. Inset figure shows the locations of these profiles. N1: oceanic / transition; N-2: Vishnu FZ; N-3: Inverted graben; N-4: Mesozoics; N-5: KT Boundary
- Fig. 6** (a) Satellite-derived free-air gravity anomaly map with sea-surface gravity anomaly data plotted perpendicular to the track over NMR; (b) Shipborne free-air gravity anomaly image over the ATTC region plotted with the background of satellite-derived free-air gravity anomaly. Also plotted the selected shipborne free-air gravity anomaly profiles perpendicular to the track. Other details are as in Fig. 1
- Fig. 7** (a) EMAG2 magnetic anomaly map with sea-surface magnetic anomaly data plotted perpendicular to the track over NMR, (b) Shipborne magnetic anomaly image over the ATTC region plotted with the background of EMAG2 magnetic anomaly grid. Also plotted the selected shipborne magnetic anomaly profiles perpendicular to the track. Other details are as in Fig. 1
- Fig. 8** Crustal model of the NMR derived based on integrated gravity-magnetic modelling along the profile di-101. The constraints used have been discussed in the text. UCC: Upper continental crust; LCC: Lower continental crust
- Fig. 9** Crustal model of the ATTC derived based on integrated gravity-magnetic modelling along the profile ABC (AB+SK221-03). UCC: Upper continental crust; LCC: Lower continental crust; LCL: High velocity lower crustal layer
- Fig. 10** (a) Plate tectonic reconstruction map (in fixed Madagascar reference frame) showing relative configuration of India and Madagascar in their pre-break up scenario (~88 Ma) with location of the profiles (shown as thick lines) along which the section of the crustal model presented as (b) and (c); (b) Selected portion of the crustal model derived in the eastern side of NMR near inferred continent-ocean boundary; (c) Selected portion of the crustal model derived in the southern end of ATTC near inferred continent-ocean boundary. Other details are as in Figs. 8 and 9

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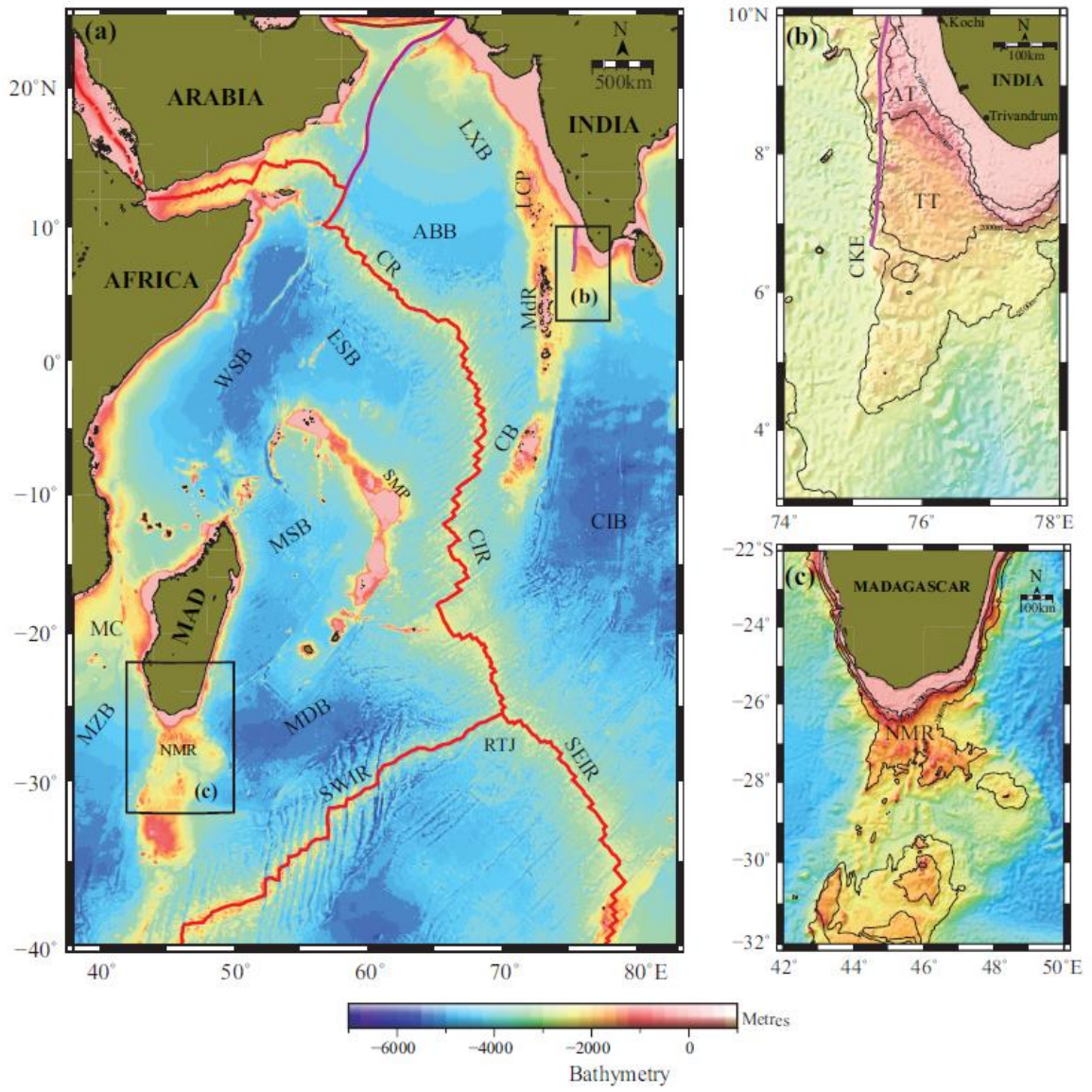


