

Morphotectonic architecture of an India-Madagascar breakup related anomalous submarine terrace complex on the southwest continental margin of India

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Abstract

An anomalous lateral bathymetric protrusion [Alleppey-Trivandrum Terrace Complex (ATTC)] in the form of two contiguous terrace-like features exists in the mid-continental slope off southwest coast of India. This bathymetric protrusion and a bathymetric notch in the Northern Madagascar Ridge (NMR) have been postulated as conjugate features related to India-Madagascar separation in Late Cretaceous. However, geoscientific studies aimed to understand the crustal structure and genesis of the ATTC or its postulated conjugate region are meagre and ambiguous. In this context, the present study, based on recently acquired as well existing bathymetry, gravity, magnetic and multi-channel seismic reflection data, was carried out to understand the morphotectonic architecture of the ATTC. The bathymetric data suggest an escarpment [Chain-Kairali Escarpment (CKE)] to demarcate the westward limit of the ATTC and another escarpment [Quilon Escarpment (QE)] to demarcate the boundary between the southerly, larger 'Trivandrum Terrace (TT)' and northerly, smaller Alleppey Terrace (AT). The multichannel seismic reflection data suggests a block-faulted basement and presence of a nearly N-S trending wide basement high in the central part of the Trivandrum Terrace. Forward modelling of gravity data constrained by seismic reflection information suggests that the crustal structure of the ATTC region is comparable to thinned continental crust. Forward modelling of prominent high amplitude magnetic anomalies suggest that the thinned continental crust of the ATTC region also contains volcanic bodies as intrusives / extrusives. The CKE is inferred to be a sheared continental margin segment along which the SE coast of Madagascar glided past India and the volcanic emplacements in the ATTC region perhaps relates to the Marion Hotspot volcanism.

Key words: Alleppey Terrace; Trivandrum Terrace; Chain-Kairali Escarpment; Quilon Escarpment; India-Madagascar separation; sheared continental margin

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1. Introduction

The passive type western continental margin of India and its adjoining deep offshore regions were considered to have been formed as a result of rifting and drifting among the continental blocks of India, Seychelles and Madagascar since Late Cretaceous. In view of above, it is expected that the continental shelf-slope region of western India have been shaped by the rifting/initial drifting processes, which caused separation of India from the contiguous Seychelles and Madagascar. In this context, the present study focuses on an anomalous, lateral bathymetric protrusion of the southwestern continental margin of India, which is located in the mid-continental slope region approximately south of the latitude of Cochin (Fig. 1) and denoted in this study as the ‘Alleppey-Trivandrum Terrace Complex (ATTC)’. It is interesting to note that such a lateral bathymetric protrusion of large areal extent (area > 35000 sq km) does not exist anywhere along the continental shelf-slope region off the west coast of India. However, this bathymetric protrusion region, even though conspicuous, did not receive much attention so far and its structure and genesis is largely unknown. Rao and Bhattacharya (1975) analyzed the magnetic and seismic data along a profile in the northern part (AT in Fig. 1) of this protrusion and proposed its genesis to block faulting of basement. Dymment (1991) suggested that the eastern part of northern Madagascar Ridge and the bathymetric high regions of the ATTC are conjugate with respect to Mascarene Basin spreading center. Yatheesh et al. (2006) specifically shown that southern part of the ATTC (TT in Fig. 1) fits well in shape and size, with a bathymetric notch located in the northern Madagascar Ridge, as a conjugate feature representing scars related to India-Madagascar break-up. They further proposed that the outlines of those bathymetric protrusion and notch were shaped by the rifted and transform segments of the initial spreading geometry and the drifting of India from Madagascar was initiated around 86.5 Ma. In this paper, we highlight some salient features of the seafloor, basement topography and the geophysical signatures associated with this ATTC region and forward inferences about the crustal structure of the region.

2. Data

The data used for this study comprise of an updated compilation of different types of new as well existing geophysical data. The new data consists of (1) the sea-surface gravity, magnetic and bathymetry transect data acquired by the National Centre for Antarctic and Ocean Research (NCAOR), India, onboard ORV Sagar Kanya during June-July 2005; and, (2) two multichannel seismic reflection profiles (SST-16 and SST-17) obtained from Directorate General of Hydrocarbons (DGH), India. Some existing sea-surface transects data extracted from the GEODAS Marine Geology and Geophysics database (National Geophysical Data Centre, 1998) has been

complemented to these new data. The locations of sea-surface gravity, magnetic, bathymetry and multichannel seismic reflection profiles used in present study are shown in Fig. 2. The seismic data were collected during 2002 using 4200 cubic inch airgun seismic source and 480 channel receiver streamer. During data acquisition, the seaward extent of the Indian survey tracks (SK and SST profiles) were limited to the western end of the bathymetric protrusion since the maritime boundary between India and Maldives Islands falls very close to that western end. The newly acquired data along the ORV Sagar Kanya transects were processed using the following approach; (i) the measured depth values were corrected for the variation of the sound velocity in seawater using Matthew's table (Carter, 1980), (ii) the total magnetic intensity data have been reduced to residual magnetic anomalies by subtracting the International Geomagnetic Reference Field for appropriate epochs (IAGA Working Group V-MOD, 2010), and (iii) the residual gravity anomalies were obtained by applying normal and Eötvös corrections to the measured gravity data. In absence of any geomagnetic observatory nearby, no diurnal correction was applied to the magnetic data. However, by manually comparing with the diurnal variation recorded at the Alibag observatory (18.64°N, 72.87°E) it was ensured that no segment of the magnetic data contain artefacts caused by geomagnetic disturbances. In addition, existing bathymetric contours from the General Bathymetric Chart of the Oceans (GEBCO) digital data (IOC-IHO-BODC, 2003) and free-air gravity anomalies derived from satellite altimetry data (Sandwell and Smith, 1997, 2003) have been used to aid and constrain the interpretation.

3. Seafloor and sub-seafloor features from bathymetric and seismic data

3.1 Seafloor features from bathymetry data

We present the seafloor topographic expression of the study area by an updated bathymetric contour map (Fig. 3) and bathymetry profiles (Fig. 4). As will be discussed later, the continental slope region of the study area contains two large contiguous terrace-like features. We denote those two features as terraces because their morphological characteristics match well with the definition of an undersea terrace as stipulated by the International Hydrographic Organization (IHO-IOC, 1989). The larger of these two terraces, denoted by Yatheesh et al. (2006) as 'Terrace off Trivandrum (TOT)', lies approximately south of the latitude of Trivandrum (Fig. 2) and a smaller terrace, referred as 'Alleppey Platform' (Singh et al., 1999) or 'Terrace off Quilon' (Rao and Bhattacharya, 1975), lies approximately between latitudes of Alleppey and Quilon. For ease of further discussion in this study, we will refer that smaller northerly terrace as 'Alleppey Terrace' (AT) and the larger southerly terrace as 'Trivandrum Terrace (TT)', and the whole region comprising those two terraces as 'Alleppey-Trivandrum Terrace Complex (ATTC)'. From various published maps (Laughton et al.,

1971; Udintsev, 1975) it appears that the broad topography and extents of the AT and TT were evident in the bathymetric data compiled during International Indian Ocean Expedition (IIOE) way back in early 1970s, however the interesting topographic anomalies of the region were never highlighted.

As can be seen in Fig. 1, the bathymetric contours of the continental slope (200 – 2000 m) have a nearly coast parallel (i.e. ~ NW–SE) trend in the regions northwards of Cochin. However, south of Cochin, the 1000-2500 m bathymetric contours abruptly change into a coast oblique nearly N-S trend, which appears as a conspicuous, nearly 500 km long, steep linear escarpment. We consider that this escarpment (Fig. 1) defines the westward boundary of the ATTC and designate it as the ‘Chain-Kairali Escarpment (CKE)’ in consideration of the fact that the escarpment appears to have been recognized for the first time along a track of the R/V Chain off the coast of the southern Indian state of Kerala. We consider that the easterly and westerly boundaries of the Alleppey Terrace are defined by the adjacent continental shelf edge and the CKE respectively, while its southerly boundary have been formed by another nearly EW trending scarp face, which we designate as the ‘Quilon Escarpment (QE)’. Similarly, we consider the TT to be bounded on the west by the ‘Chain-Kairali Escarpment’, on the north by the ‘Quilon Escarpment’. The easterly boundary of TT, is marked by the NW–SE trending upper continental slope (Figs. 1 and 2), which have two different morphological zones separated approximately along the 7°45’N latitude. In the areas north of 7°45’N latitude, this upper continental slope deepens gradually to reach the depth of the terrace, while a relatively steep upper continental slope characterizes the areas south of 7°45’ N latitude. The southern boundary of the TT is not very distinct as compared to its other boundaries; rather it appears as an undulating seafloor, which gradually deepens from the level of the TT area to reach the depths of the adjacent deep seafloor towards south.

The bathymetric contour map (Fig. 3) and bathymetric sections (Fig. 4) suggest that the seafloor depth; (i) at the shelf edge of the continental shelf adjacent to the ATTC region is about 200 m; (ii) over the relatively flat Alleppey Terrace varies between 300 to 400 m and, (iii) over the gently southwards sloping TT region varies between 1500 m and 1900 m. These indicate that the difference in levels of the adjacent continental shelf and the terraces in the AT sector is about 200 m and in the TT sector is about 1400 m. Further, the two terraces being at different levels, there is significant along strike variation in the height of the ‘Chain-Kairali Escarpment’, which separates the terraces from the adjacent deep sea region (depth ~ 2750 m) on the west. The height of the ‘Chain-Kairali Escarpment’ is about 2500 m in the areas of AT and about 1000 m in the areas of TT. The height of the ‘Quilon Escarpment’ in its steepest part is about 900 m. In some places, within the domain of the

‘Chain-Kairali Escarpment’, topographically high features are present. Prominent amongst those topographic highs are located (Fig. 3) in that segment of the CKE, which is adjacent to the ‘Alleppey Terrace’. The bathymetric contours and profiles suggest the presence of a north-south trending, nearly 100 m high, wide and gentle bulge of the seafloor flanked by troughs on both sides in the middle of the TT region. As will be discussed later, the seismic data clearly show that this bulge is not caused directly by any basement high, but it is formed by a bulging sedimentary apron over a basement high trend.

3.2 Sub-seafloor features from multichannel seismic reflection data

The sub-bottom configuration of the ‘Trivandrum Terrace (TT)’ region as revealed by multichannel seismic reflection sections along two profiles (SST-17 and SST-16) are shown in Fig. 5. These two profiles extend (Fig. 2) from southwestern limit of TT to its easterly limit. Both the sections clearly depict the presence of a wide basement high in the central part of the TT region. This basement high trend has a gently sloping easterly surface as compared to relatively steeper westerly surface. This basement high is flanked on its easterly and westerly sides by thick (~ 1.7 sec TWT) sediment filled basins, which for further discussions in this paper will be referred as ‘TT-Eastern Basin’ and ‘TT-Western Basin’ respectively. The TT-Eastern Basin appears to have been formed for its considerable extent over a gently landward sloping basement surface with no apparent symmetric graben structure (Figs. 5, S1 and S2), while the deeper part of this basin further landwards appears to be underlain by several relatively shorter faulted basement blocks. Some of these faults in the TT-EB region appear to be post-depositional as they extend even to the sedimentary layers overlying the basement. However, those faults appear to be restricted only to the sedimentary layers deeper than 3sec TWT. The TT-Western Basin on the other hand appears to have been formed over a graben structure (Fig. 5), where the entire basin is underlain by faulted basement blocks. The basement high features observed in the central part of the TT in both the sections appear to coincide with a nearly NNW-SSE trending gravity high trend (GH-3 in Fig. 6) noticeable in the satellite-derived free-air gravity anomaly map and sections (Fig. 7), which extends almost the entire N-S extent of the TT. This basement high and gravity high correspondence, we believe, suggests that the central basement high feature depicted in these two seismic sections represent a nearly NNW-SSE trending continuous feature, which extends almost the entire N-S extent of the TT and is relatively wider towards south and narrower towards north. The seismic data indicate (Figs. S1 and S2) that an acoustically transparent layer forms the uppermost sedimentary cover over the TT. However, the bathymetry as well seismic data suggest that this sedimentary cover have a gentle bulge in the regions of the basement high and depression over the basin areas. The bathymetry as well as seismic data also

suggests (Fig. S1) the presence of anomalous undulations of the seafloor at places. Such undulations of the seafloor were observed mainly in the western part of the TT and most of them are of the order of ~75 m in relief.

4. Crustal structure inferences from gravity and magnetic anomalies over the Alleppey - Trivandrum Terrace Complex

With the availability of new set of SK profiles, the ATTC region now appears to have been well covered with gravity and magnetic transects in a regional scale. In this section, we will firstly describe these geophysical signatures and then present the interpretation of their anomalies as carried out in this study for understanding the configuration and nature of the crust underlying the ATTC region. To infer the crustal structure from gravity and magnetic data, we carried out forward modelling of the gravity and magnetic anomalies along two representative profiles, one across the AT sector and the other across the TT sector. The profile (profile SK221-08) across the AT was selected in such a way that it spans (Fig. 2) from the continental shelf to the adjacent deep sea region across the CKE and at the same time covers the widest part of the AT. Similarly, the composite profile ABC (profile SG-1+SK221-05) in the TT sector was chosen in such a way that it spans from the continental shelf to the adjacent deep sea region across the CKE and at the same time lies close to a seismic reflection transect, so that the information from the seismic section can be used to provide geometric and geological constraints for models. We did not opt to model gravity anomalies along the seismic profiles of the TT region, because no magnetic data are available along them. Since potential field modelling is inherently non-unique, additional constraints are essential to narrow down the range of possible solutions. Therefore, we first carried out forward modelling of gravity profiles to get a reasonable crustal configuration and subsequently carried out forward modelling of the magnetic anomalies using the gravity modelling derived crustal configuration as the initial model. We used this approach iteratively till we obtained a crustal structure model (with magnetic bodies), that satisfies both the gravity and magnetic data.

4.1 Gravity anomalies

The free-air gravity anomaly profiles (Figs. 7 and 8) show the presence of a prominent gravity high anomaly belt in the landward end of the profiles in the regions southwards of the latitude of Quilon. Between Quilon and 7.5°N latitude this gravity high belt is over the continental shelf region coinciding approximately with the shelf edge, whereas south of 7.5°N latitude, this gravity high belt is observed to extend also over the upper continental slope region.