Figure 1

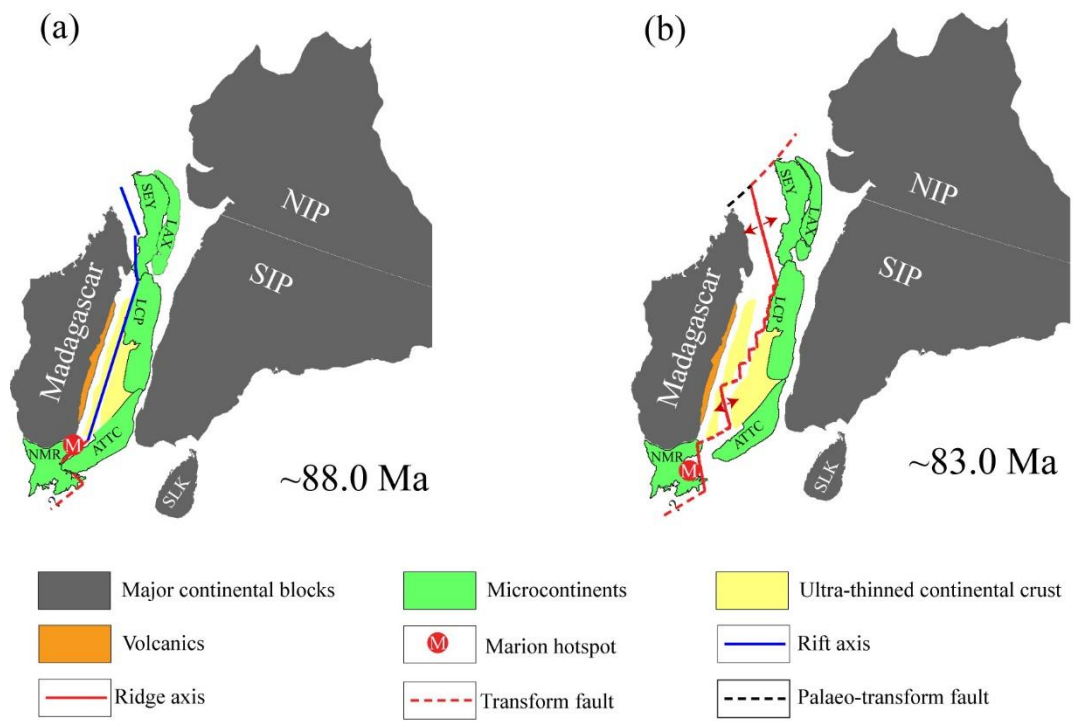


Figure 2