Seawards of this gravity high belt, the anomaly drops steeply and is expressed as broad low over the TT region and as a narrow low over the AT region. At places residual gravity high anomalies are superimposed over this broad gravity low of TT region. Some of these gravity highs (GH-1 and GH-2 of the ATTC region in Fig. 7) are localized and have clear correspondence with topographic highs. The most prominent of these superimposed gravity high anomalies, perceived better from the satellite-derived free-air gravity anomaly map, is a nearly NNW-SSE trending gravity high trend (GH-3 in Fig. 7), which extends almost the entire N-S extent of the central part of the TT region. Interestingly this prominent gravity high trend of central TT region (Figs. 6, 7) coincides with the apex region of the wide basement high feature of the central TT region observed in the multichannel seismic reflection sections (Figs. S1 and S2). We further observe (Figs. 6 and 7) that the gravity high trend of the central TT region, is wider in the south, narrows down towards north and appears to be limited in the north by the 'Quilon Escarpment', while towards south it appear to extend the whole extent of the TT.

4.2 Magnetic anomalies

The magnetic anomaly profiles (Fig. 9) show the presence of several prominent high amplitude (peak to peak amplitudes of ~300 nT) magnetic anomalies over the ATTC region. In the northern part of the CKE domain, on many profiles, we noticed the presence of bathymetric high features, which display correspondence with prominent magnetic anomalies. Locations of those bathymetric highs are marked in Fig. 10. Most prominent of those locations of correspondences was noticed along profile SK221-08 (anomaly Z in Figs. 9 and 10). In other areas of ATTC, we did not observe obvious correspondence with bathymetric highs and magnetic anomalies. In the areas south of Trivandrum (south of ~8.5°N latitude), relatively high amplitude and high frequency anomalies are present (Fig. 10) over the continental shelf region adjacent to ATTC. Interestingly this zone of high amplitude and high frequency magnetic anomalies of the continental shelf region also coincides with the prominent shelf edge gravity high belt observed over the same region. In absence of magnetic data along two profiles (SK221-05 and SK221-06) in the areas immediate north of Trivandrum, we could not decide whether these high frequency magnetic anomalies zone extends further north at least till Quilon shelf as was observed in the case of the shelf edge gravity high belt mentioned earlier.

4.3 Interpretation of gravity anomalies

To interpret the gravity anomalies, we constructed a crustal model, and assuming two-dimensionality, computed the gravity effect of the model following the method of Talwani et al.

(1959). To begin with, we constructed an initial crustal model by taking into account available geological and geophysical constraints described in the following paragraphs. Since, the constraints are not too many, hence we tried to keep the crustal model very simple with the following assumptions, which we felt are not unreasonable.

We assumed that the ATTC region is underlain by a two layered thinned continental crust. In absence of seismic velocities information from the deeper layers of this region, we assumed velocities of 6.2 km/sec and 6.7 km/sec for the upper and lower crustal layers, following the cross section and average seismic velocities shown by Fowler (2005) for an idealized rifted region. Further, the densities (ρ) corresponding to the above velocities were estimated using the velocity-density relationship of Ludwig et al. (1970) and assigned as 2.77 gm/cc and 2.89 gm/cc for the upper and lower crustal layers, respectively. In absence of any direct evidence to constrain the depth to the upper-lower crustal interface, we arbitrarily assumed this interface to lie uniformly at a depth of about 12 km, which is slightly less than half of the derived crustal thickness (~ 28 km) of the ATTC region. The Moho depth was taken as predicted by an Airy model with depth of compensation at 35 km, which is the approximate depth of Moho determined (Kumar, et al., 2001) at Trivandrum station, close to the ATTC region on the adjacent mainland. The top of upper crust is considered to be the basement and its depth was kept in the average level suggested by the seismic section over different locales. We have taken the gravity signature along the seismic section as a guide to extrapolate the locales (eg. basin/ basement high etc.) onto the gravity anomaly profiles, which were used for modelling. In the TT region the shallower part (down to the basement) was constrained by extrapolation from the multi-channel seismic reflection data along the nearby seismic profile SST-17. For the AT region we took constraint for the shallower part from a published (Rao and Bhattacharya, 1975) line drawing interpretation of a seismic profile collected on board R/V Chain in 1971 using a 40 cu inch air gun as seismic source. We attempted to assume a generalized average sedimentary column for the ATTC region based on the limited drill well and seismic velocity information available (Fig. S3) in the vicinity of the study area. The information on lithology were obtained from drill wells CH-1-1 and K-1-1 (Singh and Lal, 1993) and some information on the velocities of sediments were obtained from the sonobuoy refraction stations 87C17 and 88C17 (Naini, 1980) and drill well K-1-1 (Deeskhitulu, 1981). Though the thicknesses of the sediment layers vary, both the drill wells CH-1-1 and K-1-1 indicated a generalized two-layered sedimentary structure that mainly consists of a shallower and thinner silt/clay/limestone layer underlain by a thicker layer mainly of sandstone, with thin beds of trap basalts within them at different depth levels. The velocity information available from seismic refraction stations 87C17 and 88C17 is limited to

very shallow region and the layers with velocity of ~ 1.65 km/sec may correspond to the silt/clay/limestone lithology and the subsequent layer with velocity 4.1-4.5 km/sec may correspond to the intervening trap basalts. We noticed that the seismic sections along profiles SST-17 and SST-16 in the TT region also suggested a distinct boundary separating the upper acoustically transparent layer and the lower layered units. In view of the above information, it appears that for the study area we can reasonably assume a generalized two-layered sedimentary structure with a shallower and thinner silt/clay/limestone layer underlain by a thicker sandstone layer. The velocity corresponding to these layers were derived based on the velocity-depth information available from K-1-1 drill well and a velocity of 2.1 km/sec and 3.4 km/sec were assigned for the upper silt/clay/limestone layer and lower sandstone layer, respectively. The average thickness of these layers in each domain, i.e., Laccadive Basin, ATTC and continental shelf/slope, were assumed using the seismic section / drill hole information as guide. The densities for these sediment layers were estimated based on the velocity-density relationship of Ludwig et al. (1970) and densities of 1.98 gm/cc and 2.3 gm/cc was assigned for the upper and lower layers of sediments, respectively.

Part of these two profiles fall on the deep sea Laccadive Basin region west of the Chain-Kairali Escarpment. Difference in opinion exists about the nature of the crust for the Laccadive Basin region. Some researchers (Biswas and Singh, 1988) considered this region to be underlain by oceanic crust, while others (Chaubey et al., 2002; Ajay et al., 2010) considered a thinned continental crust. We also noted that no dependable constraints, such as, crustal velocity structure based on seismic studies or identified seafloor spreading type magnetic anomalies, are available to resolve the ambiguity about the nature of crust underlying the Laccadive Basin. In view of this, we computed gravity anomalies along the profiles for both the possibilities i.e. the crust underlying the Laccadive Basin can be either a continental crust or an oceanic crust. To begin with we assumed that the crust underlying the Laccadive Basin west of the Chain-Kairali Escarpment (CKE) is also a two-layered thinned continental crust (Model – A in Figs. 11a and 11b) with similar overlying sedimentary layers as of the ATTC. With this assumption, we computed the isostatic Moho depth for Laccadive Basin region in the same way as was done for the ATTC region. Further, we assumed the lateral boundaries of each geological domain from the structures revealed by the seismic reflection profiles and the corresponding shape of the gravity anomalies. While refining the models, we kept the bathymetry and the assumed layer densities unchanged, but made slight refinement to the depth to the basement and the deeper crustal layers. After obtaining a reasonable good fit between the observed and computed gravity anomalies, we carried out forward modelling of the magnetic anomalies using the gravity modelling derived crustal configuration as the initial model. After obtaining a reasonable

model of causative bodies predicted from modelling of magnetic anomalies, we incorporated those magnetized causative bodies as higher density bodies, possibly representing volcanic intrusives in the form of sills and dykes within the crustal layers. Subsequently gravity anomalies were recomputed with the so modified crustal structure model, and the model was refined till a good fit was obtained between computed and observed gravity anomalies. In some situations, to obtain better fit between computed and observed gravity anomalies, we had to somewhat modify the shape of the magnetic causative bodies. In such cases, we recomputed the magnetic anomalies using those modified causative body shapes and refined magnetic modelling and again incorporated those modified magnetic causative bodies in the crustal structure model for gravity anomaly modelling. This iterative approach was continued for both the profiles, till we obtained crustal structure models, that satisfy both the gravity and magnetic data.

Next we examined the gravity anomalies across the ATTC with the possibility of an oceanic crust to underlie the Laccadive Basin. For this situation, by keeping the layer parameters for ATTC regions unchanged, we first considered a two-layered oceanic crust (~2 km thick layer-2 of 2.63 gm/cc density overlying an ~5 km thick layer-3 of 2.88 gm/cc density) for the Laccadive Basin areas adjacent to CKE. The thicknesses of these oceanic layers were considered as given in Fowler (2005) for standard oceanic crust, while the densities were obtained by converting the layer velocities estimated from seismic refraction studies (Naini, 1980; Naini and Talwani, 1982) in the oceanic crust region of the nearby Arabian Basin. We observed that with the above density assumptions and by keeping the thickness of layer-2 unchanged, we can obtain a good fit between the observed and computed gravity anomalies provided we assume the existence of an ~15 km thick layer-3, which is about 3 times the thickness of normal layer-3. Next we examined an alternate situation in which, we considered a high velocity lower crustal layer (average value of 7.19 km/sec, i.e. density 3.02 gm/cc) to underlie an ~5 km thick layer-3 (Model – B in Figs. 11a and 11b). This high velocity lower crustal layer assumption is based on the fact that existence of such a layer was inferred from seismic refraction studies in number of stations located in the Laxmi Basin region, northwards of the Laccadive Basin. We observe that we can obtain a good fit between the observed and computed gravity anomalies if we assume the existence of ~13 km thick high velocity lower crustal layer in the Laccadive Basin area. It may be noted that for the models with oceanic crust assumption for the Laccadive Basin, we have not changed the magnetic causative bodies inferred from magnetic modelling, but only made minor modification of the Moho configuration in the regions of CKE and the Laccadive Basin.

The derived crustal configurations (both Model-A and Model-B) show that, in the TT region (composite profile SG-1+SK221-05 in Fig. 11a), the crustal thickness gradually decreases from ~32 km in the continental shelf region to about 29 km towards the terrace edge end of the profile in the west. In the AT region the derived crustal configuration shows that (profile SK221-08 in Fig. 11b), the crustal thickness gradually increases from ~35 km in the continental shelf region to about 34 km towards the terrace edge end of the profile in the west. For both the profiles, the crustal thickness appears to decrease rapidly across the CKE. As mentioned earlier, a prominent gravity high anomaly belt (Figs. 7 and 8) is present in the region of continental shelf edge southwards of Quilon. This shelf edge gravity high belt is more prominent south of 9°N in the continental shelf region adjacent to TT and along profile SK221-05 it is notable (Fig. 11a) between kms 275 and 310. Although, we do not have seismic constraints for the depth to the basement in this region, still we felt that it would be reasonable to assume the existence of a large basement high in the crustal structure model to explain this shelf edge gravity high belt.

4.4 Interpretative modelling of magnetic anomalies

The interpretation of gravity anomalies suggests that the crustal configuration of ATTC region is consistent with a thinned continental crust. If this inference is correct, then we considered that the bodies causing the magnetic anomalies in this region should be compatible to the gravity modelling derived crustal structure. With this consideration in mind, we carried out forwarding modelling of magnetic anomalies along two transects using the two-dimensional modelling method of Talwani and Heirtzler (1964). We appreciate the fact that modelling of magnetic bodies is problematic near the geomagnetic equator as the induced magnetic responses of bodies in this region causes absence of anomalies in the central portion of elongate N-S bodies. However, in the study area, we observed that the prominent magnetic anomalies, having peak to peak amplitude ~300 nT, are correlatable within adjacent transects and depict elongated shape (Figs. 9 and 10). Therefore, we considered that the causative magnetized bodies are two-dimensional and that they have strong remanent component. As described earlier, the prominent magnetic anomalies do not appear to have obvious correspondence with bathymetric high features except in some locations in the CKE domain. The crossings of magnetic and seismic transects did not suggest the presence of distinctive basement features, which can be obviously correlated with any of the prominent magnetic anomalies. Therefore we assumed that the magnetic anomalies observed in the study area have mainly been caused by volcanic intrusives within the crust. This assumption appear to be reasonable as presence of intrusive volcanic rocks are reported from outcrops and bore holes in the adjacent land and offshore areas (Valsangkar et al., 1981; Raju et al., 1981; Singh and Lal, 1993; Torsvik et al., 2000;

Radhakrishna et al., 1990, 1994, 1999; Anilkumar et al., 2001; Melluso et al., 2009 and references therein; Radhakrishna and Joseph, 2012).

Paleomagnetic studies of volcanic rocks from large number of sites in the adjacent mainland (Radhakrishna and Joseph, 2012) and from the offshore St. Mary Islands (Torsvik et al., 2000) suggested the existence of volcanic intrusives of mainly two age groups in this region. The older (~ 85-91 Ma) intrusives are found to have only normal magnetization (average remanent: inclination around -57° and declination around $+307^\circ$), while out of the younger (~ 65-70 Ma) intrusives studied, some were found to have reverse magnetization (average remanent: inclination around $+52^\circ$ and declination around $+155^\circ$), the others have normal magnetization (average remanent: inclination around -54° and declination around $+329^\circ$). Here, the reverse and normal polarity terms have been used in accordance to the position of the Indian subcontinent on the southern hemisphere during these periods of volcanic activity. Further, following Radhakrishna and Joseph (2012) and Torsvik et al. (2000), the ~ 85-91 Ma volcanics are considered to be associated with the Marion Hotspot activity, that was instrumental for India–Madagascar break up and the ~ 65-70 Ma volcanics are related with Reunion Hotspot. However, various plate tectonic reconstructions (Muller et al., 1993; Mahoney et al., 2002; Royer et al., 2002) also suggest that the ATTC region was in the proximity of Reunion Hotspot around 55-60 Ma. Hence, the volcanic intrusives of the ATTC region can be related to either 85-91 Ma volcanics related to Marion Hotspot activity, or to the 65-70 Ma Reunion Hotspot related volcanics sampled on adjacent land or even to the Reunion Hotspot related volcanics when this region was in close proximity of the Reunion Hotspot around 55-60 Ma. Although we are not sure about which one of these volcanic episodes have caused the inferred volcanic intrusives of the ATTC region, but we are sure that the study area was in the southern hemisphere during the time of all these volcanic episodes. Since, results of paleomagnetic measurements are available only for the land volcanics and the St. Mary Islands volcanics; hence we have taken those results to provide broad constraints for our magnetic modelling exercise. By trial and error we came to the conclusion that the magnetic anomalies along the two profiles we modeled, have been caused by normally magnetized bodies, but we can not distinguish between two slightly different directions of magnetization of the older (~ 85-91 Ma) and younger (~ 65-70 Ma) normally magnetized bodies. In view of this we modeled the bodies with magnetization directions (average remanent: inclination around -56° and declination around $+315^\circ$) obtained from averaging inclination and declination directions respectively of all normally magnetized rocks. In our magnetic modelling, we restricted the lower boundaries of the assumed intrusive bodies to about 22 km, which should be the Curie point isotherm depth (for Curie point temperature of $\sim 580^\circ$ C for magnetite) in the area considering

the average geothermal gradient in the continental crust as $\sim 25^\circ$ C/km. Similarly, we restricted the upper boundaries of the assumed intrusive bodies to the depth of the assumed basement. However, for gravity modelling the lower boundaries of those intrusive bodies were extended to the depth of the assumed Moho in that location.