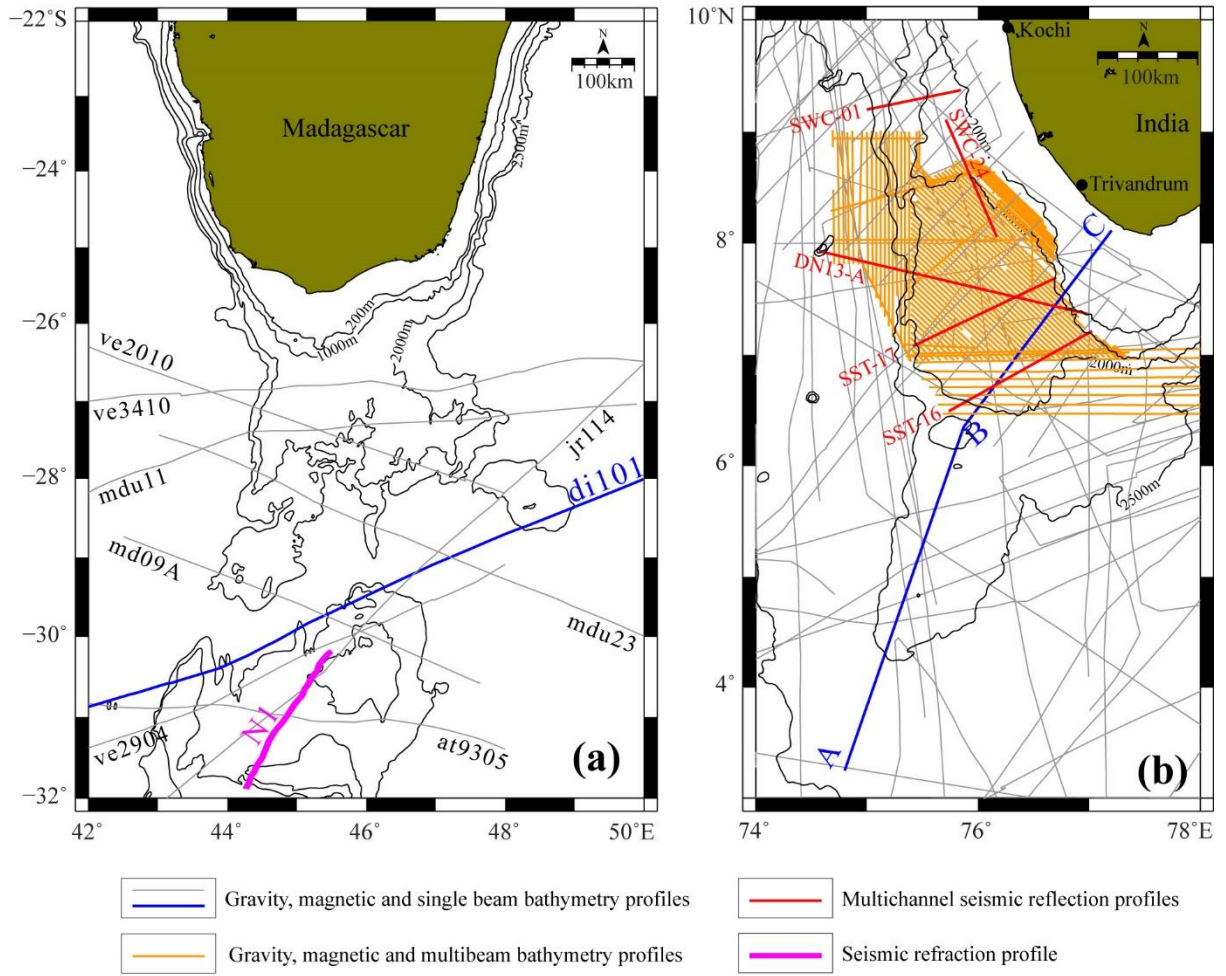


Figure 3

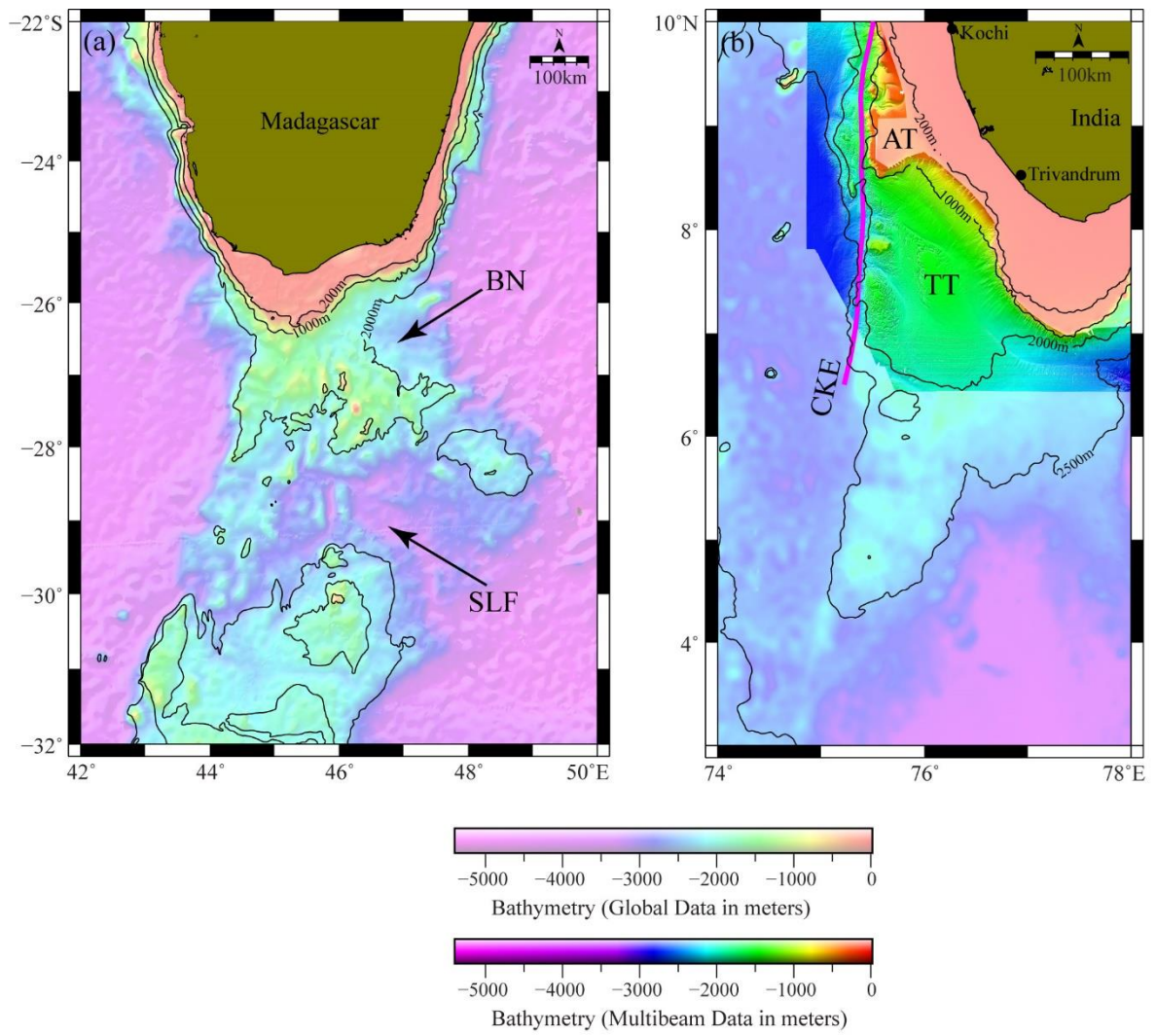