Our final magnetic models (Figs. 11a and 11b) provided very good agreement between computed and observed magnetic anomalies and appear to suggest that magnetic anomalies of the ATTC region can be inferred to have been caused by magnetized bodies that intruded within the thinned continental crust. The shallow regions of the gravity and magnetic anomaly modelling derived crustal structure across the Trivandrum Terrace (composite profile SG-1+SK221-05) and the Alleppey Terrace (profile SK221-08) are shown in Figs. S4 and S5 to highlight the basement configuration and its correspondence with the magnetic / gravity anomalies and also the nature of the Chain-Kairali Escarpment along these profiles. In addition to magnetic modelling along the two trans-ATTC representative profiles as above, we also have modelled a representative segment (segment DE of profile SK221-04) of the very high amplitude magnetic anomalies observed (Fig. 10) along some of the profiles-over the continental shelf areas southwards of Trivandrum. Magnetic anomalies in this shallow continental shelf part was modelled (Fig. S6) to substantiate our inference that these anomalies could have been caused by thick magnetized bodies existing at very shallow subsurface (i.e. top of the bodies at ~ 0.5 km) in that region. As mentioned earlier, this zone of high amplitude magnetic anomalies of the shelf also coincides with the prominent gravity high belt of the shelf edge. This shelf edge gravity high was interpreted to have been caused by a basement high. We interpret that this basement high is intruded by magnetized dykes reaching to very shallow subsurface depth.

5. Discussion:

The updated compilation of bathymetric data enabled better perception of the seafloor topography and highlights the interesting topographic anomalies of the region. Based on comparison with the multichannel seismic reflection data, it can be seen that the apparent flatness of the terrace region is due to the blanketing of the highly undulating basement topography by a sedimentary apron. In the middle of the TT region the presence of a NNW-SSE trending, nearly 100 m high, wide and gentle bulge of the seafloor flanked by troughs of the seafloor on both sides is noticeable in both the bathymetric contours and profiles. The seismic data clearly show that this bulge is not caused directly by any basement high; rather it is formed by a bulging sedimentary, most likely composed of hard calcareous material, apron over a basement high trend which exists in the central part of the TT. This nearly NNW-SSE trending wide basement high is flanked on both sides by thick sediment filled

basins, which are underlain by block-faulted basement. This wide basement high also coincides with a prominent gravity high trend, which appear to narrow towards north and terminate in the proximity of Alleppey Terrace. From the coincidence of gravity high trend and the basement high of TT, we are tempted to infer that the basement high of TT and flanking basins (TT-EB and TT-WB) do not continue into the Alleppey Terrace region. Perhaps the tectonic activity which caused the formation of this basement high and flanking basin structure got terminated on meeting a barrier in the form of Quilon Escarpment. In other words, we infer that the tectonic activity which caused the formation of the Quilon Escarpment is older than the tectonic activity which caused the formation of these basement high and basin structures over the central part of TT. This NNW-SSE trending basement high of the TT region has a gently sloping easterly surface as compared to relatively steeper westerly surface. Overall it gives the impression of a tilted basement mega block. It may be possible that the ATTC region is actually a region of faulted mega crustal blocks, which subsequently was covered with sediments to develop into a relatively flat surface. In the zone where the CKE and QE are expected to intersect, we did not notice any offset in the bathymetry contours of the CKE domain. From this observation we infer that the CKE formation event was younger than QE formation event. The two events, the CKE formation event and tectonic event forming basement high and basin structure of the TT, both are inferred to be younger to QE event.

The seafloor depicts anomalous undulations of the seafloor at places, more particularly in the regions towards the western part of the TT. Seismic data clearly indicate (Fig. 5) that this ruggedness is purely a sedimentary feature and most of them are of the order of ~75 m in relief. We believe that a sedimentary feature of such height can not be sustained in the seafloor, unless the feature is formed of hardened material. Hardened submerged reefal structures or submerged sand waves may cause such rugged seafloor. In the TT region, the seismic data suggest, these rugged features to have developed over acoustically transparent sedimentary layers and that too on the western fringes of the TT region. We therefore speculate a barrier reef type genesis to this ruggedness of the seafloor. If this inference is correct, then TT region was in very shallow waters, when this reef structures were growing in the euphotic zone and later subsided to the present depth.

Over the ATTC, we observed several high amplitude magnetic anomalies. In the northern part of CKE, some bathymetric highs appear to have correspondence with the magnetic anomalies, elsewhere, no distinctive seafloor / basement features have correspondence with the magnetic anomalies. Our magnetic model suggests that those magnetic anomalies can be reasonably explained in terms of intrusive causative bodies having negative (-56°) inclination and NW ($\sim 314^\circ$) declination. Such magnetization directions can only be acquired when bodies are magnetized in the southern

hemisphere during a normal polarity epoch. The paleomagnetic and plate tectonic reconstruction studies (Besse and Courtillot, 1988) suggest that the southwestern part of the Indian mainland and its conjugate Madagascar landmass were in the southern hemisphere at the time of India-Madagascar separation in Late Cretaceous and also were within the domain of influence of Marion Hotspot. However, at the time of Reunion Hotspot volcanism, the Madagascar landmass was far away and only the ATTC region was in the proximity of Reunion Hotspot. Since India-Madagascar separation and related Marion Hotspot volcanism have taken place during Cretaceous Long Normal period, hence all the volcanics should have acquired only normal magnetizations. However, the volcanics which are related to the Reunion Hotspot could have both normal and reverse magnetizations as polarity reversals were relatively frequent during the Paleogene. In view of these, the volcanic intrusives of the ATTC region, which have normal magnetization could have been caused by any of these two hotspots. Therefore, on the basis of only magnetization directions, we can not decide whether they are related to Marion or Reunion hotspots. However, considering the existence of ~90 Ma old volcanic rocks at St. Mary Islands in the closest proximity of the ATTC, we are inclined to believe that the volcanic intrusives of the ATTC region are all related to India-Madagascar separation either as rifting related volcanism or as Marion Hotspot influenced volcanism. Resolution of this aspect has to wait till further studies, but at present we interpret that the ATTC is underlain by a thinned continental crust intermingled with extensive volcanic emplacements.

Whitmarsh (1974) noticed the existence of a long scarp and ridge east of the Chagos Archipelago approximately between 2°S and 12°S. This scarp was inferred by him as a fracture zone (FZ) and named as 'Vishnu FZ'. In the Anomaly 22 (53 Ma) paleogeographic reconstruction of the western Indian Ocean, Norton and Sclater (1979) have shown this Vishnu FZ as conjugate to the Mauritius FZ of the Mascarene-Madagascar basins. The satellite gravity anomaly of recent years suggests a distinct gravity trend to be associated with this eastern scarp face of Chagos Archipelago (or the so-named Vishnu FZ) and quite interestingly this gravity trend when extended northwards, albeit with considerable (~300 km) discontinuity, appears to coincide with the trend of the CKE. Perhaps this alignment prompted some workers (Subrahmanyam and Chand, 2006; Nathaniel et al., 2008) to indicate the CKE region as a northward extension of the Vishnu FZ. If this CKE and Vishnu FZ correspondence is correct, then the CKE will appear as the conjugate of the Mauritius FZ since separation of India and Madagascar. However, contrary to this situation, the ~ 83 Ma reconstruction (Yatheesh et al., 2006) of India-Madagascar with the same Norton and Sclater (1979) rotation parameters or with the much more recent rotation parameters of Muller et al. (2008) suggest the CKE region as aligned with the Mahanoro FZ of the Mascarene Basin. These observations cast

doubt about the possibility of the CKE as the northwards continuation of the Vishnu FZ. Further, from a paleogeographic reconstruction (Fig. 12) of India and Madagascar in their immediate pre-drift stage, we notice that the NE-SW trending straight southeast coast of the Madagascar is very much close and strikingly parallel with the CKE. Based on these observations, we believe that CKE is not a continuation of Vishnu Fracture Zone but it was formed as conjugate to the Mahanoro FZ since the time of initiation of separation of India and Madagascar till about 72 Ma. Further, the paleogeographic reconstructions with Norton and Sclater (1979) or Muller et al. (2008) suggest some anticlockwise rotation of India with respect to Madagascar between 72 and 67 Ma. This anticlockwise rotation of India might have caused the CKE to appear as aligned to the Vishnu Fracture Zone as we observe at present. However, confirmation of this explanation has to await further studies, which are beyond the scope of this paper.

The gravity modelling suggests that, the crustal thickness in the TT region varies between 29–32 km and remains about 34 km in the AT region. From these, we infer that the crust in the ATTC region is slightly thinner than the adjacent mainland areas. However, in the AT region the crust is thicker than in the TT region. We noticed that to achieve a good fit between the observed and modelled gravity anomalies, the Moho level of the Laccadive Basin needs to be assumed at a much shallower level as compared to that of TT region and with a steep change in Moho level across the CKE if we assume a two layered continental crust to underlie this area. As a result the model yields a crustal thickness of around 17 km for the Laccadive Basin areas adjacent to CKE. We also noticed that a good fit between the observed and modelled gravity anomalies can be obtained even if we assume an anomalously thick oceanic crust in the Laccadive Basin region. The ambiguity regarding the nature of crust underlying the Laccadive Basin can not be resolved until further constraints such as; crustal velocity information, confident identification of seafloor spreading type magnetic anomaly identifications etc. are available from the Laccadive Basin region. However, the gravity modelling has definitely pointed out to the situation of rapid seaward decrease of the crustal thickness across the CKE and in the context of margins such rapid decrease of crustal thickness have been noticed usually in case of sheared continental margins.

6. Summary and conclusions

Based on a compilation of recently acquired as well existing bathymetry, gravity, magnetic and multi-channel seismic reflection data, the study attempted to understand the morphotectonic architecture of the ‘Alleppey-Trivandrum Terrace Complex (ATTC)’, which is a conspicuous and anomalous lateral bathymetric protrusion in the continental slope region off southwestern coast of India. This little studied bathymetric protrusion of large areal extent (area > 35000 sq km) have been

postulated (Yatheesh et al., 2006) to represent a scar related to India-Madagascar separation, where its conjugate feature is proposed to be a conspicuous bathymetric notch in the northern Madagascar Ridge. This conjugate association, once unambiguously established, can provide a distinct ‘piercing point’ to constrain the India-Madagascar juxtaposition in their immediate pre-drift scenario.

The bathymetric data suggest the ATTC region to consist of two large contiguous terrace-like features, named in this study as the ‘Trivandrum Terrace (TT)’ and the ‘Alleppey Terrace’ (AT). A conspicuous, nearly 500 km long, steep ‘Chain-Kairali Escarpment (CKE)’ demarcates the westward limit of the ATTC and the nearly 50 km long ‘Quilon Escarpment (QE)’ demarcate the boundary between the southerly, larger and deeper ‘Trivandrum Terrace (TT)’ and northerly, smaller and shallower ‘Alleppey Terrace (TT)’. The two terraces being at two different depth levels cause the height of the CKE to vary from about 2500 m in the areas of AT to about 1000 m in the areas of TT. The height of the QE in its steepest part is about 900 m. It may be mentioned here that the above-mentioned heights of the CKE and QE have been defined as the difference of the present day seafloor depths of concerned areas. Since this seafloor forms the top of substantial thickness of sediments overlying the basement, hence the true height of the CKE and QE may be much greater once the actual depths of the basement are known.

The multichannel seismic reflection data suggests the presence of a nearly NNW-SSE trending wide basement high in the central part of the ‘Trivandrum Terrace’. This basement high is flanked on both sides by thick (~1.7 sec TWT) sediment filled basins, which in turn, are underlain by block-faulted basement. The seafloor of at least the TT region appears to be formed of a carbonate sedimentary cover, which draped the pre-existing regions of basement highs and basinal lows. Presence of submerged barrier reef structures at the western periphery of TT appears to suggest submergence of the TT region, from the euphotic/ sub-areal level, to the depth of its present existence.

The crustal configuration of the ATTC region as obtained from forward modelling of gravity anomalies, suggest a crustal thickness varying between 29 and 32 km in the ATTC region. This crustal thickness rapidly reduces across the CKE towards the Laccadive Basin region. We infer that the crustal structure of the ATTC region is comparable to a thinned continental crust, whereas the crust in the Laccadive Basin region could either be a further thinner continental crust or an anomalously thick oceanic crust. We believe, the rapid seaward decrease of the crustal thickness across the CKE suggests the CKE to be a sheared continental margin and based on early drift (~ 85 Ma) reconstruction (Fig. 12), we infer that the ‘Chain-Kairali Escarpment (CKE)’ forms that sheared continental margin along which the continental margin off the nearly straight southeast coast of

Madagascar (SECM in Fig. 12) glided past India. Further, the prominent volcanic intrusives inferred to be present in the CKE domain perhaps represent the volcanism related to the sheared continental tectonics. Since, CKE appear to be a sheared continental margin, it may be worthwhile to mention that in some other oceanic areas, the crust immediate seaward of the sheared continental margin was found to have either wide anomalous ocean-continent transition zone (Edwards et al., 1997) or thickened oceanic layers (Lorenzo et al., 1991). It will be interesting to undertake future studies to understand the exact situation prevailing in the region seaward of CKE sheared continental margin.

The ATTC region is also characterized by the presence of several prominent high amplitude magnetic anomalies, which display peak to peak amplitudes of ~300 nT. Forward modelling of magnetic profiles suggests that those prominent magnetic anomalies can be explained in terms of extensive normally magnetized volcanic intrusive bodies, which were emplaced during a normal magnetic polarity interval, when the ATTC region was in the southern hemisphere. Based on interpretation of gravity, magnetic anomalies and basement characteristics revealed by seismic reflection data, we interpret that the ATTC region is underlain by block faulted and thinned continental crust, which probably is intermingled with extensive volcanic intrusive emplacements.