Figure 4

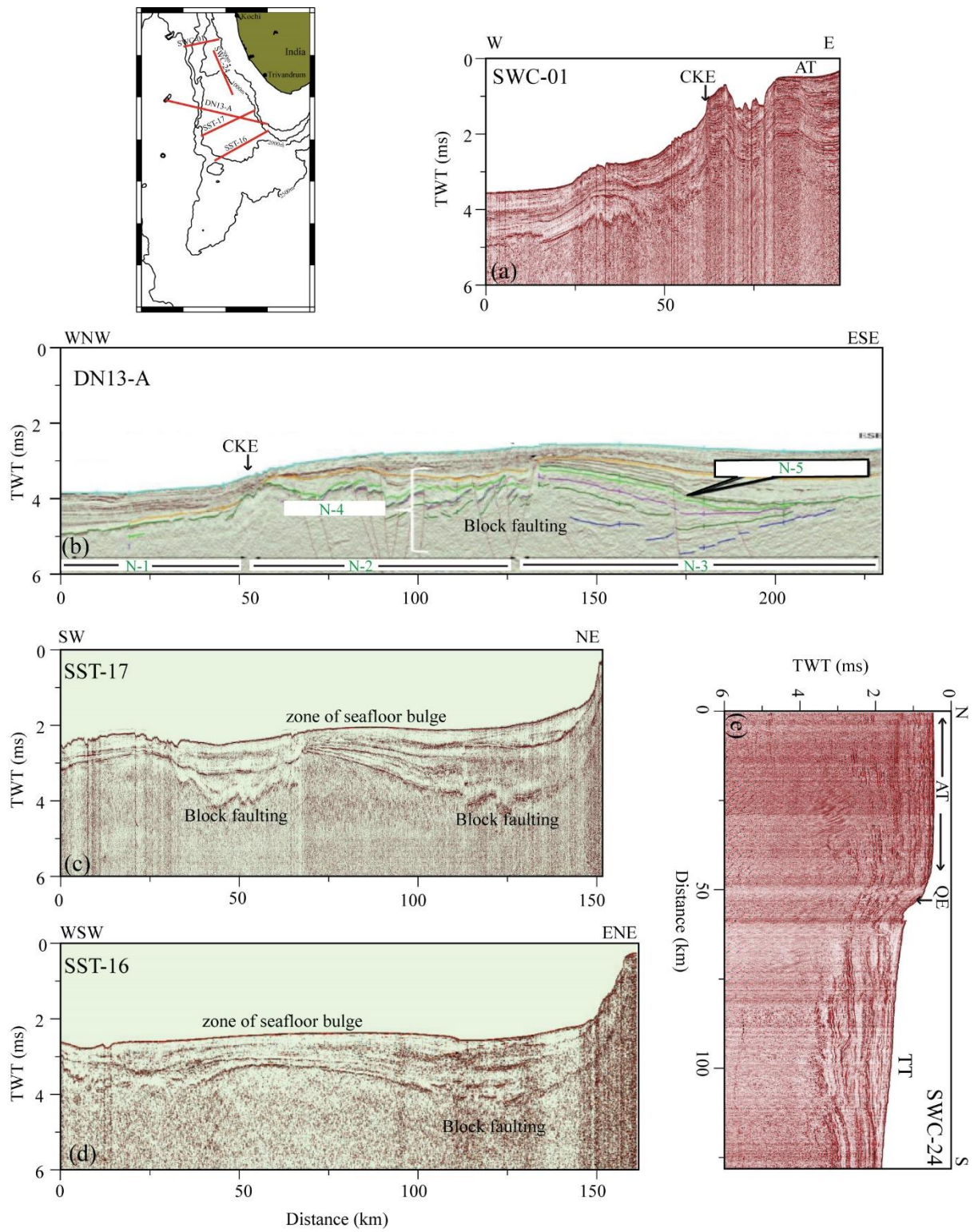