As at present we cannot definitively say that the inferred volcanic emplacements in the ATTC region are all related to Marion Hotspot activity. However, based on the proximity of this region to the St. Mary Islands, which is considered to be a product of Marion Hotspot, we are more inclined to assume these volcanic emplacements in ATTC region too are related to Marion Hotspot. However, confirmation of this assumption will require geochronological, paleomagnetic and geochemical investigations of volcanic rocks collected from the offshore ATTC region. For this purpose, the outcrop / shallow sub crop of the basement rock observed in the 'Alleppey Terrace' sector of the CKE (point Z labeled in Fig. S7) can be considered as a potential candidate site for volcanic rock sample collection.

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Figure Captions

- Fig. 1 Generalized map of the southwestern continental margin of India and adjoining deep sea regions along with selected bathymetric contours obtained from GEBCO digital data set (IOC-IHO-BODC, 2003). The open triangles and solid squares represent the locations of volcanics with estimated $\sim 85\text{-}91$ Ma ages and $\sim 65\text{-}70$ Ma ages respectively (compiled from Radhakrishna and Joseph, 2012; Torsvik et al., 2000). TT: Trivandrum Terrace; AT: Alleppey Terrace
- Fig. 2 Map showing locations of selected sea-surface gravity, magnetic, bathymetry and multichannel seismic reflection profiles used in the present study. The solid diamonds and solid triangles represent the locations of drilled wells and refraction stations respectively, which were used to obtain constraints for forward modelling of gravity data. Solid dots along the seismic lines are at 20 km interval from the western end of the profiles and they are annotated at 40 km interval. Other details as in Fig. 1.
- Fig. 3 Updated bathymetric map of the Alleppey-Trivandrum Terrace Complex area. Updated contours (black dotted lines) are drawn at 100m contour interval between 200 m and 2000 m isobaths. The solid red stars represent locations of prominent topographic highs within the domain of Chain-Kairali Escarpment (CKE). Bathymetric data tracks used for preparing updated contours are shown with blue dashed lines. QE: Quilon Escarpment. Other details as in Fig. 1.
- Fig. 4 Selected bathymetric profiles across the southwestern continental margin of India showing the sectional view of the Alleppey-Trivandrum Terrace Complex and the adjacent physiographic features. Profiles are stacked with respect to the shelf break. The locations of these profiles are given in Fig. 2 and the depth levels of 1 and 2 km are labelled on the profiles. Shaded regions represent approximate extent of the Trivandrum Terrace (TT) and the Alleppey Terrace (AT) and the blue dotted line represents approximate location of the Chain-Kairali Escarpment. Other details are as in Figs. 1 and 3.

- Fig. 5 Multichannel seismic reflection sections along profiles SST-17 and SST-16. Inset panels show detailed view of block-faulted nature of the basement along the profiles. TT-WB: Trivandrum Terrace – Western Basin; TT-EB: Trivandrum Terrace – Eastern Basin
- Fig. 6 (a) Free-air gravity anomaly map derived from satellite altimetry (Sandwell and Smith, 1997) in the study area and the neighbourhood. Also shown are the free-air gravity contours in 20 mgal interval (thin black lines) and the locations of the seismic reflection profiles (thick white lines) whose sections are given in Fig. 5. (b) Detailed view of free-air gravity signatures of the Alleppey-Trivandrum Terrace Complex showing the nearly NNW-SSE trending central gravity high trend (GH-3) that coincides with the basement high depicted in the seismic sections. Distances along the seismic reflection profiles are annotated for each 20 km interval. Approximate location of the axis of the basement high; along profile SST-17 is around 80 km mark and along profile SST-16 is around 70 km mark.
- Fig. 7 Selected free-air gravity profiles stacked with respect to the shelf break. GH-1, GH-2 and GH-3 are the gravity high trends discussed in the text. Locations of the profiles are given in Fig. 2 and other details are as in Fig. 4.
- Fig. 8 Free-air gravity anomalies over the Alleppey-Trivandrum Terrace Complex plotted perpendicular to ship's tracks. For clarity, the anomalies were plotted only along those tracks which are nearly perpendicular to the coast. The blue lines represent locations of seismic reflection profiles. The red solid stars represent locations of prominent bathymetric peaks observed on several profiles. Green shaded region defines the approximate extent of the prominent gravity high anomaly belt observed over the continental shelf region. Light grey shaded region defines nearly NNW-SSE trending central gravity high trend (GH-3). Other details are as in Figs. 2 and 3.
- Fig. 9 Selected magnetic profiles stacked with respect to the shelf break. Locations of the profiles are given in Fig. 2 and other details are as in Fig. 4.
- Fig. 10 Magnetic anomalies over the Alleppey-Trivandrum Terrace Complex plotted perpendicular to ship's tracks. Other details are as in Fig. 8.

Fig. 11 Gravity and magnetic anomaly modelling along two representative profiles across the Alleppey-Trivandrum Terrace Complex: (a) profile ABC (SG-1+SK221-05) across the Trivandrum Terrace, and (b) profile SK221-08 across the Alleppey Terrace. Both the profiles extend from Laccadive Basin in their western end to the continental shelf of India in their eastern end. Lower panels are the modelled crustal structure with densities (in gm/cc), by assuming thinned continental crust (Model-A) and anomalously thick oceanic crust (Model-B) to underlie the Laccadive Basin region. Magnetic anomalies are modeled with two-dimensional magnetic bodies of intrusive dykes and sills (Remnant magnetization= 3.5 A/m; Remnant Inclination= -56°, Remnant Declination = 315°). For magnetic anomaly computation, the lower boundaries of the intrusive bodies are limited at 22 km, the assumed depth for Curie isotherm, but for gravity anomaly computation they are considered to extend till the base of the crust. UCC: Upper continental crust; LCC: Lower continental crust; LCL: High velocity lower crustal layer. Locations of the profiles are given in Fig. 2.

Fig. 12 Paleogeographic reconstruction map (in fixed Madagascar reference frame) showing relative configuration of India and Madagascar in their early drift scenario (~ 85 Ma). The location of the Marion Hotspot (M) at this time was computed based on Muller et al. (1993) rotation parameter. Solid red triangles represent locations of ~ 85-91 Ma volcanics from the conjugate regions of India (Radhakrishna and Joseph, 2012; Torsvik et al., 2000) and Madagascar (Storey et al., 1995; Torsvik et al., 2000). SECM: Southeast coast of Madagascar; NMR: Northern Madagascar Ridge; AT: Alleppey Terrace; TT: Trivandrum Terrace.

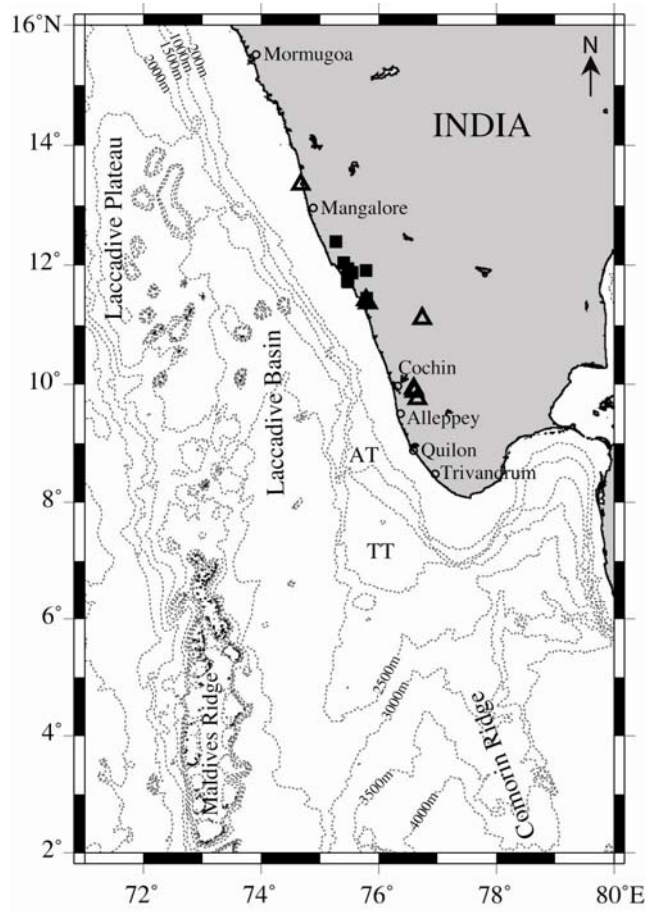


Fig. 1

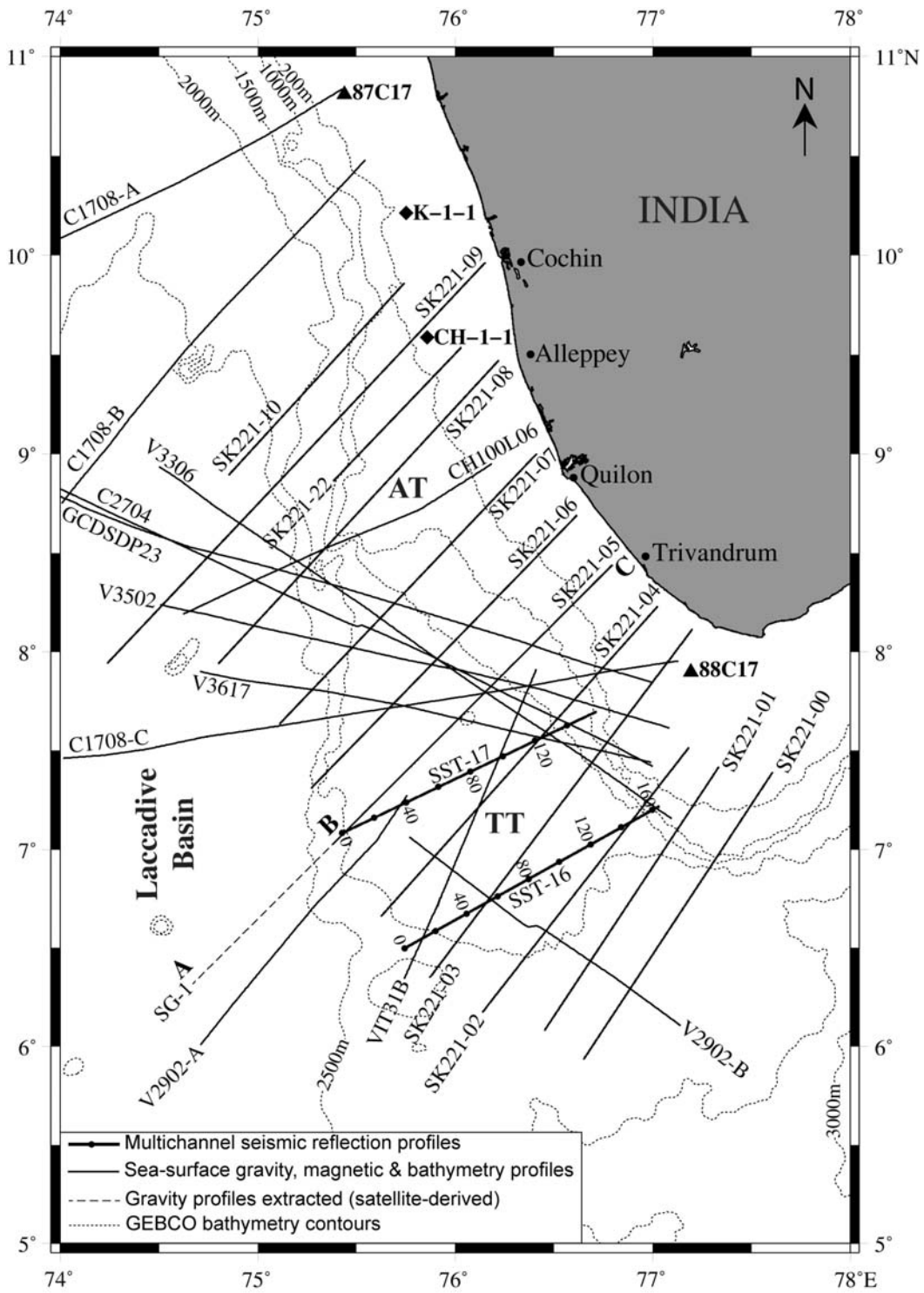


Fig. 2

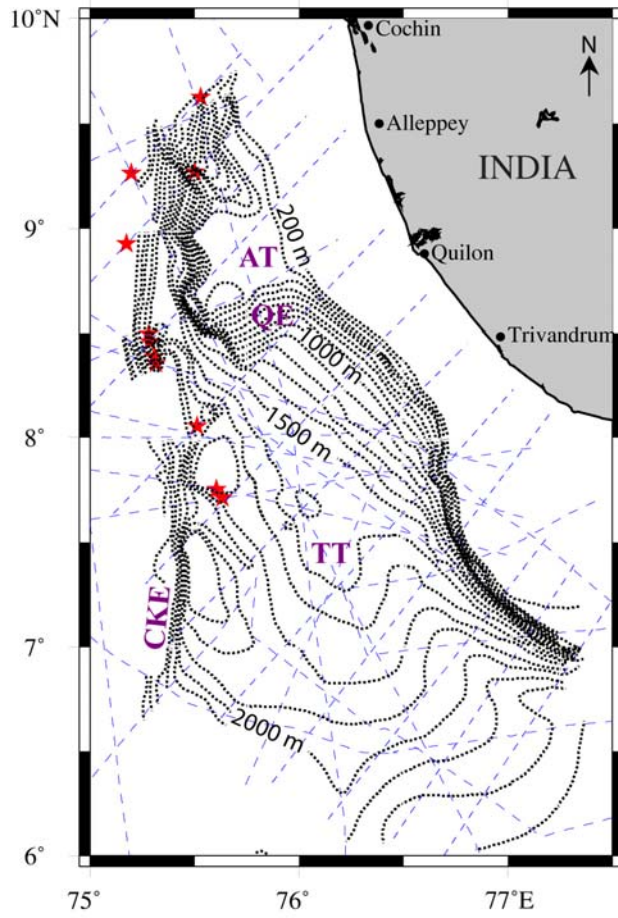


Fig. 3

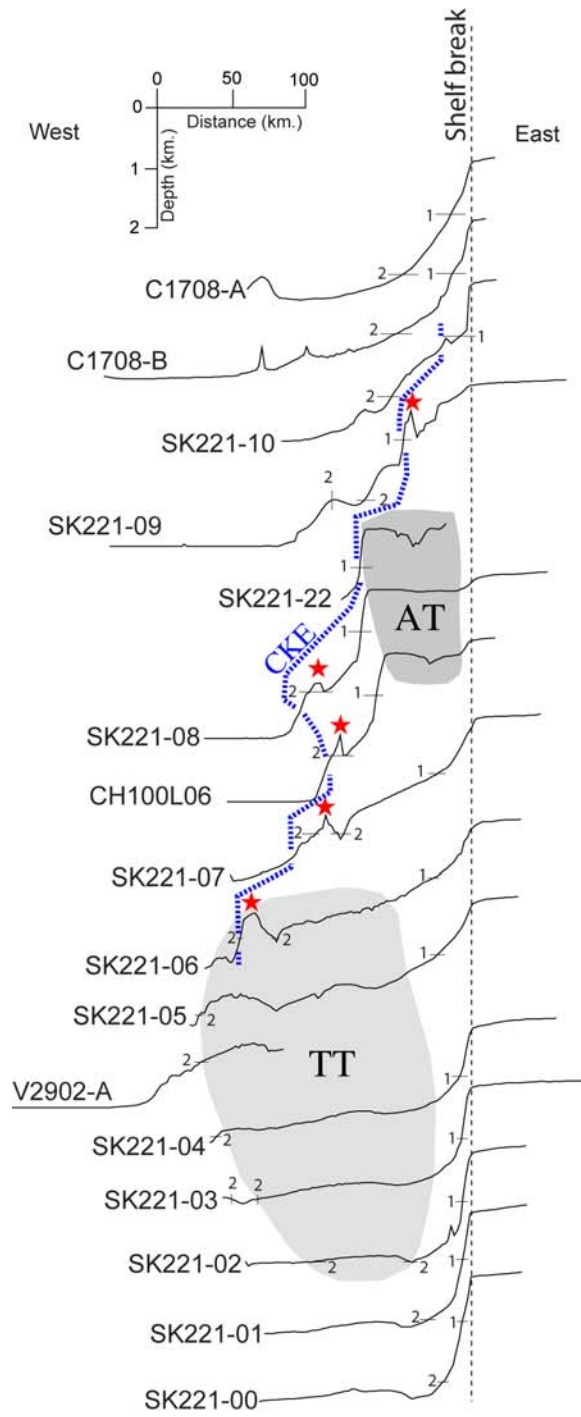


Fig. 4

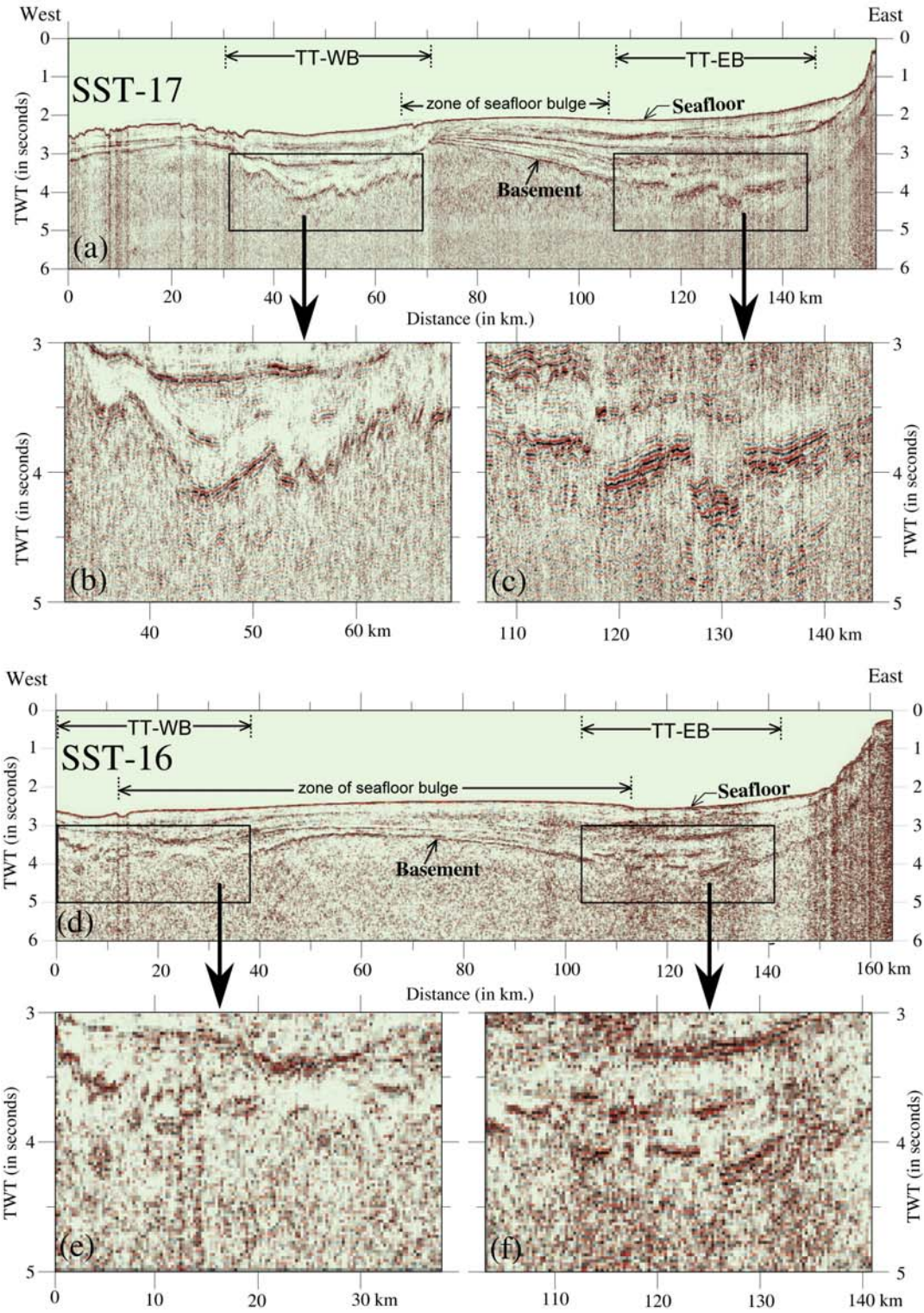


Fig. 5

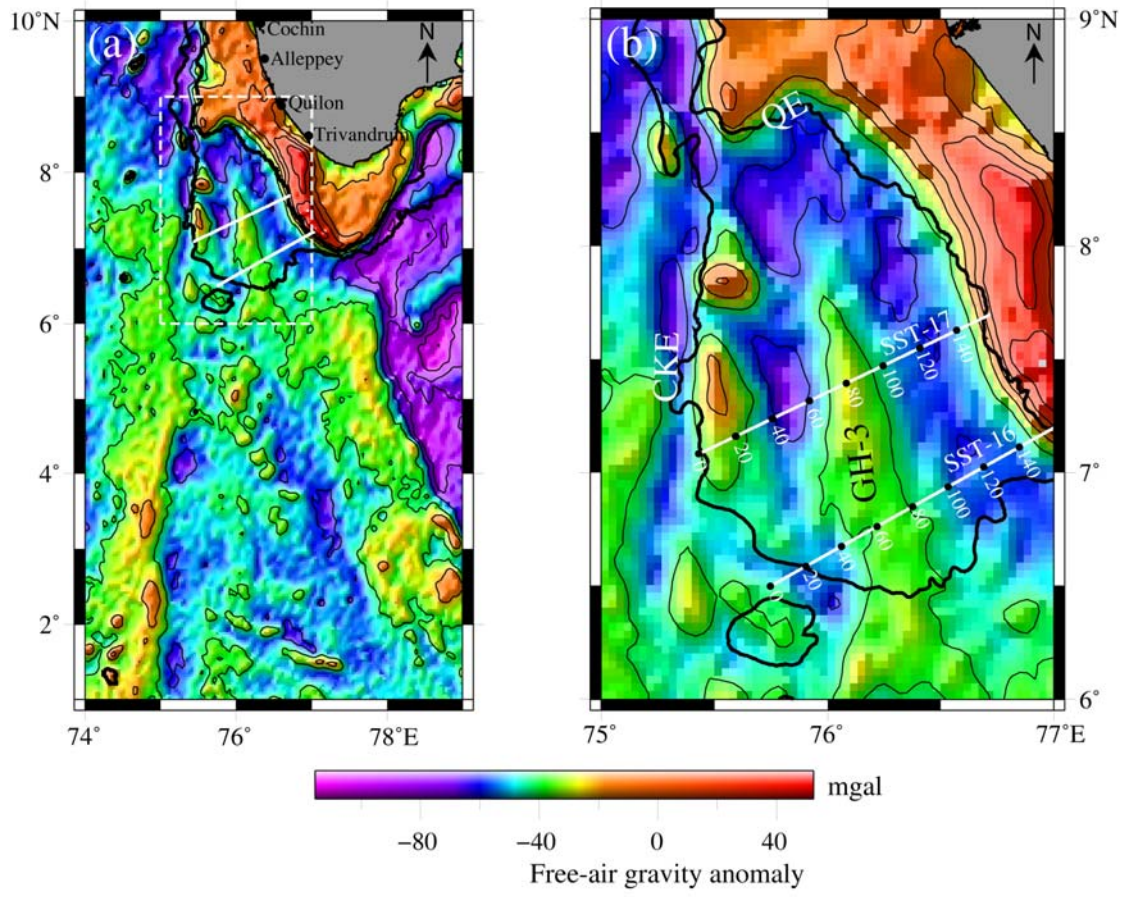


Fig. 6

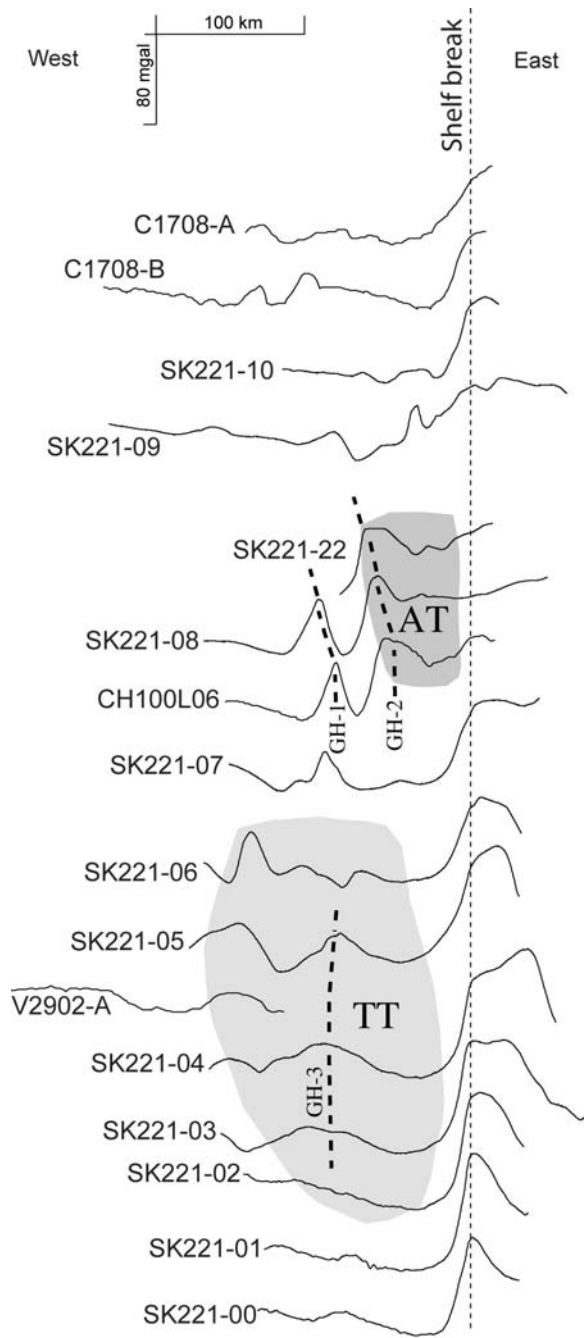


Fig. 7

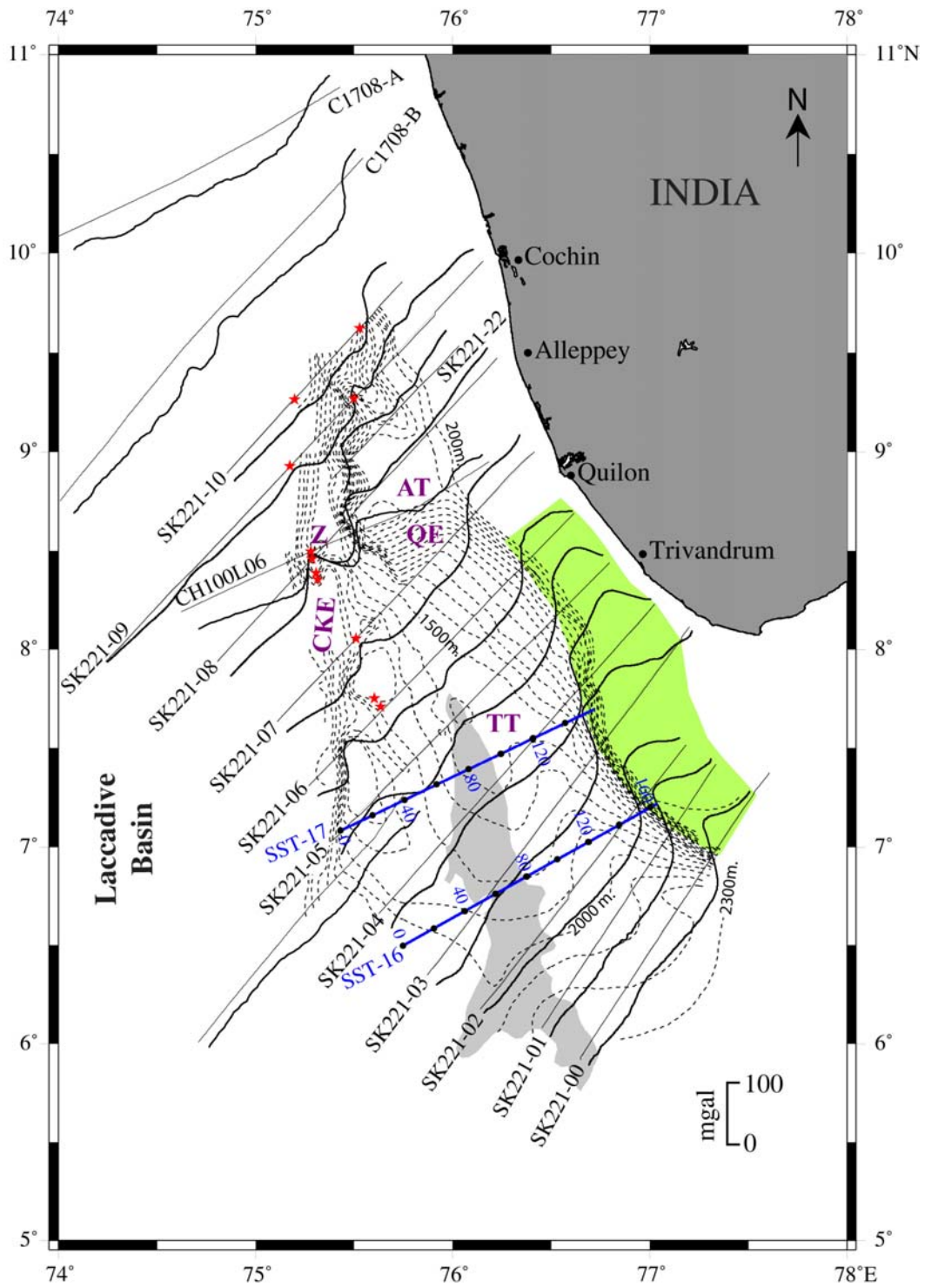


Fig. 8

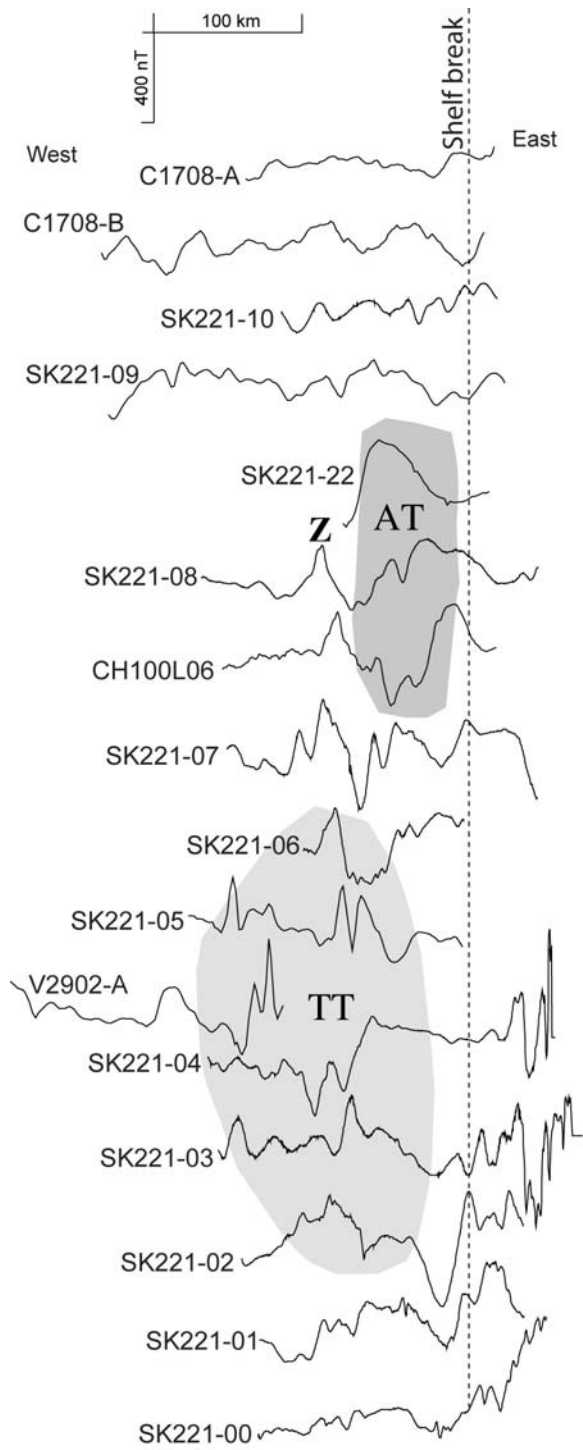


Fig. 9

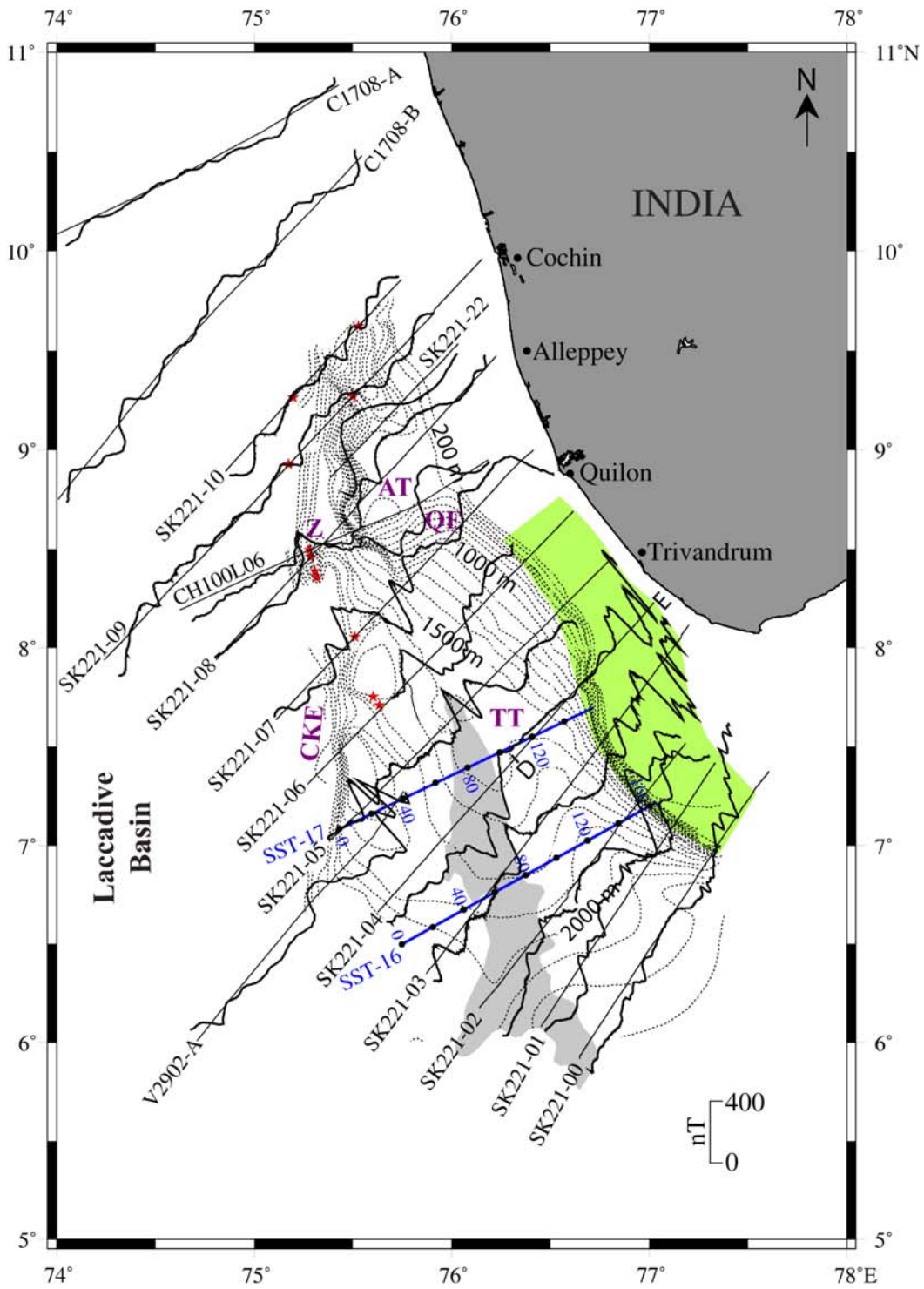


Fig. 10

Profile SG-1 + SK221-05

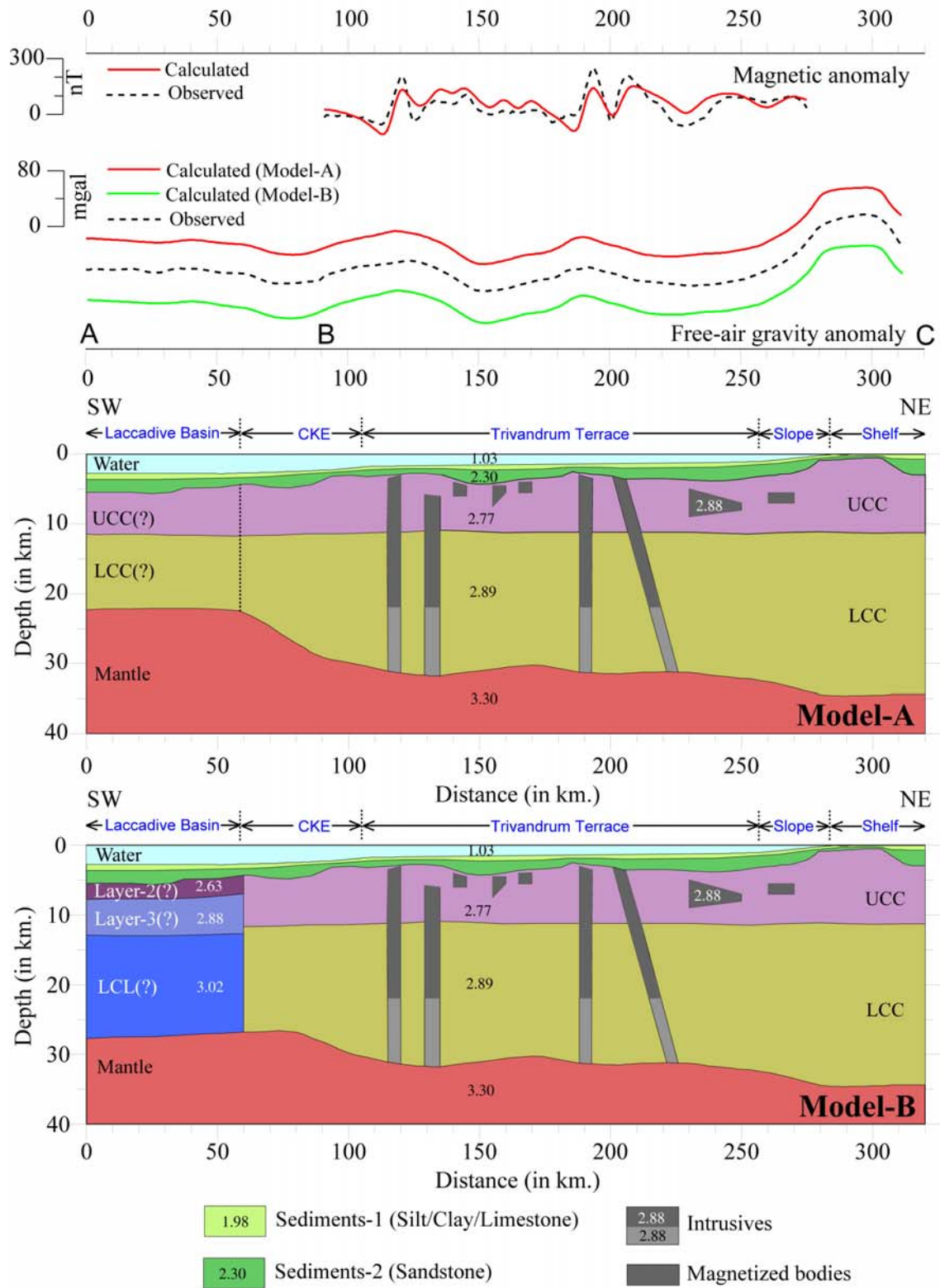


Fig. 11a

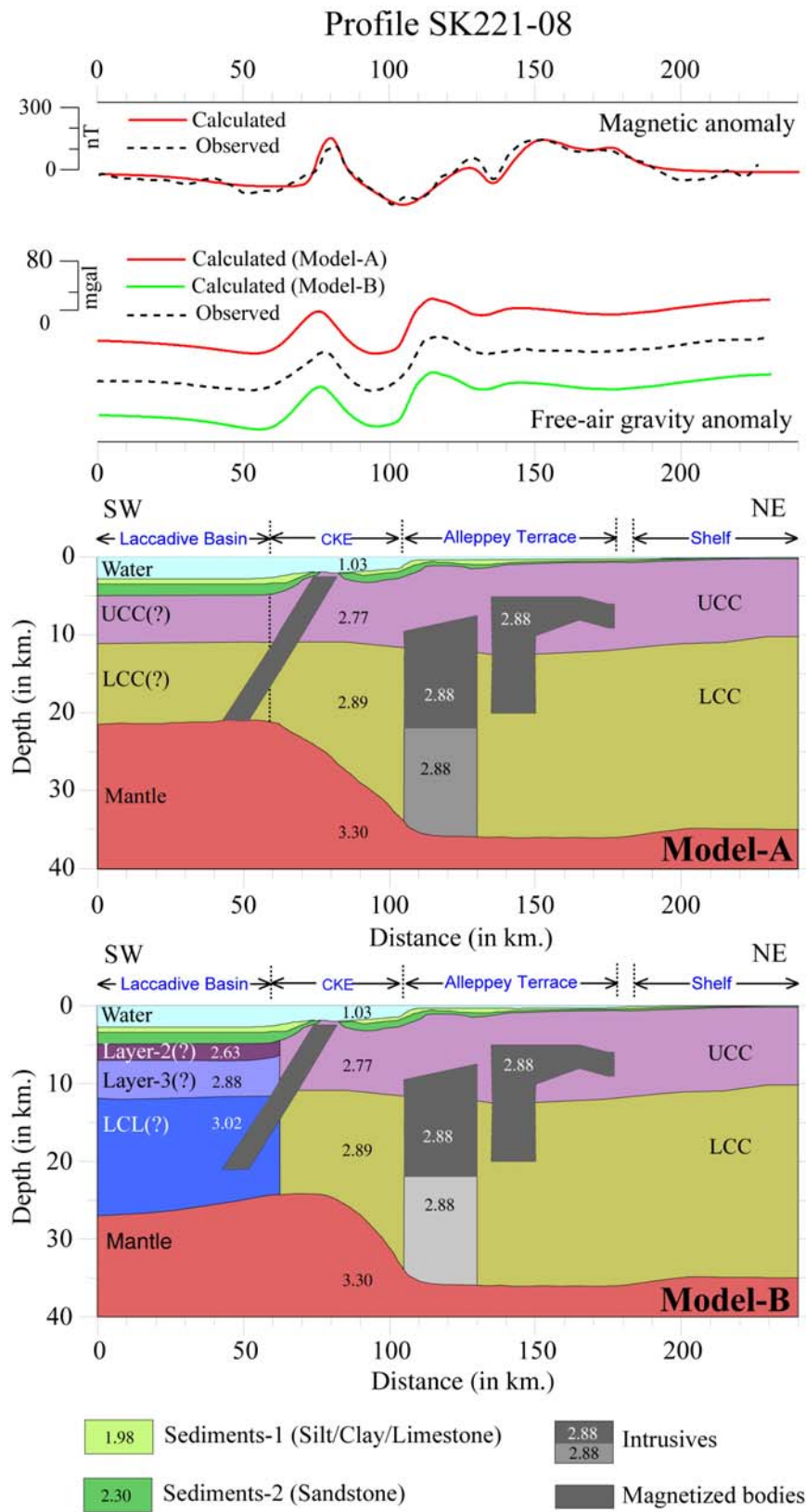


Fig. 11b

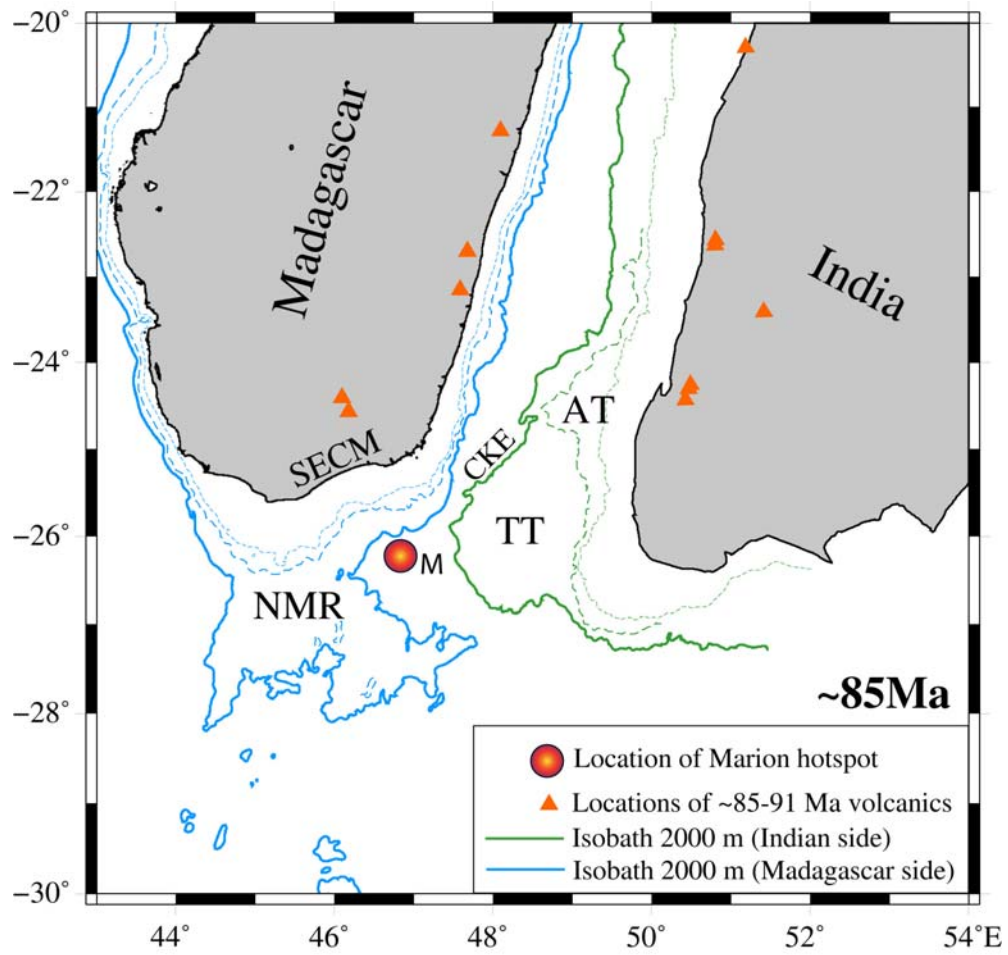


Fig. 12

Supplementary material

Morphotectonic architecture of an India-Madagascar breakup related anomalous submarine terrace complex on the southwest continental margin of India

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The supplementary material contains seven figures which provide detailed information to substantiate the results discussed in the paper.

Captions to Supplementary figures:

Figure S1: Multichannel seismic reflection sections along profile SST-17 and the corresponding gravity signatures. The gravity profiles were extracted from satellite derived free-air gravity grid [Sandwell and Smith, 1997, 2003]. In the Trivandrum Terrace region, the central basement high corresponds to a gravity high while the Eastern and Western grabens correspond to gravity lows. GH-3 is the gravity high trend marked in Figure 7. Kilometre marks along the sections corresponds to the kilometre marks along the location of profiles shown in Figure 2.