Figure 5

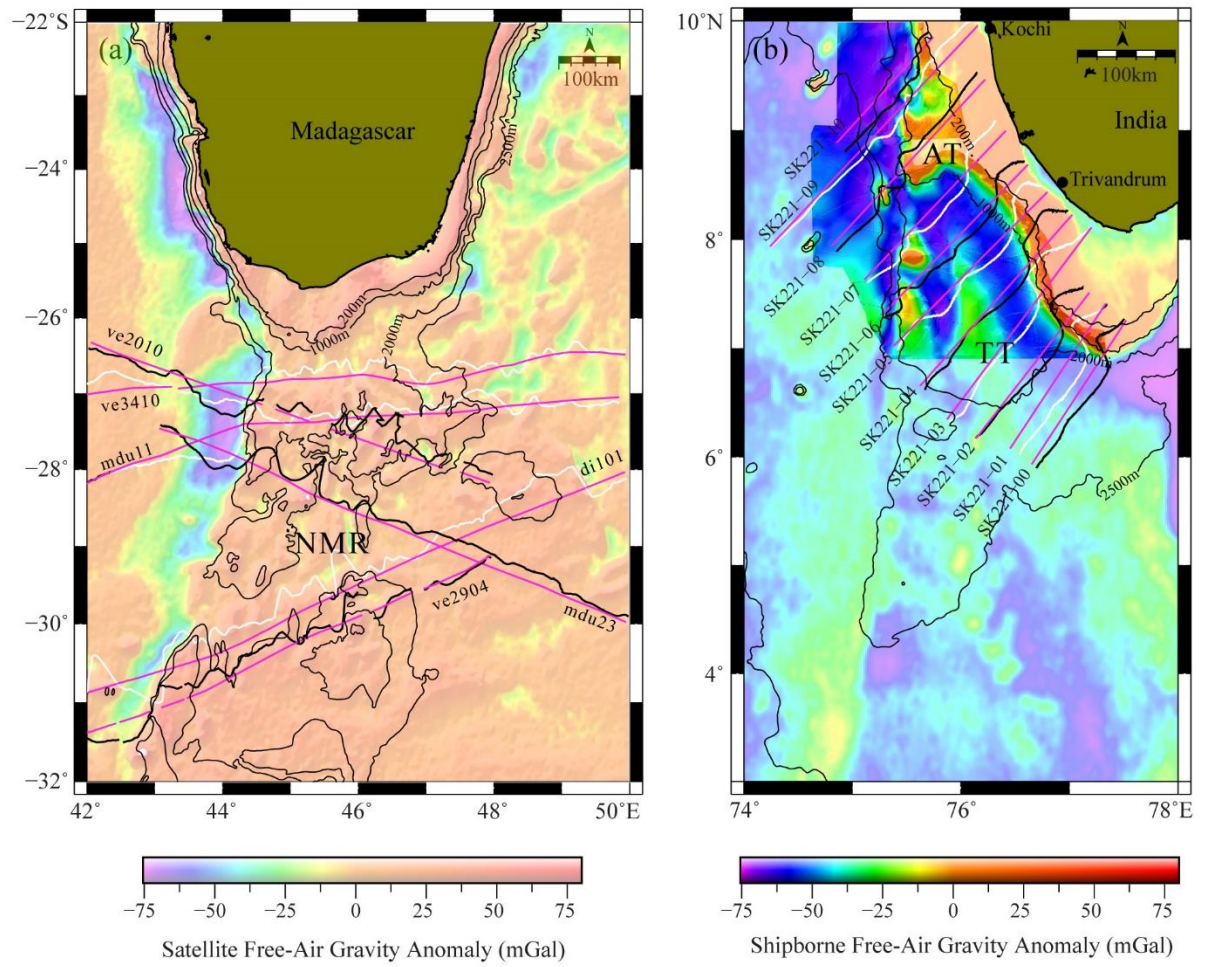


Figure 6