Figure S2: Multichannel seismic reflection sections along profile SST-16 and the corresponding gravity signatures. Other details are as in Figure S1.

Figure S3: Geological columns in the neighbourhood of the study area as available in the published drill well logs [Deeskhitulu, 1981; Singh and Lal, 1993] and seismic refraction [Naini, 1980] results. The locations of drill wells and the refraction stations are given in Figure 2.

Figure S4: Gravity and magnetic anomaly modelling derived crustal structure along profile ABC (SG-1+SK221-05) across the Trivandrum Terrace. In this figure, only the upper 10 km of the modelled crustal structure is shown to highlight the basement configuration and its correspondence with the magnetic / gravity anomalies and also the nature of the Chain-Kairali Escarpment along the profile. Other details as in Figure 11.

Figure S5: Gravity and magnetic anomaly modelling derived crustal structure along profile SK221-08 across the Alleppey Terrace. In this figure, only the upper 10 km of the modelled crustal structure is shown to highlight the basement configuration and its correspondence with the magnetic / gravity anomalies and also the nature of the Chain-Kairali Escarpment along the profile. The basement peak 'Z' in the mid-slope region of CKE is inferred as a prominent volcanic intrusive body. Other details as in Figure 11.

Figure S6: Magnetic anomaly modelling for very high amplitude magnetic anomalies observed along the continental shelf part (segment DE of profile SK221-04 as marked in Figure 10). Magnetic anomalies are modeled with two-dimensional magnetic bodies of intrusive dykes and sills (Remanent Inclination = -56° , Remanent Declination = 315° ; Remanent magnetization for bodies A and B = 3.5 A/m; Remanent magnetization for body C = 6.5 A/m). Other details are as in Figure 11.

Figure S7: (a) Part of a published seismic section AB [modified after Whitmarsh et al., 1974] across the prominent bathymetric peak 'Z' in the mid-slope region of CKE. This feature appears to be a volcanic intrusive similar to the St. Mary Islands volcanics, which so far is considered as the only volcanic feature off the western Indian coast representing the volcanism related to India-Madagascar

separation. (b) Location of the seismic section AB marked over a bathymetric contour map. The bathymetric contours shown with: (i) dotted lines within the pink coloured boundary are the updated (in this study) bathymetry contours drawn at 100m contour interval between 200 m and 2000 m isobaths, and (ii) continuous line outside this boundary are selected GEBCO bathymetry contours. The solid red stars represent locations of prominent topographic highs within the domain of Chain-Kairali Escarpment (CKE). The bathymetric peak Z represents a suitable locale in the Indian offshore areas for obtaining rock samples by dredging/ drilling for further studies, which may provide additional constraints for the volcanism related to India-Madagascar separation as well decipher the genesis of the CKE. Other details as in Figure 1.

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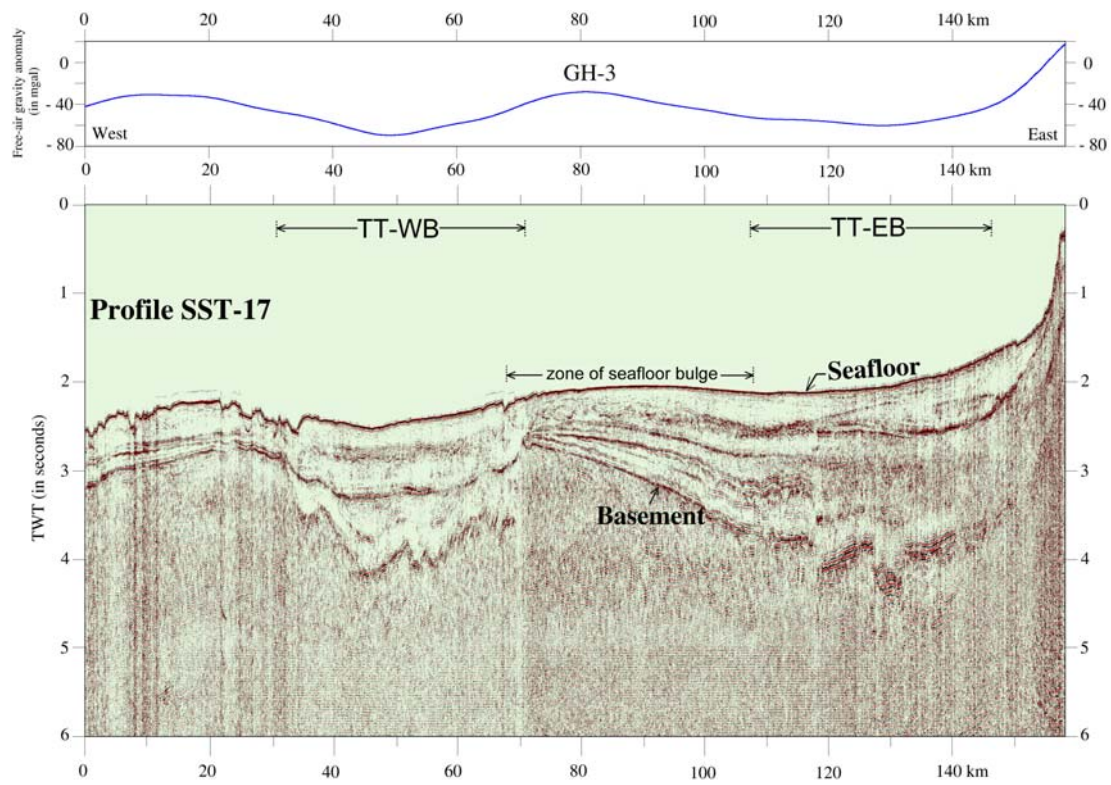