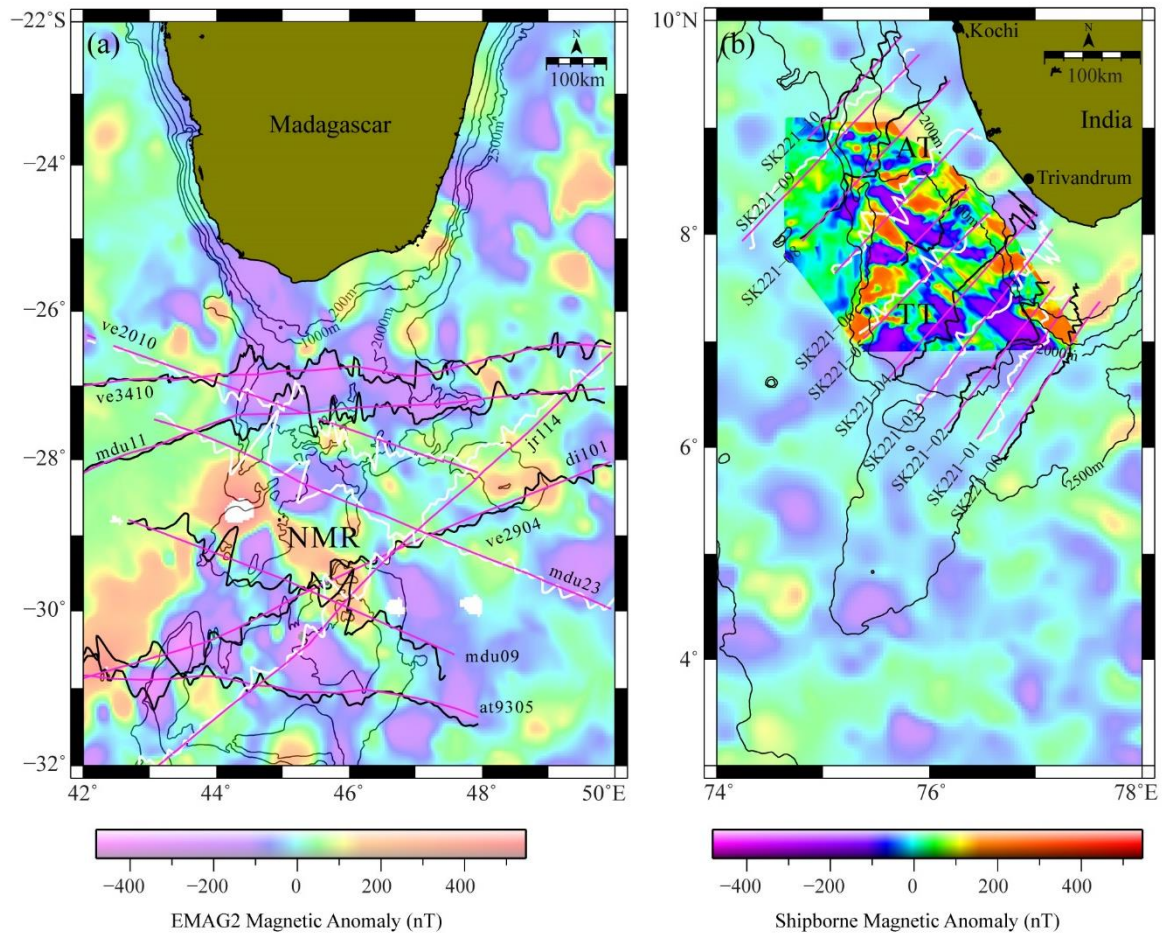


Figure 7