Fig. S1

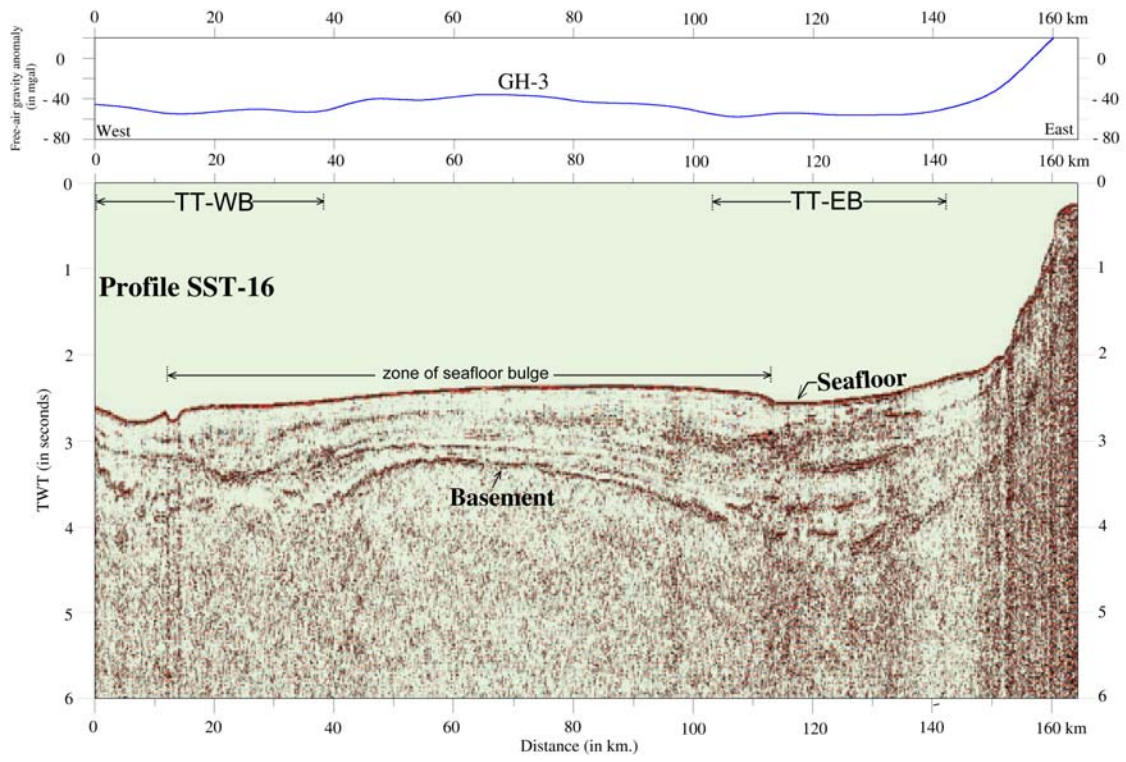


Fig. S2

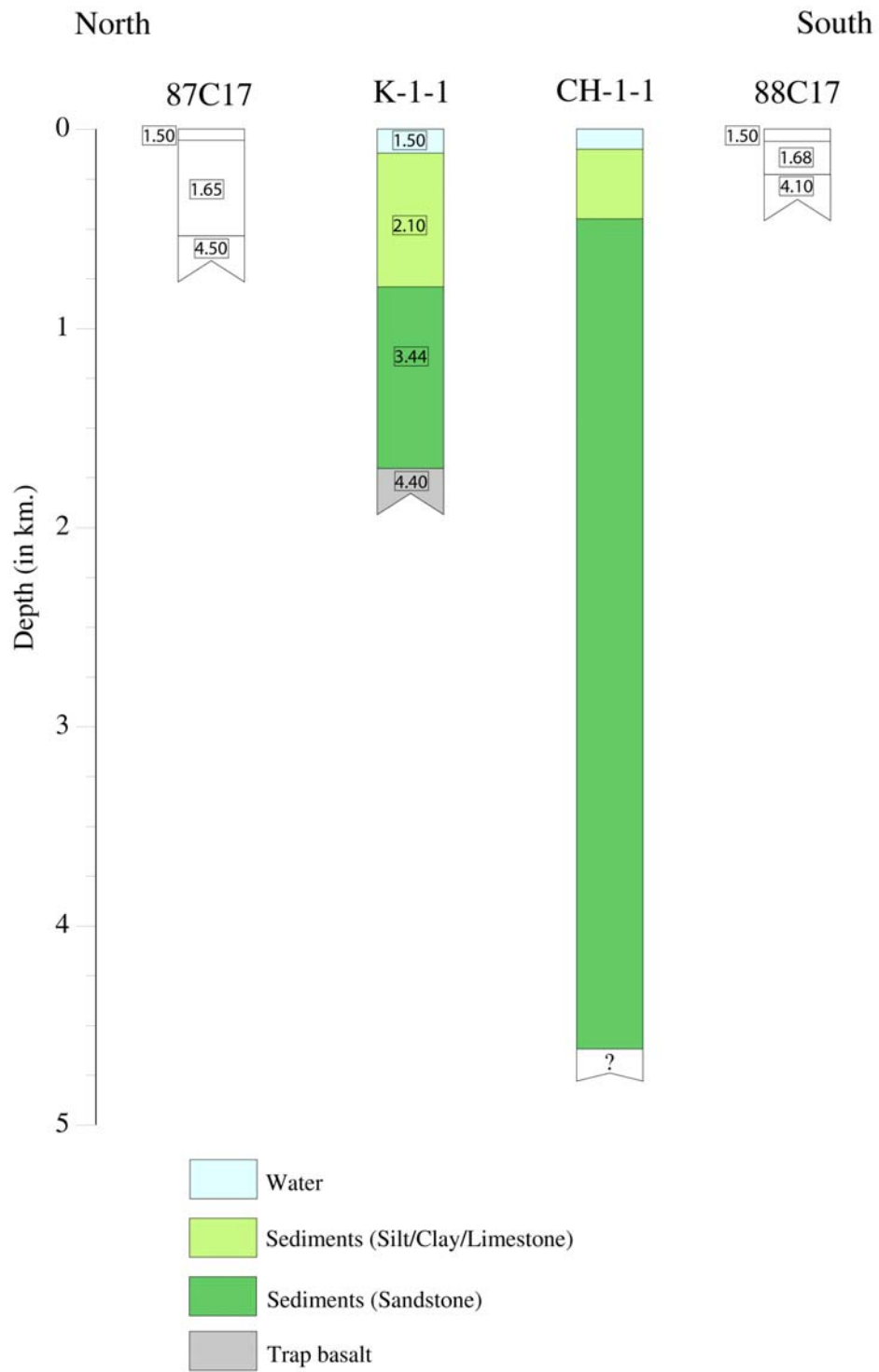


Fig. S3

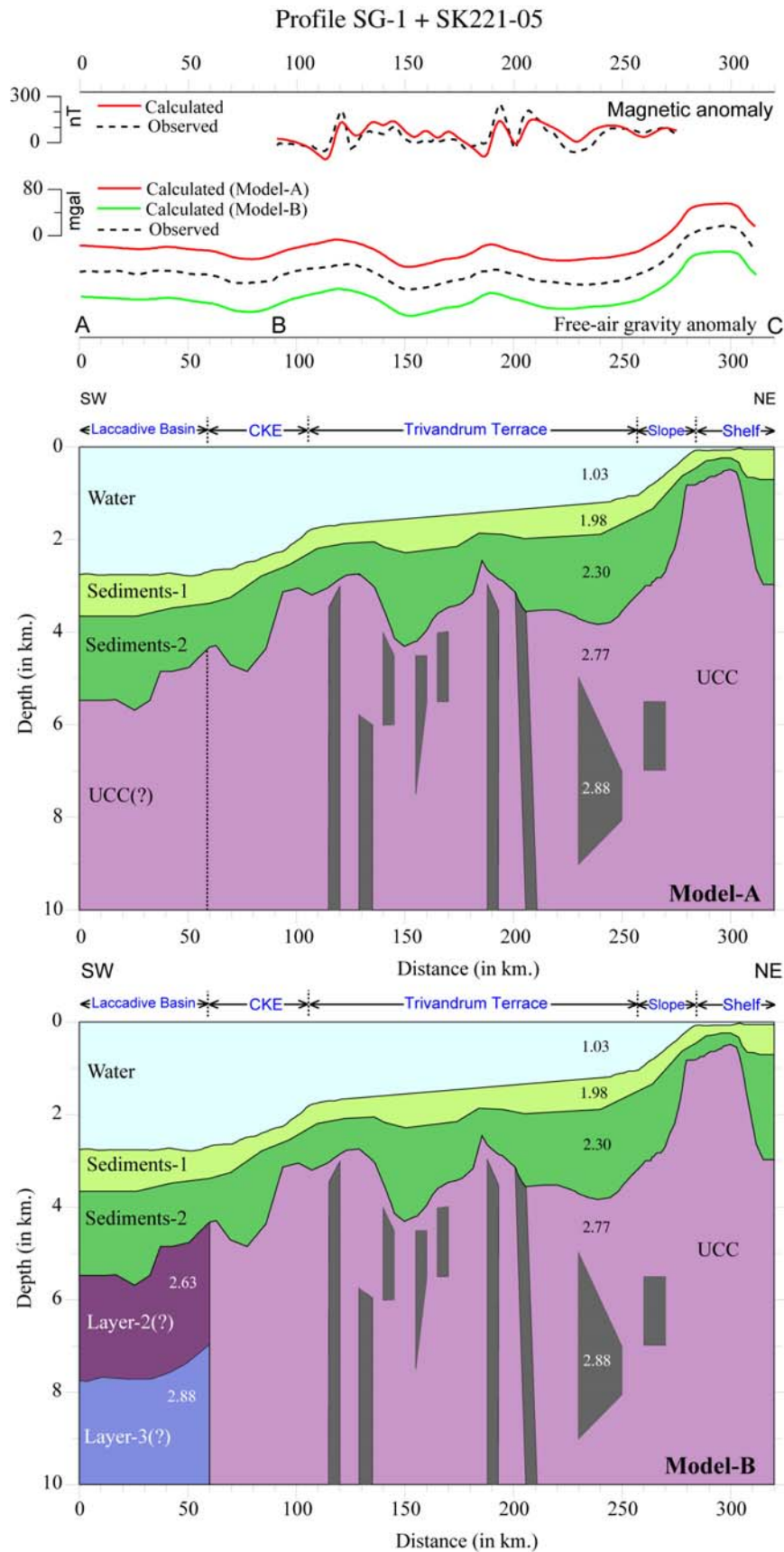


Fig. S4

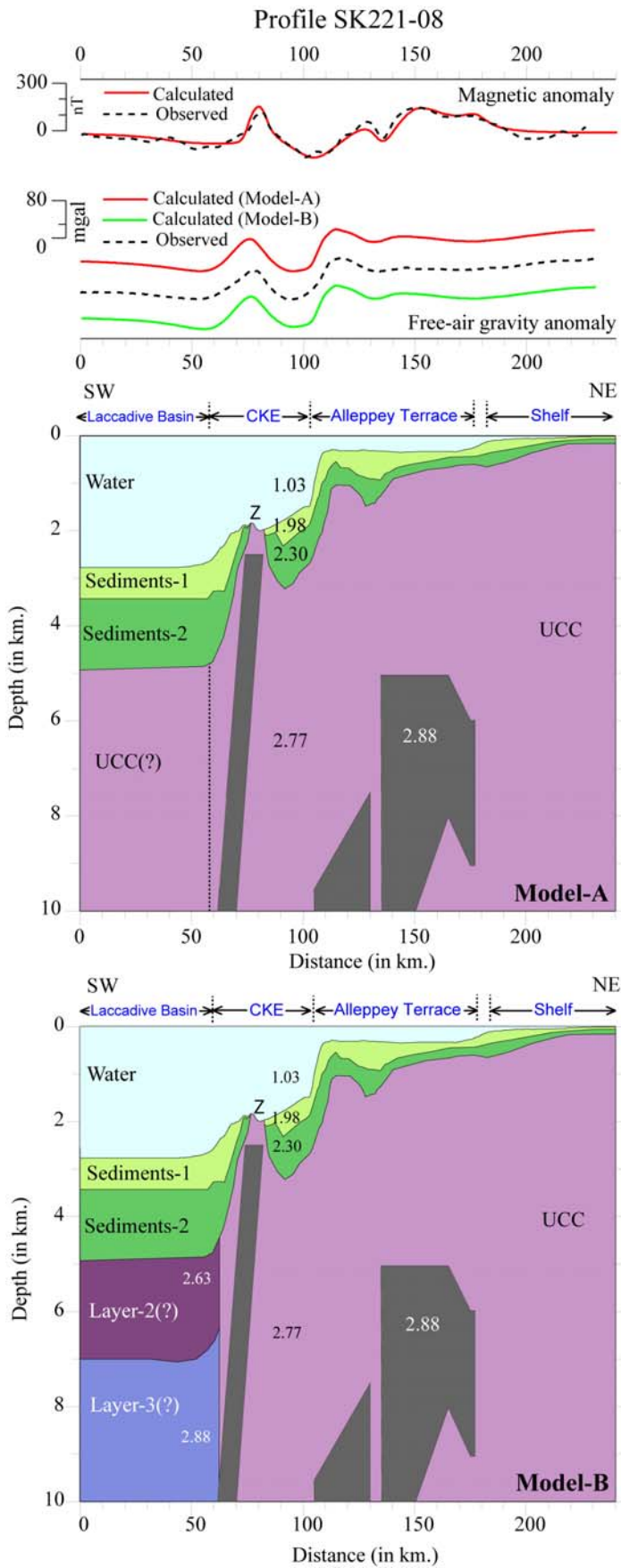


Fig. S5

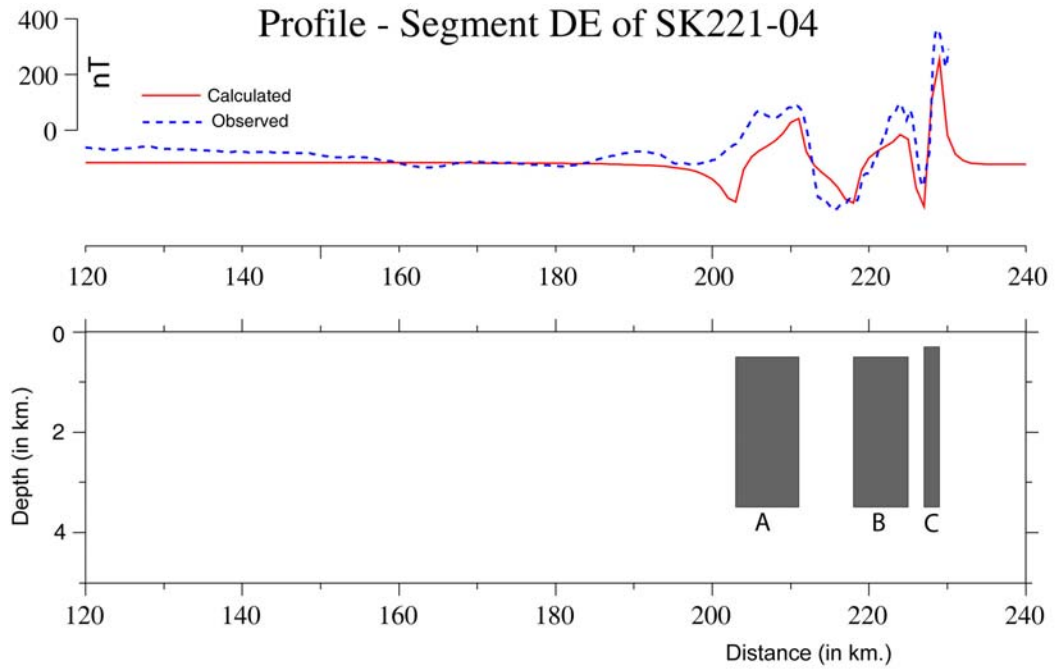


Fig. S6

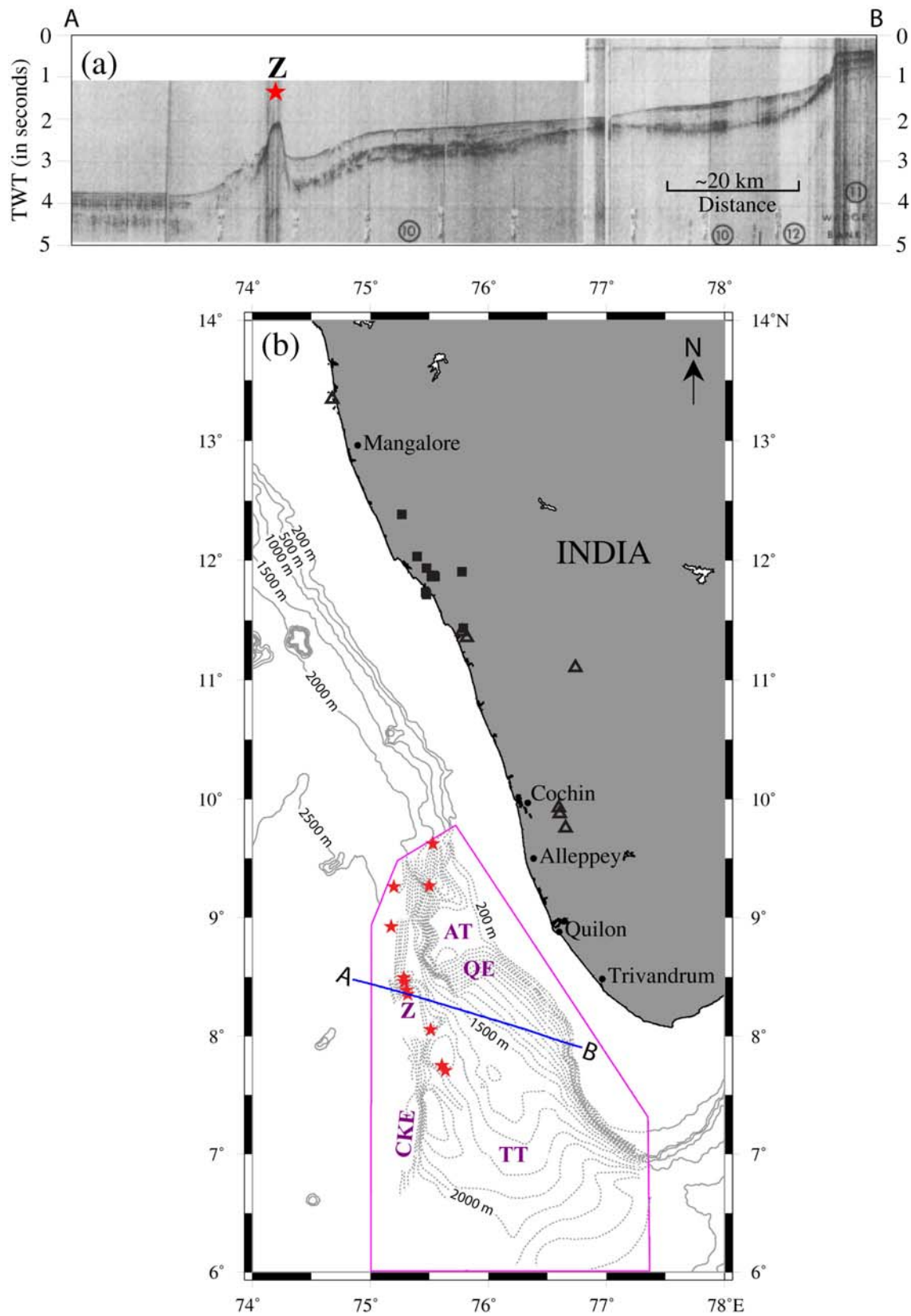


Fig. S7