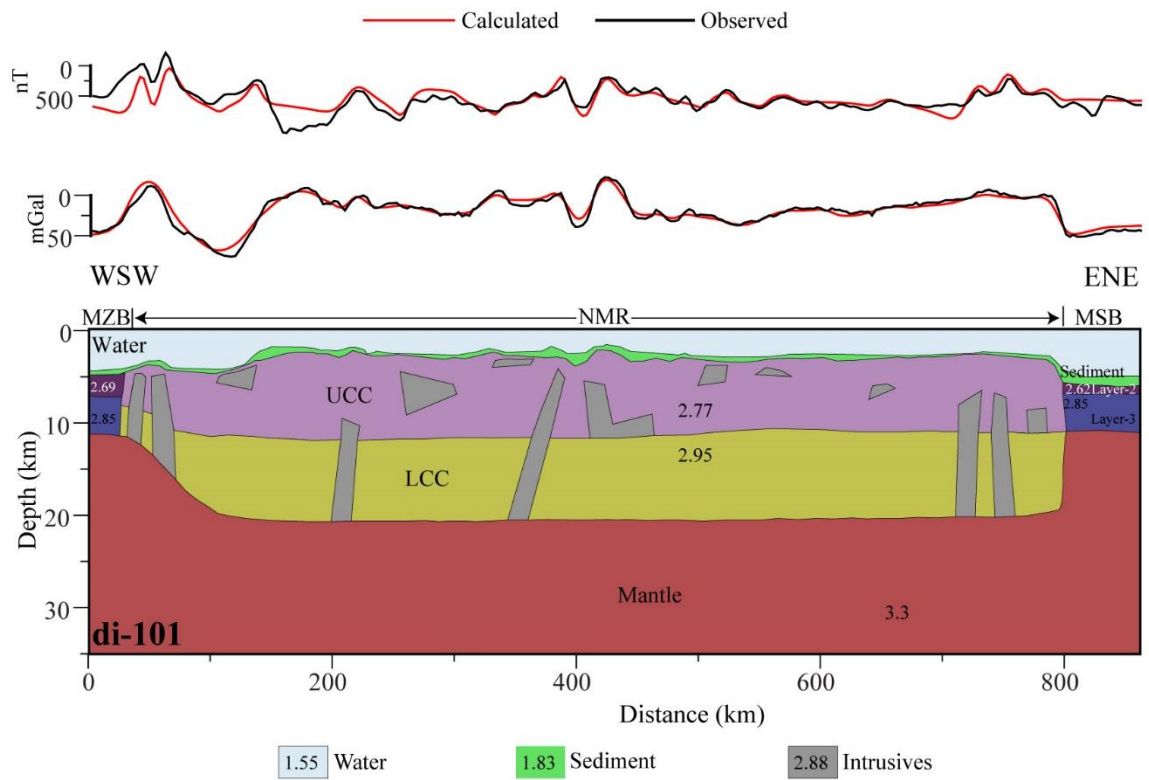


Figure 8

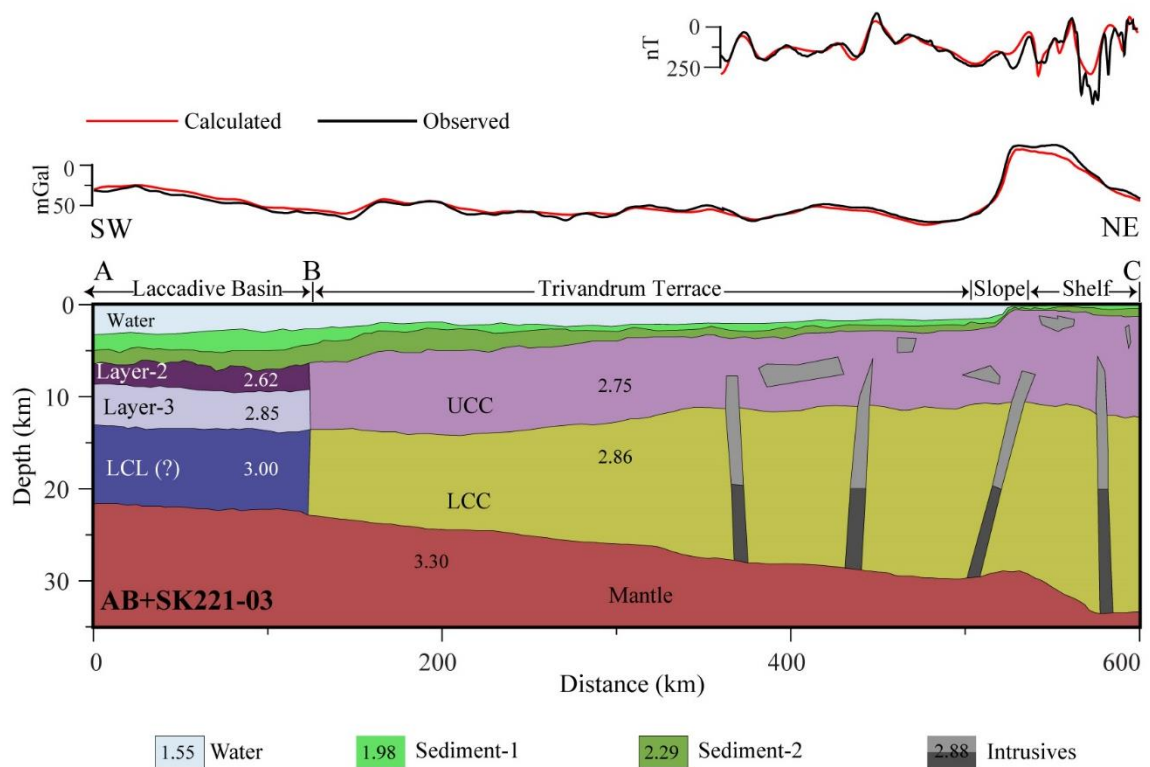


Figure 9

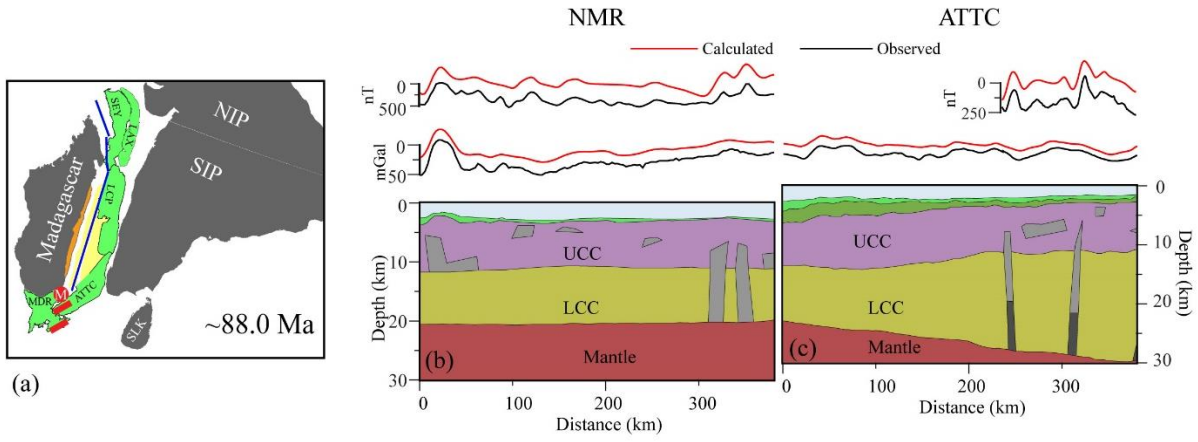


Figure 10